Investigation of the Harmonic Mixer and Low-Frequency Converter Regimes in a Superconducting Tunnel Junction

Konstantin V. Kalashnikov, Anton A. Artanov, Gert de Lange, and Valery P. Koshelets, *Member, IEEE*

***Abstract*—We experimentally investigate different mixing regimes in Nb/AlO$_x$/Nb and Nb/AlN/NbN tunnel superconductor–insulator–superconductor (SIS) junctions. The SIS mixers were studied with regard to the following modes of operation: in an extremely low-frequency range (0.1–20 GHz) and as high harmonic mixers; $n \approx 20$–30 at signal frequencies of about 500 GHz that requires high power of a local oscillator. The quasiparticle and Josephson mixing regimes have been compared. We demonstrate that, in some applications requiring high conversion efficiency, the Josephson regime can be more preferable than the quasiparticle regime due to a larger output signal and better signal-to-noise ratio. As an example of such an application, we consider the phase locking of a THz oscillator using a cryogenic harmonic phase detector, which only ought to realize all of its benefits under the Josephson mixing regime. In addition, we demonstrate that the presence of the Josephson effect results in considerable increase in conversion efficiency at the expense of the dynamic range decrease; it was measured for low-frequency up- and down-convertors, which are promising for cryogenic multiplexing systems.**

***Index Terms*—SIS mixers, frequency conversion, Josephson mixers, terahertz radiation.**

I. INTRODUCTION

SUPERCONDUCTING nanostructures, based on tunnel junctions, are widely used for submm signal mixing due to extremely strong nonlinearity and low noise temperature [1]–[3]. Mixing properties of SIS junctions are determined by two types of nonlinearity related to quasiparticle and Cooper pair tunneling currents, respectively. The nature of the quasiparticle mixing is associated with a quasiparticle tunnel current through the junction, which rapidly increases at the "gap" voltage $V_g = (\Delta_1 + \Delta_2)/e$, where $\Delta_{1,2}$ represent the energy gap values for both superconductors comprising the SIS tunnel junction, while e is the electron charge. Josephson mixing is related to the BCS pair supercurrent, which is described by the DC Josephson effect relation $I_s = I_c \cdot \sin(\varphi)$, where φ is the "phase difference" across the junction and I_c is the critical current of the junction. We will refer to the mixing regime involving both types of nonlinearity as the "Josephson regime", in contrast with the "quasiparticle regime", which is realized for the suppressed critical current.

There are a number of theoretical [4], [5] and experimental [6], [7] papers, which investigate the noise properties of the SIS mixers in the Josephson regime. In these papers, it is shown that the non-suppressed critical current causes an increase in the noise level. Instability in the working point, as well as the noise of the Josephson component itself, are usually considered to be the reason for such an increase. In heterodyne THz SIS receivers, the Josephson effect is traditionally considered to be parasitic, which is the reason why the critical current of the SIS mixer in such receivers is usually suppressed by an external magnetic field [8], [9]. In the present article, we demonstrate some practical applications where Josephson mixing can be more preferable than the quasiparticle alternative.

II. SIS-BASED HARMONIC MIXER AND CRYOGENIC HARMONIC PHASE DETECTOR

HMs based on the Schottky diode [10], [11] and the semiconductor superlattice [12] are widely employed to down-convert the THz signal of a solid-state source or a THz quantum cascade laser for their frequency and phase stabilization. At the same time there are only a few publications on the implementation of superconducting elements for frequency multiplication [13] and harmonic mixing for sub-THz-source phase-locking [14]–[16]. According to the approach proposed in [15], [16], the HM is used for study and for further phase-locking of a superconducting flux-flow oscillator (FFO) [17]–[19]. The FFO signal is applied to the HM (a small SIS junction operating in Josephson or quasiparticle mode), along with the signal from the frequency synthesizer f_{SYN} (of about 20 GHz). The intermediate frequency (IF) signal, with frequency $f_{IF} = \pm(f_{FFO} - n \cdot f_{SYN})$, is boosted by cold and room temperature amplifiers for linewidth measurements and further use in the PLL system.

