ISSN 1064-2269, Journal of Communications Technology and Electronics, 2021, Vol. 66, No. 3, pp. 278–288. © Pleiades Publishing, Inc., 2021.
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MICROWAVE ELECTRONICS

Study and Comparison of Laboratory Terahertz Sources Based on a Backward Wave Oscillator, a Semiconductor Microwave Frequency Multiplier with Large Numbers of Harmonics, and a Long Josephson Junction

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Received August 21, 2020; revised August 21, 2020; accepted September 30, 2020

Abstract—We report on a comparative analysis of three different laboratory terahertz (THz) sources emitting into open space based on a backward wave oscillator with a frequency multiplier, a microwave frequency multiplier to large numbers of harmonics based on semiconductor superlattices, and a recently developed long Josephson junction-based oscillator. The weight–size parameters, frequency responses, and radiation powers of the sources have been qualitatively and quantitatively compared, along with the complexity of their tuning and operation under laboratory conditions.

DOI: 10.1134/S1064226921030116

INTRODUCTION

In modern science and technology, instruments and methods for research in the terahertz (THz) frequency range (0.1–10 THz) attract much attention: new devices are being developed and the available sources and detectors find additional ranges of application (see, for example, review [1]). The increased interest in this field evokes the competition in the development of various THz sources for specific applications in science, industry, and socio-economic sphere. Terahertz imaging, time and frequency domain spectroscopy, heterodyne detection of weak signals, and THz microscopy are increasingly used in biology, medicine, safety systems, environmental monitoring, and astronomical research. For example, compact THz sources based on quantum cascade lasers, photomixers, and Schottky-diode and superlattice multipliers are included in high-sensitivity receiving systems at ground- and space-based radio telescopes and observatories; signal multipliers with both the low (below 5) and high (higher than 30) harmonic number are used.

At present, there are several Russian research teams that are actively engaged in the development and study of such sources. In this study, we carried out a comparative analysis of three laboratory THz sources that we have at our disposal. The first source is based on a backward wave oscillator (BWO) [2–4] with a multiplier to harmonics with numbers of 3–5; the second source is based on multiplying the input microwave signal in a structure made of GaAs/AlAs semiconductor quantum superlattices (SLs) [5–7] up to high (more than 30) harmonic numbers; and the third source developed by our team is based on a superconductor–insulator–superconductor (SIS) long Josephson junction (LJJ) matched with a transmitting slot antenna [8–13]. The idea of using the LJJ as a microwave and THz oscillator appeared quite long ago [14] and was then implemented by our team in a practical mission on studying Earth's atmosphere [15, 16]; the LJJ oscillator was integrated with an SIS mixer in one chip and represented a heterodyne for a superconducting receiver operating in the band of 500–650 GHz. Recently, we developed a LJJ source emitting into open space via a double slot antenna located on one chip with the oscillator. The frequency characteristics of transmitting antennas of different designs were studied and reported in [8, 9]. To ensure the phase synchronization of the radiation, the chip was supplemented with a harmonic mixer operating in a feedback circuit with a LJJ together with phase locking loop (PLL) system [10, 11]; the spectral characteristics of the radiation were studied in [10–12]. The operating output frequency band, which is mainly determined by the characteristics of a transmitting antenna and its impedance matching with the LJJ, was investigated for one antenna design in [13].

The frequency band of the output radiation and investigations of the devices was 480–700 GHz, which corresponds to the lower boundary of the THz range; all the devices under study are continuous (nonpulsed) radiation sources. A key objective of this study is to compare the characteristics of the recently developed LJJ-based oscillator with commonly used and well-studied types of THz oscillators. The comparative analysis of this kind gives a qualitative idea about the sources with different operation principles in terms of the possibility of their specific applications.

1. GENERAL COMPARATIVE ANALYSIS OF THE SOURCES[1]

1.1. Backward Wave Oscillator Source

BWOs are the most conventional representatives of THz sources. In such devices, the lasing is based on the interaction of an electron beam with an electromagnetic wave [1–4]; the devices have a large weight due to the need for using a strong permanent magnet and a high-voltage power supply. In this study, we used a BWO-based laboratory source developed at the Institute for Physics of Microstructures, Russian Academy of Sciences (Nizhny Novgorod). The source is a complex device (Fig. 1) consisting of a high-voltage power supply, a BWO with an output frequency in the range of 120–160 GHz, a system of PLL of the BWO output signal, and a multiplier based on a semiconductor SL with a waveguide. The multiplier waveguide is designed to provide the best operation at the 4th harmonic of the BWO signal due to filtering of the frequencies below 350–400 GHz; the radiation outcoupling into open space is ensured by a horn antenna. The mass of the entire source system is 17.4 kg, the dimensions of the functional part of the source (without a personal computer (PC)) are about 500 × 300 × 280 mm (hereinafter, L × W × H), and a power consumption from the ~220 V network is no higher than 0.25 kW. The operating output frequency range is 480–640 GHz (the 4th BWO harmonic), the frequency step is 10 kHz, and the horn antenna output power, according to the device specification, is no lower than 0.2 μW. The output radiation has a fairly narrow directivity pattern owing to the horn antenna located at the multiplier output; to transmit signals over long distances, a converging lens can additionally be used. It should be noted that the device is rather heavy and cumbersome. Under laboratory conditions, when the device is used as an external THz source, its dimensions do not cause any significant inconvenience; it seems impossible, however, to mount the source into a housing together with other devices or integrate it in a miniature complex setup. The output signal frequency is controlled using an operator's PC (usually, a laptop); the software allows automatic frequency tuning in time with a specified step.

[1] This section describes the characteristics of the specific devices at the disposal of the team at the Kotelnikov Institute of Radio Engineering and Electronics, Russian Academy of Sciences.

Fig. 1. BWO THz source: (*1*) BWO unit, (*2*) output frequency multiplier 120–160 GHz, and (*3*) power supply unit for auxiliary electronics.

