**Modern radio engineering and telecommunication systems**

**Современные радиотехнические и телекоммуникационные системы**

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RESEARCH ARTICLE

# Photonics-based modular multistate digital coherent system

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**Abstract**
**Objectives.** The study aimed to develop interspecies and interclass methods for constructing coherent radio engineering systems based on a modular complementary structure.
**Methods.** A set of modules and submodules having no narrow specialization and together constituting a flexible broadband hardware-reconfigurable software-defined radio engineering structure is considered as the basic set for constructing a digital radio photonic system path. Due to their broadbandness and complementary structure, modules and submodules have many applications both as self-sustained devices and as part of more complex systems.
**Results.** Functional diagrams of modern digital receiver-shapers, as well as modules for amplifying radio frequency signals and converting radio frequency signals into an optical signal are presented along with a radio photonic synchronization network for generating clock signals. Calculations of the introduced phase error of a quartz single-mode fiber and graphs of the dependence of the change in the signal phase on external influencing factors are given. A concept for integrating the presented modules into the construction of a modular transceiver multiposition wideband coherent digital radio photonic system is proposed. The results of calculating radiation patterns and mathematical modeling the beam deflection of a broadband antenna array are presented along with antenna systems based thereon.
**Conclusions.** The proposed circuit design solutions allow the time required for developing new types of systems to be significantly reduced due to the range of ready-made technical solutions. Not only are the parameters of the developed devices comparable to the best world analogues, but they also surpass existing solutions in terms of system integration. The developments have been tested under R&D project at the Kaluga Scientific Research Institute of Radio Technology and Hardware Solution Technologies (TAR). The proposed solutions are integrated at the subsystem level into advanced developments of products for civil and special purpose. Further development of the concept of building ultra-wideband devices allows reaching a new level in the technology of constructing modular multiposition coherent digital radio photonic systems.

**Keywords:** digital antenna arrays, radar, active phased antenna array, laser, photodiode, digital-to-analog converter, analog-to-digital converter, digital beamforming

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НАУЧНАЯ СТАТЬЯ

# Модульная многопозиционная когерентная цифровая радиофотонная система

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**Резюме**
**Цели.** Разработка межвидовых и межклассовых способов построения радиотехнических когерентных систем на основе модульной дополняемой структуры.
**Методы.** В качестве базового набора для построения тракта цифровой радиофотонной системы предлагается рассмотреть комплекс модулей и субмодулей, не имеющих узкой специализации и в совокупности составляющих широкополосную гибкую аппаратно-реконфигурируемую программно-определяемую радиотехническую структуру. Благодаря широкополосности и дополняемой структуре модули и субмодули имеют множество применений, как в качестве самостоятельных устройств, так и в составе более сложных систем.
**Результаты.** Представлены функциональные схемы современных цифровых приемников-формирователей, модулей усиления радиочастотных сигналов, модулей преобразования радиочастотных сигналов в оптический сигнал, радиофотонной синхросети формирования тактовых сигналов. Приведены расчеты вносимой фазовой ошибки кварцевого одномодового волокна и графики зависимости изменения фазы сигнала от внешних воздействующих факторов. Предложена концепция интеграции представленных модулей и построения модульной приемо-передающей многопозиционной широкополосной когерентной цифровой радиофотонной системы. Приведены расчеты диаграмм направленности и результаты математического моделирования отклонения луча широкополосной антенной линейки. Показаны антенные системы на ее основе.
**Выводы.** Предложенные методы позволят существенно сократить сроки разработки новых типов систем за счет линейки готовых технических решений. Разработанные устройства обладают параметрами, не уступающими лучшим мировым аналогам, а в рамках интеграции в систему позволяют превзойти существующие решения. Апробирование разработок проведено в рамках НИОКР на базе АО «Калужский научно-исследовательский радиотехнический институт» и ООО «Технологии аппаратных решений». Предложенные решения интегрированы на уровне подсистем в перспективные разработки продукции гражданского и специального назначения. Дальнейшее развитие концепции построения сверхширокополосных устройств позволит достигнуть нового уровня в технологии построения модульных многопозиционных когерентных цифровых радиофотонных систем.

**Ключевые слова:** цифровые антенные решетки, радар, активная фазированная антенная решетка, лазер, фотодиод, цифроаналоговый преобразователь, аналогово-цифровой преобразователь, цифровое диаграммообразование

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## INTRODUCTION

Digital antenna arrays (DAAs) in communication systems are increasingly used in radar systems (RSs), as well as for various civil and special purpose systems. Along with general development trends in electronics and the component base, the constant increase in operating frequencies and bandwidth of modern communication systems including RSs results in the displacement of traditional active-phased antenna arrays (APAs). As well as fiber optic networks for frequency transfer allowing synthesized signals to be converted to any spectral range, analog-to-digital converters (ADCs) and digital-to-analog converters (DACs) support direct digital beamforming (DBF) across a wide frequency band [1, 2]. Works [3–9] further develop the idea of constructing ultra-wideband (UWB) devices.

The paper aims to develop interspecies and interclass methods for constructing radio engineering coherent systems based on a modular supplemented structure to achieve a new level in the technology of constructing modular multiposition coherent digital photonic systems.

## FUNCTIONAL STRUCTURE OF THE DIGITAL RADIO PHOTONIC SYSTEM PATH

A set of modules and submodules having no narrow specialization and together constituting a broadband flexible hardware-reconfigurable software-defined radio structure is considered. Due to their broadbandness and complementary structure, the modules and submodules have many applications both as self-sustained devices and as part of more complex systems.