One of the novel tunnel SIS junction applications is a wideband cryogenic harmonic phase detector (CHPD) for frequency stabilization of the cryogenic THz oscillators [20], [21]. It has

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K. V. Kalashnikov and A. A. Artanov are with the Kotel'nikov Institute of Radio Engineering and Electronics, Moscow 125009, Russia and also with the Moscow Institute of Physics and Technology (State University), Dolgoprudny 141700, Russia (e-mail: kalashnikovkv@gmail.com).

G. de Lange is with the SRON Netherlands Institute for Space Research, Groningen 9747, The Netherlands.

V. P. Koshelets is with the Kotel'nikov Institute of Radio Engineering and Electronics, Moscow 125009, Russia.

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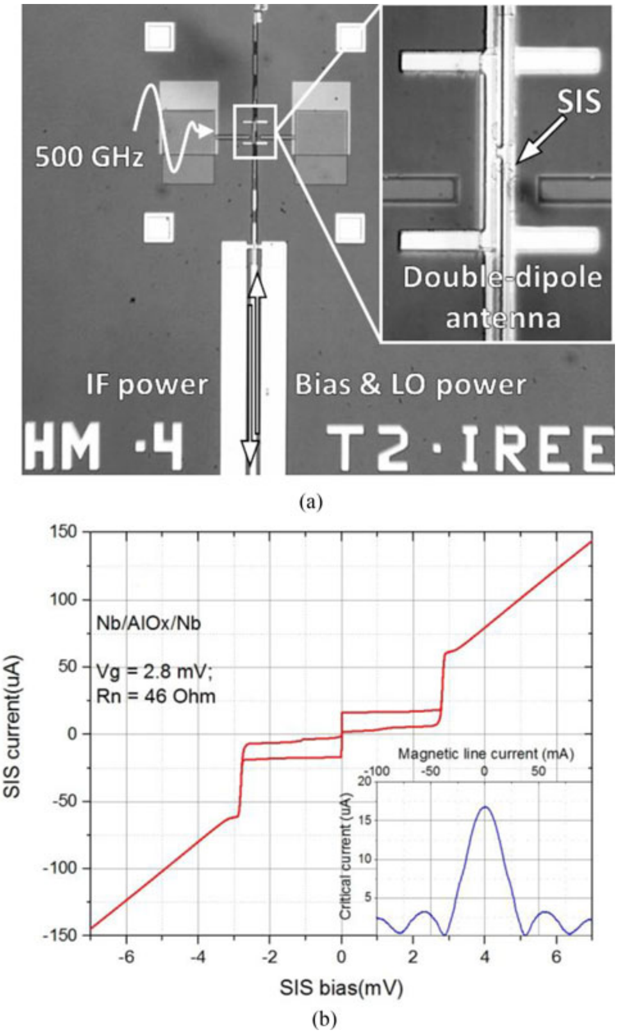
been shown that functional integration of the harmonic mixer and phase detector in a single element decreases the time delay in the feedback loop, thereby significantly expanding the synchronization bandwidth of the PLL system based on the CHPD.

By introducing CHPD concept, we are able to reduce a number of the elements in a phase lock loop to the minimum (CHPD and passive filters with very short connection lines); this system can be placed on the same microcircuit with a cryogenic oscillator. We estimate the efficiency of phase-locking by the parameter called “spectral ratio” (SR), which is the ratio of the phase-locked power in the peak to the total power emitted by the oscillator in the range of about 100 MHz around the carrier. The implemented CHPD system has a bandwidth of about 70 MHz that allows to realize SR $= 95\%$ for the free-running FFO linewidth of 3 MHz, while a conventional semiconductor room-temperature PLL provides only 75%. For the free-running FFO linewidth of 22 MHz the CHPD results in the SR $= 77\%$, compared to the SR $<5\%$ for the RT PLL [20]–[22].

