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A superconducting flux-flow oscillator of terahertz range

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Abstract. We have elaborated, fabricated and tested a THz source radiating to open space based on the superconducting flux-flow oscillator (FFO). In this concept, the oscillator is integrated with the transmitting lens antenna based on a slot structure in Nb film with a thickness of ~ 200 nm located on the same chip. The slot planar antenna is matched to the oscillator (by input) and to the semielliptical Si lens with a diameter of 10 mm (by output) providing a narrow output beam of THz emission. A harmonic mixer based on the superconductor-insulator-superconductor junction embedded in the “FFO and antenna” integrated structure has been used for the phase locking of the oscillator. Several designs of antenna coupled with the oscillator by microstrip lines have been numerically simulated, and the batches of experimental samples based on Nb-AlN-NbN superconducting trilayers with $R_n \cdot A \sim 20 \Omega \cdot \mu\text{m}^2$ ($j_c \sim 10 \text{ kA/cm}^2$) have been fabricated and tested. Two different setups were used for experimental study: a THz spectrometer based on the SIS receiver with a high spectral resolution (better than 0.1 MHz) and a Si bolometer. The overall operating range of 250 to 700 GHz is covered by all the developed designs.

1. Introduction

The lack of wideband sources in terahertz (THz) frequency range is currently one of the significant problems of radio physics, astronomy and spectroscopy. A flux-flow oscillator (FFO) based on a long Josephson junction with length $l \gg 2\lambda_J$ is promising source in THz region. Such oscillators based on tunnel structures Nb/AlOx/Nb or Nb/AlN/NbN have the operating range from 200 to 750 GHz which is about 100% of central frequency. It was successfully implemented as a local oscillator in superconducting integrated receiver (SIR) [1,2,3] for pumping the superconductor-insulator-superconductor (SIS) mixer, in such layout the FFO and the mixer are located on a single chip. The output power of such oscillator is not so large – from fractions of 1 μW up to a several μW , which is sufficient for some applications, for example, as an active source for THz spectroscopy, THz microscopy, studying the properties of material at THz frequencies at low temperatures. Recently we elaborated the idea of the integration of the FFO with an antenna [4,5], and tested it using the (SIR) for studying of the emitted spectra [6,7,8]. Since the SIR was designed to operate at 500-600 GHz, and has a reasonably good noise temperature in the range of 480 – 700 GHz, it was not possible to study carefully the properties of the antenna over the whole range of its operation due to wider antenna operating range that the SIR operating range. In this report, we carried out a new experiment to study the operating range of antenna using a wideband cooled Si bolometer [9].



2. Concept of the FFO-based THz oscillator emitting to open space

The principle of the FFO operation is discussed in classical papers (e.g., [10,11] and others), and its modern characteristics as part of the SIR are presented in [2,12]. A simplified layout of the FFO is shown in figure 1. The operating range of the sample based on the Nb/AlN/NbN trilayer with dimensions $400 \times 16 \mu\text{m}^2$ is from 200 GHz up to 750 GHz with the spectral linewidth of about $\sim 0.5 - 5$ MHz. The upper border of operating range is limited by a half of superconductor energy gap Δ and can potentially reach 1 THz. The frequency f of oscillation is defined by the Josephson equation $hf = 2eV_{DC}$, where V_{DC} is the DC voltage of the junction. The phase-lock loop (PLL) is used for the phase locking of the oscillations, the PLL system narrows the actual spectral line down to about 40 kHz and collect up to 97% of the power in the peak (Spectral ratio).