1.2. Microwave Multiplier-Based Source

Over the past two decades, microwave multipliers based on semiconductor SLs have become widespread due to the ease of operation and relative diminutiveness [1, 5–7]. Their main drawback is that their efficient operation at frequencies above 1 THz, which corresponds to high (above 50) harmonic numbers, requires signal multiplication at frequencies around 100 GHz, which is not commercially available yet. In this study, we used a sample of a GaAs/AlAs-based multiplier fabricated at the Ioffe Institute and the Nizhny Novgorod State University (Fig. 2). The multiplier is equipped with a rhomboid output horn antenna and a coaxial microwave cable for setting the input signal. The dimensions of the multiplier are about 30 × 20 × 20 mm and the mass is about 50 g, which is negligible as compared with the dimensions and mass of the basic microwave signal source. Thus, when the multiplier is used as an external THz source under laboratory conditions, its actual weight–size characteristics are determined solely by the characteristics of the original microwave source; the coaxial microwave cable alone, which efficiently operates up to 30 GHz, is comparable (or exceeds) in mass with the sample multiplier. As an example, note that a widely tunable Keysight Technologies commercial laboratory microwave oscillator (US) with a frequency from 250 kHz to 40 GHz has a mass of 20.3 kg and dimensions of 500 × 420 × 180 mm. If a problem to be solved does not require broadband frequency tuning, then a relatively miniature single-frequency source weighing from one to several kilograms can be used. Since the multiplier is a passive device, the final power consumption of the system is completely determined by the power consumption of the base source, which is

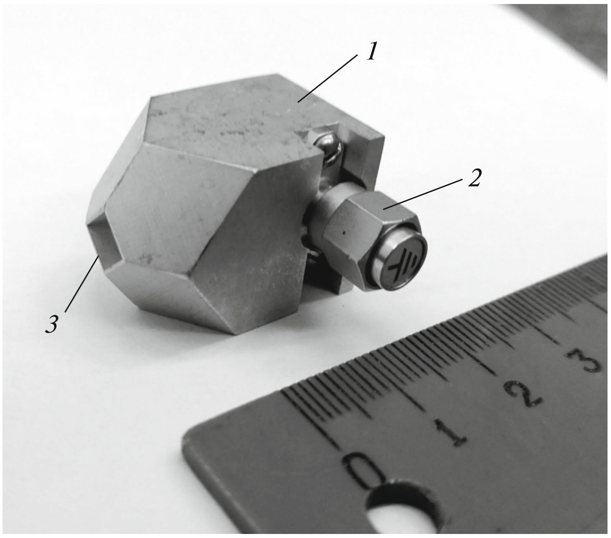

Fig. 2. SL-based microwave multiplier: (*1*) multiplier housing, (*2*) input microwave SMA coaxial connector, and (*3*) output horn antenna with the rhombus-shaped cross section.

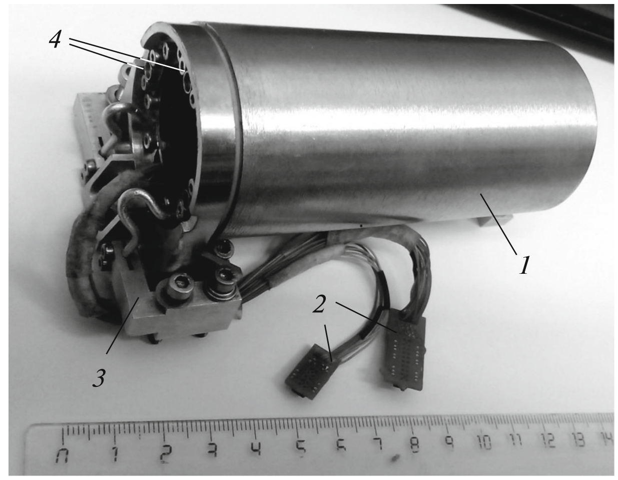

Fig. 3. Cryogenic module of the LJJ-based THz oscillator: (*1*) magnetic shield, (*2*) connectors for dc control of the chip components, (*3*) aluminum thermal straps for cooling the structure down to 4.2 K, and (*4*) input and microwave output coaxial connectors.

~0.3 kW for the above-described commercial device and can range from several watts to 1 kW.

When a signal with frequency f is supplied to the input of an SL, at its output and, correspondingly, at the waveguide input, there is a comb signal at integer harmonics $2f$, $3f$, ..., $30f$, $31f$, etc. The waveguide filters the signal at frequencies below ~350–400 GHz; thus, the signal arrives at the horn antenna and then passes into open space only at the harmonics with a frequency higher than 400 GHz. The SL design allows one to tune the bias on the structure, which determines the efficiency of conversion at even and odd harmonics, which makes it possible to amplify a required harmonic. If the application requires a single-frequency signal rather than a harmonic comb, then additional narrow-band filters should be used. The upper limit input frequency is determined by the parameters of the input microwave line and can be restricted by the input capacity. For instance, a sample of the multiplier at the BWO output (see Section 1.1) transmits input frequencies of up to 160 GHz, while the sample with the coaxial input has a limit input frequency of 24 GHz. The optimal frequency range for obtaining the best output power at a desired THz frequency is 20–24 GHz and the optimal input signal power is 10–15 dBm and depends on the chosen input frequency. Thus, since the multiplier is a passive device, the ease (complexity) of working with it is determined, in fact, by the ease (complexity) of working with the basic source; the choice of the source depends on the problem being solved. If a problem requires broadband THz frequency tuning with a small step and the possibility to adjust the output power, then a multifunctional commercial microwave source with a built-in display is needed; if in the problem solved one or several specified output frequencies of fixed power are sufficient, then it seems reasonable to use a more miniature and special microwave source. Due to its compact size, the multiplier can be easily mounted into one housing with other devices in order to integrate it into a complex miniature setup, in contrast to the BWO source.

