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SUPERCONDUCTIVITY

A Terahertz Source of Radiation to Open Space Based on a Long Josephson Junction

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Abstract—An electromagnetic source of terahertz radiation on the basis of a tunnel long Josephson junction was proposed and experimentally studied. Output radiation was transmitted to open space by means of a slot antenna, which was located on the same microcircuit with the junction and matched with the collecting lens. Several Oscillator structures designed for operation within the frequency ranges of 250–410, 330–530, and 390–700 GHz with the possibility of continuous frequency tuning were manufactured and tested. The amplitude-frequency characteristics of output radiation with a spectral resolution of nearly 0.1 MHz were studied with the use of a terahertz-spectrometer based on a superconducting receiver. The study of transmitting antenna characteristics throughout the entire bandwidth was performed with the use of a cooled highly sensitive silicon based bolometer. The experimental results correspond to numerical calculations.

Keywords: terahertz radiation sources, Josephson effect, slot antenna, harmonic mixer

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1. INTRODUCTION

Terahertz radiation sources are currently demanded in a number of scientific problems, such as heterodyne detection of ultraweak signals for radioastronomic studies and high-resolution terahertz spectroscopy. Spectroscopy of gases and living tissues is widely used in biology, medicine, environmental monitoring, and security systems. A long Josephson junction (LJJ) operates as a source of electromagnetic terahertz radiation [1], whose frequency f can be uniquely determined from the direct-current bias voltage V_{dc} on the junction by the Josephson relationship

$$hf = 2eV_{\mathrm{dc}},$$

where h is the Planck constant, and e is the charge of an electron.

Applying an external local magnetic field and specifying the LJJ bias voltage, it is possible to create a unidirectional flux of magnetic vertices (magnetic flux quanta)—fluxones—inside a tunnel junction. In recent decades, the structure of such a junction has been appreciably improved with the purpose of its application just as a widely tunable terahertz oscillator [2], and its spectral characteristics were thoroughly studied [3] with the use of a harmonic mixer to decrease the output radiation frequency to the range of 0.1–1 GHz and stabilize radiation on the basis of a phase locking loop (PLL). The signal within a frequency range of up to 1 GHz can be immediately measured with the use of a laboratory spectrum analyzer with a resolution of nearly 1 Hz. The LJJ based source output characteristics attained by now are the following: the generation frequency variates from 300 to 700 GHz with the possibility of continuous tuning, the spectral linewidth without PLL is ranged between 0.5 and 15 MHz depending on the oscillator operation mode, the frequency phase locking of output radiation has been organized within a narrow central peak with a linewidth of nearly 40 kHz and a spectral quality of up to 97%, and the output power is sufficient for heterodyne reception purposes. The set of such characteristics has enabled the successful implementation of a long Josephson junction as a heterodyne oscillator as a part of the superconducting receiver for the flight mission of Terahertz Limb Sounder (TELIS) [4, 5]. The mentioned receiver is based on a mixer in the form of a "superconductor–insulator–superconductor" (SIS) tunnel junction and called an integral receiver due to the integration of a long Josephson junction on the same microcircuit with the SIS mixer.

Some years ago we proposed and successfully implemented the concept of the integration of a long Josephson junction on the same microcircuit with the transmitting slot antenna [6–12] for the transmission of terahertz radiation to open space. The frequency characteristics of different transmitting antenna structures designed for different frequency ranges (impedance, transmitted power ratio, directivity pattern) were studied and reported in the papers [6, 7]. Afterwards, with the purpose of phase locking, we additionally built a harmonic mixer (HM) operating in the feedback circuit with the long Josephson junction in combination with PLL. The power matching of a harmonic mixer and a long Josephson junction was studied in details in the works [8–11], and the spectral characteristics of radiation to open space were investigated in the studies [9, 12]. In this work, we have performed the more profound studies of output radiation to open space by means of two different experimental setups. Section 2 describes the technological process of the manufacturing of experimental specimens and the direct-current characteristics of manufactured tunnel SIS structures. The study of amplitude–frequency characteristics (AFCs) with a spectral resolution of nearly 0.1 MHz was performed with a terahertz spectrometer on the basis of a superconducting integrated receiver; the results are given in Section 3. The frequency dependence of the integral power of radiation to open space throughout the entire LJJ generation range, governed in fact by the transmitting antenna characteristics, was studied with the use of a cooled highly sensitive silicon based bolometer; the results are given in Section 4.