According to the CHPD concept, an SIS junction is implemented for down-conversion of the FFO frequency and for phase-locking of the FFO to an external reference by applying the HPD output directly to the FFO control line. However, in the case of the CHPD-based PLL, an additional amplifier could not be used without considerable synchronization bandwidth reduction, which explains the need for the high-output signal level of the CHPD itself. To maximize the output CHPD signal, we study the mixing regimes of the harmonic mixer and dependencies of the HM output signal on its bias voltage and on the local oscillator (LO) power level.

The integrated circuit for HM study comprises an Nb/AlOx/Nb tunnel SIS junction [23] [see Fig. 1(a)]; the current-voltage characteristic and the Fraunhofer-like dependence of the critical current on the magnetic line current for this sample are shown in Fig. 1(b). The SIS junction is integrated on a chip with a planar dipole antenna designed for the frequency range of 450 to 700 GHz. In addition, the HM is connected via a coplanar line to the directional coupler and bias tee, which are mounted on a liquid helium cryostat at a temperature of 4.2 K. We apply two signals to the SIS junction: 487 GHz radiation, which is received by the antenna from the multiplier pumped by a backward-wave oscillator (BWO), and the LO signal of about 20.1 GHz, which is applied through the directional coupler. Frequency values are chosen to have an intermediate frequency (IF) signal $f_{IF} = f_{BWO} - 24 \cdot f_{LO}$ in the band of the amplifier (4–8 GHz). The critical current can be suppressed by the magnetic field, which is created by the current in the control line integrated with the SIS mixer [24]. Details of the mixer design are presented in [16]. After a tunable YIG filter (bandwidth of 70 MHz) is applied, the IF signal is detected either by a spectrum analyzer or by a power meter.

We measured the dependencies of the IF power, both on the HM’s bias voltage and on the LO power for two mixing modes: “Josephson” regime (mixing at both quasiparticle and Josephson nonlinearity, no magnetic field applied) and pure quasiparticle regime (the critical current is suppressed by the magnetic field at the first null of the suppression). For a proper comparison of the discussed regimes, the noise level was also measured by the same power meter, in which the BWO signal was shifted in frequency by about 50 MHz and the IF signal was detuned from the YIG filter band. The SNR of the down-converted signal was estimated by subtracting this level from the IF power for every bias voltage and LO power. As can be seen from Fig. 2, the maximum SNR is reached for zero bias voltage and relatively low LO power of about -11 dBm in the Josephson mixing regime.



(a)

(b)

Fig. 1. The photo of the HM microcircuit (a) and the I–V curve of the SIS junction used as a harmonic mixer (b). The parameters of the SIS junction are as follows: critical current $I_c = 17\ \mu$A, RnS $= 32\ \text{Ohm}\cdot\mu\text{m}^2$, gap voltage $=$ 2.8 mV and normal state resistance $= 46$ Ohm. The dependence of the critical current on the magnetic control line current is shown in the inset.

The benefit of the Josephson regime usage was proven by the experiments on the SIS mixer as the CHPD for the FFO phase-locking system, with the Josephson mixing providing up to 83% synchronization of the signal with 18 MHz linewidth, while critical current suppression lowers this value to 70%. It should be noticed that reported before value of the SR as high as SR $= 77\%$ for free-running FFO linewidth of 22 MHz has been obtained for the CHPD operating in the Josephson regime. Thus, the Josephson regime is preferable for the effective implementation of the SIS junction as the CHPD, where a strong output