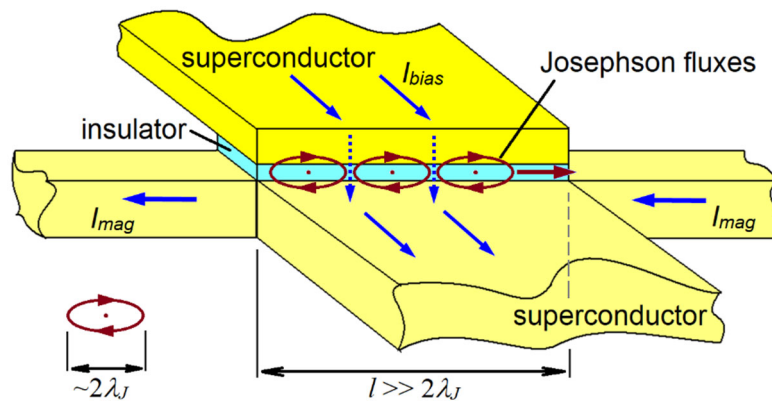


Figure 1. Scheme of the FFO based on the SIS junction having a length $l \gg 2\lambda_J$, where λ_J is a Josephson length. A biasing current I_{bias} and a current for applying the magnetic field I_{mag} are shown. Only three Josephson fluxes are sketched for clarity, the real number is much more than 1, typically of an order of a few hundred.

The principal idea of this work is the integration of such oscillator with a transmitting slot antenna on a single chip placed on the back surface of the silicon elliptical lens (figure 2). The substrate of the chip is also made of silicon with dielectric constant $\epsilon = 11.7$ to avoid the beam refractions on the chip-lens border. Thus, the main task is the coupling of the oscillator having low output impedance (about 1Ω) to the lens antenna having high impedance (tens of Ω) and forming a beam pattern required for applications. Additionally, a harmonic mixer (HM) based on the SIS junction is used for phase locking of the oscillator. Some part of the FFO power is branched to the HM used in the feedback circuit, which also contains the PLL system that requires a reference signal at 400 MHz from local oscillator. Commonly, pumping of the HM at $\sim 5\% - 10\%$ of the current jump at the SIS-mixer gap voltage is sufficient for mixing the signals of the FFO and of n -th harmonics of 20 GHz from the local synthesizer, and hence for the PLL operation.

The bandwidth of double slot antenna is less than that of the oscillator, hence the band 250 – 700 GHz is to be realized with three antenna designs with central frequencies of 300 GHz, 400 GHz and 550 GHz. The designs with a principal scheme shown in figure 2a differ from each other in geometry – the length and the width of slots and connections between them, and also in the layout of the microstrip line including the impedance transformer. Another type of the excitation of the slot antenna (shown in figure 2b) is also proposed with central frequency of 450 GHz; such design of the feeder for antenna (hereinafter named type #2) has a less bandwidth of matching than that shown in figure 2a (hereinafter named type #1) according to numerical simulations.

