EXPERIMENTAL RESULTS OF SIS MIXERS WITH DISTRIBUTED JUNCTION ARRAYS

Sheng-Cai Shi[1], Takashi Noguchi[1], Junji Inatani[2], Yoshihisa Irimajiri[3], and Toshimi Saito[4]

1. Nobeyama Radio Observatory, Nobeyama, Minamisaku, Nagano 384-13, Japan
2. Tsukuba Space Center, National Space development Agency of Japan
3. Communication Research Laboratory, Ministry of Posts & Telecommunications, Japan
4. Mitsubishi Electric Logistics Support Co., Ltd., Kamakura, Japan
e-mail: shencai@nro.nao.ac.jp; noguchi@nro.nao.ac.jp;
Inatani.Junji@nasda.go.jp; irimaji@crl.go.jp; tsaito@nro.nao.ac.jp

Abstract — The heterodyne mixing performances of three distributed junction arrays (i.e., a number of SIS junctions distributed along a thin-film transmission line) involving two, five, and ten junctions, respectively, are experimentally investigated in the frequency range of 320-540 GHz, and are compared to their Fourier-Transform-Spectroscopy detecting responses. In addition, the Josephson resonance effects of the three distributed junction arrays are examined. Finally, other possible applications of distributed junction arrays, such as harmonic mixing and direct detecting, are addressed.

1. Introduction

SIS mixers have exhibited as low a receiver noise temperature as three times the quantum limit at submillimeter wavelengths [1]. In developing submillimeter-wave SIS mixers, ones usually adopt SIS junctions of a relatively large $\omega R_n C_j$ product (R_n and C_j are junction's normal-state resistance and geometric capacitance, respectively), say four, to avoid the limitation of the junction's critical current density (J_c, approximately 10 kA/cm^2 for Nb junctions), which is proportional to the ratio of $\omega/\omega R_n C_j$. Hence, submillimeter-wave SIS mixers with a single junction, a junction array in series, or twin junctions in parallel have a limited bandwidth according to such a relation $\omega/\Delta\omega = \omega R_n C_j$. On the one hand, broadband junction devices are highly desirable for tuneless SIS mixers, are suitable to direct-detecting applications, and are beneficial to some complex systems such as millimeter-/submillimeter-wave interferometer arrays in reducing the cost and complexity.

Theoretical simulations have demonstrated that like non-linear transmission lines [2], distributed junction arrays, which are 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 junctions' $\omega R_n C_j$ product [3]. While adopting low-J_c (say less than 4 kA/cm^2) SIS junctions, distributed junction arrays are still applicable to submillimeter-wave SIS mixers. In this paper, the bandwidth performance of distributed junction arrays is experimentally studied.

2. Distributed junction arrays and a 470-GHz SIS mixer

Three distributed junction arrays involving two, five, and ten SIS junctions, respectively, have been fabricated to investigate the bandwidth performance of such a type of junction device experimentally. Their photographs are displayed in Fig. 1. The SIS junctions in the three arrays were designed to be identical for simplicity and for convenience of comparison. The junctions' critical current density was taken as 4 kA/cm^2 (relatively low for submillimeter-wave applications), while the junction area and the normal-state resistance for a single junction were 1.5 μm^2 and 31 Ω. 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 of an insulator layer as Nb_2O_5(1000 Å)/SiO_2(2700 Å)/Al_2O_3(900 Å). The length of each section separating every two junctions of the thin-film microstrip line was optimized in connection with a 470-GHz waveguide SIS mixer, which was employed to measure these junction arrays. The optimum microstrip-line lengths for the ten-, five-, and two-junction arrays were equal to 17, 22, and 26 μm (approximately $\lambda_g/13.2$, $\lambda_g/10.2$, and $\lambda_g/8.6$ at 470 GHz), respectively. It is understandable that these lengths do not differ significantly, considering that the resonance frequency of the circuit made up of two junctions and the microstrip line between them approximately defines the upper frequency limit of a distributed junction array.