1.3. Long Josephson Junction-Based Source

The third THz source investigated here is a superconducting source based on a LJJ with $Nb/AlO_x/Nb$ SIS structures with a limiting Josephson lasing frequency of about 700 GHz, which is determined by the fundamental properties of superconducting junction edges and niobium-based transmission lines. The operation principle and the most important characteristics were described in detail in [8–13], but the issues of ergonomics of the source in terms of application have not been discussed. The basic oscillator cryogenic module includes a chip with an oscillator, an antenna, and a harmonic mixer (HM) mounted on a semi-elliptical silicon lens, as well as a massive magnetic shield for screening the LJJ from external interference; the dimensions of the device are 120 × 45 × 60 mm and its mass is about 0.4 kg (Fig. 3). The oscillator operates at the temperature of liquid helium (4.2 K) and is conventionally mounted in a filling cryostat. The advantage of this source is the possibility of mounting a cryogenic module in the common cryogenic system of the problem solved; in this case, the weight–size characteristics of the module almost do not play any role in the general system. The drawback of its use in room-temperature cases is the need for independent cooling of the base oscillator module,

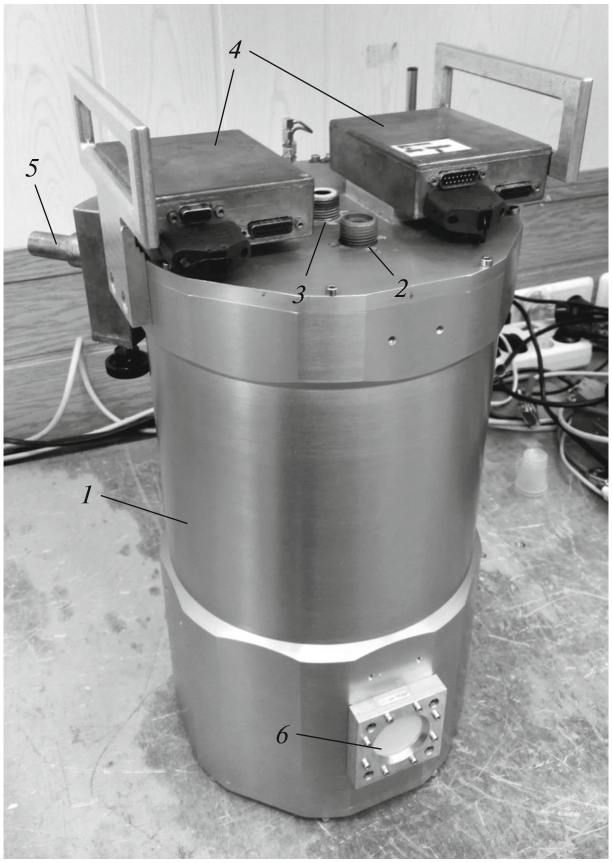

Fig. 4. Filling cryostat for operation at a temperature of 4.2 K with a cryogenic module of the THz source installed inside: (*1*) cryostat housing, (*2*) filler neck for pouring liquid nitrogen, (*3*) filler neck for pouring liquid helium, (*4*) switch boxes for dc control of all functional elements of the system, (*5*) high-vacuum valve for pumping out the internal volume of the cryostat to a pressure of about 10^{-6} mbar (at a temperature of 4.2 K), and (*6*) output window with IR filters made of Mylar and Gore-tex materials highly transparent in the THz range.

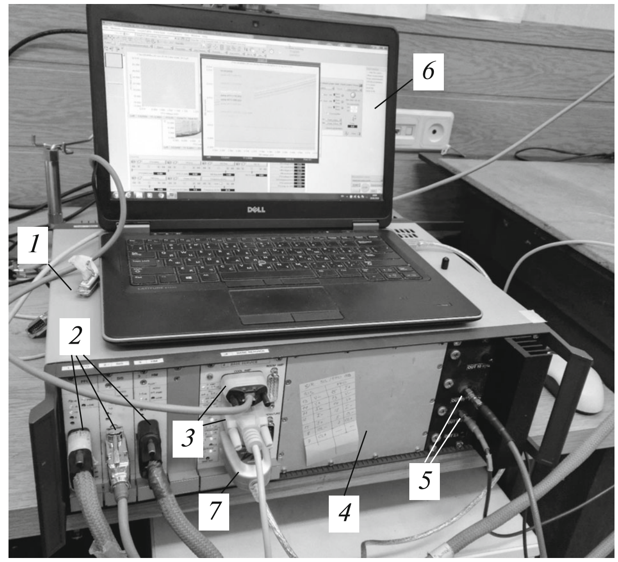

Fig. 5. Integrated unit for controlling the LJJ-based THz source system: (*1*) unit housing, (*2*) connectors for dc control (bias) of chip components, (*3*) connectors for controlling external auxiliary elements (PLL systems and microwave amplifiers), (*4*) battery unit for autonomous control of low-noise elements using a ~220 V network, (*5*) reference microwave oscillators (19–21 GHz and 400 MHz), (*6*) operator's PC (laptop) for total control of the unit, and (*7*) RS-232 standard connector for connecting to a PC via a universal port.

which requires rather a massive cryogenic system. For example, the gross weight of an equipped Infrared Lab cryostat (US) with a volume of ~4 L for liquid helium providing 8–12 h of continuous operation is 21.6 kg (without liquid helium and nitrogen) and its dimensions are 300 × 300 × 500 mm (Fig. 4). The external equipment of the cryostat includes room-temperature microwave amplifiers, an PLL system, and microwave cable routing, which are located on the back of the cryostat and cannot be seen in the photograph. These specifications already include microwave amplifiers of output signals at an intermediate frequency (IF) of up to 8 GHz, filters for reducing dc and microwave noise, an PLL system, and all electrical and microwave wiring, but do not include power supplies for all the listed items and accessories. Instead of a filling cryostat, a closed-cycle cryogenic system based on a high-performance refrigerator can be used to cool the system to the working temperature. To power the active components (the IF amplifiers and PLL system), a low-voltage (below 6 V) power source with a total current of up to 1 A is additionally needed; the PLL system requires a 400-MHz reference signal and the feedback system also requires a tunable microwave reference signal in the range of 19–21 MHz. To control the key components of the chip (the LJJ and harmonic mixer), three independent low-noise current sources (up to 200, 100, and 10 mA) are required with the desired autonomous battery operation without using a ~220 V network in order to minimize the noise, as well as a PC for convenient and operating control of all the components of the system. For visual monitoring of the phase stabilization of the output radiation, a spectrum analyzer up to 1 GHz is conventionally used, which, if necessary, can be replaced by monitoring only the mixer output power using a phase detector. The mass of all the above-listed auxiliary equipment, depending on the design and problem to be solved, can range from 10 to 30 kg, in addition to the mass of the cryogenic setup. For example, all the auxiliary equipment can be integrated into a single unit with a mass of about 20 kg and dimensions of 380 × 480 × 140 mm controlled using a compact laptop (Fig. 5), but one can use several external multifunctional devices with independent control and a full-scale high-performance PC.

