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RESEARCH ARTICLE

Fiber optical WDM multiplexers/demultiplexers with low bending losses

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Abstract
Objectives. One of the topical tasks in the development of radio electronic systems for various purposes is a sharp increase in the volume and data transfer rate between the elements of the system. This problem is most successfully solved using fiber optic technology, which has no alternative to meet a number of indicators. The use of optical fibers (OF) as a physical medium made it possible to transfer large information flows over considerable distances. Increasing the capacity of communication systems is pushing manufacturers to develop new OF brands with improved optical and operational characteristics, which makes it possible to improve various optical components that use an OF as an active information transmission medium. The dual-channel single-mode wavelength division multiplexing (WDM) multiplexers/demultiplexers, which are one of spectral selective splitters types, are most widely used in fiber-optic communication systems. Among the advantages of WDM, it is worth to note the transmission of a large amount of information over one OF by the arrangement of channels at different wavelengths and the ability to transmit signals of several wavelengths simultaneously in both directions via one OF that do not interact with each other (duplex communication). During operation, WDM multiplexers can be subjected to various external influences that affect the operation and stability of the device parameters. Currently, there are no data on the effect of OF bending on the optical characteristics of WDM multiplexers. In this regard, it is important to study this dependence, which includes measuring the parameters of optical isolation and insertion loss. The purpose of the study is to work out the manufacturing technology and investigate the manufactured WDM multiplexers based on certain types of bend-resistant OF.
Methods. For the formation of two-channel WDM multiplexers, the technology of fused biconical tapering was used, which makes it possible to achieve low insertion loss along with a high degree of channel isolation in the wide temperature range.
Results. In the paper, the possibilities of manufacturing fiber multiplexers based on bend-resistant fiber Corning SMF-28 Ultra were discussed. The results of manufacturing and studying the experimental samples of WDM multiplexers optical characteristics were presented. It was established that the use of SMF-28 Ultra quartz fiber made it possible to significantly reduce the deviation of the channel optical isolation in the event of mechanical stresses in the multiplexers OF structure.
Conclusions. The possibility of creating two-channel multiplexers with low bending losses and optical isolation up to 20–22 dB was experimentally shown. Possible mechanisms of the influence of the multiplexer fiber twisting on the optical isolation of channels were considered. The results obtained showed that when mechanical stresses in the fused structure of the multiplexer occur, the change in the optical isolation coefficient at two operating wavelengths does not exceed 1 dB.

Keywords: fiber-optic communication systems, bend-resistant optical fiber, multiplexer, WDM multiplexer, fused biconical taper technology, coupling region

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НАУЧНАЯ СТАТЬЯ

Волоконно-оптические WDM-мультиплексоры/демультиплексоры с малыми изгибными потерями

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Резюме
Цели. Одной из актуальных задач развития радиоэлектронных систем различного назначения является резкое увеличение объема и скорости передачи информации между элементами этих систем. Такая задача наиболее успешно решается с использованием средств волоконно-оптической техники, не имеющих альтернативы по ряду показателей. Применение оптических волокон (ОВ) в качестве физической среды позволило осуществить передачу больших потоков информации на значительные расстояния. Увеличение пропускной способности систем связи подталкивает производителей к разработке новых марок ОВ с улучшенными оптическими и эксплуатационными характеристиками, что позволяет усовершенствовать различные оптические компоненты, которые используют волоконный световод в качестве активной среды передачи информации. Наиболее широко используемыми в волоконно-оптических системах связи (ВОСС) являются двухканальные одномодовые WDM-мультиплексоры/демультиплексоры, представляющие собой вид спектрально-селективных разветвителей. Среди преимуществ WDM-мультиплексирования стоит отметить передачу большого объема информации по одному ОВ за счет организации каналов на разных длинах волн, возможность передавать по одному ОВ одновременно в обоих направлениях сигналы нескольких длин волн, которые не взаимодействуют друг с другом (дуплексная связь). В процессе эксплуатации WDM-мультиплексоры могут подвергаться различным внешним воздействиям, влияющим на работу и стабильность параметров устройства. В настоящее время отсутствуют данные по влиянию изгибов ОВ на оптические характеристики WDM-мультиплексоров. В связи с этим актуальным является исследование данной зависимости, которое включает в себя измерение параметров оптической изоляции и вносимых потерь. Цель работы – отработка технологии изготовления и исследование изготовленных WDM-мультиплексоров на основе определенных видов ОВ, устойчивых к изгибу.
Методы. Для формирования двухволновых WDM-мультиплексоров использована технология сплавной биконической вытяжки (FBT), позволяющей достичь низких вносимых потерь одновременно с высокой степенью изоляции каналов в широком диапазоне температур.
Результаты. В работе рассмотрены возможности изготовления волоконных мультиплексоров на основе изгибоустойчивого волокна Corning SMF-28 Ultra. Представлены результаты изготовления и исследования оптических характеристик экспериментальных образцов WDM-мультиплексоров. Установлено, что применение кварцевого волокна SMF-28 Ultra позволило существенно снизить девиацию оптической изоляции каналов при возникновении механических напряжений в световодной структуре мультиплексоров.

Выводы. Экспериментально показана возможность создания двухволновых мультиплексоров с малыми изгибными потерями и оптической изоляцией до 20–22 дБ. Рассмотрены возможные механизмы влияния скручивания волоконных выводов мультиплексора на оптическую изоляцию каналов. Полученные результаты показывают, что при возникновении механических напряжений в сплавленной структуре мультиплексора изменение коэффициента оптической изоляции на двух рабочих длинах волн не превышало 1 дБ.

Ключевые слова: волоконно-оптические системы связи, изгибоустойчивое оптическое волокно, мультиплексор, WDM-мультиплексор, FBT-технология, область связи

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INTRODUCTION

Modern fiber-optic communication systems (FOCS) are characterized by a constant increase in throughput, improvement in the optical components performance, and the ever-increasing introduction of fiber-optic devices into special equipment. This imposes increased requirements on the reliability, miniaturization, and performance of FOCS components [1].

In the recent years, FOCS with wavelength division multiplexing have been actively used in various telecommunication systems. To implement such systems, special passive optical devices are often used, such as fused wavelength division multiplexing (WDM) multiplexers/demultiplexers, designed to combine and separate several information signals with wavelengths of 1.31 μm and 1.55 μm and transmit them over a single optical fiber (OF) [2]. Such devices have been used in the market for a long time and have proven themselves due to a fairly high level of performance and low cost. Multiplexers currently produced by a number of leading companies and enterprises are usually made from standard Corning SMF-28e+ category G.652.D fiber, which is actively used in urban and access networks. However, such a fiber has one significant drawback. This is an increase in losses caused by macrobends, which degrade the data transmission and reception quality [3–5]. Therefore, multiplexers based on this fiber are also affected by the fiber bending and, as a result, the deterioration of their optical characteristics.

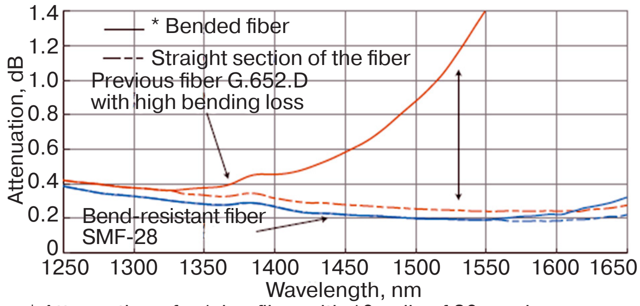
This work analyzed the issues of manufacturing technology and the possibility of forming fused multiplexers based on bend-resistant single-mode Corning SMF-28 Ultra[1] fiber and presents the results of manufacturing and studying the optical characteristics of WDM multiplexers experimental samples.

[1] SMF-28® Ultra Optical Fibers. URL: https://www.corning.com/ru/ru/products/communication-networks/products/fiber/smf-28-ultra.html. Accessed June 7, 2021 (in Russ.).

CORNING SMF-28 ULTRA QUARTZ BEND-RESISTANT FIBER

Corning SMF-28 Ultra single-mode fiber with improved optical attenuation and bending loss resistance exceeding the requirements of ITU-T G.657.A1 makes it possible to upgrade existing fiber optic telecommunications devices, in particular, two-channel WDM multiplexers, whose light guide structure is sensitive to various influencing factors.

Figure 1 shows bend attenuation for standard G.652.D fiber and bend-resistant SMF-28 Ultra fiber [6].



* Attenuation of a 1-km fiber with 10 coils of 30 mm in diameter.

Fig. 1. Bend attenuation gain in standard G.652.D fiber and bend-resistant SMF-28 Ultra fiber

Figure 1 shows that at longer wavelengths, when the optical signal is less dependent on the core of a single-mode OF, the bending losses in the G.652.D fiber increase significantly compared to the bend-resistant SMF-28 Ultra fiber.

CORNING SMF-28 ULTRA WDM MULTIPLEXER MANUFACTURING TECHNOLOGY

The manufacturing technology of fiber optic two-channel WDM multiplexers with low bending losses is based on the fusion of two bend-resistant SMF-28 Ultra fibers with simultaneous stretching of the branching section to obtain a smooth biconical taper necessary for effective waveguide coupling between the fibers (fused biconical taper (FBT) technology) [7].

The method of creating a single-mode WDM multiplexer is illustrated in Fig. 2 [8].

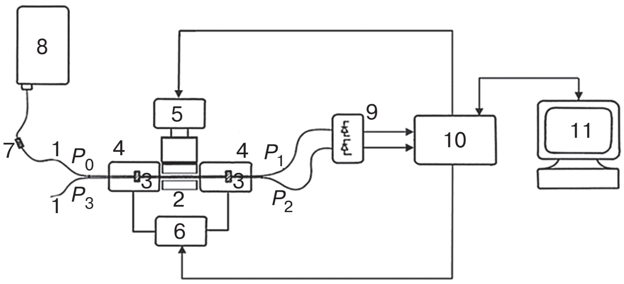


Fig. 2. Structural diagram of the device for the manufacture of fused WDM multiplexers:
(1) SMF-28 Ultra OFs,
(2) high-temperature heater,
(3) fiber clamping units,
(4) movable carriages,
(5) heater power supply,
(6) electric drive unit,
(7) place for fusing the pigtail with SMF-28 Ultra fiber,
(8) light source,
(9) photodetector,
(10) control unit,
and (11) personal computer

Sections of SMF-28 Ultra fibers prepared in advance and cleaned at a length of ≈35 mm from the protective outer coating were interconnected by twisting around the longitudinal axis for one full turn (Fig. 3), forming a branching section for forming a multiplexer, fixed on carriages and placed into the heater.

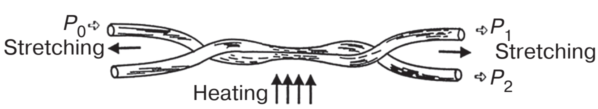


Fig. 3. Branching section of two twisted fibers

During the manufacture of the multiplexers, the current values of the radiation power P_1 and P_2 coming from the output channels of the multiplexer to the photodetectors of the computerized measuring system were monitored [9]. The process was terminated when a certain length of the coupling region (z) was reached, which is necessary for the spectral selection of two wavelengths (Fig. 4) [10, 11].

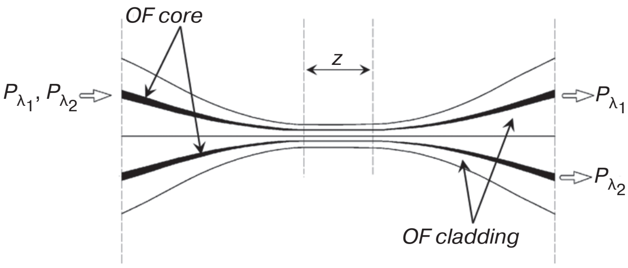


Fig. 4. Schematic representation of the FBT multiplexer

One of the main characteristics of fused WDM multiplexers is the insertion loss A_{in} and the isolation coefficient K_{is}, which determines the level of signal attenuation in those channels, in which this signal is not the main one. For this device, the above parameters are defined by the following expressions:

$$A_{in} = 10\lg\frac{P_0}{P_i};\ K_{is} = 10\lg\frac{P_0}{P_j};\ j \neq i = 1,2, \quad (1)$$

where P_0 is the optical power in the input channel at wavelength λ_i; P_i is the optical power at the output of the ith (main) channel at wavelength λ_i; P_j is the optical power in the jth (non-fundamental) channel at wavelength λ_i.

The most important requirements for optical splitters for WDM systems are to provide a given splitting ratio between channels with minimal deviations from the given value and the minimum value of insertion attenuation over the entire operating spectral range [12, 13].

MANUFACTURING AND RESEARCH OF WDM MULTIPLEXERS

In the present work, FBT multiplexers were fabricated using a Japanese FCI-0201 facility from NTT AT with a ceramic microheater [14–16].

The method for forming light guide biconical structures is schematically shown in Fig. 5 [17].

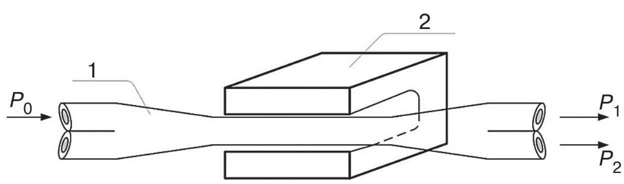


Fig. 5. Multiplexer manufacturing method: (1) SMF-28 Ultra OFs and (2) ceramic microheater

For the successful manufacture of WDM multiplexers based on SMF-28 Ultra fiber, a technology with optimal

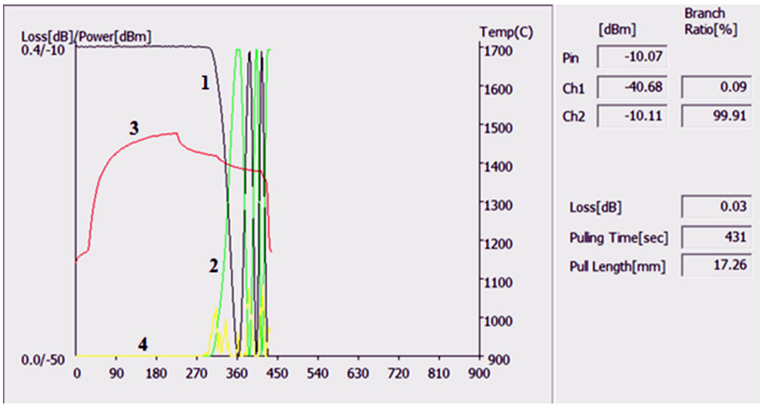


Fig. 6. The result of manufacturing the WDM multiplexer:
(1) radiation power P_1 at the output of channel Ch1,
(2) radiation power P_2 at the output of channel Ch2,
(3) heating temperature of the fiber fusion zone, and (4) insertion loss

temperature and time parameters of the process was developed. The heating temperature of the fiber fusion zone was 1500–1550°C, and the pulling speed decreased from 60 μm/s at the beginning of the process to 10 μm/s at the end.

In the process of stretching and formation of a biconical waist, the change in the radiation power P_1 and P_2 in the fiber outputs of the multiplexer was displayed, and the insertion loss for a wavelength of 1550 nm was monitored (Fig. 6). The pulling time of the sample during fusion was about 431 s. The pull length after fusion was 17.26 mm, and the total length of the multiplexer fiber structure was 53 mm. The insertion loss of the fabricated sample did not exceed 0.1 dB. The optical isolation factor of the WDM multiplexer channels was 20–22 dB.

The performance stability of WDM multiplexers under operating conditions greatly depends on their light guide structure. Various mechanical influences that a multiplexer may be subjected to during operation can lead to deformation of its biconical structure and, as a result, to a decrease in the isolation coefficient and disruption of the transmission line [18].

One of possible mechanical influences is due to the twisting of the light guide structure of the formed multiplexers that may cause the redistribution of optical power in the channels and the change in the optical isolation value. Such an effect was observed in the study of multiplexers based on the standard fiber SMF-28e+ [19].

The experiment was conducted with multiplexers manufactured based on SMF-28 Ultra bend-resistant fibers to study the effect of twisting of the fused structure on the optical isolation of channels. For this, one section (1) of the fiber leads (2) of the multiplexer on the side of the optical light source rotated around the optical axis of the biconical structure, and the other section (3) on the side of the optical power meter was fixed (Fig. 7). The distance l between sections 1 and 2 of fibers was 200 mm. During the experiment, the isolation factors were continuously measured at two operating wavelengths λ_1 = 1310 nm and λ_2 = 1550 nm.

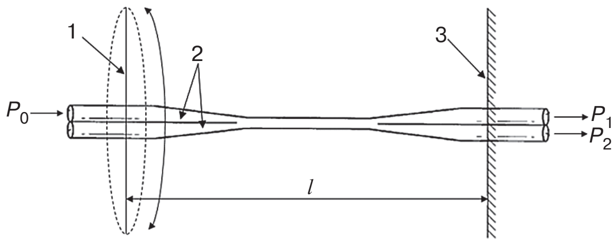


Fig. 7. Schematic representation of the twisting of the fiber structure of WDM multiplexer

As a result of the study, it was found that when mechanical stresses occurred in the fused structure of the multiplexer, the change in the optical isolation factor at two operating wavelengths did not exceed 1 dB. The use of SMF-28 Ultra quartz fibers made it possible to significantly reduce the optical isolation deviation of the channels in the event of mechanical stresses in the OF structure of the multiplexers.

CONCLUSIONS

A method for manufacturing the fused single-mode multiplexers from Corning SMF-28 Ultra fiber was presented. The optical characteristics of the fabricated samples were studied. Possible mechanisms of the influence of the multiplexer fiber leads twisting on the channels optical isolation were considered. The possibility of creating two-channel multiplexers with low bending losses and optical isolation up to 20–22 dB was experimentally shown.

REFERENCES

1. Lutchenko S.S., Kopytov E.Yu., Bogachkov I.V. Evaluation of FOCL reliability taking into account the impact of external factors. *Dinamika sistem, mehanizmov i mashin = Dynamics of Systems, Mechanisms and Machines* (*Dynamics*). 2017;5(4):34–39 (in Russ.). https://doi.org/10.25206/2310-9793-2017-5-4-34-39
2. Ivanov V.I. *Primenenie tekhnologii WDM v sovremennykh setyakh peredachi informatsii* (*Application of WDM technology in modern information transmission networks*). Kazan: Novoe znanie; 2012. 223 p. (in Russ.). ISBN 978-5-89347-679-8
3. Besprozvannykh V.G., Mosunova I.D. Optical characteristics of single-mode bend-resistant fibers at construction in small closed objects. *Innovatsionnaya Nauka = Innovation Science.* 2019;1:19–23 (in Russ.).
4. Mosunova I.D., Seleznev D.A., Remennikova M.V. Research of the spectral transmittance of optical fibers at small bends. *Prikladnaja fotonika = Applied Photonics.* 2019;6(1–2):17–23 (in Russ.).
5. Matthijsse P., Kuyt G. Influence of bending of optical fibers on their characteristics. *Kabeli i Provoda = Cables and Wires.* 2005;4(293):17–22 (in Russ.).
6. Dorozhkin A., Nanii O., Treshchikov V., Shikhaliev I. Low bendingloss fiber – a new life for C+L communication systems. *Pervaya Milya = Last Mile*. 2018;8(77):48–53 (in Russ.). https://doi.org/10.22184/2070-8963.2018.77.8.48.53
7. Rozhdestvenskii Yu.V. Fusion fiber-optic multiplexers/demultiplexers and their application in telecommunication systems. *Foton-Express*. 2004;1(31):16–18 (in Russ.).
8. Berikashvili V.Sh., Elizarov S.G., Klyuchnik N.T., Kuznetsov V.A., Yakovlev M.Ya. WDM fiber multiplexers with reduced spectral spacing between channels. *Fundamental'nye problemy radioelektronnogo priborostroeniya = Fundamental Problems of Radioengineering and Device Construction*. 2014;5:112–115 (in Russ.).
9. Basiladze G.D., Berzhanskiy V.N., Dolgov A.I., Milyukova E.T. Transformation of the fiber cores under conditions of weak and strong fusing of optical coupler. *Scientific Notes of Taurida National V.I. Vernadsky University. Series: Physics and Mathematics Sciences.* 2010;23(62):75–80 (in Russ.).
10. Berikashvili V.Sh., Dement'ev S.G., Klyuchnik N.T., Yakovlev M.Ya. Spectral selective optical splitters with increased channel isolation. *Fundamental'nye problemy radioelektronnogo priborostroeniya = Fundamental Problems of Radioengineering and Device Construction*. 2011;11(1):190–193 (in Russ.).
11. Hui R., O'Sullivan M. *Fiber Optic Measurement Techniques*. Elsevier; 2009. 672 p. ISBN: 978-0-12-373865-3
12. Bazakutsa P.V., Boyev M.A., Nikitin A.I. Investigation of the spectral characteristics of optical splitters. *Foton-Ekspress = Foton-Express.* 2019;6(158):178–179 (in Russ.). https://doi.org/10.24411/2308-6920-2019-16089
13. Shestakov I.I. Analysis of applicability of FBT 1 × 2 splitters on PON networks. *Vek kachestva = Age of Quality.* 2019;3:137–148 (in Russ.).

СПИСОК ЛИТЕРАТУРЫ

1. Лутченко С.С., Копытов Е.Ю., Богачков И.В. Оценка надежности ВОЛС с учетом влияния внешних факторов. *Динамика систем, механизмов и машин.* 2017;5(4):34–39. https://doi.org/10.25206/2310-9793-2017-5-4-34-39
2. Иванов В.И. *Применение технологии WDM в современных сетях передачи информации*. Казань: ЗАО «Новое знание»; 2012. 223 с. ISBN 978-5-89347-679-8
3. Беспрозванных В.Г., Мосунова И.Д. Оптические характеристики одномодовых изгибоустойчивых волокон при укладке в малых замкнутых объектах. *Инновационная наука.* 2019;1:19–23.
4. Мосунова И.Д., Селезнев Д.А., Ременникова М.В. Исследование спектрального пропускания оптического волокна при малых изгибах. *Прикладная фотоника.* 2019;6(1–2):17–23.
5. Matthijsse P., Kuyt G. Влияние изгибов оптических волокон на их характеристики. *Кабели и провода.* 2005;4(293):17–22.
6. Дорожкин А., Наний О., Трещиков В., Шихалиев И. Волокно с малыми изгибными потерями – новая жизнь для систем связи диапазона C+L. *Первая Миля*. 2018;8(77):48–53. https://doi.org/10.22184/2070-8963.2018.77.8.48.53
7. Рождественский Ю.В. Сплавные волоконно-оптические мультиплексоры/демультиплексоры и их применение в телекоммуникационных системах. *Фотон-Экспресс*. 2004;1(31):16–18.
8. Берикашвили В.Ш., Елизаров С.Г., Ключник Н.Т., Кузнецов В.А., Яковлев М.Я. Волоконные WDM-мультиплексоры с уменьшенным спектральным интервалом между каналами. *Фундаментальные проблемы радиоэлектронного приборостроения*. 2014;14(5):112–115.
9. Басиладзе Г.Д., Бержанский В.Н., Долгов А.И., Милюкова Е.Т. Преобразование сердцевин волокон в условиях слабого и сильного сплавления оптического разветвителя. *Вестник Физико-технического института Крымского федерального университета имени В.И. Вернадского.* 2010;23(62):75–80.
10. Берикашвили В.Ш., Дементьев С.Г., Ключник Н.Т., Яковлев М.Я. Спектрально-селективные оптические разветвители с повышенной изоляцией каналов. *Фундаментальные проблемы радиоэлектронного приборостроения*. 2011;11(1):190–193.
11. Hui R., O'Sullivan M. *Fiber Optic Measurement Techniques*. Elsevier; 2009. 672 p. ISBN: 978-0-12-373865-3
12. Базакуца П.В., Боев М.А., Никитин А.И. Исследование спектральных характеристик оптических разветвителей. *Фотон-Экспресс.* 2019;6(158):178–179. https://doi.org/10.24411/2308-6920-2019-16089
13. Шестаков И.И. Анализ применимости FBT-разветвителей 1 × 2 в сетях PON. *Век качества.* 2019;3:137–148.
14. Takeuchi Y., et al. Characteristics of ceramic microheater for fiber coupler fabrication. *Jpn. J. Appl. Phys.* 1998;37(6):3665–3668. https://doi.org/10.1143/JJAP.37.3665
15. Takeuchi Y., Horiguchi M. Microheater control of wavelength-flattened fiber coupler properties. *Appl. Opt.* 1994;33(6):1029–1034. https://doi.org/10.1364/AO.33.001029

14. Takeuchi Y., et al. Characteristics of ceramic microheater for fiber coupler fabrication. *Jpn. J. Appl. Phys.* 1998;37(6):3665–3668. https://doi.org/10.1143/JJAP.37.3665
15. Takeuchi Y., Horiguchi M. Microheater control of wavelength-flattened fiber coupler properties. *Appl. Opt.* 1994;33(6):1029–1034. https://doi.org/10.1364/AO.33.001029
16. Takeuchi Y. Characteristics analysis of wavelength-division-multiplexing fiber couplers fabricated with a microheater. *Appl. Opt.* 1996;35(9):1478–1484. https://doi.org/10.1364/ao.35.001478
17. Dement'ev S.G., Klyuchnik N.T., Kuznetsov V.A., Yakovlev M.Ya. Fiber-optic demultiplexers for information transmission systems. *Tekhnologiya i konstruirovanie v elektronnoi apparature = Technology and Design in Electronic Equipment.* 2010;2:43–36 (in Russ.).
18. Besprozvannykh V.G., Mosunova I.D., Nosova E.A., Krivosheev A.I. Investigation of the characteristics of fusion fiber splitters based on bend-resistant fiber. *Prikladnaya fotonika = Applied Photonics.* 2021;8(1):51–67 (in Russ.).
19. Dement'ev S.G., Klyuchnik N.T., Kuznetsov V.A., Yakovlev M.Ya. Singlemode wavelength-selective splitters with increased mechanical resistance. *Fundamental'nye problemy radioelektronnogo priborostroeniya = Fundamental Problems of Radioengineering and Device Construction*. 2010;10(1):164–167 (in Russ.).

16. Takeuchi Y. Characteristics analysis of wavelength-division-multiplexing fiber couplers fabricated with a microheater. *Appl. Opt.* 1996;35(9):1478–1484. https://doi.org/10.1364/ao.35.001478
17. Дементьев С.Г., Ключник Н.Т., Кузнецов В.А., Яковлев М.Я. Волоконно-оптические демультиплексоры для систем передачи информации. *Технология и конструирование в электронной аппаратуре*. 2010;2:43–46.
18. Беспрозванных В.Г., Мосунова И.Д., Носова Е.А., Кривошеев А.И. Исследование характеристик сплавных волоконных разветвителей на основе изгибоустойчивого волокна. *Прикладная фотоника.* 2021;8(1):51–67.
19. Ключник Н.Т., Дементьев С.Г., Кузнецов В.А., Яковлев М.Я. Одномодовые спектрально-селективные разветвители с повышенной механической стойкостью. *Фундаментальные проблемы радиоэлектронного приборостроения*. 2010;10(1):164–167.

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RESEARCH ARTICLE

Safety of electromagnetic factors for the workplace equipped with personal computers in residential premises

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Abstract
Objectives. The aim of this paper is to analyze the electromagnetic safety of 50Hz industrial frequency electrical networks in residential buildings when using workplaces equipped with personal computers (PCs), as well as to develop recommendations on reducing the impact of levels of industrial frequency electromagnetic fields on human health in residential premises.
Methods. Electromagnetic fields in residential premises with the single-phase TN mode industrial frequency power supply system regulated by the Rules of Electrical Installations Design were measured and calculated in accordance with Russian and international legislative documents.
Results. It was established that electromagnetic fields induced by TN networks in workplaces equipped with PCs might increase significantly and even exceed the maximum permissible level of 25 V/m and 0.25 μT recommended by Sanitary and Epidemiological Standards. Residential buildings are not subject to the requirements of the Energy Supervision services; therefore, any unprofessional modification of electrical networks in residential premises, including the use of unapproved extension cords, may result in sparking, high-frequency harmonics, and, in turn, conditions which impact human health, as well as electric injures, fires, and gas explosions.
Conclusions. It has been shown that IT (TT) mode symmetrical two-phase electrical networks may function efficiently for decades without accidents and effects of industrial frequency electromagnetic field on humans, as they are used in medical institutions, defense enterprises, and state institutions. Thus, legislative transition to installing IT (TT) systems in residential buildings, replacement of existing TN power supply systems with IT (TT) system, and legislative strengthening of requirements for household protection and commutation devices, may also be required to reduce man-made disaster risks in residential buildings.

Keywords: residential premises, remote workplace, incompatible standards, dangers of the single-phase electrical network, symmetric network efficiency, ungrounded network efficiency, recommended conditions, self-monitoring

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НАУЧНАЯ СТАТЬЯ

Безопасность электромагнитных факторов на компьютерных рабочих местах в жилых помещениях

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Резюме
Цель. Проанализировать электромагнитную безопасность электрических сетей промышленной частоты (ПЧ) 50 Гц в жилых домах при длительной работе на рабочих местах (РМ) с персональными компьютерами (ПК). Выработать рекомендации по уменьшению воздействия уровней электромагнитных полей (ЭМП) ПЧ на здоровье людей в жилых помещениях.
Методы. В соответствии с российскими и международными нормативными документами проведены измерения и расчеты электромагнитных полей в жилых помещениях, где применяется однофазная система электроснабжения типа TN ПЧ, регламентированная правилами эксплуатации электроустановок.
Результаты. Выявлено, что на РМ с ПК электромагнитные поля, индуцируемые сетями типа TN, существенно возрастают, превышая предельно допустимые уровни: 25 В/м и 0.25 мкТл, рекомендуемые санитарно-эпидемиологическими требованиями. На жилые здания требования служб Энергонадзора не распространяются, поэтому любые непрофессиональные переделки электрических сетей в квартирах и использование несертифицированных удлинителей приводят к искрообразованию, появлению высокочастотных гармоник и, в свою очередь, к дискомфортным условиям, влияющим на здоровье, а также к электропоражениям, пожарам и взрывам газа.
Выводы. Показано, что двухфазные симметричные электрические сети системы IT (TT) эффективно функционируют без аварий и воздействия ЭМП ПЧ на людей десятки лет и используются в медицинских, оборонных предприятиях и госучреждениях. С целью уменьшения техногенных катастроф в жилых домах необходимо законодательно перейти на систему IT (TT) в жилых домах, заменить существующие системы электроснабжения TN на систему IT (TT) и, кроме того, законодательно повысить требования к бытовым устройствам защиты и коммутации.

Ключевые слова: жилое помещение, дистанционная работа, несовместимые нормы, опасности однофазной электросети, эффективность симметричной сети, рекомендуемые условия, самоконтроль

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INTRODUCTION

In practice, even one workplace equipped with PC (WP PC) (sometimes more than 8 hours and during night-time) in residential premise may give rise to problems threatening the life and health of employees (students), as well as other residents. Some households have three or more WP PCs. In addition to the negative stress impact of domestic and family worries, many other cases of extreme fatigue, tiredness, and decreased performance at the end of the working day have been identified in results of private surveys and remote employee complaints, when compared with using WP PCs located in offices.

According to Order No. 33n of January 24, 2014 of the Ministry of Labor and Social Protection of the Russian Federation[1], a special assessment of working conditions in respect to WP PCs was nearly canceled. The new version of the Sanitary and Epidemiological Norms (SanPiN)[2] approved by the Federal Service for Surveillance on Consumer Rights Protection and Human Well-being (Rospotrebnadzor) entered into force. This was without any argumentation in terms of sanitary impacts, or discussions with experts on Internet. This also excluded Swedish electromagnetic compatibility (EMC) requirements for WP PCs (SanPiN 2.2.4.3359-16[3], paragraph 7.2.7, Table 1), while canceling SanPiN itself.

Remote WP PCs are located usually in residential premises often unadapted for this purpose (power supply, Internet connection, office equipment, and communication). While the employer is responsible for safety in office WP PCs, ensuring responsibility for the fire, electrical, and electromagnetic safety of the remote workplace does not fall under supervision of the Russian Ministry of Emergency Situations, Energy, and Sanitation Departments.

All departmental documents related to ensuring safe conditions in housing and communal services (HCS) refer to paragraph 1 of Article 161 of the Housing Code of the Russian Federation of 03.04.2018 № 59-FZ[4]. This states that "the management of an apartment building should ensure the favorable and safe living conditions for citizens". It also proposes a General Declaration. Thus, users themselves are now responsible for monitoring living conditions in premises and safety of WP PCs, in order to preserve their health as well as the health of other residents.

Remaining indoors for too long may become uncomfortable and dangerous in conditions of weakened geomagnetic field (GMF) and distorted geoelectric field (GEF), as well as in conditions of increased man-made electromagnetic fields (EMF). Residents today may not even realize the reduced natural EMF and increased man-made EMF in their homes, WP PCs, bedrooms, and kitchens. The Ministry of Emergency Situations, health and sanitary information, and mass media cannot encourage residents to monitor EMF conditions in their premises independently, despite the simplicity of such monitoring comparable with the use of a smartphone [1–7].

After monitoring complaints from house residents for several years concerning dangerous and uncomfortable living conditions has revealed that up to 60% of all cases are caused by electrical networks with TN earth system[5] with solidly grounded neutral (French: Terre – Neuter) in accordance with the Rules of Electrical Installations Design (PUE)[6] for residential premises (PUE, paragraph 7.1.13) and public buildings (PUE, paragraph 7.2.9) [1]. Left over many years, unattended household TN electrical networks may result occasionally in sparking and short circuits (SC). This may result in multiple accidents, such as explosions, fires, and electrical injuries causing destruction of buildings and loss of life.

In contrast to international standards on electrical safety, Russian electrical networks are equipped with circuit breakers (CBs) and residual current devices (RCDs) with reduced reliability requirements. This exacerbates the risks of explosion, fire, and electrical hazards in buildings with TN mode single-phase power supply. Two-phase symmetrical IT (TT) networks[7] with safety criteria much higher than those of TN networks should be used in residential and public buildings

[1] Order of the Ministry of Labor and Social Protection of the Russian Federation No. 33n of January 24, 2014 on the endorsement of the Method of special assessment of working conditions, Classifier of adverse and/or hazardous production factors, form of report of the carried out special assessment of working conditions and its filling instruction. Amended on April 27, 2020 (in Russ.).

[2] SanPiN 1.2.3685-21 Hygienic Standards and Requirements for Ensuring Safety and/or Harmlessness of Environmental Factors for Humans. Approved by the Order No. 2 of 28.01.2021 of the Chief State Sanitary Physician of the Russian Federation (in Russ.).

[3] SanPiN 2.2.4.3359-16 Sanitary and Epidemiological requirements for physical factors in the workplace. Approved by the Order No. 81 of 21.06.2016 of the Chief State Sanitary Physician of the Russian Federation (in Russ.).

[4] Federal Law on Amendments to Housing Code of Russian Federation No. 59-FZ, dated April 3, 2018 (in Russ.).

[5] Electrical network with solidly grounded neutral in accordance with PUE, paragraph 1.7.3 (in Russ.).

[6] Rules of Electrical Installations Design (PUE). Approved by the Order No. 204 of the Ministry of Energy of the Russian Federation on July 8, 2002 (in Russ.).

[7] Electrical network with isolated neutral in accordance with PUE, paragraph 1.7.3 (in Russ.).

with no actual network supervision (before failure or emergency).

Forty-four cases of domestic gas explosions in Russian residential buildings in 2017–2018 have resulted in victims and casualties. The explosions in Izhevsk (09.11.2017) and Magnitogorsk (31.12.2018) were the most devastating. In the latter case, repair costs are estimated at over RUR 5 bn. The recent explosions (in Noginsk on September 8, 2021 and Yeletz on August 11, 2021) resulted in more than ten dead and about hundred injured people. The total damage to the Budget and expenditures of the affected population amounts to billions of rubles.

Even S.K. Shoigu, the Minister of Emergency Situations, has stated that every third fire and explosion in the HCS sector is caused by the TN electrical network. Every year up to 30000 people die due to electric shock in Russia. The level of electrical injury in Russian households is much greater than that in the USA and Japan[8].

TN networks with an industrial frequency (IF) of 50 Hz, network extension cords, and appliance and adapter cords may induce a wide spectrum of EMF harmonics with amplitude exceeding maximum permissible level (MPL) of 25 V/m for WP PCs, according to SanPiN 2.2.4.3359-16, in living spaces (WP PC, bedroom, and kitchen) at a distance of over 0.5 m, thus creating uncomfortable living and working conditions [1].

INCOMPATIBILITY BETWEEN SANPIN CONCERNING IF EMF FOR RESIDENTIAL PREMISES AND WP PC CONDITIONS

The sanitary and hygiene standards and rules for IF EMF (EF and MF are electric and magnetic fields, respectively), and MPL established by SanPiN 2.1.2.2645[9] for living conditions in residential buildings and premises do not meet MPL requirements for WP PCs as specified in the latest version of SanPiN 2.2.4.3359-16 (paragraph 7.2.7).

The MPL of significant EMF factors for WP PCs as specified in SanPiN 2.2.4.3359-16 is compared in Table 1 with the IF EMF (EF and MF) MPL as specified in SanPiN 2.1.2.2645-10. For many years, designers and power engineers have been using this reference MPL (500 V/m and 5 μT). The aim is to avoid using safe symmetrical two-phase IT mode power supply system (PUE, Fig. 1.7.4) in residential and public buildings instead of TN networks which are potentially dangerous to households. However, the use of an IT system may reduce the risk of emergencies and maintain suitable conditions for IF EMF factors [1].

This paper proposes advisable practically achievable criteria of safe conditions for EMF factors in their combined effect on WP PCs, in order to reduce the risk of emergencies, while preserving the health of remote WP PC users. This also prevents the uncontrollable effects of uncomfortable IF EMF factors along with other significant EMF factors. The recommended criteria were developed on the basis of experimental data and are compatible with the EMF values specified in SanPiN 2.2.4.3359-16 (Table 1), the criteria of Standard der Baubiologischen Messtechnik (SBM-2015) (Germany)[10] for sleeping areas, and the World Health Organization (WHO) principles [1, 2].

The primary aim of the paper is to establish the following: the causes of TN network operational hazards in residential premises; the safety and efficiency of IT networks; and the need for self-monitoring of recommended IF EMF criteria for WP PCs.

Uncomfortable EMF conditions in premises today depend not only on the construction quality and external environment, but also on the residents and their qualifications, as well as self-monitoring system and the capability to normalize these conditions. Equipping WP PC should be accompanied with continuous monitoring of IF EMF and other factors (Table 1). Periodic monitoring should be carried out when WP PCs are operating, as well as changes to conditions in the premises. Individual study recorders (ISR) used as control devices are used for nondestructive testing and are not subject to state verification (Art. 1.23, Federal Law No 102-FZ[11] of 26.06.2008, as amended on 23.06.2014).

[8] About active harmonic filters for "weasels" and the rules for choosing filter compensating devices. URL: https://www.mircond.com/blog/ob-aktivnykh-filtrakh-garmonik/. Accessed April 20, 2020 (in Russ.).

[9] SanPiN 2.1.2.2645-10 Sanitary and Epidemiological Requirements for Living Conditions in Residential Buildings and Premises. Approved by the Order No.64 of 10.06.2010 of the Chief State Sanitary Physician of the Russian Federation (in Russ.).

[10] Supplement to the Standard of Building Biology Testing Methods SBM-2015 and the associated Building Biology Evaluation Guidelines for Sleeping Areas. [Acting from 5th Draft 5/2015]. Germany: Institut für Baubiologie + Ökologie IBN; 2015, p. 18.

[11] Federal Law No. 102-FZ On Ensuring the Uniformity of Measurements, dated 26.06.2008 (in Russ.).

Table. 1. Comparison of EMF MPL for WP PC and EMF MPL for the residential premise

SanPiN 2.2.4.3359-16 (8 h)		Background MPL	SanPiN 2.1.2.2810-10* (24 h)	MPL
EF intensity	5–2000 Hz	25 V/m	50 ± 2 Hz EF background in the premise	500 V/m
	2–400 kHz	2.5 V/m		
MF intensity	5–2000 Hz	0.25 μT	50 ± 2 Hz MF background in the premise	5(4) μT (A/m)
	2–400 kHz	25 nT		
SHF frequency	300–300000 MHz	10 μW/cm^2	300–300000 MHz	10 μW/cm^2
ESF intensity		15 kV/m	–	15 kV/m
GMF reduction factor, K_g		$K_g \leq 2.0$	–	$K_g \leq 1.5$

Notes:
1. ESF is electrostatic field measured according to paragraph 7.3.7. of SanPiN 2.2.4.3359-16; it specifies the superposition of GEF and ESF in the premise.
2. GMF is geomagnetic field; K_g is GMF reduction factor, according to GOST (State Standard) R 51724–01(08)**.