The 470-GHz waveguide tuneless mixer mount used here is similar to that described in [4,5], but has a larger waveguide and a larger SIS-chip slot to fit the broadband characteristic of distributed junction arrays. Its detailed structure, together with the integrated circuits on the SIS chip, is displayed in Fig. 2a. The RF and LO signals are transmitted to the distributed junction array through a diagonal horn, a waveguide-to-microstrip transition, and a quarter-wavelength impedance transformer. The diagonal horn [6], of a feed waveguide just as the mixer's input waveguide, has an aperture measuring 3.5 mm x 3.5 mm and a length of 16 mm. The waveguide-to-microstrip transition, featuring a 'built-in' DC/IF return path and an offset probe (for larger bandwidth) [7], transforms the waveguide impedance (~289 Ω at 470 GHz) to an output impedance of 75 Ω, which is just equal to the characteristic impedance of the output microstrip line. Transforming the 75-Ω output impedance to the input impedance of the distributed junction array (approximately equal to R_n/N, here N is the number of junctions), the quarter-wavelength impedance transformer is composed of three sections, with one being a conventional microstrip line of a 44.7-Ω characteristic impedance and the other two a thin-film microstrip line (of different characteristic impedances for the three distributed junction arrays). The calculated RF embedding impedance seen before the distributed junction array is demonstrated in Fig. 2b for the three instances. The IF signal is outputted through the IF choke filter, which has an RF impedance nearly equal to zero at 470 GHz and is not followed by any IF impedance transformers whereas distributed junction arrays may have an output impedance around 50 Ω owing to a small equivalent normal-state resistance (several ohms).

3. Experimental results and discussions

3.1 Josephson resonance effects

The fabricated junction arrays have a critical current density of about 3.4 kA/cm^2 (slightly lower than the desired value, 4 kA/cm^2), while their normal-state resistances are equal to 2.2, 4.4, 11 Ω, being apparently smaller than the respective design values of 3.1, 6.2, 15.5 Ω. The resistance difference, together with a lower junction current density, suggests that the actual junction area is 66% larger than the designed one. An over-estimated 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 have been identically defined because the arrays' equivalent normal-state resistances scale exactly with the number of junctions.

In case of twin SIS junctions connected in parallel (with a tuning inductance between them), it has already known that two Josephson resonance steps will appear on the junction I-V curve [5]. The resonance steps are the dc responses of the Josephson ac currents through the two SIS junctions, indeed indicating two resonance frequencies for two respective circuits — one consists of the tuning inductance and one junction, and the other the tuning inductance and the two junctions. Here we have examined the I-V characteristics of the three fabricated junction arrays (from the same batch). Their resonance effects are shown in Figs. 3a-c with respective I-V curves (enlarged for Figs. 3b and 3c). Note that the resonance steps for both the five- and the ten-junction array are not completely exhibited because they are very sensitive to magnetic field. It can be observed from Figs. 3a-c that for the two-junction array a resonance step (higher one) occurs around 0.7 mV (corresponding to 339 GHz, a low frequency obviously due to an enlarged junction area), whereas for the five- and ten-junction arrays multi-steps (>2) occur with the highest voltage being around 0.9 mV. Apparently, the more the junctions, the more the resonance steps. Such a multi-step structure, indeed arising from the multi-resonance loops of a distributed junction array, suggests that distributed junction arrays can perform over a large bandwidth, which will increase with the number of junctions. This conclusion is coincident with the simulation results plotted in Fig. 3d, which are the calculated input S_{11} parameters for the three distributed junction arrays with the assumption of that each junction is a parallel combination of its actual normal-state resistance and geometric capacitance (i.e., 22 Ω and 90 fFx1.66). Notice that for S_{11}-parameter simulations, the parameters of the thin-film microstrip line are kept the same as the design values.

It should be pointed out that for mixing applications with distributed junction arrays, especially in the terahertz regime, the Josephson current must be completely suppressed as the resonance steps may extend to a relatively high voltage so as to affect the IF response of the mixing considerably.