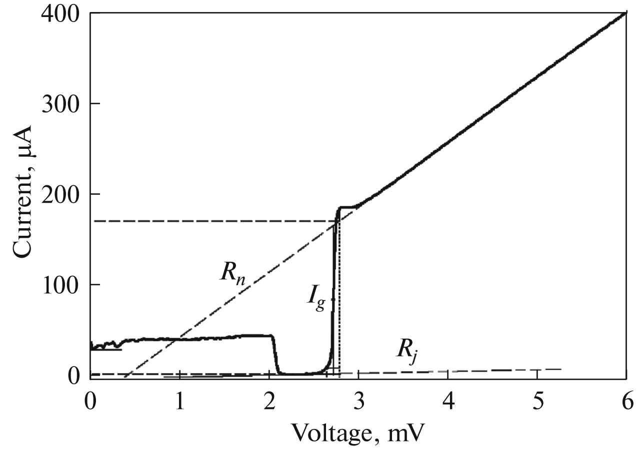

Fig. 1. Voltage–current characteristic of the $Nb/AlO_x/Nb$ based tunnel junction with a surface area of 1.4 μm^2. Junction parameters: normal resistance R_n = 14.1 Ω; ratio of the sub-gap resistance R_j characterizing the leak current to the normal resistance R_j/R_n = 34.7; gap voltage V_g = 2.71 mV; current jump at a gap voltage I_g = 161 μA. Auxiliary dashed lines are given for the more comprehensive specification of parameters.

2. FABRICATION OF EXPERIMENTAL SAMPLES OF TERAHERTZ SOURCE

A series of experimental microcircuits of 4 × 4 mm^2 in size on a silicon substrate with a thickness of nearly 0.5 mm was manufactured. Superconducting tunnel structures were fabricated on the basis of $Nb/AlO_x/Nb$, and the technological process of the formation of such structures is described in more details in the papers [13, 14]. To prevent the substrate from etching, the deposition of a buffer Al_2O_3 layer with a thickness of 100 nm is used in the process of plasma etching during the formation of tunnel junctions. The following stage is the deposition of a three-layered $Nb/AlO_x/Nb$ structure by magnetron sputtering. The geometry of electrodes is formed by means of lift-off technology. The thickness of the lower and upper niobium based electrodes is nearly 200 and 400–450 nm, respectively. The microstrip transmission lines were manufactured on the basis of $Nb/SiO_2/Nb$ with an insulator thickness of nearly 400 nm. The opening of contacts to the structures was also performed by means of lift-off technique, after which gold contact pads were sputtered. As a result, the experimental specimens of three integrated structures, which incorporated a long Josephson junction, a slot antenna, and a harmonic mixer and were designed for tuning the working frequency within 250–410 GHz (hereinafter, structure S-300), 330–530 GHz (structure S-450), and 390–700 GHz (structure S-550), were fabricated. For clarity, the number in the names of these structures denotes the central frequency of their working band in gigahertzs. The size of a long Josephson junction in the experimental microcircuits is 160 × 400 μm^2 for S-450 and S-550 and 16 × 700 μm^2 for S-300. The direct-current testing of the experimental specimens has demonstrated a high quality of tunnel structures. The current–voltage curves (IVC) of the $Nb/AlO_x/Nb$ based junction incorporated into S-300 with a surface area of 1.4 μm^2 at a temperature of 4.2 K is plotted in Fig. 1. The IVC region at voltages below 2 mV is characterized by the SIS junction current, which has not been suppressed in this case. The density of tunnel current in the SIS structure is nearly 6.5 kA/cm^2.

3. STUDY OF SPECTRAL CHARACTERISTICS

The amplitude–frequency characteristics of output radiation were studied with a spectral resolution of better than 0.1 MHz with a spectrometer based on a superconducting integrated receiver (SIR) [4, 5]. The experimental setup is schematized in Fig. 2. A source and a receiver are installed into two isolated floodable helium cryostats: the upper part of the scheme represents cryostat no. 1 with the studied oscillator, and the lower part of the scheme is cryostat no. 2 with the receiver microcircuit (in the scheme, SIR, i.e., "superconducting integrated receiver"). The SIR operation principle is described, e.g., in the papers [15, 16]. This setup simultaneously uses two LJJs (in the scheme, FFO, i.e., "flux flow oscillator"): the radiation from the first (FFO #1) is an object of study in our work, and the second (FFO #2) is a heterodyne SIR. The spectral line shape is recorded by means of

