Experimental Results of SIS Mixers with Distributed Junction Arrays

Sheng-Cai Shi, *Member, IEEE,* Takashi Noguchi, Junji Inatani, Yoshihisa Irimajiri, and Toshimi Saito

***Abstract*— The heterodyne mixing performance of three respective distributed junction arrays (i.e., a number of superconductor–insulator–superconductor (SIS) junctions distributed along a thin-film transmission line involving two, five, and ten junctions are measured and compared to their Fourier Transform Spectroscopy (FTS) detection responses. It has been found that distributed junction arrays have rather large a bandwidth in comparison to conventional SIS junction devices, while still keeping a quantum-limited noise performance. Detailed experimental results are presented.**

***Index Terms*—Distributed array, mixer, SIS.**

I. Introduction

THE bandwidth performance of superconductor–insulator–superconductor (SIS) mixers with a single junction, a junction array in series, or twin junctions in parallel depends largely upon the junction's $\omega R_n C_j$ product (R_n and C_j are junction's normal-state resistance and geometric capacitance, respectively): the larger the $\omega R_n C_j$ product is, the smaller the mixer bandwidth [1]. On the other hand, when selecting the $\omega R_n C_j$ product of an SIS junction one needs to avoid the actual limitation for the junction's critical current density (J_c), which is approximately 10 kA/cm^2 for Nb ones, as J_c is proportional to the ratio of $\omega/\omega R_n C_j$. It is therefore common to look for a tradeoff between the junction's $\omega R_n C_j$ product and the mixer bandwidth in developing SIS mixers, especially at submillimeter wavelengths.

Theoretical simulations have demonstrated that, like nonlinear transmission lines [2], distributed junction arrays, which comprise a number of SIS junctions connected in parallel with every two junctions separated by a short thin-film transmission line (like a conventional tuning inductance), have a bandwidth performance nearly independent of the junction's $\omega R_n C_j$ product [3]. While adopting low-current-density (say less than 4 kA/cm^2) SIS junctions, distributed junction arrays are still applicable to submillimeter-wave SIS mixers.

Manuscript received June 8, 1998.

S.-C. Shi was with the Nobeyama Radio Observatory, Nagano 384-13, Japan. He is now with the Purple Mounatin Observatory, JiangSu 210008, China.

T. Noguchi is with the Nobeyama Radio Observatory, Nagano 384-13, Japan.

J. Inatani is with the Tsukuba Space Center, National Space Development Agency of Japan.

Y. Irimajiri is with the Communication Research Laboratory, Ministry of Posts & Telecommunications, Japan.

T. Saito is with the Mitsubishi Electric Logistics Support Co., Ltd., Kamakura, Japan.

Publisher Item Identifier S 1051-8207(98)09522-1.

II. Distributed Junction Arrays

Three distributed junction arrays involving two, five, and ten SIS junctions, respectively, have been fabricated to experimentally investigate the bandwidth performance of such a type of junction device. Their photographs are displayed in Fig. 1. The SIS junctions in the three arrays were designed to be identical for simplicity and for ease of comparison. The junctions' critical current density was taken as 4 kA/cm^2, which is relatively low for SIS junctions operating at submillimeter wavelengths, while the junction area and the normal-state resistance for a single junction were 1.5 μm^2 and 31 Ω, respectively. With the assumption of a junction specific capacitance of 60 fF/μm^2, the junctions' $\omega R_n C_j$ product is equal to 8.2 at 470 GHz. The transmission line housing the SIS junctions was a Nb-based thin-film superconducting microstrip line of a 4.5-μm width and an insulator layer of Nb_2O_5(100 nm)/SiO_2(270 nm)/Al_2O_3(90 nm). The length of the short thin-film microstrip line between two junctions was optimized in connection with a 470-GHz waveguide SIS mixer (its detailed structure can be found in [4]), which was employed to measure these junction arrays. The lengths of the short microstrip lines for the ten-, five-, and two-junction arrays were found to be 17, 22, and 26 μm (approximately λ g/13.2, λ g/10.2, and λ g/8.6 at 470 GHz), respectively.