This system may include the following components: basic digital module (BDM), submodule for direct radio frequency (RF) signal amplification (SRFA), submodule for optoelectronic frequency conversion (SOFC), auxiliary module for controlling and powering submodules, photonic synchro network (PSN), and wideband phased antenna arrays.

The basic digital module, which comprises a self-sustained receiving and transmitting device, is designed for the digital processing and synthesis of RF signals across a wide frequency range. The functionality of the basic digital module can be extended by installing additional submodules. Generally, it is proposed to include the following: two-channel ADC and DAC, programmable logic device (PLD), digital signal processor (DSP), low-noise amplifiers (LNA), controlled attenuators (At), set of switches (S), bandpass filters (BPF), and input signal quadrature processing circuit via a dual ADC containing switches and directional dividers (D). The block diagram of such a basic digital module is shown in Fig. 1.

The SRFA is designed for amplifying the received and transmitted signals as well as switching antenna inputs for receiving and transmitting. The block diagram of the submodule is shown in Fig. 2.

The SRFA consists of receiving and transmitting paths. A switched control signal path and transmitter channels with integrated directional dividers were used for self-monitoring. In functional terms, the SRFA comprises directional dividers, directional couplers, controlled attenuators, low-noise amplifiers, power amplifier stages, switches, and limiters (LIM). The submodule was installed on a printed circuit board (PCB) of the basic digital module in which the standardized circuit of submodule power supply and information exchange channel with end-to-end control protocol and initialization of submodules were organized.

The SOFC comprises a four-channel bi-directional (2 × 2) submodule for optoelectronic and electrooptical frequency conversion of broadband signals synthesized and digitized by transceiver channels of the basic digital module. The SOFC spaced-apart modules were coupled. The SOFC receiving channel consists of a photonic LNA, an optical modulator performing additional modulation by local heterodyne signal, and an output photodetector for converting the optical signal into RF signal. The transmission channel was intended for converting RF signal to the optical band and transmitting the signal to the receiver of the spaced-apart coupled SOFC through fiber-optic communication lines. The scientific, technological, and practical groundwork for implementing SOFC is based on research and development activities carried out by the company Hardware Solution Technologies (TAR) under the project Development, Manufacture