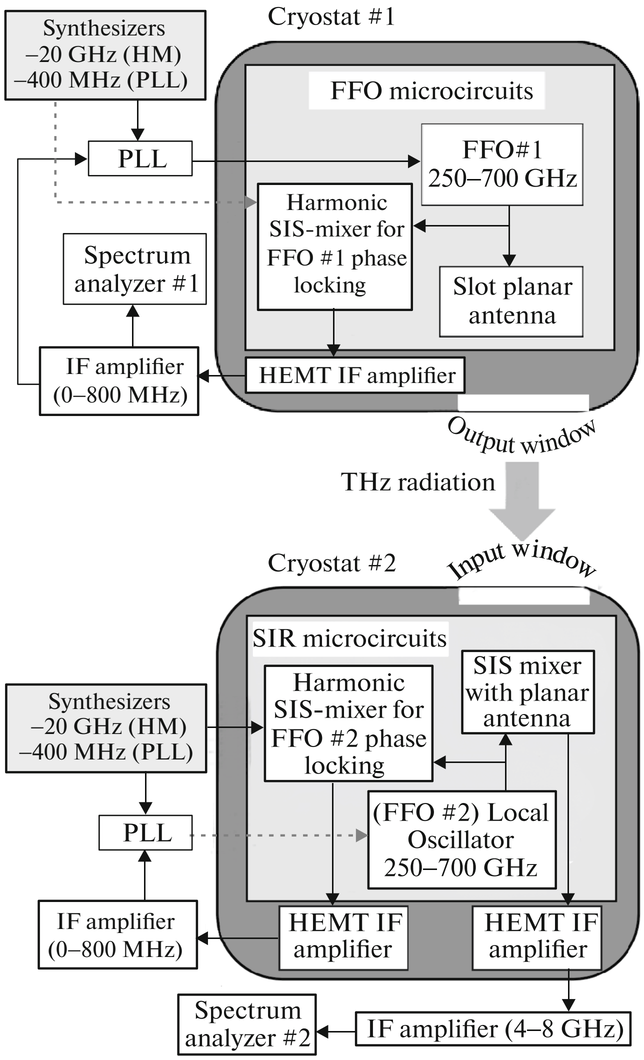

Fig. 2. Scheme of the setup for studying the spectral characteristics of radiation from a LJJ based source installed in cryostat no. 1 to open space with the use of a terahertz SIR based spectrometer installed in cryostat no. 2.

