ANTENNA AND FEEDER SYSTEMS

An Antenna with a Feeder for a Superconducting Terahertz Josephson Oscillator with Phase Locking

N. V. Kinev[a, *], K. I. Rudakov[a, b], L. V. Filippenko[a], A. M. Baryshev[b], and V. P. Koshelets[a]

[a] *Kotelnikov Institute of Radio Engineering and Electronics, Russian Academy of Sciences, Moscow, 125009 Russia*
[b] *Kapteyn Astronomical Institute, University of Groningen, Groningen 9712 CP, the Netherlands*
***e-mail: nickolay@hitech.cplire.ru**

Abstract—A principal layout of a Josephson terahertz radiation oscillator integrated with a transmitting antenna-lens system and a harmonic mixer (HM) for phase locking of radiation has been proposed and was successfully implemented. Two antenna-feeder systems designed for the central frequencies of 0.3 and 0.6 THz and located on the same chip with the oscillator are numerically simulated and fabricated. A microstrip transmission line between the oscillator and the antenna is used as the feeder. A study was carried out on matching the oscillator power and HM for two designs; the frequency range of pumping HM was 0.25−0.45 and 0.5−0.68 THz for the designs at 0.3 and 0.6 THz, respectively. Good agreement was obtained between experimental results and numerical simulations. A study of the spectral characteristics of the radiation of the oscillator into the external space for the 0.6 THz design using a superconducting integrated spectrometer was carried out. The linewidth of an emission line in free-running regime was of the order of several megahertz; in the phase locking regime down to tens of kilohertz with a signal-to-noise ratio of more than 20 dB was obtained.

INTRODUCTION

There is a high demand in science and technology for tunable sources of terahertz (THz) radiation, due to the rapid development of applications for THz technologies [1]. This is primarily hypersensitive heterodyne detection of weak signals, including in the composition of radio astronomy observatories, those on the ground and space-based ones. In addition to detection, terahertz technologies are in demand in spectroscopy, since in this frequency range there are sufficiently powerful absorption lines for most organic compounds, which is especially important for applications in medicine and biology. This paper presents the latest achievements in the field of developing a THz oscillator system for radiation into open space based on a long Josephson junction (LJJ) with an ultra-wide frequency tuning range (approximately 100% of the center frequency) and a generation line width in a stabilized mode of the order of tens of kHz. Such an oscillator is made on the basis of an Nb–AlO$_x$–Nb tunnel junction superconductor–insulator–superconductor (SIS) with sizes of 16×400–700 μm^2 and a barrier thickness of approximately 1 nm located in the plane of a single-chip chip, integrated with a transmitting lens antenna and radiating a signal at the THz frequency in open space. In earlier studies, such an oscillator has already been successfully applied as a terahertz heterodyne SIS receiver as part of an integrated

chip, when the reference oscillator and receiver element based on the SIS junction were located on the same chip [2].