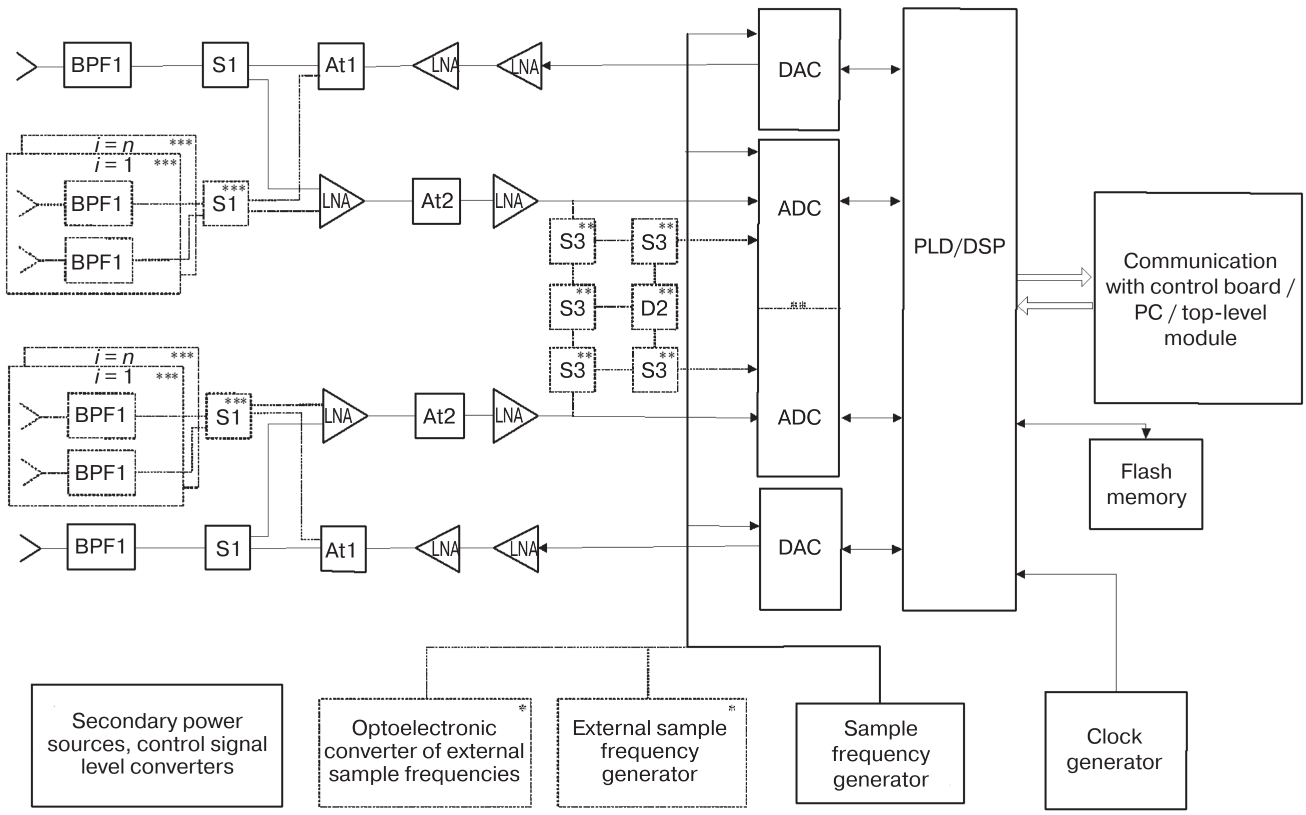


**Fig. 1.** BDM block diagram

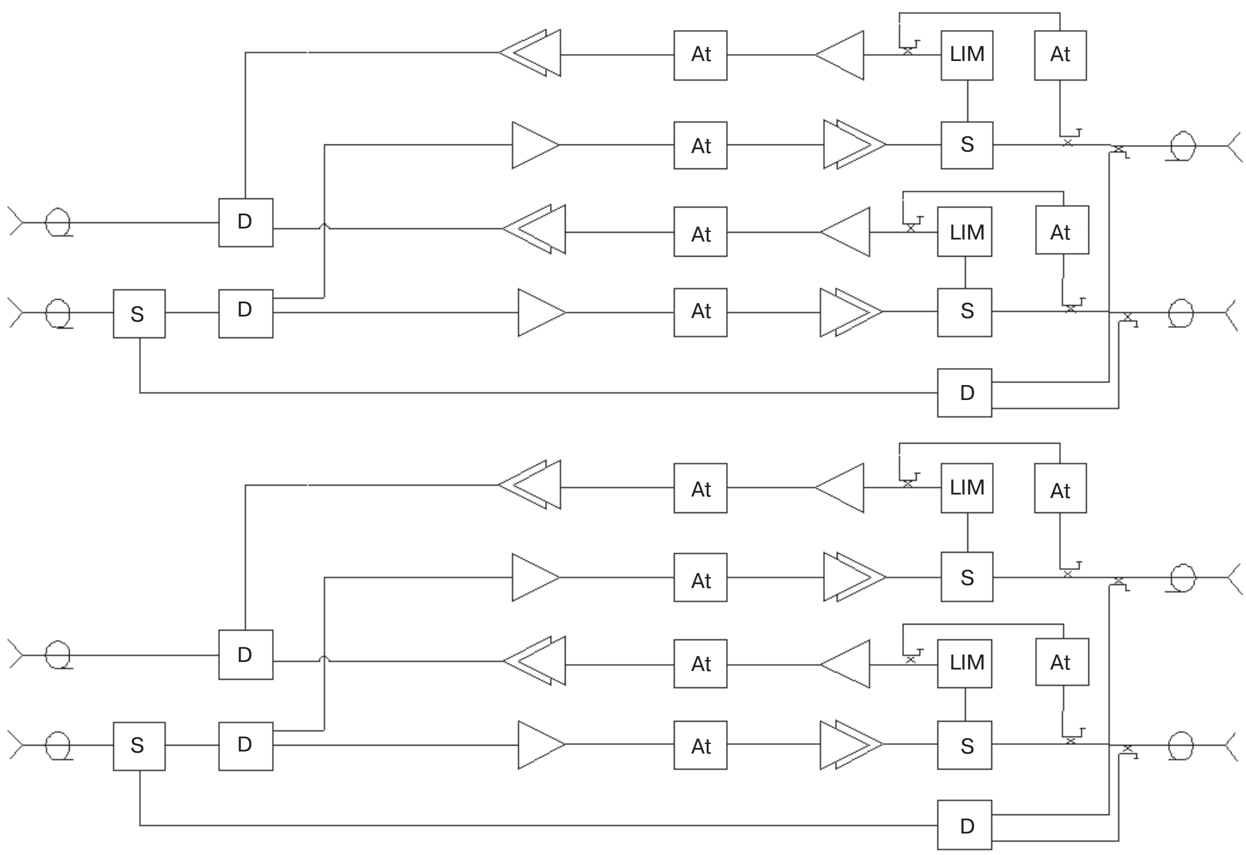


**Fig. 2.** SRFA block diagram

and Testing of a Prototype Photonic Transceiver[1, 2, 3] supported by the Foundation for Assistance to Small Innovative Enterprises in Science and Technology[4].

The SOFC block diagram is shown in Fig. 3.

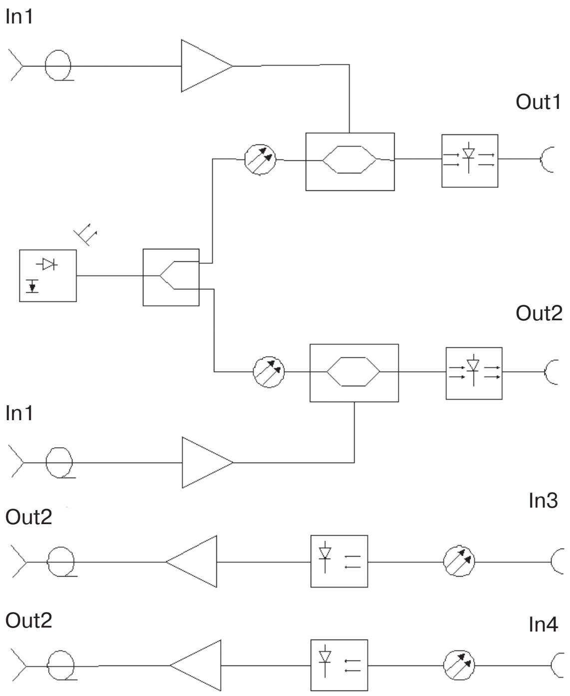


**Fig. 3.** SOFC block diagram

## PHOTONIC SYNCHRO NETWORK

The photonic synchro network is intended for clocking a basic digital module using an optical sync signal. The characteristic feature of the proposed phase synchronization system for all ADCs, DACs and PLDs comprises using the use of a unified highly stable clock signal source distributed through single-mode fiber optic cables of equal electric length to reduce the impact of inherent noise in the clock source and common clock distribution circuits (up to the optical divider) on measuring errors in the received signal phase difference. The use of single-mode fiber can reduce losses in the transmission channel, as well as eliminating the influence of intermodal dispersion, resulting in signal distortion and fiber optic bandwidth reduction on the signal[5]. The PSN structure including a master oscillator and two spaced-apart ADC radioelectronic modules is shown in Fig. 4.