* SanPiN 2.1.2.2801-10 Amendments and additions No. 1 to SanPiN 2.1.2.2645-10 Sanitary and epidemiological requirements for living conditions in residential buildings and premises (with amendments approved by the Order No. 2403 of the Russian Government dated 31.12.2020) (in Russ.).

** GOST R 51724-2001. Shielded facilities, spaces, installations. Reduced geomagnetic field. Methods of measuring and assessment of field intensity compliance with technical requirements and hygiene standards. Moscow: Standartinform; 2001 (in Russ.).

CAUSES OF UNSUITABLE CONDITIONS FOR REMOTE WP PCS IN RESIDENTIAL PREMISES

Millions of WP PCs located in offices, classrooms, and factories are subject to EMF requirements and standards (Table 1) and these should also be extended to remote users in residential premises. These requirements were first set out in the MPR 1990 standard (Sweden)[12], and have been used worldwide as MPL for WP PCs equipped with electronic tube displays. Since 2000, WP PCs have been equipped with new and safer LCD displays. At the same time, secondary switched power supplies (SMPS), such as adapters, electric appliances, light-emissive device, and etc., distorting IF currents and voltages of 50 Hz in TN network have come into broader use. This induces a parasitic EF and MF spectrum on frequency bands almost equal to the MPR 1990 standard in the premises.

Figure 1 shows typical voltage and current waveform distortions in a three-phase 50 Hz electrical network of a residential building.

[12] Standard MPR 1990:10 1990-12-31 within MPR II standards developed by the Swedish Board for Technical Accreditation (SWEDAC) as the User's Handbook for Evaluating Visual Display Units. Adopted as European Standard in June 1992 by the Council Directive 90/270/EEC of May 29, 1990.

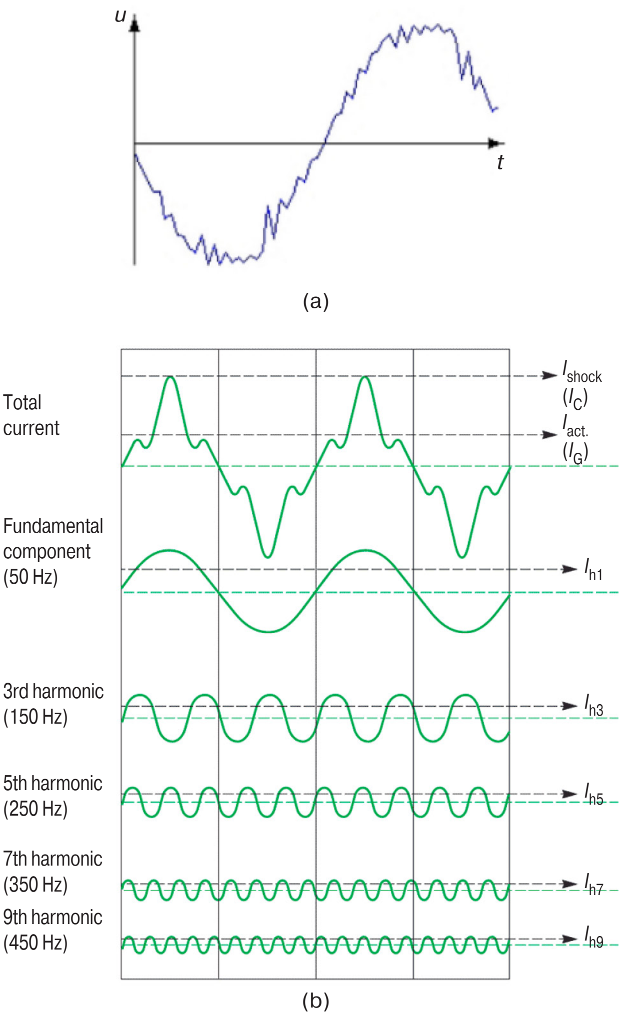

Fig. 1. Typical distortions:
(a) of voltage;
(b) of currents and their harmonics distorting the current waveform in the three-phase 50 Hz electrical network of a residential building;
the *x*-axis shows time while the *y*-axis corresponds to the parameter amplitude

Current distortions may be caused mainly by asymmetry of consumer phase loads in the building network and nonlinear current loads in phases. Each current (voltage) harmonic of the TN network phase induces MF (EF) in living spaces and form a wideband spectrum with energy possibly greater than that of the 1st harmonics. The Swedish standard requirements for IF EMF (Table 1) are kept in SanPiN 2.2.4.3359-16 for office WP PCs. In the meantime, they have proven their efficiency in terms of preventing harmful effects on users and fail-safety. Today, the monitoring of these requirements is provided by a large network of devices in Russia.

However, paragraph 7.2.7. of SanPiN 2.2.4.3359-16 (Table 1) concerning EMF norms for WP PCs has been completely removed from the new SanPiN 1.2.3685-21 version. This was done with no argumentation in terms of sanitary and discussions with experts on Internet, while the SanPiN norms were cancelled themselves. The impact of this initiative on the health of WP PC users located in offices, and especially remote users in residential premises where TN networks induce uncontrolled high IF EMF exceeding MPL for WP PCs, is unpredictable. Today even entrepreneurs and administrative managers (constructors and power engineers) are interested in accident-free conditions and protecting the health of their remote employees. Their business depends on their efficiency, and they are keen to protect the health of children, pregnant women, students, and etc.

The SanPiN 2.1.2.2645-10 (Table 1) requirements and their control methods do not reflect the sanitary hazard of IF EMF in natural conditions of residential premises (as well as in the equipped WP PC, respectively) for the following reasons:

1. Today, up to 80% of the parasitic energy of the IF EF and MF harmonic induction spectrum which actually affects individuals in residential premises (Fig. 1) is not controlled. According to the "thermal concept" criteria established in Russia and applied to standards in other countries, e.g., to Directive 2013/35/EU[13] of 26 June, 2013, MPL induction norms should be reduced in the low frequency range in proportion to the increasing frequency (minus 6 dB per octave). SanPiN sets flat MPL norms, irrespective of frequency.

   The flat wideband MPL norms for exposure to EMF of band frequencies ranging from 10 kHz to 300 GHz as established in the USSR in the 1960s (also given in the new version of SanPiN 1.2.3685-21) were developed secretly. This prevents the possibility of determining the narrowband frequencies of codes, heterodyne radiations, transceivers, and antennas. Incompatibility between foreign standards for the specific absorption rate (SAR) and MPL set in SanPiN may require additional costs for controlling imported facilities. This approach prevents the harmonization of Russian sanitation and hygiene standards with those of the developed Western countries.

   Network harmonics may result in additional heating of power transformer windings. This also decreases their rated power and residual life. Industrial standards for the harmonic levels in

[13] Directive 2013/35/EU of the European Parliament and of the Council of 26 June 2013 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (electromagnetic fields) (20th individual Directive within the meaning of Article 16(1) of Directive 89/391/EEC) and repealing Directive 2004/40/EC

industrial (but not residential) building networks have been already standardized to the 40th harmonic (up to 2000 Hz) in GOST 32144-2013[14] (for voltage) and GOST IEC 61000-3-2-2017[15] (for current). Thus, damage to power equipment and unscheduled power outages may occur more often in HCS.

2. The entire TN network including socket and lighting circuits, network extension cords, inter alia are sources of IF EF and MF induction in the premises (also in WP PCs). Plugged in SMPS extensions and cord (~220 V, 50 Hz), as well as two-wire networks even without load are the most intensive EF sources close to the user. Due to specificity of SMPS (adapters), their cords may induce the EF frequency spectrum of 100–500(2000) Hz with intensity $E \geq 25$ V/m at a distance up to 0.5 m, where first EF harmonic is 100 Hz rather than 50 Hz [3].
3. Exposure energy of EP and MF harmonics may increase in premises due to the broad introduction of wireless power transfer (WPT) sources for charging mobile and portable devices, household appliances, and electric cars. In the USA, more than 30% of cell phones are now charged from WPT sources.
4. In SanPiN 2.1.2.2810-10 (Table 1), MPLs for IF EMF are given on the assumption that EF and MF induction may occur in residential premises from the single-phase network only. However, some locations including WP PCs may be in the region of rotating IF EMF (REMF) (REF and RMF for components) induced via a three-phase cable layout connecting kitchen cookers, transformers, engineering equipment, distribution panels, and elevators.

   The effect of RMF on living organisms may be more dangerous when compared with the effect of MF from a single-phase circuit. Right-hand RMF is less destructive than left-hand. Exposure to lefthand RMF is more dangerous even at low levels. Today, there are no standards for REMF directions. Premises intended for remote work should be inspected for the absence of RMF and REF from external and internal sources [8–10].

   The results of measuring zones of spatial distribution of 50 Hz IF EMF levels (MF, EF, and their ellipticity) in four directions, according to the method specified in SanPiN 2.2.4.3359-16, paragraph 7.3.4, induced by five types of cast resin dry type transformers (CRT) ranging from 1000 kVA to 2500 kVA used in urban transformer substations and facilities are given in [11].

   About forty transformer substations built-in and attached to building in Moscow, Moscow region, and Samara are equipped with shields (thin-walled steel sheets with a grid between them). They convert elliptical IF RMF of the source to the quasi-linear component of IF MF (less dangerous), according to the method described in [11].
5. Today, foreign environmental organizations recommend (oblige) builders to comply with rigid SBM-2015 standard (8th edition) for advisable 50 Hz IF background in residential premises. This should be no more than 5 V/m and 0.1 μT, motivated by WHO warning provisions for residents' exposure to household EMF and other harmful factors. The SBM-2015standard of building biology methods is used as a guide for professionals and independent testing of residential buildings worldwide, including Europe, Israel, USA, Canada, Australia, and New Zealand [12].
6. In the European Union, the transition to standards for IF MF ranging from 0.2 to 0.4 μT is considered as a promising target for coming years. The decisions at the WHO level are expected to be made in 2022–2024 [13].

CAUSES OF DANGEROUS CONDITIONS IN RESIDENTIAL PREMISES DUE TO TN POWER SUPPLY SYSTEMS

The mass media often cite TN electrical networks among the causes and conditions of accidents occurring in residential and public buildings, resulting in injury and death. According to the degree of potential danger to the quality of life (QOL) and health of the residents, costs of treating victims, as well as damage to work results along with costs of future restoration and repair, these accidents should be classified as extremely dangerous for their resulting frequently in catastrophic damage.

Two-wire TN-C network[16], among other TN modes, may most frequently cause domestic gas explosions, fires, electrical injuries, and parasitic inductions of 50 Hz IF fields in premises. These networks may be found in building walls towards outlets and light sources (due to mistakes

[14] GOST 32144-2013. Electric energy. Electromagnetic compatibility of technical equipment. Power quality limits in the public power supply systems. Moscow: Standartinform; 2014 (in Russ.).

[15] GOST IEC 61000-3-2-2017. Electromagnetic compatibility (EMC). Part 3–2. Limits. Limits for harmonic current emissions (equipment input current no more 16 A per phase). Moscow: Standartinform; 2020 (in Russ.).

[16] TN electrical network with combined earthing (PE) and neutral (N) wires.

of constructors) as well as in cases of contact failures in the third PE[17] wire and non-standard extension cords. The two-wire network may be detected by the increased EF induction.

A short circuit in a TN-C network can result in fire. When a PEN[18] neutral wire is broken or burnt, the voltage at the L (phase wire) terminals may increase up to 0.4 kV. This voltage is dangerous to people and may appear on all metal parts connected to the PEN wire. According to PUE, paragraph 7.1.78, plugged in and unprotected domestic appliances, adapters, and light sources may be burnt. In Russia, using the TN-C networks and two-wire extension cords are currently prohibited by fire authorities.

Despite the use of upgraded TN-S[19] and TN-C-S[20] power supply systems in residential buildings, according to PUE, paragraph 7.1.13, gas explosions, fires, and electric injuries may also occur from time to time in recently constructed buildings. In Russia, about 30–50% of annual household gas explosions are caused by sparking in TN electrical network. This usually happens when commutating light switches, socket contacts, electrical appliances, inter alia. Spark intensity may increase due to the additional discharge energy of the distributed capacitance C_D = 110...130 pF/m from the "earth" wire. It is therefore not recommended to use TN networks in areas of possible concentrations of dust and air explosive mixtures. Sparking may be dangerous for electronic devices in the event of earth fault (contact loss) and other factors.

Today, protection against electrical hazards and short circuits in TN-S and TN-C-S building networks depends on the CB and RCD response speed. Fires and electrical hazards may often occur due to the low contact reliability of electromechanical devices and long response time (up to 5 seconds, according to PUE, paragraph 1.7.79) in residential and public building networks. According to the expert opinion on the cause of the fire in the Zimnyaya Vishnya shopping mall: "The fire started in the LED light fixture which was inundated by melt water from the roof. The circuit breakers intended for switching off the lighting device and then the power supply failed to actuate[21]."

Electric shock and commutation sparking occurring in TN building networks is always added to the discharge energy of the distributed capacity C_D. This causes degradation (erosion) of contacts. In TN system, the presence of electromechanical CB and RCD does not mean full protection against short circuits and electrical hazards. Protection devices with a cut-off time two orders of magnitude less than that established in PUE [1, 2] are required.

CAUSES OF UNSUITABLE CONDITIONS FOR REMOTE WP PCS DUE TO IF EMF

Complaints from domestic residents with regard to unsuitable living conditions are often due to the 50 Hz IF EF and MF induction. These frequently do not exceed the MPL established by SanPiN 2.1.2.2810-10 (Table 1). Voltages in TN electrical networks running in walls, ceiling, and floor may actuate steel rebars and wall grids (not earthed) and induce parasitic (secondary) EF with intensity up to 25 V/m (MPL for WP PCs) in premises at 0.4–1.0 m from walls. Network extension cords running under the user's feet, especially two-cable ones (used at more than 50% of WP PCs in Russia), appliance and adapter cords, and table (wall) lamps may induce EF in the surrounding space. This excites secondary EF in metal objects located close to the user, such as tabletop, chair, armchair, support, spring mattress, inter alia.

In the case of locating WP PCs, conditions may become unsuitable even when all the cords of IT devices and adapters are merely plugged into the sockets and extension cords of the TN power supply (~220V). IF EMF intensity at a distance of 0.1 m from cords and three-wire extensions may reach 100–125 V/m. This is 4–5 times more than MPL for WP PCs (25 V/m) established by SanPiN 2.2.4.3359-16 (Table 1) [1, 2].

The need to multiply the TN network (plugging appliance cords, adapters, and etc. in) by means of extension cords, as well as increasing the number of current commutations when equipping and operating WP PCs in residential premises, may increase the risk of explosion, fire, electrical sparking, and unsuitable conditions, which are monitored and protected by nobody. In TN network, dangerous conditions often arise when the contacts of the working and protective earth wires are broken or lost even before entering the premises, apartment, distribution board, inter alia.

[17] PE is protective earthing. It is used for protection against electric shock and emergency shutdown of differential protection and circuit breakers in case of insulation failure in electrical appliances with earthed enclosure.

[18] Protective earthed neutral (PEN) conductor is a single conductor combining the function of the neutral and protective earth conductor.

[19] TN electrical network with earthing (PE) and neutral (N) wires.

[20] TN electrical network with combined earthing (PE) and neutral (N) wires at the network beginning and separate earthing (PE) and neutral (N) wires further on.

[21] The Kommersant newspaper of August 24, 2018 (in Russ.).

There have been a number of instances, when a baby's bed located close to and exposed to EF voltage of ~(80–100) V/m emitted by device cords (heater, ionizer, baby monitor, etc.) has been relocated to another place, thus normalizing EF conditions to less than 10 V/m, resulting in the disappearance of chronic diseases [2].

SAFE POWER SUPPLY SYSTEMS REQUIRED FOR REMOTE WP PCS

There is no statistical data regarding accidents and excesses of IF EF and MF values in healthcare facilities, defense enterprises, and banks using potentially safe two-phase symmetrical IT (TT) networks, manufactured pursuant to GOST R 50571.28-2006 (IEC 60364-7-710: 2002)[22] (PUE, Fig. 1.7.4).

The results of inspections and tests performed in buildings in accordance with RD 153-34.0-15.501-00[23] and RD 153-34.0-15.502-2002[24] show that the IT electrical network efficiency is higher than that of the TN, in terms of the following values:

- Explosion and fire risks, up to 5 times;
- Electrical safety, more than 10 times;
- Electromagnetic safety, at least 10 times;
- Pulse (lightning) resistance, by 1.5–3 times (civil defense);
- Energy saving (current drain reduction), up to 5%;
- Resource conservation including network isolation and commutation device contacts as well as reduction in the electro corrosion rate of building engineering systems, by 2–3 times, etc.

Contact with any wire of the IT network is safe, and secondary inductions from ungrounded objects do not occur. IF EF inductions from network extensions decrease. Conventional CB and RCD protection devices, as well as electromagnetic shielding would be more effective for these networks. When commutating current loads and short circuits, the spark energy is several times lower due to the absence of capacity discharge C_D. This energy may be compensated by multidirectional bias currents from each wire of the network. The cases of domestic gas explosions are unknown yet [1–3].

In the case of a single ground fault in one of the IT network conductors, even though the circuit breakers have not tripped, the IT network may be converted provisionally into TN-C network until the fault is eliminated. In the case of a ground fault in the second conductor, the emergency network should be switched off. Voltage to earth from each IT network wire is about 110 V. The EF intensity is 1–2 V/m, while the MF one is about 10 nT at 0.1 m from the wires [2].

Today, the service entrance for the three-phase TN network (~220V) in an apartment or detached house may have been equipped by certain enterprising people with an isolation transformer (PUE, paragraph 1.7.85) up to 15.0 kW. This transmits an already potentially safe electrical IT network or TT network earthed via a middle point (PUE, Fig. 1.7.5) to WP PCs in residential premises through the same wires. In order to protect a detached house from EF and MF parasitic inductions, as well as from parasitic interferences in the electrical network which may occur during thunderstorm, short-circuit, and wire breakage, an isolation transformer with separate windings (or with the earthed shield) and overvoltage suppressors may be installed on the property line [2].

In order to protect remote WP PCs from IF EF of TN network (~220 V), neutralizers may be used for decoupling ~220 V from ground (earth), suppressing EF in the range from 5 Hz to 400 kHz, with a noise level up to 20 dB, such as Cyclone 650 with 4 sockets (produced by the Cyclone-Test[25]).

RECOMMENDED VALUES AND CRITERIA OF EMF CONDITIONS FOR REMOTE WP PCS

Table 2 indicates the values for EMF factors recommended for different degrees of harm and/or danger criteria for WP PC, where 1 is comfortable, 2 is allowable, 3 is safe, and 4 is unacceptable. These values are harmonized with SBM-2015 standard criteria and WHO principles.

EMF factor levels for WP PCs may be monitored pursuant to the methods described in paragraph 7.3.7 and Appendix 11 of SanPiN 2.2.4.3359-16, until a time when new recommended methods are proposed. IF EMF criteria 1 and 2 (comfortable and acceptable conditions) in residential premises (in WP PC, also)

[22] GOST R 50571.28-2006 (IEC 60364-7-710: 2002). Electrical installations of buildings. Part 7-710: Requirements for special installations or locations. Medical locations. Moscow: Standartinform; 2007 (in Russ.).

[23] RD 153-34.0-15.501-00 Guidelines for monitoring and analyzing the quality of electric energy in general-purpose power supply systems. Part 1. Electrical energy quality control (approved by Ministry of Energy of the Russian Federation on December 27, 2000) (in Russ.).

[24] RD 153-34.0-15.502-2002 Methodological guidelines for control and analysis of power quality in power supply systems for general purposes. Part 2. Analysis of power quality (approved by Rostechnadzor on July 15, 2002) (in Russ.).

[25] www.ciklon.ru

are reliably fulfilled, provided that an IT network (or TT network) is used and there is no induction or radiation from external sources which exceed the criteria, specified in Table 2.

JUSTIFICATION FOR EMF RECOMMENDED CRITERIA (TABLE 2) FOR WP PCS

An example of parasitic EF (23 V/m) induced by a cord plugged into the network adapter (~220 V) at ~0.5 m (wooden ruler) close to IF EF MPL for WP PC (Table 1) is shown in Fig. 2. However, the EMF MPL value is currently measured at 0.1 m from the device (SMPS for WP PC of ≤25 V/m), according to SanPiN 2.1.2.1002-003[26], paragraph 6.4.3.1.

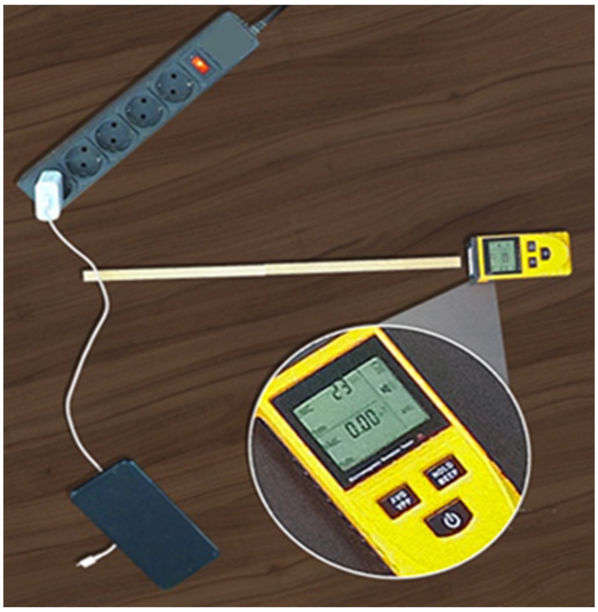

Fig. 2. Induction of EF (23 V/m) at ~0.5 m from cord plugged into a network adapter (~220 V)

An example of a household WP PC is shown in Fig. 3 [14]. Clearly the PC power cords and LCD display and laptop cables are hanging down from the metal tabletop and are plugged into extension outlet sockets. When a TN network is used, the EF and MF secondary induction (ranging from 5 Hz to 2 kHz) from the tabletop and cords near the user's knees may be up to 80 V/m and 0.6 μT instead of MPL amounting to 25 V/m and 0.25 μT.

[26] SanPiN 2.1.2.1002-00. 2.1.2. Design, construction and operation of residential buildings, public utilities companies, education, culture, recreation, and sport institutions. Sanitary and epidemiological requirements for residential buildings and premises. Sanitary and epidemiological rules and regulations (Approved by the Chief State Sanitary Physician of the Russian Federation, December 15, 2000, edited August 21, 2007) (in Russ.).

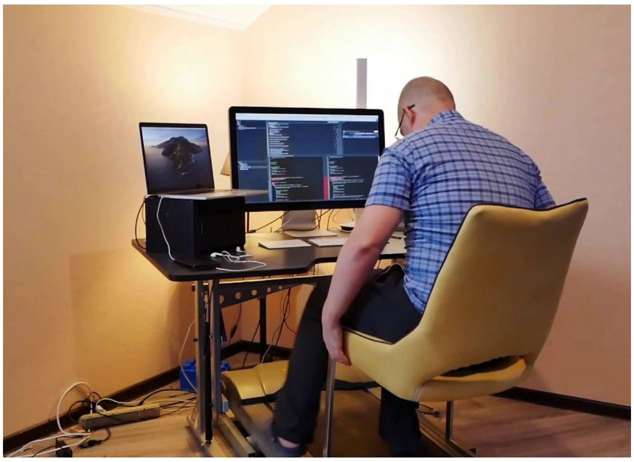

Fig. 3. Household WP PC [14]

Other factors of discomfort (Fig. 3) may be: IF MF, EF, and RMF induction from power cables behind the wall; inductions of the opposite directions of GEF or ESF vectors of the armchair, foot support and floor laminate; reduction of GMF due to wall metal structures; SHF radiation from nearby devices, such as Wi-Fi devices, laptop board, and cell phones (especially, using GSM standard). When an IT network is used, IF EF and MF values would *automatically* meet the conditions specified in Table 2.

Remote WP PCs should comply with EMF values and criteria (Table 2) rather than EMF MPL established by SanPiN (Table 1) for living conditions. The reasons are as follows:

1. Hygiene and sanitary documents for residential premises as developed by the Research Institute of Occupational Medicine contain MPL values for single-component exposures to EMF factors only (Table 1). In addition, these MPL values (500 V/m and 5 μT) conflict with EMF norms as established by SanPiN 2.2.4.3359-16 for office WP PCs (25 V/m and 0.25 μT).
2. WP PC users today may be exposed to the range of EMF factors, all of which can have a devastating impact on health. Based on publications by medical and other experts, the following body systems may be susceptible to each EMF factor exposure (Table 1): nervous system; cardiovascular system; endocrine system; immune system; digestive system; and the reproductive system [10]. When WP PC is exposed to the range of EMF factors, the intensity of each factor should be reduced to protect against the devastating health impact on users.
3. The recommended criteria for factors 4 (Table 2) are more severe than EMF MPL (Table 1). Here, the following aspects have been considered:

Table 2. Recommended values and criteria of EMF conditions for remote WP PCs

Values		UM	Criteria			
			1	2	3	4
EF intensity, line-to-earth	5–2000 Hz	V/m	<1	1–5	5–25	>25
	2–400 kHz	V/m	<0.1	0.1–0.25	0.25–2.5	>2.5
EF intensity, ungrounded	5–2000 Hz	V/m	<0.3	0.3–1.5	1.5–10	>10
	2–400 kHz	V/m	<0.02	0.02–0.1	0.1–0.5	>0.5
MF intensity	5–2000 Hz	nT	<2.5	2.5–7.5	7.5–25	>50
	2–400 kHz	nT	<0.25	0.25–0.75	0.75–25	>5
SHF energy flux density	300–300000 MHz	$\mu W/m^2$ $\mu W/cm^2$	<1.0 $<10^{-4}$	1–100 10^{-4}–10^{-2}	100–1000 10^{-2}–0.1	>1000 >0.1
ESF intensity	E	kV/m	<0.1	0.1–0.5	0.5–3.0	>+3.0
ESF leakage time in humidity conditions	t_l (30–60)%	s	<2.0	2.0–6.0	6.0–15	>15
GMF reduction factor, K_r	$K_r = H_{OS}/H_{IN}$	Ratio	<1.1	1.1–1.3	1.3–1.5	>1.5

Notes:
1. ESF (E) intensity is measured under simulated conditions for WP PCs and leakage time (t_l) of induced ESP charge on the floor and WP PC dielectric materials (including electrostatic charging of the user body [clothes and shoes] in motion), according to GOST 31610.32-2-2016 / IEC 60079-32-2:2015*.
2. Safety analysis, as well as the monitoring and justification of the recommended criteria for SHF, ESF, and GMF factors for remote WP PCs in residential premises will be given in subsequent papers.
3. H_{OS} is open space GMF intensity; H_{IN} is indoor GMP intensity.

* GOST 31610.32-2-2016/IEC 60079-32-2:2015. Explosive atmospheres. Part 32-2. Electrostatics hazards. Tests. Moscow: Standartinform; 2017 (in Russ.).

use of safe IT (TT) network in buildings and premises; exposure to the reduced and distorted GMF factors in premises practical achievability of the criteria indicated in Table 2; MPL reduction of other physical factors in the event of 24 hours, instead of 8 hours, in the office.

CONCLUSIONS

1. Based on the above results, the following priority activities should be implemented in residential buildings and premises as legislation:
   - Replacement of TN power supply system with IT (TT);
   - Use of a more reliable commutation and protection systems;
   - Implementation of a system for monitoring physical factor conditions by residents and users of household WP PCs who use modern mobile devices.
2. The following requirements should be conveyed to the Government of the Russian Federation, regional authorities, population, investors, constructors, and power engineers: use of ungrounded IT power supply system in designing new residential and public buildings, rebuilding, and overhauling; recommendation for the safe and comfortable EMF factor conditions as shown in Table 2 for sleeping accommodation and WP PC.
3. It is recommended that the Head of Rospotrebnadzor perform the following activities:
   - To include the canceled SanPiN 2.2.4.3359-16, Table 7.12, defining the EMF MPL values for WP PCs (preferably, as indicated in Table 1 in the paper) in new version of SanPiN 1.2.3685-21.
   - To promote the self-monitoring of safety conditions for remote WP PCs.

Authors' contribution

Yu.G. Ryabov—development of the research concept; conducting research, in particular, analysis of standards for the impact of EMF in Russian and foreign regulatory documents and analysis of dangerous conditions for RM PCs in existing electrical networks of residential buildings; development of recommendations for reducing EMF and formulation of required EMF indicators for RM PC in residential buildings; writing the text of the article.

N.M. Legkiy—design of key goals and objectives; conducting research, in particular, analysis of means of protection against electric shocks and short circuits in electrical networks; analysis of safe power supply systems required for RM PCs in residential buildings; analysis of literature data; formulation of required EMF indicators for RM PCs in residential buildings; writing and editing the text of the article.

G.V. Lomaev—design of key goals and objectives; conducting research, in particular, analysis of the Russian regulatory documents for EMF and interpretation of the data obtained; development of criteria for assessing the safety of electrical networks in residential buildings; analysis of literature data; formulation of required EMF indicators for RM PC in residential buildings; critical revision of the article with the introduction of valuable comments.

All authors—interpreting the study results, formulating the conclusions, and final approval of the version to be published.

REFERENCES

1. Ryabov Yu.G., Yakovlev G.N., Lomaev G.V., Yashin A.A., Biletskii S.E. Weather in the house. *Okhrana truda i sotsial'noe strakhovanie*. 2014;4:60–70 (in Russ.).
2. Repin A.A., Lomaev G.V., Ryabov Yu.G. The advantages of the IT (TT) systems in residential buildings. *Standarty i Kachestvo = Standards and Quality*. 2020;4:105–109 (in Russ.).
3. Dugan R., McGranaghan M., Santoso A., Beaty H. *Electrical power systems quality*. 3rd ed. New-York: McGraw-Hill; 2012. 580 p.
4. Johnson D.O., Hassan K.A. Issues of power quality in electrical systems. *International Journal of Energy and Power Engineering*. 2016;5(4):148–154. http://doi.org/10.11648/j.ijepe.20160504.12
5. Khalid S., Dwivedi B. Power quality issues, problems, standards & their effects in industry with corrective means. *International Journal of Advances in Engineering & Technology*. 2011;1(2):1–11.
6. Canteli M.M. Power Quality monitoring. In: Moreno-Muñoz A. (Ed.). *Power Quality: Mitigation Technologies in a Distributed Environment*. London: Springer; 2007. P. 15–40.
7. Bol'shakov O.V., Vasil'eva O.A. On the origin and measurement of harmonic distortions in electrical networks. In: *Upravlenie kachestvom elektricheskoi energii*: (*Power Quality Management*): Proceedings of the International Scientific and Practical Conference. Moscow: Tsentr poligraficheskikh uslug Raduga; 2017. P. 57–75 (in Russ.).
8. Arhipov M.E., Kurotchenko L.V., Novikov A.S., Subbotina T.I., Khadartsev A.A., Yashin A.A. *Vozdeistvie pravo- i levovrashchayushchikhsya elektromagnitnykh polei na bioob"ekty: fizicheskie modeli i eksperiment*. (*Impact of right and left rotating electromagnetic fields on biological objects: physical models and experiment*). Subbotina T.I., Yashin A.A. (Eds.). Moscow: Triada; 2007. 200 p. (in Russ.). ISBN 978-5-94789-249-9
9. Drandić A., Trkulja B. Transformer electric field calculation using BEM and FEM. *Procedia Engineering*. 2017;202:312–318. https://doi.org/10.1016/j.proeng.2017.09.719

СПИСОК ЛИТЕРАТУРЫ

1. Рябов Ю.Г., Яковлев Г.Н., Ломаев Г.В., Яшин А.А., Билецкий С.Э. Погода в доме. *Охрана труда и социальное страхование*. 2014;4:60–70.
2. Репин А.А., Ломаев Г.В., Рябов Ю.Г. Преимущества электроснабжения IT (TT) вместо TN в жилых домах. *Стандарты и Качество*. 2020;4:105–109.
3. Dugan R., McGranaghan M., Santoso A., Beaty H. *Electrical power systems quality*. 3rd ed. New-York: McGraw-Hill; 2012. 580 p.
4. Johnson D.O., Hassan K.A. Issues of power quality in electrical systems. *International Journal of Energy and Power Engineering*. 2016;5(4):148–154. http://doi.org/10.11648/j.ijepe.20160504.12
5. Khalid S., Dwivedi B. Power quality issues, problems, standards & their effects in industry with corrective means. *International Journal of Advances in Engineering & Technology*. 2011;1(2):1–11.
6. Canteli M.M. Power Quality monitoring. In: Moreno-Muñoz A. (Ed.). *Power Quality: Mitigation Technologies in a Distributed Environment*. London: Springer; 2007. P. 15–40.
7. Большаков О.В., Васильева О.А. О происхождении и измерении гармонических искажений в электрических сетях. В сб.: *Управление качеством электрической энергии*. Сборник трудов Международной научно-практической конференции. М.: ООО «Центр полиграфических услуг Радуга»; 2017. С. 57–75.
8. Архипов М.Э., Куротченко Л.В., Новиков А. С., Субботина Т.И., Хадарцев А.А., Яшин А.А. *Воздействие право- и левовращающихся электромагнитных полей на биообъекты: физические модели и эксперимент*; под. ред. Т.И. Субботиной и А.А. Яшина. М.: Триада; 2007. 200 с. ISBN 978-5-94789-249-9
9. Drandić A., Trkulja B. Transformer electric field calculation using BEM and FEM. *Procedia Engineering*. 2017;202:312–318. https://doi.org/10.1016/j.proeng.2017.09.719
10. Легкий Н.М., Шумилин В.К., Елин А.М. *Современные подходы по организации и проведению работ по оценке и снижению профессиональных и производственных рисков*. М.: Онтопринт; 2021. 512 с.

10. Legkiy N.M., Shumilin V.K., Elin A.M. *Sovremennye podkhody po organizatsii i provedeniyu rabot po otsenke i snizheniyu professional'nykh i proizvodstvennykh riskov* (*Modern approaches to organizing and carrying out work to assess and reduce professional and industrial risks*). Moscow: Ontoprint; 2021. 512 p. (in Russ.).
11. Dixon L.H. *Magnetic field evaluation in transformers and inductors*. Texas Instruments Application Note SLUP171. 2004. 14 p. Available from URL: https://www.ti.com/lit/ml/slup171/slup171.pdf
12. Glaria F., Arnedo I., Sánchez-Ostiz A. Advances in residential design related to the influence of geomagnetism. *Int. J. Environ. Res. Public Health*. 2018;15(2):387. https://doi.org/10.3390/ijerph15020387
13. Sturman V.I. The pattern of power frequency electromagnetic fields in the Pushkin municipal area of Saint Petersburg. *Izvestiya Russkogo geograficheskogo obshchestva*. 2019;151(6):58–68 (in Russ.). https://doi.org/10.31857/S0869-6071151658-68
14. Bingi V.N. *Printsipy elektromagnitnoi biofiziki* (*Principles of electromagnetic biophysics*). Moscow: FIZMATLIT; 2011. 592 p. (in Russ.). ISBN 978-5-9221-1333-5

11. Dixon L.H. *Magnetic field evaluation in transformers and inductors*. Texas Instruments Application Note SLUP171. 2004. 14 p. URL: https://www.ti.com/lit/ml/slup171/slup171.pdf
12. Glaria F., Arnedo I., Sánchez-Ostiz A. Advances in residential design related to the Influence of geomagnetism. *Int. J. Environ. Res. Public Health*. 2018;15(2):387. https://doi.org/10.3390/ijerph15020387
13. Стурман В.И. Пространственное распределение электромагнитных полей промышленной частоты в городе Пушкин (Санкт-Петербург). *Известия Русского географического общества*. 2019;151(6):58–68. https://doi.org/10.31857/S0869-6071151658-68
14. Бинги В.Н. *Принципы электромагнитной биофизики*. М.: ФИЗМАТЛИТ; 2011. 592 с. ISBN 978-5-9221-1333-5

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RESEARCH ARTICLE

Local piezoelectric properties of perforated ferroelectric barium–strontium titanate films

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Abstract

Objectives. Focused ion beam etching remains one of the most common methods for fabricating 2D photonic crystals and structures based on functional materials. This technique is quite well developed for semiconductors. But at the same time, the change in the properties of ferroelectric materials under the action of a focused ion beam, including parameters of distribution and switching of the polarization state under the action of an electric field, remains poorly studied. The purpose of this work is to determine the local piezoelectric parameters in perforated ferroelectric films of barium strontium titanate ($Ba_{0.8}Sr_{0.2}TiO_3$) with ordered vertical air channels fabricated by focused ion beam etching.

Methods. Experimental studies were conducted using piezoresponse force microscopy under applied electric field in planar geometry.

Results. It is shown that the perforation of a ferroelectric film leads not only to the formation of significant inhomogeneities in the piezoelectric response distribution in the structure, but also to the noticeable increase in the magnitude of both the vertical and lateral components of the piezoresponse near the perforation holes. The calculation results showed that the greatest enhancement is observed for the lateral component of the piezoresponse: from 5 pm/V for a nonperforated film to 65 pm/V in the perforated area.

Conclusions. The most probable mechanism for such a change in properties is the influence of a disturbed layer that occurs at the boundary and the inner surface of vertical air channels. The properties of this layer are due to two factors: amorphization of the structure as a result of the focused ion beam etching and the appearance of pinned domain states near the hole, leading to the formation of the complex piezoresponse distribution both at the hole boundary and in the gap between the perforations. The information obtained is important for understanding the peculiarities of the formation of local piezoelectric and ferroelectric responses in photonic crystals fabricated by focused ion beam etching, as well as for finding ways to control their state when an external electric field is applied.

Keywords: ferroelectrics, photonic crystals, piezoresponse force microscopy, focused ion beam etching

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НАУЧНАЯ СТАТЬЯ

Локальные пьезоэлектрические свойства перфорированных сегнетоэлектрических пленок титаната бария-стронция

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Резюме
Цели. Методика травления фокусированным ионным пучком остается одной из наиболее востребованных для изготовления двумерных фотонных кристаллов и структур на основе функциональных материалов. Данная методика достаточно хорошо отработана для полупроводников. Но в то же время изменение свойств сегнетоэлектрических материалов под действием фокусированного ионного пучка, в т.ч. параметров распределения и переключения поляризационного состояния под действием электрического поля, остается слабоизученным. Цель работы – определение локальных пьезоэлектрических параметров в перфорированных сегнетоэлектрических пленках титаната бария-стронция ($Ba_{0.8}Sr_{0.2}TiO_3$) с упорядоченными вертикальными воздушными каналами, изготовленными методом травления фокусированным ионным пучком.
Методы. Экспериментальные исследования проведены методом силовой микроскопии пьезоотклика при приложении электрического поля в планарной геометрии.
Результаты. Показано, что перфорация сегнетоэлектрической пленки приводит не только к формированию значительных неоднородностей в распределении пьезоэлектрического отклика в структуре, но и к заметному росту величины как вертикальной, так и латеральной компоненты пьезоотклика вблизи отверстий перфорации. Результаты расчета показали, что наибольшее усиление наблюдается для латеральной компоненты пьезоотклика: от 5 пм/В для неперфорированной пленки до 65 пм/В в области перфорации.
Выводы. Наиболее вероятным механизмом подобного изменения свойств является влияние нарушенного слоя, возникающего на границе и внутренней поверхности вертикальных воздушных каналов. Свойства этого слоя обусловлены двумя факторами: аморфизацией структуры в результате травления фокусированным ионным пучком и возникновением вблизи отверстия закрепленных доменных состояний, приводящих к формированию сложного распределения пьезоотклика как на границе отверстий, так и в промежутке между отверстиями перфорации. Полученная информация имеет значение для понимания особенностей формирования локальных пьезо- и сегнетоэлектрических откликов фотонных кристаллов, изготовленных травлением фокусированным ионным пучком, а также для поиска путей управления их состоянием при приложении внешнего электрического поля.