The total working power consumption also significantly depends on the design: when a filling cryostat is

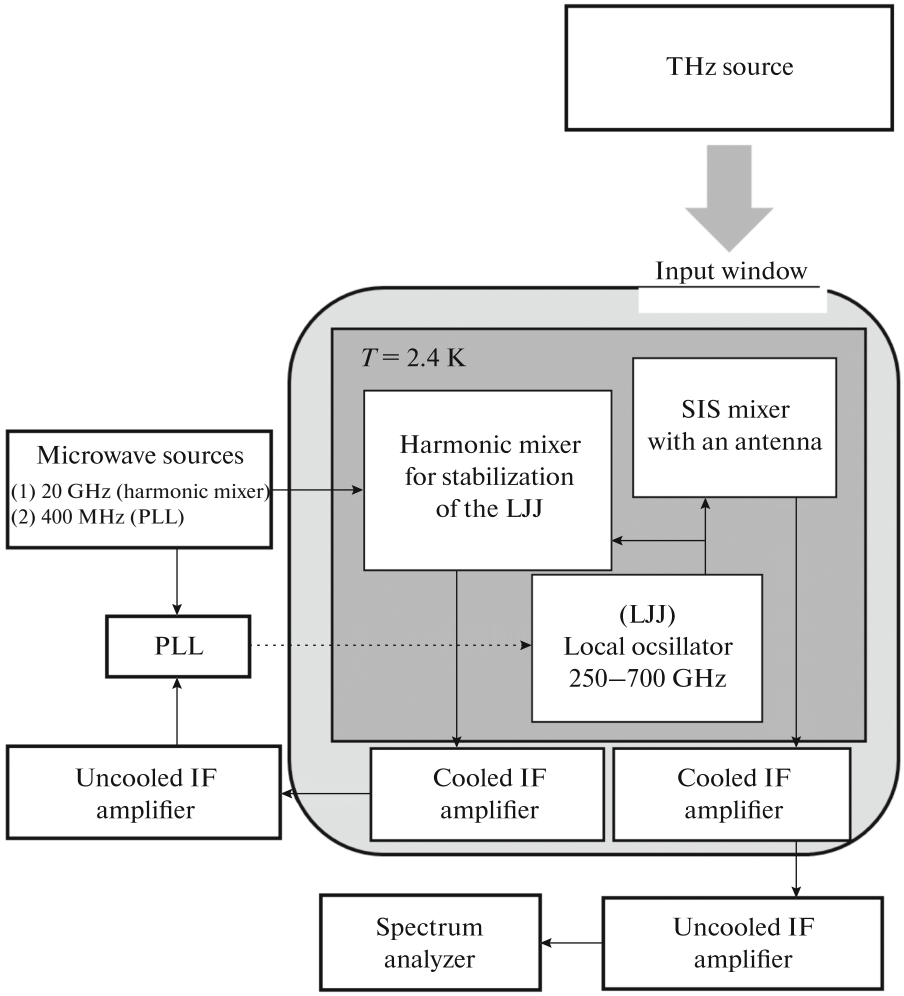

Fig. 6. Block diagram of the experimental setup for studying the spectral characteristics of the external THz source.

used, the power consumption is only determined by that of the auxiliary equipment and usually amounts to 1 kW, but if a cryogenic refrigerator is included in a closed-loop system, then additional power of several kilowatts is needed for operation of a compressor.

With the above-described design complexity of this source, its indisputable advantages are the frequency tuning bandwidth, which attains 70% of the center frequency for one experimental sample, and the lack of necessity to redesign the entire system for operation in a different frequency range: it is sufficient to change the chip with the oscillator and antenna. In [11, 12], samples with the working frequency bands of 250–420 and 400–720 GHz were developed and investigated, which form tuning bandwidths of 50 and 57% of the center frequency, respectively. The tuning range can be extended by more careful design of a dual-slot antenna topology and matching structures, as well as by using a different-type antenna, e.g., a log-periodic one. Another advantage is the possibility of integrating the module into a common cryogenic system for solving low-temperature problems, for example, in studying low-temperature properties of materials and in THz microscopy.

2. COMPARATIVE ANALYSIS OF SPECTRAL CHARACTERISTICS

The spectral characteristics of the radiation of sources into open space were investigated using a THz spectrometer based on a receiver with high spectral resolution. In the experimental setup (see the schematic diagram in Fig. 6), the three devices studied here are used as sources and a spectrum analyzer is a device for recording the spectrum. The detector included in the THz spectrometer is a complex superconducting device based on an integrated circuit (for more details, see, for example, [15–17]). The spectral resolution of the spectrometer based on an SIS mixer is determined by the spectral characteristics of both the LJJ-based heterodyne and the microwave reference source used for phase stabilization of the heterodyne; it amounts to about 40 kHz. The spectral resolution of the output spectrum analyzer depends on the analysis bandwidth and is up to 1 Hz in the narrowest band, which obviously exceeds the spectrometer resolution. The signal at the SIS mixer output is a convolution of two signals: from the LJJ-based heterodyne oscillator stabilized by the PLL system and from the investigated source. The working band of the spectrometer is 480–700 GHz; the exact spectral resolution depends on a specified receiving frequency, because the spectral characteristics of the LJJ and the number of the reference microwave source harmonic used are different at each operating point. The typical value of the 20 GHz harmonic number used is from 25 to 35. In addition, it should be noted that, in studying the characteristics of the LJJ-based source, a receiver heterodyne is also the LJJ-based oscillator; i.e., the operation of the setup involves two LJJs simultaneously stabilized by independent PLL systems and distant from one another by the IF bandwidth (about 6 GHz) in operating frequency.