The clock signal generator produces ADC clock frequency $f_1$ (S-band), signal processor clock frequency $f_2$ (for fast-acting ADC, usually, $f_1 = 2if_2$, where $i = 1, 2, 4$), and ADC synchronization and reset pulse signals. To exclude the time divergence of these four signals, they are all transmitted through a single optical fiber several tens of meters long, while four frequency spaced lasers, optical spectral multiplexers, and demultiplexers are used for independent transmission and reception. Bandpass filters are installed after photodiodes in clock circuits, with no filtering required for the PLD (DRR) and ADC (ASYNC) reset signals.

In addition to phase noise, other sources of phase distortion in optical fibers include: temperature, vibration and acoustics, chromatic dispersion, polarization mode dispersion, and transient interferences [10]. Based on the data presented in [10], the introduced phase error was calculated. The calculation results are set out in the Table.

In the table, the following notation is used: $n$ is the effective group refractive index of quartz fiber (typical value $n = 1.468$ for standard single-mode fiber SMF-28[6]); $L$ is a fiber length (20 m for the considered system); c is the speed of light; $\omega_r$ is an angular frequency of S-band synchronous signal; $T$ is temperature, °C; $(1/L)dL/dT$ is the coefficient of thermal expansion (typical value $5.6 \cdot 10^{-7}$/°C, 1/°C); $dn/dT$ is the temperature coefficient of refractive index (typical value $1.2 \cdot 10^{-5}$, 1/°C; $[(1/L)dL/d\sigma]^{-1}$); $dn/d\sigma$ are Young's moduli (typical values by length and refractive index of fiber are $7.2 \cdot 10^{10}$ Pa and $-3.4 \cdot 10^{-12}$/Pa, 1/Pa, respectively); $D$ is a chromatic dispersion coefficient (typical value 18 ps/nm·km); $\Delta\lambda$ is the wavelength difference between the optical carrier and components of the first order sidebands in the spectrum of the intensity-modulated optical signal propagating along the fiber, determined for C-optical range (1551–1563 nm) by the clock radio signal frequency in gigahertz from proportion 10 GHz ≈ 80 pm; $D_{pmd}$ is the coefficient of polarization mode dispersion (typical value $0.1\ \mathrm{ps}/\sqrt{\mathrm{km}}$;) $A_c$ is the relative level of transient interference appearing during multiplexing (value is ≈30 dB ).

Thus, the phase synchronization system proposed in the paper is capable of distributing a single clock signal from one source to all ADCs at distance up

[1] *Development, manufacture and testing of a prototype photonic transceiver*: R&D report (interim), TAR, LLC. Director Unchenko I.V., executives: Emelyanov A.A., Unchenko I.V., et al. Maloyaroslavets, 2021. 48 p. Grant No. 121031900169-9. https://www.rosrid.ru/ikrbs/detail/MYS684SV1OP68CW4NR4SZHWO. Accessed June 01, 2022 (in Russ.).

[2] *Photonic radio transceiver: know-how*. TAR, LLC. Director Unchenko I.V., executives: Emelyanov A.A., Unchenko I.V., et al. Maloyaroslavets, 2022. 53 p. Grant No. 622011200395-5. https://www.rosrid.ru/rid/detail/QPGRZIV0EEAEYARJU4BQ3I34. Accessed June 01, 2022 (in Russ.).

[3] *Development, manufacture and testing of a prototype photonic transceiver*: R&D report (interim), TAR, LLC. Director Unchenko I.V., executives: Emelyanov A.A., Unchenko I.V., et al. Maloyaroslavets, 2022. 70 p. Grant No. 222021700414-1. https://www.rosrid.ru/ikrbs/detail/UJCVU86GQ2YVRM2MUVQMY79U. Accessed June 01, 2022 (in Russ.).

[4] https://fasie.ru/. Accessed June 01, 2022 (in Russ.).

[5] Belkin M.E. *Components of fiber-optic systems:* tutorial. Moscow: MIREA; 2010. 112 p. (in Russ.).

[6] https://www.corning.com/media/worldwide/coc/documents/Fiber/PI-1463-AEN.pdf. Accessed June 01, 2022.