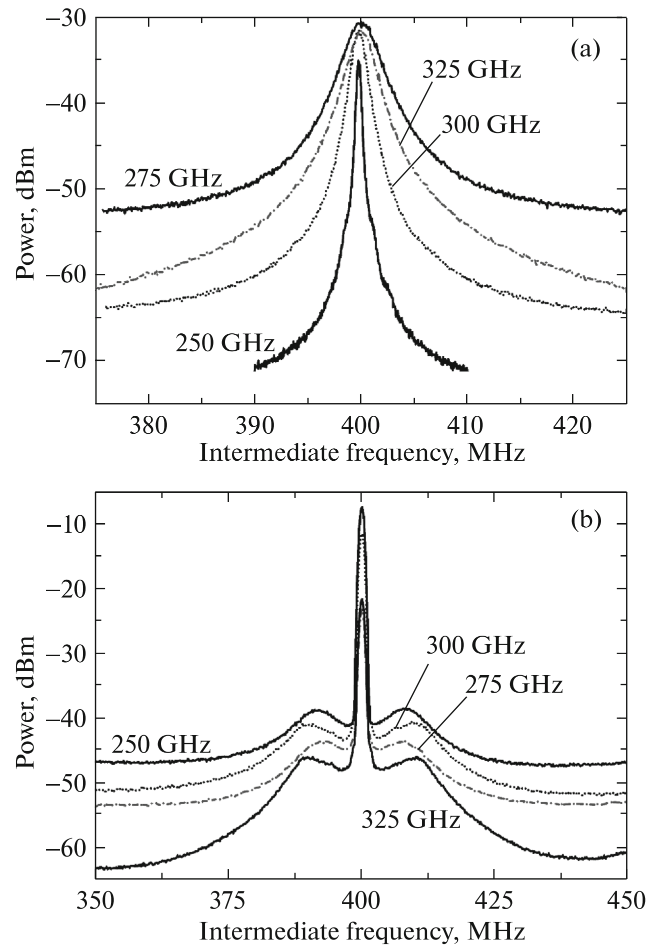

Fig. 3. Radiation spectra recorded with the use of spectrum analyzer no. 2 (see Fig. 2) for the source of structure S-300 in the mode of (a) free-running oscillation and (b) phase locking with the use of phase locking loop. Radiation frequency f for each AFC is specified in the plots. Spectral linewidth from (a) is 0.4 MHz for $f = 250$ GHz, 2.9 MHz for $f = 275$ GHz, 1.2 MHz for $f = 300$ GHz, and 2.2 MHz for $f = 325$ GHz. Spectral quality from (b) is 97% for $f = 250$ GHz, 77% for $f = 275$ GHz, 96% for $f = 300$ GHz, and 91% for $f = 325$ GHz.

two independent methods: spectrum analyzer no. 1 through the feedback circuit for the locking of radiation with the use of HM and PLL ("phase locking loop") at an intermediate HM frequency within a range of 0–800 MHz and spectrum analyzer no. 2 at the SIR output within an intermediate frequency range of 4–8 GHz. In the intermediate frequency sections of both harmonic and SIS mixers, semiconducting superhigh-frequency amplifiers (in the scheme, IF, i.e., "intermediate frequency amplifier") are used with an amplification of nearly 30 dB for the cooled amplifiers and 60 dB for the uncooled amplifiers operating at room temperature such that the total amplification of an output microwave signal is 90 dB. It should be noted that such a setup can be used for the investigation of radiation to open space only within the working SIR frequency range of 480–730 GHz, so the described study was performed for structures S-450 and S-550. The study of spectral characteristics for structure S-300 is still possible with the use of spectrum analyzer no. 1 without the outer receiver.

The results of measuring the amplitude-frequency characteristics of radiation from the experimental specimen of structure S-300 with the use of spectrum analyzer no. 1 at four frequencies of 250, 275, 300, and 325 GHz at a step of 25 GHz are shown in Fig. 3. The radiation spectra shown in Figs. 3a and 3b were recorded in the free-running generation mode and the mode of radiation phase locking to the reference generator with a frequency of 400 MHz, respectively. The linewidth of the presented radiation lines in the free-running mode variated from 0.4 to 2.9 MHz, and the

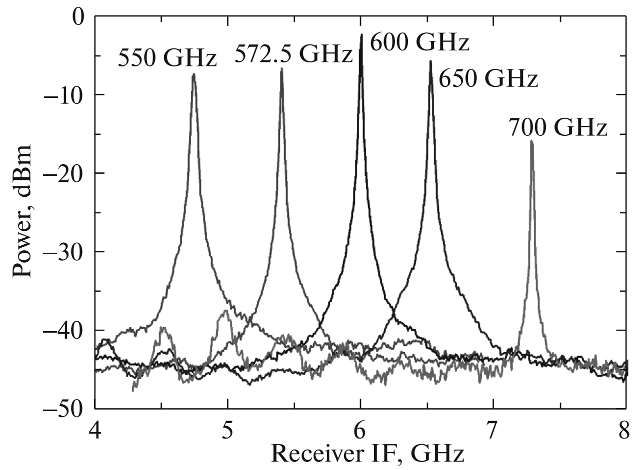

Fig. 4. Radiation spectra recorded for the source of structure S-550 with the use of spectrum analyzer no. 2 (see Fig. 2) in the free-running oscillation mode. Radiation frequency foe each spectral line is specified at the curves. Linewidth is 14.7 MHz for f = 550 GHz, 13.7 MHz for f = 572.5 GHz, 9.4 MHz for f = 600 GHz, 12 MHz for f = 650 GHz, and 4.3 MHz for f = 700 GHz.

spectral quality determined in the phase locking mode as the fraction of power concentrated within the narrow central peak was from 77 to 97%. In the papers [9, 11], it has been shown that the shape of a spectral line of radiation to open space corresponds to the shape of a radiation line measured in the feedback loop through the output section of the harmonic mixer with consideration for the reference synthesizer noise, which makes a contribution to the signal oscillator noise in the form proportional to the squared harmonic number ~n^2. Hence, the signal radiated to open space has spectral characteristic close to the characteristics plotted in Fig. 3 for each frequency.