In this work, the oscillator radiation is brought out of the chip plane into open space by integration with the transmitting slot antenna based on a thin film of niobium made in a single process with the oscillator. The power transmission line to the antenna is a microstrip line that is matched at the input with an oscillator with low impedance (fractions of ohms) and at the output with a quasi-optical antenna with a relatively high impedance (tens of ohms). Two transmission line topologies with an antenna designed for central frequencies of 300 and 600 GHz have been developed, with a working band width according to numerical calculation of approximately 40−50% of the central frequency in terms of the power emitted into the open space, 0.7 of the total oscillator output power. Part of the power is branched off through a specially designed transmission line to a harmonic mixer (HM), constructed on the basis of a concentrated tunnel SIS junction and located on the same chip as the antenna and oscillator and used in the feedback loop with the oscillator for its phase stabilization using a phase-locked loop (PLL). The pumping of the oscillator with oscillator power was experimentally investigated and the experimental results were compared with the calculated ones. For the 600 GHz antenna, the spectral characteristics of the output radiation
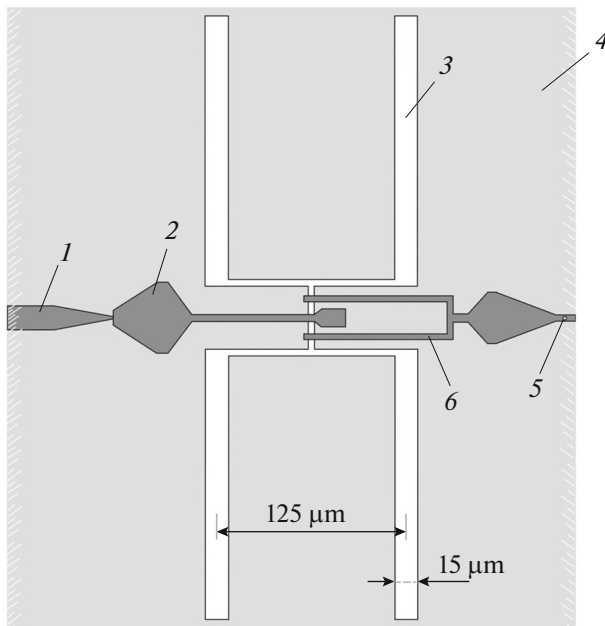
Fig. 1. The scheme of the planar integral structure of the oscillator: (*1*) THz oscillator; (*2*) microstrip transmission line between oscillator and antenna; (*3*) dual slot antenna; (*4*) metallization layer; (*5*) harmonic mixer; (*6*) microstrip transmission line between oscillator and harmonic mixer.

were studied using a spectrometer based on a superconducting integrated receiver (SIR) with an operating frequency range of 500−700 GHz [3].

1. THE BASIC DESIGN OF AN OSCILLATOR WITH A TRANSMITTED ANTENNA AND HARMONIC MIXER CONSTRUCTION

The oscillator concept was based on a distributed Josephson junction with length $l \gg \lambda_J$, where λ_J is the Josephson penetration depth described in [4]; the recent idea of the authors of the article on integrating such an oscillator with a transmitting slot antenna on a single chip to output a THz signal to the open space was presented in [5−7]. However, the recent work does not provide the ability to stabilize the radiation of the oscillator, which is a key point for practical applications of the oscillator as a heterodyne of receiving systems or an active source in spectroscopy. In this work, we developed an additional feedback circuit with the oscillator, which directs part of the output power (approximately 10−20%) to the harmonic mixer, whose signal at the intermediate frequency (IF) in the 0−0.8 MHz range is analyzed by the PLL.

A schematic diagram of the integrated structure of the oscillator with a double slit antenna and HM is presented in Fig. 1 for a 300 GHz center frequency design. The size of the oscillator is 16×700 μm^2, the area of the HM based on the SIS transition is 1.4 μm^2, and the distance between the slits of the antenna is

125 μm with a slit width of 15 μm. The oscillator is matched to the antenna and the HM via two microstrip transmission lines. A slit antenna is made in the metallization layer, which is also the bottom electrode of the microstrip lines. To provide directional radiation with an angle of divergence of the radiation pattern on the order of several degrees, a microcircuit with an integrated structure is installed on a flat surface of a collecting semi-elliptical lens [8] so that the center of the antenna is located exactly at the far focus of the lens (see, for example, [6], Fig. 1c). The oscillator operates at a temperature of liquid helium of 4.2 K; the cryogenic oscillator module, taking the magnetic shielding and holders into account, has dimensions (D × Sh × AT) 12 × 4.5 × 6 cm and a mass of approximately 0.1 kg without the large magnetic screen consisting of two concentric cylinders, or approximately 0.4 kg with the screen (Fig. 2).