The fabricated junction arrays had a critical current density of about 3.4 kA/cm^2, while their normal-state resistances were equal to 2.2, 4.4, and 11 Ω. Obviously, both parameters are smaller than the respective design values. Their differences suggest that the actual junction area is 66% larger than the designed one. An overestimated margin for junction shrinking (in photomask design) and imperfect fabrication process might account for the enlargement of the junction area. Nevertheless, it appears that the junctions were identically defined because the arrays' equivalent normal-state resistances scale exactly with the number of junctions.

III. Experimental Results and Discussions

A. Fourier Transform Spectroscopy (FTS) Detection Responses

Prior to measuring the heterodyne mixing performance of the three distributed junction arrays, we have studied their FTS responses with the aid of the 470-GHz waveguide mixer (acting as a direct detector here), in which the distributed junction arrays are mounted. The measured direct-detection

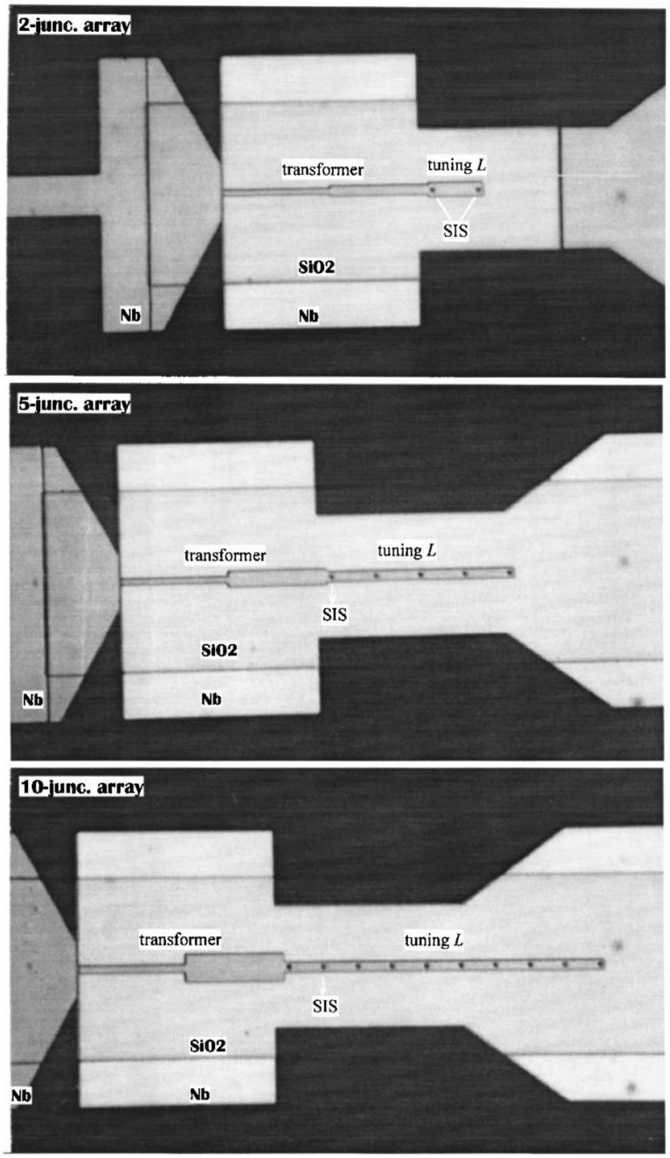
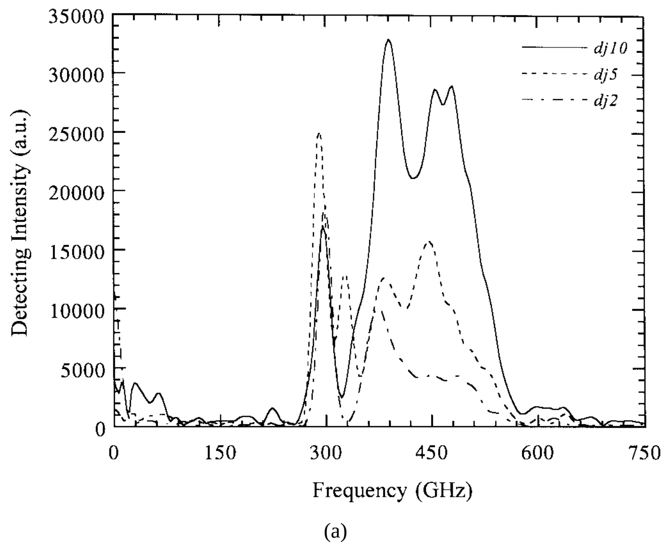


Fig. 1. Photographs of three distributed (two-, five-, and ten-) junction arrays.