Ключевые слова: сегнетоэлектрики, фотонные кристаллы, силовая микроскопия пьезоотклика, травление фокусированным ионным пучком

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INTRODUCTION

The practical application of ferroelectric thin films is due to the peculiarities of the formation of the domain structure and its change under the action of an external electric field. At film thicknesses below 100 nm the average domain size becomes close to the film thickness, and the distribution of domains per unit volume is significantly affected by defects of various nature, surface topology, and properties of interfaces. These factors lead not only to noticeable distortions of the switching parameters (for example, the magnitude of the coercive field changes, the asymmetry of the hysteresis loop arises, etc.), but also to changes in the optical and nonlinear optical properties of the ferroelectric film due to its polarization state [1, 2]. Nevertheless, this approach opens up the possibility of creating, within the framework of one technology, a wide range of functional elements of integrated electronics and photonics with a controllable change in parameters due to the formation of ordered structures with certain geometry on the surface or in the volume of a functional material—superlattices and photonic crystals (PCs).

With the evolution of integrated photonics and the development of new principles for the functioning of its elements, systems, based on a combination of PCs of several types (for example, one-dimensional–two-dimensional) or on a combination of PCs of the same type, but with different geometric parameters, are of particular relevance, which ensures the implementation of various processes within a chip. This approach is already used in the design of hybrid electron-photonic chips based on semiconductor materials. Similar devices based on two-dimensional ferroelectric photonic crystals (FEPCs) are obviously not so common, but the fundamental possibility of creating tunable devices controlled by an electric field with their help maintains the interest of researchers in these materials [3–6].

Focused ion beam (FIB) etching is one of the most common methods for fabricating two-dimensional FEPCs, which, compared with lithography methods, has a number of advantages. It is easier to adapt to various materials and makes it possible to fabricate structures with different geometries within one technological cycle, while providing relatively low energy consumption at the sufficiently high spatial resolution, up to 5 nm [7].

Based on numerical simulations, it was shown in [8] that the domain structure of two-dimensional FEPCs, which are an ordered array of submicron holes, is quite complex even in simplified model that does not take into account defects in the structure and surface layer. In this case, the polarization distribution depends on the number and mutual arrangement of the channels, as well as on the depolarizing field that appears on the inner surface of the channels. In particular, it was shown that periodic perforation of a homogeneous ferroelectric film by cylindrical vertical air channels leads to the formation of polarization vortices at the edge of the holes, which, in turn, significantly increase the electric field in the region between the holes. This statement was partially confirmed by the method of electric force microscopy and optical second harmonic generation (SHG) in [9−11]. However, the results obtained by the SHG method, due to the spatial resolution of the technique, which is limited by the wavelength of the radiation used, make it possible to obtain only a qualitative agreement with the results of [8].

Despite the significant number of studies, the influence mechanism of the manufacturing method and geometric parameters of FEPC elements on the polarization distribution in the perforated region and, consequently, on the ability to control the state and properties of the material when an external electric field is applied, remains poorly understood. This paper presents the results of the experimental study by piezoresponse force microscopy (PFM) of the ferroelectric polarization state in the edge region of holes in perforated ferroelectric films of barium strontium titanate when an electric field is applied in planar geometry. Such a structure makes it possible to carry out local studies of the switching process both in the film and in the near-electrode region; in this case, in contrast to the z-geometry, the recorded piezoresponse is not averaged over the entire film thickness.

RESEARCHED STRUCTURES AND EXPERIMENTAL DETAILS

Thin barium–strontium titanate films $Ba_{0.8}Sr_{0.2}TiO_3$ (BST) of 1 μm thick were epitaxially grown on a MgO(001) substrate by high-frequency sputtering of ceramic targets [12]. An external electric field was formed in the film plane using an aluminum interdigital electrode (IDE) system with a gap between the electrodes of 1 μm and a period of 2 μm; the electrode height was 200 nm. Using the FIB method, a system of ordered vertical air channels with a hole diameter of about 880 nm was formed in the gaps between the electrodes. A Quanta 3D microscope (FEI Technology, United States) was used for etching; etching was performed with gallium ions; the etching current was 0.5–0.7 nA (Fig. 1a). The hole depth estimated by the etching time was about 1 μm.

The local piezoelectric properties of the obtained structure were studied by the PFM method using the contact mode of an Ntegra Aura scanning probe microscope (NT-MDT, Russia) in the vertical and

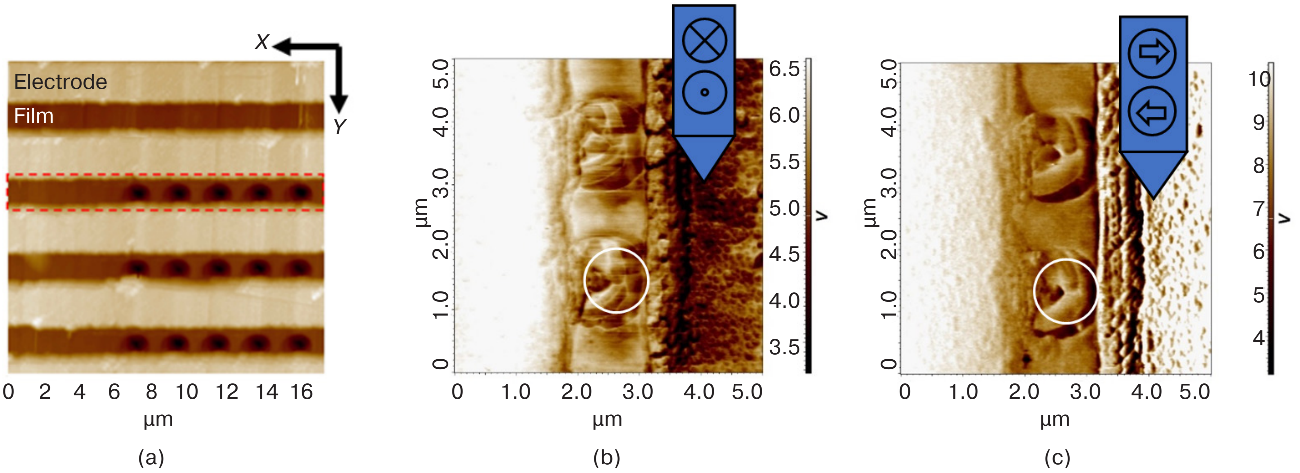

Fig. 1. Topography of the studied structure in the perforation area obtained by atomic force microscopy (a) and the distribution of the vertical (b) and lateral (c) components of the piezoresponse obtained by the PFM method for two adjacent perforation holes in the area marked by a dotted line at position (a). The white circle marks the vertical channel boundary

horizontal planes (Figs. 1b and 1c), respectively. During the scan, the movement of the cantilever was severely limited by the complex structure of the connecting electrodes and significant fluctuations in the sample topography. Therefore, scanning was carried out only in one direction perpendicular to the electrodes (along the *Y* axis in Fig. 1a). Cantilevers of the PPP-EFM series (resonant frequency 45–115 kHz; force constant 0.5–9.5 N/m, NANOSENSORS, Switzerland) were used for measurements; the voltage applied to the IDE system was in the range of 5–30 V. PFM measurements were carried out with alternating voltage applied with a frequency of 50 kHz and an amplitude of 5 V.

RESULTS AND DISCUSSION

Examples of PFM images of the vertical (vertical piezoresponse force microscopy, VPFM) and lateral (lateral piezoresponse force microscopy, LPFM) components of the piezoresponse at the edge of the air channel (region 1) and in the region located approximately in the middle between the two channels (region 2) are shown in Fig. 1b and Fig. 1c, respectively. It can be seen that the distributions of the piezoresponse in these regions are distinctly different. In the nonperforated region between the electrodes, the distributions of both components of the piezoresponse are more or less uniform. When voltage is applied to the electrodes in a nonperforated structure, the maximum value of the piezoresponse is localized in the near-electrode region. This agrees with the results of [13], in which it is shown that both components of the electric field sharply increase at the electrode boundary. In our measurements, the decrease in intensity from the maximum to the average value in the gap is observed at a distance of approximately 250 nm for both the lateral and vertical components. When a field of the opposite sign is applied, the near-electrode peak of the piezoresponse has a different value: the maximum intensity of the piezoresponse, when a constant voltage of +10 V is applied, significantly (by a factor of 2.8 for the lateral and about 1.7 times for the vertical component of the piezoresponse) exceeds the same value when a constant voltage of −10 V is applied. One of the reasons for this difference may be the nonswitchable polarization, which usually occurs at the film/substrate interface due to mechanical stress caused by the lattice period mismatch. However, at a film thickness of 1 µm the effect of this polarization on the lateral component of the piezoresponse near the surface can be considered insignificant. Another explanation for this difference in the piezoresponse may be the contribution to the recorded signal due to a change in the profile of the entire structure caused by the piezoelectric effect in the film under the electrodes. Previously, we showed [9] that an electric field can lead to a change in the structure profile within a few hundred nanometers. When a voltage of +10 V is applied, the change in the profile does not exceed 50 nm, but this may be sufficient for a noticeable shift of the laser beam in the recording system of an atomic force microscope, which, as a result, manifests itself in the asymmetry of the piezoresponse. This issue requires clarification.

On the perforated structure hole boundary, there are points at which a change (switching) of polarization is observed when an opposite potential difference is applied to the electrodes (for example, region 1) and points that retain their state at any value of the applied field (Fig. 2a). This distribution is explained by the influence of not only the features

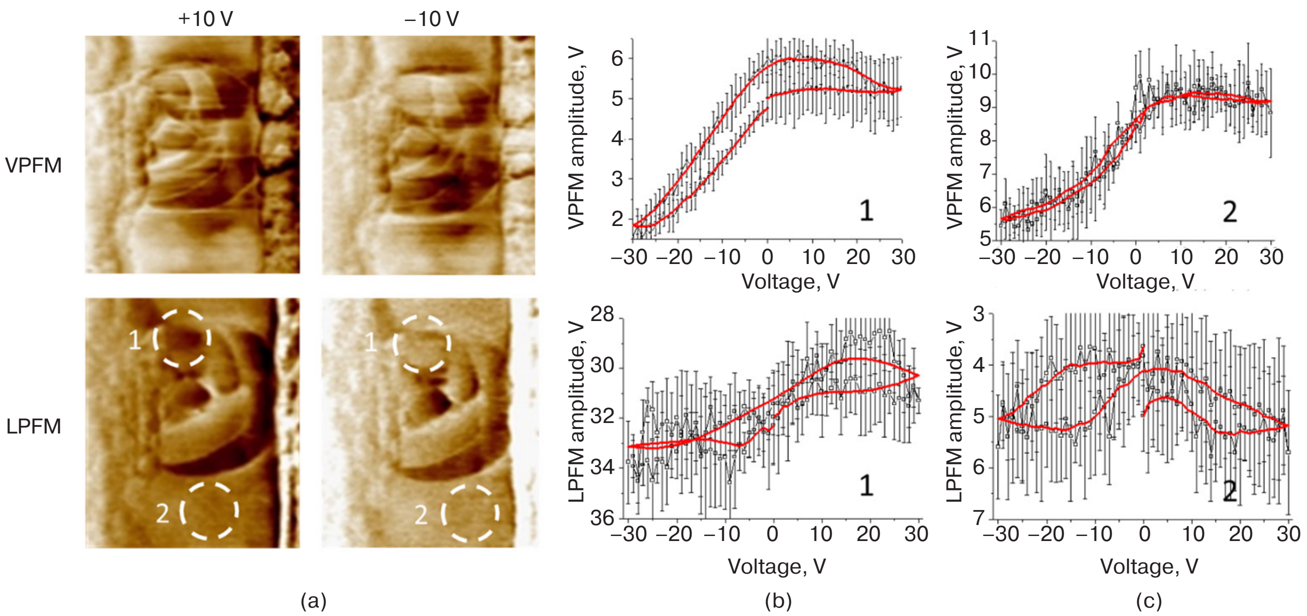

Fig. 2. Maps of the distribution of the piezoresponse in the area of one hole of the perforated structure when an external field is applied to the interdigital electrodes (a) and the dependence of the amplitude of the vertical (upper panels) and lateral (lower panels) piezoresponse on the voltage at the electrodes of the interdigital system of electrodes measured in regions 1 (Fig. 2b) and 2 (Fig. 2c). The red line is the result of averaging over 5 measurements for each cycle

of the topography, but also several mechanisms. The distribution of the piezoresponse is affected by structural defects that appear on the inner surface and on the hole edge as a result of etching. Firstly, the impact of high-energy ions is manifested in the implantation of high-energy Ga^+ ions into the material structure, and secondly, in the formation of a large number of microdamages on the surface and, as a result, in the amorphization of the near-surface layer. These factors create a defective layer on the structure surface (on the hole edge and on the air channel inner surface), which properties may differ significantly from those of the base material [14, 15]. It was also shown in [15] that the damaged region is not limited by the structure specified by the electronic template but extends no less than 1 μm from its edge into the depth of the region not subjected to etching. These damages and related distortions of properties are all the more significant, the more complex and more dependent on local polarization properties is the structure of PC elements. A rough estimate of the grains parameters in the hole region, performed using the NT-MDT Ntegra Aura scanning probe microscope software, showed that most of the grains in the holes have an average size of less than 100 nm, which corresponds to an amorphous structure.

Another factor affecting the inhomogeneity of the resulting distribution of the piezoresponse is the pinning of domains to the inner surface of the air channel, which interact with the side surface of the conducting needle of the cantilever. As a result, the overall piezoresponse in the hole region has a much greater intensity and inhomogeneity than the typical response of an amorphous structure.

To study the effect of a defective layer on the piezoresponse parameters, piezoelectric hysteresis loops were measured in the region containing the switched domain (region 1 in Fig. 2a) and in the gap between two air channels (region 2 in Fig. 2a). Details of the measurement technique are given in [9]. Since the structure has a significant number of defects, 5 measurements for each cycle were averaged. The results of individual measurements, the averaged value, and the errors for the vertical and lateral piezoresponse are shown in Figs. 2b and 2c, respectively. During the measurements, the external bias voltage changed from the initial state (0 V) to a positive value and back.

The vertical piezoresponse loop in region 1 is not symmetrical and has a relatively low saturation state at +10 V and a large, about 3 GV/m, saturation field at a negative value of the applied field (Fig. 2). The vertical piezoresponse loop in region 2 (in the gap between the holes) is more symmetrical and slightly shifted to the negative part. The nonswitchable polarization caused by mechanical stresses at the interface with the substrate does not affect the formation of the piezoresponse. Therefore, such a shift can be explained by the influence of pinned domain states near the boundary of the air channel opening. The possibility of the formation of short-range mesoscale domains in a perforated ferroelectric structure is confirmed in a number of works (e.g., [16]).

The field dependences of the lateral piezoresponse recorded in region 1 show a more complex piezoelectric behavior compared to that observed in the gap between holes (region 2). This behavior is consistent with the relaxation of mechanical strain near the holes, where the film material is removed by ion etching [17]. However, an important feature of these results is that the perforated structure showed a high response in the LPFM signal even with hysteresis behavior. The increase in the PFM signal and the different loop termination tendencies can be explained by the assumption that the LPFM domains formed a closed structure around the hole with the opposite orientation of the spatial domains. In accordance with this assumption, the LPFM signal in the second region is formed under the influence of two 180-degree domains from adjacent holes, resulting in the formation of 90-degree domains between the holes, which are visualized by measuring VPFM. This mechanism partly agrees with the simulation results presented in [8] and requires further detailed study.

Based on the measured piezoelectric hysteresis, the piezoelectric coefficients in regions 1 and 2 were estimated in accordance with the approach described in [9, 10], in which it is assumed that the effective piezoelectric coefficients of the vertical d_V and lateral response d_L are: $d_V \approx d_{33}$, $d_L \approx d_{15} \pm d_{31}$.

The calculation results showed that perforation of a ferroelectric film leads to an increase in the lateral component of the piezoresponse from d_L = 5 pm/V for a nonperforated film to 65 pm/V in the region of perforation. The VPFM tensor also increased but not as sharply, from 11 to 40 pm/V.

CONCLUSIONS

When an ordered structure of vertical air channels is formed in an epitaxial film of the $Ba_{0.8}Sr_{0.2}TiO_3$ ferroelectric by etching with a focused ion beam, a damaged layer is formed on the inner surface of the air channel, the properties of which are due to two factors: amorphization of the structure and the appearance of pinned domain states near the channel boundary. This, in turn, leads to the formation of a complex piezoresponse distribution in the area of the perforation hole. If the vertical component of the piezoresponse dominates in the nonperforated structure, then in the perforated structure the contribution of the lateral component increases due to the formation of a complex structure with opposite domain orientations in the region adjacent to the hole boundary. Perforation leads to an increase in both the vertical and lateral components of the piezoresponse compared to the nonperforated film. The results obtained must be taken into account when calculating and modeling the distribution of the piezoelectric properties of two-dimensional photonic crystals based on ferroelectric films.

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REFERENCES

1. Scott J.F., Paz de Araujo C.A. Ferroelectric memories. *Science*. 1989;246(4936):1400–1405. https://doi.org/10.1126/science.246.4936.1400
2. Wang Y.G., Zhong W.L., Zhang P.L. Surface and size effects on ferroelectric films with domain structures. *Phys. Rev. B*. 1995;51(8):5311–5314. https://doi.org/10.1103/PhysRevB.51.5311
3. Lin P.T., Yi F., Ho S.-T., Wessels B.W. Two-dimensional ferroelectric photonic crystal waveguides: simulation, fabrication, and optical characterization. *J. Lightwave Technol*. 2009;27(19):4330–4337. https://doi.org/10.1109/JLT.2009.2023808
4. Matveev O., Morozova M., Romanenko D. Concept of using composite multiferroic structure magnonic crystal – ferroelectric slab as memory unit. *J. Phys.: Conf. Ser*. 2019;1389(1):012041(1–5). https://doi.org/10.1088/1742-6596/1389/1/012041
5. Hu X., Gong Q., Feng S., Cheng B., Zhang D. Tunable multichannel filter in nonlinear ferroelectric photonic crystal. *Opt. Commun*. 2005;253(1–3):138–144. https://doi.org/10.1016/j.optcom.2005.04.056
6. Takeda H., Yoshino K. Tunable photonic band gaps in two-dimensional photonic crystals by temporal modulation based on the Pockels effect. *Phys. Rev. E*. 2004;69(1Pt2):016605(1–5). https://doi.org/10.1103/PhysRevE.69.016605
7. Ferri A., Rémiens D., Desfeux R., Da Costa A., Deresmes D., Troadec D. Evaluation of damages induced by Ga+-focused ion beam in piezoelectric nanostructures. In: Wang Z. (Ed.). *FIB Nanostructures. Lecture Notes in Nanoscale Science and Technology*. Cham: Springer; 2013. V. 20. P. 417–434.
8. Levanyuk A.P., Misirlioglu I.B., Mishina E.D., Sigov A.S. Effects of the depolarization field in a perforated film of the biaxial ferroelectric. *Phys. Solid State*. 2012;54(11):2243–2252. https://doi.org/10.1134/S1063783412110170
9. Sherstyuk N.E., Ivanov M.S., Ilyin N.A., Grishunin K.A., Mukhortov V.M., Kholkin A.L., Mishina E.D. Local electric field distribution in ferroelectric films and photonic crystals during polarization reversal. *Ferroelectrics*. 2016;503(1):138–148. https://doi.org/10.1080/00150193.2016.1217143
10. Ivanov M.S., Sherstyuk N.E., Mishina E.D., Khomchenko V.A., Tselev A., Mukhortov V.M., Paixao J.A., Kholkin A.L. Enhancement of local piezoelectric properties of a perforated ferroelectric thin film visualized via piezoresponse force microscopy. *J. Phys. D: Appl. Phys*. 2017;50(42):425303(1–6). https://doi.org/10.1088/1361-6463/aa8604

11. Mishina E., Zaitsev A., Ilyin N., Sherstyuk N., Sigov A., Golovko Yu., Muhortov V., Kolesnikov A., Lozovik Yu., Yemtsova M., Rasing Th. Switchable nonlinear metalloferroelectric photonic crystals. *Appl. Phys. Lett.* 2007;91(4):041107(1–6). https://doi.org/10.1063/1.2762284
12. Mukhortov V.M., Golovko Y.I., Tolmachev G.N., Klevtzov A.N. The synthesis mechanism of complex oxide films formed in dense RF – plasma by reactive sputtering of stoichiometric targets. *Ferroelectrics*. 2000;247(1):75–83. https://doi.org/10.1080/00150190008214943
13. Brekhov K.A. Electric field intensity in a planar capacitor based on thin $BaSrTiO_3$ Ferroelectric Film. *Nano- i Mikrosistemnaya Tekhnika = Nano- and Microsystems Technology*. 2018;20(9):555–561 (in Russ.). https://doi.org/10.17587/nmst.20.555-561
14. Volkert C.A., Minor A.M. Focused ion beam microscopy and micromachining. *MRS Bulletin*. 2007;32(05):389–399. https://doi.org/10.1557/mrs2007.62
15. Morelli A., Johann F., Schammelt N., Vrejoiu I. Ferroelectric nanostructures fabricated by focused-ion-beam milling in epitaxial $BiFeO_3$ thin films. *Nanotechnology*. 2011;22(26):265303(1–6). https://doi.org/10.1088/0957-4484/22/26/265303
16. Kholkin A.L., Kalinin S.V., Roelofs A., Gruverman A. *Scanning Probe Microscopy: Electrical and Electromechanical Phenomena at the Nanoscale.* Kalinin S., Gruverman A. (Eds.). New York: Springer; 2006. 988 p.
17. Nagarajan V., Roytburd A., Stanishevsky A., Prasertchoung S., Zhao T., Chen L., Melngailis J., Auciello O., Ramesh R. Dynamics of ferroelastic domains in ferroelectric thin films. *Nat. Mater*. 2003;2(1):43–47. https://doi.org/10.1038/nmat800

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RESEARCH ARTICLE

Application of an integrated method to improve the quality of manufacturing parts of electronic warfare devices

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Abstract

Objectives. The development of technological methods with the purpose of increasing the structural strength of defense engineering products can be carried out by creating new methods for obtaining and processing parts or improving traditional methods based on an integrated (synergistic) approach. The article presents a complex method for surface treatment of parts and assessment of the hardness and surface roughness of the initial workpiece from alloys of the Al–Mg system to improve the quality of manufacturing the module cases of the *MSP-418K* product related to electronic warfare devices.

Methods. This approach consists in the vision of a metallic material as a system subjected to a chain of technological impacts in the process of chemical, thermodynamic, and mechanical interaction of its components. The workpieces were obtained by metal pressure treatment according to various schemes and temperature conditions Then they were processed with a blade tool using a dynamometer. The resulting cut was examined using a metallographic method along the entire end face from the outer surface to the center of the sample of workpieces.

Results. Experiments were carried out for the case of Al–Mg alloys. It made it possible to reveal the relationship between the parameters of the change in the structure of the material being processed and the stability of the cutting process, as well as the quality of the surface during finishing turning.

Conclusions. The proposed technological solutions based on a synergistic approach provided a balanced improvement in material parameters by eliminating the shortcomings of the original semi-finished product. The obtained experimental data allowed concluding the deformation of workpieces according to complex schemes at low temperature has a beneficial effect on the machinability of the metal material, ordering the structure and improving the quality of the surface of the parts. Using a synergistic approach, it became possible to correct the poor technological heredity of material properties obtained in previous operations: the surface quality of the workpieces due to the continuity of the processed material and the strength properties of parts for critical and especially critical purposes were improved. The existing technological process for manufacturing the “petal” part was changed in practice using an integrated method, which made it possible to improve its technological and technical characteristics.

Keywords: machinability, annealing, surface quality, cutting tool load, material structure, hot-rolled plates, extruded bar

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НАУЧНАЯ СТАТЬЯ

Применение комплексного метода для улучшения качества изготовления деталей приборов радиоэлектронной борьбы

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Резюме
Цель. Разработка технологических приемов, направленных на повышение конструктивной прочности изделий оборонного машиностроения, может осуществляться с помощью создания новых способов получения и обработки деталей или улучшения традиционных приемов на основе комплексного (синергетического) подхода. В статье приводится комплексный метод обработки поверхности деталей, оценки твердости и шероховатости поверхности исходной заготовки из сплавов системы Al-Mg для улучшения качества изготовления корпусов модулей изделия МСП-418К, относящегося к приборам систем радиоэлектронной борьбы.
Методы. Данный подход заключался в видении металлического материала как системы, подвергаемой цепочке технологических воздействий в химическом, термодинамическом и механическом взаимодействии своих составляющих. Заготовки получали методом обработки металла давлением по различным схемам и в различных температурных режимах, затем обрабатывали их лезвийным инструментом с использованием динамометра и исследовали полученный рез металлографическим способом по всему торцу от наружного диаметра к центру образца.
Результаты. На примере Al-Mg сплавов проведены эксперименты, позволившие обнаружить зависимость между параметрами изменения структуры обрабатываемого материала и стабильностью процесса обработки резанием, а также качеством поверхности при чистовом точении детали.
Выводы. Предложенные технологические решения на основе синергетического подхода обеспечили сбалансированное улучшение параметров материала за счет устранения недостатков исходного полуфабриката. На основании полученных опытных данных сделан вывод о том, что проводимая деформация заготовок по сложным схемам при пониженной температуре благотворно влияет на обрабатываемость металлического материала, упорядочивание структуры и повышает качество поверхности деталей. При применении синергетического подхода есть возможность исправить плохую технологическую наследственность свойств материалов, полученную на предыдущих операциях; повысить качество поверхности заготовок за счет сплошности обрабатываемого материала; улучшить прочностные свойства деталей ответственного и особо ответственного назначения. Благодаря полученным результатам на практике подвергнут изменению существующий технологический процесс изготовления детали «лепесток», который позволил улучшить ее технологические и технические характеристики.

Ключевые слова: обрабатываемость, отжиг, качество поверхности, нагрузка на режущий инструмент, структура материала, горячекатаные плиты, прессованный пруток

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Автор заявляет об отсутствии конфликта интересов.

INTRODUCTION

Electronic warfare (EW) is an armed struggle during which an effect of electromagnetic interference (EMI), also called radio-frequency interference (RFI), or jamming on the electronic means of enemy control, communication, and reconnaissance systems. Electronic warfare products are used to protect electronic equipment from exposure to powerful electromagnetic and acoustic radiation, as well as high-precision weapons equipped with passive homing devices for RFI sources. The use of selectively directed weapons against radioelectronic means (REM), as a rule, does not lead to catastrophic destruction and irreparable losses [1]. Such weapons deprive electronic devices of the possibility of normal, regular functioning. One of these products is the small jamming station *MSP-418K* (Fig. 1).

FIBER OPTIC WDM MULTIPLEXERS/DEMULTIPLEXERS WITH LOW FLEXURAL LOSS FACTOR

The station is designed to equip targets, aviation decoys, individual and individual-mutual protection of small-sized aircraft, for example, the *MiG29* and *MiG31* by creating deliberate active jamming of radioelectronic weapons controls (REWC), included in antiaircraft missile, antiaircraft artillery and aviation and missile systems. This station belongs to the means of radioelectronic countermeasures (REC) of the fifth generation, as it enables significant expansion of the combat capabilities of aviation.

The station ensures the simultaneous creation of deliberate targeted active interference to at least four REWCs, including homing radio heads (HRH), with their carrier frequencies separated by more than 100 MHz. Sensitivity in the operating frequency range at the input for a pulsed signal is no more than 51 dB W; for a continuous signal, a quasi-continuous signal, and a long (pulse) signal—no more than 68 dB W. The mass of the product is no more than 170 kg, the operating frequency range is from 4 to 18 GHz.

The *MSP-418K* station consists of several units, two switches *PK-1-2*, a set of cable assemblies *KKS L-281*, a set of low-frequency bundles *KNChZh L-281-1*, a set of attenuators *Kat L-281-1*, two sets of mounting parts *KMCh L-281-1*, as well as *KMCh*(*U*) *L-281-1*.

The product *L-281-1* is developed based on digital signal processing using digital radio frequency memory

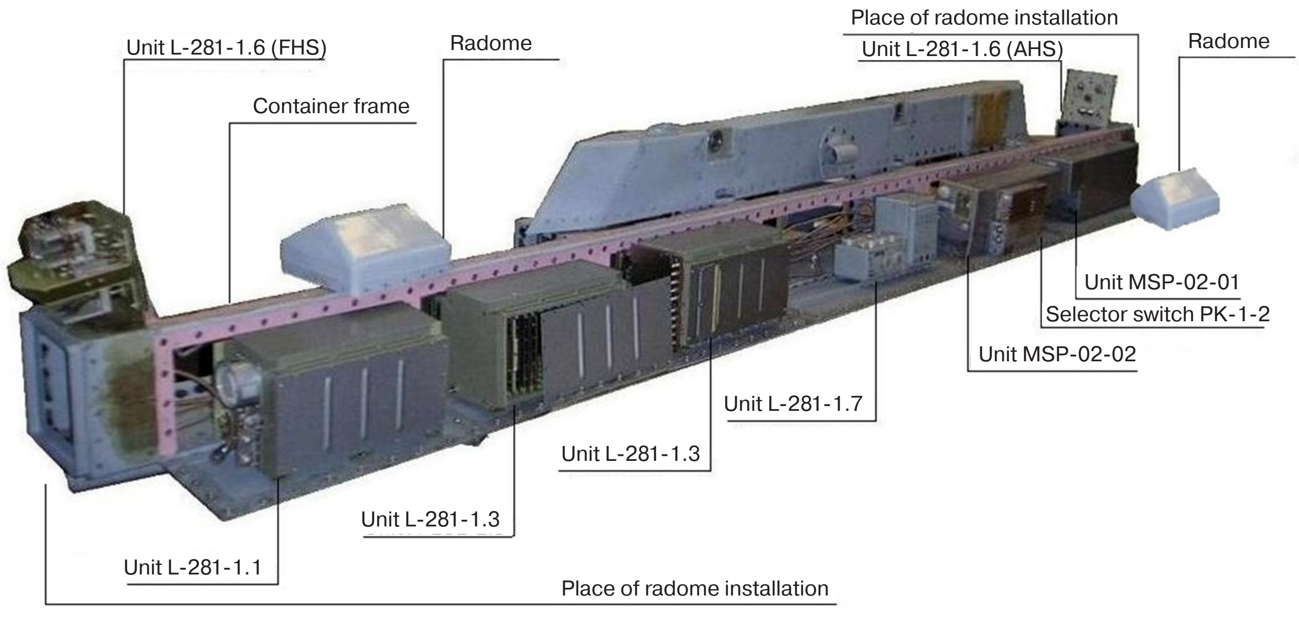
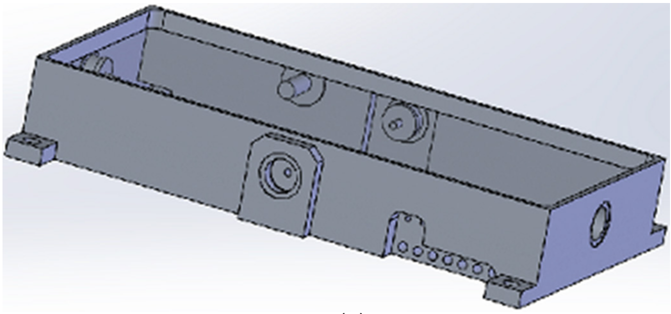
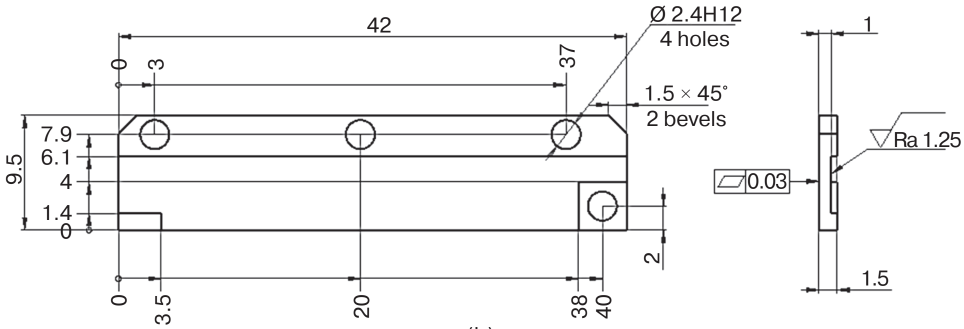


Fig. 1. Design of the small jamming station *MSP-418K*



(a)



(b)

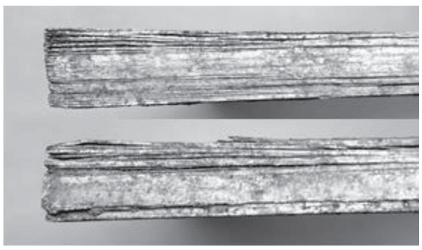
Fig. 2. Case model (a) and frame drawing (b) from steel *MD-40*

technology and is designed to counteract the REWC, operating in pulsed, continuous, pulse-Doppler, and long-pulse modes[1]. The station units include various standardized modules, which consist of a body and electronic filling, as well as typical standardized microassembly parts (Fig. 2).

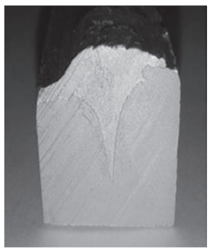
These parts belong to the class of critical and especially critical applications. They provide vacuum tightness and geometric accuracy over the full-service life. At the same time, despite many years of manufacturing practice, a general cause of electrical breakdown and failure of their electronic filling are failures of the vacuum sealing of cases and failures of the geometry of microassembly parts [2].

The housings of microassemblies are made from hot-rolled plates based on aluminum alloys of the Al–Mg system (Fig. 3a). Their use is justified by the simplicity of the technological process[2, 3]. This does not take into account the high level of internal stresses in the material obtained during rolling (Fig. 3b), which are the higher, the greater the thickness of the plate [2, 3]. In addition, "lines" of intermetallic phases Mg_2Al_3 and Mg_5Al_{18} are formed in the structure of hot-rolled plates, and their appearance is especially pronounced in the zones of localization of deformations and discontinuity of their rates (Fig. 3c) [4].

(a)



(b)



(c)

Fig. 3. The process of manufacturing microassembly cases from hot-rolled aluminum alloys of the Al–Mg system (a); result of plate delamination due to intergranular corrosion (b); a defect in the materials of the hot-rolled plate (c)

The loss of tightness of microassembly housings, as industrial practice shows [5], occurs due to "leakage through the material" of the housing (Fig. 4a),

[1] Compact JAMMER MSP-418K. *Zhurnal oboronno-promyshlennogo kompleksa*. 18.08.2009. URL: http://bastion-karpenko.ru/compact-jammer-msp-418k/. Accessed November 10, 2021 (in Russ.).

[2] GOST 17232–99. Aluminium and aluminium alloys plates. Specifications. Moscow: Izd. standartov; 2000. 10 p. (in Russ.).

[3] GOST 4784–97. Aluminium and wrought aluminium alloys. Grades. Moscow: Izd. standartov; 2001. 12 p. Edited (in Russ.).

(a) (b) (c)

Fig. 4. Types of damage to the surface of the housings due to "leakage through the material" of the housing (a); delamination of the coating of the base material (b) and "leakage along cracks" (c)

delamination of the coating from the base material (Fig. 4b) or "leakage along cracks" formed during the chemical nickel-plating of the body and cover of the microassembly before soldering (Fig. 4c). A number of works are devoted to this problem, for example, [6, 7], but they do not take into account the influence of the structure and properties of the material of these cases.

The article [7] considers a method for improving the quality of finished units' parts in the *MSP-418K* product by introducing an additional technological operation to optimize the structure of the starting material in the manufacture of radioelectronic warfare parts. This makes it possible to exclude the invariance of hereditary factors obtained in previous technological operations[4].

With an increase in the grain size, the tendency of the metallic material to destruction increases due to phase separation and thermal diffusion of the melt substances that leads to an increase in the number of defects and impurities displaced from the volume. Plastic deformation during rolling makes it possible to resist this process [8]. Workpieces that have undergone additional deformation are usually characterized by increased strength properties of the material. Depending on the requirements for the material of the workpiece, one of the recommended forging schemes is assigned and the temperature of heating the material before forging is selected.

MATERIALS AND METHODS

In the case of aluminum alloys of the Al–Mg system, experiments on using a complex technological process for manufacturing electronic warfare parts were conducted. The technological process includes forging the original bar workpieces according to various schemes of the All-Russian Research Institute of Aviation Materials, *VIAM* (State Scientific Center of the Russian Federation) [9, 10] and temperature parameters; stabilizing annealing of three forgings at 320°C in comparison with three forgings carried out at a temperature of 420°C for 1 h, followed by air cooling of each batch of forgings; processing of samples on a screw-cutting lathe; dynamometric and metallographic studies to measure the hardness and roughness of the treated surfaces of the samples.

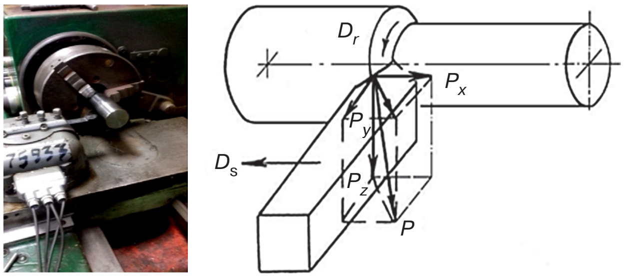
The manufacture of a part under different temperatures is necessary for increasing the strength properties of the material [11]. The number of defects and impurities in the initial material increases with the increase of grain size. Grain crushing during the forging process reduces the content of grain boundary impurities, making the material of the part more uniform and balanced in properties.

The temperature for stabilized annealing was chosen in accordance with *VIAM* recommendations. The recommended forging temperatures are 350–430°C [12]. However, based on previous studies, it was decided in the experiment to set the forging temperature at the upper and lower values: 420°C and 320°C, respectively.

The studies were performed with six forgings (samples No. 1–6) with dimensions Ø70 × 140 mm; the results were compared with the original material of the workpiece (pressed rod) with dimensions Ø70 × 120 mm, (sample No. 0). The permissible degree of deformation during forging on the "hammer" of forging and pressing equipment was 50% [11]. In an electric muffle furnace (SNOL), the workpiece (samples No. 1–3) was heated to a temperature of 420°C, and samples Nos. 4–6 were heated to a temperature of 320°C. The draft was up to 60 mm.

After stabilized annealing, the samples were machined on a *16K20* screw-cutting lathe using a dynamometer (Fig. 5a). Figure 5b shows that when turning along the generatrix (diameter) and along the end face of experimental samples, the load force on the cutting tool (cutter) is distributed over three coordinates: P_x is the feed force, P_y is the radial force, and P_z is the cutting force [7].

[4] Kovka i shtampovka deformiruemykh alyuminievykh splavov: Proizv. Instruktsiya (Forging and stamping of wrought aluminum alloys: Prod. Instruction) PI 1.2.085–78. [Approved VIAM]. 01.09.1978. 17 p. (in Russ.).

