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RESEARCH ARTICLE

Investigation of the profilogram structure of microstrip microwave modules manufactured using additive 3D-printing technology

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Abstract
Objectives. The aim of the work is to study the surface roughness of the current-carrying topology and dielectric of the upper (Top Layer) and lower (Bottom Layer) sides of microwave modules manufactured using additive three-dimensional printing technology when prototyping prototypes of microwave modules on a 3D printer of DragonFly 2020 LDM multilayer printed circuit boards.
Methods. Methods of metallographic analysis in bright and dark fields, surface roughness profiling, and computer modeling were used.
Results. Experimental samples of microstrip microwave elements of modules of multilayer boards of a given configuration, telemetry sensors, printed circuit board (PCB) antennas were obtained. The topological and radiophysical features of the additively formed upper and lower surface layers of experimental samples of boards of strip modules were studied. Optical profilogram measurements of the roughness of the outer sides of the board were carried out at 10 points, amounting to 2 μm for the upper layer of the topology and 0.3 μm for the lower layer; the average grain size of the dielectric base was determined at 0.007 mm^2. The roughness of the conductive topology and upper side dielectric was shown to correspond to an accuracy class of 6–7, while the roughness of the microstrip conductive topology and the dielectric of the lower side of the board corresponds to an accuracy class of 10–12.
Conclusions. It is established that an uneven formation of the lower and upper strip layers of the printed module can affect the inhomogeneity of the distribution of radiophysical parameters (dielectric permittivity, surface conductivity, etc.), as well as the instability of the structural (adhesion ability, thermal conductivity, etc.) characteristics of the strip module, which must be taken into account when prototyping devices using inkjet 3D printing technology, including when adapting Gerber projects of PCB modules created for classical board production technology.

Keywords: 3D printing, microwave module, prototyping, additive technology, nanoink, microstrip sensors, microwave elements, multilayer printed circuit boards, radiophysical parameters, structural heterogeneity

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НАУЧНАЯ СТАТЬЯ

Исследование профилограммной структуры микрополосковых СВЧ-модулей, изготовленных по аддитивной технологии трехмерной печати

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Резюме
Цели. Целью работы является исследование шероховатости поверхности токонесущей топологии и диэлектрика верхней (Top Layer) и нижней (Bottom Layer) сторон СВЧ-модулей, изготовленных по аддитивной технологии трехмерной печати при прототипировании опытных образцов СВЧ-модулей на 3D-принтере многослойных печатных плат DragonFly 2020 LDM.
Методы. Использованы методы металлографического анализа в светлом и темном поле, профилографирование шероховатости поверхностей, компьютерное моделирование.
Результаты. Получены экспериментальные образцы микрополосковых СВЧ-элементов модулей многослойных плат заданной конфигурации, датчиков телеметрии, PCB-антенн (антенн на печатных платах). Исследованы топологические и радиофизические особенности аддитивно сформированных верхнего и нижнего поверхностных слоев экспериментальных образцов плат полосковых модулей. Проведены оптические профилограммные измерения шероховатости наружных сторон платы по 10 точкам, которые составили для верхнего слоя топологии – 2 мкм, для нижнего – 0.3 мкм, а также определен средний размер зерна диэлектрической основы – 0.007 мм^2. Показано, что шероховатость токопроводящей топологии и диэлектрика верхней стороны соответствует 6–7 классам точности. При этом шероховатость микрополосковой токопроводящей топологии и диэлектрика нижней стороны платы соответствует 10–12 классам точности.
Выводы. Установлено, что неравномерное формирование нижнего и верхнего полосковых слоев печатного модуля способно оказывать влияние на неоднородность распределения радиофизических параметров (диэлектрическую проницаемость, поверхностную проводимость и т.д.), а также на нестабильность конструктивных характеристик (адгезионной способности, теплопроводности и т.д.) полоскового модуля, что необходимо учитывать при прототипировании устройств по технологии струйной 3D-печати, в т.ч. при адаптации Gerber-проектов PCB-модулей, созданных под технологию классического производства плат.

Ключевые слова: 3D-печать, СВЧ-модуль, прототипирование, аддитивная технология, наночернила, микрополосковые датчики, СВЧ-элементы, многослойные печатные платы, радиофизические параметры, структурная неоднородность

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Авторы заявляют об отсутствии конфликта интересов.