3.2 FTS responses and heterodyne mixing performances

Prior to measure the heterodyne mixing performances of the three distributed junction arrays, we have studied their Fourier-Transform-Spectroscopy responses with the aid of the 470-GHz waveguide mixer (acting as a direct detector here), in which the distributed junction array is mounted. The measured direct-detecting responses are presented in Fig. 4a. The upper- and lower-frequency limits of these responses are caused mainly by the adopted mixer mount, while the dips in the response curves are partly the intrinsic behaviors of the distributed junction arrays and partly due to the measurement system (i.e., spectrometer itself). These direct-detecting curves predict the RF-coupling behaviors of the three distributed junction arrays, though not exact ones. As can be clearly observed from Fig. 4a, the response curve for the two-junction array is peaked around 375 GHz, which is very close to the displaced center frequency due to an enlarged junction area (i.e., 470 GHz/$1.66^{1/2} \approx 365$ GHz). Note that the difference between this frequency and the two-junction-array's resonance frequency (i.e., 339 GHz) is caused by the embedding impedance (of a negative susceptance around 339 GHz, refer to Fig. 2b) of the adopted 470-GHz mixer mount. In addition, 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≈57 GHz). On the contrary, the response curves for the five- and ten-junction arrays have a larger bandwidth and are centered around 450 GHz, even though the junction area in the two instances is similarly enlarged. Obviously, the frequency responses of distributed junction arrays become less sensitive to the junction area and the junctions' $\omega R_n C_j$ product with the increase of the number of junctions. Being in good agreement with the simulation results described in [3], the direct-detecting results are very encouraging for the development of SIS mixers with distributed junction arrays.

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 receiver noise temperatures (DSB) are plotted in Fig. 4b. Notice that the noise contribution due to 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, and an elliptical mirror and a 25-μm thick Mylar beam splitter both angled at 45 degrees, were not calibrated out, and that the equivalent noise temperature of the IF-chain following the 470-GHz SIS mixer was found to be about 15 K. The noise performance in the frequency range of 360-470 GHz was not measured for lack of LO sources. Nevertheless, the general trends of the three noise-temperature curves should not be changed if looking into the results shown in Fig. 4a. Of the three measured instances, the ten-junction array has the best noise performance, giving a minimum noise temperature of 150 K at 470 GHz and being less than 400 K from 320-540 GHz. The frequency response of the receiver noise temperature for the two-junction array is clearly centered at a frequency of lower than 360 GHz, in like manner proving that the actual junction area is larger than the desired one. This frequency displacement attributes to a high receiver noise temperature in case of the two-junction array, as the junction device and the mixer mount were optimized at completely different frequencies (~365 and 470 GHz). The results shown in Fig. 4b are generally in good agreement with those in Fig. 4a.

Another 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 (very close to the respective design values), have been fabricated with an improved fabrication process. As demonstrated in Fig. 5, their measured noise performances are improved considerably compared to those given in Fig. 4b. The receiver noise temperature for the ten-junction array is less than 220 K from 325-535 GHz (namely, of a relative bandwidth approximately equal to 50%), and has a minimum value of around 95 K at 485 GHz, which is four times as large as the quantum limit. It should be pointed out that the LO pumping power level was insufficient around 425 GHz somehow in the case of the ten-junction array. Similarly, the ten-junction array has shown a larger bandwidth than the five-junction array.

3.3 Discussions

Both the five- and the ten-junction array have demonstrated a relative bandwidth of much large than $1/\omega R_n C_j$ (~12% for the two instances), namely, the relative bandwidth for a single junction or twin junctions. In fact, their bandwidths might be even larger if eliminating the effect of the adopted waveguide mixer mount, which has a smaller bandwidth. Therefore, the RF bandwidths of distributed junction arrays (for N>5) are nearly independent of the junctions' $\omega R_n C_j$ product (the more the junctions, the less the dependency). Accidentally, it has been observed that for distributed junction arrays the junction area is no longer as critical to the mixing performance as for a single junction or twin junctions. This conclusion is similar to such a simulation result that the performance of SIS mixers with distributed junction arrays is insensitive to the tuning inductance [3] (not experimentally confirmed here). The measured receiver noise temperature is already quite low, but could be further reduced if using an IF chain of a lower noise temperature.

