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Laser technologies used in manufacture of components of vacuum millimeter-wave electronic devices

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The study outlines the micro-dimensional structures fabricated for the vacuum millimeter waveband electronics devices using micro-processing with nanosecond laser pulses. The specifics of laser cutting technology for thin plates made of various materials (copper, molybdenum) are discussed. The mockups of rectangular W-band (75−110 GHz) waveguides and decelerating V-band (50−65 GHz) systems were fabricated. The results of morphological analysis and experimental investigation of S-parameters of the fabricated samples are described. The design of a micro-sized electron gun has been developed, and the results of its components (cathode, focusing electrodes) fabrication are presented.

Keywords: laser micro-processing, traveling wave tube, decelerating system, electron gun, rectangular waveguide.

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Introduction

In recent years, the short-wave part of the millimeter waveband has been actively developed for various applications, primarily for wireless information and telecommunication systems [1–3]. Such applications require coherent radiation sources providing output power of 10−100 W at frequencies 0.1 THz and higher. Similar characteristics can be achieved using vacuum electronic devices [4–6]. Of particular interest are such devices as traveling wave tubes (TWT) and backward-wave tubes (BWT). However, the components of such devices (electron-optical systems, electrodynamic systems, etc.) are difficult to fabricate, since the characteristic dimensions of the structures are on the order of hundreds of microns or less. This task requires the use of modern micro-processing technologies. Photolithography and its modifications (e.g., LIGA technology), deep reactive ion etching, precision micro-milling, and electric spark treatment have become the most commonly used technologies (see, for example, [6–10]). However, they also have a number of disadvantages, in particular, high cost, labor intensity and long duration of the process, in some cases the need to use aggressive chemicals.

Previously, we had developed a technology for manufacturing the micro-size electrodynamic structures based on laser ablation with nano- and picosecond pulses (see, for example, [8,11–13]). Its benefits include high production speed (a full manufacturing cycle can take less than one working day), low cost, as well as flexibility in terms of rapid changes to the design of the fabricated structures. This technology was used, in particular, to develop and manufacture planar microstrip periodic deceleration systems (DS) on dielectric substrates in the short-wavelength millimeter band (up to 170 GHz) [11–13]. An experimental study of their electrodynamic characteristics has shown that they have low transmission and reflection losses. Thus, DS systems of V-band had an attenuation 0.17−0.39 dB by the structure period, reflection coefficient below −10 dB within the frequency range of 45−70 GHz and less than dB in the bandwidth of 15 GHz [13]. Such parameters make them promising for use in miniature low-voltage TWT. The planar design obviously contributes to a miniaturization of the device's transverse dimensions, while the high deceleration coefficient allows operation at low accelerating stresses, which leads to a decrease in the longitudinal size.

However, DS on dielectric substrates also have certain disadvantages associated with possible destruction of thin-film (units of microns) metal coatings and deposition of an electron beam onto a dielectric substrate. In this regard, designs of all-metal electrodynamic structures as a composite package of metal plates have been proposed [14], free from the mentioned drawbacks. In this paper, the possibilities of fabricating such structures using laser micro-processing are investigated. The paper gives an insight on fabrication of regular rectangular waveguides and periodic DS in the millimeter-wave band. Also, the paper describes the results of manufacturing the micro-sized electron gun components (cathode, focusing electrode).

1. Manufacturing process

Two systems of precision laser mcro-processing were used in this study. To fabricate the structures as a composite package of oxygen-free copper plates 150 μm thick a laser setup MicroSET RA (OOO „Lazerny tsentr", Russia) based on ytterbium pulse fiber laser IPG-Photonics (NTO „IRE−Polus", Russia) with a 1064 nm wavelength was used. The laser beam was focused into a spot with a diameter of $20-25\,\mu$m. The positioning accuracy was $1-2\,\mu$m. At the first stage, a precise channel was formed on the surface of the copper plate, forming the contour of the structure. For this, a „delicate" mode of laser micro-processing was used with the following parameters: pulse duration no more than 8 ns, pulse energy no more than 80 mJ, pulse repetition rate and frequency no more than 4 mm/s and 20 kHz, respectively. This mode allows reducing the material overlaps and form a more even edge of the ablation zone. Next, the structure was cut out of the copper plate through the formed channel. In this case, the pulse duration and pulse energy can be increased to 14 ns and 135 mJ, respectively.