2. THE RESULTS OF NUMERICAL SIMULATIONS

The characteristics of the antenna-feeder system, as well as the matching of the oscillator and harmonic mixer power, were calculated in a specialized software package for three-dimensional numerical modeling of microwave and microwave structures. The main results for 300 and 600 GHz designs are shown in Fig. 3. The following constants were used to account for the superconducting state of the antenna and microstrip transmission lines based on thin Nb films: the value of the London penetration depth of the magnetic field $\lambda_L = 85$ nm and the dielectric constant SiO_2 was equal to 4.2. The topology parameters of the integrated microcircuit were also included in the computational model: the thickness of the Nb film that provides the lower electrode of the transmission lines and the antenna metallization layer was 200 nm, the thickness of the upper electrode based on Nb was 350 nm, the thickness of SiO_2 between the upper and lower electrode was 400 nm; the geometrical dimensions of each element of the topology was provided as well. Following the harmonic mixer along the propagation of the radiation of the oscillator, a radial element is located with a relatively large area, approximately 2000 μm^2 (not shown in Fig. 2 and located to the right of the HM), which is a large capacitance for connecting the segment of the microstrip line that "compensates" the capacitance of the HM at the operating frequency. The output of the HM is presented in the form of a coplanar transmission line, through which the reference signal of the external synthesizer at a frequency of approximately 20 GHz is fed to the mixer and the output microwave signal is output on the IF in the range up to 1 GHz. According to the calculation, the share of oscillator power that went to the coplanar line was less than 1% of the total oscillator output power and was taken into account in the calculation of curve *3* in Fig. 3 for each design. Thus, according to the results of
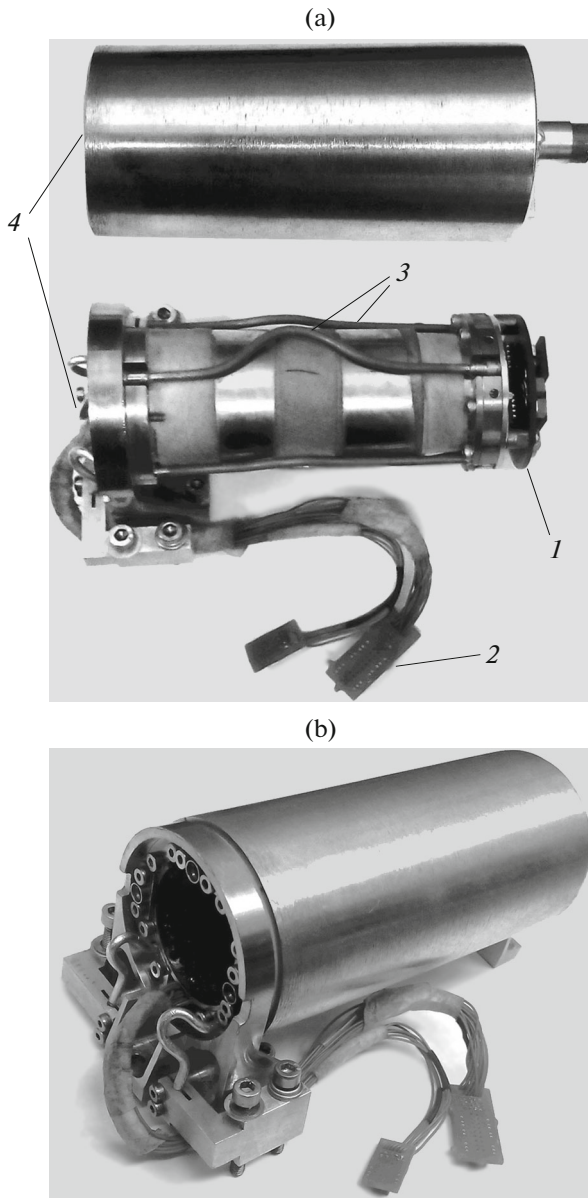
Fig. 2. The cryogenic module of the THz oscillator and the magnetic screen (a): (*1*) a chip with a DC offset card; (*2*) cables for displacement and measurement of current-voltage characteristics; (*3*) microwave cables; (*4*) a window for outputting THz radiation into the open space, as well as a general view of the assembled cryogenic oscillator module with a magnetic screen (b).