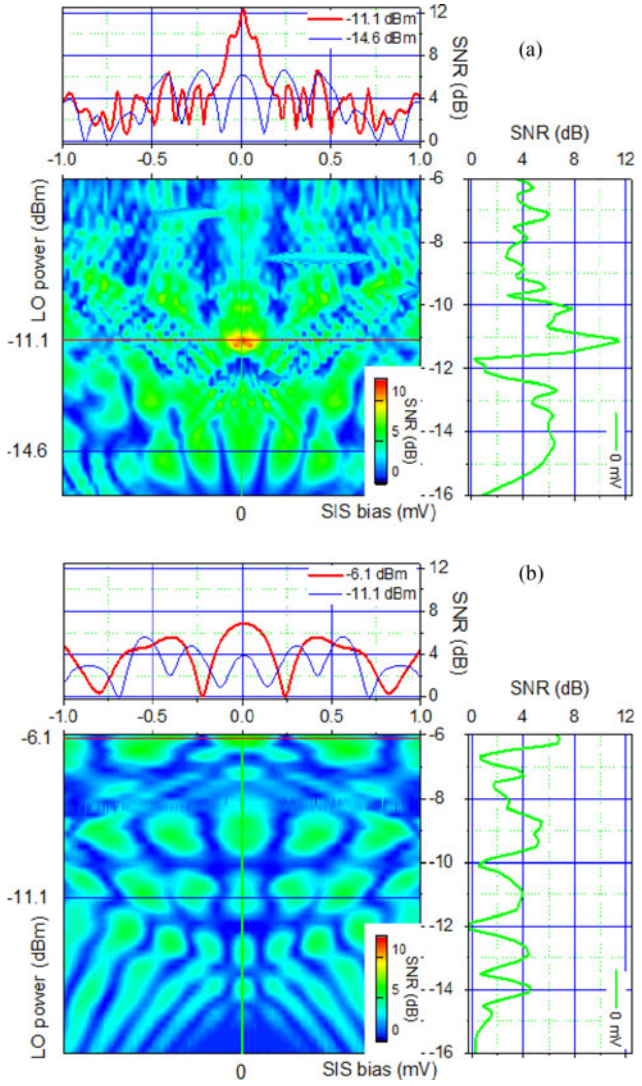


Fig. 2. The dependency of the SNR on SIS bias voltage and LO signal power for Josephson (a) and quasiparticle (b) regimes. The insets show the profiles of these dependencies for fixed values of LO power (top) and bias voltage (right).

signal with a satisfactory noise level is required. It should be emphasized that the successful implementation of the superconducting integrated receiver [16], [24], onboard the high-altitude balloon for Earth atmosphere monitoring [25], becomes possible due to the FFO phase-locking by the HM, as operated under the Josephson regime.

III. SIS-Based Low-Frequency Converter

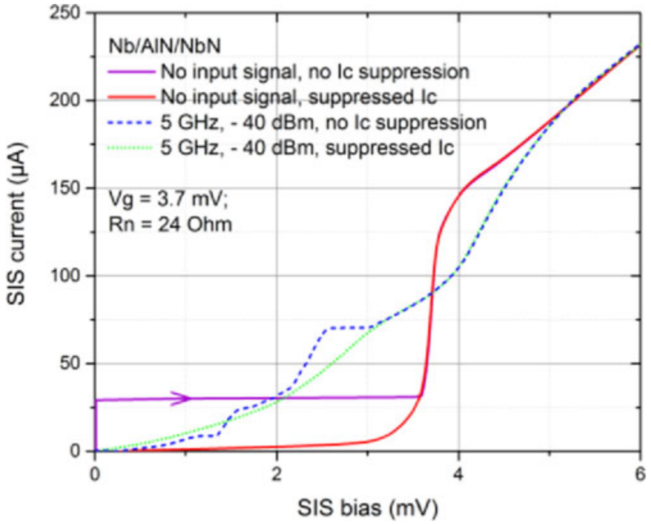


Fig. 3. The I–V curves of the SIS junction used as a low-frequency converter. The parameters are as follows: area $= 1\ \mu\text{m}^2$, gap voltage $Vg = 3.7$ mV, normal state resistance $= 24$ Ohm, quality factor $Rj/Rn = 34$.