Further, the fabricated plates were subjected to post-treatment in order to clean the surface, remove metal oxides and other contaminants, as well as reduce surface roughness. The post-treatment consisted of dry cleaning and laser resurfacing. Dry cleaning was carried out using an ultrasonic bath and chemical reagents. First, the samples were placed in an orthophosphoric acid solution. At this step, the oxides and material overlaps formed during the cutting process were removed. This was followed by the treatment of structures in an alkaline solution of sodium bicarbonate, which neutralized the remnants of orthophosphoric acid and removed organic pollutants. Next, the samples were washed in deionized water, which ensured the removal of chemical residues. Finally, the structures were soaked in isopropyl alcohol. Due to this, the surface of the structures was degreased and their drying was accelerated, which helped to minimize the formation of oxide films on the surface.

After dry cleaning, to smooth out the edge irregularities, the side walls of the structure were gently polished by laser: pulse duration no more than 4 ns, pulse energy no more than 28 mJ, laser beam travel speed no more than 800 mm/s, pulse repetition frequency no more than 200 kHz. After that, all the steps of chemical cleaning were repeated.

Subsequent electroplating of the mockup with copper was possible in order to reduce ohmic losses.

To fabricate the structures made of $(200-400\,\mu\text{m})$ thick copper plates and molybdenum plates the laser setup BY-100GS was used based on ytterbium pulse fiber laser JPT YDFLP-E-100-M7-M-R (China) with the wavelength of 1064 nm, average radiation power up to 100 W, energy of pulse up to 2 mJ. The laser beam was focused into a spot with diameter of $\sim 22\,\mu$m, positioning accuracy was $1-2\,\mu$m, treated area — 50×50 mm.

For processing molybdenum plates with a thickness of 150 μm, a special metal clip-frame was used as a tool, which allows stretching the sheet of material in the treated area. The burst-mode processing mode was mainly used with the following parameters: there were 14 pulses in one burst, the average radiation power was 70 W, pulse repetition rate was 45 kHz, pulse duration was 500 ns, pulse repetition period was ~ 2 ms, step between bursts was 15 μm. When processing thicker pieces, the power was increased to 80 W, and the number of pulses per train was also increased to 30.

The most labor-intensive process is fabrication of periodic DS, which have a complex shape, including sections in the form of thin (less than 100 μm) slits(section 2). During the experiments, it was found that such sections need to be milled with multiple laser passes with a reduced step (9 μm or less). To reduce the side effects caused by thermal expansion of the material, which inevitably occur when processing such small objects, a stream of cold air was supplied to the treatment area through a special nozzle. The basic process mode described above was used to cut out the remaining structural elements of the DS. After laser processing, mechanical grinding was used to remove the products of laser processing from the metal surface, as well as chemical treatment.

2. Results and discussion

2.1. W-band waveguide

Mockup of a rectangular waveguide with a cross-section of 2.54×1.3 mm was fabricated using MicroSET RA tool. These dimensions are close to the cross-section of the standard WR-10 waveguide, however, the height of the waveguide differs slightly from the standard one (1.27 mm), since the structure is made of plates with a thickness of 150 μm. The design includes fifteen plates: nine form the side walls, and the remaining six form the upper and lower parts, in which holes are provided for assembly and alignment. The package plates were positioned between each other using cylindrical mounting pins. The positioning accuracy was ensured by selecting the diameter of the pins, which were measured with an accurate micrometer that had passed metrological certification. The package of plates was then assembled using mechanical fastening with screws. In the future, laser soldering and welding are expected to be used to create a vacuum-dense package.