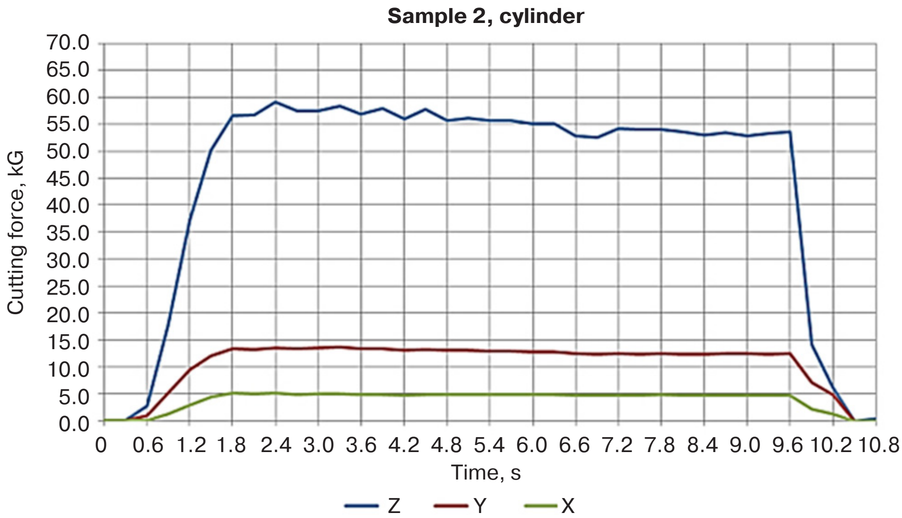


(a) (b)

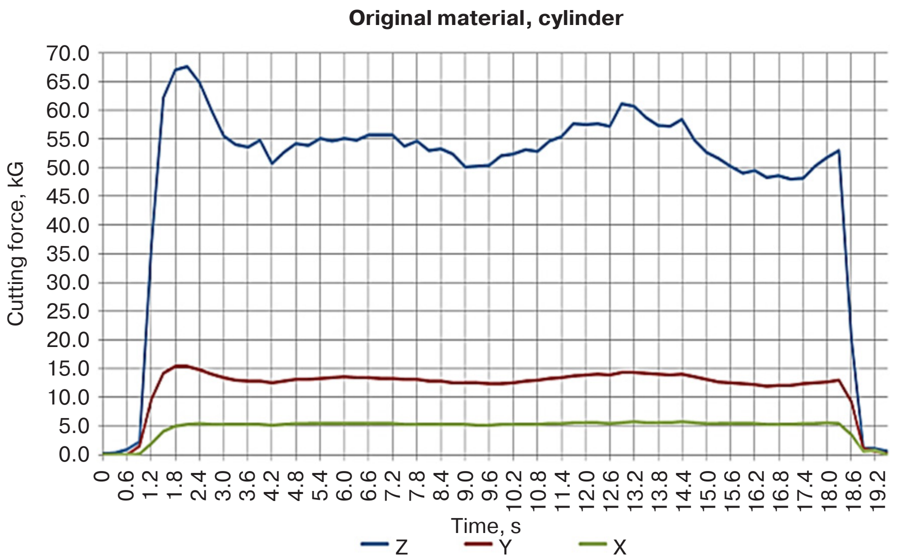
Fig. 5. General view of the *16K20* screw-cutting lathe with an automated dynamometer *UDM 600* (a); schematic description of the distribution of the load force on the cutter during the processing of samples on a screw-cutting lathe (b)

RESULTS AND DISCUSSION

The dynamometric method of research showed that the distribution of load forces in the cutting tool (cutter) during the treatment of samples in three coordinates corresponds to their classical relationship: the value of the feed force P_x varies from ⅛ to ¼, and the radial force P_y—from ¼ to ½ of the cutting, P_z. Comparison of experimental, mechanically turned samples (Fig. 6a) with the original bar (Fig. 6b) showed that when machined samples with the same oriented structure in the material are obtained by forging operations, it is possible to ensure the lowest roughness of the machined surface. This is because a more effective dynamic damping of vibrations during cutting is achieved by a large dissipative resistance force of the material of the workpiece with a texture of the deformed metal oriented in different directions.



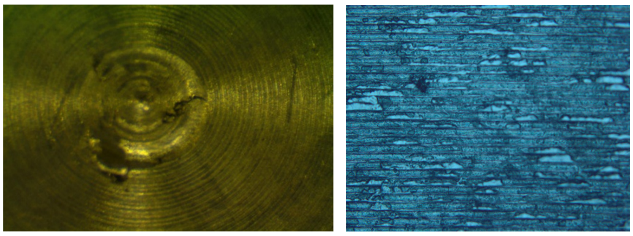
(a)



(b)

Fig. 6. The surface roughness distribution of the experimental forgings (a) and the original billet (b)

A comparison of the microstructure and roughness (texture) of the surface of the original workpiece showed that the coincidence of the grain size and the magnitude of the force of removal and feed of the tool leads to tearing in the material of the original workpiece and sticking of the material to the cutter (Fig. 7a). In this case, pull-out usually occurs at the triple junctions of grains, where there are places of accumulation of impurity phases [13].



(a) (b)

Fig. 7. The surface of the original workpiece with material tearing out during turning and machining and chips on its surface (a); the surface obtained after forging with interlayers of inclusions (b)

At the same time, an increase in the density and hardness of the material of workpieces facilitates chip flow and improves the quality of their surface after turning (Fig. 7b). Elongated non-metallic inclusions located along the cut boundaries are weakly bound to the metal matrix or differ sharply from it in terms of elastic characteristics. Microscopic metal discontinuities near the boundaries of non-metallic inclusions are located differently in relation to the external force applied during the turning process. All these imperfections (interlayers of inclusions) enhance the dissipation of vibration energy during the turning and machining of experimental samples after forging.

We can draw some conclusions analyzing the magnitude and nature of the loads on the cutter during turning along the generatrix and along the end of the original bar and experimental forgings, as well as the roughness (texture) of the machined surface and the hardness of the material of the machined workpieces at various points.

First, the load force on the cutter increases with an increase in the forging and a decrease in the deformation temperature. In this case, the force becomes kinematic (uniform) in comparison with the machining of the original material of the workpiece.

Secondly, forging according to complex schemes at low temperatures not only improves the characteristics of the vacuum tightness and corrosion resistance of the metal material, but also reduces the roughness of the machined surface of the samples. On the contrary, the smaller the deformation reduction achieved, the larger the grain of the material and the chains of intermetallic phases, as well as the softer the sample material and the rougher its surface after machining with a blade tool on a screw-cutting lathe.

CONCLUSIONS

The paper presents a complex method for improving the quality of manufacturing electronic warfare parts based on alloys of the Al–Mg system. Machining the workpiece under conditions providing its uniform deformation makes it possible to obtain a balanced set of technological and special properties. Good machinability and surface quality of workpieces by cutting are achieved via increased hardness of the material of the workpiece, and at the same time via critically important for a number of parts increased resistance of the material to development of corrosion processes and its vacuum tightness.

Manufacturing the microassembly body from a workpiece obtained according to the complex forging scheme ensures uniform deposition of a nickel coating with a minimum level of tensile stresses formed in the surface layer of the workpiece material.

REFERENCES

1. Dobykin V.D., Kupriyanov A.I., Ponomarev V.G., Shustov L.N. *Silovoe porazhenie radioelektronnykh sistem* (*Force defeat of radio-electronic systems*). Moscow: Vuzovskaya kniga; 2007. P. 10–16 (in Russ.).
2. Khadi O.Sh., Litvinov A.N. Simulation of the stress-strain state of microassembly housings during their manufacture and operation. In: *Dynamics and strength*. Proceedings. Moscow: Ross. Akad. Nauk; 2013. P. 3–26 (in Russ.).
3. Golovkin P.A., Fesenko S.A., Kryukov A.V. Deformation mechanism control as a tool to improve the quality of titanium alloy forgings. In: *Progressive developments of scientists – new products of rocket and space technology*. Collection of scientific papers; 2013. P. 189–194 (in Russ.).

СПИСОК ЛИТЕРАТУРЫ

1. Добыкин В.Д., Куприянов А.И., Пономарев В.Г., Шустов Л.Н. *Силовое поражение радиоэлектронных систем*. М.: Вузовская книга; 2007. С. 10–16.
2. Хади О.Ш., Литвинов А.Н. Моделирование напряженно-деформированного состояния корпусов микросборок в процессе их изготовления и эксплуатации. В сб.: *Динамика и прочность*. Избранные труды Всеросс. научн. конф. по проблемам науки и технологий. М.: РАН; 2013. С. 3–26.
3. Головкин П.А., Фесенко С.А., Крюков А.В. Управлением механизмами деформации как инструмент повышения качества поковок из титановых сплавов. В сб.: *Прогрессивные разработки ученых – новым изделиям ракетно-космической техники*. Сб. научн. трудов. 2013. С. 189–194.

4. Stepanov V.G., Klestov M.I. *Poverkhnostnoe uprochnenie korpusnykh konstruktsii* (*Surface hardening of hull structures*). Leningrad: Sudostroenie; 1977. 197 p. (in Russ.).
5. Dal'skii A.M., Bazrov B.M., Vasil'ev A.S. *Tekhnologicheskaya nasledstvennost' v mashinostroitel'nom proizvodstve* (*Technological heredity in machine-building production*). Moscow: MAI; 2000. 360 p. (in Russ.). ISBN 5-7035-2322-2
6. Gorenskii B.M., Lapina L.A., Lyubanova A.Sh., et al. *Modelirovanie protsessov i ob''ektov v metallurgii* (*Modeling of processes and objects in metallurgy*). Krasnoyarsk: Siberian Federal University; 2008. 145 p. (in Russ.). ISBN 978-5-7638-1266-4
7. Litvinov A.N., Khadi O.Sh. Estimation of the accuracy of an approximate method for determining the allowable pressure for microassembly bodies. In: *Actual problems of modern mechanical engineering.* Proceedings of the Intern. scientific and practical. conf. Tomsk: Tomsk. politekh. inst.; 2014. P. 191–194 (in Russ.).
8. Kishkina S.I., Fridlyander I.N. (sci. eds.). *Aviatsionnye materialy*: spravochnik v 9 t. T. 4. *Alyuminievye i berillievye splavy*. Chast' 1. *Deformiruemye alyuminievye splavy i splavy na osnove berilliya* (*Aviation materials*: a reference book in 9 v. V. 4. *Aluminum and beryllium alloys*. Part 1: *Wrought aluminum alloys and beryllium-based alloys*). Moscow: VIAM; 1982. 628 p. (in Russ.).
9. Amosov I.S., Skragan V.A. *Tochnost', vibratsii i chistota poverkhnosti pri tokarnoi obrabotke* (*Accuracy, vibration and surface finish in turning*). Anserov M.A. (Ed.). Leningrad: Mashgiz; 1958. 91 p. (in Russ.).
10. Teleshov V.V., Churyumov A.Yu. Analysis of the influence of the characteristics of a two-phase matrix structure on the fracture toughness of wrought aluminum alloys. *Tekhnologiya legkikh splavov = Technology of Light Alloys*. 2012;2:22–40 (in Russ.).
11. Golovkin P.A. Improving the microassamblies cases quality of the electronic microwave devices be using forging operations. *Tekhnologiya mashinostroeniya*. 2020;9:5–7 (in Russ.).
12. Kryukov A.V., Volkov A.V., Golovkin P.A., Galkin V.I. Improving the quality of microwave electron microwave instruments – detailed at optimization of structural changes. *Vestnik RAEN = Bulletin of the Russian Academy of Natural Sciences*. 2019;19(3):36–41 (in Russ.).
13. Verbovoi F.P., Kalugin A.A., et al. Dependence of the quality of forgings from the $AlMg_6$ alloy on the initial billet and the magnitude of the deformation during forging. *Alyuminievye splavy i spetsial'nye materialy* (*Aluminum alloys and special materials*). *Sb. trudov. VIAM = Proceedings of VIAM*. 1975. V. 9.

4. Степанов В.Г., Клестов М.И. *Поверхностное упрочнение корпусных конструкций*. Л.: Судостроение; 1977. 197 с.
5. Дальский А.М., Базров Б.М., Васильев А.С. *Технологическая наследственность в машиностроительном производстве*. М.: Изд-во МАИ; 2000. 360 с. ISBN 5-7035-2322-2
6. Горенский Б.М., Лапина Л.А., Любанова А.Ш. и др. *Моделирование процессов и объектов в металлургии*. Красноярск: Сибирский федеральный университет; 2008. 145 с. ISBN 978-5-7638-1266-4
7. Литвинов А.Н., Хади О.Ш. Оценка точности приближенного метода определения допустимого давления для корпусов микросборок. В сб.: *Актуальные проблемы современного машиностроения*. Сборник трудов Междунар. научно-практ. конф. 11–12 декабря 2014 г. Юргинский технологический институт. Томск: Изд-во Томского политехнического университета; 2014. С. 191–194.
8. Кишкина С.И., Фридляндер И.Н. (науч. ред.). *Авиационные материалы*: справочник в 9 т. Т. 4. *Алюминиевые и бериллиевые сплавы*. Часть 1. *Деформируемые алюминиевые сплавы и сплавы на основе бериллия,* Кн. 1. М.: ВИАМ; 1982. 628 с.
9. Амосов И.С., Скраган В.А. *Точность, вибрации и чистота поверхности при токарной обработке*; под общ. ред. М.А. Ансерова. Л.: Машгиз; 1958. 91 с.
10. Телешов В.В., Чурюмов А.Ю. Анализ влияния характеристик двухфазной матричной структуры на вязкость разрушения деформируемых алюминиевых сплавов. *Технология легких сплавов*. 2012;2:22–40.
11. Головкин П.А. Повышение качества корпусов микросборок электронных СВЧ-приборов с использованием ковочных операций. *Технология машиностроения*. 2020;9:5–7.
12. Крюков А.В., Волков А.В., Головкин П.А., Галкин В.И. Повышение качества корпусов микросборок электронных СВЧ-приборов за счет оптимизации структурных изменений. *Вестник РАЕН*. 2019;19(3):36–41.
13. Вербовой Ф.П., Калугин А.А. и др. Зависимость качества поковок из сплава $AlMg_6$ от исходной заготовки и величины деформации при ковке. *Алюминиевые сплавы и специальные материалы. Сб. трудов. ВИАМ*. 1975. Вып. 9.

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RESEARCH ARTICLE

Study of the reliability of quartz resonators in miniature ceramic packages

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Abstract
Objectives. In the development of radio electronics and communications, it is important that the requirements for the reliability, stability of the generated frequencies, and selectivity of the receiving equipment are fulfilled. The use of quartz resonators, widely used in radio circuits today, has partially allowed for the reliability of communication devices and guaranteed high frequency stability to be enhanced without complicating the circuit. Modern global trends in the development of electrical equipment are associated with miniaturization. The dimensions of quartz resonators are decreasing every year, while the requirements for reliability remain high. The study aimed to evaluate the possibility of using quartz resonators packaged in a miniature ceramic case 2.5 × 2.0 × 0.6 mm, under conditions of elevated ambient temperature. It has also allowed for the development of optimal requirements for the thermal training regime as the basic technological operation for stabilizing the oscillation frequency.
Methods. Reliability testing of quartz resonators and methods of statistical modeling in radio engineering.
Results. The results established the requirements for the reliability of *RK588* quartz resonators in miniature ceramic cases 2.5 × 2.0 × 0.6 mm in size under the influence of elevated ambient temperatures of +85°C and +125°C. The requirements for frequency drift when exposed to elevated ambient temperature on the crystalline plate type based on RF patent No. 27122426 “Method of manufacturing thin crystalline plates and thin crystalline elements” were also specified. The method of thermal training was optimized and the ageing coefficients were established.
Conclusions. The coefficients of ageing calculated for the resonators during the reliability tests was as follows: Batch No. 1 at a temperature of +85°C was 0.75; and for Batch No. 2 at a temperature of +125°C was 0.18. For this type of piezoelectric element with a size of 1.5 × 1.0 mm at an operating temperature of +125°C the ageing coefficient is 4 times lower than at a temperature of +85°C. This indicates the possibility of using the *RK588* resonator at elevated ambient temperatures.

Keywords: quartz resonator, reliability, ceramic case, oscillation frequency, temperature

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НАУЧНАЯ СТАТЬЯ

Исследование надежностных характеристик кварцевых резонаторов в миниатюрных керамических корпусах

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Резюме

Цели. При разработке современных приборов радиоэлектроники и связи большое значение имеет выполнение требований, предъявляемых к ее надежности, стабильности генерируемых частот, избирательности приемной аппаратуры. Применение кварцевых резонаторов, широко используемых в радиосхемах сегодня, частично позволило повысить надежность средств связи и гарантировало высокую стабильность частоты без усложнения схемы. Современные мировые тренды разработки электротехнической аппаратуры связаны с ее миниатюризацией. Габариты кварцевых резонаторов с каждым годом уменьшаются, при этом требования к надежностным характеристикам остаются высокими. Цель работы – оценка возможности применения кварцевых резонаторов, представленных в миниатюрном керамическом корпусе размером 2.5 × 2.0 × 0.6 мм, в условиях повышенной температуры окружающей среды, а также выработка оптимальных требований к режиму термотренировки, который является базовой технологической операцией для стабилизации частоты колебаний.

Методы. Испытание кварцевых резонаторов на безотказность и методы статистического моделирования в радиотехнике.

Результаты. Установлены требования к надежностным характеристикам кварцевых резонаторов РК588 в миниатюрных керамических корпусах размером 2.5 × 2.0 × 0.6 мм при воздействии повышенной температуры окружающей среды +85°С и +125°С. Установлены требования по уходу частоты при воздействии повышенной температуре окружающей среды на тип кристаллической пластины, созданной на основе патента РФ № 27122426 «Способ изготовления тонких кристаллических пластин и тонких кристаллических элементов». Оптимизирован способ термотренировки и установлены коэффициенты старения.

Выводы. Расчетный коэффициент старения резонаторов в процессе испытаний на безотказность для партии № 1 при температуре +85°С составил 0.75, а для партии № 2 при температуре +125°С составил 0.18. Для данного типа пьезоэлемента размером 1.5 × 1.0 мм при рабочей температуре +125°С коэффициент старения ниже в 4 раза, чем при температуре +85°С, что говорит о возможности применения резонатора РК588 в условиях повышенной температуры окружающей среды.

Ключевые слова: кварцевый резонатор, надежность, керамический корпус, частота колебаний, температура

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INTRODUCTION

In the development of devices for radio electronics and communications, it is important that the high requirements for its reliability, stability of the generated frequencies, and selectivity of the receiving equipment are fulfilled. The problem of increasing the reliability of communications has been partially resolved through the use of quartz resonators as widely used in radio circuits today. The use of quartz resonators in power generators has allowed for high frequency stability to be guaranteed without complicating the circuit. Electronic filters with quartz resonators have a higher performance than similar filters with inductors and capacitors[1].

At the present time, the production of quartz resonators is considered economically profitable, despite the appearance of materials whose stability of some parameters is higher than that of quartz.

One way in which the competitiveness of production can be enhanced is to reduce the price of products. This can be achieved by changing the technology of their manufacture. For example, by changing the thermal training regime, it is possible to reduce the production time without compromising the quality of the product. However, not all technological processes can be changed.

Heat treatment, i.e., maintaining at a high temperature for a certain time, is one of the important steps in manufacturing quartz resonators. This process takes place at the final stage of production [1]. This aim of this technological operation is to create artificial conditions for the ageing of a quartz resonator.

The quartz resonator ageing process is a combination of different physical processes which over time lead to a change in the resonant frequency of the product. Since most of these processes tend to return to the state of thermodynamic equilibrium after their completion, the resonator goes into a stable state, while frequency drifts become insignificant and acceptable for most devices [2].

The ageing process is complex and multi-stage. Thus, the thermal training regime is selected experimentally, based on the operating conditions of the given type of quartz resonator.

Thermal training most often requires more time than the manufacture of the resonator itself. The complexity and diversity of the quartz resonator ageing processes do not allow for an evaluation of the behavior of each specific product, or calculation of the most suitable regimes [3].

The aim of this study is to evaluate the possibility of using quartz resonators packaged in a miniature ceramic case 2.5 × 2.0 × 0.6 mm, under conditions of elevated ambient temperature. An additional objective is to develop optimal requirements for the thermal training regime as the basic technological operation for stabilizing the oscillation frequency.

STUDY OF THE RELIABILITY CHARACTERISTICS OF *RK588*

Change in the frequency of a quartz resonator over time occurs under stable operating conditions. This is due to irreversible changes in the properties of crystals, fasteners, and associated devices. In this case, several particular features are observed:

- in most cases, the ageing process is described by the exponential law of resonator frequency drift over time. The smooth course of the ageing curve is disturbed. Its magnitude and nature depend on the type of resonator;
- the rate of ageing increases with increasing temperature;
- the relative frequency drift during ageing and its characteristics depend on the properties of the inert gas in the case where the quartz resonator is located [4].

Quartz Oscillators and Resonators, a research and production facility of the joint-stock company *LIT-FONON*, possesses equipment which allows for experiments at temperatures of +85°C and +125°C to be conducted. For the experiment, 42 resonators of the *RK588* type in a ceramic case with overall dimensions of 2.5 × 2.0 × 0.6 mm and a nominal frequency of 40 MHz (Fig. 1) were selected at random. These resonators were created based on the RF patent No. 27111426 “A method of manufacturing thin crystalline plates and thin crystalline elements.” The size of a quartz piezoelectric element with a sputtered silver-containing electrode was 1.5 × 1.0 mm.

[1] Boychuk M.I. *Digital temperature-compensated crystal oscillator in a ceramic case for surface mounting*. Cand. Sci. Thesis. Moscow: MIREA; 2019. 163 p. (in Russ.).

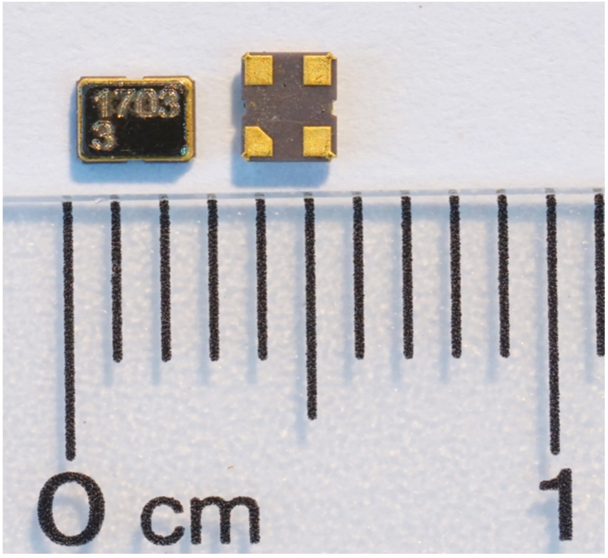

Fig. 1. General view of quartz resonator *RK588*

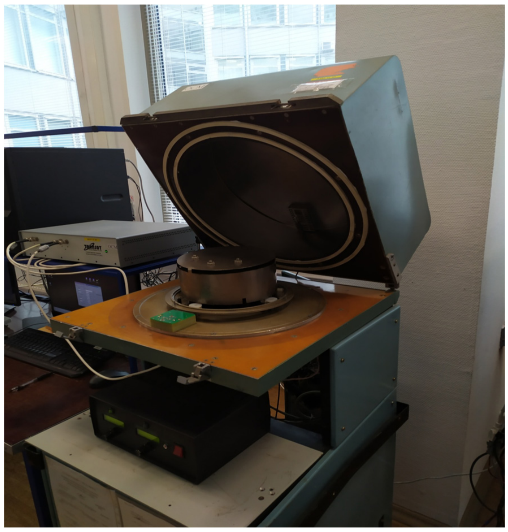

Fig. 2. Dinar temperature-controlled setup for frequency measurements

Of 42 resonators, 3 batches of 14 resonators were formed (hereinafter—Batch No. 1, Batch No. 2, and Batch No. 3). Batch No. 1 consisted of resonators which underwent thermal training at a temperature of +85°C for 1000 h. Batch No. 2 consisted of resonators which were studied at a temperature of +125°C for 1000 h. Batch No. 3 was also studied at 125°C, but over a period of 100 h. The frequency of the resonators in batches No. 1 and No. 2 was measured in the following order of thermal training time: 125, 250, 500, and 1000 h. For Batch No. 3, measurements were performed daily every 24 h. Before starting the experiment, the frequencies of all resonators were measured using the Dinar technological equipment (Fig. 2). After measuring Batch No. 1, the resonators were placed in a heat chamber at a temperature of +85°C. For batches Nos. 2 and 3 a temperature regime of +125°C was set. After each preset period of time, the thermal chamber entered a slow cooling regime. This prevented a high temperature in the crystal piezoelectric element of the quartz resonator which could lead to a high load on the crystal, electrode and affect its frequency [5].

The resonators reached thermodynamic equilibrium with the environment at room temperature 12 h after the thermal chamber had completed the process of slow cooling. Under such conditions, the frequency measurements described below were performed.

All tests and measurements of the frequencies in this experiment were conducted using the Dinar frequency measuring setup. The setup allows for measurements of resonator frequencies in the range from 1 Hz to 100 MHz. Measurement accuracy decreases with increasing resonator frequency. In order to avoid errors in the calculation of the frequency deviation from the norm, the measurement error for each type of a resonator needs to be determined.

Most often, frequency measurements are carried out in relative units [6]:

$$\frac{\Delta f}{f_{\mathrm{DAC}}} = \frac{f - f_{\mathrm{DAC}}}{f_{\mathrm{DAC}}}, \tag{1}$$

where f_{DAC} is the nominal resonance frequency of the resonator, Hz; f is the actual resonator frequency, Hz.

For resonators in a sealed case, the dimensionless relative frequency, expressed in relative units, is applicable. In order to reduce the probability of an accidental error, measurements of the resonators frequencies were conducted in the same pads (sockets) of the Dinar setup.

Fourteen resonators with a frequency of 40 MHz were selected. They underwent thermal training for 1000 h at a temperature of +85°C. If we assume completion of the ageing processes in these resonators, then the frequency distribution of the resonators over a short time interval can be used to determine the error of the Dinar frequency-measuring setup.

The measurements were performed at a temperature of +25°C, low air humidity, and normal pressure. First, the frequency of each resonator of a given batch was determined. Then, the resonators were removed from the Dinar setup and remained under unchanged conditions for 4 h.[2] Subsequently repeated frequency measurements were carried out under the same conditions. As a result, relative frequency offsets were obtained. Their distribution is shown in Fig. 3. During repeated measurements, the frequency offsets changed, but their interval did not become larger and was in the range from $-0.5 \cdot 10^{-5}$ to $+0.4 \cdot 10^{-6}$. Based on the

[2] Determination of the parameters of quartz resonators. URL: http://www.cqham.ru/ua1oj_2.htm. Accessed November 17, 2021 (in Russ.).

results of the experiment, we can conclude that the error in measuring the frequency using the Dinar setup does not exceed $\pm 0.5 \cdot 10^{-6}$, i.e., the absolute error in measuring the frequency of resonators with a nominal frequency of 40 MHz obtained by the Dinar setup is no more than 11 Hz.[3]

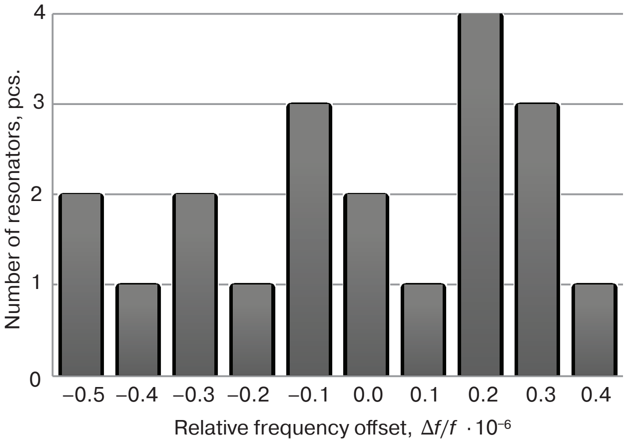

Fig. 3. Frequency distribution of resonators

In accordance with the reliability requirements for resonators of the *RK588* type, the relative frequency drift during and after testing should not exceed $\pm 15 \cdot 10^{-6}$. Graphs of the frequency drift of Batch No. 1 of quartz resonators after thermal training operation are shown in Fig. 4. All resonators passed the reliability test, while the frequency deviations did not exceed $\pm 15 \cdot 10^{-6}$. This indicates the high quality of the products [7].

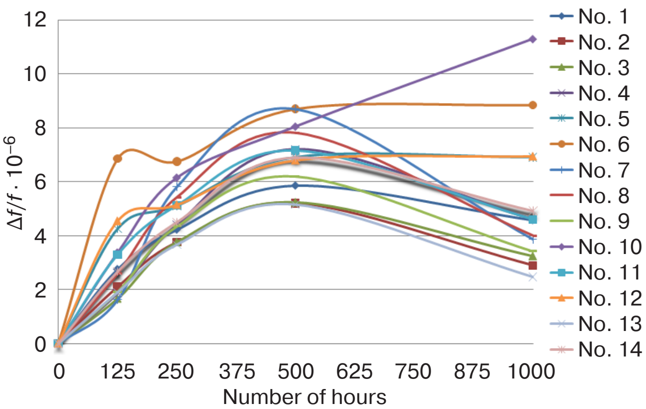

Fig. 4. Relative frequency drift over time of each resonator of Batch No. 1 at a temperature of +85°C and total testing time of 1000 h

From the graphs presented, we can conclude that after 500-h measuring, the frequency drift decreased for all resonators, with the exception of resonator No. 10. On the contrary, its frequency drift increased, but did not exceed the norm of $\pm 15 \cdot 10^{-6}$. The frequency drift of resonators No. 5, 6, and 12 decreased; the resonators stabilized [8].

Based on the data presented in Fig. 4, the coefficient of ageing of the resonators *k* was calculated. The average value of the sum of the relative frequency deviations of the resonators at two key points was found:

$$s = \frac{\frac{\Delta f_1}{f_1} + \frac{\Delta f_2}{f_2} + \ldots + \frac{\Delta f_n}{f_n}}{n}, \qquad (2)$$

where, n is the number of units; $\frac{\Delta f_i}{f_i}$, $i = \overline{1, n}$ is the frequency offset of each resonator [9].

It is considered by most researchers and developers of quartz resonators involved in reliability prediction that long-term change in frequency over time is exponential. At the first stage, the frequency change is nonlinear. At the second stage, an almost linear section in the graph is observed with a slight change in frequency which stabilizes and smoothly decreases. It is worth noting that most products stabilize within 500 h and reach their upper frequency value, after which frequency begins to gradually decrease. Therefore, the 500-h maximum point was chosen as the base for calculating the ageing coefficient. Furthermore, in order to obtain the ageing coefficient, the resulting average value of the sum of relative frequency offsets at the 1000-h end point is divided by the average value of the sum of relative frequency offsets at the 500-h point:

$$k_1 = \frac{5.18}{6.87} = 0.75.$$

Graphs of the frequency drift of quartz resonators of Batch No. 2 after performing the thermal training operation at a temperature of +125°C are shown in Fig. 5.

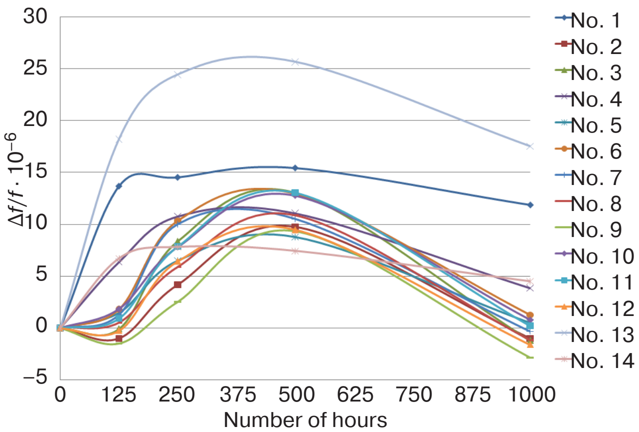

Fig. 5. Relative frequency drift over time of each resonator of Batch No. 2 at a temperature of 125°C and total testing time of 1000 h

[3] Designation of a quartz resonator in the diagram: principle of operation and design. URL: https://math-nttt.ru/teoriya/kvarcevyj-rezonator-dlya-chego-nuzhen.html. Accessed November 15, 2021 (in Russ.).

The graphs in Fig. 5 show that the frequency drifts of resonators No. 2, 3, 5–12 at the 125-h point are minimal. The frequency drifts of resonators No. 4 and 14 at the 125-h point slightly exceed $+5 \cdot 10^{-6}$. After completion of the measurement at the 500-h point, the frequency drift of the resonators gradually decreases. However, the frequency drifts of the two resonators No. 1 and 13 go beyond the limits of $\pm 15 \cdot 10^{-6}$ established in this test. Therefore, these products will not pass the reliability test at such a high temperature[4]. The data presented in Fig. 5 was used to calculate the ageing factor:

$$k_2 = \frac{2.3}{12.14} = 0.18.$$

In order to assess the possibility of reducing the time of thermal training by increasing the temperature more precisely, the frequency drift of quartz resonators at a temperature of +125°C over 100 h with more frequent measurements of parameters needs to defined. Taking the results obtained earlier into account, we planned a same frequency drift of quartz resonators as at a temperature of +85°C for 250 h.[5]

Figure 6 shows the relative frequency drifts of the resonators of Batch No. 3 after thermal training at a temperature of +125°C with daily frequency measurements every 24 h over 100 h.

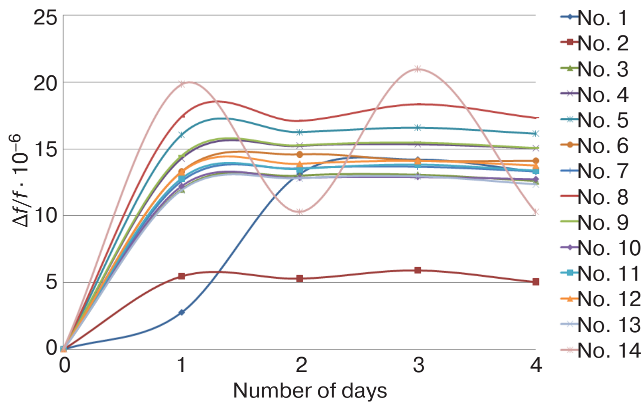

Fig. 6. Relative frequency drift over time of each resonator of Batch No. 3 at a temperature of 125°C and total testing time of 100 h

The relative frequency drift of almost all resonators of Batch No. 3 for the first day is significantly higher than for the rest of the period. After that the frequency drift stabilizes. The frequency drift of the resonators Nos. 5, 8, and 14 slightly exceeds the norm $\pm 15 \cdot 10^{-6}$.

[4] Generators with quartz resonators. URL: https://inventori-steam.ru/elektroteoriya/kvarcevyj-generator-princip-raboty.html. Accessed November 20, 2021 (in Russ.).

[5] Quartz resonators. Types and application. Device and work. URL: https://34rozetki.ru/svet/chto-takoe-kvarcevyj-rezonator.html. Accessed November 20, 2021 (in Russ.).

Thus, in order to stabilize the frequency of quartz resonators in miniature ceramic cases, a minimum of 24 h is required at a temperature of +125°C.

CONCLUSIONS

As a result of the research, requirements were formulated to define the reliability characteristics of *RK588* quartz resonators in miniature ceramic packages measuring 2.5 × 2.0 × 0.6 mm when exposed to elevated ambient temperatures of +85 and +125°C. Furthermore, requirements were developed for a frequency drift at elevated ambient temperature for this type of quartz resonator. These were created pursuant to RF patent No. 27122426 "Method of manufacturing thin crystalline plates and thin crystalline elements." The method of thermal training was optimized and the ageing coefficients established.

It is worth noting that the products of Batch No. 1 and Batch No. 2, when exposed to high temperatures, reach their upper frequency value within 500 h, after which the frequency of the resonators begins to gradually decrease. Therefore, the maximum point was chosen as the base for calculating the ageing coefficient [10].

Thus, based on the results of tests of quartz resonators for failure-free operation for Batch No. 1 at a temperature of +85°C, the calculated ageing coefficient was $k_1 = 0.75$. For Batch No. 2 at a temperature of +125°C it was $k_2 = 0.18$. The ratio of the coefficients during the ageing processes was:

$$d = \frac{k_1}{k_2} = \frac{0.75}{0.18} = 4.1. \quad (3)$$

For this type of piezoelectric element with a size of 1.5 × 1.0 mm at an operating temperature of +125°C, the ageing coefficient is 4 times lower than that at a temperature of +85°C. This indicates the possibility of using the *PK588* resonator at elevated ambient temperatures.

Authors' contribution

M.I. Boychuk—organizing experimental tests based on the LIT-FONON equipment, forming a schedule for tests, selecting the test methods, preparing the necessary equipment and tools, system analysis of the obtained results, and preparation of a technical report.

V.E. Krivonogov—carrying out initial and intermediate measurements of quartz resonators during and after tests and monitoring compliance with test deadlines.

S.A. Mikaeva—analysis of the technical report and test results, systematization of the data obtained, writing and editing the text of the article, and consultations on the selection and analysis of the literature used.

L.A. Vasilieva—selection of quartz resonators for tests, statistical analysis of the test results, and entering the data obtained on the frequency drift of the resonators at elevated ambient temperatures in the technical report.

REFERENCES

1. Boychuk M.I. Influence of fastenings on the temperature-frequency response of resonators. *Komponenty i tekhnologii = Components & Technologies.* 2011;9:188–190 (in Russ.).
2. Boychuk M.I., Mikaeva S.A. Build crystal oscillators. *Sborka v mashinostroenii, priborostroenii = Assembling in Mechanical Engineering and Instrument-Making.* 2016;10:7–11 (in Russ.).
3. Boychuk M.I., Mikaeva A.S., Mikaeva S.A. Temperature-frequency characteristics of the resonators. *Avtomatizatsiya. Sovremennye tekhnologii = Automation. Modern Technologies.* 2019;73(8):343–348 (in Russ.).
4. Boychuk M.I., Mikaeva S.A. Testing and control of electronic component technology. In: *Computer science and technology. Innovative technologies in industry and informatics*. Russian scientific and technical conference with international participation. Collection of conference reports. Moscow: RTU MIREA; 2019. V. 2. P. 258–261 (in Russ.).
5. Boychuk M.I., Vlasov K.V., Cherpukhina G.N., et al. Method of making thin crystal plates and thin crystalline elements: Pat. RF 27122426. Publ. 28.01.2020 (in Russ.).
6. Khomenko I.V., Kosykh A.V. *Kvartsevye rezonatory i generatory* (*Quartz resonators and generators*). Omsk: OmGTU; 2018. 160 p. (in Russ.).
7. Boychuk M.I., Vasilyeva L.A., Mikaeva S.A. Method for calculating the reliability of quartz resonators. *Spravochnik. Inzhenernyi zhurnal* (*s prilozheniem*) = *Handbook. An Engineering Journal with Appendix.* 2020;7(280):53–58 (in Russ.). https://doi.org/10.14489/hb.2020.07.pp.053-058
8. Vasilyeva L.A., Boychuk M.I., Mikaeva S.A. Control of piezoelectric products junction. *Spravochnik. Inzhenernyi zhurnal* (*s prilozheniem*) = *Handbook. An Engineering Journal with Appendix.* 2020;9(282):20–24 (in Russ.). https://doi.org/10.14489/hb.2020.09.pp.020-024
9. Belov A.A., Stepanov A.V. *Opisanie zadachi spetspraktikuma*. *Kvartsevye rezonatory* (*Description of the task of the special practice. Quartz resonators*). Moscow: MGU; 2012. 18 p. (in Russ.). Available from URL: http://www.osc.phys.msu.ru/mediawiki/upload/9/99/KRR.pdf
10. Gorevoi A.V., Lirnik A.V. Measurement of noise parameters of a resonator on a quasi-SAW. In: *25th International Crimean Conference of Microwave Engineering and Telecommunication Technologies.* Conference materials. In 2th parts. Sevastopol. 2015. Part 1. P. 900–901 (in Russ.).

СПИСОК ЛИТЕРАТУРЫ

1. Бойчук М.И. Влияние креплений на температурно-частотную характеристику резонаторов. *Компоненты и технологии*. 2011;9:188–190.
2. Бойчук М.И., Микаева С.А. Сборка кварцевых генераторов. *Сборка в машиностроении, приборостроении*. 2016;10:7–11.
3. Бойчук М.И., Микаева А.С., Микаева С.А. Температурно-частотные характеристики резонаторов. *Автоматизация. Современные технологии.* 2019;73(8):343–348.
4. Бойчук М.И., Микаева С.А. Проведение испытаний и контроль электронной компонентной техники. В сб.: *Информатика и технологии. Инновационные технологии в промышленности и информатике.* Сб. докладов Российской научно-технической конференции с международным участием. М.: РТУ МИРЭА; 2019. Т. 2. С. 258–261.
5. Бойчук М.И., Власов К.В., Черпухина Г.Н. и др. *Способ изготовления тонких кристаллических пластин и тонких кристаллических элементов*: Пат. РФ № 27122426. Заявка № 2019104435; заявл. 18.02.2019, опубл. 28.01.2020.
6. Хоменко И.В., Косых А.В. *Кварцевые резонаторы и генераторы*. Омск: Издательство ОмГТУ; 2018. 160 с.
7. Бойчук М.И., Васильева Л.А., Микаева С.А. Методика расчета надежности кварцевых резонаторов. *Справочник*. *Инженерный журнал* (*с приложением*). 2020;7(280):53–58. https://doi.org/10.14489/hb.2020.07.pp.053-058
8. Васильева Л.А., Бойчук М.И., Микаева С.А. Контроль спая пьезоэлектрических изделий. *Справочник*. *Инженерный журнал* (*с приложением*). 2020;9(282):20–24. https://doi.org/10.14489/hb.2020.09.pp.020-024
9. Белов А.А., Степанов А.В. *Описание задачи спецпрактикума. Кварцевые резонаторы*. М.: МГУ; 2012. 18 с. URL: http://www.osc.phys.msu.ru/mediawiki/upload/9/99/KRR.pdf
10. Горевой А.В., Лирник А.В. Измерение шумовых параметров резонатора на квази-ПАВ. В сб.: *СВЧ-техника и телекоммуникационные технологии.* Материалы 25-й Международной Крымской конференции. В 2-х ч. Севастополь; 2015. Ч. 1. С. 900–901.