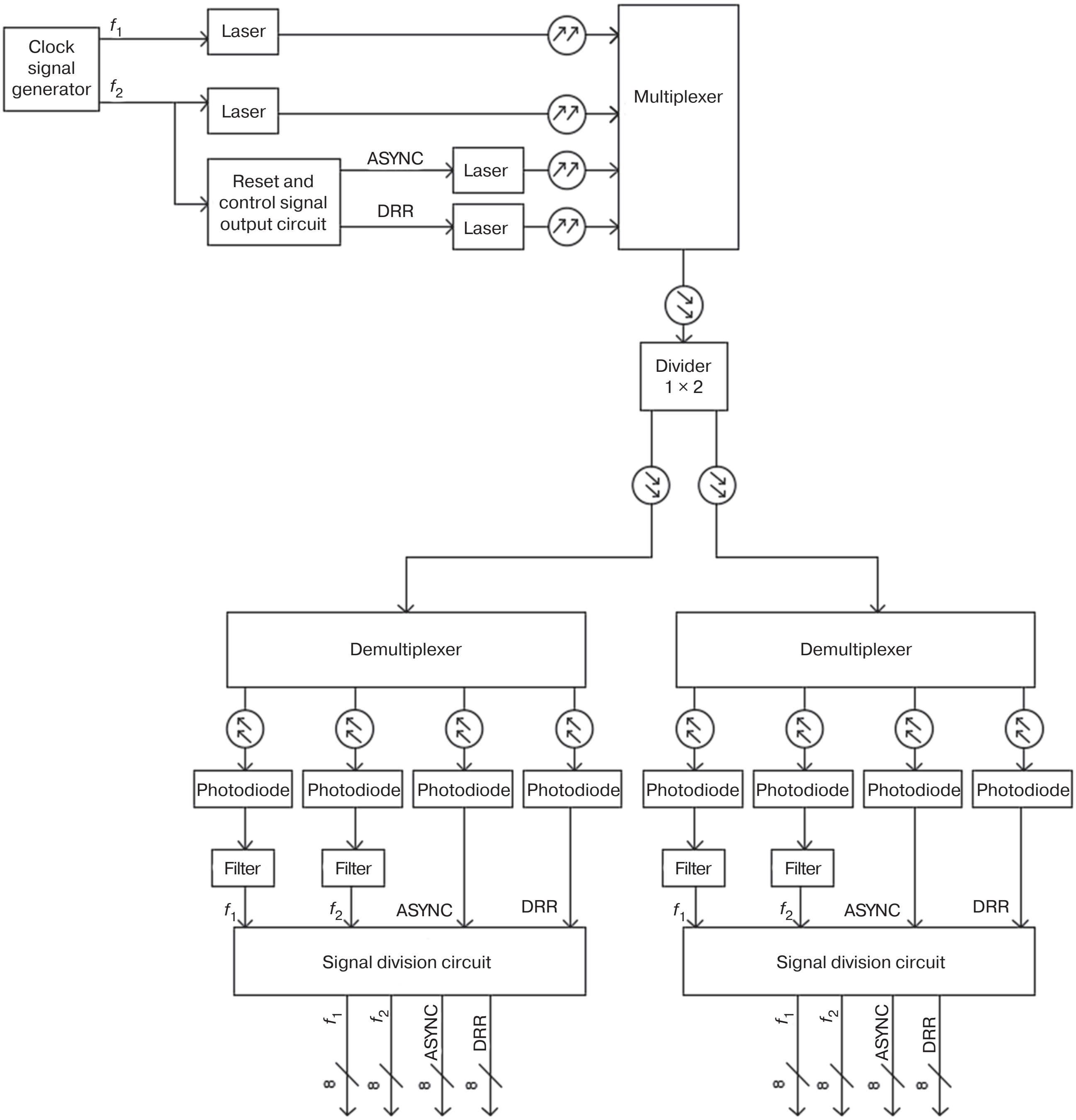


**Fig. 4.** PSN structure

**Table.** Calculation results for the introduced phase error

| No. | Effect | Calculating formula | Calculated value |
|---|---|---|---|
| 1 | Temperature | $\frac{d\varphi}{dT}=\frac{\omega_r L}{c}\left(\frac{n}{L}\frac{dL}{dT}+\frac{dn}{dT}\right)$ | Fig. 5 |
| 2 | Vibrations and acoustics | $\frac{d\varphi}{d\sigma}=\frac{\omega_r L}{c}\left(\frac{n}{L}\frac{dL}{d\sigma}+\frac{dn}{d\sigma}\right)$ | Fig. 6 |
| 3 | Chromatic dispersion | $\Delta\varphi=\omega_r DL\Delta\lambda$ | $1.1\cdot10^{-4}$ deg |
| 4 | Polarization mode dispersion | $\Delta\varphi=\omega_r D_{pmd}L^{1/2}$ | $2.2\cdot10^{-4}$ deg |
| 5 | Transient interferences | $\Delta\varphi=\mathrm{arctg}(10^{A_c/20})$ | 1.8 deg |

to tens meters, as well as transferring the reset and synchronization signals to processing devices. Here, the theoretical phase error of the processed signals, which would be no more than 1.8 deg, is primarily introduced by the signal multiplexing unit.

