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mm-wave harmonic generation in an array of SIS junctions

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Abstract. We report the first experimental off-chip detection of frequency multiplication in a distributed array of Superconductor-Insulator-Superconductor (SIS) junctions. A test device consisting of series array of 68 Nb/Al-AlOx/Nb tunnel junctions was designed to study generation of the second harmonic. We measured extremely sharp spectral signals, associated with the ×2 frequency multiplication. Distinct single and multi-photon processes were observed in the test device response operated in quantum mode. The mechanism of device saturation was experimentally studied. The test device when connected to the input of an SIS mixer, and pumped, showed $10 - 20\%$ increase in the SIS junction dark current.

1. Introduction

The ability of a Superconductor-Insulator-Superconductor (SIS) tunnel junction to respond to a single absorbed photon and extremely sharp nonlinearity in their current-voltage (I-V) characteristics, due to quasi-particle tunneling, has been utilized in ultra-low noise millimeter wave receivers [1]. The possibility of using this non-linear property of an SIS junction for frequency multiplication was suggested earlier[2], but there has not been any experimental effort to investigate this possibility further.

In this paper we present the first experimental demonstration of frequency multiplication using SIS junction-array operating in quasi-particle branch. We recognize that, in principle, the SIS junction as a frequency multiplier could operate in different modes. One can think of a purely classical scenario, when both input and output frequencies are less than the voltage nonlinearity ($\hbar\omega/e < \delta V_{gap}$). A classical-quantum mode, where the input pumping frequency does not produce quantum response ($\hbar\omega/e < \delta V_{gap}$) whereas output frequency is in the quantum regime. For a quantum-classical mode, one can think of a scenario, where the output frequency exceeds twice the gap frequency ($\hbar\omega/e > 2V_{gap}$). In this paper we investigate a quantum-quantum mode, where both the pumping and the output frequencies produce quantum response ($\hbar\omega/e > \delta V_{gap}$).

2. Design of test device

The quantum theory of mixing[3] describes in great details the mechanism of tunneling current at different harmonics. The tunneling current through the SIS junction as a response to the applied local oscillator signal (ω) is represented as [3], $I_{LO}\left(t\right) = a_0 + \sum_{m=1}^{\infty}\left(2a_m \cos m\omega t + 2b_m \sin m\omega t\right)$ where, the coefficients a_m and b_m are given by,

$$2a_m = \sum_{n=-\infty}^{\infty} J_n(\alpha)\left[J_{n+m}(\alpha) + J_{n-m}(\alpha)\right] \times I_{dc}\left(V_0 + n\hbar\omega/e\right) \quad (1)$$

$$2b_m = \sum_{n=-\infty}^{\infty} J_n(\alpha)\left[J_{n+m}(\alpha) - J_{n-m}(\alpha)\right] \times I_{KK}\left(V_0 + n\hbar\omega/e\right) \quad (2)$$

where, J is the Bessel function, a_0 is the DC component of the current, and I_{KK} Kramers-Kronig transform of the DC current-voltage characteristics of the tunnel junction.

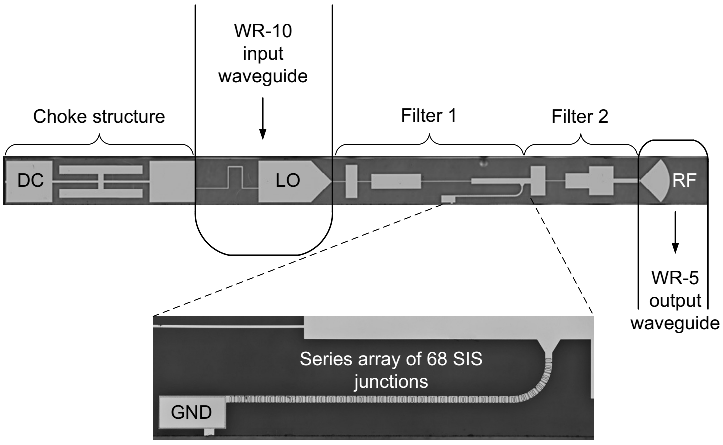

Figure 1. Photograph of the test chip showing the series array of 68 SIS junctions, two filter sections, RF and LO probes, position of the input and the output waveguides, and DC bias and ground (GND) ports. Each junction is 25 μm^2 in area with the overall chip dimensions of $415\,\mu m \times 6700\,\mu m$.