The mockup assembly is shown in Fig. 1, *a*. The mockup transverse dimensions are 2.54×2.25 mm; and

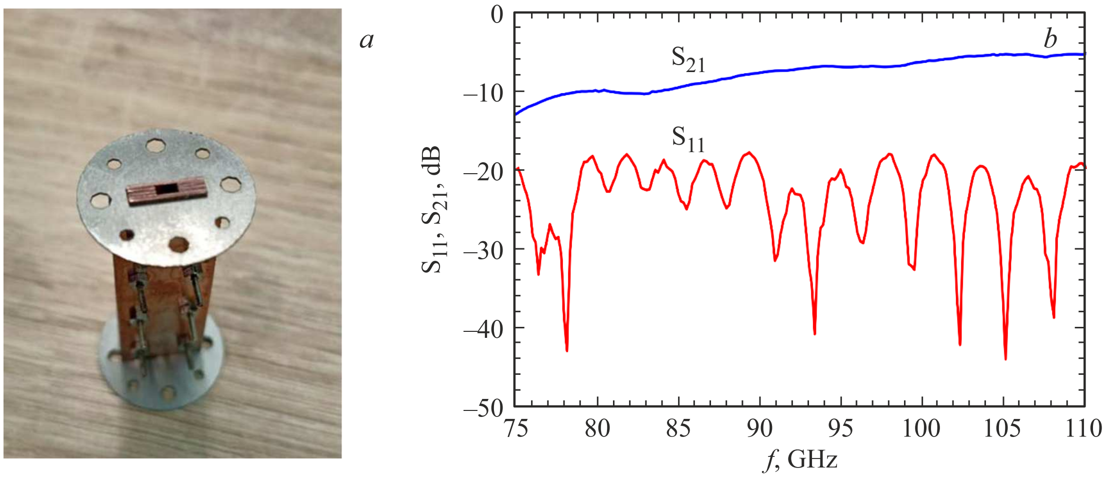

Figure 1. Mockup of a rectangular waveguide assembly with flanges (*a*) and experimental curves of S-parameters versus frequency f (*b*).

its longitudinal length is 42 mm. To integrate with the measuring stand, a mounting flange plate was made from 400 μm thick molybdenum sheets, for which laser microprocessing was also used.

An experimental study of S-parameters of the fabricated W-band mockups was carried out using a ZVA40 vector circuit analyzer and two ZVA-Z110 frequency converters (Rohde–Schwarz, Germany), which convert the analyzer frequency range into 75−110 GHz range. The measurements showed the reflection coefficient no more than −17 dB and a decay from −5 to −10 dB (Fig. 1, *b*).

2.2. Layout of a rectangular W-band waveguide with turns

The fabricated mockup is a composite package of molybdenum plates with a thickness of 150 μm: 13 plates form a central portion of the waveguide, 17 — inlet and outlet waveguides. The plates also have openings for alignment and further assembly.

Measurements of S-parameters of the fabricated waveguide mockup were carried out on the setup mentioned above based on ZVA40 vector circuit analyzer (Rohde–Schwarz). A photo of the measuring setup with a waveguide is shown in Fig. 2, *b*, and the measurement results are shown in Fig. 2, *c*. The cutoff frequency was $\sim$ 76 GHz, which was in good agreement with the calculated value. Reflection losses did not exceed dB in the frequency band of 77−90 GHz, which also perfectly matched the computational modeling data. The relatively high values of transmission losses (about −10 dB) were caused by insufficiently tight fit of the plates to each other and roughness of the waveguide walls surface. To reduce losses, it is further assumed that the walls of the waveguide will be coated with copper and the plates package will be soldered.

2.3. V-band decelerating system

After testing the technology using rectangular waveguides as an example, we started fabricating the periodic decelerating structures. As a specific example, a ladder-type DS with dumbbell-shaped slits was chosen, proposed in [15]. The scheme of DS period is shown in Fig. 3, *a*. It is important to note that this DS demonstrates the properties of a doubly negative metamaterial. Such structures are of interest from the miniaturization standpoint, as well as in terms of their wide capabilities in control of dispersion characteristics [16,17]. As seen from the computer modeling, this DS may serve the basis for fabrication of a TWT of middle and short parts of the millimeter-wave band with an output power of up to 100 W and an amplified frequency band of over 5 GHz jcite15.

The design of V-band DS with the following dimensions has been developed and optimized: $a = 400\,\mu$m, $b = 650\,\mu$m, $l = 70\,\mu$m, $w = 550\,\mu$m, $p = 800\,\mu$m. The central plate of DS was placed in the waveguide with a section of 1.0×1.0 mm.