Regarding the LO power level necessary for distributed junction arrays, it has been found that the optimum LO pumping current for the ten-junction array is typically one-tenth of the current at the gap voltage, a level lower than for a single junction (i.e., of a smaller reduced LO voltage). Hence, the necessary LO power level may not increase to some degree with the increase of the number of junctions. Moreover, it has been observed that though the junctions in a distributed junction array are quite separated, suppressing the Josephson current is just as easy as in case of a single junction.

As distributed junction arrays can offer a very large bandwidth, it is likely to have a good matching at the fundamental and harmonic frequencies simultaneously, thereby being possible to use distributed junction arrays for harmonic mixing, which requires both the fundamental and the harmonic frequency port well matched [unpublished simulation results]. It is already known that there are some ripples in the RF-response curves of distributed junction arrays. Increasing the number of junctions may reduce the ripples, but will make RF matching difficult (or degrade the RF-matching bandwidth) because of a smaller equivalent normal-state resistance. Adopting non-identical junctions (i.e., of different areas) and non-uniform separations between every two junctions might be a good alternative. Additionally, distributed junction arrays should be applicable to direct-detecting applications as far as the bandwidth is concerned.

4. 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 demonstrated that the more junctions the array has, the larger the bandwidth is. Though adopting junctions of a relatively low current density (i.e., 3.8 kA/cm^2), the ten-junction array has exhibited a good performance, giving a minimum receiver noise temperature of 95 K at 485 GHz ($\sim 4\hbar\omega/k$) and as large a relative bandwidth as 50%. It has also been found that in comparison to a single junction, distributed junction arrays have a frequency response much less dependent on the junction area. Good agreement between FTS responses and heterodyne mixing responses has also been observed. Distributed junction arrays should be of good use for heterodyne mixing (either fundamental or harmonic) and direct detecting in the terahertz frequency regime.

Acknowledgment

Hiroshi Matsuo of NRO and Akahori of Shinshu University are thanked for their help in measuring the FTS responses of distributed junction arrays.

References

1. J.E. Carlstrom and J. Zmuidzinas, "Millimeter and submillimeter techniques," in *Reviews of Radio Science 1993 - 1995*, W. R. Stone, ed., The Oxford University Press, Oxford, 1996.

2. C.E. Tong, R. Blundell, B. Bumble, J.A. Stern, and H.G. LeDuc, "Quantum limited heterodyne detection in superconducting non-linear transmission lines at sub-millimeter wavelengths," *Appl. Phys. Lett.*, vol.67, pp.1304-1306, Aug. 1995.

3. S.C. Shi, T. Noguchi, and J. Inatani, "Analysis of the bandwidth performance of SIS mixers with distributed junction arrays," *Proc. 8th Int. Symp. on Space Terahertz Tech.*, Boston, USA, Mar. 1997, pp.81-90.

4. S.C. Shi, T. Noguchi, and J. Inatani, "A fixed-tuned 100-GHz SIS mixer exhibiting broad bandwidth and very low noise temperature," *IEEE Trans. Appl. Supercond.*, vol.7, no.4, pp.3850-3857, Dec. 1997.

5. S.C. Shi, T. Noguchi, and J. Inatani, "Development of a 500-GHz band SIS mixer," *IEEE Trans. Appl. Supercond.*, vol.7, no.2, pp.2587-2590, June 1997.

6. A.W. Love, *Electromagnetic Horn Antennas*, IEEE Press, New York, 1976.

7. S.C. Shi and J. Inatani, "A waveguide-to-microstrip transition with DC/IF return path and an offset probe," *IEEE Trans. Microwave Theory Tech.,* vol.45, no.3, pp.442-445, Mar. 1997.