Fig. 3. The frequency dependence of power absorbed by a harmonic mixer (curve *1*), power, gone into the integral structure at the oscillator output (curve *2*) and the power radiated by the antenna into the open space (curve *3*) for an integrated structure designed for a center frequency of 300 GHz (a) and 600 GHz (b). The power value is normalized to the total output power of the oscillator.

numerical simulation at the level of 0.7 of the total output power of the oscillator, the working range of the 300 GHz design was 250−420 GHz, while for the 600 GHz design it was 400−700 GHz.

3. EXPERIMENTAL RESULTS AND DISCUSSION

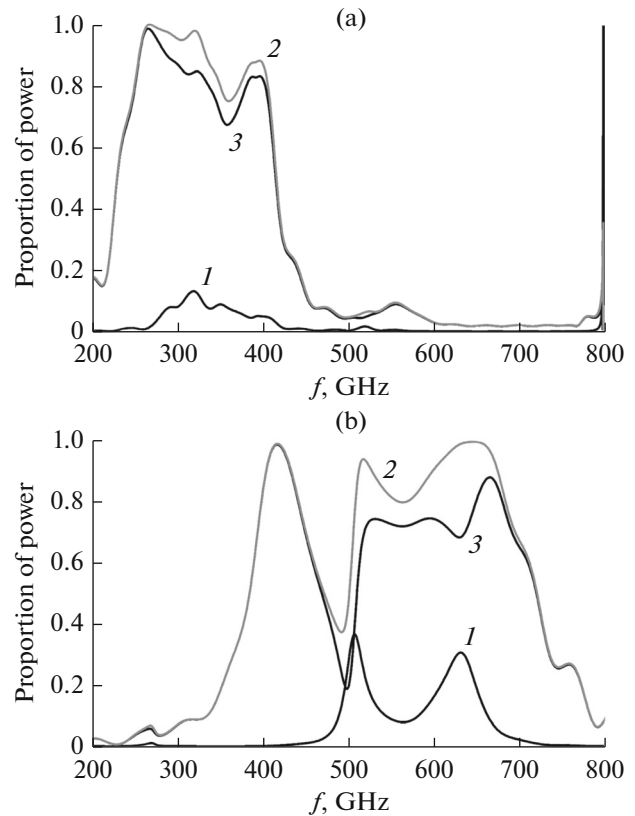A series of experimental samples of integrated circuits were fabricated according to the results of numerical simulation, including the LJJ and HM with matching transmission lines and an antenna-feeder system. The characteristics of the samples were investigated using two different experimental setups. The first is a probe insert immersed in a Dewar vessel with liquid helium (an operating temperature of 4.2 K) with the ability to measure current-voltage characteristics of all elements of the chip. The second, more complex, experimental setup is designed to study the THz radiation of an oscillator into the external space and consists of two cryogenic systems based on flood cryostats, one of which is equipped with a microcircuit with an oscillator, while the other has an SIR microchip as part of a THz spectrometer [2, 8]; the output and input windows of the cryostats are located opposite each other (Fig. 4). Such a system makes it possible to measure the spectral characteristics of the oscillator with a resolution higher than 0.1 MHz and the operating radiation range to the external space within the operating range of the SIR, which is 500−700 GHz.