A series of V-band decelerating structures made of copper and molybdenum plates of various thickness 200−400 μm was fabricated (Fig. 3, *b*). Each structure contained 18 dumbbell-shaped slits and had matching elements in the form of pins with a length of 725 μm and a width of 200 μm at the ends.

The fabricated structures were analyzed using the atomic-force microscope Olympus MX51 (Japan). The measurement results are shown in the table below (the symbols used are explained in Fig. 3, *a*). As can be seen from the table, the fabricating accuracy is quite high. The deviation from the design values generally does not exceed 10−20 μm, i.e. about the diameter of the laser spot (except for the gap width w, for which it is about twice as large). As noted above, the greatest difficulty was fabrication of a miniature gap. Accordingly, the highest relative measurement error (above 20 %) is observed for its length l. The fabricated

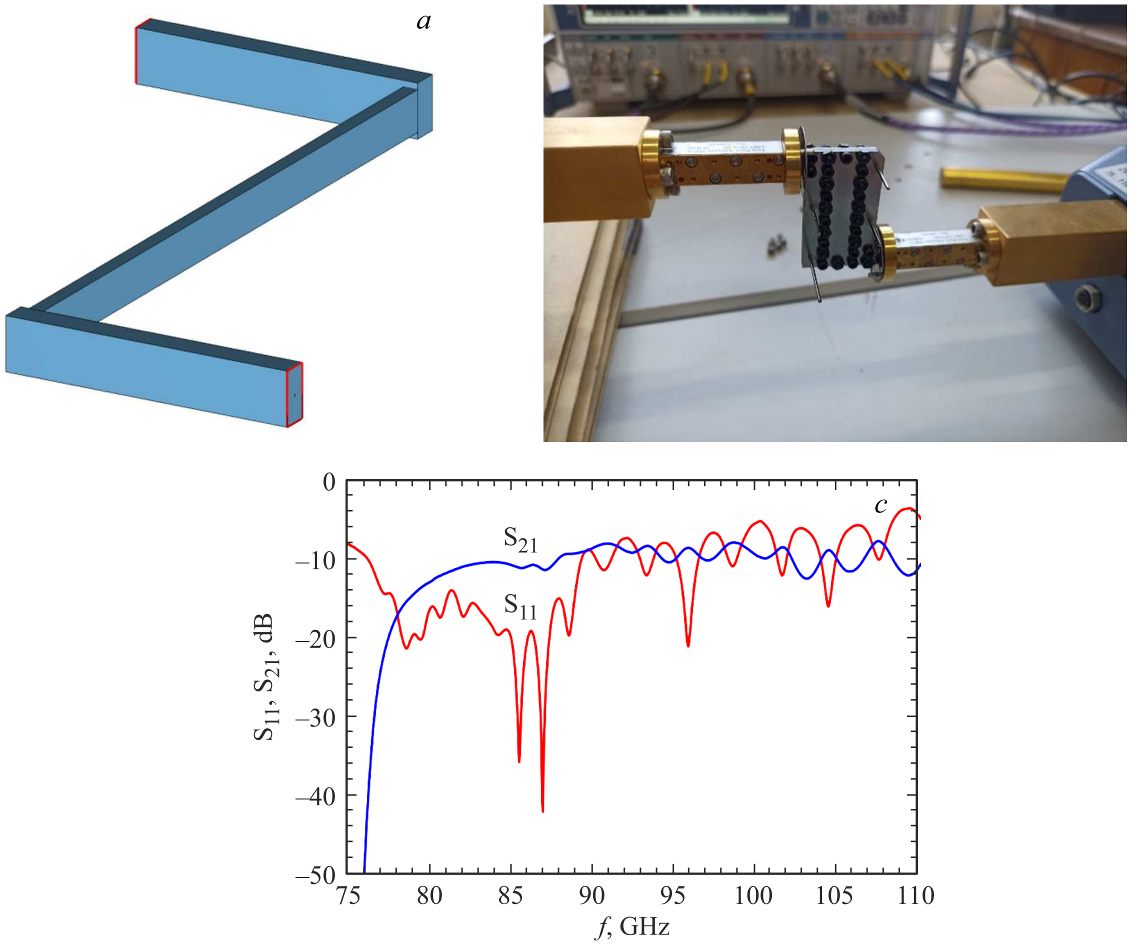

Figure 2. 3D-model of a rectangular waveguide with bends (a), photo of the measuring setup (b) and experimental curves of S-parameters versus frequency (c).

structures are quite homogeneous: the spread of parameter values for each of the structures is no more than 5 μm. In the future, the fabrication accuracy can be improved by adjusting the operating modes of the laser system.