Another perspective application of a tunnel SIS mixer is as a multiplexed readout system for a large number of transition-edge sensor (TES) arrays [26], [27]. The proposed readout makes use of frequency up-down conversion for extra level signal multiplexing and radio frequency (RF)-to-DC conversion for SQUID amplifier biasing with SIS junctions operating at GHz frequencies, in combination with existing frequency multiplexed readout at MHz frequencies. SIS devices recommended themselves as low-noise mixers, capable of working at liquid helium temperatures and having low power dissipation; that is essential for the proposed multiplexed readout system. Note that high conversion efficiency is extremely important for practical implementation of the SIS junctions in the readout circuits. Such readout schemes can drastically reduce the wiring from room temperature to the cryogenic detectors, with a possibility to read out and control as many as 30,000 pixels over three coaxial lines within a bandwidth of 1 GHz. In a TES readout system, the SIS junction is used as a low-frequency (0.1–10 GHz) up-down converter. It means that the photon-associated quasiparticle steps ($h\nu/2e$), which are expected to appear in the I-V curve due to LO pumping, are actually too narrow and comparable to the smearing of the sharp current increase in the gap voltage. Therefore, the photon steps are virtually not present, and the mixing regime is more similar to classical mixing than quantum mixing [2].

We applied a 233 MHz RF signal and an LO signal of 5 GHz directly to the SIS mixer, then detected an IF signal of 5.233 GHz on the output. The dissipation losses in the chain were taken into account during the data processing, such that all the results below present the properties and parameters of the SIS junction itself. The I–V curve and parameters of the employed Nb/AlN/NbN junction [28] are shown in Fig. 3; wiring of the circuits was made by Nb layer.

The spectra of the converted signal for both mixing regimes, at the same working point, are shown in Fig. 4. This result proves that the higher output signal in the Josephson regime is indeed the narrowband signal (the shape corresponds to the input signal and to the shape measured in the quasiparticle regime with accuracy about 1 kHz). It can be seen that the Josephson regime has a noise level that is about 5 dB larger, which, at the same time, provides IF signal power that is about 10 dB larger, thus the SNR is about 5 dB better.

The considerable increase in the conversion gain is associated with the steep but stable bumps in the pumped I–V curve with high differential resistance, as can be easily observed in Fig. 3 at voltages of about $1-1.3$ mV and $2.5-3$ mV (see also [29]).

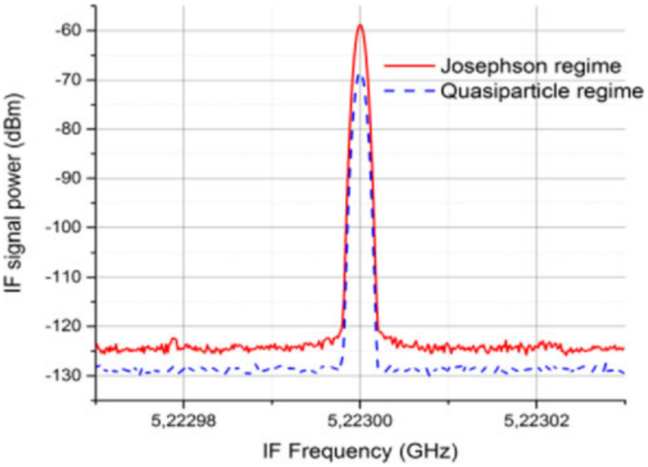


Fig. 4. Spectra of IF signal for the Josephson and quasiparticle regimes, with a resolution bandwidth of 910 Hz.