The parameters of the three-layer Nb−AlO$_x$−Nb SIS structure, of which both the oscillator based on
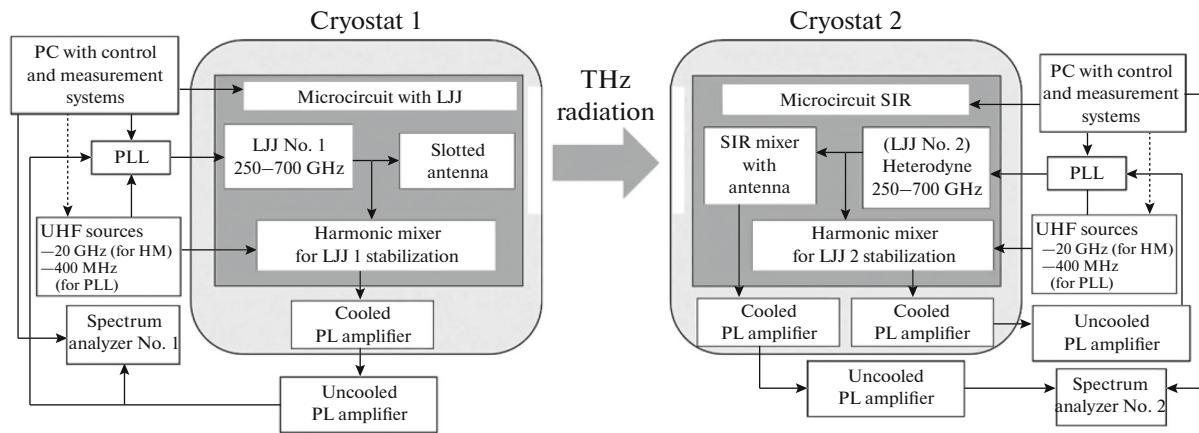
Fig. 4. The scheme of the experimental setup for measuring the radiation of the oscillator based on the LJJ, located in the cryostat 1, in the open space using a THz spectrometer based on SIR, located in the cryostat 2.

the LJJ and the HM are made, were investigated using an immersion probe insert. The density of the tunneling current of the manufactured SIS structure was approximately 8 kA/cm². A typical CVC of the HM without external influence is presented in Fig. 5 (curve *1*), the "slit" voltage of the tunnel contact is approximately 2.7 mV, the normal state resistance for a given transition area of approximately 1.5 μm² is 13.5 Ω, and the "slit" current jump $I_u = 175$ μA. The ratio of the "base" resistance to the normal resistance of approximately 30 indicates the high quality of the tunnel structure. When acting on the transition by THz radiation from the oscillator, a series of clearly
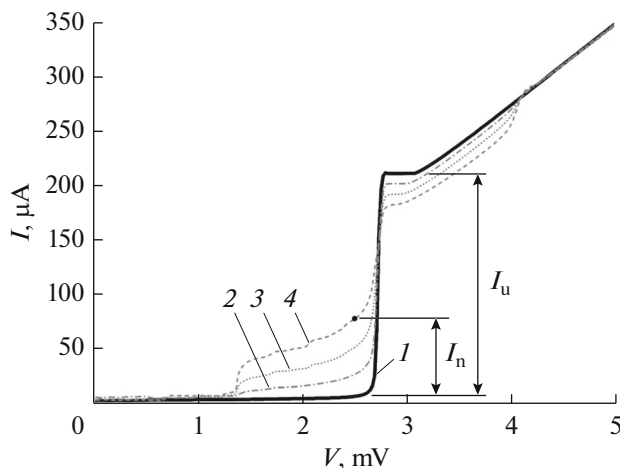
defined quasiparticle pump stages occurs on the current−voltage characteristics of the HM (see Fig. 5, curves *2−4* measured at 340 GHz irradiation).

The study of the frequency dependence of the matching power oscillator with the HM was performed using an immersion probe-insert as follows: The HM was installed at the operating point at a predetermined voltage of 2.5 mV; the series of current-voltage characteristics of the oscillator was then measured. During this measurement, the oscillator was automatically scanned over the entire output frequency band of the oscillator, because the frequency is uniquely determined by the voltage at the transition through the Josephson ratio $f = 2eV/h$, where V is the constant voltage at the junction, h is the constant bar, and e is the electron charge. Thus, at each operating voltage on the oscillator, the magnitude of the pump current was measured, I_n on the HM at a given voltage of 2.5 mV (in Fig. 5 the value of I_n for curve *4*).