It should be noted that the fabricated samples have a small cross-section taper, which was determined by comparing the sizes of the slits on the front and back surfaces of the processed plates. Copper plates had a taper less than 3°, molybdenum plates — around 1°.

To measure S-parameters, special measuring setup was used, fabricated using 3D-printing from heat-resistant photopolymer resin and subsequent metallization by magnetron sputtering [18]. The setup contains a longitudinal groove for the installation of DS and matching transitions to WR-15 waveguide path. Fig. 3, c illustrates a photo of DS in the setup.

Figure 4 shows the results of measurements of the DS electrodynamic characteristics. To carry out the measurements the chains vector analyzer PNA N5227A Keysight Technologies (USA) was used. The best results were obtained for the DS made of a copper plate with a thickness of 400 μm. Because the setup dimensions didn't match the design values, it was not possible to ensure good alignment, as a result of which the wave has a pronounced resonance (Fig. 4, a). Nevertheless, despite sufficiently strong reflections, the transmission losses did not exceed −10 dB, and the measured bandwidth of the DS was in good agreement with the calculated data.

Also, based on the frequency dependence of the phase of S_{21} parameter, the structure's dispersion curve was plotted using a well-known technique described, for example, in [19–21]. As can be seen from Fig. 4, b, the experimental measurements are in good agreement with the calculated dispersion characteristic after adjusting the DS size in accordance with the results of microscopic analysis (see the table).

2.4. Electron gun components

The developed laser micro-processing technology has been used to fabricate not only high-frequency electrodynamic structures, but also electronic gun components. A structure shown in Fig. 5 was developed. The gun contains a cathode with a diameter of 1.26 mm, a focusing electrode located under the cathode potential, and an

