Study of the THz Oscillator Based on Josephson Junction and Comparative Review with THz Sources – Backward Wave Oscillator and Semiconductor-based Frequency Multiplier

Nickolay V. Kinev
Laboratory of Superconducting Devices for Signal Detection and Processing
Kotel'nikov Institute of Radio Engineering and Electronics of RAS
Moscow, Russia
nickolay@hitech.cplire.ru

Valery P. Koshelets
Laboratory of Superconducting Devices for Signal Detection and Processing
Kotel'nikov Institute of Radio Engineering and Electronics of RAS
Moscow, Russia
valery@hitech.cplire.ru

***Abstract*—A study of the output terahertz (THz) emission to open space from Nb/AlO$_x$/Nb-based long Josephson junction (LJJ) was carried out. Both bolometric technique with a frequency resolution of about1 GHz and heterodyne technique with spectral resolution of about 0.1 MHz were used for detection of the THz emission. A comparative analysis with other types of THz sources was made, such as backward wave oscillator (BWO) and frequency multiplier based on a semiconductor superlattice GaAs/AlAs with large harmonic numbers. A qualitative and quantitative comparison with respect to weight and size characteristics, the spectral properties, the emission power, as well as a general usability in laboratory conditions, was made. The highest detected power was achieved with an LJJ-based oscillator, and the most convenience was demonstrated using a superlattice-based oscillator with large harmonic numbers.**

Keywords—terahertz radiation, Josephson junctions, backward wave oscillators, frequency multipliers

I. Introduction

In modern science and technology, there is a great interest in instruments and research methods in the THz frequency range, which is from 0.1 THz to 10 THz. The highly sensitive receiving systems at ground-based and space-based radio telescopes and observatories utilize compact THz sources based on quantum-cascade lasers, photo-mixers, multipliers based on Schottky diodes and superlattices (SL) with both low (up to 5) and high (more than 30) number of harmonics are used. THz sources are also used in laboratory tasks and research. There are several scientific groups in Russia actively engaged in the development and study of such sources. In this work, we carried out a comparative analysis of three laboratory sources of the THz range. The first one is based on a BWO with a multiplying to harmonics 3-5; the second one is based on a microwave multiplier based on GaAs/AlAs semiconductor quantum SL, and the last one is based on a "superconductor-insulator-superconductor"-type (SIS) LJJ matched with the transmitting antenna. The last of the mentioned sources – the LJJ-based oscillator is made of a Nb/AlO$_x$/Nb trilayer and is recently developed in our group [1-3]. The comparative analysis of sources based on different principles is useful from the point of view of applicability in practical tasks.

The development and study of the Josephson oscillator was supported by the Russian Science Foundation (project No. 17-79-20343). The study of the both backward wave-based and superlattice-based oscillators was carried out in the framework of the state task, and was partially supported by the RFBR (project No. 19-52-80023). A fabrication of the Josephson oscillator was carried out using a Unique Science Unit (#352529) at Kotel'nikov Institute of Radio Engineering and Electronics of RAS.

II. Study Techniques

Both bolometric and heterodyne techniques were used to study the output radiation of THz sources. The study of the uncalibrated power was carried out using a highly sensitive broadband silicon-based semiconductor bolometer. This commercially available device manufactured by Infrared Labs™ (USA) is a sample of a bolometer operating at 4.2 K in a liquid helium cryostat. The block diagram of the experimental setup is shown in Fig. 1, where three different devices studied in this work were used as a source, and a lock-in amplifier is the back end device for signal recording. One should note that detected signal in this setup depends on the beam patterns of both oscillator and bolometer.

The study of the spectral characteristics of the emission to open space was carried out using a THz spectrometer based on a superconducting integrated receiver (SIR) [4-5] with a high spectral resolution. The block diagram of the experimental setup is shown in Fig. 2, where three different devices studied in this work were used as a source, and a spectrum analyzer is the back end device for recording the spectrum. The operating range of the SIR is 480-700 GHz, while the bandwidth of the spectral analysis determined by the intermediate frequency range of 4-8 GHz, is 4 GHz, accordingly.

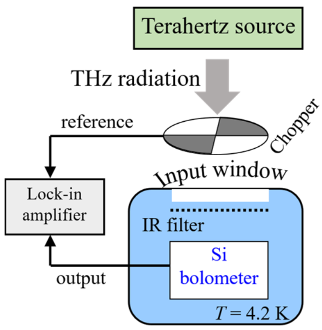

Fig. 1. Block diagram of an experimental setup for studying the emission power of an external THz source.