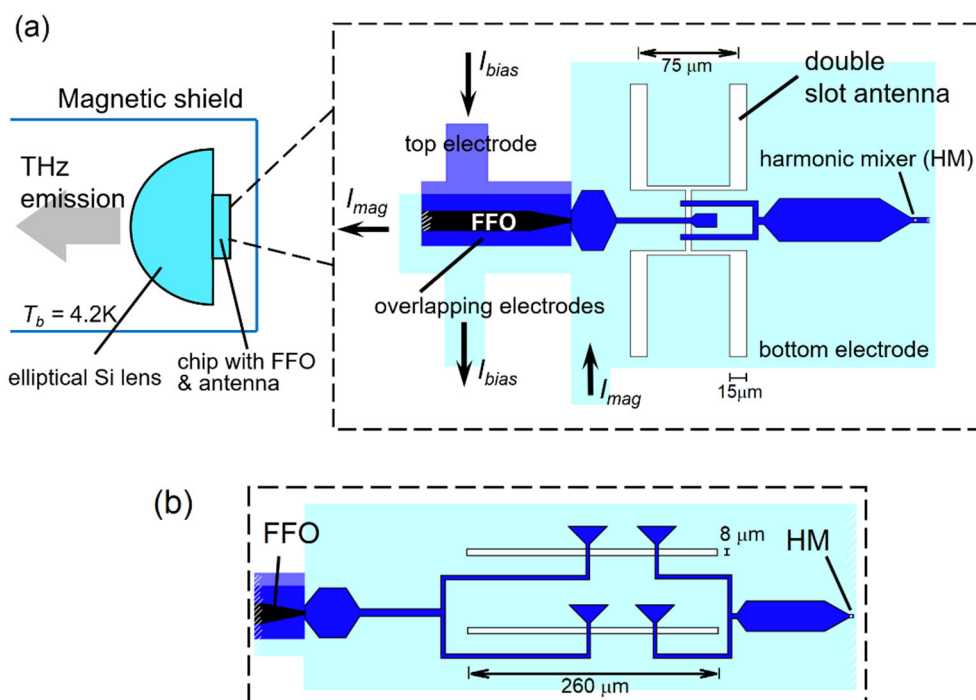


Figure 2 (a) layout of the chip with the oscillator, the antenna and the HM placed at the far focus of elliptical silicon lens (on the left), and the layout of the planar structure of THz oscillator based on a long SIS junction coupled to slot antenna by microstrip line, a metallization layer of the antenna is also the bottom electrode of the microstrip and the SIS junction (on the right); excitation type #1 of the double slot antenna (b) an optional layout of the integrated structure with another excitation type (type #2) of the antenna. The dimensions of antennas are shown for clarity of the scale.

All the slot antennas presented were fabricated from superconducting Nb thin film with the thickness of 200 nm. The elliptical converging lens with the diameter of 10 mm were used in the experiment, the same lens is used for superconducting receiver of 450 – 650 GHz in the TELIS instrument [2]. As the FFO based on Nb/AlN/NbN trilayer requires cooling for superconducting state, the chip with the lens are placed in the liquid helium cryogenic system with the temperature of 4.2 K, so that the antenna and all the microstrip lines made of Nb with critical temperature of about 9 K are also in the superconducting state.

3. Numerical simulations

The calculations of power coupling of oscillator with the antenna are made using the specialized software for microwave 3D modeling – CST Studio. For taking into account the superconducting state of the antenna and microstrip lines, London penetration depth for thin Nb films $\lambda_L = 85\ \text{nm}$ was used. The results of the numerical simulations of the coupling for three designs of type #1 developed for the central frequencies 300 GHz, 400 GHz and 550 GHz, and for design of type #2 for the central frequency of 450 GHz are presented in figure 3, the radiated part to open space is shown. More than 70% of oscillator output power is radiated in the ranges of 250 – 410 GHz, 330 – 530 GHz and 390 – 700 GHz for three designs of type #1. The microstrip line is designed for the matching of the low output impedance of the FFO which was set equal to $0.5\ \Omega$ in the simulation model with the high input impedance of the slot antenna. In the figure 4, the impedances of the antennas of 400 GHz and 550 GHz (type #1) in the point of connection to microstrip line are presented. For both designs the frequency dependence of the impedance is rather flat, without any jumps in the operating region: full impedance is changing from $30\ \Omega$ to $40\ \Omega$ for 400 GHz design and from $26\ \Omega$ to $40\ \Omega$ for 550 GHz design.

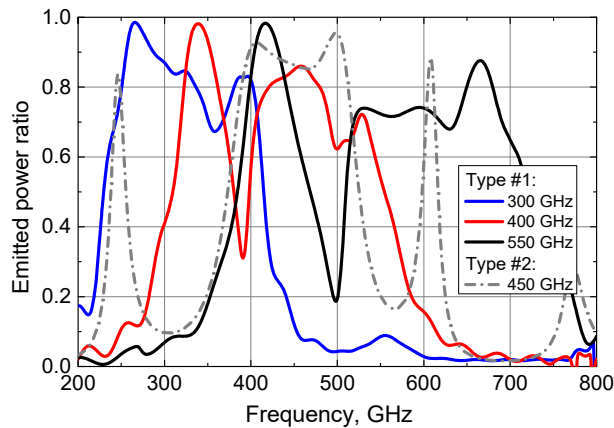


Figure 3. Emitted power ratio into solid angle 4π by antennas of four different designs

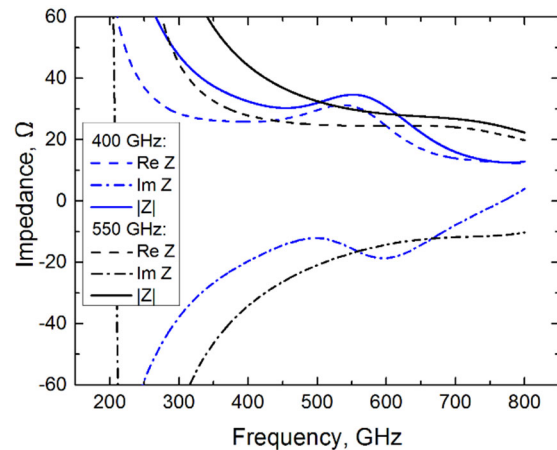


Figure 4. The impedances of the slot antenna of designs of type #1 for 400 GHz and 550 GHz.

