owse Journals & Magazines > IEEE Microwave and Wireless C... > Volume: 26 Issue: 10 Back to Results | Next > THz Frequency Up-Conversion using Superconducting Tunnel Junction

IEEE Microwave and Wireless Components Letters (ISSN: 1531-1309)

Citation for the published paper:
Rashid, H. ; Desmaris, V. ; Pavolotsky, A. et al. (2016) "owse Journals & Magazines > IEEE Microwave and Wireless C... > Volume: 26 Issue: 10 Back to Results | Next > THz Frequency Up-Conversion using Superconducting Tunnel Junction". IEEE Microwave and Wireless Components Letters, vol. 26(10), pp. 831-833.

THz Frequency Up-Conversion using Superconducting Tunnel Junction

Hawal Rashid, Vincent Desmaris, Alexey Pavolotsky and Victor Belitsky

***Abstract*— In this paper we present the characterization of the first frequency up-converter using distributed superconducting tunnel junctions. The power of the frequency up-converted signal was large enough to pump an SIS mixer. The efficiency of the distributed superconducting tunnel junction is 11-22 % for a fractional bandwidth of 7% with excellent spectral line purity. The -3 dB line width of the up-converter signal is better than 1 Hz, which was the lowest resolution bandwidth of the spectrum analyzer.**

***Index Terms*—SIS frequency up-converters, THz technology, Superconducting tunnel junctions.**

I. Introduction

MODERN cryogenic heterodyne millimeter and sub millimeter receivers for radio-astronomy employ Superconductor-Insulator-Superconductor (SIS) tunnel junctions or Hot Electron Bolometers (HEB) as mixers depending on the frequency [1]. These receivers provide the ultimate sensitivity and possibilities for spectral line (spectroscopic) observations [1, 2].

Generally, in these ultrasensitive SIS/HEB systems, the LO source is placed at room temperature, where the LO signal is coupled to the mixer either using long stainless- steel waveguide or quasi-optics. In the case of waveguide LO coupling, a substantial fraction of the LO power is lost because of the waveguide losses. For multi-pixel receivers, the LO distribution system introduces even a bigger challenge as it becomes bulky and extremely complex. Because useful solid-state fundamental sources apart from quantum cascade lasers are not available above approximately 200 GHz [3], the LO source end stage is typically some sort of frequency multiplier, where the nonlinear element is usually a Schottky diode. These LO frequency multipliers can generate adequate signals power up to 1-2 THz [4, 5].

In contrast to LO sources that multiply the frequency of the input signal by an integer, a nonlinear element can also produce frequency down and up conversion if supplied with two different pumping signals. In fact, the frequency up-converter (F-uC) source may also have the advantage of being wideband, since either of the two input signals can be adjusted such that the tuning range of the $f_0 = f_1 + f_2$ will be a sum of the tuning ranges for f_1 and f_2 sources. Furthermore, it would be advantageous to place the F-uC close to the SIS or HEB mixer, as this would reduce the power loss due to LO transport chain. Perhaps, the optimum solution would be have the LO source integrated on the same chip as the SIS or HEB mixer.

For this reason, we suggest to use a SIS tunnel junction as the F-uC element because it is fully integrable with the SIS mixer tri-layer -or with HEB- technologies. Moreover, the extremely nonlinear behavior and quantum nature of operation of a SIS tunnel junction gives reasons to believe that an SIS device designed for frequency up-conversion can operate with very high conversion efficiencies. The up-converted output power ranges over a few nano-watts to few hundreds of nano-watts depending on the SIS junction structure and size. The output power can be further increased by power combining techniques [6]. Furthermore, most sensitive heterodyne receivers in the millimeter/submillimeter region use SIS or HEB mixers, depending of the frequency, which require very low LO power typically below 0.5 µW [7, 8]. From this perspective, the SIS F-uC is completely compatible with the SIS/HEB system with respect to their operating environment and power requirements [7].