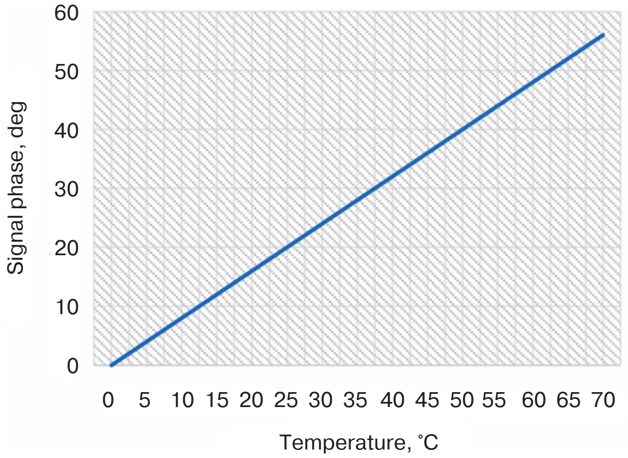


**Fig. 5.** Dependence of the signal phase change on temperature

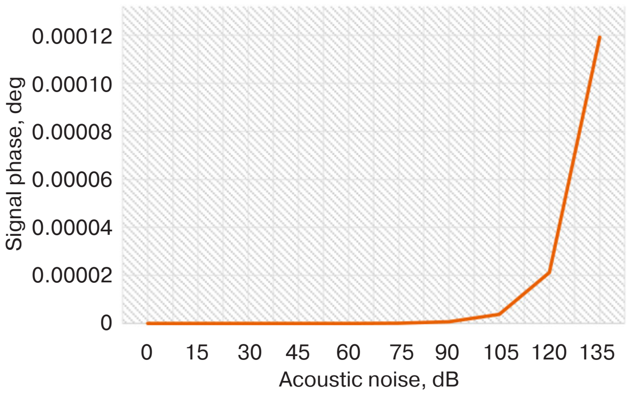


**Fig. 6.** Dependence of the signal phase change on the level of acoustic noise

## DAA MODULAR ARCHITECTURE

The proposed solutions for constructing the synchronization system and integral path when using directional antennas with optimal step already comprise both self-sustained devices and the DAA element. The basic digital module and submodule for direct RF signal amplification may be integrated into DAA via the external interfaces of the basic digital module using solutions in the field of on-board computers and data processing centers. The main limitation for DAA extension is the bandwidth of the information exchange channel interfaces. In addition, maximum synchronization accuracy between the ADC and DAC is required for plotting the directional pattern and providing DAA electronic scanning. The DAA block diagram based on the modular architecture is shown in Fig. 7, where CLOCK1–CLOCK*n* comprise the PLD, while the ADC synchronizes and resets signals generated by the photonic synchro network.

The required values for phase distribution between channels are calculated depending on the antenna array (AA) design determining the directional pattern, the viewing angle, and the required number of beam positions. The eight-element antenna array based on the Vivaldi aerial shown in general in Fig. 8 is considered to plot the directional pattern for such system.