The dependence of the maximum pump current on the frequency for structures of 300 and 600 GHz is shown in Fig. 6 (solid lines); the current is normalized to I_u, for visual comparison, the calculated dependencies (dashed lines), which duplicate the lines, are also presented in line 1 in Figs. 3a, 3b. The frequency dependence according to the results of the experiment not only agrees qualitatively with the numerical calculations, but also coincides quite accurately in the frequency of the pump peaks and the width of the frequency range. Thus, the working range of pumping a harmonic mixer with oscillator power to stabilize it was 250−450 GHz for the 300 GHz design and 500−680 GHz for the 600 GHz design.

The spectral characteristics of the oscillator were investigated using the apparatus whose scheme is shown in Fig. 4. This experiment turned out to be fundamentally possible only for the 600 GHz design, since the operating range of the superconducting receiver is 500−700 GHz. It should be noted that this
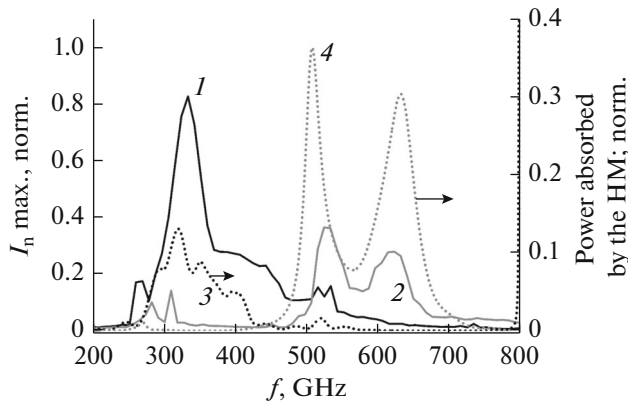

Fig. 5. Current-voltage characteristics of a harmonic mixer without external influence (curve *1*) and with the power of the THz oscillator at a fixed frequency of 340 GHz with different pump power levels (curves *2*, *3* and *4* in order of increasing power). The tunnel current jump I_u at a "slit" voltage value above which the SIS tunnel contact goes to the normal state, as well as the pump current I_n for curve *4* with a "baseline" voltage of 2.5 mV.

Fig. 6. The experimental results of the frequency dependence of the maximum pump current I_n normalized to I_u (curves *1*, *2*), and the results of the numerical calculation of the agreement on power LJJ and HM (curves *3*, *4*) for 300 GHz antenna-feeder system designs (curves *1*, *3*) and 600 GHz (*2*, *4*).

Fig. 7. The spectral characteristics of an oscillator based on a LJJ with a 600 GHz antenna-feeder system, measured at a generation frequency of 576 GHz using an integrated circuit on a single HM chip *1,2*) and using an external spectrometer based on SIR (curves *3,4*) (see Fig. 4, signals of spectrum analyzers No. 1 and 2, respectively): curve *1*, *3*, phase-stabilized PLL system; curves *2*, *4*, without phase stabilization; *SNR*, the ratio of the signal power to the noise level, which for curve *2* is 22.8 dB.

apparatus uses two THz oscillators based on the LJJ, one of which (LJJ No. 1) is the object of development and research in this work, and the other (LJJ No. 2) is used as a reference oscillator for the superheterodyne receiver. In the apparatus, two stabilization systems are simultaneously used with the HM and PLL loops for two LJJs. Thus, the apparatus has the ability to measure the spectral characteristics of the oscillator in stabilization mode or without it in two independent ways: through a feedback loop using the HM path located on the same chip as the oscillator (the signal on the spectral analyzer No. 1) using the output path of the IF of the SIS-mixer (the signal on the spectral analyzer No. 2). To enhance the output signals of the IF HM for LJJ No. 1 and the receiver SIS mixer, microwave amplifiers of different ranges with different gain parameters were used; therefore, the signal powers measured by spectral analyzers No. 1 and 2 differ.

