Superconducting Flux-Flow Oscillator as a Terahertz External Local Oscillator for Heterodyne Receiving

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***Abstract*—We have developed, fabricated and tested a terahertz (THz) source based on the long Josephson junction acting as the flux-flow oscillator (FFO). The FFO was integrated to the lens antenna on a single chip providing the THz emission to open space. We used the double slot type of antenna coupled to the semielliptical silicon lens to form a narrow output beam. The impedance and the emission properties of the antenna were numerically simulated. The experimental samples were fabricated with the FFO based on Nb/AlN/NbN superconductor–insulator–superconductor (SIS) trilayers with a current density of 11 kA/cm^2 and a gap voltage of about 3.55 mV. The output radiation was studied by a THz spectrometer based on the SIS receiver with high spectral resolution, the signal has been observed in the range of 440-700 GHz with the signal-to-noise ratio up to 55 dB. A feasibility of the phase locking by using the harmonic mixer has been discussed.**

A flux-flow oscillator (FFO) based on the unidirectional flow of magnetic vortexes (fluxes) in a long Josephson junction is a promising solution of local source for heterodyne receiving in terahertz (THz) region [1],[2]. Its frequency tuning range up to 100% of central frequency is unique among other types of THz sources. The FFO output power of about 0.1-1 μW gained in the peak with a linewidth of ~40 kHz by using the phase-locking loop (PLL) is sufficient for heterodyne requirements. Up to now, the FFO has been implemented as the local oscillator utilizing the on-chip integration with the receiving SIS-mixer at the on-board superconducting receiver for the TELIS balloon instrument [3],[4].

In this study, we have coupled the FFO output radiation to a transmitting lens antenna and developed a compact THz oscillator emitting to open space. The idea of the oscillator is presented in Fig. 1. The cryogenic module with the oscillator can be installed on the same cold plate as a detector and operate as a heterodyne source. Recently we tested this concept using also a double slot antenna but with another type of the excitation and another topology of the antenna [5],[6].

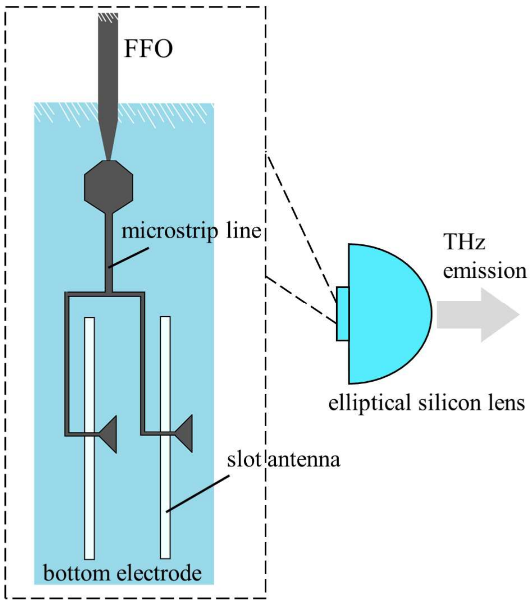

Fig. 1. On the left – layout of the planar structure with the FFO coupled by a microstrip line to the slot antenna; on the right – the scheme of the chip containing a microcircuit placed at the focus of the silicon lens. The scheme on the right is not to scale.

The numerical simulations were performed using a specialized microwave 3D-modeling software. The impedance of the antenna and the power emitted to open space are presented in Fig. 2. According to simulations, the antenna operating range is 350-550 GHz defined by a power level of emission to open space higher than 0.5 of the total output FFO power. After this, the batch of the samples containing the FFO with dimensions 16×400 μm^2 based on Nb/AlN/NbN trilayer and the slot antenna based on Nb film with a thickness of ~200 nm was fabricated. The current density of SIS trilayer on the batch is about 11 kA/cm^2, which corresponds to parameter

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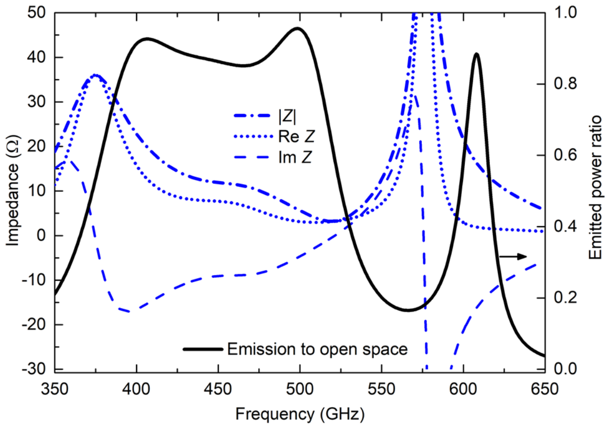

Fig. 2. Input impedance Z of the antenna at the point of connection to the impedance transformer (the real part – dot line, the imaginary part – dashed line, and the absolute value – dash-dot line), and the emitted power (solid line) normalized to the total output FFO power.