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Mathematical modeling

Математическое моделирование

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RESEARCH ARTICLE

Semantics of visual models in space research

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Abstract
Objectives. The aim of the study is to develop a methodology for assessing the semantics of weakly structured or morphologically complex visual information models. In order to achieve the goal, a criterion for classifying visual models as complex and an algorithm for obtaining a gradient image with several levels of density were introduced. The gradient image is not binary, thus increasing the reliability of finding boundaries or contours. An auxiliary structural visual model was introduced, and a series of images of different densities was used in processing. Next, the concept of a conditional image coordinate system was introduced. This allows for information to be transferred from different visual models to a synthetic resulting visual model.
Methods. Using gradient image processing and constructing a new intermediate structural model allows models with different densities to be linked. A system of conditional image coordinates was introduced and a series of models with different densities to obtain a synthetic image was processed.
Results. The visual models obtained from satellite images with poor visibility of objects were processed in the Sun–Earth–Moon system. The Sun–Earth system was chosen as the basis. A characteristic of space images is the fact that the bright light of the Sun "clogs" the images of other objects with large phase angles. The use of the contouring technique allows for the visibility of images of low brightness and high brightness to be equalised. The shift of the frequency response after detection of all objects enabled the formation of a clear visual model.
Conclusions. In primary visual models, low brightness images were not visible. They appeared when exposure was increased, while high-density objects merged into one. Because of this, it is fundamentally impossible to obtain a high-quality image of all objects, or the complete semantics of a visual model from a single high, medium, or low-density image. In order to obtain the complete semantics of the visual model, a series of images need to be processed with the transfer of images to a common synthetic image. The proposed technique allowed for such problems to be resolved. A comparison of the results obtained using the methods of processing a single image proved the reliability and high information content of the method.

Keywords: mathematical modeling, semantics, visual model, figurative model, visual structural model, information field, information semantics, cognitive semantics, information model, cognitive model

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НАУЧНАЯ СТАТЬЯ

Семантика визуальных моделей в космических исследованиях

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Резюме

Цели. Цель работы – разработка методики для оценки семантики слабо структурированных или морфологически сложных визуальных информационных моделей. Для достижения цели вводится критерий отнесения визуальных моделей к сложным и алгоритм получения градиентного изображения с несколькими уровнями плотности. Градиентное изображение не является бинарным, что повышает надежность нахождения границ или контуров. Вводится вспомогательная структурная визуальная модель, и в обработке используется серия изображений разной плотности. Далее вводится понятие условной системы координат изображения, позволяющей переносить информацию с разных визуальных моделей на синтетическую результирующую визуальную модель.

Методы. Использование градиентной обработки изображений и построение новой промежуточной структурной модели, которая позволяет связывать модели с разной плотностью. Введение системы условных координат изображения. Обработка серии моделей с разной плотностью для получения синтетического изображения.

Результаты. Проведена обработка визуальных моделей, полученных с космических снимков со слабой различимостью объектов. Обработаны снимки в системе «Солнце – Земля – Луна». В качестве базиса выбрана система «Солнце – Земля». Для космических снимков характерно то, что яркий свет Солнца «забивает» изображения других объектов с бóльшими фазовыми углами. Применение методики оконтуривания позволило выровнять изображения объектов слабой яркости и большой яркости. Смещение частотной характеристики после выявления всех объектов позволило сформировать четкую визуальную модель.

Выводы. На первичных визуальных моделях изображения слабой яркости не видны. При увеличении экспозиции они появляются, но объекты высокой плотности могут сливаться в один. Из-за этого по одному снимку высокой, средней или слабой плотности принципиально невозможно получить качественное изображение всех объектов или полную семантику визуальной модели. Для получения полной семантики визуальной модели необходима обработка серии изображений с переносом изображений на общее синтетическое изображение. Предложенная методика позволяет решать такие задачи. Сравнение полученных результатов с методами обработки одного изображения показывает надежность и большую информативность метода.

Ключевые слова: математическое моделирование, семантика, визуальная модель, образная модель, визуальная структурная модель, информационное поле, информационная семантика, когнитивная семантика, информационная модель, когнитивная модель

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INTRODUCTION

The widespread use of semi-structured visual models is caused by their application in many areas: radiation diagnostics, space research, radar images, thermal images, laser scanning systems, etc. At the present time, the processing of such images to obtain the semantics of the image is a matter of relevance.

Each model has a presentation or description form and a content part. The morphology or formal representation of the model and its semantics therein is a matter of discussion. The semantics of any model refers to its semantic content, including the description of its structure and spatial relationships. The semantics of a visual model is related to the extent to which it provides information [1, 2]. In many informational and visual models, the formalism of the model and its content are created separately. In practice, these technological stages of creating a model are called formalization and collection of semantics. This is because a formal model can have different meanings and should not be rigidly bound to semantics. The same formal model can have different meanings. For example, the image of a rectangle on a visual model may represent a house, a land plot, an engineering structure, or a computational unit (in an algorithm diagram). The meaning of the visual model or its semantics is determined by analyzing additionally collected information. This technique is practiced in geoinformatics, in which metric and attribute information is collected separately.

Among visual models, two types of models can be distinguished according to the criterion of perception. The first type consists of well-structured and recognizable visual models with clear contours and known objects. Examples are snapshots of an urban area, scanned images of drawings, or maps. This type of visual models can be characterized by the term “objective.” For this type of visual models, there is a natural decomposition. The semantics can be easily collected separately and then combined with the model. The second type consists of visual models with fuzzy contours or their absence, and images of objects of an unknown class. This type of visual models can be characterized by the term “figurative” or “morphological.” Collecting semantics separately for such models is a difficult matter. This type of models is found in space research, in the processing of radar images, and in X-ray images. There is no natural decomposition for this type of visual models. Therefore, the decomposition problem becomes an additional task. The problem of the semantics of such visual models is closely related to the extraction of implicit knowledge [3]. The general problem of the content accuracy of visual models belongs to the field of artificial intelligence. This problem is indirectly connected to the information field [4, 5], information relations, and information-cognitive semantics. The term “information perception” and the term “cognitive perception” can also be added. The semantics of visual models has cognitive and informational components. Therefore, both of these factors must be investigated when analyzing the semantics of visual models.

1. RESEARCH METHODOLOGY

The study was carried out using the methods of gradient, statistical, comparative, and qualitative analysis. Publications in the field of analysis and processing of semi-structured images, as well as satellite images were used as materials.

2. RESEARCH RESULTS

2.1. Formation of a visual model

Unlike other information models, visual information models must have three characteristics: morphology, topology, and spatial relationships. In some cases, the topology defines the structure. Topology and spatial logic are most often present in visual models of the first type. In visual models of the second type, there are only morphological features and spatial relationships. Two types of visual models can be used to construct formational schemes.

Figure 1 shows the scheme for constructing a visual model of the first type. The source of information is a spatial image (a snapshot of a spatial image), which contains clear boundaries and allows a natural decomposition of the objects comprising this image.

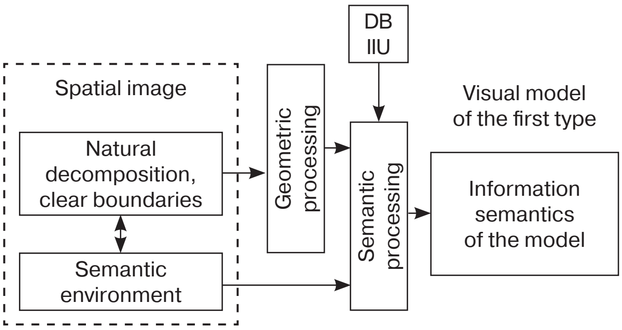

Fig. 1. Block-diagram of a model of the first type. DB IIU—Database of information interpretation units

Natural decomposition and clear boundaries allow an independent semantic environment to be identified and each part of the spatial image (map, urban area) to be described. Natural decomposition and clear boundaries make it possible for the visual model to be divided into morphological and semantic parts. In Fig. 1, this is shown by a double-sided arrow between the semantic environment and the morphological part. For visual models of the first type, the morphological part and semantics can be separated at the level of model components. This separation enables independent processing of the morphological part and subsequent semantic processing of information. This leads to a formation of the semantics of the model which can be called informational.

A special database of interpretive units is used to form the semantics of the model. It can be a symbol classifier or a thesaurus. The visual model conveys the meaning of the spatial image in a compact form. In order to convey the same semantics using a natural or artificial language, large informational descriptions are needed.

Figure 2 shows the scheme for constructing a visual model of the second type.

According to the diagram in Fig. 2, the spatial image does not contain clear boundaries and clear decomposition of parts. Therefore, the semantics of the parts of the image, as well as the image as a whole, is implicit. This image is conveyed not in the form of separated parts, but as an informational situation containing objects and implicit relations. Therefore, the first stage of processing and extracting the meaning of such an image is the associative decomposition of the situation. It relies on a database of associations contained in the cognitive domain of an expert [6] or an intelligent processing system [7]. There are a large number of software tools which assist the expert in the analysis and interpretation of images. Such a software product can be used to simplify the image and create a model that combines different images of the same object.

The cognitive and informational semantics of the visual model is created as a result of processing, since the cognitive factor affects its creation at the level of associative decomposition. For visual models of the second type, the semantics is more informative compared to the semantics of models of the first type.

2.2. Experimental studies

When processing space images, the concept of "primary images" should be introduced. These are pictures taken by cameras directly in the process of observation without any processing.

The following figures show the results of experimental work. Figure 3 shows a visual model, which is the primary image obtained during the initial survey. It gives an image of three spatial objects: the

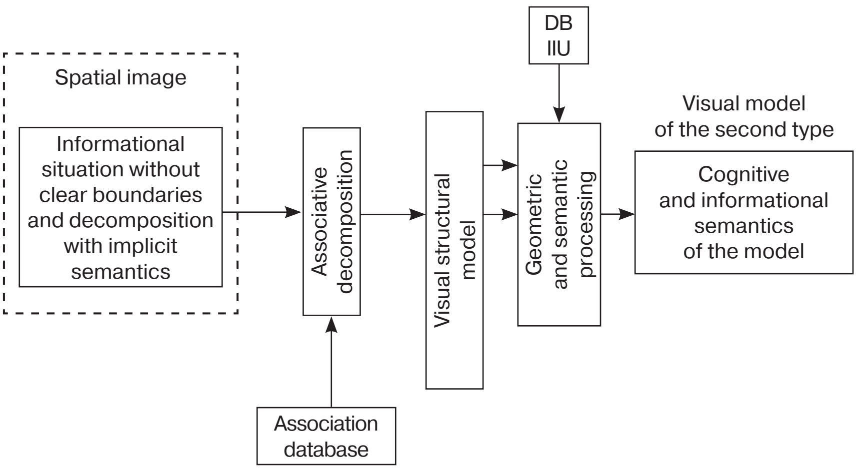

Fig. 2. Block-diagram of a model of the second type

Moon, the Earth, and the Sun. Due to the direct light of the Sun "clogging" the brightness of the reflected light of other objects, the images of objects are barely visible.

The objects in Fig. 3 have the following characteristics: the distance to the Moon is 10897 km; the apparent diameter of the Moon is 15°48'33.8" and the phase angle is 166.6°; the distance to the Earth is 406300 km; the visible diameter is 1°46'16.0" and the phase angle is 152.3°. The distance to the Sun is 0.99124 AU and its visible diameter is 32'16.2". Recall that the phase angle is called the angle in the Sun–object–observer system. This angle is defined as the angle between the incident and reflected light from the object, as perceived by the observer [8].

The image is poorly recognizable, so a gradient processing or a structural visual model was made for it, shown in Fig. 4.

The structural visual model plays the role of a map. It can be schematized, vectorized and made into vector tracing paper to be superimposed on other image options. Figure 5 shows this vector tracing paper or structural vectorized model.

The structural vectorized model shows three basic objects and a conditional object, the position of which needs to be determined.

Between Fig. 5 and Figs. 3 and 4 there is a complete informational geometric correspondence [9]. The model in Fig. 5 is a typical informational spatial model [10]. This allows for measurements to be made, in order to "connect" informational factors to visual ones.

In Fig. 5, the symbol S stands for the Sun, E for the Earth, M for the Moon, and O for an arbitrary cosmic body. A visual structural model or a geometric model allows a conditional image coordinate system relative to the selected objects to be established. For Fig. 5 it is the Earth–Sun direction. The second axis is perpendicular to this direction. By measuring the distances on the image from an arbitrary body to the selected objects, the coordinates of the object in the conditional coordinate system can be determined using the formulae:

$$N = 2\, S_{SOE}/B_{SE},$$
$$L = (R_E{}^2 - N^2)^{1/2}. \quad (1)$$

All parameters are shown in Fig. 5. In (1), S_{SOE} is the area of the triangle SOE calculated through the lengths of its sides. It should be emphasized that the N and L values are conditional image coordinates, corresponding to spatial relationships rather than to real spatial coordinates. The characteristic curve can be adjusted by means of computer processing. Enhancing weak light tones and general equalization of tones gives the image shown in Fig. 6.

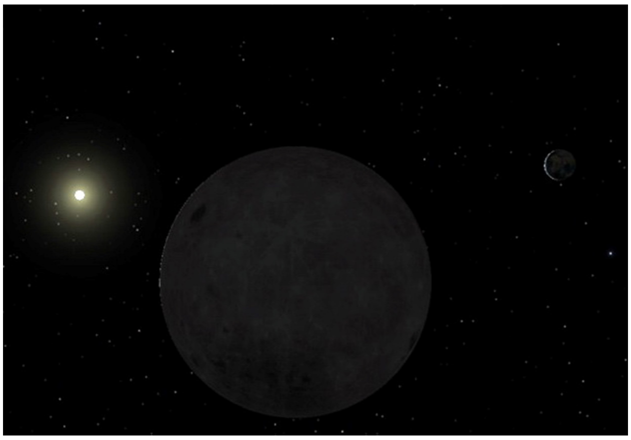

Fig. 3. Primary image of the Sun, the Earth, and the Moon

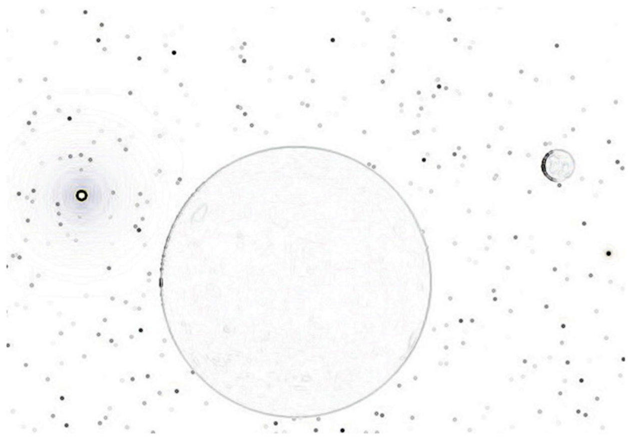

Fig. 4. Structural visual model obtained on the base of gradient processing of the primary image

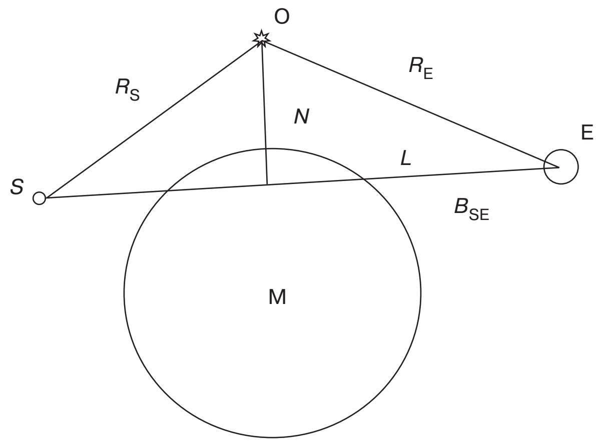

Fig. 5. Vectorized or geometric model to superimpose a series of images

The image of objects in Fig. 6 is given in pseudo-colors. In Fig. 6, the stars which are not visible in the first picture are clearly visible. The Sun has a clearly visible halo as a set of concentric circles of different brightness. Based on Fig. 5, it is possible to estimate the locations

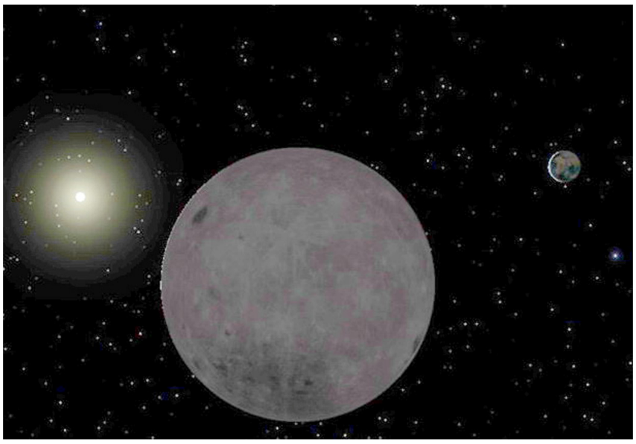

Fig. 6. The image obtained by processing the primary image

of recognizable objects in Fig. 6. Albeit not the primary ones, they are derived from the image shown in Fig. 3.

Using and obtaining a visual structural model (VSM) allows for a series of images of different densities and different detail to be processed. VSM objects of different density and visibility to be combined into a general visual model.

This approach is based on transition from a visual model to a geometric informational model and the subsequent use of geometric image processing [11]. It is already being applied in the processing of aerospace images [12], albeit with the implementation of regression methods and direct measurements of images. The primary images (for example, Fig. 3) do not have high measurable properties. The method proposed eliminates the measurement of the primary image and uses a clear geometric model (Fig. 5). This model allows not only measurements to be performed, but for the quality of the primary image to be improved and made more visual (Fig. 6).

CONCLUSIONS

The semantics of visual models contain not only attributive characteristics, but also the characteristics of their visibility and spatial relationships. When analyzing complex visual models which display complex or unrecognizable images, the use of an intermediate visual structural model is advisable. This model can be created either only based on gradient characteristics (Fig. 4), or with subsequent vectorization and addition of objects “invisible” in the image (Fig. 5). The introduction of a new concept of VSM creates conditions for the serial processing of images with different spectral characteristics. VSM allows images from different spectral ranges to be combined. For complex visual images, the concept of an informational visual situation is acceptable.

Informational visual situation unites objects and the relations between them. For complex images such as X-ray or radar images, such a model is the primary concept. The studies conducted give grounds for the concept of VSM to be introduced. It is advisable that such a model be created from images with maximum details. At the same time, it can be supplemented with other pictures. The VSM model can depict objects invisible to the human eye in the primary image. This research sets out the grounds for introducing the concept of “semantics of complex visual images.” Complex visual images are difficult to describe in language, so they can be viewed as a coded message. Visual images are informative, so they require less memory. This technique allows different images to be processed altogether and renders objects which are poorly recognizable in primary images to become visible. The proposed technique makes it possible for visual images obtained by other sensors, such as thermal or acoustic, also to be processed.

Authors’ contribution

V.P. Savinykh—obtaining and processing satellite images, qualitative and comparative analysis of images.

S.G. Gospodinov—analysis of algorithms for processing space images and compilation of an algorithm for chosen technique.

S.A. Kudzh—development of the image processing technique.

V.Ya. Tsvetkov—development of the image overlay technique and justification of the choice for the image coordinate system.

I.P. Deshko—algorithm implementation, software debugging, and computer processing.

REFERENCES

1. Nomokonov I.B. Descriptiveness X-ray image. *Slavyanskii forum = Slavic Forum*. 2015;2(8):233–239 (in Russ.).
2. Nomokonov I.B. The semantic informativeness. *European Journal of Medicine. Series B*. 2015;3(4):141–147.
3. Bolbakov R.G. Tacit knowledge as a cognitive phenomenon. *European Journal of Technology and Design*. 2016;1(11):4–12.
4. Tsvetkov V.Ya. Information field and information space. *Mezhdunarodnyi zhurnal prikladnykh i fundamental’nykh issledovanii = International Journal of Applied and Fundamental Research*. 2016;1–3:455–456 (in Russ.). Available from URL: https://applied-research.ru/ru/article/view?id=8536

СПИСОК ЛИТЕРАТУРЫ

1. Номоконов И.Б. Информативность рентгеновского изображения. *Славянский форум*. 2015;2(8):233–239.
2. Nomokonov I.B. The semantic informativeness. *European Journal of Medicine. Series B*. 2015;3(4):141–147.
3. Bolbakov R.G. Tacit knowledge as a cognitive phenomenon. *European Journal of Technology and Design*. 2016;1(11):4–12.
4. Цветков В.Я. Информационное поле и информационное пространство. *Международный журнал прикладных и фундаментальных исследований*. 2016;1–3:455–456. URL: https://applied-research.ru/ru/article/view?id=8536

5. Gospodinov S.G. Semantic tree in the information field. *Slavyanskii forum = Slavic Forum*. 2018;3(21):73–79 (in Russ.).
6. Kudzh S.A., Tsvetkov V.Ya. Cognitive expert assessment. In: Silhavy R. (Ed.). *Artificial Intelligence in Intelligent Systems. proceedings of Computer Science On-line Conference. Ser. "Lecture Notes in Networks and Systems."* 2021. V. 229. P. 742–749. https://doi.org/10.1007/978-3-030-77445-5_66
7. Zafar B., et al. Intelligent image classification-based on spatial weighted histograms of concentric circles. *Comput. Sci. Inf. Syst*. 2018;15(3):615–633. https://doi.org/10.2298/CSIS180105025Z
8. Savinych V.P. Determination of the linear parameters of the planet by measuring the angular diameter. *Russian Journal of Astrophysical Research. Series A*. 2021;7(1):28–34 (in Russ.).
9. Ozherel'eva T.A. Information conformity and informational morphism in the information field. *ITNOU: Informatsionnye tekhnologii v nauke, obrazovanii i upravlenii*. 2017;4(4):86–92 (in Russ.).
10. Lototsky V.L. Spatial information modeling. *European Journal of Computer Science*. 2016;1(2):38–46.
11. Egoshkin N.A. Dynamic models of geometric image processing in Earth remote sensing systems. *Tsifrovaya obrabotka signalov = Digital Signal Processing*. 2017;1:8–12 (in Russ.).
12. Zlobin V., Eremeev V. *Obrabotka aerokosmicheskikh izobrazhenii* (*Aerospace image processing*). LitRes; 2018. 287 p. (in Russ.).

5. Господинов С.Г. Семантическое дерево в информационном поле. *Славянский форум*. 2018;3(21):73–79.
6. Kudzh S.A., Tsvetkov V.Ya. Cognitive expert assessment. In: Silhavy R. (Ed.). *Artificial Intelligence in Intelligent Systems. proceedings of Computer Science On-line Conference. Ser. "Lecture Notes in Networks and Systems."* 2021. V. 229. P. 742–749. https://doi.org/10.1007/978-3-030-77445-5_66
7. Zafar B., et al. Intelligent image classification-based on spatial weighted histograms of concentric circles. *Comput. Sci. Inf. Syst*. 2018;15(3):615–633. https://doi.org/10.2298/CSIS180105025Z
8. Савиных В.П. Определение линейных параметров планеты по измерению углового диаметра. *Russian Journal of Astrophysical Research. Series A*. 2021;7(1):28–34.
9. Ожерельева Т.А. Информационное соответствие и информационный морфизм в информационном поле. *ИТНОУ: Информационные технологии в науке, образовании и управлении*. 2017;4(4):86–92
10. Lototsky V.L. Spatial information modeling. *European Journal of Computer Science*. 2016;1(2):38–46.
11. Егошкин Н.А. Динамические модели геометрической обработки изображений в системах дистанционного зондирования Земли. *Цифровая обработка сигналов*. 2017;1:8–12.
12. Злобин В., Еремеев В. *Обработка аэрокосмических изображений*. ЛитРес; 2018. 287 с.

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RESEARCH ARTICLE

Application of bioinspired global optimization algorithms to the improvement of the prediction accuracy of compact extreme learning machines

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Abstract
Objectives. Recent research in machine learning and artificial intelligence aimed at improving prediction accuracy and reducing computational complexity resulted in a novel neural network architecture referred to as an extreme learning machine (ELM). An ELM comprises a single-hidden-layer feedforward neural network in which the weights of connections among input-layer neurons and hidden-layer neurons are initialized randomly, while the weights of connections among hidden-layer neurons and output-layer neurons are computed using a generalized Moore–Penrose pseudoinverse operation. The replacement of the iterative learning process currently used in many neural network architectures with the random initialization of input weights and the explicit computation of output weights significantly increases the performance of this novel machine learning algorithm while preserving good generalization performance. However, since the random initialization of input weights does not necessarily guarantee optimal prediction accuracy, the purpose of the present work was to develop and study approaches to intelligent adjustment of input weights in ELMs using bioinspired algorithms in order to improve the prediction accuracy of this data analysis tool in regression problems.
Methods. Methods of optimization theory, theory of evolutionary computation and swarm intelligence, probability theory, mathematical statistics and systems analysis were used.
Results. Approaches to the intelligent adjustment of input weights in ELMs were developed and studied. These approaches are based on the genetic algorithm, the particle swarm algorithm, the fish school search algorithm, as well as the chaotic fish school search algorithm with exponential step decay proposed by the authors. By adjusting input weights with bioinspired optimization algorithms, it was shown that the prediction accuracy of ELMs in regression problems can be improved to reduce the number of hidden-layer neurons to reach a high prediction accuracy on learning and test datasets. In the considered problems, the best ELM configurations can be obtained using the chaotic fish school search algorithm with exponential step decay.
Conclusions. The obtained results showed that the prediction accuracy of ELMs can be improved by using bioinspired algorithms for the intelligent adjustment of input weights. Additional calculations are required to adjust the weights; therefore, the use of ELMs in combination with bioinspired algorithms may be advisable where it is necessary to obtain the most accurate and most compact ELM configuration.

Keywords: neural networks, extreme learning machine, bioinspired algorithms, genetic algorithm, particle swarm optimization algorithm, fish school search algorithm, machine learning, regression analysis

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НАУЧНАЯ СТАТЬЯ

Применение биоинспирированных алгоритмов глобальной оптимизации для повышения точности прогнозов компактных машин экстремального обучения

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Резюме
Цели. В результате современных исследований в машинном обучении, направленных на повышение точности и снижение вычислительной сложности алгоритмов анализа данных, была предложена новая архитектура искусственной нейронной сети – машина экстремального обучения. Это нейронная сеть прямого распространения с единственным скрытым слоем. В этой сети веса соединений между входными нейронами и нейронами скрытого слоя инициализируются случайно, а веса соединений между нейронами скрытого слоя и выходными нейронами вычисляются с использованием операции псевдообращения Мура – Пенроуза. Замена итерационного процесса обучения, присущего многим архитектурам нейронных сетей, на случайную инициализацию одной части весов и вычисление другой части делает рассматриваемый инструмент существенно более производительным, с сохранением хорошей обобщающей способности. Однако случайная инициализация входных весов не гарантирует оптимальной точности прогнозов. Цель работы – разработка и исследование подходов к интеллектуальной настройке входных весов в машинах экстремального обучения биоинспирированными алгоритмами для повышения точности прогнозов этого инструмента анализа данных в задачах восстановления регрессии.
Методы. Использованы методы теории оптимизации, теории эволюционных вычислений и роевого интеллекта, теории вероятностей и математической статистики, системного анализа.
Результаты. Разработаны и исследованы подходы к интеллектуальной настройке входных весов в машинах экстремального обучения, основанные на применении генетического алгоритма, алгоритма роя частиц, алгоритма поиска косяком рыб, алгоритма хаотического поиска косяком рыб с экспоненциальным убыванием шага, предложенного авторами настоящего исследования. Выявлено, что применение биоинспирированных алгоритмов способно улучшить точность прогнозов машин экстремального обучения в задачах восстановления регрессии, причем машине экстремального обучения с уточненными биоинспирированными алгоритмами весами требуется меньшее число нейронов на скрытом слое для достижения высокой точности прогнозов на тренировочных и тестовых наборах данных. С помощью хаотического алгоритма поиска косяком рыб

с экспоненциальным убыванием шага могут быть получены наилучшие конфигурации машин экстремального обучения в рассмотренных задачах.
Выводы. Полученные результаты показывают, что точность прогнозов машин экстремального обучения может быть улучшена посредством применения биоинспирированных алгоритмов интеллектуальной настройки входных весов. Для выполнения настройки весов требуются дополнительные вычисления, поэтому использование машин экстремального обучения в сочетании с биоинспирированными алгоритмами может быть целесообразно в тех областях, где необходимо получение наиболее точной и компактной конфигурации машины экстремального обучения.

Ключевые слова: нейронные сети, машины экстремального обучения, биоинспирированные алгоритмы, генетический алгоритм, алгоритм роя частиц, алгоритм поиска косяком рыб, машинное обучение, регрессионный анализ

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INTRODUCTION

Due to the digitalization of the economy, an increasing number of enterprises are integrating intelligent modules into their products and enterprise information systems in order to automate and accelerate business processes. These modules often comprise decision support systems, expert systems, and prediction systems that use machine learning algorithms. Such algorithms are used to automate the discovery of hidden relationships in datasets to make predictions without human intervention. Due to the increasing amounts of data being processed by intelligent systems, there is a need to increase the efficient performance of machine learning algorithms while preserving the accuracy of automated decisions.

In studies of classification, regression analysis, and prediction of time series, a variety of efficient machine learning approaches have been proposed, e.g., *k*-nearest neighbors [1], support vector machines [2], various hybrid versions [3], random forests [4], and artificial neural networks [5], which allow a high decision accuracy to be achieved.

A widely used and efficient supervised machine learning approach uses artificial neural networks (ANN), which can automate decision-making via the evolution of a complex nonlinear system [6]. Numerous ANN architectures and training methods have been developed, which demonstrate high efficiency in solving classification problems using deep learning, convolutional layers, and dropout layers [7], as well as solving regression layers using hybrids of population- and gradient-based algorithms of ANN learning [8, 9]. To find the optical hyperparameters of ANNs, bio-inspired algorithms are often used. For example, the particle swarm optimization algorithm was used to optimize the hyperparameters of a recurrent network with long short-term memory to predict time series [10].

The ANN training problem reduces to a problem of minimizing a certain ANN loss function on a training dataset. Researchers and practitioners conventionally train ANNs using an iterative backpropagation method and algorithms based on stochastic gradient descent [11, 12]. However, with increasing amounts of analyzed data, the time required for the convergence of gradient methods increases, especially when using deep ANN architectures. In order to accelerate ANN training, Google researchers proposed a distributed stochastic gradient descent algorithm [13], in which subsets of the training dataset are placed at several slave nodes of the computational network. At each iteration, slave computational nodes compute multidimensional gradient matrices for the proper data subset. A master node receives the computed multidimensional gradient matrices from the slave nodes, subtracts the gradients from the ANN weight matrix, and then sends the updated multidimensional weight matrix to the slave nodes, after which the process is repeated until the stopping criterion is satisfied. However, even when using distributed ANN training methods, the training may take a long time: from several hours to several days.

To accelerate ANN training, Huang et al. [14] proposed a novel ANN architecture referred to as an extreme learning machine (ELM). An ELM comprises a single-hidden-layer ANN in which the weights of connections among input-layer neurons and hidden-layer neurons, as well as the hidden-layer shift vector, are initialized randomly, whereas the weights of connections among hidden-layer neurons and output-layer neurons are computed using a generalized Moore–Penrose pseudoinverse operation [15]. Besides, the hidden-layer activation function should be infinitely differentiable [14]. By using an ELM, it is possible to eliminate the iterative process of optimizing the ANN loss function from the process of preparation of an ANN model capable of making accurate decisions, thus significantly reducing the computational effort to train the ANN. The absence of an iterative training process does not prevent the ELM from demonstrating good generalization performance in a number of applied problems [16–18].

However, the random initialization of the weights of connections among input-layer and hidden-layer neurons along with the hidden-layer shift vector does not guarantee the optimal configuration of an ELM. Instead, the problems of intelligent refinement of input weights and hidden-layer shift vector of ELMs may be solved using bioinspired optimization algorithms [16, 19]. Such algorithms are heuristic methods of global optimization that process several solutions at each iteration without using information on the derivative of the function for their optimization; this simplifies the launch of these algorithms in parallel and distributed modes [20]. Widely used bioinspired algorithms included the genetic algorithm (GA) [21], the particle swarm optimization (PSO) [22], the fish school search (FSS) [23, 24], and others. Cai et al. [16] used particle swarm optimization to obtain the optimal ELM configuration for traffic flow forecasting. Song et al. [19] carried out a comparative analysis of the classical realization of ELM and the ELM, in which the intelligent selection of input weights was performed using the genetic algorithm, demonstrating the high efficiency of the ELM configuration obtained via GA.

In the present work, the efficiencies of various bioinspired algorithms were studied, including the genetic algorithm, the particle swarm algorithm, the standard fish school search algorithm, as well as a chaotic fish school search algorithm with exponential step decay, which were used in the problem of choosing the optimal weights of connections among input-layer and hidden-layer neurons, as well as the hidden-layer shift vector. Regression estimation problems were considered on three datasets; the generalization performances were compared between the classical ELM [14] and the ELMs in which the intelligent adjustment of input weights was made using bioinspired algorithms. Additionally, landscapes optimized using bioinspired loss function algorithms were studied in the course of the refinement of the input weights and shifts in the ELMs.

EXTREME LEARNING MACHINE

In a supervised machine learning problem, a set of objects, $X = X_L \cup X_T$, is given, where X_L is a learning dataset, and X_T is a test dataset; also given are a set of possible answers, Y, and an unknown objective function, f: X → Y, which maps the set of objects to the set of possible answers. The f values are known for each object in the set X. The set X_L is used during the training of the model, and the trained model quality is evaluated on the set X_T. The learning dataset X_L has the form $\{\vec{x}_1, \vec{x}_2, ..., \vec{x}_s\}$, where s is the number of objects in X_L; each (ith) object $\vec{x}_i \in X_L$ is represented as a set of features, $\vec{x}_i = (h_1, h_2, ..., h_n)$, which characterize the object $\vec{x}_i$; and the $\vec{y}_i$ values are known for each (ith) object $\vec{x}_i$ and are equal to $f(\vec{x}_i)$. In the course of the training, the machine learning algorithm constructs the function a: X → Y to sufficiently approximate the unknown objective function f on $X = X_L \cup X_T$.

An extreme learning machine (ELM) is a supervised machine learning algorithm, which, similarly to an ANN, can make decisions by automatically configuring a complex nonlinear system for a certain problem. It comprises a single-hidden-layer feedforward neural network with an infinitely differentiable activation function in the hidden layer [14] where the weights of connections among input-layer neurons and hidden-layer neurons, as well as hidden-layer shifts, are initialized randomly, whereas the weights of connections among hidden-layer neurons and output-layer neurons are computed. Figure 1 presents the structure of the ELM.

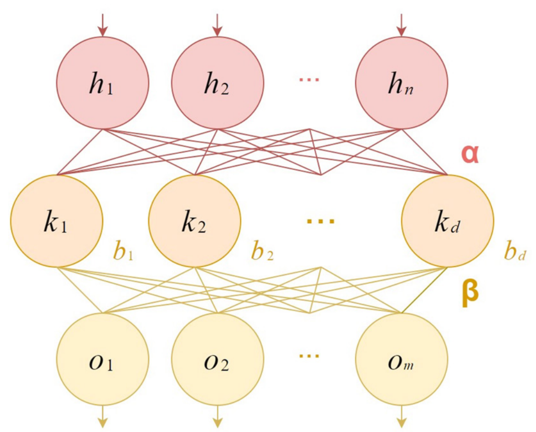

Fig. 1. Extreme learning machine

Elements of the matrix **α** of the weights of connections among input-layer neurons $h_1, h_2, \ldots h_n$ and hidden-layer neurons $k_1, k_2, \ldots k_d$, having the form $\mathbb{R}^{d \times n}$, where n is the number of the input-layer neurons, and d is the number of the hidden-layer neurons, are initialized randomly; shifts $b_1, b_2, \ldots b_d$ of the hidden-layer neurons are also initialized randomly, while the vector of the shifts has the form $\mathbb{R}^d$. The matrix $\boldsymbol{\beta}$ of the weights of connections among the hidden-layer neurons $k_1, k_2, \ldots k_d$ and output-layer neurons $o_1, o_2, \ldots o_m$, which has the form $\mathbb{R}^{d\times m}$, where m is the number of the output-layer neurons, is calculated as

$$\boldsymbol{\beta} = \mathbf{H}^{\dagger}\mathbf{Y}_{\mathrm{L}}, \text{where } \mathbf{H}^{\dagger} = (\mathbf{H}^{\mathrm{T}}\mathbf{H})^{-1}\mathbf{H}^{\mathrm{T}}, \ \mathbf{H} = g(\mathbf{X}_{\mathrm{L}}\boldsymbol{\alpha}^{\mathrm{T}} + \mathbf{b}). \quad (1)$$

Here, $\mathbf{X}_{\mathrm{L}}$ is a matrix having the form $\mathbb{R}^{s\times n}$, in which the rows code s objects in the learning dataset X_{L}, with each object being represented as a set of n features $\{h_1, h_2, \ldots h_n\}$. $\boldsymbol{\alpha}^{\mathrm{T}}$ is the transposed matrix of the weights of connections among neurons of the form $\mathbb{R}^{n\times d}$, where n is the number of the input-layer neurons and d is the number of the hidden-layer neurons. $\mathbf{b}$ is a matrix of the form $\mathbb{R}^{s\times d}$ that is obtained by the transformation of the vector of shifts of the hidden-layer neurons of the form $\mathbb{R}^d$ to a matrix of the form $\mathbb{R}^{1\times d}$ in which the first row is repeated s times. g is an infinitely differentiable activation function, which is applied element-by-element to each element of the matrix. $\mathbf{H}$ is the output matrix of the hidden-layer neurons of the form $\mathbb{R}^{s\times d}$. $\mathbf{H}^{\dagger}$ is the Moore–Penrose pseudoinverse of the matrix $\mathbf{H}$ [15] of the form $\mathbb{R}^{d\times s}$. $\mathbf{Y}_{\mathrm{L}}$ is the matrix of answers of the form $\mathbb{R}^{s\times m}$, in which the row code answers correspond to objects in the learning dataset X_{L}, each answer having the form $\{o_1, o_2, \ldots o_m\}$. Thus, the matrix $\boldsymbol{\beta}$ of the weights of connections among d hidden-layer neurons and m output-layer neurons has the form $\mathbb{R}^{d\times m}$. For the hidden-layer activation function g in ELMs, the sigmoid activation function is often used [25]:

$$\sigma(x) = \frac{1}{1 - \mathrm{e}^{-x}}. \quad (2)$$

Here, x is an element of the hidden-layer output matrix of the form $\mathbb{R}^{s\times d}$, which is obtained by the multiplication of the matrix $\mathbf{X}_{\mathrm{L}}$ and the matrix $\boldsymbol{\alpha}^{\mathrm{T}}$ with the subsequent addition of the matrix $\mathbf{b}$.

The number d of the hidden-layer neurons, which is an ELM hyperparameter, should be adjusted to the problem to be solved. The number n of features of each object in the learning dataset is determined according to the specificity of the domain of the problem being solved. In solving the regression estimation problem using the ELM considered in this work, the number m of output-layer neurons is taken to be 1.

INTELLIGENT SELECTION OF INPUT WEIGHTS USING BIOINSPIRED ALGORITHMS

The random initialization of the weights $\boldsymbol{\alpha}$ of connections among input-layer neurons and hidden-layer neurons, as well as the hidden-layer shifts $\mathbf{b}$, does not guarantee the optimal ELM configuration [16, 19]. Studies have been carried out in which particle swarm optimization was used to obtain the optimal ELM configuration in traffic flow forecasting problems [16], with a genetic algorithm being applied in regression estimation problems [19]. In these works, the root mean square error (RMSE) was selected as the objective function for the bioinspired algorithms:

$$\mathrm{RMSE} = \sqrt{\frac{1}{s}\sum\nolimits_{i=1}^{s}(a(\vec{x}_i) - y_i)^2}, \quad (3)$$

where $\vec{x}_i$ is the ith object in the learning dataset X_{L} comprising s objects, y_i is the answer for the ith object, and $a(\vec{x}_i)$ is the prediction of the ELM for the ith object $\vec{x}_i$.

The generalization performance of a trained ANN model is often evaluated using the mean absolute error (MAE) function:

$$\mathrm{MAE} = \frac{1}{s}\sum\nolimits_{i=1}^{s}\left|a(\vec{x}_i) - y\right|_i, \quad (4)$$

where $\vec{x}_i$ is the ith object in the learning dataset X_{L} comprising s objects, y_i is the answer for the ith object, and $a(\vec{x}_i)$ is the prediction of the ELM for the ith object. The mean absolute error function was used [16] to evaluate the ELM model quality.