The result of this study of the spectral characteristics for some arbitrarily chosen frequency of 576 GHz, which is close to the center of the operating range of the antenna-feeder system, is shown in Fig. 7. Spectral curves *1* and *2* were measured using the HM in the intermediate frequency range f_{if} 0–800 MHz, while curves *3* and *4* were measured using a THz spectrometer in the range f_{if} 4–8 GHz. Curves *3* and *4* artificially moved to the frequency range of curves *1* and *2* for visual comparison. The signal spectrum in the autonomous mode (without phase stabilization) has a Lorentz shape with a high degree of accuracy, the spectral width of the generation line in the autonomous mode is 3.97 MHz for curve *2* and 3.85 MHz for curve *4*. Such close values of the spectral width of the line indicate that the spectral shape of the signal emitted into open space corresponds exactly to the shape of the signal measured in the feedback loop through the output IF path of the harmonic mixer. The line width
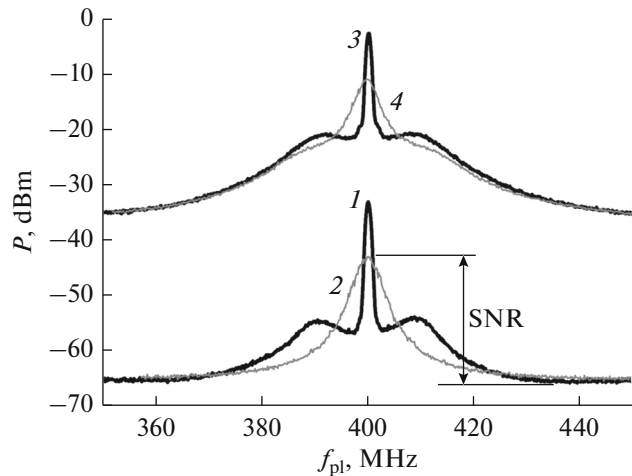
of the stabilized signal using the PLL in Fig. 7 is determined by the selected resolution of the used spectrum analyzer [9, 10], which in this case is 1 MHz for curve *1* and 1.8 MHz for curve *3*. The real line width of the stabilized signal is approximately 100 kHz (with a selected spectral resolution of the spectrum analyzer not lower than this value); thus, the line shape with a sufficient degree of accuracy is a δ-function for most practical applications.

As shown in Fig. 7 the study was carried out at selected frequencies of the oscillator in a wide range of frequencies, as determined by the working range of SIR, while the oscillator radiation into the external space was successfully demonstrated in the 500–700 GHz band, which corresponds well to the numerical calculation from Fig. 3b, taking the fact into account that the 400–500 GHz region is outside the working range of the SIR. At all studied frequencies, the ratio of the signal power to the noise power (Fig. 7, curve *2*) was approximately 20 dB or more.

CONCLUSIONS

In this work, a terahertz frequency range oscillator based on a Josephson tunnel junction coordinated with a transmitting antenna-feeder system based on a slit antenna made of a thin Nb film was developed and experimentally studied. The oscillator has a unique bandwidth and emits a signal with a power of approximately 1 μW into open space, so it can be used in almost any task where a widely tunable THz oscillator is needed. These tasks include spectroscopy and het-

erodyne detection, and the field of application of these tasks is extremely wide, radio astronomy and space exploration, monitoring of the Earth's atmosphere and technological processes in production, information, and telecommunication systems, instruments for medical diagnostics and security systems. Two designs of antenna-feeder system for the oscillator have been developed, whose working range was 250−420 and 400−700 GHz; the spectral line of the emitted signal without stabilization has a Lorentz shape with a line width of the order of several megahertz. Thus, the two designs in total cover a rather wide range, 250−700 GHz. To stabilize the oscillator in both designs, a harmonic mixer was also developed and investigated, which is used in the feedback loop with the oscillator in conjunction with a phase locked loop system that collects up to 95% of the signal power at a central peak of approximately 100 kHz with a signal-to-noise power ratio 20 dB. The pumping range of the oscillator power oscillator for structures of 300 and 600 GHz, which was 250−450 and 500−680 GHz, respectively, was investigated.

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