Figure 7 shows the measured frequency responses of the investigated sources detected by a Keysight Technologies (USA) spectrum analyzer. The spectrometer output range (the IF bandwidth) is 4–8 GHz; the measurements were performed at the center of the 6-GHz IF bandwidth. All the spectra shown in Fig. 7 were recorded at a wide frequency span (several gigahertz) of the spectrum analyzer and a spectral resolution of 1.8 MHz in order to visualize the waveform of the recorded signal and are shown in an analysis bandwidth of 300 MHz. Since the recorded signal is a convolution of signals of the spectrometer heterodyne and the investigated source, when the spectral linewidth of the investigated source is much narrower than the linewidth of the heterodyne signal, the frequency response of the recorded signal actually repeats the frequency response of the heterodyne. This is the case illustrated in Figs. 7a and 7b, since the spectral linewidths of the 4th BWO harmonic and higher harmonics of the microwave multiplier numbered from 25 to 60 is smaller than the linewidth of the LJJ-based heterodyne in the phase stabilization mode by approximately 1–2 orders of magnitude. In addition, there is a feature in the side peaks with a height of about 10 dB located above and below the carrier frequency by about 100 MHz (see Fig. 7a). This is most likely caused by the spurious leakage of high-power reference signals in the microwave path. A fundamental difference in the signal shape is observed in Fig. 7c, since the recorded spectrum is a convolution of signals from two LJJs with similar frequency responses. Interestingly, the typical widths of the autonomous emission lines of two LJJs are different at the same (similar) frequencies, since the LJJ included in the investigated source is based on the $Nb/AlO_x/Nb$ trilayer, while the heterodyne oscillator is based on the Nb/AlN/NbN structure. The fundamental difference between these structures is different total energy gaps

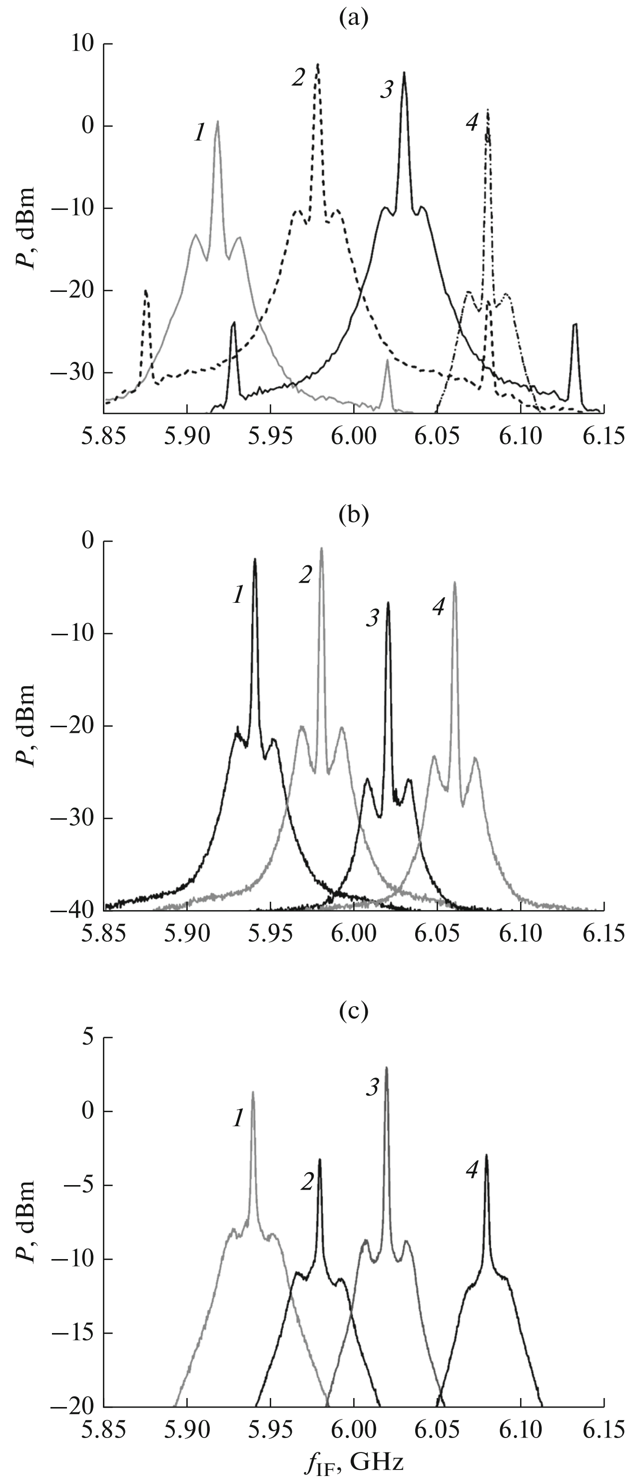

Fig. 7. Series of frequency responses of the THz sources based on (a) the BWO at frequencies of (*1*) 480, (*2*) 500, (*3*) 550, and (*4*) 600 GHz (all the frequency response curves were measured for the signal of the 4th BWO harmonic); (b) the microwave multiplier at frequencies of about 600 GHz for harmonics of m = (*1*) 25, (*2*) 30, (*3*) 50, and (*4*) 60; and (c) the LJJ with a transmitting antenna at frequencies of (*1*) 500, (*2*) 550, (*3*) 600, and (*4*) 650 GHz.