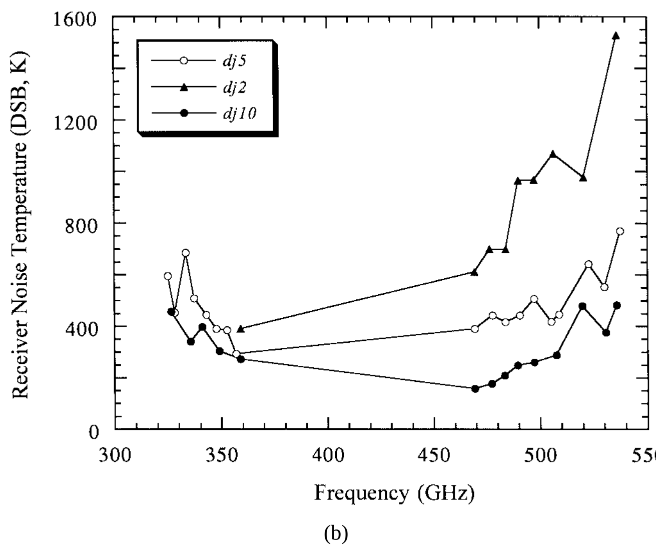


Fig. 2. (a) Measured FTS responses and (b) measured receiver noise temperatures (DSB) for three distributed (two-, five-, and ten-) junction arrays of a ~66% enlarged (over the design value) junction area and a critical current density equal to 3.4 kA/cm^2.

responses are presented in Fig. 2(a). The upper- and lower-frequency limits of these responses are caused mainly by the adopted mixer mount, while the dips in the response curves result partly from the intrinsic behaviors of the distributed junction arrays and partly from the measurement system (i.e., spectrometer itself). As can be clearly observed from Fig. 2(a), the response curve for the two-junction array is peaked around 375 GHz, which is approximately the displaced center frequency due to an enlarged junction area (i.e., 470 GHz/1.66$^{1/2}$ $\approx$ 365 GHz). Its 3-dB bandwidth is approximately 60 GHz, apparently defined by the junctions' $\omega R_n C_j$ product (i.e., 470 GHz/8.2 $\approx$ 57 GHz). The response curves for the five- and ten-junction arrays have a larger bandwidth and are centered around 450 GHz, even though the junction areas in the two instances are similarly enlarged. It is clear that the frequency responses of distributed junction arrays with more junctions are less sensitive to the junction area and the junctions' $\omega R_n C_j$ product.

B. Heterodyne Mixing Performances

Using the conventional Y-factor method, we have measured the noise performance of the 470-GHz waveguide SIS mixer for the three distributed junction arrays. The measured DSB (double-sideband) receiver noise temperatures are plotted in Fig. 2(b). Notice that the noise contribution of the quasi-optical system for measurement, which is located just in front of the measured SIS mixer and consists of a 25-μm-thick Mylar vacuum window, an elliptical mirror and a 25-μm-thick Mylar beam splitter (both angled at 45 degrees) is included, and that the equivalent noise temperature of the IF-chain following the 470-GHz SIS mixer is about 15 K. It should be pointed out here that the noise performance in the frequency range of 360–470 GHz was not measured for lack of LO (local oscillator) sources. Nevertheless, the general trends of the three noise temperature curves should not change if looking into the results shown in Fig. 2(a). Of the three measured arrays, the ten-junction one has the best noise performance, giving a