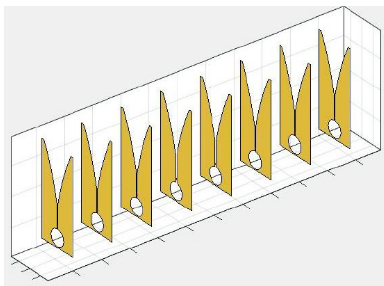

**Fig. 8.** General view of the antenna array

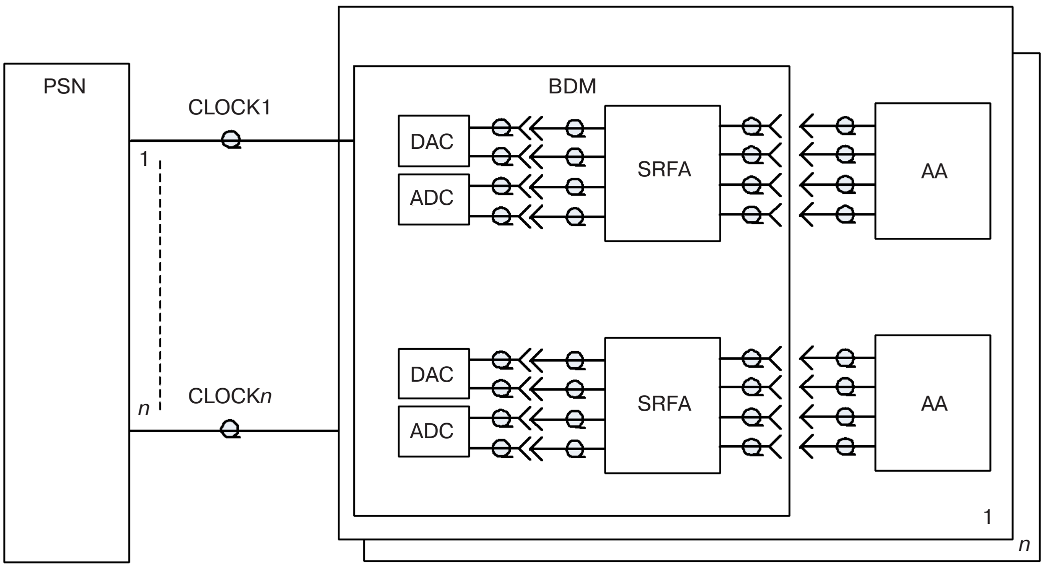


**Fig. 7.** DAA block diagram

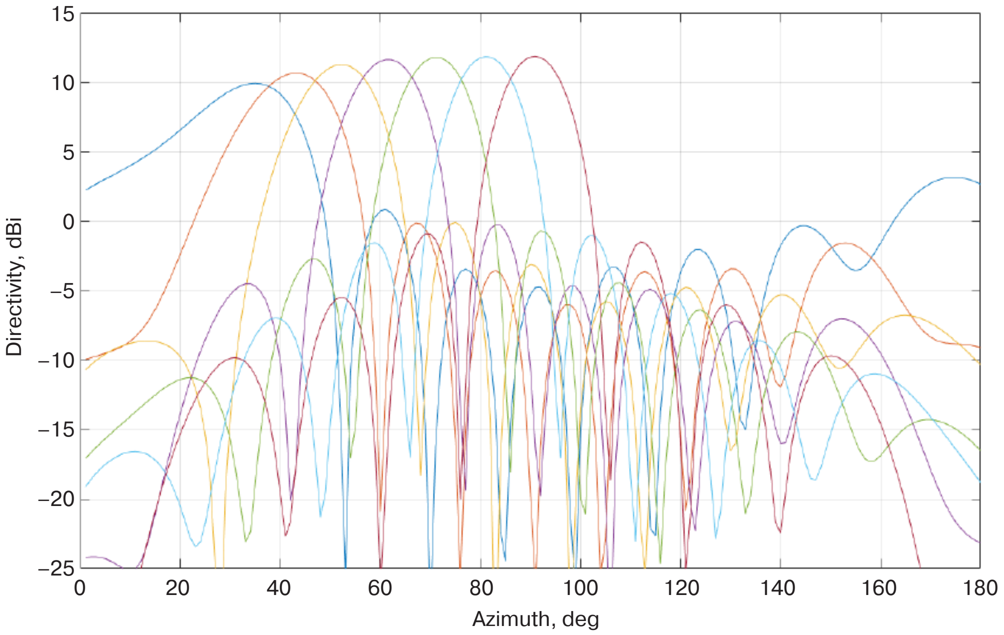


**Fig. 9.** Calculation results for AA directional patterns

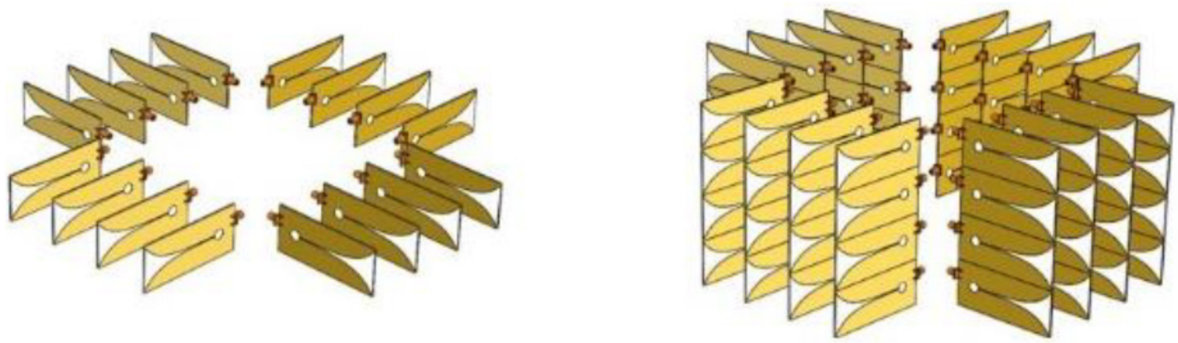

**Fig. 10.** DAA antenna systems

The modifications of wideband radiators based on symmetric slot lines (Vivaldi aerial) are widely presented in [11, 12]. DBF methods are described in [13–15], while beamforming options, APA scanning methods, as well as phase distribution calculations for such array, are given in [12, 13].

The calculated directional pattern and beam deflection of the eight-element AA are shown in Fig. 9.

The antenna systems constructed according to the DAA integration and scaling principle based on modular architecture, providing reception and transmission of signals in the range of angles 360° in azimuth and angular planes, are shown in Fig. 10. Each module is based on the Vivaldi type radiator having exponential aperture, one of whose advantages is broadbandness [16, 17].

## CONCLUSIONS

The proposed circuit design solutions allow the time required for developing new system types to be significantly reduced due to the range of ready-made technical solutions. Not only are the parameters of developed devices equivalent to state-of-the-art analogues, but they also improve on existing solutions in terms of integration into the system. The developments were tested as part of an R&D project carried out at the Kaluga Scientific Research Institute of Radio Technology in partnership with TAR. The proposed solutions are integrated at the subsystem level into advanced developments of products for civil and special purpose.

**Authors' contribution.** All authors equally contributed to the research work.

## REFERENCES

1. Du J.F., Fan X.J., Cao X.H., Li M., Zhu N.H., Li W. Transmission of dual-chirp microwave signal over fiber with suppression chromatic-dispersion-induced power-fading based on stimulated Brillouin scattering. *Opt. Commun*. 2022;508:127787. https://doi.org/10.1016/j.optcom.2021.127787
2. Mo Zh., Li R., Yang J., Dong J., Cao J., Li W. A photonics radar with remoting antenna based on photonic assisted signal generation and stretch processing. In: *2019 IEEE Radar Conference* (*RadarConf*). 2019. Accession Number: 18993737. https://doi.org/10.1109/RADAR.2019.8835512
3. Kashin V.A., Shurygina I.S. Synthesis of multibeam directivity patterns to improve performance of radar stations with an active phased antenna array. *J. Commun. Technol. Electron*. 2021;66(10):1155–1162. https://doi.org/10.1134/S1064226921100089
4. Bystrov R.P., Sokolov S.A., Cherepenin V.A. On the possibility of radio photonics technique in radar applications. *Zhurnal radioelektroniki = J. Radio Electronics*. 2017;6 (in Russ.). Available from URL: http://jre.cplire.ru/jre/jun17/3/text.pdf.
5. Golov N.A., Usachev V.A., Boev S.F., Savchenko V.P., Shulunov A.N., Zubarev Yu.B. Evolution of radiophotonics and prospects for its application in radar. In: *RTI Systems VKO 2017: Proceedings of the V All-Russian Scientific and Technical. Conf*. 2018. P. 292–320 (in Russ.).
6. Lee J.J., et al. Photonic wideband array antennas. *IEEE Transactions on Antennas and Propagation*. 1995;43(9):966–982. https://doi.org/10.1109/8.410214
7. Winnall S.T., Lindsay A.C., Knight G.A. A wide-band microwave photonic phase and frequency shifter. *IEEE Transactions on Microwave Theory and Techniques*. 1997;45(6):1003−1006. https://doi.org/10.1109/22.588620
8. Yao J. Microwave photonics. *J. Lightwave Technology*. 2009;27(3):314−335. https://doi.org/10.1109/JLT.2008.2009551
9. Unchenko I.V. Modular multi position digital radio frequency photonics system. In: *Youth and the Future of Aviation and Cosmonautics 2020*: *Collection of abstracts of competitive works. The 12th All-Russian Intersectoral Youth Competition of Scientific and Technical Works and Projects in the Field of Aviation and Rocket and Space Technologies*. 2020. P. 123 (in Russ.).
10. Emel'yanov A.A. Belkin M.E., Toporkov N.V., Masnoi V.A. The features of designing onboard fiber-optic syncronetwork. *Radiotekhnika = J. Radioengineering*. 2017;8:121–126 (in Russ.).
11. Voskresenskii D.I., Kotov Yu.V., Ovchinnikova E.V. Trends in the development of broadband phased antenna arrays (review). *Antenny = J. Antennas*. 2005;11(102):7–21 (in Russ.).
12. Wang F., Wang P., Zhang X., Li H., Himed B. An overview of parametric modeling and methods for radar target detection with limited data. In: *IEEE Access*. 2021;9:60459–60469. https://doi.org/10.1109/ACCESS.2021.3074063
13. Grigor'ev L.N. *Tsifrovoe formirovanie diagrammy napravlennosti v fazirovannykh antennykh reshetkakh* (*Digital Beam Forming in Phased Antenna Arrays*). Moscow: Radiotekhnika; 2010. 144 p. (in Russ.). ISBN 978-5-88070-243-5