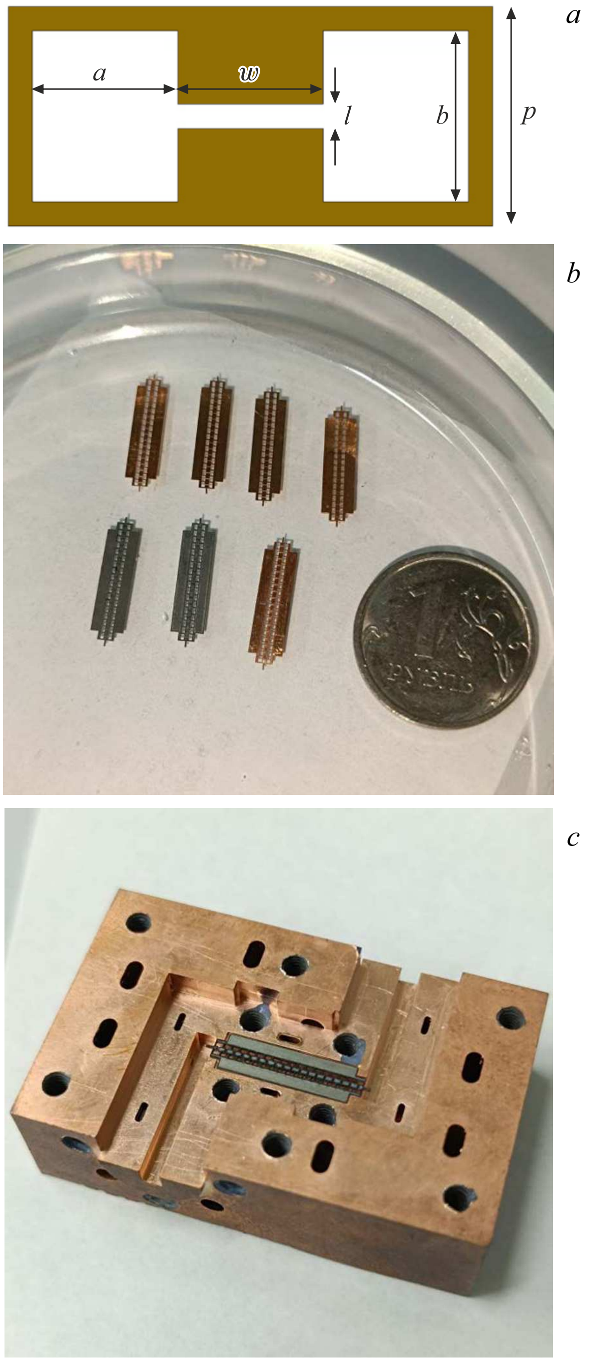

Figure 3. A diagram of one period of a ladder-type DS with dumbbell-shaped slits (a), photos of the fabricated DS (b) and a photo of one of DS mockups in the measuring setup (c).

anode. The focusing electrode consists of several parallel plates (diaphragms) with holes of various diameters. By selecting the hole diameters appropriately, it is possible to approximate the complex curved shape of the focusing electrode. Computational modelling has shown that three $200\,\mu$m thick plates to focus the beam were enough. The anode has round inlet and outlet holes with diameters of 0.54 and 0.33 mm, respectively.

The electron gun was simulated using COMSOL Multiphysics software. The model of thermal electron emission was used, whereas the work function was $\varphi = 2.055$ eV, and cathode temperature was $T = 1473$ K. Such values were chosen based on the experimental study of an electron gun outlined in [22]. The current-voltage curve of the electron gun was plotted at various anode voltages up to 15 kV. At such voltages, the beam passes through the anode hole, and in the anode voltages of 10–15 kV, the beam current is 80–150 mA. Figure 5 illustrates the beam formation at an operating voltage of 12.4kV. The diameter of the anode outlet beam is $260\,\mu$m. The average current density along the beam cross-section at the outlet of the electron gun is approximately $200\,A/cm^2$ with a current density at the cathode of $8\,A/cm^2$. The beam compression over the area makes about 25 units. Such values meet the requirements for use in miniature millimeter-wave band TWT.

The cathodes were made from lanthanum hexaboride LaB_6 tablets with a diameter of 3 mm. Each cathode included a rectangular base and a cylindrical emission protrusion, which ensured integration into the assembly of the electron gun. Previously, using BY-60GS laser system based on the ytterbium pulsed fiber laser JPT YDFLP-E-60-M7-M-R with a power of up to 60 W, a cross-piece blank was cut out of the tablet. Subsequent high-precision micro-processing of the cathode protrusions was carried out using a 20W setup MicroSET RA. A photo of the workpiece with a cathode protrusion is shown in Fig. 6. After the protrusions were formed, the workpiece was divided into four separate cathodes.

The diaphragms forming the focusing electrode, mounting elements in the form of plate holders and the cathode heater were made of molybdenum plates with a thickness of $200\,\mu$m (Fig. 7, a) using MicroSET RA setup. Micro-sized grooves were used to connect the holders to the focusing electrodes, which made it possible to precisely connect the parts. The use of laser cutting technology makes it possible to produce a series of identical electrodes with minimal size variation. The pilot model of the focusing electrode assembly is shown in Fig 7, b. At the next stage, experimental studies of the current-voltage curves of the electronic gun and the focusing processes of the electron beam are planned.

Conclusion

The problem of the microwave vacuum devices miniaturization is a key issue in transition to the shortwave part of the millimeter-wave band. This paper demonstrates the possibilities of using nanosecond pulse laser micro-processing technology for the fabrication of miniature electrodynamic structures in the millimeter band. The advantages of this technology include relative simplicity of the process route, versatility, low cost and high fabrication rate.