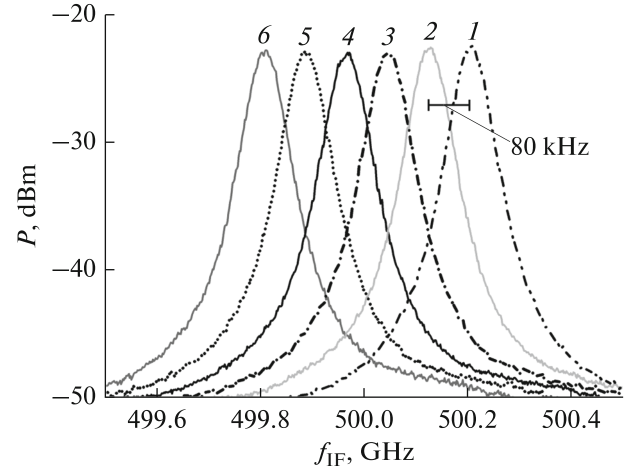

Fig. 8. Series of frequency responses of the BWO THz sources at frequencies of about 600 GHz with a step of 80 kHz: (*1*) 600000.00, (*2*) 600000.08, (*3*) 600000.16, (*4*) 600000.24, (*5*) 600000.32, and (*6*) 600000.40 MHz.

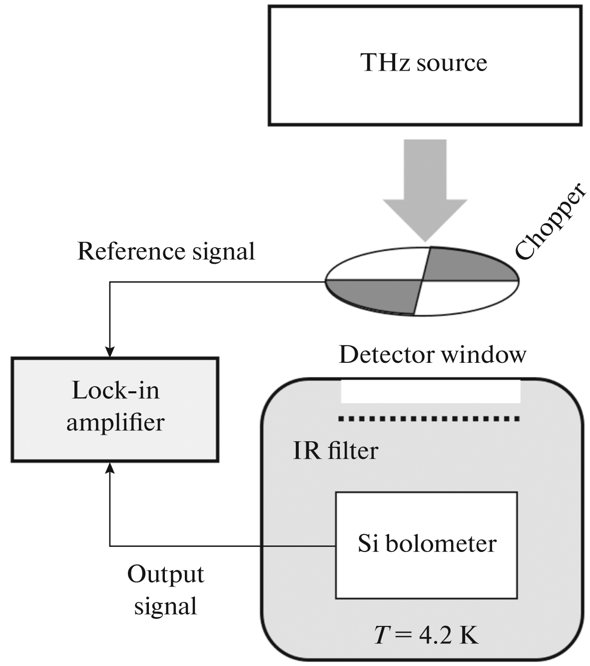

Fig. 9. Block diagram of the experimental setup for studying the integrated emitted power of an external THz source.

of the tunnel junctions (about 2.8 mV for Nb/AlO_x/Nb and about 3.6 mV for Nb/AlN/NbN). Both structures exhibit the self-pumping effect [18–20], due to which differential resistance R_d and, consequently, the lasing linewidth in the autonomous mode (without PLL) increases upon approaching cutoff frequency f_b and abruptly drops in a narrow region around f_b. The f_b value is determined by the energy gap of the structure and is equal to the frequency corresponding to a third of the gap junction voltage, which is about 450 GHz for Nb/AlO_x/Nb with a sharp increase in R_d at frequencies of 455–490 GHz and about 600 GHz for Nb/AlN/NbN with a sharp increase in R_d at frequencies of 605–630 GHz. For this reason, there are differences in the shape of the convolution signals of the spectra for two LJJs at different frequencies (curves *1–4* in Fig. 7c). The width of the recorded spectral lines of the lasing for all the investigated sources with the PLL mode with regard to the convolution with the heterodyne signal was about 40–50 kHz, which is the spectral resolution of the spectrometer with a LJJ-based heterodyne. In this case, the spectral linewidth for the LJJ-based source in the PLL mode is about 50 kHz or more, since the spectral resolution of the device is determined by the characteristics of the LJJ as a heterodyne, while the real spectral width of the frequency response of the sources based on the BWO and the microwave multiplier is 1–2 orders of magnitude smaller.

Figure 8 shows a series of frequency responses of the BWO source measured with a spectrometer in a narrower (1 MHz) band with a spectral resolution of 1 kHz, and a step of the output frequency of the source of 80 kHz. The signal was detected using an additional down-frequency stage based on a semiconductor mixer and a reference signal of 6 GHz, so that the IF range in the experiment with the BWO-based source was 0–1 GHz centered at 500 MHz. It can be seen that the vertices of curves *1–6* are separated from each other exactly by a source frequency step of 80 kHz and each curve can easily be distinguished as a curve different from others, which indicates that the spectral resolution of the spectrometer is tens of kilohertz. Thus, we can state that all three sources can potentially be used to solve the problems where the lasing linewidth of about 50 kHz in the stabilized mode is sufficient. If the frequency response of a source with a characteristic peak width of the order of a few kilohertz or less is required, then the source based on the LJJ is not suitable for such tasks, and the characteristics of sources based on the BWO and the output harmonics of the microwave multiplier require more careful study.

3. COMPARATIVE ANALYSIS OF THE RADIATION POWER

The power in the uncalibrated mode was studied using an Infrared Lab (USA) commercial high-sensitivity silicon-based broadband bolometer, which represents a sample bolometer cooled to 4.2 K mounted in a filling cryostat (Fig. 9); the devices investigated in this study were used as sources and a lock-in amplifier was used to detect the output signal. The optimal frequency of the optical chopper, which depends on the bolometer operation speed and is lower than, e.g., the speed of superconducting detectors, was chosen to be