INTRODUCTION

Additive 3D-printing technologies using homogeneous materials are constructively applied in various branches of science and technology to reduce the time involved in the pre-production prototyping of industrial products. High-precision printing techniques using polymers or powder metals for the prototyping of enclosures, parts, and assembly units used in radioelectronic products have been in operation for over 15 years. Having by now been sufficiently researched and systematically worked out, such 3D printing technologies are widely used by various companies of technological equipment and composites presented on the industrial market [1]. However, in the radioelectronic sector, industrial technologies for printed electronics appeared only in 2019 due to the need to solve technological problems related to the development of special materials collectively known as nanoink comprising a solution of nanoparticles in a dispersed medium [2]. Additive two-component printing solution requires the combined use of nanoink (conductive and dielectric) offering compatible radiophysical properties to provide printing with the required resolution and uniformity in terms of the distribution of the specified parameters in the multilayer structure of the printed module. The successful development and creation of suitable nanoink with low sintering temperature characteristics has opened a new direction of additive printed electronics in the radioelectronic industry [2–6]. Today, the rapid development of printed electronics used to solve various prototyping problems including in the field of microwave technology comprises a new layer of technological solutions used in rapid production processes. The possibility of printing device prototypes on multilayer printed circuit boards directly in design centers bypasses the need for third-party contract manufacturers, reducing the time needed to prototype and debug new designs. Modified versions produced as part of product debugging cycles require the cycle to be repeated, often several times, until the final circuitry and device layout are released. However, printing prototype production files directly in the design center on a 3D printer takes only a few hours, after which the prototype can be assembled and tested for performance, followed by making all necessary changes to repeat the cycle. Due to ongoing research and innovation in the field, the possibilities of printed electronics are constantly expanding. In particular, printed microwave electronics technology offers more flexibility to designers, allowing printed elements such as capacitors, transformers, antennas, radio frequency identification (RFID) tags to be printed on various substrates including flexible at an accuracy of a few microns on the board [7, 8]. Additive 3D technology is additionally used to protect the original product design and intellectual property from reverse engineering prior to its serial production at the production-technological level of development protection[1], [2] [9].

The aim of the present work is an experimental study of the standard modes of additive technology of three-dimensional printing of microwave electronics products and elements using a DragonFly (Nano Dimension, Israel) 3D printer to achieve optimal results in terms of the resultant uniformity of conducting and dielectric layers, as well as surface roughness topology of multilayer printed circuit boards microwave modules, which is important for ensuring the stability of radio physical parameters.

1. PRINTED RADIOELECTRONICS USING THE DRAGONFLY 3D PRINTER

Research was performed using DragonFly LDM 2020 3D-printer operating in the Radioelectronic Technologies megalaboratory cluster of the Institute of Radio Electronics and Informatics of RTU MIREA. This equipment represents a “minifab” or minifactory (Fig. 1), comprising an automated full-cycle system for manufacturing electronic devices by the additive two-component ink-jet printing method. Printing is performed by two ink-jet heads (conductive and dielectric) with subsequent layer-by-layer curing: infrared for conductive ink and UV system for dielectric ink. Although the setup can be used to print up to 55 circuit board layers for testing in laboratory conditions, the working area of printing inside the machine room of the system represents the actual technological limitation. The main characteristics and technological standards of radio electronics printing on 3D printer DragonFly LDM 2020 are shown in Table 1, as well as those relating to the conductive and dielectric ink.

Prototype samples of the printed boards with microwave element topology for studying the surface structure of the outer sides (layers) carried out according to the technology of printed radioelectronics are shown in Fig. 2 and in Fig. 3.

[1] Khesin S. The DragonFly 3D printer is a revolution in the manufacture of multilayer printed circuit boards. *Vektor Vysokikh Tekhnologii = The Hi-Tech Vector Research and Practice Journal*. 2018;4(39):38–41 (in Russ.). https://ostec-group.ru/upload/iblock/3fd/hesin.pdf. Available February 08, 2023.

[2] DragonFly LDM. Inks User Guide NanoDimension. Ness Ziona: Nano Dimension Technologies Ltd. 2020. 52 p. https://www.nano-di.com/ame-dragonfly-ldm-2-0. Available February 08, 2023.