In this paper, we present the design of the first distributed (long) SIS device as a frequency up-converter. The distributed SIS junction [9] was used to obtain sufficiently high power. For the first demonstration of the distributed SIS junction used as a frequency up-converter, we opt for a nonintegrated approach as it is more practical at this stage.

II. Design

The power spectrum of the distributed (long) superconducting tunnel junction (D-SIS) as frequency up-converter was modelled using the large signal analysis in time domain similar to [9], with the main difference that two pumping signal (PS) sources were used here. The equivalent circuit diagram of the D-SIS is shown in Fig. 1. The circuit diagram is bisected at the linear-nonlinear interface and each half is treated separately. The nonlinear portion of the circuit is modelled in the time domain whereas the embedding network, which included the surface impedance and the geometrical capacitance of the distributed SIS junction, is treated in frequency domain. The modeling of the power spectrum obtained with the large signal simulations is shown in Fig.2. The pumping factor, α, which is the normalized to the quanta size voltage amplitude of the PS source is approximately α≈3 for both PS sources (notice that the quanta size for each PS is different).

The in- and output impedance of the distributed SIS junction was calculated similar to [9], and found to be approximately $Z_1 \approx 1$ Ω and $Z_2 \approx 2.3$ Ω respectively. Furthermore, a bandpass (BP) filter with a fractional bandwidth of 40 % was used both at the input and the output of the D-SIS F-uC in order to short-circuit unwanted

Manuscript received February 05, 2016; revised May 24, 2016; accepted July 07 2016.

The authors are with the *Group of Advanced Receiver development* (GARD) at Chalmers University of Technology, Gothenburg, Sweden.

harmonics. Detailed information on the device fabrication could be found in [9]. In order to feed the two pumping signals in one waveguide to the D-SIS F-uC, a waveguide hybrid [10] covering 40% fractional bandwidth, i.e., 80-120 GHz was designed and fabricated.

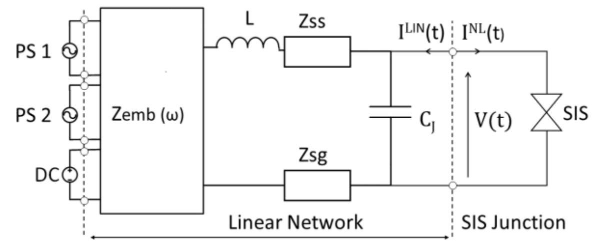

Fig. 1: Circuit diagram of the distributed SIS frequency up-converter. L and C_J are geometrical inductance and capacitance of the distributed SIS junction represented as a transmission line, whereas *Zss* and *Zsg* are the surface resistance of the microstrip and ground electrode respectively.

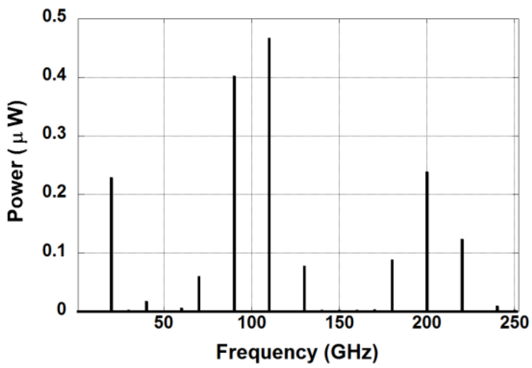

Fig. 2: The simulated large signal power spectrum of the up-converter. The plot shows the down converted (difference) signal, the second harmonic signals of each PS source and the sum frequency signal of the two PS sources. The frequencies of the two PS sources in this large signal simulation was 90 GHz and 110 GHz respectively.