Dimensions of V-band DS with dumbbell-shaped slits according to optical microscopy data

№	a, μm	b, μm	l, μm	w, μm	p, μm
Copper, 200 μm					
1	399.40 ± 3.48	653.83 ± 4.70	87.74 ± 2.52	506.01 ± 3.09	780.34 ± 1.46
2	401.06 ± 1.98	655.29 ± 2.56	89.14 ± 1.83	508.00 ± 2.56	783.37 ± 1.65
3	403.04 ± 2.67	652.72 ± 2.63	85.93 ± 2.12	507.76 ± 1.92	783.70 ± 1.95
Copper, 400 μm					
1	398.71 ± 4.79	652.41 ± 2.47	85.53 ± 4.38	504.20 ± 4.28	784.08 ± 2.14
2	396.97 ± 3.15	649.38 ± 4.55	79.42 ± 4.08	512.58 ± 5.47	785.20 ± 1.69
Molybdenum, 400 μm					
1	393.38 ± 2.99	646.01 ± 4.19	84.71 ± 1.91	514.46 ± 2.45	784.97 ± 2.22
2	405.54 ± 3.89	660.33 ± 3.22	87.81 ± 3.14	504.57 ± 4.46	782.10 ± 3.24

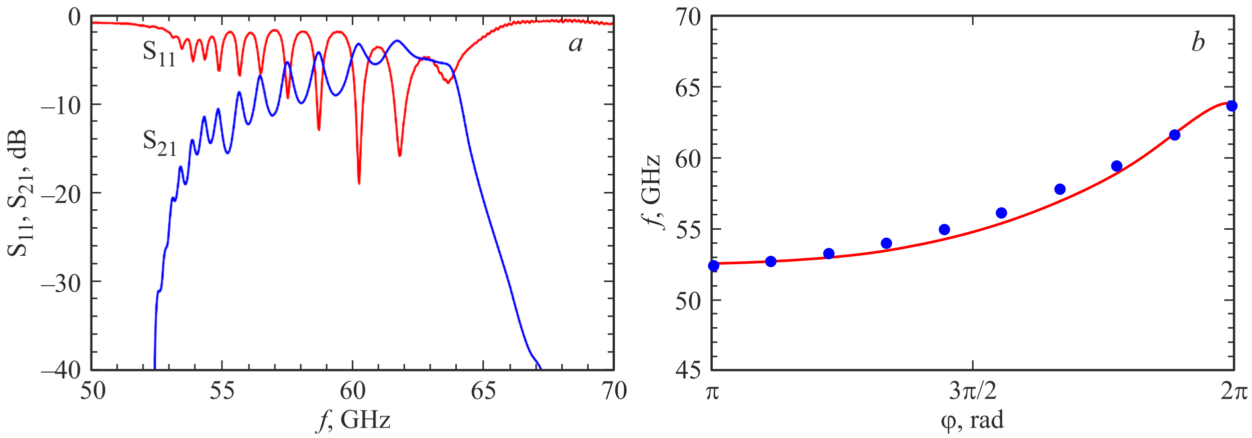

Figure 4. S-parameters (a) versus frequency; experimental (circles) and calculated (solid lines) dispersion characteristics of DS (b).

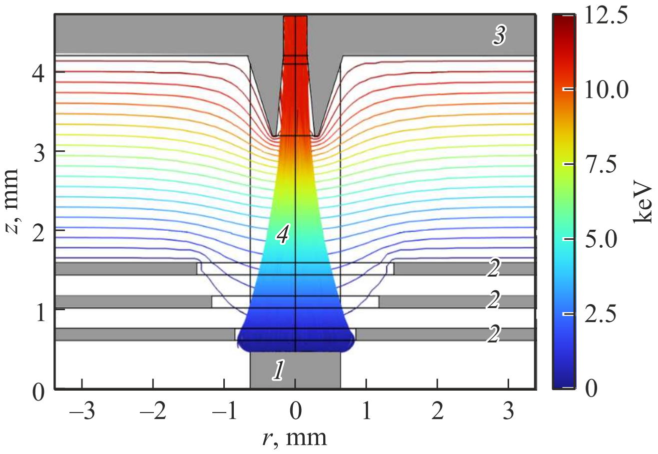

Figure 5. Electron beam formation pattern and distribution of electrostatic potential in the electron gun at an accelerating voltage of 12.4 kV: *1* — cathode, *2* —focusing electrodes, *3* — anode, *4* — electron beam.