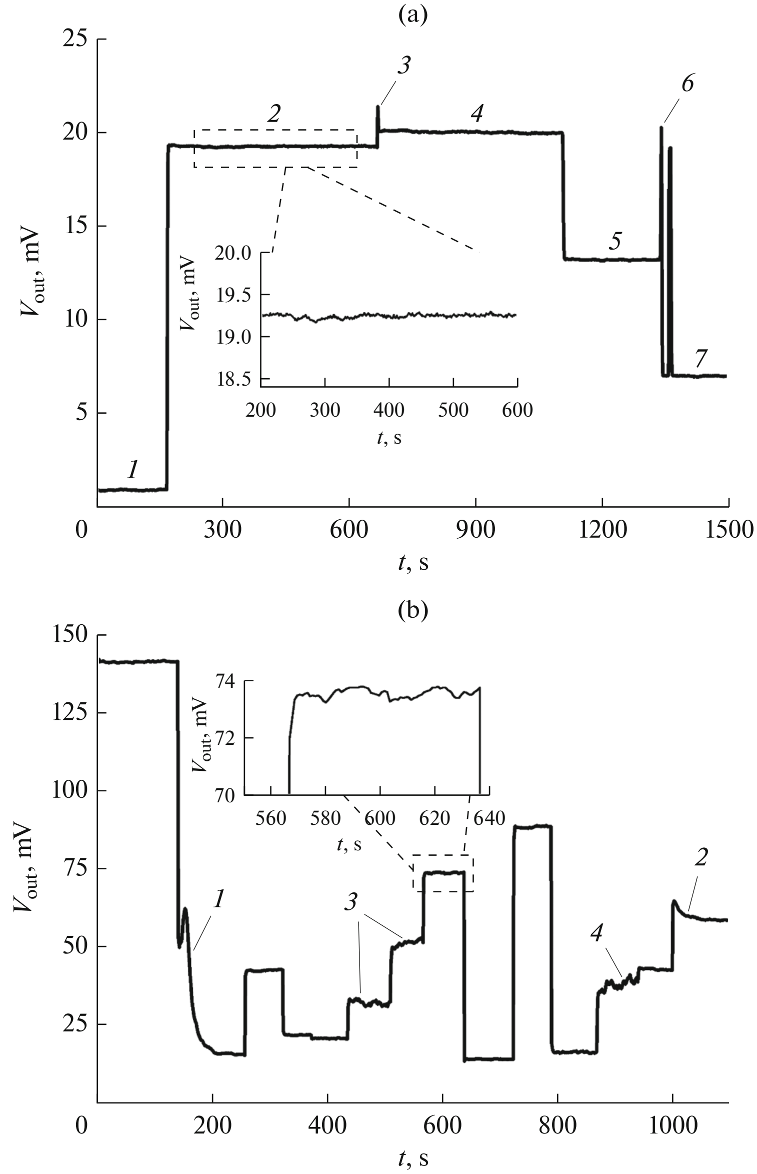

Fig. 10. Time dependence of the signal at the bolometer output under irradiation by a THz signal from the sources based on (a) the microwave multiplier and (b) the LJJ without a stabilization system. (a) (*1*) The source is off, (*2*, *4*, *5*, *7*) different output power of the multiplier, and (*3*, *6*) "bursts," due to process of manual tuning of the multiplier power. (b) (*1*, *2*) Transient processes of establishing the operating point due to thermal relaxation and (*3*, *4*) unstable operating points. Insets: enlarged scale.

170 Hz. The integrating time constant of the lock-in amplifier was chosen to be 900 ms. This set of parameters appeared optimal in terms of the duration of the experiment and the level of fluctuations of the detected signal, which was negligible as compared with the useful signal at the chosen parameters. The main technical difficulty upon detecting a THz signal with this bolometer is its high sensitivity to the IR signal, which is noise for the current configuration. To minimize it, a quartz IR filter transmitting THz signals was placed inside the cryostat at the bolometer input. Since the calibrated power measurement on this experimental setup is fairly complex (the P–V characteristic of the bolometer is specified for the IR radiation and unknown for the THz frequency band and the signal detected by a lock-in amplifier depends on too many factors), the measurements performed are of interest for the comparative study of the detected power of different sources, regardless of the beam geometry, as well as the study of the frequency dependence of the output power for a single source.

Figure 10 shows the output signal power measured upon variation in the operating point in time in the manual mode for the microwave multiplier and LJJ-based sources. The horizontal portions in both figures correspond to the constant operating point of the sources, i.e., the signal lasing in a constant mode; the vertical portions correspond to the moments of instantaneous rearrangement of the operating point. The background IR signal at the selected measurement mode and laboratory conditions is about 2 mV and quite stable (portion *1* in Fig. 10a); in this case, the useful signal is about 20 mV for the multiplier-based source (portions *2*, *4*, and *5*) and about 50–100 mV for the LJJ-based source. The inset in Fig. 10a shows a detected signal fluctuation level of about 0.1 mV, which is determined by a number of different fluctuations in the system, including the background fluctuations of the IR signal in the laboratory space, the power fluctuations of the basic microwave source, the fluctuations of the bolometer operating point, the fluctuations of the optical chopper frequency (about 170 Hz) and, correspondingly, of a reference signal for the lock-in amplifier, as well as the electromagnetic fluctuations in a room at a low (about 50 Hz) frequency and in a ~220 V network supplying the system components. All these factors or a part of them affect or can affect, to different extents, the stability of the detected signal; the fluctuation level was negligible as compared with the useful signal. The inset in Fig. 10b shows a higher fluctuation level (about 0.5 mV) and portions *3* and *4* are characterized by the instability of the operating point in the I–V characteristic of the LJJ. Since the measurement systems for different sources are completely identical, we can state that the high signal fluctuation level for the LJJ-based source is only related to the system of the source itself, specifically, to the instability of the operating point in the I–V characteristic of the junction with the idle PLL system. In addition, it is interesting to note the fairly slow processes of establishing the operating point due to the thermal relaxation in portions *1* and *2* (see Fig. 10b) after switching the operating point with the strongly changed Joule heat release in the junction.

The uncalibrated study of the THz source signal power at different output frequencies yielded the following: characteristic values of 10–50 mV and a maximum value of 57.8 mV for the BWO source; characteristic values of 10–20 mV and a maximum value of about 28 mV for the microwave multiplier-based source; and, for the LJJ-based source, characteristic values from 20 to 100 mV, depending on experimental sample designs intended for operation in different frequency bands between 200 and 700 GHz and a maximum value of about 150 mV for the sample with frequency tuning between 400 and 570 GHz. It is important that, in this experiment, the detected signal depends, to a great extent, on both the geometry of the emitted beam and the bolometer directivity pattern, which were not studied here.