When solving the problem of selecting the optimal values of the input weights given by the matrix $\boldsymbol{\alpha}$ of the form $\mathbb{R}^{d\times n}$ and the hidden-layer shift vector $\{b_1, b_2, \ldots, b_d\}$ of the form $\mathbb{R}^d$ (Fig. 1), each (ith) agent in the population of bioinspired algorithms can be represented as the vector $\{\alpha_{11}^i, \alpha_{12}^i, \ldots, \alpha_{1n}^i, \alpha_{21}^i, \alpha_{22}^i, \ldots, \alpha_{2n}^i, \ldots, \alpha_{d1}^i, \alpha_{d2}^i, \ldots, \alpha_{dn}^i, b_1^i, b_2^i, \ldots, b_d^i\}$.

The genetic algorithm used in the problem of intelligent selection of the input weights and hidden-layer shifts in the ELM [19] is a heuristic population optimization algorithm inspired by evolutionary processes occurring in biological nature. Algorithm 1 determines the pseudocode of the genetic algorithm. The selection, crossover, and mutation operators are sequentially applied to the agents in the population at each iteration using various selection strategies, e.g., tournament selection and truncation selection [21].

The particle swarm optimization (PSO) algorithm used in the problem of selecting the optimal values of the input weights and hidden-layer shifts in the ELM [16] is the well-known global optimization algorithm proposed by Kennedy and Eberhart [22], which was inspired by the coordinated flight of bird flocks. Algorithm 2 determines the pseudocode of the particle swarm algorithm.

The fish school search (FSS) algorithm is a global optimization algorithm inspired by the behavior of fish schools swimming in search of food. The algorithm, which was proposed by Bastos Filho et al. [23], has found application in solving numerous problems, including image reconstruction [26] and distribution of weights in ANN [27].

The modification of the fish school search algorithm proposed by Demidova and Gorchakov [24], which converges faster than FSS, is called tent map-based fish school search with exponential step decay (ETFSS). The ETFSS pseudocode is determined by Algorithm 3.

In Algorithm 3, uniformly distributed random numbers for the vectors $\vec{r}_1$ and $\vec{r}_2$ are generated by the mapping tent using a dynamic system in a chaotic state. The dynamic system is described by time set T, state set S, and mapping M: $T \times S \rightarrow S$, which characterize the evolution of the dynamic system. The mapping tent is defined as

$$y_{n+1} = \mu \min(y_n, 1 - y_n), \text{ where } \mu = 1.9999. \quad (5)$$

Here, the number μ is a bifurcation parameter, and y_n determines the state of the dynamic system at time t.

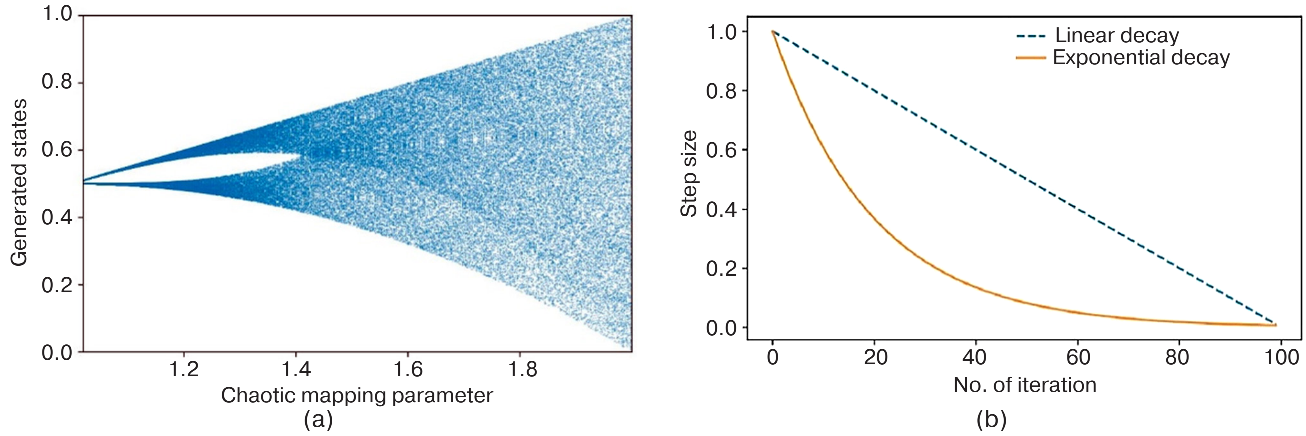

Fig. 2. (a) Bifurcation diagram of the dynamic system of mapping (5) and (b) the comparison of the linear and exponential step decays in FSS and ETFSS, respectively

Algorithm 1. Genetic algorithm

Start: $P_{\text{crossover}}$ is the crossover probability, P_{mutation} is the mutation probability.

define fitness function (f)
set the number of a generation to be 0 (t = 0)
randomly generate agents in the initial population P_t
calculate the f value for each agent in P_t
until the stopping criterion is satisfied, **do**
  $t = t + 1$
  select agents for the population P_t from the population P_{t-1}
  change agents in P_t using the *crossover* operator with the probability $P_{\text{crossover}}$
  change agents in P_t using the *mutation* operator with the probability P_{mutation}
  calculate the f value for each agent in P_t
complete cycle
return the best evolved solution

Algorithm 2. Particle swarm algorithm*

Start: w, c_1, c_2, $v_{\max}$

define fitness function (f)
set the number of a generation to be 0 (t = 0)
randomly generate agents in the initial population P_t

randomly generate the velocities V_t of agents in the range $[-v_{\max}, v_{\max}]$
calculate the f value for each agent in P_t
select agent $\vec{p}_{\text{gbest}} \in P_t$, such that $\forall \vec{p}_{i,t} \in P_t : f(\vec{p}_{\text{gbest,t}}) \le f(\vec{p}_{i,t})$
for each particle $\vec{p}_{i,t} \in P_t$, set the best position $\vec{p}_{\text{pbest},i}$ to be equal to $\vec{p}_{i,t}$
until the stopping criterion is satisfied, **do**
    $t = t + 1$
    for each agent $\vec{p}_{i,t} \in P_t$, **do**
        randomly generate $\vec{r}_1$ and $\vec{r}_2$, the components of which $\in [0,1]$
        $\vec{v}_{i,t} = w\vec{v}_{i,t-1} + c_1\vec{r}_1(\vec{p}_{\text{gbest}} - \vec{p}_{i,t}) + c_2\vec{r}_2(\vec{p}_{\text{pbest},i} - \vec{p}_{i,t})$
        restrict $\vec{v}_{i,t}$ to the range $[-v_{\max}, v_{\max}]$
        $\vec{p}_{i,t} = \vec{p}_{i,t-1} + \vec{v}_{i,t}$
        calculate the f value for the agent $\vec{p}_{i,t}$
        if $f(\vec{p}_{i,t}) < f(\vec{p}_{\text{pbest},i})$, **then** $\vec{p}_{\text{pbest},i} = \vec{p}_{i,t}$
    complete cycle
    select agent $\vec{p}_{\text{gbest},t} \in P_t$, such that $\forall \vec{p}_{i,t} \in P_t : f(\vec{p}_{\text{gbest},t}) \le f(\vec{p}_{i,t})$
    if $f(\vec{p}_{\text{gbest},t}) < f(\vec{p}_{\text{gbest}})$, **then** $\vec{p}_{\text{gbest}} = \vec{p}_{\text{gbest},t}$
complete cycle
return the best found solution $\vec{p}_{\text{gbest}}$

*gbest is the global best solution at iteration *t* in terms of particle swarm optimization algorithm and pbest is the best solution found by a certain agent (personal best) at iteration *t* in terms of particle swarm optimization algorithm.

Algorithm 3. Chaotic fish school search algorithm with exponential step decay*

Start: $step_{\text{ind,initial}}$, $step_{\text{vol,initial}}$, $\gamma = 5$
define fitness function (f)
set the number of a generation to be 0 ($t = 0$)
randomly generate agents in the initial population P_t
calculate the f value for each agent in P_t
select agent $\vec{p}_{\text{gbest}} \in P_t$, such that $\forall \vec{p}_{i,t} \in P_t : f(\vec{p}_{\text{gbest},t}) \le f(\vec{p}_{i,t})$
until the stopping criterion is satisfied, **do**
    $t = t + 1$
    $step_{\text{ind},t} = step_{\text{ind,initial}} e^{\frac{-\gamma t}{iter_{\max}}}$
    $step_{\text{vol},t} = step_{\text{vol,initial}} e^{\frac{-\gamma t}{iter_{\max}}}$
    for each agent $\vec{p}_{i,t} \in P_t$, **do**
        randomly generate $\vec{r}_1$ and $\vec{r}_2$, the components of which $\in [0,1]$
        $\vec{p}_{i,t} = \vec{p}_{i,t-1} + step_{\text{ind},t}\vec{r}_1$
        calculate the f value for $\vec{p}_{i,t}$

if $f(\vec{p}_{i,t}) \geq f(\vec{p}_{i,t-1})$, **then** $\vec{p}_{i,t} = \vec{p}_{i,t-1}$

$w_{i,t} = w_{i,t-1} + \dfrac{\Delta f_{i,t}}{\max(\Delta f_{i,t+1})}$

complete cycle

$\vec{I} = \dfrac{\sum_{i=1}^{n} (\vec{p}_{i,t} - \vec{p}_{i,t-1}) \Delta f_{i,t}}{\sum_{i=1}^{n} \Delta f_{i,t}}$

for each agent $\vec{p}_{i,t} \in P_t$, **do** $\vec{p}_{i,t} = \vec{p}_{i,t} + \vec{I}_t$

$\vec{B} = \dfrac{\sum_{i=1}^{n} \vec{p}_{i,t} w_{i,t}}{\sum_{i=1}^{n} \vec{p}_{i,t}}$

for each agent $\vec{p}_{i,t} \in P_t$, **do**

$\vec{p}_{i,t} = \vec{p}_{i,t} \pm step_{\text{vol},t} \vec{r}_2 \dfrac{\vec{p}_{i,t} - \vec{B}_{t+1}}{\left| \vec{p}_{i,t} - \vec{B}_{t+1} \right|}$; the sign is minus, if $\sum_{i=1}^{n} w_{i,t} > \sum_{i=1}^{n} w_{i,t-1}$; otherwise, the sign is plus

complete cycle

select agent $\vec{p}_{\text{gbest},t}$, such that $\forall \vec{p}_{i,t} \in P_t : f(\vec{p}_{\text{gbest},t}) \leq f(\vec{p}_{i,t})$

if $f(\vec{p}_{\text{gbest},t}) < f(\vec{p}_{\text{gbest}})$, **then** $\vec{p}_{\text{gbest}} = \vec{p}_{\text{gbest},t}$

complete cycle

return the best found solution $\vec{p}_{\text{gbest}}$

* $step_{\text{ind}}$ is the maximum step size of the individual movement in terms of the fish school optimization algorithm, $step_{\text{vol}}$ is the maximum step size of the collective-volitive movement in terms of the fish school optimization algorithm, *iter* is the number of iterations, and $iter_{max}$ is the maximum allowable number of iterations in the algorithm.

Figure 2a presents the bifurcation diagram of system (5).

Figure 2b compares the exponential step decay used in the ETFSS algorithm and the linear step decay used in the original fish school search algorithm. The efficiency of using a chaotic pseudorandom number generator (5) and exponential step decay (Fig. 2b) in the fish school search algorithm has been previously shown [24].

COMPUTATIONAL EXPERIMENT

To study the efficiencies of the algorithms GA, PSO, FSS, and ETFSS in the problem of distribution of input weights and shifts in the ELM and compare the obtained ELM configurations with the classical realization of ELM, in which the input weights and shifts are initialized randomly, three earlier described [28, 29] open datasets were considered. The first set, which contained Central Processing Unit (CPU) Performance data, comprised 209 rows and 10 columns. Each row was used to code 9 features; these could potentially affect the 10th feature, which quantitatively characterized the processor performance. The second set, which contained auto imports data, comprised 206 rows and 26 columns. Each row coded 25 features of an object, which could affect the 26th feature: car price. The third dataset contained Boston Housing data and comprised 506 rows and 14 columns. Each row coded 13 features of objects, which potentially affected the 14th feature.

To solve the regression estimation problem for the above datasets using the ELM, a sigmoid activation function (2) in the hidden layer was used. In the classical realization of ELM, each of the datasets was divided 10 times into learning dataset X_L, which contained 70% of the total number of objects in the set X, and test dataset X_T, which contained 30% of objects of the set X. The classical realization of ELM was trained 10 times on the set X_L by formula (1) and estimated 10 times on the set X_T by formula (4) in order to select the optimal number of neurons in the hidden layer. Figure 3 illustrates the process of selection of the number of neurons, while the selected numbers of neurons are given in Table 1.

Table 1. Selected number of hidden-layer neurons in the classical ELM

Dataset	CPU Performance	Auto Imports	Boston Housing
Number of neurons	30	20	60

The number of neurons in the ELM trained by the bioinspired algorithms was selected in a similar fashion. It was shown [16, 19] that compact ELM (in which the number of hidden-level neurons is relatively small) can achieve better generalization performance in the case of using bioinspired algorithms for selection of input weights and shifts. For this reason, the upper bound of the number of hidden-level neurons was set according to Table 1. In a preliminary study in which cross validation was carried out over 10 blocks at various numbers of hidden-level neurons in the ELM, with the input weights and the hidden-level shifts being distributed by the bioinspired algorithms, it was determined that models with the best generalization performance can be obtained using ETFSS. Table 2 and Fig. 4 present the results of the selection of the number of neurons for the ELM optimized by ETFSS (ETFSS-ELM).

Table 2. Selected number of neurons in the ELM adjusted by the ETFSS algorithm

Dataset	CPU Performance	Auto Imports	Boston Housing
Number of neurons	10	10	30

As Figs. 3 and 4 show, if the selected number of neurons is too small or too large, the ELM prediction accuracy decreases as a consequence of underfitting or overfitting of the model, respectively. The ETFSS-ELM requires fewer neurons to achieve better accuracy on the test data than the classical ELM.

Figure 5 presents the convergence curves of the GA, PSO, and ETFSS algorithms in the optimization of root-mean-square loss function (3) of the compact ELM on learning datasets at the values of the parameters of the bioinspired algorithms that are given in Table 3. Table 2 presents the numbers of hidden-layer neurons in the compact bioinspired ELM.

Table 3. Values of the parameters of the bioinspired algorithms

Algorithm	Selected parameter values
GA	$P_{crossover} = 0.9$, $P_{mutation} = 0.1$
PSO	$v_{max} = 5$, $c_1 = 0.8$, $c_2 = 0.5$, $w = 0.8$
FSS, ETFSS	$step_{ind,initial} = 0.7$, $step_{vol,initial} = 0.7$
All algorithms	300 iterations, 100 population agents

It is evident from the curves in Fig. 5 that the ETFSS algorithm, which is an improved version of the FSS algorithm, can find better solutions to the problem of searching for the optimum of loss function (3) in comparison with the GA, PSO, and FSS algorithms.

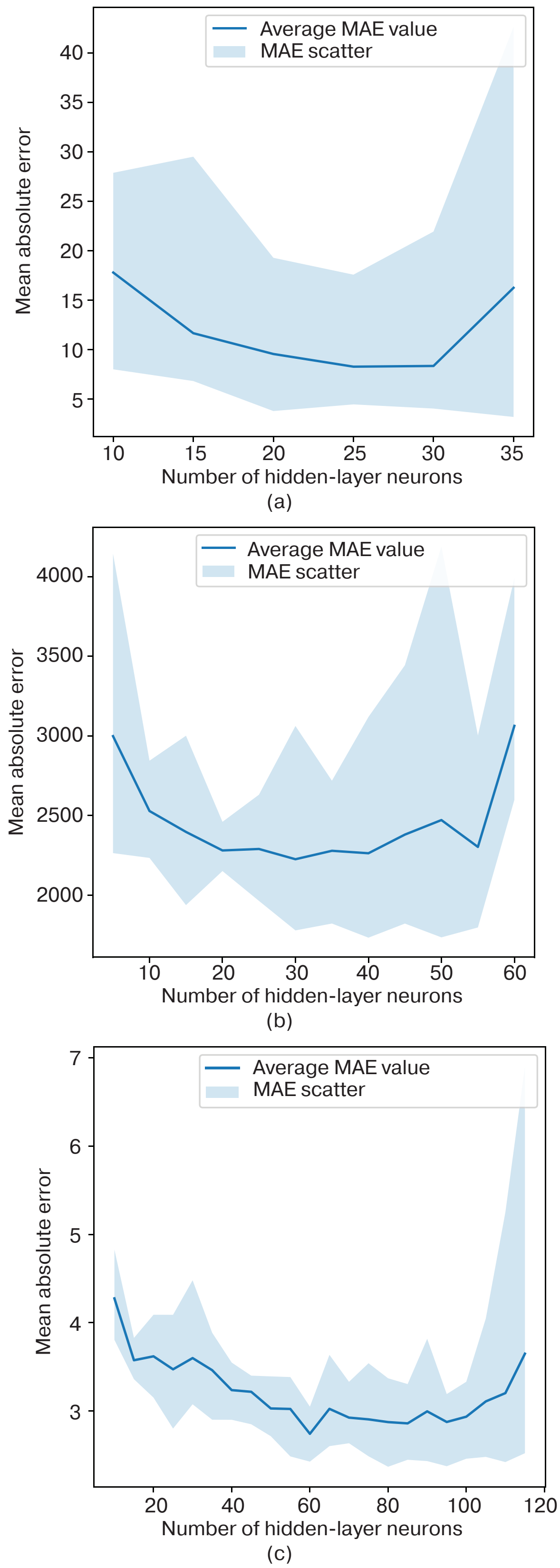

Fig. 3. Selection of the optimal number of neurons in ELM. The shaded areas represent the scatter of the values of function (4) on X_T in 10-block cross-validation; the lines represent the averaged values of function (4) for the (a) CPU Performance, (b) Auto Imports, and (c) Boston Housing datasets

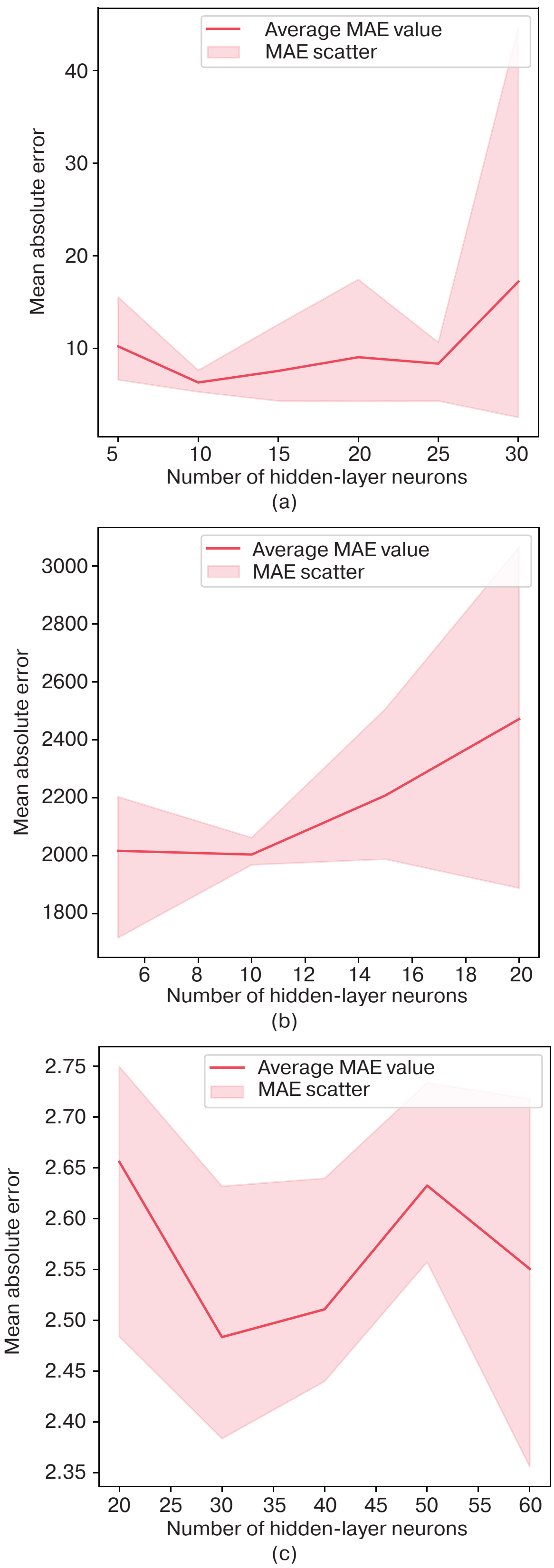

Fig. 4. Selection of the number of neurons in the ELM in which the input weights and shifts were adjusted by the ETFSS algorithm. The shaded areas represent the scatter of the values of function (4) on X_T; the lines represent the averaged values of function (4) for the (a) CPU Performance, (b) Auto Imports, and (c) Boston Housing datasets

The generalization performances of the models GA-ELM, PSO-ELM, FSS-ELM, and ETFSS-ELM obtained by refining the weights by the algorithms GA, PSO, FSS, and ETFSS, respectively, were estimated using the box-and-whisker plots of the values of mean average error (MAE) function (4) (Fig. 6). Table 4 presents the average MAE values on the test subsets of the considered datasets. The comparison also included the classical realizations of ELM with random initialization of input weights and shifts with the numbers of neurons given in Table 1 and 2.

Table 4. Average values of MAE (4) on the test subsets of the considered datasets, which are obtained by 10-block cross validation of ELM-1 with the numbers of hidden-level neurons given in Table 2; ELM-2 with the numbers of hidden-level neurons given in Table 1, GA-ELM, PSO-ELM, FSS-ELM, and ETFSS-ELM

Dataset	ELM-1	ELM-2	GA-ELM	PSO-ELM	FSS-ELM	ETFSS-ELM
CPU Performance	13.2	10.4	9.4	8.8	10.3	**6.2**
Auto Imports	2657	2354	2155	2199	2522	**2124**
Boston Housing	3.47	2.89	2.69	2.86	3.11	**2.64**

Figure 6 and Table 4 show that the ETFSS-ELM model has the best generalization performance among the studied models. GA-ELM, PSO-ELM, FSS-ELM, and ETFSS-ELM, in which intelligent adjustment of weights and shifts was carried out, demonstrate the best generalization performance for all the datasets in comparison with the classical ELM with the same number of hidden-layer neurons. The ELM with the increased numbers of hidden-layer neurons as given in Table 1 is superior to the compact classical ELM and inferior to the compact ELMs that were adjusted by the bioinspired algorithms and have the numbers of hidden-layer neurons as indicated in Tables 2 and 4.

VISUALIZATION OF THE LANDSCAPES OF THE OPTIMIZED LOSS FUNCTION

Landscapes of objective function (3) were visualized to illustrate the process of the search for the optimal values of input weights $\boldsymbol{\alpha}$ of dimension $\mathbb{R}^{d \times n}$, where d is the number of hidden-layer neurons in the ELM, and n is the number of input-layer neurons and shifts of dimension $\mathbb{R}^d$. Objective function (3) in this problem of intelligent adjustment of the input weights and shifts in the ELM inputs multidimensional; vector $\vec{w}$ of the form $\mathbb{R}^q$, where $q = d \times n + d$. Table 5 presents the q values for each of the considered datasets.

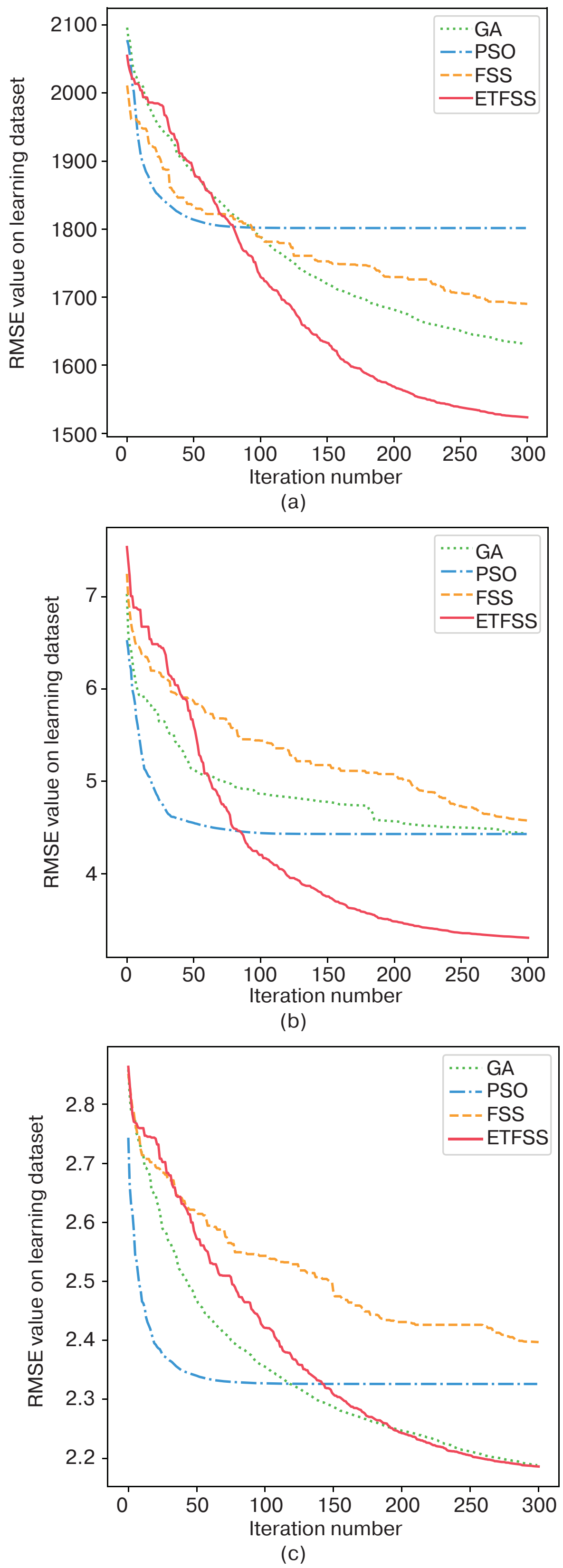

Fig. 5. Convergence of the bioinspired algorithms in the optimization of function (3) to select the input weights and shifts in the ELM for the (a) CPU Performance, (b) Auto Imports, (c) Boston Housing datasets

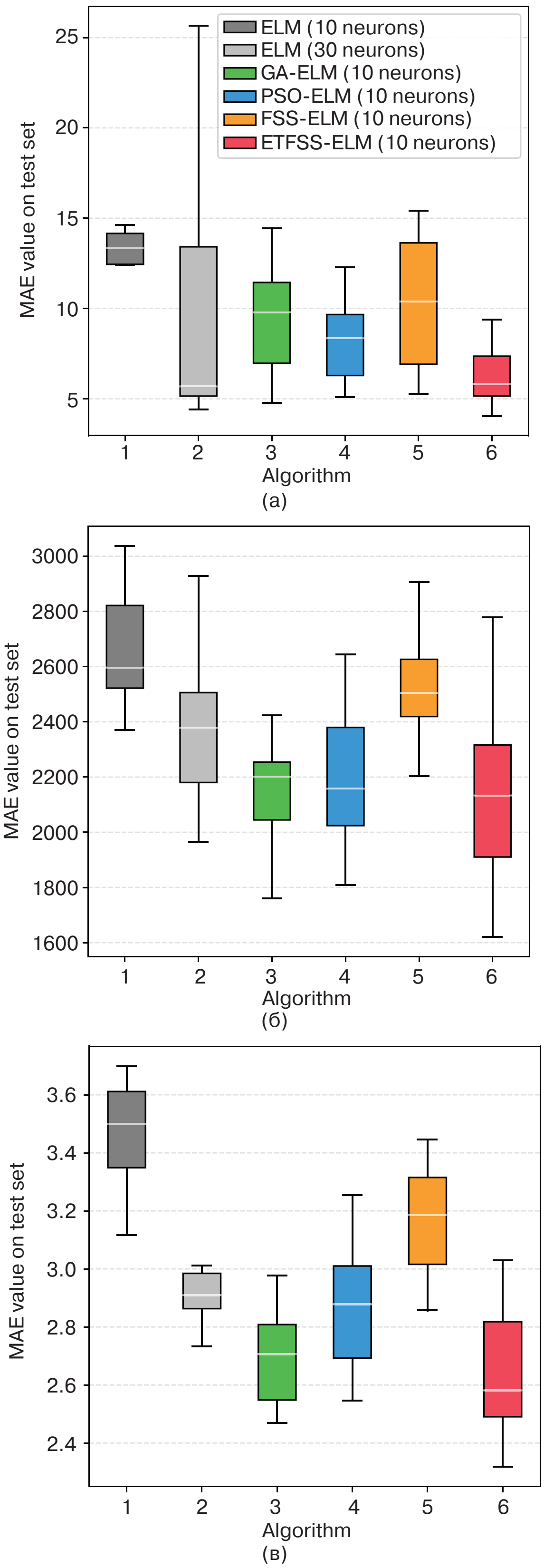

Fig. 6. Box-and-whisker plots of the values of MAE (4) on test data for the classical and bioinspired ELMs with various numbers of hidden-layer neurons for the (a) CPU Performance, (b) Auto Imports, and (c) Boston Housing sets

Table 5. Dimensions of the vector $\vec{w}$ of weights and shifts in the ELM

Dataset	CPU Performance	Auto Imports	Boston Housing
Dimension of *w*	100	260	420

As Table 5 shows, the dimension of objective function (3) is high enough in each of the analyzed problems, but the landscapes can be visualized only for two-dimensional functions. There are a number of approaches to visualizing multidimensional functions in a three-dimensional rectangular coordinate system. For example, it was proposed [30] to define two orthogonal vectors, $\vec{a}$ and $\vec{b}$, the dimension of which coincides with the dimension of $\vec{w}$, and then define function u to be visualized as

$$u(\alpha,\beta) = f(\vec{w} + \alpha\vec{a} + \beta\vec{b}). \quad (5)$$

Here, f is the initial function, $\vec{w}$ is a multidimensional vector, α and β are scalar parameters, $\vec{a}$ and $\vec{b}$ are orthogonal unit vectors the dimension of which coincides with that of vector

In the problem under consideration, the function f is defined by formula (3); the vector $\vec{w}$ contains the input weights and shifts in the optimal ELM configuration; $\vec{a} = \{0,1,0,1,...\}$; $\vec{b} = \{1,0,1,0,...\}$; and the dimensions of the vectors $\vec{a}, \vec{b}$, and $\vec{w}$ coincide. For each of the considered datasets, the landscapes of function (3) near the found optimum $\vec{w}$ were visualized (Figs. 7, 8). The scalar parameters α and β were varied during the visualization in the range [−1, 1] at an interval of 0.02.

To visualize the process of convergence of the ETFSS algorithm in spaces containing many local extrema shown in Figs. 7 and 8, the changes in the position of a randomly selected agent of the ETFSS algorithm at every 25th iteration were determined. For each position $\vec{p}$ of the agent, the nearest point was chosen in the grid constructed during the landscape visualization by varying the scalars α and β. The proximity of the vector $\vec{p}$ to the point $\{\alpha_i, \beta_i\}$ was determined by calculating the Manhattan distance with a shift with respect to the vector $\vec{w}$, near which the visualization is performed:

$$dist(\vec{p}, \alpha_i, \beta_j) = \left|(\vec{p} - \vec{w}) - (\alpha_i\vec{a} + \beta_j\vec{b})\right| = \\ = \sum_{k=1}^{n}\left|(p_k - w_k) - (\alpha_i a_k + \beta_j b_k)\right|. \quad (6)$$

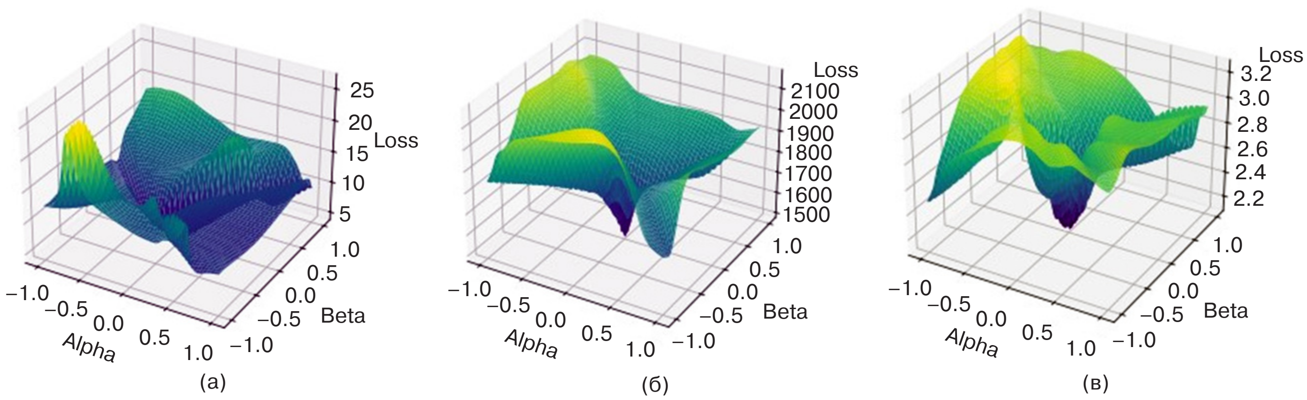

Fig. 7. Visualization of landscapes of multidimensional loss functions near the found optimum for the (a) CPU Performance, (b) Auto Imports, and (c) Boston Housing datasets

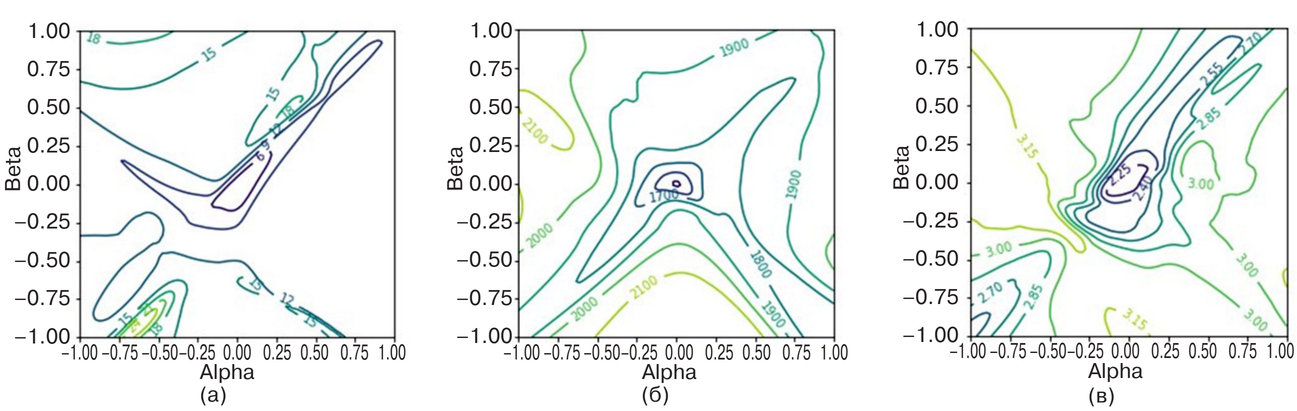

Fig. 8. Visualization of contour lines of multidimensional loss functions near the found optimum for the (a) CPU Performance, (b) Auto Imports, and (c) Boston Housing datasets

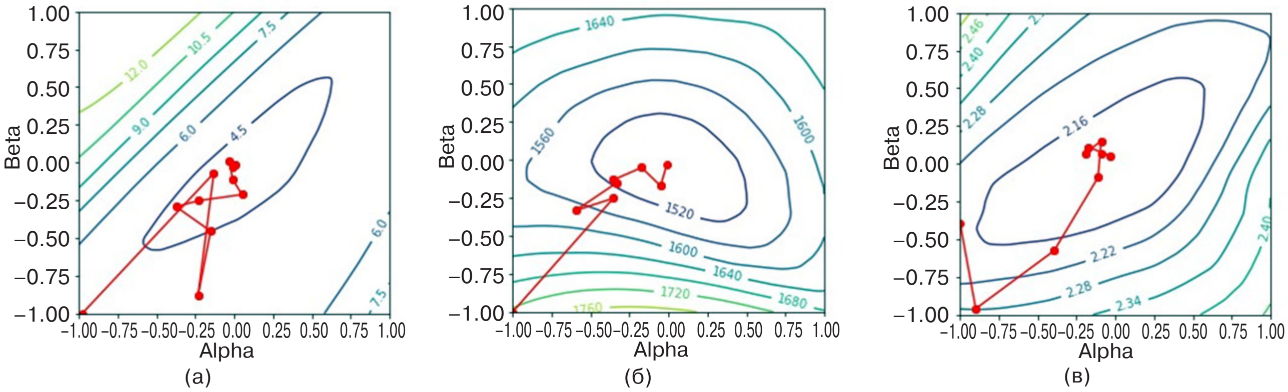

Fig. 9. Changes in the position of a randomly selected agent of the ETFSS algorithm near the found solution for the (a) CPU Performance, (b) Auto Imports, and (c) Boston Housing datasets

Here, n is the dimension of the agent position vector $\vec{p}$; this dimension coincides with that of the vector $\vec{w}$, which codes the input weights and shifts in the found optimal ELM coordination. The dimension of the agent position vector $\vec{p}$ also coincides with that of the mutually orthogonal vectors $\vec{a}$ and $\vec{b}$, $\vec{a} = \{0,1,0,1,...\}$, $\vec{b} = \{1,0,1,0,...\}$, where α_i and β_i are the coordinates of a visualization grid point.

Figure 9 presents the visualizations of the change in the position $\vec{p}$ of the randomly selected agent of the ETFSS algorithm at every 25th iteration in the process of the search for the optimal values of the input weights and shifts in the ELM by optimizing loss function (3) near the found solution .

It can be seen from Figure 7 and 8 that function (3) in the considered problems has a large number of extrema, which are successfully passed by the bioinspired optimization algorithms in the search for the optimal values of the input weights and hidden-layer shifts in the ELM. The trajectories in Fig. 9 suggest that the ETFSS algorithm improves the solutions obtained by the population of agents at each iteration until the completion of the execution of the algorithm.

CONCLUSIONS

In this work, the efficiency of bioinspired algorithms was studied in the problem of intelligent selection of the weights of connections among input-layer neurons and hidden-layer neurons and also the hidden-layer shifts in extreme learning machines in regression estimation problems.

Generalization performances between the classical, compact classical, and compact ELMs were compared, in which the intelligent adjustment of input weights and hidden-layer shifts was made using the genetic algorithm (GA-ELM), the particle swarm optimization (PSO-ELM), the fish school search (FSS-ELM), and the chaotic fish school search with exponential step decay (ETFSS-ELM). It was determined that the compact ELM in which the input weights are adjusted by the bioinspired algorithms achieves a better generalization performance using fewer hidden-layer neurons. The chaotic fish school search with exponential step decay (ETFSS) [24] can ensure the best ELM configurations in the considered problems.

The constructed visualizations of the multidimensional loss function landscapes in the three-dimensional rectangular coordinate system near the found solution demonstrate the presence of numerous extrema, which makes it expedient to use bioinspired algorithms in the search for the global optimum. The obtained visualization of the trajectory of a randomly selected agent of the ETFSS algorithm shows that, iteration by iteration, the algorithm improves the solutions found by the population.

Further studies may be aimed at exploring the possibility of using ETFSS to refine the weights of an online extreme learning machine capable of further learning as new data are received without iterative retraining [31] Analysis of the dependence of the results obtained using bioinspired algorithms on their hyperparameters is also a promising research direction.

Authors' contribution

L.A. Demidova—conceptualization, guidance, supervision, validation, and original draft preparation.

A.V. Gorchakov—software, resources, visualization, testing, and original draft preparation.

All authors have read and agreed to the published version of the manuscript.