Table 1. Technological capabilities of the DragonFly LDM 2020 3D printer

Process parameter	Parameter value/characteristic
Conductor/gap	100 µm
Minimum layer thickness	17 µm
Dielectric droplet diameter	3 µm
Droplet diameter of a current-conducting ink	0.4 µm
Number of layers	Up to 55
Minimum diameter of the metallized through holes	400 µm
Minimum diameter of the non-metallized through holes	400 µm
Minimum diameter of the transition holes	<200 µm
Maximum board dimensions	160 × 160 × 3 mm
Board printing time	From 3 to 20 h
Maximum soldering temperature	165°C
Conductive ink	AgCite 90072 Silver Nanoparticle Conductive Ink (Nano Dimension, Israel)
Dielectric ink	Dielectric Ink 1092 – Dielectric UV Curable Acrylates Ink (Nano Dimension, Israel)

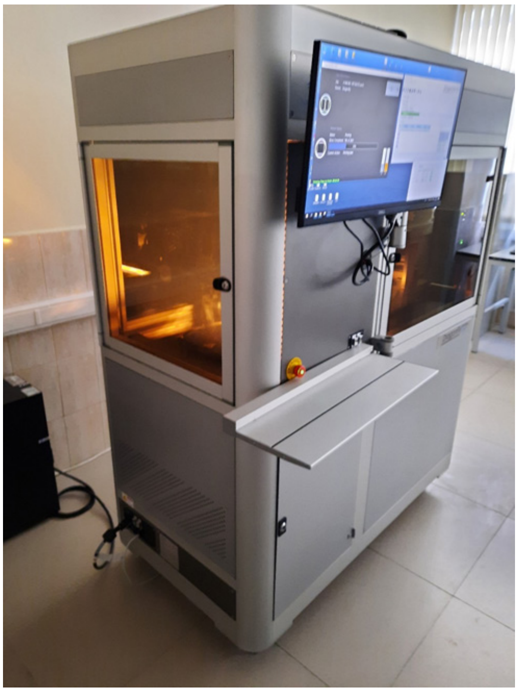


Fig. 1. DragonFly LDM 2020 3D printer operating in the Radioelectronic Technologies megalaboratory cluster at the Institute of Radio Electronics and Informatics of the RTU MIREA

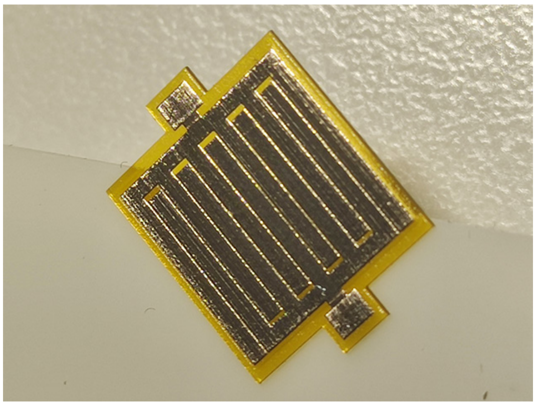


Fig. 2. Printed microwave sensor produced by RTU MIREA in the course of design research for Technopark of St. Petersburg

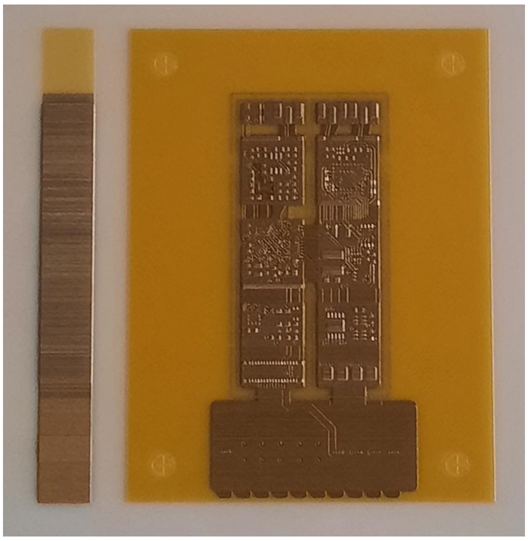


Fig. 3. Printed microwave module of a four-layer board for a global navigation satellite system manufactured by the RTU MIREA in the course of design work at the Technological Center Research and Production Complex (total thickness of the printed module – 0.123 mm)