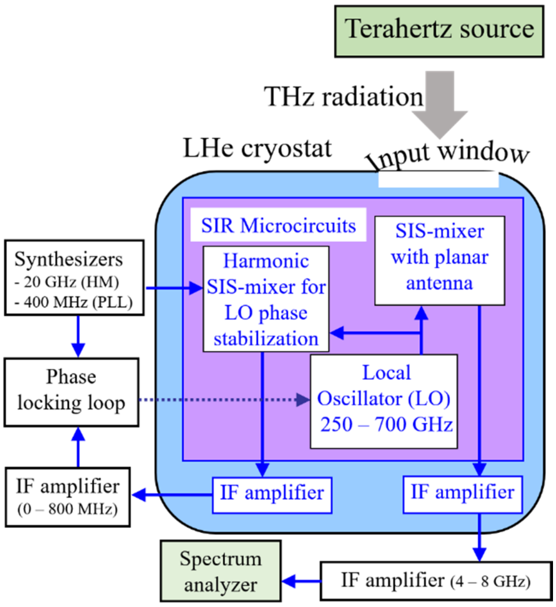

Fig. 2. Block diagram of an experimental setup for studying the spectral characteristics of an external THz radiation source.

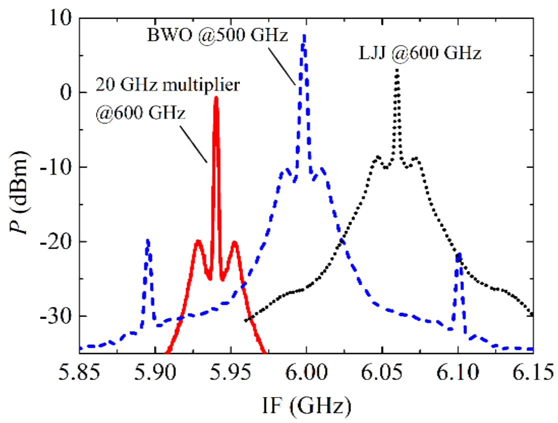

Fig. 3. Spectral characteristics of THz sources measured using a THz spectrometer: SL-based multiplier (input frequency 20 GHz, harmonic number 30) – red curve, a BWO-based source at 500 GHz (BWO frequency 125 GHz, 4th harmonic) – blue curve, an LJJ-based source – black curve. The operating frequencies are specified on the graph.

III. RESULTS

The spectral characteristics of the three sources at certain frequencies are shown in Fig. 3. All spectra were recorded in a band of 5-7 GHz of the spectrum analyzer with resolution bandwidth of 1.8 MHz, and are presented in a bandwidth of 300 MHz. Since the recorded signal is a convolution of the phase-locked local oscillator (LO) of the SIR and the source under study, in the case when the spectral linewidth of the source under study is much less than the linewidth of the LO, the recorded spectrum actually repeats the spectrum of the LO. This is the case for sources based on BWO and SL, since the linewidth of the spectral lines of the 4th harmonic of the BWO and of high harmonics of the multiplier (from 25 to 60) is approximately 1–2 orders of magnitude less than the linewidth of the phase-locked LO of the SIR based on the LJJ.

The following values of detected power in uncalibrated mode were obtained using a silicon bolometer: for a BWO-based source typical values are 10 – 50 mV, the maximum value is 57.8 mV; for an SL-based multiplier typical values are 10 – 20 mV, the maximum value is about 28 mV; for an LJJ-based source typical values are from 20 mV to 100 mV, depending on the design of the experimental sample, which are designed to operate in different frequency ranges between 200 GHz and 700 GHz, and the maximum value is about 150 mV for a sample with frequency tuning in the 400 – 570 GHz range. Taking into account the volt-watt sensitivity of the bolometer of $2.82 \cdot 10^5$ V/W specified for infrared range, the absolute detected power of sources is roughly 35 nW per each 10 mV, i.e. about 175 nW for a BWO-based source, about 70 nW for a SL-based multiplier and about 0.53 μW for an LJJ-based source. It could seem unusual such a small power for a BWO-based source, but one should note that we detected a 4^{th} harmonic (of 120-160 GHz) that is several orders of magnitude lower than the origin BWO signal. In addition, since the bolometer volt-watt sensitivity is specified for infrared range and can be different in THz range, so the numbers presented are an estimation.

IV. COMPARATIVE REVIEW

The results of a comprehensive comparative analysis of three sources are presented in Table 1. The simplest source for operation, but having the lowest detected power, is a multiplier based on GaAs/AlAs superlattices. Its main advantage is compactness and, therefore, the possibility of integration into a single unit (module) with other devices. The

TABLE I. COMPARATIVE REVIEW OF THREE TERAHERTZ SOURCES.