In the figure 5, the calculated beam patterns at the fixed frequency for 300 GHz, 400 GHz and 550 GHz antenna designs of type #1, and for design of type #2 for the central frequency of 450 GHz are shown. It can be seen that the main power is concentrated in the center lobe. The numerical simulations of beam patterns were made not taking into account the elliptical lens which greatly narrows and gains the central lobe, and has no influence on the dependence in figure 3. The overall operating frequency range for all the proposed designs of slot antenna is from 250 GHz to 700 GHz.

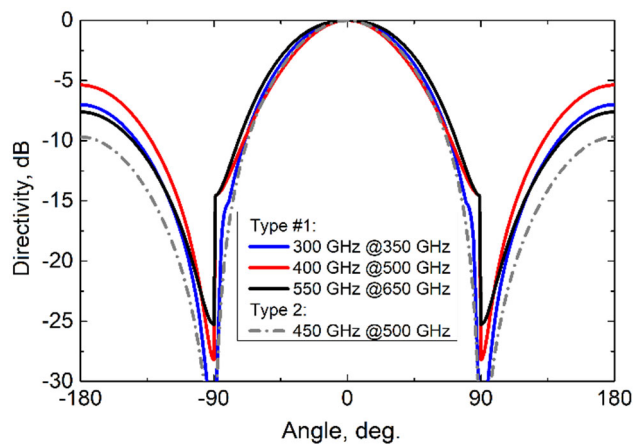


Figure 5. Beam patterns of four antenna designs at the fixed frequency in the region of operation.

4. Experiment

A fabrication of samples, an experimental setup and results are discussed below.

4.1. Fabrication

A batch of samples with developed designs of two excitation types of antenna was fabricated using Nb/AlN/NbN trilayers for Josephson junctions, and Nb/SiO₂/Nb trilayers for transmission microstrip and coplanar lines. The technology for fabrication of samples containing integrated circuits with all-Nb and Nb/NbN tunnel junctions down to submicron dimensions developed in our team, has been described elsewhere [13,14]. According to DC testing, the tunnel junctions on the batch have a normal state resistance – area product $R_n \times A \sim 20 \Omega \mu\text{m}^2$, which corresponds to a current density of $J_c \sim 10 \text{ kA/cm}^2$. The gap voltage V_g is about 3.5 mV, and the quality factor defined as the sub-gap

resistance to normal-state resistance ratio R_j/R_n is about 30, which is a good result for the NbN technique. The typical value of R_j/R_n is about $23 \div 30$ and discussed elsewhere [13,15].

4.2. Experimental setup

The output emission was studied using two independent techniques: a THz spectrometer based on the SIS receiver with a high spectral resolution (better than 0.1 MHz) and a Si bolometer. The experimental setup utilizing a spectrometer based on the SIR is discussed in details in [8].

The diagram of the experimental setup utilizing the cooled Si bolometer is presented in figure 6. Two 4.2 K liquid helium cryostats were used simultaneously: one for cooling down the FFO microcircuit mounted on the lens and another one for cooling down the bolometer located opposite the oscillator. IR filters are used in both cryostats: the Gore-Tex filters were installed inside cryostat with the oscillator, and a quartz filter was mounted in cryostat with the bolometer. The bolometer response was measured using a lock-in amplifier, so that the emission was modulated by an optical chopper with a frequency of about 170 Hz.