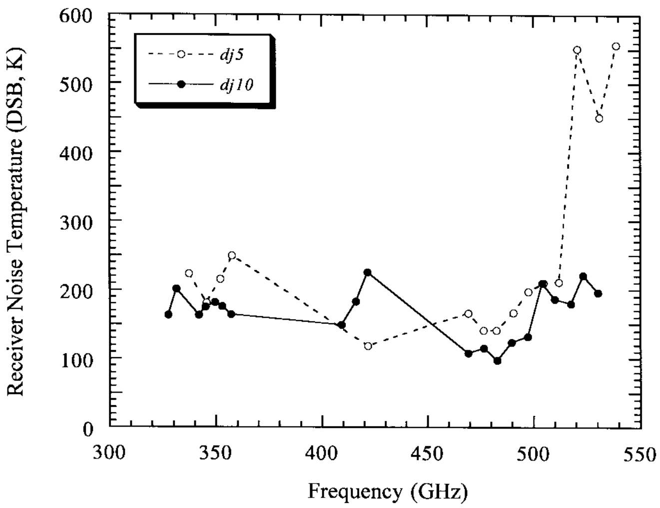


Fig. 3. Measured receiver noise temperature (DSB) as a function of frequency. Results are shown for a five- and a ten-junction array of a junction area as the design value and a critical current density equal to 3.8 kA/cm^2.

receiver noise temperature of 150 K at 470 GHz and less than 400 K from 320 to 540 GHz. The frequency response of the receiver noise temperature for the two-junction array is clearly centered at a frequency lower than 360 GHz, again indicating that the actual junction area is larger than the desired one. It is this frequency displacement that made the receiver noise temperature higher in case of the two-junction array, as the junction device and the mixer mount were optimized at two completely different frequencies (~365 and 470 GHz). The results shown in Fig. 2(b) are generally in good agreement with those in Fig. 2(a).

Additional five- and ten-junction arrays of a critical current density and equivalent normal-state resistances equal to 3.8 kA/cm^2 and 6.6/3.3 Ω, which are very close to the respective design values, have been fabricated with an improved fabrication process. As demonstrated in Fig. 3, the measured receiver noise temperatures are improved considerably compared to those given in Fig. 2(b). The receiver noise temperature for the ten-junction array is less than 220 K from 325 to 535 GHz (namely, of a 50% relative bandwidth, approximately), and has a minimum value of around 95 K at 485 GHz, which is only four times as large as the quantum limit. Notice that the applied LO pumping power level was indeed insufficient around 425 GHz for the ten-junction array. Similarly, the ten-junction array shows a larger bandwidth than the five-junction array.

C. Discussions

There was a concern of that, because having more junctions, distributed junction arrays may consume more LO power. Experimental results have demonstrated that the optimum LO pumping current (i.e., the current at the first photon step below the array's gap voltage) for the ten-junction array is typically one-tenth of the current at the array's gap voltage, a level lower than for a single junction, indeed indicating a smaller reduced LO voltage $(eV_{\mathrm{LO}}/h\nu)$. Hence, the LO power level necessary for distributed junction arrays may not increase considerably with the increase of the number of junctions. It is well known that the junction's Josephson current must be suppressed for submillimeter-wave SIS mixers. We have observed that suppressing the Josephson current in a distributed junction array is just as easy as in case of a single junction, though the junctions in an array are quite separated.

As distributed junction arrays can offer a very large bandwidth, they are likely to be well matched at the fundamental and harmonic frequencies simultaneously, thereby making it possible to use distributed junction arrays for harmonic mixing, which requires both the fundamental and the harmonic frequency port matched [unpublished simulation results]. Additionally, distributed junction arrays should be advantageous for direct-detection applications as far as the bandwidth is concerned.

IV. Summary

The noise performance of distributed junction arrays has been experimentally investigated with the help of a 470-GHz waveguide mixer mount. Measurement results clearly demonstrate that arrays with more junctions have larger bandwidths. While adopting junctions of a relatively low current density (i.e., 3.8 kA/cm^2), a ten-junction array has exhibited a good performance, giving a minimum receiver noise temperature of 95 K at 485 GHz $(\sim 4h\nu/k)$ and as large a relative bandwidth as 50%. It has been found that, in comparison to a single junction, distributed junction arrays have a frequency response which is much less dependent on the junction area. Good agreement between the FTS detection and heterodyne mixing responses has also been observed. Distributed junction arrays should be applicable to heterodyne mixing (either fundamental or harmonic) and direct detection in the terahertz frequency regime.

Acknowledgment

The authors would like to thank H. Matsuo of NRO and H. Akahori of Shinshu University for their help in measuring the FTS responses of distributed junction arrays.

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