As part of the technological cycle of additive 3D printing of a multilayer microstrip line board of a microwave module, its top layer (Top Layer side) and bottom layer (Bottom Layer side) are shown to be formed under different environmental conditions (contact/noncontact position of the sample topology formation). Unlike conventional multilayer printed circuit board technology having the same structure of copper traces and dielectric on both outer layers, the resultant surface roughness of the sides varies by an order of magnitude. This circumstance may affect design characteristics of the board (adhesion of the conductive layer to the dielectric, gas adsorption, residual mechanical stress, thermal properties, miscibility of solder on the adhesive conductive layer, etc.) and lead to the uneven distribution of its radiophysical parameters (surface resistivity, dielectric permittivity, impedance heterogeneity, signal delay, etc.), which must be taken into account when prototyping microwave modules implemented by technology of additive printed electronics.

Surface roughness, which determines the homogeneity of the structure of the conducting layer, is typically estimated by profile irregularities (Fig. 4), which are obtained by comparing the actual surface with a plane [5].

From the estimated parameters of the profilogram characteristic of the board roughness the following parameters are determined:

1. Average deviation of the profile R_{av}

$$R_{\text{av}} = \frac{1}{l}\int_0^l |y(x)|\,dx, \tag{1}$$

where l is the base length; y is the profile deviation; x is the horizontal coordinate.

With the discrete method of profile processing, the parameter R_{av} is calculated by the formula:

$$R_{\text{av}} = \frac{1}{n}\sum_{i=1}^{n} |y_i|, \tag{2}$$

where y_i are the measured profile deviations in discrete points; n is the number of measured discrete deviations on the base length.

2. Height of profile irregularities by ten points R_z.

$$R_z = \frac{\sum_{i=1}^{5}|y_{\text{p}i}| + \sum_{i=1}^{5}|y_{\text{v}i}|}{5}, \tag{3}$$

where $y_{\text{p}i}$ is the height of the ith highest protrusion of the profile; $y_{\text{v}i}$ is the depth of the ith lowest hollow of the profile.

3. The greatest height of profile curvature R_{max}.
4. The average pitch of the profile curvature S_{m}.
5. Average pitch of the local protrusions S.

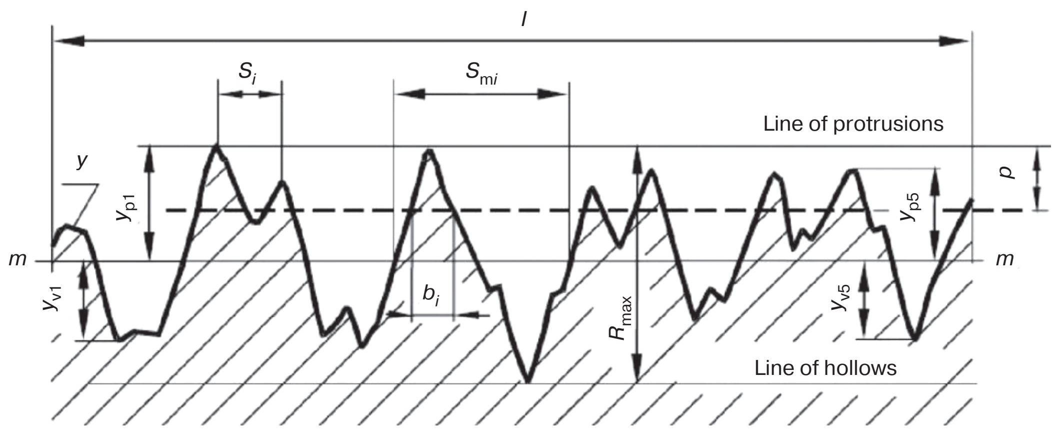


Fig. 4. Profilogram characteristics of the board roughness

6. Relative reference length of the profile t_p (where p are the values of the section level of the profile), determined by the formula:

$$t_p = \frac{1}{l}\left(\sum_{i=1}^{n} b_i\right) \cdot 100\%, \quad (4)$$

where $\sum_{i=1}^{n} b_i$ is the reference length of the profile; b_i is the components of the reference length.