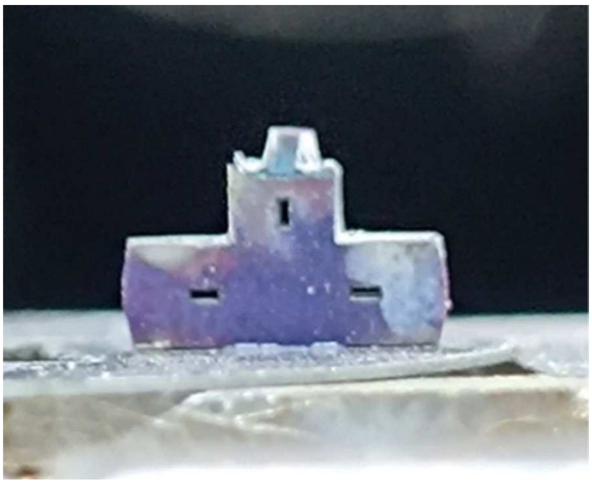

Figure 6. Photo of a crosspiece blank with a cathode protrusion on it.

Models of rectangular W-band waveguides were made in the form of composite packages made of copper and molybdenum plates with a thickness of 150 μm. The measurements of their S-parameters showed values of

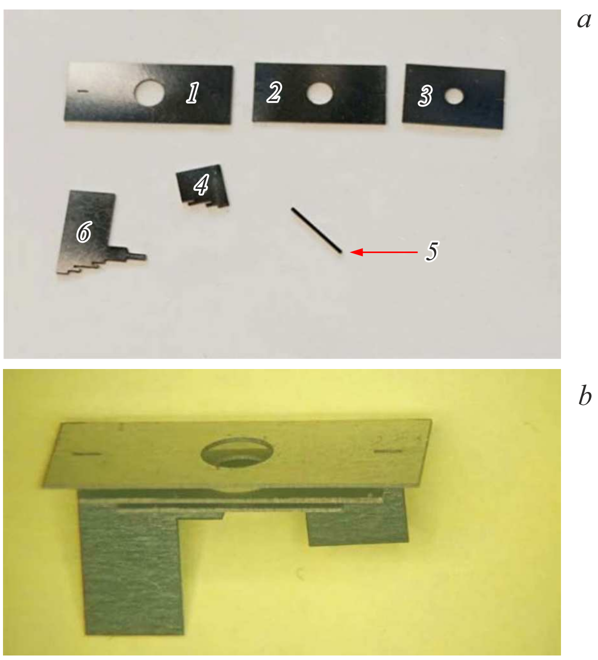

Figure 7. Photos of the fabricated electron gun components (*a*) and the focusing electrode assembly (*b*). *1–3* — focusing diaphragms, *4, 6* — mounting elements, *5* — heater foot.

the reflection coefficient of no more than -17 dB and transmission losses in the range of $5-10$ dB.

Also, based on the new technology, samples of a V-band miniature periodic structure — ladder type DS with dumbbell-shaped slits were made from copper and molybdenum plates of various thicknesses ($150-400\,\mu$m). Morphological analysis showed that the size deviations from the design values do not exceed $10-20\,\mu$m, which is comparable to the diameter of the laser spot. The largest relative error is observed for miniature capacitive gaps with a characteristic size of less than $100\,\mu$m, however, the structure as a whole retains high uniformity (a spread of less than $5\,\mu$m). The dispersion characteristic of DS, reconstructed after measuring the phase rise of the signal transmission coefficient, is in good agreement with the calculation results. Transmission losses in the frequency band of 10 GHz are no more than -10 dB.

In addition, a design of a miniature electron gun has been developed that forms a converging electron beam with a current of up to 150 mA and a diameter of less than $300\,\mu$m. The focusing electrode of the gun consists of several parallel plates with holes. With the help of the developed laser micro-processing technology, test samples of the gun's structural elements were made from a $200\,\mu$m thick molybdenum foil: focusing electrodes, mounting hardware, and a heater. Also, cathodes were made from the tablets LaB_6.

Thus, the proposed technology of micro-processing with nanosecond laser pulses allows to fabricate the micro-sized electrodynamic and electro-optical components for the millimeter-wave band vacuum devices with sufficiently high precision from various materials. Further research will be aimed at optimizing technological modes to improve the fabrication precision and improve the quality of micro-processing.

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Conflict of interest

The authors declare that they have no conflict of interest.

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