## СПИСОК ЛИТЕРАТУРЫ

1. Du J.F., Fan X.J., Cao X.H., Li M., Zhu N.H., Li W. Transmission of dual-chirp microwave signal over fiber with suppression chromatic-dispersion-induced power-fading based on stimulated Brillouin scattering. *Opt. Commun*. 2022;508:127787. https://doi.org/10.1016/j.optcom.2021.127787
2. Mo Zh., Li R., Yang J., Dong J., Cao J., Li W. A photonics radar with remoting antenna based on photonic assisted signal generation and stretch processing. In: *2019 IEEE Radar Conference* (*RadarConf*). 2019. Accession Number: 18993737. https://doi.org/10.1109/RADAR.2019.8835512
3. Kashin V.A., Shurygina I.S. Synthesis of multibeam directivity patterns to improve performance of radar stations with an active phased antenna array. *J. Commun. Technol. Electron*. 2021;66(10):1155–1162. https://doi.org/10.1134/S1064226921100089
4. Быстров Р.П., Соколов С.А., Черепенин В.А. Системы и устройства на основе радиофотоники применительно к радиолокации. *Журнал радиоэлектроники*. 2017;6. URL: http://jre.cplire.ru/jre/jun17/3/text.pdf
5. Голов Н.А., Усачев В.А., Боев С.Ф., Савченко В.П., Шулунов А.Н., Зубарев Ю.Б. Эволюция радиофотоники и перспективы ее применения в радиолокации. *РТИ Системы ВКО – 2017: Труды V Всерос. научно-техн. конф*. 2018. С. 292–320.
6. Lee J.J., et al. Photonic wideband array antennas. *IEEE Transactions on Antennas and Propagation*. 1995;43(9):966–982. https://doi.org/10.1109/8.410214
7. Winnall S.T., Lindsay A.C., Knight G.A. A wide-band microwave photonic phase and frequency shifter. *IEEE Transactions on Microwave Theory and Techniques*. 1997;45(6):1003−1006. https://doi.org/10.1109/22.588620
8. Yao J. Microwave photonics. *J. Lightwave Technology*. 2009;27(3):314−335. https://doi.org/10.1109/JLT.2008.2009551
9. Унченко И.В. Модульная многопозиционная цифровая радиофотонная система. В сб.: *Молодежь и будущее авиации и космонавтики – 2020*: *Сборник аннотаций конкурсных работ. 12-й Всероссийский межотраслевой молодежный конкурс научно-технических работ и проектов в области авиационной и ракетно-космической техники и технологий*. 2020. 123 с.
10. Емельянов А.А. Белкин М.Е., Топорков Н.В., Масной В.А. Особенности построения бортовой волоконно-оптической синхросети. *Радиотехника*. 2017;8:121–126.
11. Воскресенский Д.И., Котов Ю.В., Овчинникова Е.В. Тенденции развития широкополосных фазированных антенных решеток (обзор работ). *Антенны*. 2005;11:7–21.
12. Wang F., Wang P., Zhang X., Li H., Himed B. An overview of parametric modeling and methods for radar target detection with limited data. In: *IEEE Access*. 2021;9:60459–60469. https://doi.org/10.1109/ACCESS.2021.3074063
13. Григорьев Л.Н. *Цифровое формирование диаграммы направленности в фазированных антенных решетках*. М.: Радиотехника; 2010. 144 с. ISBN 978-5-88070-243-5

14. Maltsev S.B., Shcherbakov M.V., Voitovych O.N., et al. Investigation and tuning procedure of Ka-band phased antenna array. *Radioelectron. Commun. Syst*. 2021;64(9):501–508. https://doi.org/10.3103/S0735272721090053
15. Legkiy N.M., Unchenko I.V. Formation of the direction diagram in phased antenna arrays. *Russian Technological Journal*. 2019;7(2):29–38 (in Russ). https://doi.org/10.32362/2500-316X-2019-7-2-29-38
16. Gross F.B. *Frontiers in Antennas: Next Generation Design & Engineering*. The McGraw-Hill Companies; 2011. 526 p.
17. Unchenko I.V. Diagram formation of active phased antenna arrays. *Sovremennye problemy sovershenstvovaniya raboty zheleznodorozhnogo transporta*. 2018;14:331–337 (in Russ.).

14. Maltsev S.B., Shcherbakov M.V., Voitovych O.N., et al. Investigation and tuning procedure of Ka-band phased antenna array. *Radioelectron. Commun. Syst*. 2021;64(9):501–508. https://doi.org/10.3103/S0735272721090053
15. Легкий Н.М., Унченко И.В. Формирование диаграммы направленности в фазированных антенных решетках. *Российский технологический журнал*. 2019;7(2):29–38. https://doi.org/10.32362/2500-316X-2019-7-2-29-38
16. Gross F.B. *Frontiers in Antennas: Next Generation Design & Engineering*. The McGraw-Hill Companies; 2011. 526 p.
17. Унченко И.В. Диаграммообразование активных фазированных антенных решеток. *Современные проблемы совершенствования работы железнодорожного транспорта*. 2018;14:331–337.

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