III. Measurements and Results

A. *Measurement Setup*

The characterization of the device performance was carried out at 4 K in a cryostat with a closed-cycle refrigerator similar to [9]. Fig. 3 shows a schematic of the test setup used for the measurements of the D-SIS F-uC. To investigate the frequency response from D-SIS F-uC a double-sideband SIS mixer [11] that covers the RF frequencies from 163–211 GHz with 4–8 GHz intermediate frequency (IF) bandwidth, was connected at the output of D-SIS F-uC. The D-SIS F-uC was pumped with two different Gunn oscillators; one was fixed at 95.62 GHz, whereas the frequency range of the other Gunn oscillator was varied in the band of 82-94.8 GHz. The signals from the Gunn oscillators where first coupled via a WR-10 waveguide hybrid and then transmitted to the D-SIS F-uC chip through a WR-10 waveguide, whereas the output of the D-SIS F-uC was coupled to the input of the mixer using a 3 cm WR-5 waveguide.

In this experiment, the Josephson effect for both the SIS mixer and D-SIS F-uC was suppressed using two independent magnetic coils. An isolator and a cryogenic low-noise amplifier were used at the output of the SIS mixer. The SIS mixer was pumped using a 171-203 GHz LO consisting of an Agilent frequency synthesizer and active multiplier chain (×6) [5]. The IF output was studied with a spectrum analyzer.

In order to investigate the spectral response of the D-SIS F-uC, the LO frequency of the SIS mixer used for this purpose was set between 174–203 GHz, and the D-SIS F-uC was pumped with frequencies such that the expected SIS F-uC output power at the second harmonic would always fall inside the 4–8 GHz band of the down converted mixer IF.

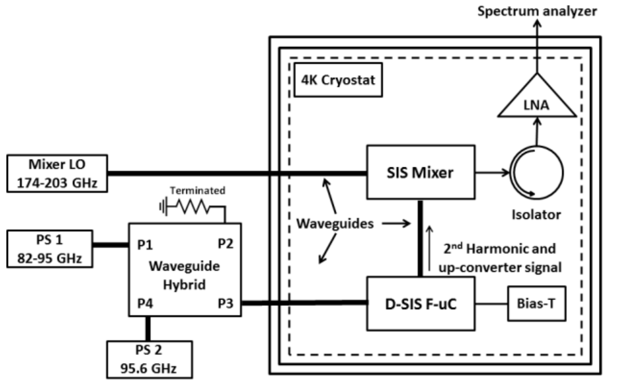

Fig. 3: Schematic of the experimental setup used to study the test device. The cryostat contains the SIS F-uC test chip mounted into a waveguide block connected through a WR-5 waveguide to a 163–211 GHz SIS mixer. Both the SIS mixer and the SIS F-uC test chip are pumped using two separate local oscillators.

B. *Measurement results*

The output power dependence of the frequency up-converter on the bias voltage was investigated by measuring the IF power of the SIS mixer through sweeping the D-SIS F-uC bias voltage. In this case, the frequencies and the output powers of the PS sources used for the SIS mixer and the D-SIS F-uC test chips respectively were fixed. The process was repeated for different pumping factors α. The peak power vs. the frequency at the up-converted signal, which corresponds to a fractional band width of 7% in this experiment, is shown in Fig. 5.

During the same experiment, we were also able to pump the SIS mixer only with the output signal of the D-SIS F-uC test chip. In this case, the LO power of the SIS mixer was switched off and the D-SIS F-uC was biased at the maximum power at the pumping factor α≈3.7. Once, the D-SIS F-uC parameters were set, a bias voltage sweep of 0-3.4 mV of the SIS mixer was conducted. The pumped dc I-V characteristic of the SIS mixer is shown in Fig. 6. The pumped SIS mixer tunnel current at 2.5 mV was approximately 6 times higher than in the un-pumped state. The pumping factor, α_{mix}, of the SIS mixer due to the output signal of the D-SIS F-uC test chip was estimated to be approximately $\alpha_{mix} \approx 0.35$, using the same extraction method as described in [9]. However, for a practical mixer, a higher output power is desired for comfortable operation. Moreover, the conditions of the test setup is not optimum for achieving high pumping factor at the mixer, since the output signal of the D-SIS F-uC is transmitted through several passive components and WR-5 waveguides before it arrived to the SIS mixer. Using the same approach as [9], we estimated that the losses and mismatch of various circuit components between the output of the D-SIS F-uC and the input of the SIS mixer is approximately 4.3-7.4 dB. This indicates that the output power at the D-SIS F-uC is 4.3-7.4 dB higher than the measured power at the SIS mixer junction. The efficiency of the D-SIS F-uC after removing the losses was estimated to be 11-22%.