The lines of radiation to open space from structures S-450 and S-550 were recorded with the use of spectrum analyzer no. 2 at frequencies belonging to the operating bandwidth of the SIR based spectrometer. The results of study are shown in Fig. 4 within an intermediate frequency range of 4–8 MHz, and the typical linewidth of radiation at the given frequencies is from ~5 to 15 MHz in the free-running generation mode. In the paper [12], it has been demonstrated that the radiation power can not be judged from the power of a recorded AFC peak in the case of such measurements, as the efficiency of conversion in the SIS mixer incorporated into the receiver and, consequently, the receiver sensitivity is different at each working frequency. For this reason, we have studied the integral uncalibrated power of radiation to open space by means of a broadband highly sensitive silicon based bolometer (Infrared Laboratories), and the results are given in Section 4.

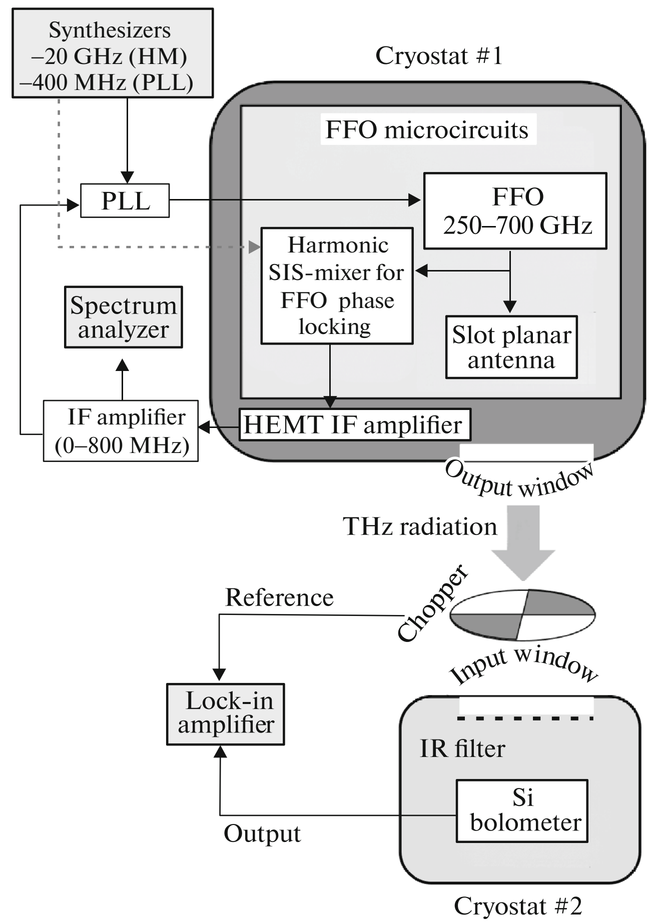

Fig. 5. Scheme of the experimental setup for the detection of output terahertz LJJ radiation with the use of a silicon bolometer.

4. STUDY OF THE OPERATING BANDWIDTH

The experimental setup for studying the working bandwidth of output frequencies by measuring the integral power of radiation with a broadband bolometer is schematized in Fig. 5. As in the study of amplitude-frequency characteristics, we used two floodable cryostats with a working temperature of 4.2 K: cryostat no. 1 with a studied source specimen (the upper part of the scheme) and cryostat no. 2 with a cooled silicon based bolometer. To suppress the background infrared (IR) signal, to which the bolometer is sensitive, a quartz IR filter (in the scheme, IR filter) on the input window of cryostat no. 2 was used. The bolometer response was measured with a lock-in amplifier (in the scheme, Lock-in amplifier) with the use of an optical chopper (in the scheme, Chopper) with a chopping frequency of nearly 170 Hz. The study was performed throughout the entire LJJ frequency tuning bandwidth, and the generation frequency was uniquely determined from the Josephson relationship. The frequency estimation precision was nearly 1 GHz. Similarly to the case of spectral studies, this experimental