REFERENCES

1. Wu Y., Ianakiev K., Govindaraju V. Improved *k*-nearest neighbor classification. *Pattern Recognition*. 2002;35(10):2311–2318. https://doi.org/10.1016/S0031-3203(01)00132-7
2. Noble W.S. What is a support vector machine? *Nat. Biotechnol*. 2006;24(12):1565–1567. https://doi.org/10.1038/nbt1206-1565
3. Demidova L.A. Two-stage hybrid data classifiers based on SVM and kNN algorithms. *Symmetry*. 2021;13(4):615. https://doi.org/10.3390/sym13040615
4. Lin W., Wu Z., Lin L., Wen A., Li J. An ensemble random forest algorithm for insurance Big Data analysis. *IEEE Access*. 2017;5:16568–16575. https://doi.org/10.1109/ACCESS.2017.2738069
5. Deng L., Hinton G., Kingsbury B. New types of deep neural network learning for speech recognition and related applications: An overview. In: *2013 IEEE International Conference on Acoustics, Speech and Signal Processing*. 2013:8599–8603. https://doi.org/10.1109/ICASSP.2013.6639344
6. Rosenblatt F. The perceptron: a probabilistic model for information storage and organization in the brain. *Psychological Review*. 1958;65(6):386–408. https://doi.org/10.1037/h0042519
7. Affonso C., Debiaso Rossi A.L., Antunes Vieira F.H., Ponce de Leon Ferreira de Carvalho A.C. Deep learning for biological image classification. *Expert Systems with Applications*. 2017;85:114–122. https://doi.org/10.1016/j.eswa.2017.05.039
8. Chen N., Xiong C., Du W., Wang C., Lin X., Chen Z. An improved genetic algorithm coupling a back-propagation neural network model (IGA-BPNN) for water-level predictions. *Water*. 2019;11(9):1795. https://doi.org/10.3390/w11091795
9. Such F.P., Madhavan V., Conti E., Lehman J., Stanley K.O., Clune J. Deep neuroevolution: Genetic algorithms are a competitive alternative for training deep neural networks for reinforcement learning. arXiv preprint arXiv:1712.06567. 2017. https://arxiv.org/abs/1712.06567
10. Shao B., Li M., Zhao Y., Bian G. Nickel price forecast based on the LSTM neural network optimized by the improved PSO algorithm. *Mathematical Problems in Engineering*. 2019;2019(2):1934796. https://doi.org/10.1155/2019/1934796
11. Ruder S. An overview of gradient descent optimization algorithms. arXiv preprint arXiv:1609.04747. 2016. https://arxiv.org/abs/1609.04747
12. Kulikov A.A. The structure of the local detector of the reprint model of the object in the image. *Russ. Technol. J.* 2021;9(5):7–13. https://doi.org/10.32362/2500-316X-2021-9-5-7-13
13. Dean J., Corrado G.S., Monga R., Chen K., Devin M., Le Q.V., Mao M.Z., Ranzato M.A., Senior A., Tucker P., Yang K., Ng A.Y. Large scale distributed deep networks. *Advances in Neural Information Processing Systems*. 2012;25:1223–1231.
14. Huang G.B., Zhu Q.Y., Siew C.K. Extreme learning machine: theory and applications. *Neurocomputing*. 2006;70(1-3):489–501. https://doi.org/10.1016/j.neucom.2005.12.126
15. Rao C.R. Generalized inverse of a matrix and its applications. In: *Proceedings of the Sixth Berkeley Symposium on Mathematical Statistics and Probability*. 1972. V. 1. *Theory of Statistics*. 1972:601–620. https://doi.org/10.1525/9780520325883-032
16. Cai W., Yang J., Yu Y., Song Y., Zhou T., Qin J. PSO-ELM: A hybrid learning model for short-term traffic flow forecasting. *IEEE Access*. 2020;8:6505–6514. https://doi.org/10.1109/ACCESS.2019.2963784
17. Liu Y., Loh H.T., Tor S.B. Comparison of extreme learning machine with support vector machine for text classification. In: *International Conference on Industrial, Engineering and Other Applications of Applied Intelligent Systems. Innovations in Applied Artificial Intelligence*. 2005;3533:390–399. http://doi.org/10.1007/11504894_55
18. Li G.X. Application of extreme learning machine algorithm in the regression fitting. In: *2016 International Conference on Information System and Artificial Intelligence* (*ISAI*). 2016:419–422. https://doi.org/10.1109/ISAI.2016.0095
19. Song S., Wang Y., Lin X., Huang Q. Study on GA-based training algorithm for extreme learning machine. In: *2015 7th International Conference on Intelligent Human-Machine Systems and Cybernetics*. *IEEE.* 2015;2:132–135. https://doi.org/10.1109/IHMSC.2015.156
20. Nikonov V.V., Gorchakov A.V. Train machine learning models using modern containerization and cloud infrastructure. *Promyshlennye ASU i kontrollery = Industrial Automated Control Systems and Controllers*. 2021;6:33–43 (in Russ.). https://doi.org/10.25791/asu.6.2021.1288
21. Eremeev A.V. A genetic algorithm with tournament selection as a local search method. *J. Appl. Ind. Math*. 2012;6(3):286–294. https://doi.org/10.1134/S1990478912030039
22. Kennedy J., Eberhart R. Particle swarm optimization. In: *Proceedings of ICNN'95-International Conference on Neural Networks*. 1995;4:1942–1948. https://doi.org/10.1109/ICNN.1995.488968
23. Bastos Filho C.J.A., de Lima Neto F.B., Lins A.J.C.C., Nascimento A.I.S., Lima M.P. A novel search algorithm based on fish school behavior. In: *2008 IEEE Int. Conference on Systems, Man and Cybernetics*. 2008:2646–2651. https://doi.org/10.1109/ICSMC.2008.4811695
24. Demidova L.A., Gorchakov A.V. A study of chaotic maps producing symmetric distributions in the fish school search optimization algorithm with exponential step decay. *Symmetry*. 2020;12(5):784. https://doi.org/10.3390/sym12050784
25. Cao W., Gao J., Ming Zh., Cai Sh. Some tricks in parameter selection for extreme learning machine. *IOP Conf. Ser.: Mater. Sci. Eng*. 2017;261(1):012002. https://doi.org/10.1088/1757-899X/261/1/012002
26. Dos Santos W., Barbosa V., de Souza R., Ribeiro R., Feitosa A., Silva V., Ribeiro D., Covello de Freitas R., Lima M., Soares N. Image reconstruction of electrical impedance tomography using fish school search and differential evolution. In: *Critical Developments and Applications of Swarm Intelligence*. IGI Global; 2018. P. 301–338. https://doi.org/10.4018/978-1-5225-5134-8.ch012

27. Demidova L.A., Gorchakov A.V. Application of chaotic Fish School Search optimization algorithm with exponential step decay in neural network loss function optimization. *Procedia Computer Science*. 2021;186(6):352–359. https://doi.org/10.1016/j.procs.2021.04.156
28. Harrison D. Jr., Rubinfeld D.L. Hedonic housing prices and the demand for clean air. *J. Environ. Econ. Manag*. 1978;5(1):81–102. https://doi.org/10.1016/0095-0696(78)90006-2
29. Kibler D., Aha D.W., Albert M.K. Instance-based prediction of real-valued attributes. *Comput. Intell*. 1989;5(2):51–57. https://doi.org/10.1111/j.1467-8640.1989.tb00315.x
30. Li H., Xu Z., Taylor G., Studer C., Goldstein T. Visualizing the loss landscape of neural nets. In: *NIPS'18: Proceedings of the 32nd International Conference on Neural Information Processing Systems*. 2018:6391–6401. https://arxiv.org/abs/1712.09913v3
31. Dai B., Gu C., Zhao E., Zhu K., Cao W., Qin X. Improved online sequential extreme learning machine for identifying crack behavior in concrete dam. *Adv. Struct. Eng*. 2019;22(2):402–412. https://doi.org/10.1177/1369433218788635

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Economics of knowledge-intensive and high-tech enterprises and industries. Management in organizational systems

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RESEARCH ARTICLE

Features of assessing the investment attractiveness of high-tech projects

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Abstract
Objectives. The creation of high-tech projects is one of the main stages of the transition to an innovative economy. This can further be explained by the intensive development of globalization processes in the economic system of Russia. High-tech projects have lower profitability when compared to venture projects, but a higher probability of commercial success. In Russia, there are currently six areas of support programs for high-tech projects. Moreover, there are a large number of operators supporting high-tech projects actively working in the Russian market. The acceleration of the technological development requires an intensification of innovation policy and a revision of the portfolio of its acting instruments. In turn, this makes the matter of analyzing their significance and relevance for participants in innovation processes more pertinent. The purpose of this work is to identify features of the investment process in the Russian Federation, and determine criteria for selecting priority high-tech projects and methods of evaluating high-tech projects, in the aim of making informed investment decisions.
Methods. Models for assessing the investment attractiveness of high-tech projects were constructed using economic and mathematical modeling methods, in particular, nonlinear and dynamic programming methods.
Results. The general principles and approaches to methods of evaluating the efficiency were analyzed. A model of the priorities of high-tech projects was presented. Models which take into account cash flows after the expiration of the payback period were also considered (by means of the nonlinear programming of calculation of the discounted payback period of investment costs and the modernized discounted payback period of investment costs). An algorithm for assessing the investment attractiveness of high-tech projects was demonstrated.
Conclusions. To date, there has been no single algorithm for assessing the investment attractiveness of high-tech projects. However, the integrated application of the methods and models proposed in this work will allow investors to make informed investment decisions despite the complexity of project financing in innovative developments.

Keywords: high-tech projects, innovative projects, government support, evaluation of the financial and economic efficiency of the project, evaluation methods, project financing

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НАУЧНАЯ СТАТЬЯ

Особенности оценки инвестиционной привлекательности высокотехнологичных проектов

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Резюме
Цели. Создание высокотехнологичных проектов является одним из главных этапов перехода к инновационной экономике, что объясняется интенсивным развитием процессов глобализации в экономической системе нашей страны. Высокотехнологичные проекты обладают меньшей доходностью по сравнению с венчурными проектами и более высокой вероятностью коммерческого успеха. На данный момент в России есть шесть направлений программ поддержки высокотехнологичных проектов. Кроме того, на российском рынке активно работает большое количество операторов поддержки таких проектов. Ускорение технологического развития требует активизации инновационной политики и пересмотра «портфеля» ее действующих инструментов. Это, в свою очередь, актуализирует задачу анализа их значимости и востребованности для участников инновационных процессов. Целью статьи является выявление особенностей процесса инвестирования в РФ, определение критериев отбора приоритетных высокотехнологичных проектов и методов их оценки для принятия взвешенных инвестиционных решений.
Методы. При построении моделей оценки инвестиционной привлекательности высокотехнологичных проектов использованы экономико-математические методы моделирования, а именно методы нелинейного и динамического программирования.
Результаты. В рамках статьи проанализированы общие принципы и подходы к методам оценки эффективности проекта. Представлены модель приоритетов высокотехнологичных проектов и модели (нелинейного программирования расчета дисконтированного срока окупаемости инвестиционных затрат и модернизированного дисконтированного срока окупаемости инвестиционных затрат), позволяющие учесть денежные потоки после истечения срока окупаемости. Показан алгоритм оценки инвестиционной привлекательности высокотехнологичных проектов.
Выводы. На сегодняшний день не существует единого алгоритма оценки инвестиционной привлекательности высокотехнологичных проектов. Тем не менее, комплексное применение предложенных методов и моделей позволит инвесторам, несмотря на сложность проектного финансирования инновационных разработок, принимать обоснованные инвестиционные решения.

Ключевые слова: высокотехнологичные проекты, инновационные проекты, государственная поддержка, оценка финансово-экономической эффективности проекта, методы оценки, финансирование проекта

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INTRODUCTION

The creation of high-tech projects is one of the main stages in the transition to an innovative economy. This is explained by the intensive development of globalization processes in the economic system of Russia. High-tech projects have a lower profitability compared to venture projects, but a higher probability of commercial success.

At the present time, there are a large number of operators supporting high-tech projects actively working in Russia (Fig. 1). The acceleration of technological development requires an intensification of innovation policy and revision of the portfolio of its acting instruments. In turn, this makes the matter of analyzing their significance and relevance for participants in innovation processes more pertinent.

The purpose of this work is to identify features of the investment process in the Russian Federation, and to determine criteria for selecting priority high-tech projects and methods of evaluating high-tech projects in the aim of making informed investment decisions.

The study aims to analyze the general principles and approaches to methods of evaluating project efficiency. A model of priorities of high-tech projects was presented. Models which take into account cash flows after the expiration of the payback period were also considered, as well as an algorithm for assessing the investment attractiveness of high-tech projects.

INVESTIGATION OF FEATURES OF THE INVESTMENT PROCESS IN RUSSIA

In order to resolve current problems, it should be noted that an important component in high-tech projects is novel science-intensive technologies. The key industries which ensure the sustainable growth of the economic system of Russia are now those sectors of economy which use science-intensive technologies [1]. The commitment of the economic system to innovation is one of the driving forces of the social and economic development and the improvement of the competitiveness of the national economy.

Attracting Russian investment in the domestic economy has become a task of primary importance [2]. Support programs for high-tech projects include[1]:

- support for small innovative enterprises,
- support for pilot projects of implementation of domestic digital solutions,
- support for projects of implementation of domestic IT solutions,
- support for projects of development and improvement of domestic software,
- support for industrial developments,
- concessional lending to companies.

The "Digital Technologies" Federal Project of the "Digital Economy" National Program[2] includes an integrated system of measures for the state support of projects for the development and implementation of domestic digital products, services, and platform solutions. The "Measures for the Support of Digital Initiatives" Portal[3] was created especially for the information support of enterprises in the implementation of this Program.

The Industry Development Fund (IDP) proposes 10 concessional project financing programs with loans amounting to RUR 5 to 750 mln, at an interest rate of 1 to 5%. In 2015–2019, IDP financed 27 Republican projects to an amount of more than RUR 6 bn.

Since 2016, in Russia under the auspices of the Ministry of Economic Development of the Russian Federation, there is a project entitled "Support for the Leading Private High-Tech Companies" ("National Champions")[4] which creates conditions necessary for the leading private domestic export-oriented high-tech companies. This project assists the formation of Russia-based transnational companies.

In order to participate in the project, companies are selected from the database of winners of the TekhUspekh (Tech Success) Rating.[5] The annual revenue of a company in the project ranges from RUR 400 mln to RUR 20 bn. The companies specialize in such segments as pharmaceutics, medical equipment production, machine building, electronics and instrument manufacturing, novel materials, information technologies and telecommunications, chemical industry, and industrial automation.[6]

Not all the projects, however, provide the expected results, and, on the whole, Russian enterprises are insufficiently involved in the innovation process. Only those companies operating in high tech segments of the processing industry are active in innovation, even though high-tech companies that should be interested in state support. State support was used only by 46% of all the respondents and about 48% of innovative companies.

Figure 2 presents the percentages of state-supported high-tech enterprises.

Those companies most interested in state support are machine and equipment manufacturers (transport machine building). They are the main recipients of subsidies of state and federal target innovation

[1] Navigator of Support Measures. Federal Project "Digital Technologies" of National Program "Digital Economy." URL: https://digital.ac.gov.ru/support/. Accessed December 1, 2020 (in Russ.).

[2] Passport of National Program "Digital Economy of Russian Federation." URL: http://static.government.ru/media/files/urKHm0gTPPnzJlaKw3M5cNLo6gczMkPF.pdf. Accessed December 5, 2020 (in Russ.).

[3] Support Measures for Digital Initiatives. URL: https://e-digital.tatar/. Accessed December 5, 2020 (in Russ.).

[4] National Champions. Priority Project of the Ministry of Economic Development of the Russian Federation "Support for the Leading Private High-Tech Companies." URL: http://national-champions.ru/. Accessed December 7, 2020 (in Russ.).

[5] TekhUspekh. National Rating of Russian Fast-Growing Technology Companies. URL: http://ratingtechup.ru/. Accessed December 7, 2020 (in Russ.).

[6] Support for the Leading Private High-Tech Companies. URL: https://www.economy.gov.ru/material/departments/d01/razvitie_sistemy_gosudarstvennoy_podderzhki_innovaciy_v_subektah/nacionalnye_chempiony/. Accessed December 7, 2020 (in Russ.).

Name of event	Program operator (contest organizer), source of financing, and type of event
Refinancing of present credits for capital investment of investment projects in monotowns	Monotown Development Foundation (loan), Federal Corporation for the Development of Small and Medium Enterprises (FCDSME) (guarantee), Guarantee Fund (guarantee), Government of the Russian Federation (compensation of difference between interest rates). Concessional loan is provided to small, medium-sized, and large business unrelated to activities of town-forming enterprises (TFEs) at annual interest rate of 0 or 5%
Subsidy (co-financing of expenditures) for creation and development of industrial parks	Ministry of Economic Development (MED) of Russia within the National Project “Development of SME and Entrepreneurship”.[1] RF Government Regulation no. 2489 of December 25, 2021,[2] and no. 316 of April 15, 2014.[3] MED Order no. 125 of March 14, 2019,[4] and no. 67 of February 14, 2018.[5] Subsidy (target budget co-financing) is provided by MED of RF.
Co-financing of municipal expenditures on retrofit of utility, road, and civil engineering infrastructure of accredited industrial parks and industrial estates	Ministry of the Economy of RT. Subsidy (target budget co-financing) is provided to municipality
Subsidy of interest rates on target credits to small and medium-sized enterprises (SME) in priority industries and residents of industrial estates (industrial parks)	Entrepreneurship Support Fund of RT. Compensation of part of interest rate (to 15 p.p.) on credits for SME in priority industries and residents of industrial estates (industrial parks)
Priority research and development tax exemption	Tax Code of RF. Deduction of research and development expenses multiplied by 1.5 from taxable profit
RAZVITIE-SOPR Contest for development of socially oriented projects	FGBU Foundation for Assistance to Small Innovative Enterprises in Science and Technology. R&D grant up to RUR 10 mln for socially oriented projects
Concessional loans for social entrepreneurs from Entrepreneurship Support Fund of Republic of Tatarstan (RT)	Entrepreneurship Support Fund of RT (Ministry of the Economy of RT). Concessional microloan up to RUR5 mln at interest rate of 5% is provided to social entrepreneurs
Tax exemptions for residents of priority social and economic development areas (PSEDA) in the Russian Federation (Naberezhnye Chelny, Mendeleevsk)	Ministry of the Economy of RT, Municipal Executive Committee. Profit, property, and land tax relief and other benefits for PSEDA residents (including support for IT companies as PSEDA residents)
Concessional (0% or 5%) loans for business in monotowns	VEB.RF–Monotown Development Foundation (loan), FCDSME (guarantee). Concessional loan is provided to small, medium-sized, and large business unrelated to activities of TFEs at annual interest rate of 0% or 5%
Concessional loans for SME from Federal Corporation for Development of Small and Medium-Sized Business	FCDSME and MED. FCDSME concessional loan is provided in priority industries at annual interest rate of 8.5% (through partner banks) with subsidization (compensation) of shortfall in income of banks; business in priority industries, 9.6%; and other SME, 10.6% (through partner banks)

Fig. 1. Programs of state support for high-tech projects (*Sheet 1*)

[1] Passport of National Project "Small and Medium-Sized Enterprises and Support for Individual Entrepreneurial Initiative." URL: http://static.government.ru/media/files/qH8voRLuhAVWSJhIS8XYbZBsAvcs8A5t.pdf. Accessed January 26, 2022 (in Russ.).

[2] Regulation of the Government of the Russian Federation No. 2489 of December 25, 2021, "On the Amendments to the State Program of the Russian Federation 'Economic Development and Innovative Economy' and the Annulment of Certain Acts and Individual Provisions of Certain Acts of the Government of the Russian Federation." URL: http://publication.pravo.gov.ru/Document/View/0001202112300075. Accessed January 26, 2022 (in Russ.).

[3] Regulation of the Government of the Russian Federation No. 316 of April 15, 2014, "On the Approval of the State Program of the Russian Federation 'Economic Development and Innovative Economy,'" https://base.garant.ru/70644224/. Accessed January 26, 2022 (in Russ.).

[4] Order of the Ministry of Economic Development of the Russian Federation No. 125 of March 14, 2019, "On the Approval of the Requirements for the Implementation of Measures by the Subjects of the Russian Federation the Budgets of Which Are Granted Subsidies for the State Support for Small and Medium-Sized Enterprises in the Subjects of the Russian Federation in Order to Reach Goals, Metrics, and Results of Regional Projects that Ensure the Achievement of Goals, Metrics, and Results of Federal Projects Being Parts of the National Project 'Small and Medium-Sized Enterprises and Support for Individual Entrepreneurial Initiative,' and the Requirements for Organizations Forming the Infrastructure of the Support for Small and Medium-Sized Enterprises." URL: https://www.economy.gov.ru/material/file/f01d6c61e7595ef12bc1e93f156a95ec/prikaz_125_14032019.pdf. Accessed January 26, 2022 (in Russ.).

[5] Order of the Ministry of Economic Development of the Russian Federation No. 67 of February 14, 2018, "On the Approval of the Requirements for the Implementation of Measures by the Subjects of the Russian Federation the Budgets of Which Are Granted Subsidies for the State Support for Small and Medium-Sized Enterprises, Including Peasant (Farm) Enterprises, and Also for the Implementation of Support Measures for Youth Entrepreneurship, and the Requirements for Organizations Forming the Infrastructure of the Support for Small and Medium-Sized Enterprises." URL: https://normativ.kontur.ru/document?moduleId=1&documentId=356380. Accessed January 26, 2022 (in Russ.).

Fig. 1. Programs of state support for high-tech projects (*Sheet 2*)

	Pharmaceutics	Computers, instrument manufacturing, and telecommunications	Chemicals	Electrical equipment	Transport machine building (except aviation)	Aerospace	Other machine building
Share of companies that have used at least one measure for support	51.3	42.8	40.1	30.5	65.8	51.4	49.3
Measures of state support of innovation activity: 1	13.2	10.8	12.5	4.9	6.0	17.1	13.2
2	13.2	6.5	12.5	6.0	13.6	23.7	7.4
3	24.7	9.5	27.1	17.1	44.2	21.2	21.4
4	21.7	10.2	17.0	11.7	16.3	22.6	16.3
5	9.5	8.6	17.4	8.8	20.5	10.8	13.1
6	9.2	0.0	5.1	1.7	0.0	5.2	7.9
7	7.6	2.6	10.6	6.0	14.1	17.0	6.8
8	12.2	4.7	15.2	6.5	30.4	11.7	9.6
9	8.9	3.9	10.0	1.9	15.0	16.4	8.4
10	16.8	7.2	14.7	1.3	12.3	3.2	9.8
11	13.2	3.4	13.6	4.1	33.4	9.8	14.7
12	4.6	3.0	8.0	3.6	14.3	9.8	6.0
13	3.9	0.8	5.5	1.9	0.0	11.8	5.4
14	6.6	2.1	10.0	5.1	8.4	27.2	9.1
15	0.0	4.7	10.0	1.9	0.0	5.3	6.5
16	8.9	9.6	8.1	1.3	4.9	10.9	11.0
17	21.0	9.5	21.4	11.0	32.7	27.9	18.0
18	9.9	8.7	17.7	6.3	10.8	18.5	8.7

Fig. 2. Percentages of state-supported enterprises in 2019

Источник: Demand for Instruments of State Innovation Policy from Enterprises of High-Tech Industries, URL: https://issek.hse.ru/news/293711880.html. Accessed July 4, 2021 (in Russ.).

programs and concessional loans from the Industry Development Fund. Those least interested are manufacturers of electrical equipment, computers, instruments, and telecommunications.

In order to more efficiently support technological startups and develop high-tech industries, an active innovation policy vector was formulated in 2020 through the revision of the portfolio of acting instruments[7]. Another new instrument facilitating the development of high technologies is corporate venture fund (CVF). The classical process of new product development in large companies has become increasingly lengthier and more risky. Therefore, wider use is made of alternative methods to implement innovation through external investment obligations in technology alliances. CVF is a unique instrument in comparison with independent venture funds (IVFs) because it typically strives to reach the strategic, rather than financial, objectives of the parent company. These objectives are directly or indirectly aimed at increasing sales and profits of its ongoing business by accessing new technologies, resources, and markets, rather than the startup which was invested.

High-tech projects are characterized by a high added value of project products. This is due to using breakthrough technologies and other achievements of science and technology.[8]

High-tech projects are developed using the latest achievements and results of research and design in priority industries. The development of such projects is costly and requires significant investment. They are also high risk because these projects are characterized by high uncertainty at each lifecycle stage.

Increasingly larger investment in high-tech industries is a trend of recent decades and they end to control the qualitative growth of economy. New technologies have become a driver of growth of national economies and determine a country's ability to hold its competitive position in the global market [3]. Investment in high-tech projects is a complex and, at the same time, very promising activity. They can be highly significant for society and the country as a whole [4].

When choosing high-tech project are factors which affect priorities are very important. These factors can be used to create a model of priorities. The complexity of given factors can be represented using a classification based on financed projects and projects awaiting financing. Such a classification is quite general and it would be more more expedient to use a ranking of

[7] Demand for Instruments of State Innovation Policy from Enterprises of High-Tech Industries, URL: https://issek.hse.ru/news/293711880.html. Accessed July 4, 2021 (in Russ.).

[8] Decree of the President of the Russian Federation No. 642 of December 1, 2016, "On the Strategy of the Science and Technology Development of the Russian Federation." URL: http://government.ru/docs/all/109256/. Accessed January 26, 2022 (in Russ.).

projects in terms of priority, normal, and background projects (Fig. 3).

Project priority criteria are illustrated by impetuously accelerated trends:

1. Promotion of import substitution.
2. Access to foreign markets—export of Russian technologies and business models.
3. Sharp increase in the number of remote workers. This factor has prompted the development of teamwork services, videoconferencing, cloud storage and cybersecurity, and production of computers and electronic and optical products.
4. Increase in the importance of the development of public health infrastructure projects because of the development of the medical rehabilitation market in the post-pandemic period.
5. Technological solutions purpose-built for state needs (GosTekh). The drivers of the implementation of innovation in the state sector are such factors as the digitalization of state services and digitalization of business processes in government agencies.

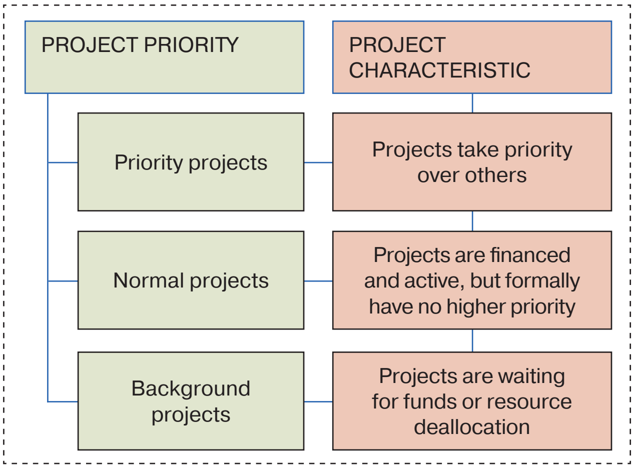

Fig. 3. High-tech project priority model

More complex priority models can be constructed using various mathematical methods [5]. However, there is a contradiction: funds, which are earmarked for finding promising investment projects are not keen on widely disseminating information about themselves, since they consider that investment should be applied by project developers, Meanwhile, project developers very often consider investors unavailable and, therefore, do not apply to them for support measures.

The main financial instruments of state and private financing programs are grants, subsidies, subsidized loans and credits, investment loans, subsidized leasing, government research contracts, syndicated transactions, and convertible loans and venture capital funding.

INVESTIGATION OF METHODS AND MODELS OF EVALUATING THE EFFICIENCY OF HIGH-TECH PROJECTS

Figure 4 presents the general principles and approaches to methods of evaluating the project efficiency.

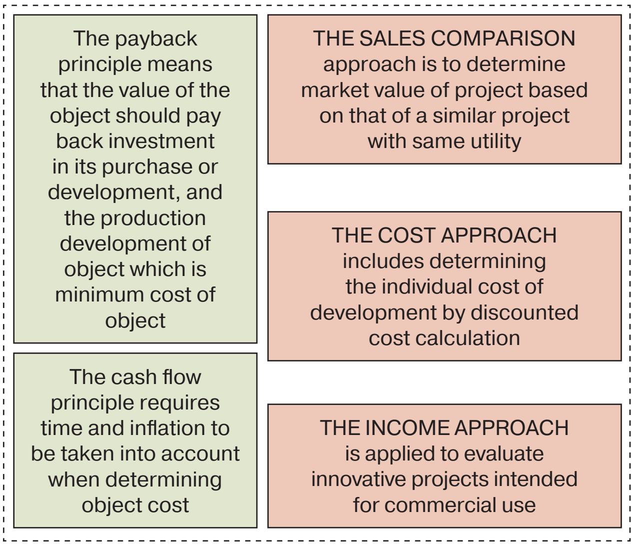

Fig. 4. General principles and approaches to methods of project efficiency evaluation

The general principles and approaches to methods of project efficiency evaluation (Fig. 4) can be used by investors both separately and jointly. Their selection depends on the competitive characteristics of project/product and on factors affecting the innovative project [6].

The effectiveness of a project determines its relevance to the desired objectives and stakeholder interests [7]. The financial and economic efficiency of a project is the ratio of the financial and economic results of the activities of the project team in relation to the financial and economic cost of the project. Depending on whether or not cash flow discounting is used, evaluation methods are divided into two large groups: static and dynamic (Fig. 5).

Investors more frequently use dynamic methods of efficiency evaluation. These methods are more advantageous, since they take into account time as a significant factor of change in the value of money. Such methods of investment project efficiency evaluation better meet current requirements since they are based on a discounted cash flow model.[9] Nevertheless, in the case of investment in short-term projects, wherein time changes can be assumed to be statically insignificant,

[9] Evaluation of Efficiency of Investment Project: Methods and Recommendations. URL: https://www.business.ru/article/1829-otsenka-effektivnosti-investitsionnogo-proekta. Accessed July 4, 2021 (in Russ.).

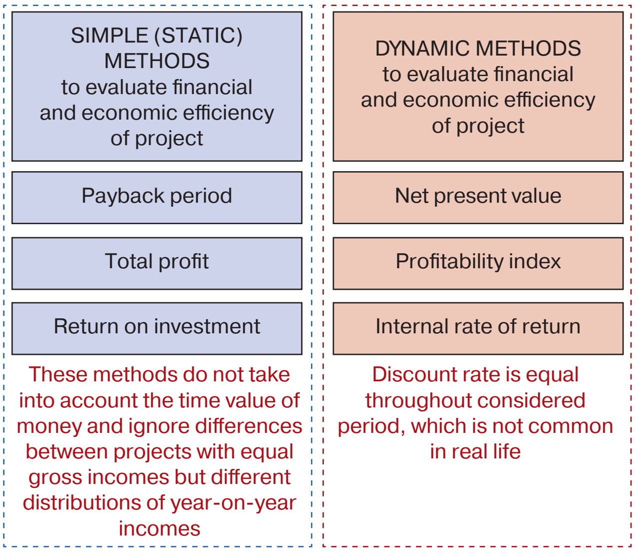

Fig. 5. Main project efficiency evaluation methods

simple methods of evaluating financial and economic efficiency are often used. However, they cannot take into account numerous factors significant for the project in calculations [8].

The models presented below take into account cash flows after the expiration of the payback period. This is an extremely important factor when it came to making the decision of whether or not it is expedient to invest in a high-tech project.

The first of these models (Fig. 6) is a nonlinear programming model of calculating the discounted payback period of investment. This model makes it possible to determine the time needed for the net present value of a high-tech project to be equal to the investment. Figure 6 also gives the parameters of this model [9].

Calculations using this model are quite easily performed in the Microsoft Excel Solver add-in. This add-in is a very good tool for solving optimization problems.

Further reinvestment is not taken into account in this solution. However, if the conditions for the reinvestment of net present values are known, then the modernized discounted payback period can be found.

The second model (Fig. 7) is a nonlinear programming model for calculating the modernized discounted payback period of investment. This model determines the time it takes for the net present value and additional net reinvestment income of a high-tech project to be equal to the initial investment [9].

The methods and models of evaluating the efficiency of high-tech projects presented herein help investors to make an informed decision. However, for a more in-depth analysis, it would be advisable to carry out not an isolated study of only the financial component of a project, but a more extensive investigation. This would take into account the area of implementation of the high-tech project.

The following algorithm of economic assessment of investment attractiveness of high-tech projects (Fig. 8) is also recommended.

The algorithm for the economic assessment of investment attractiveness of high-tech projects consists of two steps:

- selection of priority high-tech projects and their substantiation according to selected criteria;
- evaluation of the economic efficiency of high-tech projects in terms of the financial and economic methods which take into account maximum possible number of factors significant for project.

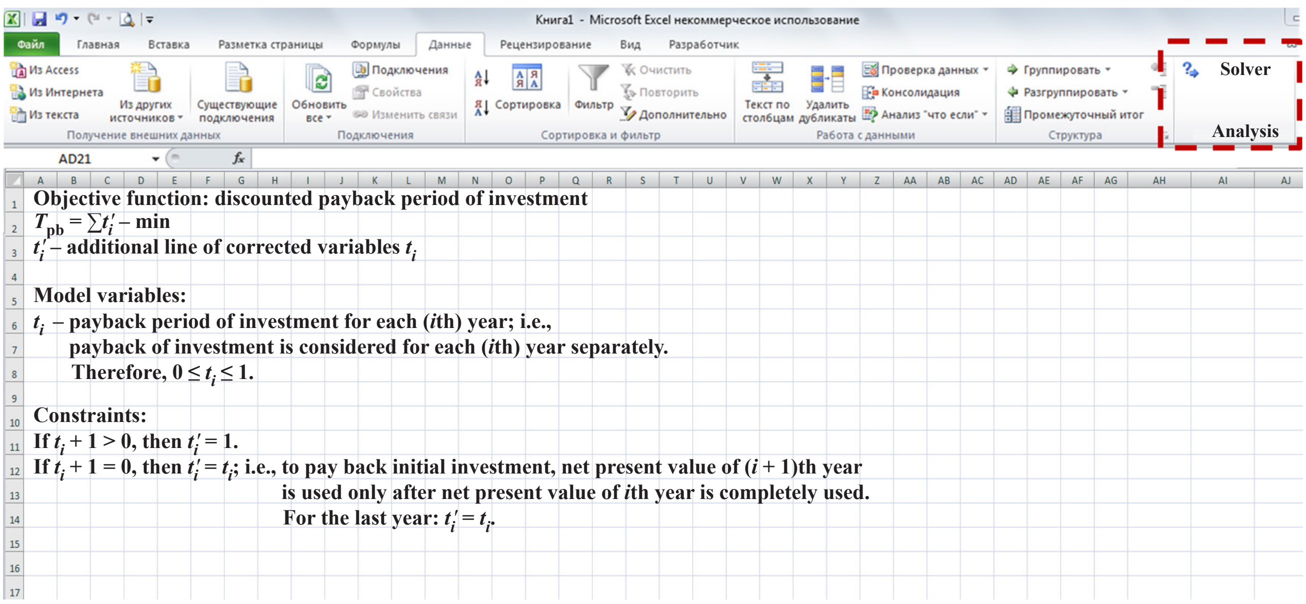

Fig. 6. Parameters of the first model of evaluating the financial and economic efficiency of a high-tech project

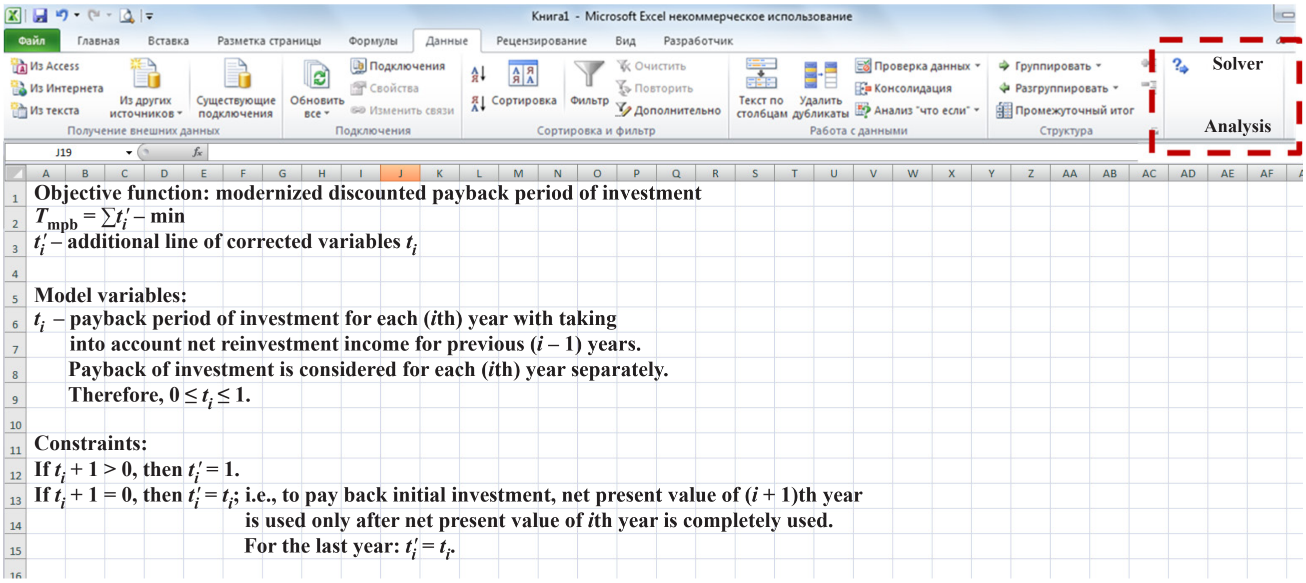

Fig. 7. Parameters of the second model of evaluating the financial and economic efficiency of a high-tech project

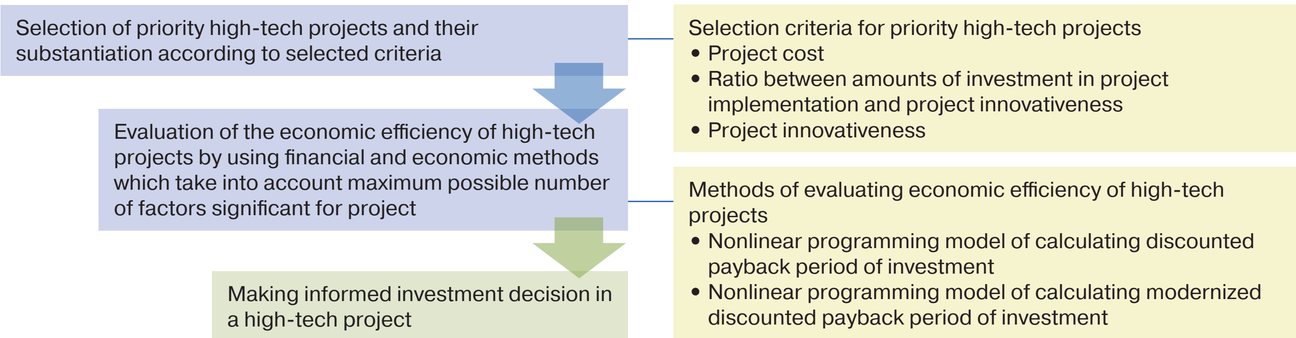

Fig. 8. Algorithm of economic assessment of investment attractiveness of high-tech projects

In the first step, the selection criteria for priority high-tech projects are chosen. The main criteria are project cost, ratio between amounts of investments in project implementation and project innovativeness (technological, marketing, or organization innovations). In terms of the latter, we mean the probability of commercial success (expected added value of project product),

In the second step, the project is evaluated in terms of the financial and economic methods using models which take into account as many factors significant for project as possible:

- nonlinear programming model of calculating discounted payback period of investment;
- nonlinear programming model of calculating modernized discounted payback period of investment.

Importantly, the investment decision lead time is very short. The key stage at which investors decide to invest is the Seed stage. At this stage which, investment is required to bring the product to market requirements (in this case, investment can reach RUR 10 mln). Consequently, the assessment algorithm should be sufficiently simple, and the evaluation methods should be efficient. They should take into account the maximum possible number of factors which are significant for high-tech project.

Figure 9 represents the main stages of financing high-tech projects in terms of rounds of financing.

Certain financing sources correspond to each stage of the project, for example, at the Pre-Seed stages, grants and investment of own resources are required. There may also be a requirement for the support of business angels or seed funds. At later stages, subsidies or convertible loans may be needed.