One of the most important requirements on any frequency multiplier or F-uC is that it preserves the spectral purity of the input signal.

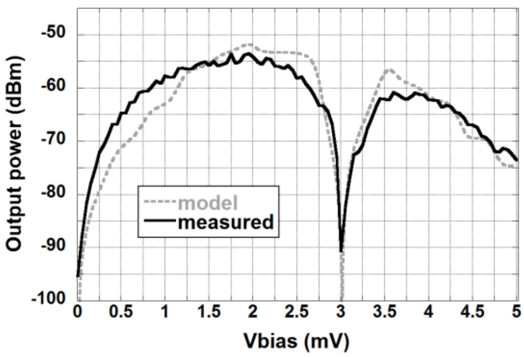

Fig. 4: A comparison of the measured and predicted sum power of the up converted signals at 94.89 GHz and 95.62 GHz vs. bias voltage at pumping factor $\boldsymbol{\alpha} \approx \mathbf{3}.7$.

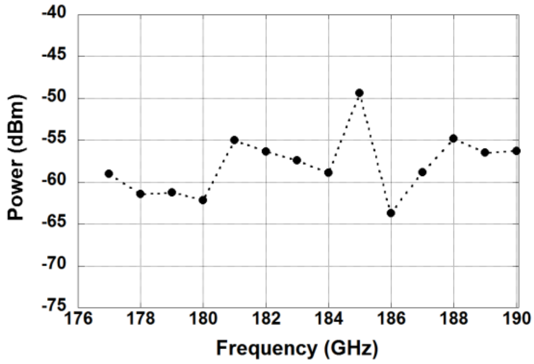

Fig. 5: The peak power vs the frequency at the sum of the up converted signal over a fractional bandwidth of 7%.

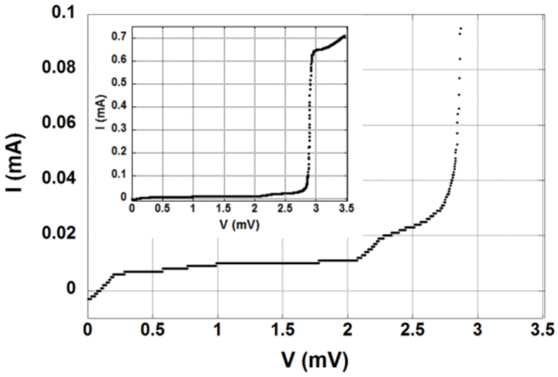

Fig. 6: Pumped dc I-V characteristics of the SIS mixer. The plot clearly shows the quantum response of the SIS mixer for the output power of the D-SIS F-uC at twice the input frequency i.e., at 186 GHz.

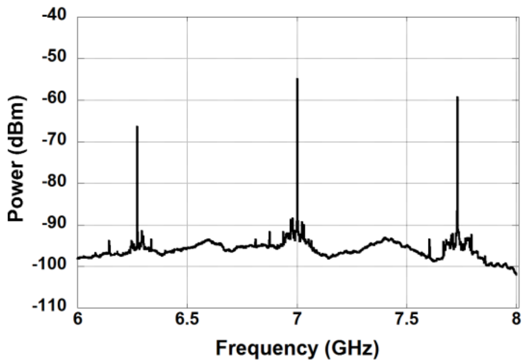

Fig. 7: The recorded power spectrum at the output out the down converter. The spectral line to the left and right is due to the down converted second harmonics of the two RF source at 94.89 GHz and 95.62 GHz respectively. The spectral line at the center is the down converted sum of the two PS sources.