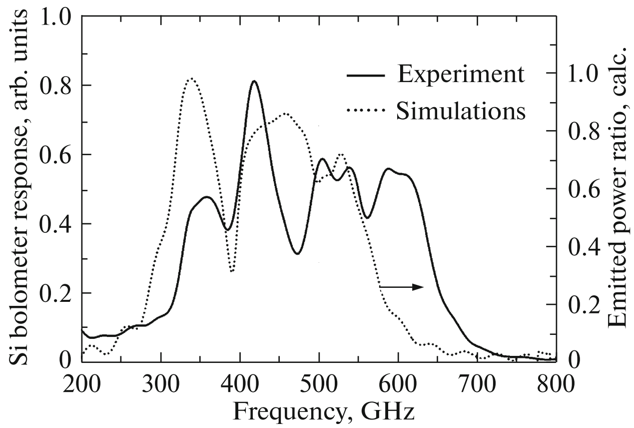

Fig. 6. Radiation from the source of structure S-550 to open space: experiment (solid curve) and calculation (dashed curve). Radiation power was normalized in the course of calculation to the total output DJJ power.

setup provides the possibility to perform the locking of oscillator radiation and the measurements of spectral radiation characteristics with a resolution of 1 Hz, which is governed by the characteristics of a spectrum analyzer and a reference signal from an outer microwave source at a frequency of 400 MHz, simultaneously with the measurement of a bolometric response. For this purpose, a feedback circuit incorporating a harmonic mixer, a cascade of output HM signal amplifiers at an intermediate frequency, and a phase locking loop has been provided.

The experimental results on the study of radiation to open space are plotted for structure S-450 in Fig. 6 together with the numerical simulation results. The frequency dependence of the power of radiation to open space is generally governed by the frequency characteristics of a transmitting antenna. The numerical and experimental results demonstrate good agreement in the series of peaks and "dips" and the operating bandwidth. Incomplete correspondence is due to a number of simplifications taken in the course of numerical simulation. Thus, for example, the output LJJ power is taken for calculations as independent of the frequency, whereas the power in a real system depends on both the operational mode of a oscillator [17, 18] (resonance or viscous flux flow modes) and the locking of LJJ radiation to the output transmission line at a certain generation frequency. Moreover, the simulation of superconducting lines was performed with the use of a simplified model. In the process of numerical simulation, the presence of a harmonic LJJ radiation component has not also been taken into account. Thus, for example, there also exists second harmonic generation at f_{2nd} = 600 GHz at the main working frequency f = 300 GHz corresponding to the bias voltage V_{dc} = 0.62 mV. The operating bandwidth of generation frequency tuning for the given structure at a level of 0.5 from the maximum radiation power was 340–650 GHz at its theoretical values of 330–530 GHz. The study results for structures S-300 and S-550 also demonstrate qualitative agreement between the numerical and experimental values with consideration for the above described factors, which have not been reflected in calculations.

5. CONCLUSIONS

The terahertz LJJ based source is a promising type of source for different applications in modern terahertz technologies due to a broad bandwidth of frequency tuning for one experimental sample. We proposed, numerically modelled, and experimentally studied the concept of a source of radiation to open space on the basis of a long Josephson junction integrated with a transmitting slot antenna. For the phase locking of output radiation, a harmonic mixer providing the feedback circuit with the oscillator on the basis of a phase locking loop was additionally integrated into the circuit of the long Josephson junction with the antenna. Several integrated microcircuit structures designed for different working bandwidths were numerically modelled, and some experimental specimens on the basis of tunnel $Nb/AlO_x/Nb$ structures with a tunnel current density of nearly 6.5 kA/cm^2 and a working temperature of 4.2 K were manufactured and studied. The study of output radiation was performed with the use of two experimental setups: a terahertz spectrometer with a SIS receiver with a spectral resolution of better than 0.1 MHz and a highly sensitive silicon based bolometer cooled to 4.2 K. The spectral radiation linewidth in the free-running mode was from several fractions of megahertzs to nearly 15 MHz depending on the working frequency and operational mode of the oscillator and the spectral quality attained 97%. The operating bandwidth of the source exceeded 50% of the central frequency: for example, 340–650 GHz for structure S-450 or 62%, if the central frequency is taken to be 495 GHz. This is a reasonable result for the transmission bandwidth of a slot antenna. The total frequency bandwidth of all the three studied structures was from 200 to 750 GHz.

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CONFLICT OF INTERESTS

The authors declare that they have no conflicts of interests.

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