Parameters & properties	BWO-based source	Superlattice-based multiplier	LJJ-based source
Dimensions of the basic module, mm	500×360×280	30×20×20	120×45×60
Weight of the basic module, kg	17.4	0.05	0.4
Additional required components	Personal computer (laptop)	Basic oscillator with power not less than 10 dBm	Cryogenic system, system for biasing, oscillators and amplifiers up to 1 GHz
Power consumption, kW	< 0.25	Defined by power consuption of the basic oscillator, typically < 0.3	Defined by by power consuption of additional elements, typically < 1
Operating temperature, K	293	293, could be cooled down to 4.2	4.2
Operating frequency range, GHz	480 – 640	Higher than 350	200 – 750
Possibility of compact integration with another device	No	Yes	Yes, assuming the common 4.2 K cryogenic system
Spectral linewidth in phase-locked mode, kHz	<< 40	<< 40	~ 40
Typical detected power in operating range, mV	10 – 50	10 – 20	20 – 100
Maximum power detected, mV	57.8	28	~150
Other features & remarks	A BWO operating range 120 – 160 GHz; ×3-4 multiplier at output; operation from PC	Passive device; frequency comb; dimensions and weight are defined by a basic oscillator	Phase locking in manual regime from PC; dimensions and weight are defined by additional components including the cryogenic system

main disadvantages are the low power and the frequency comb at the output, which does not allow using it in tasks requiring a single-frequency oscillator without harmonics. The most difficult technically and for operation is a source based on a long Josephson junction, while it demonstrated the highest detected power and the widest tuning band without harmonic composition. The technical requirements for working with such a source include not only the 4.2 K cryogenic setup, but also a low noise power supply for biasing the superconducting elements of the microcircuit, as well as low-noise high-frequency amplifiers up to 1 GHz. On the other hand, the ability to embed a source into a complex cryogenic system can be considered as an advantage in some cases. Such integration can be useful, for example, when studying the properties of materials at low temperatures, as well as in solving other cryogenic issues where a THz source is required. A compromise in power and simplicity in operation is a source based on a BWO with a multiplier. It is quite convenient in laboratory applications, where the weight and size of the device are not important, while the source has enough power for many tasks in the THz frequency range. Since a multiplier is used at the BWO back end, the source has a frequency comb at the output with a frequency difference of 120 – 160 GHz between nearest harmonics, which is not a problem for most cases.

This comparison is given for devices of a specific design available in laboratory of the authors. The characteristics of devices based on the same principles of operation, and developed for specific applications in accordance with some technical specifications, might be significantly different from those described in this work.

V. Conclusions

In this work, a comprehensive comparative analysis of three principally different laboratory sources of the THz range is carried out: based on a backward wave oscillator with a multiplier at the output, based on a frequency multiplier on semiconductor superlattices with a large number of harmonics, and also based on a superconducting long Josephson junction. Each of the investigated sources has specific properties and is used in modern developments and studies in THz range. In general, areas of practical applications for these sources are different. All three sources are successfully used today at frequencies up to 700 GHz. This work can be useful not only regarding to a review of the characteristics of various sources of the THz range and their comparative analysis, but also from the point of view of the experimental study of their characteristics.

References

[1] N. V. Kinev, K. I. Rudakov, L. V. Filippenko, A. M. Baryshev, and V. P. Koshelets, “Flux-flow Josephson oscillator as the broadband tunable terahertz source to open space,” J. Appl. Phys., vol. 125, pp. 151603-1–151603-7, March 2019. DOI: 10.1063/1.5070143

[2] N. V. Kinev, K. I. Rudakov, L. V. Filippenko, A. M. Baryshev, and V. P. Koshelets, "An Antenna with a Feeder for a Superconducting Terahertz Josephson Oscillator with Phase Locking," J. Commun. Technol. Electron., vol. 64, pp. 1081-1086, October 2019. DOI: 10.1134/S1064226919090122

[3] N. V. Kinev, K. I. Rudakov, L. V. Filippenko, A. M. Baryshev and V. P. Koshelets, "Terahertz Source Radiating to Open Space Based on the Superconducting Flux-Flow Oscillator: Development and Characterization," IEEE Trans. Terahertz Sci. Technol., vol. 9, pp. 557-564, November 2019. DOI: 10.1109/TTHZ.2019.2941401

[4] G. de Lange et al., “Development and characterization of the superconducting integrated receiver channel of the TELIS atmospheric sounder,” Supercond. Sci. Technol., vol. 23, pp. 045016-1 – 045016-8, March 2010. DOI: 10.1088/0953-2048/23/4/045016

[5] V. P. Koshelets et al., “Superconducting Integrated Terahertz Spectrometers,” IEEE Trans. Terahertz Sci. Technol., vol. 5, pp. 687–694, July 2015. DOI: 10.1109/TTHZ.2015.2443500