The spectral line-width of the F-uC signal was measured with the resolution and video bandwidth of the spectrum analyzer set to 1 Hz (lowest value the spectrum analyzer could set) and 10 Hz respectively. The -3dB line-width of the output signal is better than 1 Hz. From our presented measurements with a spectrum analyzer (Fig. 7), we can estimate with the aid of Agilent application note [12] that the phase noise is approximately -80 dBc /Hz at 100 Hz frequency offset, corresponding actually to the phase noise of the pumping source (GUNN oscillator) signal itself.

IV. CONCLUSIONS

In this paper, we present the characterization of the first frequency up-converter using distributed SIS junctions. The distributed SIS junction frequency up-converter was for the first time able to pump an SIS mixer. The efficiency of the distributed SIS junction up-converter is 11-22 % for a fractional bandwidth of 7%, with excellent spectral line purity. The -3 dB line-width of the multiplied signal is better than 1 Hz, which was the lowest resolution bandwidth of the spectrum analyzer. Consequently, the results attained in this work show that the distributed SIS junction frequency up-converter has considerable future potential, and could possibly be used as a wideband LO source in SIS/HEB mixer layouts.

ACKNOWLEDGMENT

The authors would like to thank Sven-Erik Ferm, Mathias Fredrixon and Eric Sundin for the assistance in fabrication of the hybrid assembly and help with measurement equipment.

References

[1] F. Sizov and A. Rogalski, "THz detectors," *Progress in Quantum Electronics,* vol. 34, pp. 278-347, 9// 2010.

[2] B. Billade, O. Nystrom, D. Meledin, E. Sundin, I. Lapkin, M. Fredrixon, *et al.*, "Performance of the First ALMA Band 5 Production Cartridge," *Terahertz Science and Technology, IEEE Transactions on,* vol. 2, pp. 208-214, 2012.

[3] H. Eisele and G. I. Haddad, "State of the Art of Two-Terminal Devices as Millimeter- and Submillimeter-Wave Sources," in *The 11th International Symposium on Space Terahertz Technology*, Michigan, USA, 2000.

[4] A. Maestrini, B. Thomas, H. Wang, C. Jung, J. Treuttel, Y. Jin, *et al.*, "Schottky diode-based terahertz frequency multipliers and mixers," *Comptes Rendus Physique,* vol. 11, pp. 480-495, 8// 2010.

[5] *Virginia diodes, Inc*. Available: http://vadiodes.com/

[6] G. Chattopadhyay, "Technology, Capabilities, and Performance of Low Power Terahertz Sources," *Terahertz Science and Technology, IEEE Transactions on,* vol. 1, pp. 33-53, 2011.

[7] V. Belitsky, "Local Oscillator Power Requirements for ALMA SIS Mixers," ed. http://legacy.nrao.edu/alma/memos/html-memos/alma264/memo264.pdf, 1999.

[8] S. Cherednichenko, M. Kroug, H. Merkel, and E. Kollberg, "Local oscillator power requirement and saturation effects in NbN HEB mixers.," in *The 12th International Symposium on Space Terahertz Technology*, San Diego, CA, USA, 2001.

[9] H. Rashid, S. Krause, D. Meledin, V. Desmaris, A. Pavolotsky, and V. Belitsky, "Frequency Multiplier Based on Distributed Superconducting Tunnel Junctions: Theory, Design and Characterization," *Terahertz Science and Technology, IEEE Transactions on,* 2016, Submitted.

[10] H. Rashid, V. Desmaris, V. Belitsky, M. Ruf, T. Bednorz, and A. Henkel, "Design of Wideband Waveguide Hybrid With Ultra-Low Amplitude Imbalance," *Terahertz Science and Technology, IEEE Transactions on,* vol. PP, pp. 1-8, 2015.

[11] B. Billade, A. Pavolotsky, and V. Belitsky, "An SIS Mixer With 2hf/k DSB Noise Temperature at 163 - 211 GHz Band," *Terahertz Science and Technology, IEEE Transactions on,* vol. 3, pp. 416-421, 2013.

[12] *Agilent Application Note 150*.