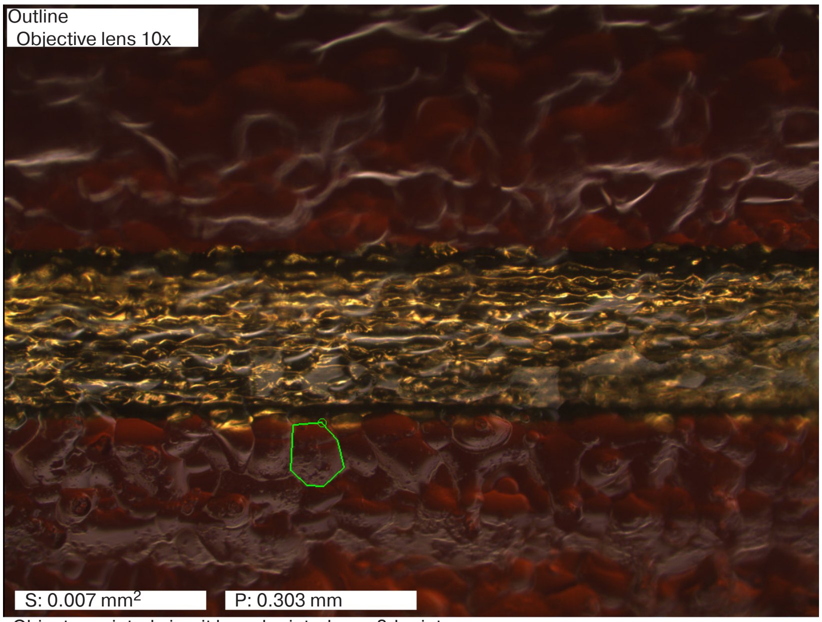
When combined, the calculated formulas (1)–(4) allow the profilogram characteristics of the microstrip line structure of the microwave module to be further estimated.

2. RESEARCH OF THE PROFILOGRAM STRUCTURE OF THE OUTER LAYERS OF A MULTILAYER PRINTED CIRCUIT BOARD OF MICROWAVE MODULES

The top side (Top Layer) of a multilayer printed circuit board of a microwave module is formed by additive printing on the previous layer. The outer layer is printed with nanoink, which solidifies when coming into contact with the air environment. In this process mode, the top layer has a much higher surface roughness and granularity than the bottom layer. Figure 5 shows a two-dimensional microvision profilogram of the top layer of a prototype printed microwave module board (Fig. 3) with measurement of the grain size of the dielectric layer.

The surface structure study and measurements were carried out using a dark-field technique on a µVizo-MET-221 microimager (LOMO, Russia). The significant dielectric part grain area, which, as shown on the microvision image of the fragment, is on average 0.007 mm^2 or more, is caused by printing the layer with nanoparticles with their further baking by the curing system. The surface roughness was measured by changing the sharpness between the protrusion and the depression according to the two-dimensional profilogram obtained by the optical method from the microscope; here the focal difference between the sharpness is the depth of the measured groove. The measurements were carried out at ten points of the fragment of the upper side of the multilayer printed circuit board presented in the profilogram (Fig. 6). The measured roughness of the upper side is 2 µm.

The bottom layer is additively formed on a smooth single-use mylar substrate placed on a vacuum stage. Although other layers will be added to the underside during printing, only the bottom layer is directly physically printed on the smooth substrate, reducing the roughness by an order of magnitude compared to the top layer. Measurements were made at ten points on the roughness of the underside using a similar technique, and a profilogram is shown in Fig. 7. The measured roughness of the underside is 0.3 µm.



Object: a printed circuit board printed on a 3d printer
File: ____612M.bmp Date: 27.03.2022 15:23:57
Number: XT0044 Operator: Dmitry Sergeevich Vorunichev
Comment: DRAGON FLY
Brightness: 412.4 Contrast: –1 Hardness: 0 Objective lens: 10x Scale: x10
Density: 0 Background: 0 Multiplication factor: 1.00 Shade: 0

Fig. 5. Fragment of a printed circuit board of a microwave module prototype with superimposed measurement of dielectric grain size (in the center—conductor printed with conductive ink; the remainder—dielectric part printed with dielectric ink)