An array of SIS junction was used to boosting the total power in the multiplied signal. Figure 1 shows a test device consists of 68 identical $Nb/Al\text{-}AlO_x/Nb$ junctions connected in series, was fabricated on a 90 μm thick crystal Quartz substrate using in-house *Nb* thin-film technology[4]. Each junction has an area 25 μm^2 and a R_nA value of 50 $\Omega \cdot \mu m^2$. The test device was placed inside a split-block waveguide mount with possibility of applying magnetic field across the chip. The two filter structures (Filter 1 & Filter 2) provides isolation between the pumping frequency and the output (×2) frequency, and also matching between the SIS array and the embedding circuitry. In principle, different multiplication factors are possible, though in this experiment (×2) scheme was chosen because of the availability of measurement system at the output frequency.

For DC biasing, one end of the SIS array was connected directly to the waveguide block using bond wires, which provides the DC ground for the array. The bias current was supplied through a choke structure at the low frequency side.

3. Results and Discussion

The characterization of the test device was carried out at 4 K in a cryostat, Figure 2, with a closed cycle refrigerator. From the DC I-V characteristics, the gap voltage and the normal state resistance (R_n) of the whole array was found to be 195 mV and $R_n = 137\,\Omega$ respectively. Which corresponds to 2.86 mV gap voltage and $R_n = 2.01\,\Omega$ per junction, showing excellent agreement with the design value of $R_n = 2\,\Omega$.

To investigate the response from distributed SIS array, we use a double sideband SIS mixer [5] that covers the RF frequencies from 163 to 211 GHz with 4 to 8 GHz intermediate frequency (IF) bandwidth, connected at the output of the test device. The SIS array was pumped using a quasi-optically coupled W-band (83 – 105 GHz) Gunn oscillator and the output from the SIS array was coupled to the input of the mixer using a short piece of waveguide. In the experiment,

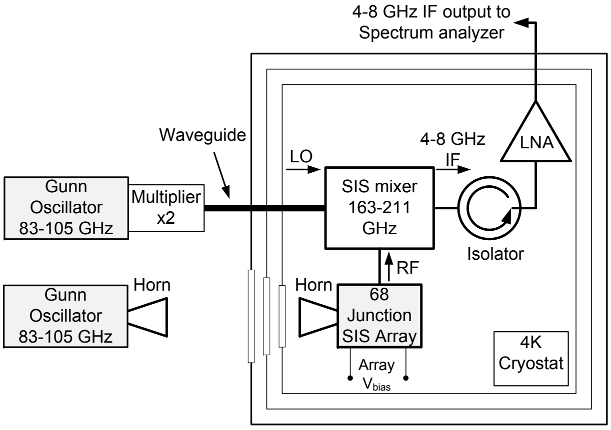

Figure 2. Schematic of the experimental setup used to study the test device. The cryostat contains the SIS junction array connected directly to a 163 – 211 GHz SIS mixer. Both the SIS mixer and the test array are pumped using two separate Gunn oscillators.

the Josephson effect was carefully suppressed using the magnetic field. The SIS mixer was pumped using a similar W-band Gunn oscillator and a frequency doubler [6], and the IF output was analyzed with a spectrum analyzer.

The LO for the SIS detector mixer $\left(f_{LO}^{SIS}\right)$ was swept between $171 - 203$ GHz, with the array excitation in the frequency range of, $f_{array} = \frac{f_{LO}^{SIS} \pm (4 \rightarrow 8\,GHz)}{2}$and the corresponding down converted IF response was studied.

Figure 3 shows the measured spectral response of the device, when the SIS detector mixer was pumped with LO frequency $\approx$ 190.3 and the SIS array excitation frequency was swept between 95 GHz to 100 GHz. We observed extremely sharp spectral signal between the $4 - 8$ GHz IF band, corresponding to the second harmonic of the input pump frequency. The solid black curve at 5.7 GHz IF in Figure 3 corresponds to a 98×2 GHz output frequency from the SIS multiplier array. Similarly, the dashed gray curve at 7.7 GHz IF corresponds to output frequency of 99×2 GHz. Measurements with several combination of the LO and RF frequencies were performed, all confirming frequency multiplication at second harmonics by the SIS array.