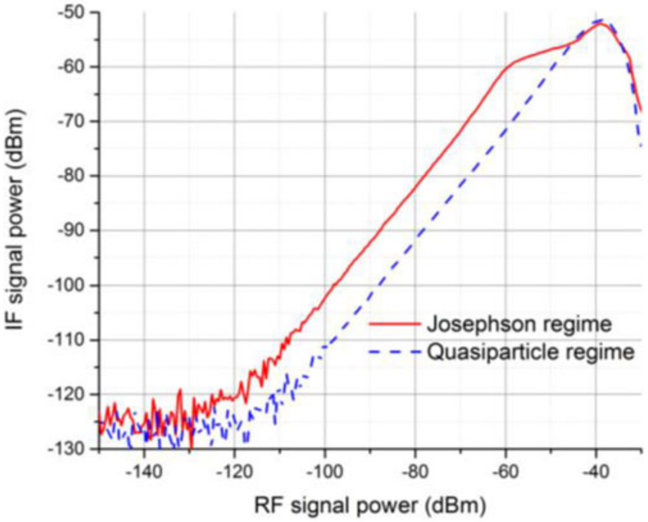


Fig. 5. The dependencies of IF signal power on the input signal for the Josephson and quasiparticle regimes at the same working point: LO power = −40 dBm, bias voltage = 2.7 mV, integration bandwidth = 1 kHz.

These bumps have been observed on both the Nb/AlOx/Nb and the Nb/AlN/NbN junctions, whereby their localization depends on the applied LO power, they disappear when the critical current is suppressed. Fig. 5 demonstrates the dynamic ranges of the Josephson and quasiparticle regimes. High-input signal power suppresses the Josephson effect, which means that Josephson mixing does not work at high-power signals (in our case) greater than −60 dBm. This effect and additional Josephson noise reduces the dynamic range of the Josephson regime by 10 dB, compared to the quasiparticle regime. However, the Josephson regime has a conversion gain that is 10 dB better, which means that the Josephson regime is preferable when conversion efficiency is the main issue.

As Figs. 4 and 5 demonstrate, the Josephson mixing regime has smaller conversion loss and larger SNR than the quasiparticle regime. It makes the Josephson regime preferable for applications where higher conversion efficiency is required. On the other hand, in the quasiparticle regime it is easier to adjust working point due to the smooth dependency of the conversion gain on bias voltage and LO power. Moreover, the dynamic range of the Josephson regime is smaller than the quasiparticle one by 10 dB. Trade-offs between the mentioned above issues (as well as between additional Josephson noise) and the necessity of extra circuits for critical current suppression need consideration when choosing the appropriate regime for each specific application.

IV. DISCUSSION

We suppose that the shape of the IV curve (which determines parameters of Josephson mixing regime) could be explained using the model of resistive-shunted Josephson junction (RSJ), driven by DC and AC current sources. The low-frequency pumping of high-damped junction [30] could be approximately described as a continuous changing of SIS operating point. Thus, the step on the IV curve corresponds to the transition between two modes: i) high dc biasing and weak microwave signal - in this case the total current across the junction permanently exceeds the value of critical current, so the junction is in the resistive state during the whole oscillation period; ii) the amplitude of the applied AC signal becomes comparable with DC bias - the instantaneous current across the junction is equal to zero for the part of oscillation period, that abruptly decreases the average (dc) voltage. In this case the operation point is periodically moving between superconductive and resistive states with different conversion efficiency, which corresponds to the amplitude modulation of the output signal. Such modulation leads to the significant increasing of the output power at moderate rise of the noise power and the modest broadening of the converted spectra. As we experimentally showed above, this broadening does not exceed 1 kHz, the gain performance of Josephson mixing regime could be up to 10 dB and SNR up to 5 dB more in comparison with the quasiparticle mixing. This makes Josephson mixing prospective for some applications, demanding high output levels, but allowing some spectra disturbing.

V. CONCLUSION

In this work, we experimentally demonstrated the advantages of the Josephson mixing regime for some SIS mixer applications. Providing optimal power with regard to the LO signal and optimum bias voltage, the Josephson regime offers not only lower conversion loss, but also a higher SNR in comparison to the quasiparticle regime. Since some practical applications demand mixers and frequency convertors with high-output power and a relatively low-noise level, the Josephson mixing regime has been examined. We have experimentally demonstrated that the best SNR of a high harmonic mixer ($n \approx 20-30$) could be achieved at the Josephson mixing regime; that allows to realize a more efficient synchronization of the THz oscillator by the CHPD operated under this regime. The converters for comparatively low frequencies (0.1–10 GHz) also show the higher conversion gain under the Josephson regime, albeit a narrower dynamic range.

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