$R_n \times A \sim 20\ \Omega\ \mu m^2$, and the quality factor R_j/R_n is about 30, where R_n is the normal-state resistance, R_j is the sub-gap resistance and A is the area of the junction.

The microchip with "FFO & antenna" integrated circuit was mounted on the back flat surface of a semielliptical silicon lens, so that the center of the antenna was located in the far focus of the lens. For proper FFO operation, the chip was also located inside the magnetic shields. The module was installed in the liquid helium cryostat opposite an output THz window with IR filters. The measurements of the emission to open space were carried out using a THz spectrometer based on the superconducting integrated receiver (SIR) [2],[3] utilizing another FFO as a local oscillator and located in a separate cryostat opposite the "emitting" cryostat. The experimental setup is simpler than discussed in [6] (see Fig. 4 in [6]) due to the harmonic mixer is not used in the present paper.

The emission of the FFO in the range from 440 GHz up to 700 GHz, available for the SIR operation, was studied by the SIR at the intermediate frequency (IF) range of 4 - 8 GHz. The results for recorded spectra at some selected frequencies are presented in Fig. 3. The signal-to-noise ratio for the recorded

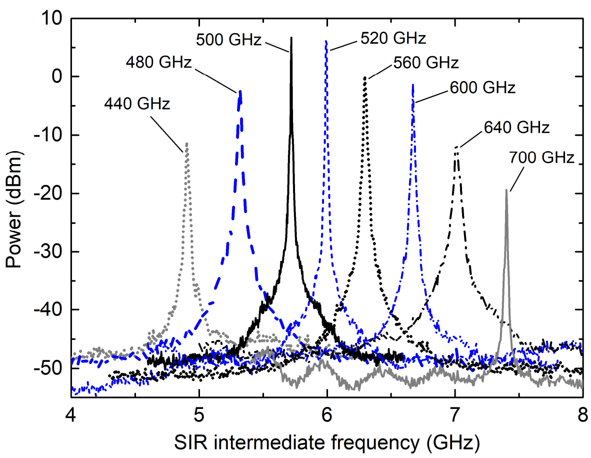

Fig. 3. Emission spectra of the FFO recorded using the SIR by a spectrum analyzer with the resolution bandwidth of 1 MHz. The frequency of emission is pointed for each curve.

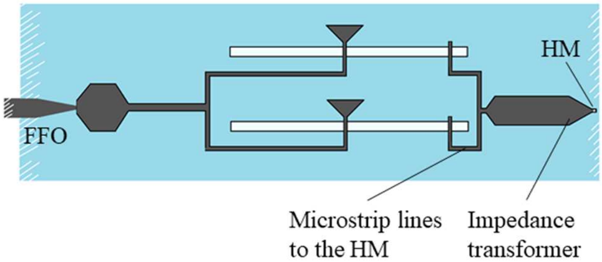

Fig. 4. The idea of embedding the HM into the FFO-based integrated structure shown in Fig. 1 not changing the geometry of the slot antenna.

spectral lines is up to 55 dB (see solid and short-dash curves in Fig. 3 for 500 GHz and 520 GHz, respectively), the spectral linewidth is estimated to be 2 - 15 MHz. We had no ability to get a higher accuracy for the shape and the linewidth definition since the oscillator has not been locked. Note that the actual upper border of the studied operating range is at least 150 GHz higher than the range defined by 0.5 level in simulations, and the signal-to-noise ratio at 700 GHz is as high as 25 dB. The frequencies below 440 GHz are out of the receiver operating range.

For practical applications as a heterodyne, the FFO should be phase locked. For this, the harmonic mixer (HM) based on the SIS junction and the PLL are commonly used [1],[2],[3],[6]. We are planning to embed the HM into integrated "FFO & antenna" structure using two symmetric microstrip lines that connect to a single line with an impedance transformer (see Fig. 4); at the output edge of the transformer the HM will be located. This idea is to be elaborated and tested.

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