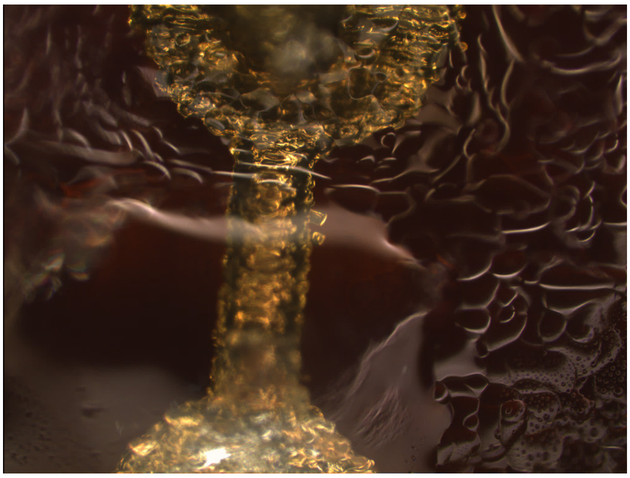


Fig. 6. Profilogram of the top side of the printed microwave module sample board

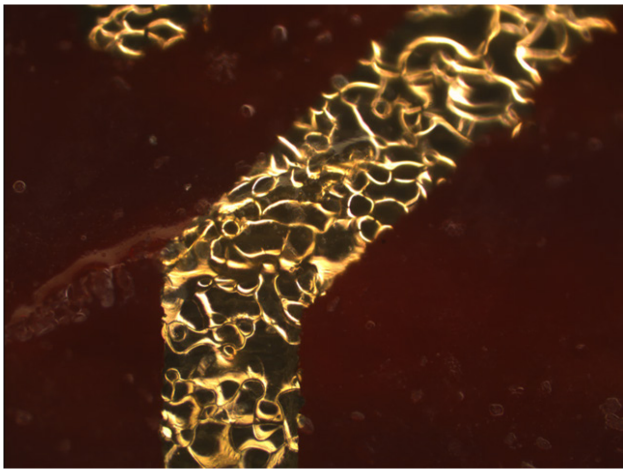


Fig. 7. Profilogram of the underside of the printed microwave module sample board

Using a software profilograph (Mitutoyo, Japan), we built profilograms of the top and undersides of the multilayer board of the microwave module sample for the conductive and dielectric structural layers. The results of fragmentary measurements of the microstrip line profilograms of the conductive topology and dielectric base of the prototype samples are shown in the Table 2.

The results of the profilograph measurements correspond to the optical measurements by the microvisor and are as follows:

- Top Layer: roughness of the microstrip line element (conductive layer of the printing topology) R_{av} = 1.6–2.1 (6–7 grade), dielectric roughness R_{av} = 1.7–1.8 (6–7 grades);
- Bottom Layer: roughness of the microstrip line element (conductive layer of the printing topology) R_{av} = 0.04–0.12 (10–12 grade), dielectric roughness R_{av} = 0.03–0.08 (11–12 grades).

When using an additive technology, the irregular profilogram formation of the lower and upper strip layers of a microwave module determines the regularity of the internal material structure, which can impact on the non-uniformity of the distribution of the radiophysical parameters (dielectric permittivity, surface conductivity, microstrip line impedance characteristic, signal delay, etc.)[3] [9–14], as well as on the stability of the structural characteristics of the strip module (adhesion of the conductive layer with the dielectric, gas adsorption, residual mechanical stress, thermal properties, solder miscibility on the adhesive conductive layer, etc.). This should be taken into account when prototyping devices

[3] DragonFly LDM. Inks User Guide NanoDimension. Ness Ziona: Nano Dimension Technologies Ltd. 2020. 52 p. https://www.nano-di.com/ame-dragonfly-ldm-2-0. Available February 08, 2023.