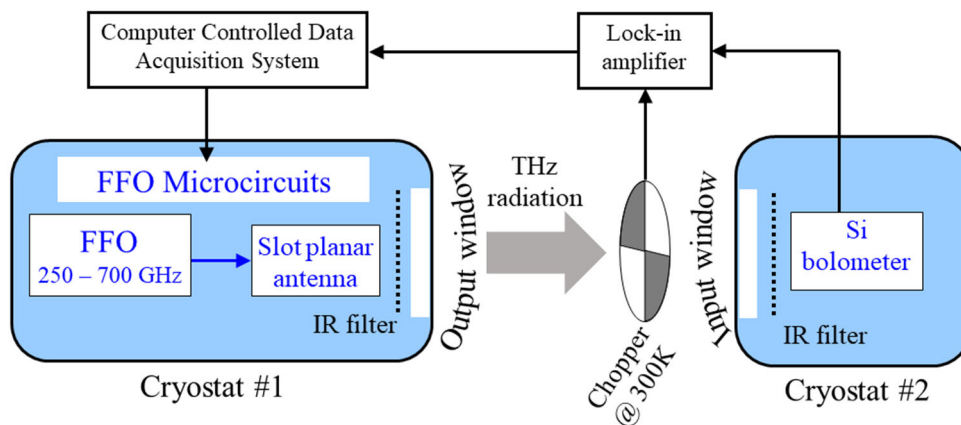


Figure 6. Block diagram of the experimental setup for studying the radiation of the FFO-based source radiating to open space, using a cooled Si bolometer.

4.3. Experimental results

The emission of the FFO-based source of type #2 (for central frequency of 450 GHz) was detected by the Si bolometer over the full range of the FFO operation. The complete frequency range was studied via slow sweeping of the FFO voltage with a small step size of $\sim 1-2 \mu\text{V}$ (corresponding to a frequency step of $\sim 0.5 - 1 \text{ GHz}$), by changing the current I_{mag} with a step size of 0.05 mA supplying the magnetic field. This sweeping was carried out over the wide range of the bias current I_{bias} . The experimental results are presented in figure 7 and compared with numerical simulations. A reasonable agreement between experimental data and numerical simulations can be observed for the main emission peak with a central frequency of 450 GHz. There is a shift in frequency of about 20-30 GHz between the lower and the upper borders of the main peak: the experimental range is a little narrower in frequency than the calculated range. We believe this shift is due to not perfect accuracy of simulations, because the exact values of some parameters are unknown, such as a London penetration depth for Nb films, a dielectric constant and a thickness of SiO_2 fabricated films, as well as the FFO output impedance Z_{FFO} . It was found that the numerical results are most sensitive to changing of Z_{FFO} . Another shortcoming of the simulation model is that some damping effects are not taken into account. One effect is the increase of surface losses in Nb lines at frequencies higher than 650 GHz, in accordance to the Mattis–Bardeen theory. Another reason for damping is a self-pumping effect in a long Josephson junction at the voltage above $V_g/3$ [16].

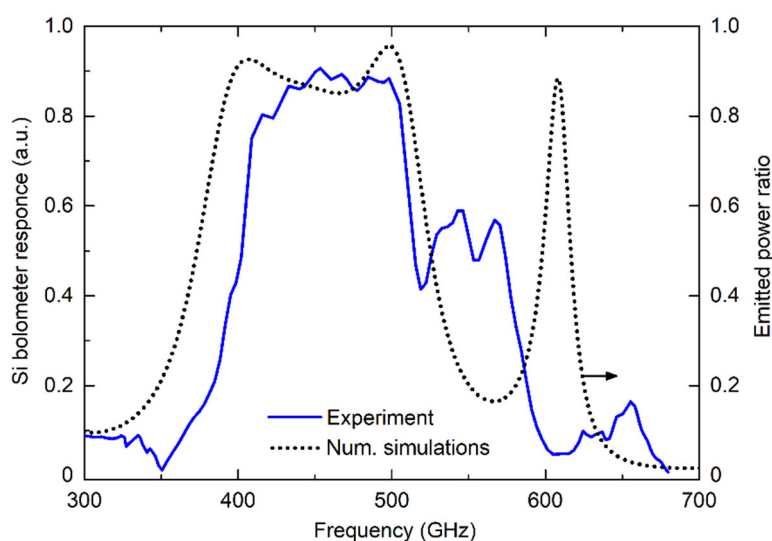


Figure 7. FFO emission (design of type #2) to open space detected by the Si bolometer (solid curve, related to the left axis) and numerical simulations of emitted power normalized to the total output power (dot curve, related to the right axis). The simulation curve is the same as the dash-dot curve in figure 3.