The dependence of frequency multiplication on the array bias voltage was investigated by fixing both, the LO signal for the SIS mixer, and the excitation signal for the array, and measuring the IF power while sweeping the array bias voltage. Figure 4 shows the dependence of frequency multiplication on the array bias voltage, where peak power of the multiplied signal (after down conversion to IF) was plotted with respect to array bias voltage. In this case, the LO frequency for the SIS detector mixer was set to 190 GHz, and the input frequency for array was set to 98 GHz. We observed multi-photon process in the SIS array response to the applied microwave excitation. The first peak below the gap voltage is believed to be associated with absorption of one photon whereas the second peak below the gap voltage corresponds to absorption of two photons at the pumping frequency. We also observed significant conversion of the input pumping signal into the second harmonic for DC bias above the gap voltage. The plot shows the IF power hence includes, mixer conversion loss, gain of the LNA at 4 K, room temperature amplifier, and IF cables.

4. Conclusion

In summary, we present results of the first experimental study of frequency multiplication in a distributed SIS multiplier array consisting of 68 SIS junctions. We experimentally observed off-chip generation of the second harmonic signal in $180 - 200$ GHz frequency band. The generated signal shows dependence on the DC bias voltage. The dependence exhibits features corresponding to single and multi-photon processes in the tunnel junction array. The device modeling shows good resemblance with the measurements. The device, although far from

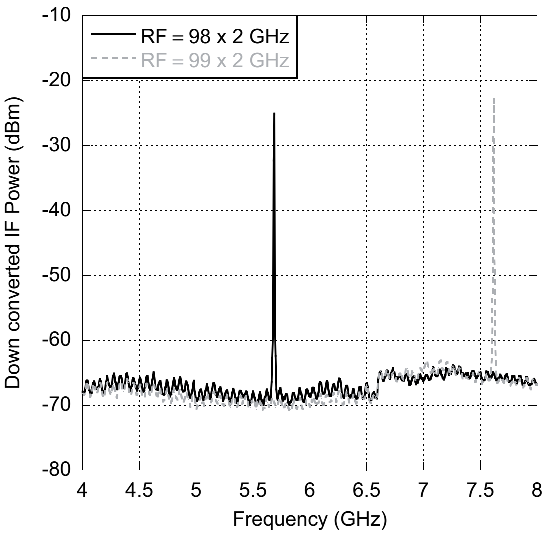

Figure 3. Measured down converted output response of the SIS array. The SIS detector was pumped with a LO frequency of ≈ 190.3 GHz, and the SIS array was exited with a signal at 98 GHz (solid black curve) and with 99 GHz (dashed gray curve).

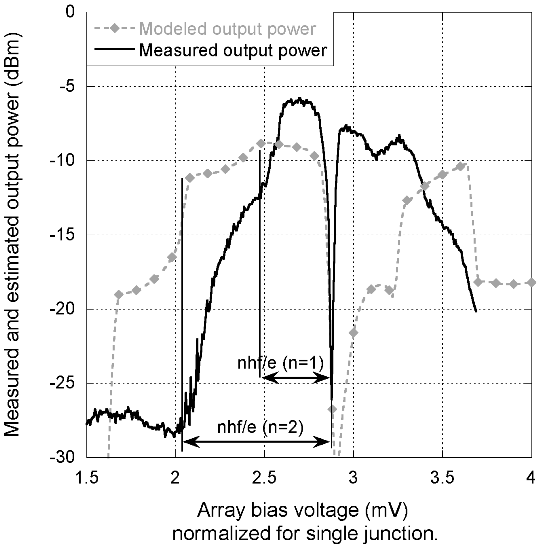

Figure 4. Bias voltage dependence of the multiplied signal. Down converted power of the 196 GHz signal was measured (solid black curve) at 6 GHz IF using spectrum analyzer. The voltage axis for the entire array is normalized for single junction. The dashed gray curve shows the estimated output power from the model.

providing enough power to pump a practical SIS mixer, may be considered as a first experimental step towards SIS frequency multipliers. Further development of the demonstrated principle of frequency multiplication may lead to a practical frequency multiplier device.

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