Table 2. Profilogram characteristics of the printing topology elements (fragments) of multilayer printed circuit board of the microwave module prototype

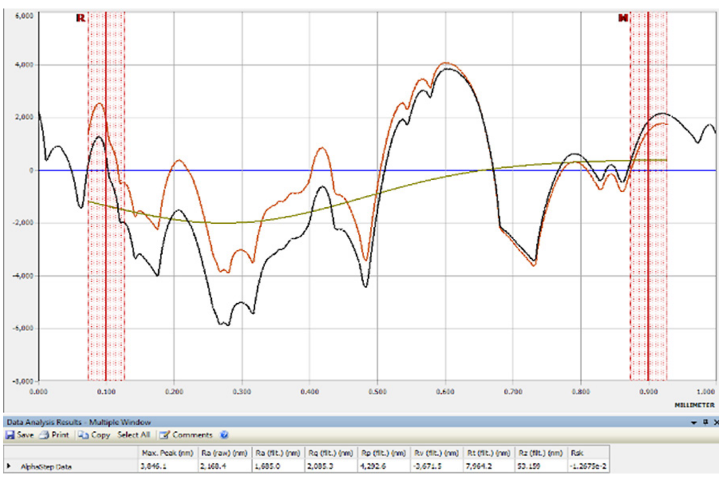
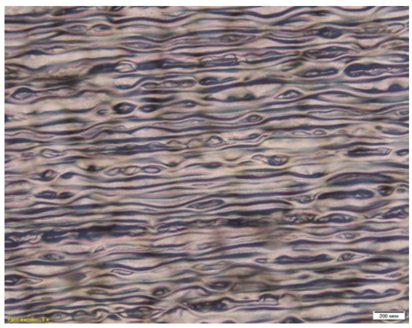
<table>
<tr><th colspan="3">Upper side (Top Layer)</th></tr>
<tr><td>Microstrip line element, multiple magnification ×5</td><td>
</td><td></td></tr>
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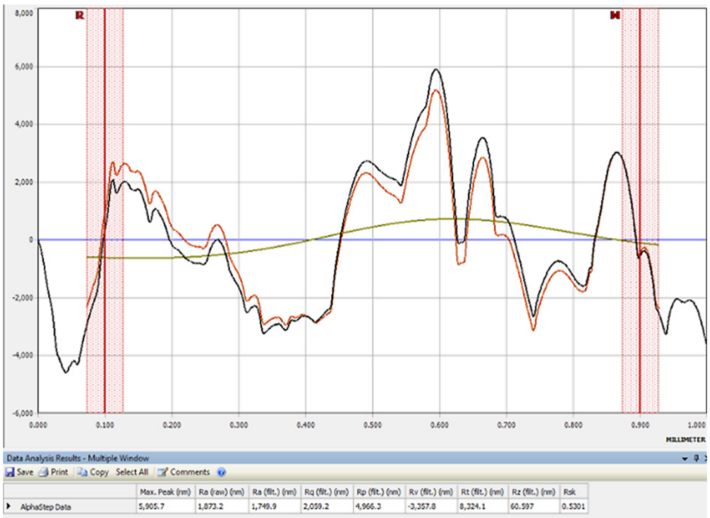
Table 2. Continued

<table>
<tr><th colspan="3">Upper side (Top Layer)</th></tr>
<tr><td>Dielectric, multiple magnification ×5</td><td>



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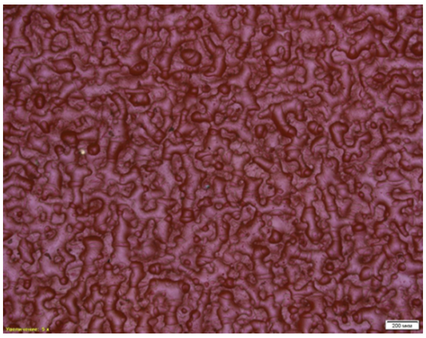
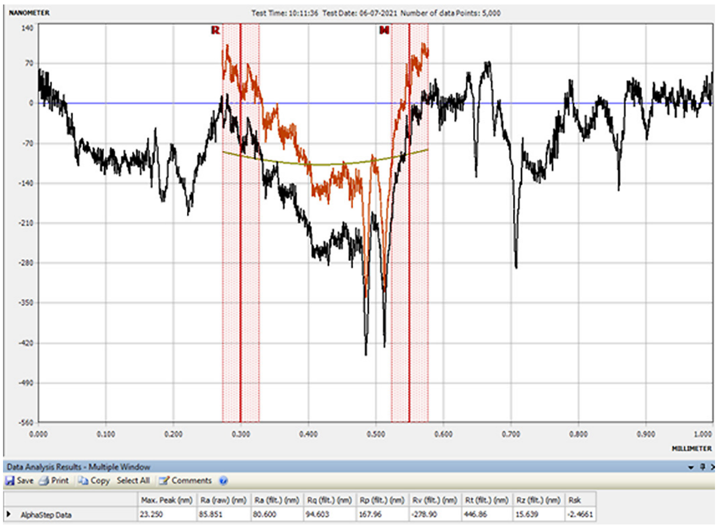