Thus, the highest detected power of the THz signal was demonstrated by the LJJ-based source and the lowest power, by the source based on the microwave multiplier. In addition, this experiment does not distinguish the harmonic composition of the THz signal, but integrates the entire power of the received radiation; the maximum radiation for the BWO and LJJ-based sources corresponds to the fundamental harmonic and the signal at the multiplier output is a comb of frequencies above 350 GHz with a step of ~20 GHz (see Section 1), so the signal power at a specific frequency is unknown.

4. RESULTS OF THE COMPARATIVE ANALYSIS AND DISCUSSION

The results of the comprehensive comparative study of three sources for all the characteristics analyzed above are given in Table 1.

Thus, the simplest to operate but the one with the lowest power among the three investigated THz sources in a specific design is the microwave multiplier based on GaAs/AlAs SLs. The main advantage of the device is its compactness and, consequently, the ability to be integrated in one unit (module) with other devices. The main drawbacks are the low output power and a frequency comb at the output, which does not allow it to be used in solving problems that require a single-frequency oscillator without harmonic composition. To obtain higher power levels, commercially unavailable microwave amplifiers up to 100 GHz are needed. The most technically and operationally difficult is the LJJ-based source, which, at the same time, demonstrated the highest detected power and the broadest operation frequency band and does not have a “rich” harmonic composition. The technical requirements for working with such a source include not only the presence of a 4.2-K cryogenic setup, but also low noise in the power supply of the main chip components, as well as low-noise microwave amplifiers (up to 1 GHz). Another advantage is the possibility of integrating a composite device into a single cryogenic system, which can be useful, for example, in studying the properties of materials at low temperatures. A compromise in the detected power and ergonomics between the low-power source based on a microwave multiplier and the technically complex source based on a LJJ is the BWO source with a multiplier. It is quite convenient for laboratory application, when the weight and size of a device are unimportant, and, simultaneously, has a power sufficient for many problems solved in the THz frequency band. Similar to the source based on the microwave multiplier, it has a frequency comb at the output, but the distance between adjacent frequencies is 120–160 GHz (in contrast to the range of 10–24 GHz for the microwave multiplier), which, in most cases, does not present challenges.

Table 1. Comparative characteristics of three different sources

Parameters	Source base		
	BWO	microwave multiplier	LJJ
Basic module (block) dimensions L × W × H, mm	500 × 360 × 280	30 × 20 × 20	120 × 45 × 60
Base module (block) mass, kg	17.4	0.05	0.4
Additional required components	Personal computer/laptop	Basic microwave oscillator with a power of at least 10 dBm	Cryogenic system; integrated power supply and control system; microwave sources and amplifiers
Power supply, kW	Below 0.25	Usually no more than 0.3 (determined by the power consumption of the base oscillator)	Usually no more than 1 (determined by the power consumption of additional components)
Working temperature, K	293	293, cooling down to 4.2 is allowed	4.2
The ability to be integrated into a compact unit with other devices	No	Yes	Yes, under the condition of a common cryogenic system
Output frequency range, GHz	480–640	Above 350	200–750
Linewidth in the phase stabilization mode, kHz	<40	<40	~40
Characteristic output power in the range of up to 700 Hz, arb. units	10–50	10–20	20–100
Maximum detected power, mV	57.8	28	150
Other features	BWO frequency 120–160 GHz, multiplier at the BWO output; PC control	Passive device; frequency comb at the output; weight–size characteristics are determined by the base oscillator	Manual signal stabilization control using a PC; weight-size characteristics are determined by additional components

CONCLUSIONS

In this study, we carried out a comprehensive comparative analysis of three laboratory THz sources based on devices with different operation principles: a BWO with a multiplier at the output, a microwave multiplier on semiconductor superlattices with a high harmonic number, and a superconducting LJJ. The experimental samples at the disposal of the group of authors at the Kotelnikov Institute of Radio Engineering and Electronics, Russian Academy of Sciences were reseached. The study of the characteristics of the THz sources was original and did not repeat the results of other papers.

The frequency responses of the sources were investigated using a THz spectrometer based on a superconducting integrated receiver with a spectral resolution of about 40 kHz. The radiation power was studied using a broadband cooled silicon-based bolometer. The radiation linewidth of all the sources at operating frequencies ranging between 500–600 GHz in the phase stabilization mode was smaller than 100 kHz. The highest detected power was obtained by the LJJ-based source and the best ergonomics of room-temperature operation was demonstrated by the SL-based microwave multiplier with a high harmonic number.

Each of the investigated sources has specific features and holds a certain area in the modern development and study in the THz range; in common, these areas do not overlap. Now, all three sources are successfully used at frequencies of up to 700 GHz. This study can be useful not only regarding a comprehensive review of the characteristics of different THz sources and their comparative analysis, but also from the viewpoint of techniques for the experimental study of the characteristics of oscillators.

ACKNOWLEDGMENTS

We are grateful to V.L. Vaks, E.G. Domracheva, and V.A. Anfert'ev (Institute for Physics of Microstructures, Russian Academy of Sciences, Nizhny Novgorod), D.G. Pavel'ev (Nizhny Novgorod State University, Nizhny Novgorod), A.M. Baryshev (Kapteyn Astronomical Institute, Groningen, Netherlands), K.I. Rudakov, L.V. Filippenko, V.V. Khanin, N.A. Khval'kovskii, I.N. Dyuzhikov, and O.Yu. Volkov (Kotelnikov Institute of Radio Engineering and Electronics, Russian Academy of Sciences, Moscow) for providing experimental samples and equipment for research and fruitful discussions of the results.

FUNDING

This study was carried out within a framework of a state task and partially supported by the Russian Foundation for Basic Research, project no. 19-52-80023. The LJJ-based source was developed with support of the Russian Science Foundation, project no. 17-79-20343 and fabricated using the unique science unit (USU no. 352529) at the Kotelnikov Institute of Radio Engineering and Electronics, Russian Academy of Sciences.

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Translated by E. Bondareva