The spectral measurements were discussed in details in [8]. The main idea is that emission spectral line were recorded using two independent techniques in different intermediate frequency (IF) ranges: by the THz spectrometer based on the SIR in the IF range of 4-8 GHz, and by using the HM and a PLL system in the IF range of 0.1-1 MHz. The results of this study is that the spectral properties, i.e. the shape of the emission line and hence the linewidth, are the same regardless the technique of recording the spectra. The typical emission line in free-running and phase-locked regimes at the frequency of 572 GHz for the sample of type #1 (design for central frequency of 400 GHz) is shown in figure 8. The linewidth and the spectral ratio defined for a phase-locked radiation line as the percentage of the power concentrated in the peak are indicated. The linewidth of the spectra in phase-locking regime is completely defined by the resolution bandwidth (RBW) of the spectrum analyzer and proved to be about 100 kHz when RBW = 100 kHz is used during the measurements.

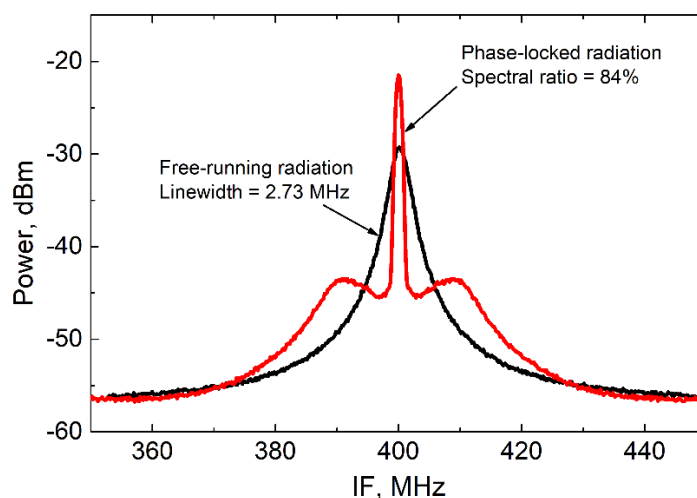


Figure 8. Power spectra of the FFO at the frequency of 572 GHz for the sample with design of type #1 (central frequency 400GHz) measured using the on-chip HM: the free-running regime (black line) and the phase-locking regime (red line). The RBW of the spectrum analyzer is 1 MHz.

5. Conclusion

The superconducting THz oscillator based on the long Josephson junction with unidirectional flow of the Josephson fluxes (flux-flow oscillator or FFO) is an encouraging solution of the THz source for the tasks where wideband frequency tuning is required and the high power is not necessary. The applications of such oscillator are the heterodyne receiving and THz spectroscopy, for instance, in the radio astronomy, Earth atmosphere monitoring, medicine devices and security systems, telecommunications etc. Another possible application is a multifunctional laboratory phase locked THz source with wideband tuning that can be used as an active source for THz spectroscopy, THz microscopy, studying the properties of material at THz frequencies at low temperatures.

In this report, we proposed and elaborated the idea of the external THz source based on the FFO integrated with the transmitting slot antenna and the harmonic mixer for the phase locking. The lens is used forming the narrow beam pattern of the lens antenna. A several designs of integrated structure were developed using two different types of the antenna excitation, and the operating ranges of 250 – 410 GHz, 330 – 530 GHz and 390 – 700 GHz is obtained in numerical simulations, which covers the range from 250 GHz up to 700 GHz. An adequate agreement between the simulations and the experiment is proved using the direct detecting of output signal by the Si bolometer. The spectral properties of output emission were studied using the spectrometer based on the SIS receiver in THz range, the linewidth of about 1-10 MHz is obtained experimentally. For increasing the upper limit of the frequency range up to 1 THz, Al/NbTiN-based transmission lines with much lower surface losses should be used.

Acknowledgments

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