</td></tr>
<tr><th colspan="3">Underside (Bottom Layer)</th></tr>
<tr><td>Microstrip line element, multiple magnification ×20</td><td>



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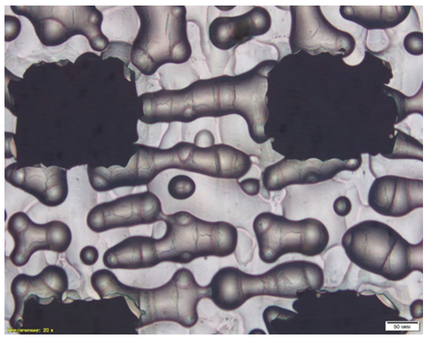
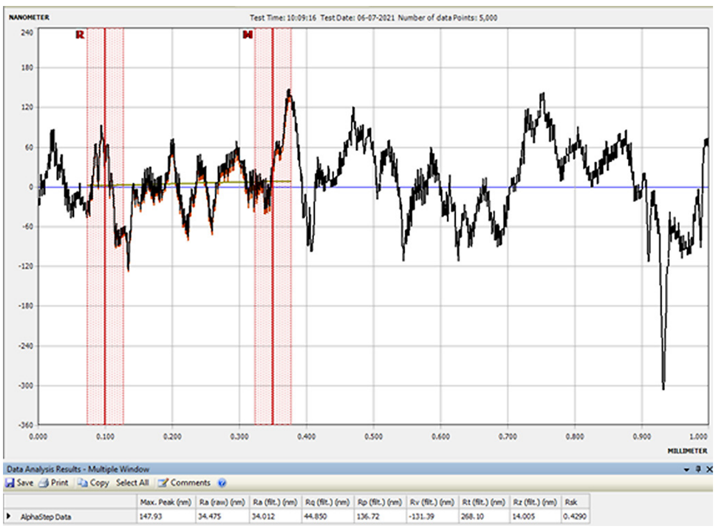


</td></tr>
<tr><th colspan="3">Underside (Bottom Layer)</th></tr>
<tr><td>Dielectric, multiple magnification ×20</td><td>



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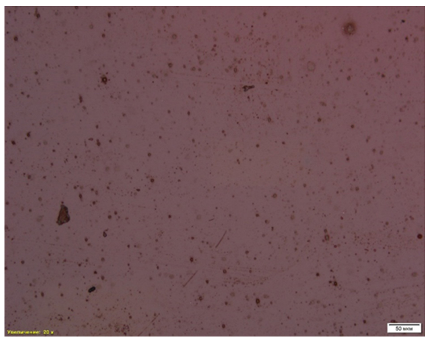

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</table>

using additive 3D printing technology, including the adaptation of the Gerber-projects[4] of PCB-modules created for classic board production technology.

CONCLUSIONS

Topological and radiophysical features of additively formed upper and lower surface layers of experimental samples of strip-module boards were investigated using the DragonFly LDM 2020 3D printer. Optical profilogram measurements of the roughness of the outer sides of the board in the dark field were caried out on a metallographic microscope µVizo-MET-221 along with a profilograph used to construct the corresponding characteristics.

The conducted research of the prototypes showed a significant difference in surface roughness: in microvision measurements, upper side—2 µm, lower side—0.3 µm; in profilograph measurements, upper side—1.8 µm, lower side—0.1 µm. This parameter can influence the structural, technological, and electrical characteristics of the product. The average grain size of the dielectric part—0.007 mm^2—was determined along with the reasons for the difference in the roughness of the sides.

The results of the implemented research into side roughness and profilograms of the multilayer printed circuit boards can be used in the design of microstrip line products manufactured by printed electronics, as well as to develop solutions for improving the technology in order to compare the characteristics of the vector analysis of structural heterogeneity with the topology of prototypes of microwave modules.

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

[4] Gerber-format files for PCB modules production.

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