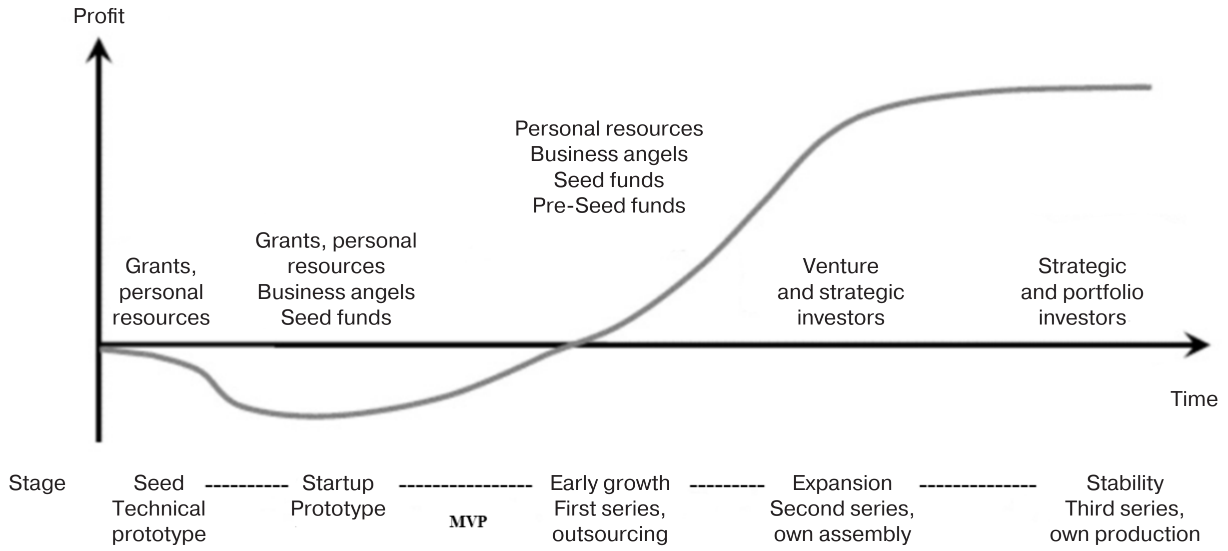

Fig. 9. Rounds of financing

Source: Morozov A. Having a startup capital of RUR 10–15 mln, it is no problem to raise about RUR 600 mln more for a hardware project. There is a lot of money in the country, especially for industry. URL: https://json.tv/ict_news_read/aleksandr-morozov-akselerator-territoriya-imeya-10-15-mln-rubley-pervonachalnogo-kapitala-privlech-esche-poryadka-600-millionov-na-hardware-proekt-dlya-promyshlennosti-ne-problema-deneg-v-strane-ochen-mnogo-20171228014631. Accessed February 3, 2022 (in Russ.).

CONCLUSIONS

Project financing in innovative developments is a complex and time-consuming process, requiring the attention of investors and meticulous evaluation.

This study aimed to identify features of the investment process in the Russian Federation, as well as the criteria for selecting priority high-tech projects and methods of evaluating these projects, in the aims of making informed investment decisions.

The general principles and approaches to project efficiency evaluation methods were analyzed. A model of priorities of high-tech projects was presented, as well as two models which take cash flows into account after the expiration of the payback period. Furthermore, an algorithm for the economic assessment of investment attractiveness of high-tech projects was also demonstrated. Thus, this work considered all the instruments which investors require, in order to make the decision of whether or not it is expedient to invest in high-tech projects.

Authors' contribution

I.A. Mandych—data acquisition, analysis, and interpretation, writing the article, the analysis of scientific work, final processing the article.

A.V. Bykova—conception and design of the study, data acquisition, analysis, and interpretation, writing the article.

O.B. Gaiman—data acquisition, analysis, and interpretation, writing the article, formalization of the list of references.

All authors have read and approved the final manuscript for publication.

REFERENCES

1. Kolegova O.A. Basic concepts of a high-tech project. In: *Modern decision support technologies in the economy.* Proceedings of the All-Russian Scientific and Practical Conference of students, postgraduates and young scientists. Tomsk: Izd. Tomsk. Politekh. Univ.; 2015. P. 80–82 (in Russ.). Available from URL: https://www.lib.tpu.ru/fulltext/c/2015/C79/030.pdf
2. Kotsyubinskiy V.A., Komarov V.M. *Perspektivy razvitija vysokotehnologichnogo sektora* (*Prospects for the Development of the High-Tech Sector*). Moscow: RANKHiGS; 2015. 65 p. (in Russ.).
3. Zemtsov S.P., Barinova V.A., Semenova R.I. Public support of high technologies and innovations in Russia. *Innovatsii = Innovations*. 2019;3(245):33–44 (in Russ.).

СПИСОК ЛИТЕРАТУРЫ

1. Колегова О.А. Основные понятия высокотехнологичного проекта. В сб.: *Современные технологии поддержки принятия решений в экономике*. Сборник трудов Всероссийской научно-практической конференции студентов, аспирантов и молодых ученых. Томск: Изд-во Томского политехнического университета; 2015. С. 80–82. URL: https://www.lib.tpu.ru/fulltext/c/2015/C79/030.pdf
2. Коцюбинский В.А., Комаров В.М. *Перспективы развития высокотехнологичного сектора*. М.: РАНХиГС; 2015. 65 с.
3. Земцов С.П., Баринова В.А., Семенова Р.И. Государственная поддержка высоких технологий и инноваций в России. *Инновации*. 2019;3(245):33–44.

4. Zinov V.G. Index of specialisation according to technological fields and the perspectives of technological leadership of Russia. *Ekonomika nauki = The Economics of Science*. 2016;2(2):96–110 (in Russ.).
5. Archibal'd R.D. *Upravlenie vysokotekhnologichnymi programmami i proektami* (*Managing High-Technology Programs and Projects*): transl. from Eng. Moscow: Kompaniya Aiti; DMK Press; 2010. 464 p. (in Russ.). ISBN 5-98453-002-3 (AiTi); ISBN 978-5-9706-0045-0 (DMK Press)
6. Lyukmanov V.B., Mandych I.A. *Upravlenie finansami + ePrilozhenie*: testy. (*Bakalavriat*): uchebnoe posobie (*Financial management*). Moscow: KnoRus; 2021. 206 p. (in Russ.). ISBN 978-5-406-06330-9
7. Galimzyanov M.D. Project stakeholder analysis methods. *Molodoi uchenyi = Young Scientist*. 2019;35(273):35–37 (in Russ.). Available from URL: https://moluch.ru/archive/273/62188/
8. Timchenko T.N. *Ekonomicheskaya otsenka investitsii* (*Economic assessment of investments*). Moscow: RIOR; 2010. 61 p. (in Russ.). ISBN 978-5-369-00554-5. Available from URL: https://znanium.com/catalog/product/221240
9. Mandych I.A., Lyukmanov V.B., Kudryavtseva I.G. Modern methods for calculating economic indicators of investment projects. *Finansovyi menedzhment = Financial Management*. 2018;1:60–70 (in Russ.)

4. Зинов В.Г. Индекс специализации по технологическим областям и перспективы технологического лидерства России. *Экономика науки*. 2016;2(2): 96–110.
5. Арчибальд Р.Д. *Управление высокотехнологичными программами и проектами*: пер. с англ. под ред. А.Д. Баженова. М.: Компания АйТи; ДМК Пресс; 2010. 464 с. ISBN 5-98453-002-3 (АйТи); ISBN 978-5-9706-0045-0 (ДМК Пресс).
6. Люкманов В.Б., Мандыч И.А. *Управление финансами + еПриложение: тесты.* (*Бакалавриат*): учебное пособие. М.: КноРус; 2021. 206 с. ISBN 978-5-406-06330-9
7. Галимзянов М.Д. Методики анализа стейкхолдеров проекта. *Молодой ученый*. 2019;35(273):35–37. URL: https://moluch.ru/archive/273/62188/
8. Тимченко Т.Н. *Экономическая оценка инвестиций:* учебное пособие. М.: РИОР; 2010. 61 с. ISBN 978-5-369-00554-5. URL: https://znanium.com/catalog/product/221240
9. Мандыч И.А., Люкманов В.Б., Кудрявцева И.Г. Современные методы расчета экономических показателей инвестиционных проектов. *Финансовый менеджмент*. 2018;1:60–70.

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RESEARCH ARTICLE

Identification of knowledge sources for micro- and nanoelectronics technologies

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Abstract
Objectives. Over the past few decades, multiple knowledge management models have been developed by many research groups studying the innovation process in companies. However, these knowledge and information management models are rather general, and do not consider the dynamics and variability of technology development. This implies involving specific organizations in different types of knowledge generation activities. The paper aims to reveal the importance of a knowledge management system in micro- and nanoelectronics technologies as well as identify and systematize the sources of knowledge in the scientific and technical field.
Methods. In this paper, the method for analyzing the relationship between key business indicators of the companies is applied. The results are then represented in a causal loop diagram. The stakeholder analysis method is also used here.
Results. Three relevant trends in developing the knowledge management system for knowledge-intensive enterprises involved in micro- and nanoelectronics technologies are identified with respect to the social, commercial, and scientific and technical aspects in research organizations. The key sources of knowledge on micro- and nanoelectronics technologies include universities, institutions of the Russian Academy of Sciences, industry-specific institutions, customers, manufacturers, and consumers. Also, the authors consider digital twins to be a promising source of knowledge on micro- and nanoelectronics technologies.
Conclusions. The analysis of the technology life cycle curve using the example of micro- and nanoelectronics allows correlating single stages of this life cycle with specific activities during which new knowledge is generated. These activities include fundamental and applied research, requirements management, implementation in manufacturing, and operation analysis. For microelectronics, they correspond to the areas of emergence, peak of inflated expectations, trough of disillusionment, slope of enlightenment, and plateau of productivity on the technology life cycle curve.

Keywords: knowledge, knowledge management, nanoindustry, digital twin

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НАУЧНАЯ СТАТЬЯ

Определение источников знаний о технологиях микро- и наноэлектроники

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Резюме
Цели. В течение последних десятилетий разработано множество моделей управления знаниями. Однако использование данных моделей для создания информационной системы в интересах исследовательских предприятий микроэлектроники не представляется возможным, поскольку они не учитывают динамику и характер развития технологий, а также специфику деятельности организаций в разных видах работ по генерации знаний. Цель работы – выявить направления актуальности разработки системы управления знаниями о технологиях микро- и наноэлектроники, определить и систематизировать источники знаний в данной научно-технической области.
Методы. Использованы метод анализа взаимосвязи бизнес-показателей компаний с последующей визуализацией в виде циклической диаграммы причин, метод анализа заинтересованных сторон.
Результаты. Сформулированы три направления актуальности разработки системы управления знаниями в наукоемкой области технологий микро- и наноэлектроники – с точки зрения социальных, коммерческих и научно-технических эффектов в соответствующих организациях. К ключевым источникам знаний о технологиях микро- и наноэлектроники отнесены университеты, институты РАН, отраслевые институты, заказчики, производства и потребители. Обоснована важность рассмотрения цифровых двойников электронных компонент как перспективного источника знаний в данной области.
Выводы. Анализ кривой жизненного цикла технологии на примере области микро- и наноэлектроники позволяет соотнести отдельные этапы данного жизненного цикла с конкретными видами работ, в ходе выполнения которых происходит выработка новых знаний. В качестве видов работ выделены фундаментальные и прикладные исследования, изучение требований, реализация на производстве и анализ эксплуатации. Для отрасли микроэлектроники на кривой жизненного цикла технологий они соответствуют участкам появления, пика ожиданий, избавления от иллюзий, преодоления недостатков и плато продуктивности.

Ключевые слова: знания, управление знаниями, наноиндустрия, цифровой двойник

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INTRODUCTION

Enhancing and applying total professional knowledge is an integral part of fundamental and applied research carried out by modern research organizations. According to [1], this knowledge may be considered as a part of an organization's intellectual capital and, consequently, as a management object. In [2, 3], some of the best-known models of knowledge management are given, such as the Choo decision-making model based on comprehension of information, the Hedlund model based on the knowledge transfer and transformation, the von Krogh and Roos model of individual and collective knowledge, and others. In general, they are all based on categorizing into the following two types of knowledge depending on the formalization state (the capability to be stored and transferred):

1) Formalized (explicit) knowledge, presented in a particular form: e.g., in the form of records using natural language and binary code, in the form of instructions in a programming language, etc. Explicit knowledge is systematized; it can be packaged in the form of a service (for example, online courses or professional development programs) or product (manuals, videos, notes, etc.) and transferred during the teaching process;
2) Unformalized (tacit) knowledge, usually stored in the minds of particular individuals including dynamically changing adaptive understanding, collective knowledge, and expertise in terms of "know-how." Such knowledge may be transferred through training and mentoring. This type of knowledge was proposed by Michael Polanyi in 1958 [4].

According to the Socialization, Externalization, Combination, and Internalization (SECI) model proposed by Ikujiro Nonaka in 1990[1], knowledge "moves" in a spiral cycle wherein tacit knowledge is "extracted" to become explicit knowledge while explicit knowledge is "re-internalized" into tacit knowledge. Thus, information passes through four stages: socialization, externalization, combination, and internalization; and it is in multiple transitions between formalized and unformalized states that new knowledge is generated.

These definitions are completely suitable for use in terms of knowledge management in micro- and nanoelectronics technologies. However, due to their generality, none of the described models could be directly applied to describe the process of enhancing intellectual capital in organizations of specific knowledge-intensive industries involved in multiple collaborations and project studies as well as performing a diversity of internal R&D activities. It would be advisable to start developing the model description of the knowledge management process by identifying their sources.

COMPONENTS OF THE KNOWLEDGE MANAGEMENT PROCESS IN TECHNOLOGICAL ORGANIZATIONS

Comparing the above models, principal components of the knowledge management process of organizations that are collection (acquisition), transfer (providing access and transmission), application, protection, and storage may be identified [5].

[1] Management for Knowledge Creation, Tokyo: Nihon Keizai Shimbun-sha, 1990, (in Japanese).

It should be noted, that these actions play a determining role in the operational efficiency of knowledge-intensive sectors, such as microelectronics, which combines nanoscale physics, solid-state electronics, quantum theory, chemistry, and other fields of science [6]. However, the study of Russian enterprises engaged in the development of micro- and nanoelectronics technologies has not revealed the existence of knowledge management systems having a complete set of key components. At the same time, several processes (e.g., accumulation of information in the form of project documentation) are being successfully implemented by certain departments for decades.

The systemic approach to knowledge management in micro- and nanoelectronics technologies would allow the following:

1) monitoring the research and technology development in microelectronics for correct positioning in the industry as well as for making decisions on participation in joint projects [7];
2) controlling the progress at the applied research stage so that not to miss changing trends;
3) accessing the maturity of new solutions with respect to opportunities for improvement of reliability and obtaining new functional properties.

THE RELEVANCE OF DEVELOPING A KNOWLEDGE MANAGEMENT SYSTEM IN MICROELECTRONICS

Creating, populating, and managing the knowledge base for micro- and nanoelectronics technologies may be relevant for R&D companies involved in this field from three perspectives: social, commercial, and scientific and technical. Thus, by sharing information, the scientific results generated by research departments may be more likely to find application in work of design departments. At the same time, the problems formulated by technical specialists that require scientific studies would become known to the research teams of companies due to the common information system. Thus, connecting the researchers and developers of microelectronic technologies communicatively would allow accelerating solution of common tasks of the entire enterprise; in particular, increasing the knowledge base. Moreover, the accumulated knowledge would allow analyzing commercially available products and technologies as well as scientific achievements in more detail, thus providing a more accurate picture of microelectronic technologies available in the Russian and world markets. Formally, these fields may be covered by the terms "innovation and technology exploration" or "scouting." Adjusting the objectives in product development and goals of theoretical and experimental research, one

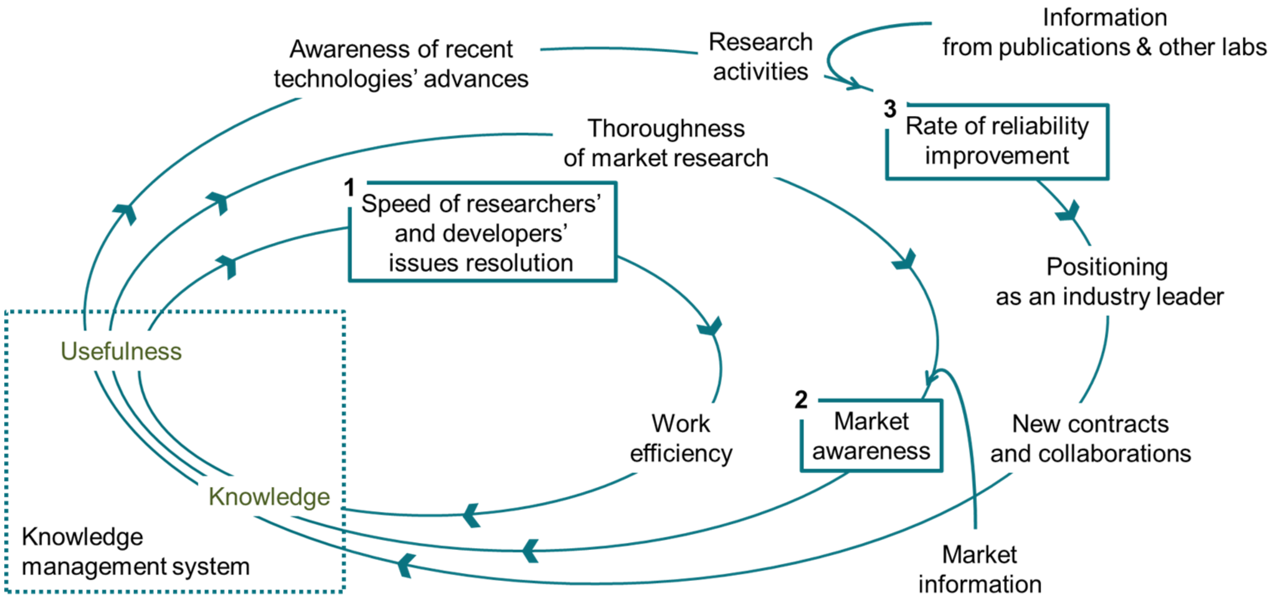

Fig. 1. Positive feedback loops with respect to business processes in the social, commercial, and scientific and technical aspects formed when implementing the corporate knowledge management system for microelectronics technologies

may eventually achieve the new results in high external demand. Solving development and manufacturing problems by performing additional research would result in better product reliability through improved microelectronics technology.

The relevant trends are shown in Fig. 1 schematically as three circuits of positive feedback, i.e., an increase in one indicator improves the next one, moving clockwise.

SYSTEMATIZING SOURCES OF KNOWLEDGE

Using the S-curve concept of the technology life cycle introduced by Gartner in 1995 (the Gartner Hype Cycle), it may be assumed that micro- and nanoelectronics as a set of manufacturing technologies have reached the plateau of productivity phase [8]. This means that the knowledge accumulated in these fields is sufficient for starting commercial microelectronic manufacturing. In addition, advances in related fields (materials science, optics, and nanophysics) may allow for new improvements in basic microelectronics technology, each undergoing the entire life cycle from emergence to widespread adoption.

The chronological comparison proposed by the authors between the phases of the Gartner Hype Cycle and the sources of knowledge identified by classifying market counterparties in micro- and nanoelectronics technologies by activity area is shown in Fig. 2.

Knowledge accumulation occurs at all phases of the technology life cycle. In addition, after the successful completion of each stage, new organizations are involved in the activities in this field, thus becoming new sources of knowledge. For convenience, the following two types of activities resulting in generation of new knowledge may be specified:

1) research activities consisting of fundamental and applied ones;
2) engineering activities consisting of requirements management, manufacturing, and operation.

SOURCES OF KNOWLEDGE IN THE RESEARCH PHASE

The first phase implies **fundamental** research including the study of physical processes and identification of opportunities and acceptable limitations. In this phase, academic institutions and universities are the key players carrying out the main work of knowledge accumulation.

The principle of Coulomb blockade based on two tunnel junctions may exemplify a physical principle remaining in the fundamental research phase for decades. So far, this principle has not yet resulted in the appearance of the single-electron transistor and other alternative transistor structures as microelectronic devices.

The next phase includes **applied** research consisting of attempts to implement the physical principles studied thoroughly in previous phase in devices. As of 2021, this phase is presented by memristors and ferroelectric memory circuits [9, 10] as well as active and passive elements of photonic integrated circuits, fabricated using microelectronic

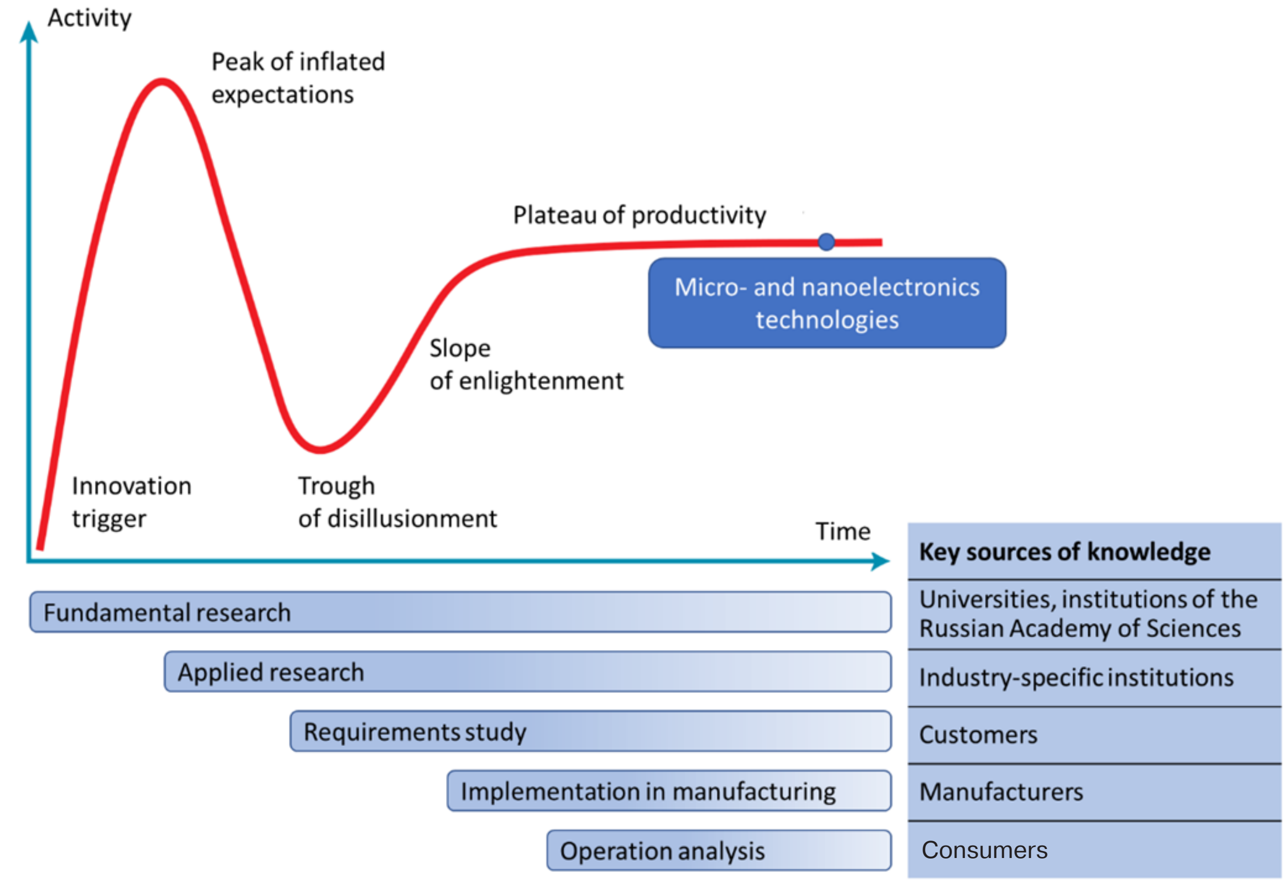

Fig. 2. The technology life cycle curve, phases of knowledge accumulation and sources of knowledge on microelectronics technologies

technologies [11]. Once the research becomes mature, it moves on to the stage of R&D activities resulting in creating prototypes.

In particular, the transition towards new materials [12] requires a large-scale set of tests to make sure that the introduced modifications did not lead to performance degradation of the final devices, primarily in terms of reliability [13, 14]. This is crucial for military application [15] and critical for unmanned space systems manufactured using micro- and nanoelectronics technologies [16].

SOURCES OF KNOWLEDGE IN THE CHIP DESIGN ENGINEERING PHASES

The miniaturization of already designed chips by implementing them in the form of microsystem units was among the main trends stimulating development of Russian microelectronics in the 1970s. The use of integrated circuits (ICs) for custom systems with predetermined functional and reliability requirements is the next step in that process. So far, microelectronics has remained the element base of informatics.

Contemporary methods for requirement-driven design of devices include the widespread use of automation. The use of fundamental parametric synthesis at the initial stage of development, allowing for selecting more effective design decisions using the principle of measuring environmental parameters [17], may add to the existing design algorithms. Awareness of such principles is the result of fundamental and applied research.

Another area of knowledge in microelectronics technologies is related to the changing **requirements to the development** of computing devices. The progress in some areas, such as neural network algorithms [18] and artificial intelligence, may give rise to special-purpose processors with the architecture optimized to solve a certain class of computational tasks with minimal instruction set due to the reduced information storage capabilities.

A key source of knowledge on technologies is related to their implementation in specific **manufacturing**. With the industry being developed, the problems of clean technology environment are being addressed—first, at the level of particles per area, then microparticles per volume, and now the task of airborne molecular contamination removal is of great importance. Significant progress has been made in solving the issue of early failures by introducing process tests and design enhancements [19].

Another source of knowledge relates to issues arising in the phase of the manufactured chips **operating**. Some aspects refer to possibilities of expanding the application boundaries and increasing functionality by software modification. In addition, chip failure cases are analyzed, in particular, breakdowns expressed as an irreversible change in the system induced by localized heating effects.

DIGITAL TWINS AS PROSPECTIVE SOURCES OF KNOWLEDGE

A relatively recent trend in science and technology is application of the model-based systems engineering (MBSE). This implies the integration of executable models as a single source of new information. The creation of the so-called digital twin may be the final objective for this type of systems engineering.

Digital twins may allow modeling semiconductor devices and finite electronic systems at both hardware and software levels [20]. Of particular importance may be considering environmental conditions having varying impacts on equipment and software, such as the effects of external electromagnetic fields and acoustic waves, penetration of high-energy particles, etc. [21]. Modeling of physical processes in integrated circuits and microsystems allows assessing the impact of various internal and external factors on temperature and electrical parameters determining the reliability and noise immunity of the component base.

Compared to system-level models, the digital twin of a semiconductor component reflects the system behavior not only at a particular stage but throughout the entire life cycle. This includes the following stages:

1) concept description, statement of work;
2) architecture design;
3) IC logic development;
4) IC topology development;
5) verification;
6) photomask approval;
7) photomask manufacturing;
8) validation;
9) route map development;
10) fabrication;
11) packaging;
12) benchmarking;
13) testing;
14) certification;
15) series manufacturing;
16) operation.

Implementation of the digital twin involves concurrent data collection and analysis for all stages and participants in the process of a particular semiconductor device manufacturing, ranging from the design centers through the manufacturing site to the user. In fact, a management system for data appearing in developing and process designing as well as for the processes of appearance and transformation of this data is required. The integrated system would allow managing the design project, accounting for the limited time, cost, resources, and quality metrics of the final products [22], as well as thoroughly monitoring, if required, particular operating components up to the formation of structures within IC using micro- and nanoelectronics technologies.

It may be concluded that digital twins of electronic systems as a single channel of new information would be an additional source of knowledge on the micro- and nanoelectronics technologies. However, there is no existing information on complete digital twins at present, so this source is missed in our chart of knowledge sources in micro- and nanoelectronics technologies.

CONCLUSIONS

It should be emphasized in conclusion that existing knowledge management models may be successfully used only within separate knowledge-intensive enterprises. The systematization carried out in the paper may be useful due to the noticeable difference in types of activities in microelectronics performed by different organizations (yet, closely cooperating for solving common scientific and technical problems). The proposed definition of players involved in microelectronics is the information tool prototype allowing project teams to identify the range of promising partners in accordance with the stages of technology development along the life cycle curve. Some details may be added to this chart, e.g., the specific research fields or organization names.

Processing the information streams from the revealed sources of knowledge on micro- and nanoelectronics technologies will allow constructing an effective knowledge base structure for the enterprise as well as the related means of access, use, and management of the stored information. In addition, this will allow for an approach to processing of open-source information for automatic update of knowledge base to be defined.

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REFERENCES

1. Nadtochiy Yu.B., Budovich L.S. Intellectual capital of the organization: the essence, structure, approaches to evaluation. *Rossiiskii tekhnologicheskii zhurnal = Russian Technological Journal*. 2018;6(2):82–95 (in Russ.). https://doi.org/10.32362/2500-316X-2018-6-2-82-95
2. Mohajan H.K. The impact of knowledge management models for the development of organizations. *J. Environ. Treat. Tech*. 2017;5(1):12–33.
3. Marinko G.I. Modern models and schools in knowledge management. *Vestnik Moskovskogo universiteta. Seriya 21: Upravlenie* (*gosudarstvo i obshchestvo*) = *Moscow University Bulletin. Series 21. Public Administration*. 2004;2:45–65 (in Russ.)
4. Polanyi M. *Personal knowledge: towards a post-critical philosophy*. Chicago: University of Chicago Press; 1958. 464 p.
5. Lytras M.D., Pouloudi A. Project management as a knowledge management primer: the learning infrastructure in knowledge-intensive organizations: projects as knowledge transformations and beyond. *The Learning Organization*. 2003;10(4):237–250. https://doi.org/10.1108/09696470310476007
6. Gornev E.S. National microelectronics: expectations and prospects. *Nanoindustriya = Nanoindustry*. 2018;11(6):392–398 (in Russ.). https://doi.org/10.22184/1993-8578.2018.11.6.392.398
7. Gornev E.S., Zaitsev N.A., Ravilov M.F., Romanov I.M., Ranchin S.O., Bylinkin D.A. The analysis of the developed foreign products of microsystem techniques. *Mikrosistemnaya tekhnika = Nano- and Microsystems Technology*. 2002;7:6–11 (in Russ.).
8. Krasnikov G.Ya., Gornev E.S., Matyushkin I.V. *Obshchaya teoriya tekhnologii i mikroelektronika* (*General Theory of Technology and Microelectronics*). Moscow: TEKhNOSFERA; 2020. 434 p. (in Russ.).
9. Teplov G.S., Gornev E.S. Multilevel bipolar memristor model considering deviations of switching parameters in the Verilog-A language. *Russian Microelectronics*. 2019;48(3): 131–142. https://doi.org/10.1134/S1063739719030107
[Original Russian Text: Teplov G.S., Gornev E.S. Multilevel bipolar memristor model considering deviations of switching parameters in the Verilog-A language. *Mikroelektronika*. 2019;48(3):163–175 (in Russ.). https://doi.org/10.1134/S0544126919030104]
10. Krasnikov G.Ya., Zaitsev N.A., Krasnikov A.G. Current state of development in the nonvolatile memory. *Nano- i mikrosistemnaya tekhnika = Nano- and Microsystems Technology*. 2015;4(177):60–64 (in Russ.).
11. Sharapov A.A., Shamin E.S., Skuratov I.D., Gornev E.S. Grounds and problem statement for software complex for photolithography optimization for minimization of losses in optical structures of photonic integrated circuits. *IOP Conference Series: Materials Science and Engineering*. 2020;939:012070. https://doi.org/10.1088/1757-899X/939/1/012070
12. Bokarev V.P., Krasnikov G.Ya. Estimation of the change in the physicochemical properties of Nanosized crystalline materials. *Doklady Physical Chemistry*. 2008;420(1):96–99. https://doi.org/10.1134/S0012501608050047
[Original Russian Text: Bokarev V.P., Krasnikov G.Ya. Estimation of the change in the physicochemical properties of Nanosized crystalline materials. *Doklady Akademii nauk*. 2008;420(2):186–189 (in Russ.).]

СПИСОК ЛИТЕРАТУРЫ

1. Надточий Ю.Б., Будович Л.С. Интеллектуальный капитал организации: сущность, структура, подходы к оценке. *Российский технологический журнал*. 2018;6(2): 82–95. https://doi.org/10.32362/2500-316X-2018-6-2-82-95
2. Mohajan H.K. The impact of knowledge management models for the development of organizations. *J. Environ. Treat. Tech*. 2017;5(1):12–33.
3. Маринко Г.И. Современные модели и школы в управлении знаниями. *Вестник Московского университета. Серия 21: Управление* (*государство и общество*). 2004;2:45–65.
4. Polanyi M. *Personal knowledge: towards a post-critical philosophy*. Chicago: University of Chicago Press; 1958. 464 p.
5. Lytras M.D., Pouloudi A. Project management as a knowledge management primer: the learning infrastructure in knowledge-intensive organizations: projects as knowledge transformations and beyond. *The Learning Organization*. 2003;10(4):237–250. https://doi.org/10.1108/09696470310476007
6. Горнев Е.С. Отечественная микроэлектроника: ожидания и перспективы. *Наноиндустрия*. 2018;11(6):392–398. https://doi.org/10.22184/1993-8578.2018.11.6.392.398
7. Горнев Е.С., Зайцев Н.А., Равилов М.Ф., Романов И.М., Ранчин С.О., Былинкин Д.А. Анализ разработанных зарубежных изделий микросистемной техники. *Микросистемная техника*. 2002;7:6–11.
8. Красников Г.Я., Горнев Е.С., Матюшкин И.В. *Общая теория технологий и микроэлектроника*. М.: ТЕХНОСФЕРА; 2020. 434 с.
9. Теплов Г.С., Горнев Е.С. Модель на языке Verilog-A многоуровневого биполярного мемристора с учетом девиаций параметров переключения. *Микроэлектроника*. 2019;48(3):163–175. https://doi.org/10.1134/S0544126919030104
10. Красников Г.Я., Зайцев Н.А., Красников А.Г. Современное состояние разработок в области энергонезависимой памяти. *Нано- и микросистемная техника*. 2015;4(177):60–64.
11. Sharapov A.A., Shamin E.S., Skuratov I.D., Gornev E.S. Grounds and problem statement for software complex for photolithography optimization for minimization of losses in optical structures of photonic integrated circuits. *IOP Conference Series: Materials Science and Engineering*. 2020;939:012070. https://doi.org/10.1088/1757-899X/939/1/012070
12. Бокарев В.П., Красников Г.Я. Оценка изменения физико-химических свойств наноразмерных кристаллических материалов. *Доклады Академии наук*. 2008;420(2):186–189.
13. Просий А.Д., Ранчин С.О., Шелепин Н.А. Обеспечение качества в современном полупроводниковом производстве. *Электронная техника. Серия 3: Микроэлектроника*. 2015;4(160):39–43.
14. Соловьев А.В., Селецкий А.В. Недостатки отечественных расчетно-экспериментальных методик прогнозирования надежности интегральных схем. *Проблемы разработки перспективных микро- и наноэлектронных систем* (*МЭС*). 2020;1:76–81. https://doi.org/10.31114/2078-7707-2020-1-76-81

13. Prosii A.D., Ranchin S.O., Shelepin N.A. Quality assurancein modern semiconductor manufacturing. *Elektronnaya tekhnika. Seriya 3: Mikroelektronika = Electronic Engineering. Series 3. Microelectronics*. 2015;4(160):39–43 (in Russ.).
14. Solov'ev A.V., Seletskii A.V. Disadvantages of domestic analytical-experimental methods prediction of integrated circuits reliability. *Problemy razrabotki perspektivnykh mikro- i nanoelektronnykh sistem* (*MES*) = *Problems of Advanced Micro- and Nanoelectronic Systems Development* (*MES*). 2020;1:76–81 (in Russ.). https://doi.org/10.31114/2078-7707-2020-1-76-81
15. Gavrilov S.V., Zheleznikov D.A., Zapletina M.A., Khvatov V.M., Chochaev R.Zh., Enns V.I. Layout synthesis design flow for special-purpose reconfigurable systems-on-a-chip. *Russian Microelectronics*. 2019;48(3):176–186. https://doi.org/10.1134/S1063739719030053
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16. Krasnikov G.Ya., Meshchanov V.D., Shelepin N.A. Family 4–64 Mbit ROM integrated circuits for space applications. *Elektronnaya tekhnika. Seriya 3: Mikroelektronika = Electronic Engineering. Series 3. Microelectronics*. 2015;2(158):4–10 (in Russ.).
17. Koldaev I.M. The fundamental parametric approach to synthesis of electronic systems. *Nanoindustriya = Nanoindustry*. 2020;S96(1):265–269 (in Russ.). https://doi.org/10.22184/1993-8578.2020.13.3s.265.269
18. Tel'minov O.A., Gornev E.S., Moshkarova L.A., Yanovich S.I., Morozov E.N. Evaluation of bayes neural network approach for determining transistor characteristics and operational process control correlation. *Nanoindustriya = Nanoindustry.* 2020;13(S4,99):559–560 (in Russ.) https://doi.org/10.22184/1993-8578.2020.13.4s.559.560
19. Gornev E.S. Methods for ensuring the reliability of modern ULSI. In: *Mathematical Modeling in Materials Science of Electronic Components ICM3SEC–2020*. October 19–20, 2020, Moscow. Proceedings of the international conference. Moscow: MAKS Press; 2020. P. 13–21 (in Russ.).
20. Tel'minov O.A., Gornev E.S., Chernyaev N.V., Yanovich S.I., Moshkarova L.A., Shakhmanova M.V. Research on the possibility of constructing a digital twin of integrated circuits for analyzing and predicting their reliability. *Nanoindustriya = Nanoindustry*. 2021;14(S7,107):694–695 (in Russ.). https://doi.org/10.22184/1993-8578.2021.14.7s.694.695
21. Il'in S.A., Lastochkin O.V., Nadin A.S., Novikov A.A., Shipitsin D.S. Design platform for CMOS RHBD 90 nm technology. *Nanoindustriya = Nanoindustry*. 2019;S(89):254–257 (in Russ.).
22. Sharapov A.A., Baranov G.V. Comparative analysis of nanoscale roughness measurement methods. *Trudy MFTI*. 2018;10(2,38):72–79 (in Russ.).

15. Гаврилов С.В., Железников Д.А., Заплетина М.А., Хватов В.М., Чочаев Р.Ж., Эннс В.И. Маршрут топологического синтеза для реконфигурируемых систем на кристалле специального назначения. *Микроэлектроника*. 2019;48(3):211–223. https://doi.org/10.1134/S0544126919030050
16. Красников Г.Я., Мещанов В.Д., Шелепин Н.А. Семейство микросхем ПЗУ информационной емкостью 4-64 Мбит для космических применений. *Электронная техника. Серия 3: Микроэлектроника*. 2015;2(158):4–10.
17. Колдаев И.М. Фундаментальный параметрический подход к синтезу электронных систем. *Наноиндустрия*. 2020;S96(1):265–269. https://doi.org/10.22184/1993-8578.2020.13.3s.265.269
18. Тельминов О.А., Горнев Е.С., Мошкарова Л.А., Янович С.И., Морозов Е.Н. Оценка возможности применения нейросетевого байесовского подхода к выявлению корреляции между параметрами тестовых элементов для межоперационного контроля технологического процесса и характеристиками формируемой транзисторной структуры. *Наноиндустрия*. 2020;13(S4,99):559–560. https://doi.org/10.22184/1993-8578.2020.13.4s.559.560
19. Горнев Е.С. Методы обеспечения надежности современных СБИС. Математическое моделирование в материаловедении электронных компонентов. В сб.: *Математическое моделирование в материаловедении электронных компонентов* (*МММЭК–2020*). Сборник материалов II международной конференции. 19–20 октября 2020 г. М.: МАКС Пресс; 2020. С. 13–21.
20. Тельминов О.А., Горнев Е.С., Черняев Н.В., Янович С.И., Мошкарова Л.А., Шахманова М.В. Исследование возможности построения цифрового двойника интегральных схем для анализа и прогнозирования их надежности. *Наноиндустрия*. 2021;14(S7,107):694–695. https://doi.org/10.22184/1993-8578.2021.14.7s.694.695
21. Ильин С.А., Ласточкин О.В., Надин А.С., Новиков А.А., Шипицин Д.С. Конструкторско-технологическая платформа проектирования радиационно-стойких СБИСБ на базе отечественной технологии КМОП 90 нм на основе RHBD методологии. *Наноиндустрия*. 2019;S(89):254–257.
22. Шарапов А.А., Баранов Г.В. Сравнительный анализ методик оценки количественных характеристик шероховатости наноразмерных структур. *Труды МФТИ*. 2018;10(2,38):72–79.

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Page 28, after the title of the article instead of
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