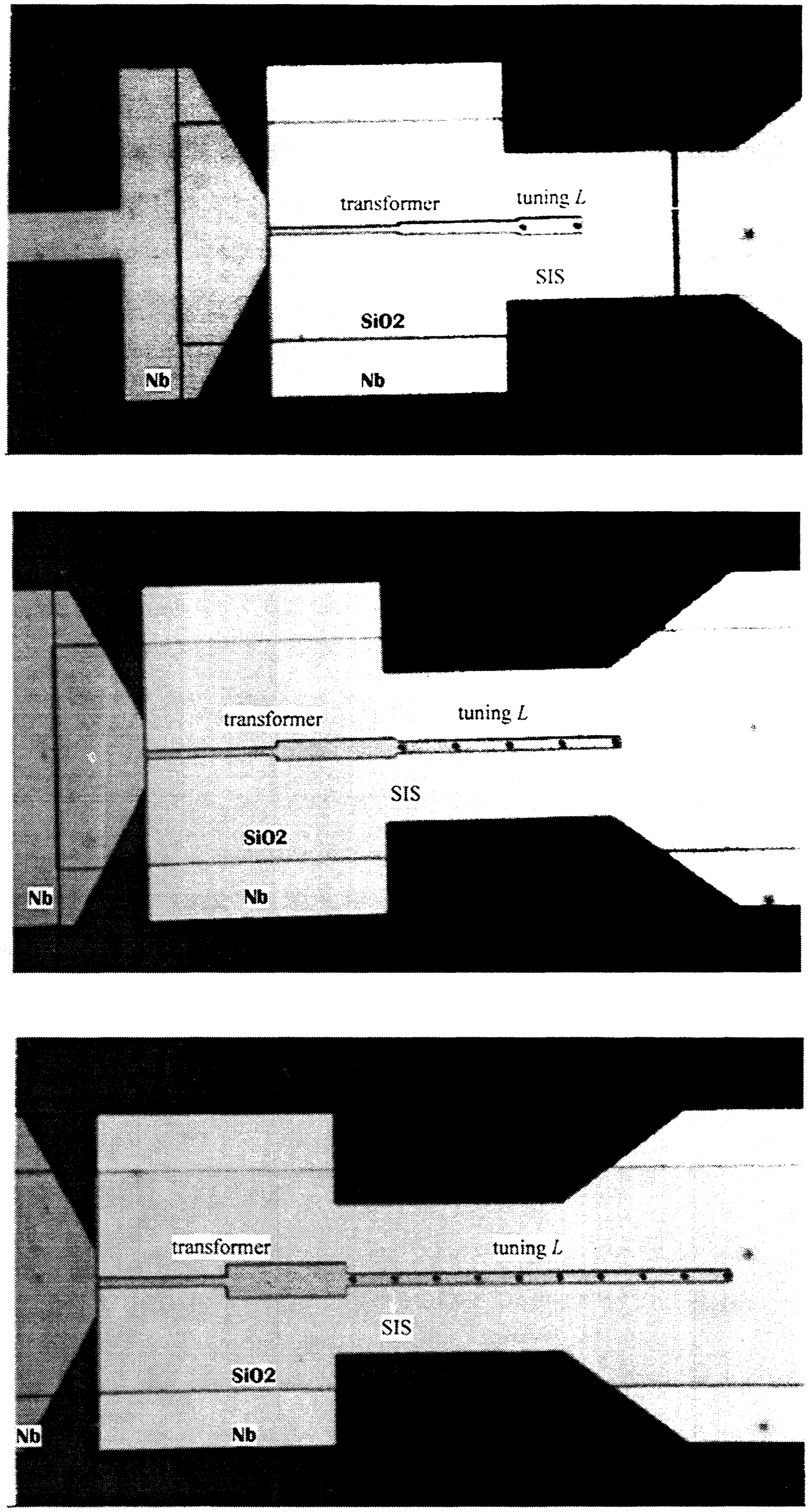


Fig. 1 Photographs of three distributed junction arrays, with (a) two junctions, (b) five junctions, and (c) ten junctions.

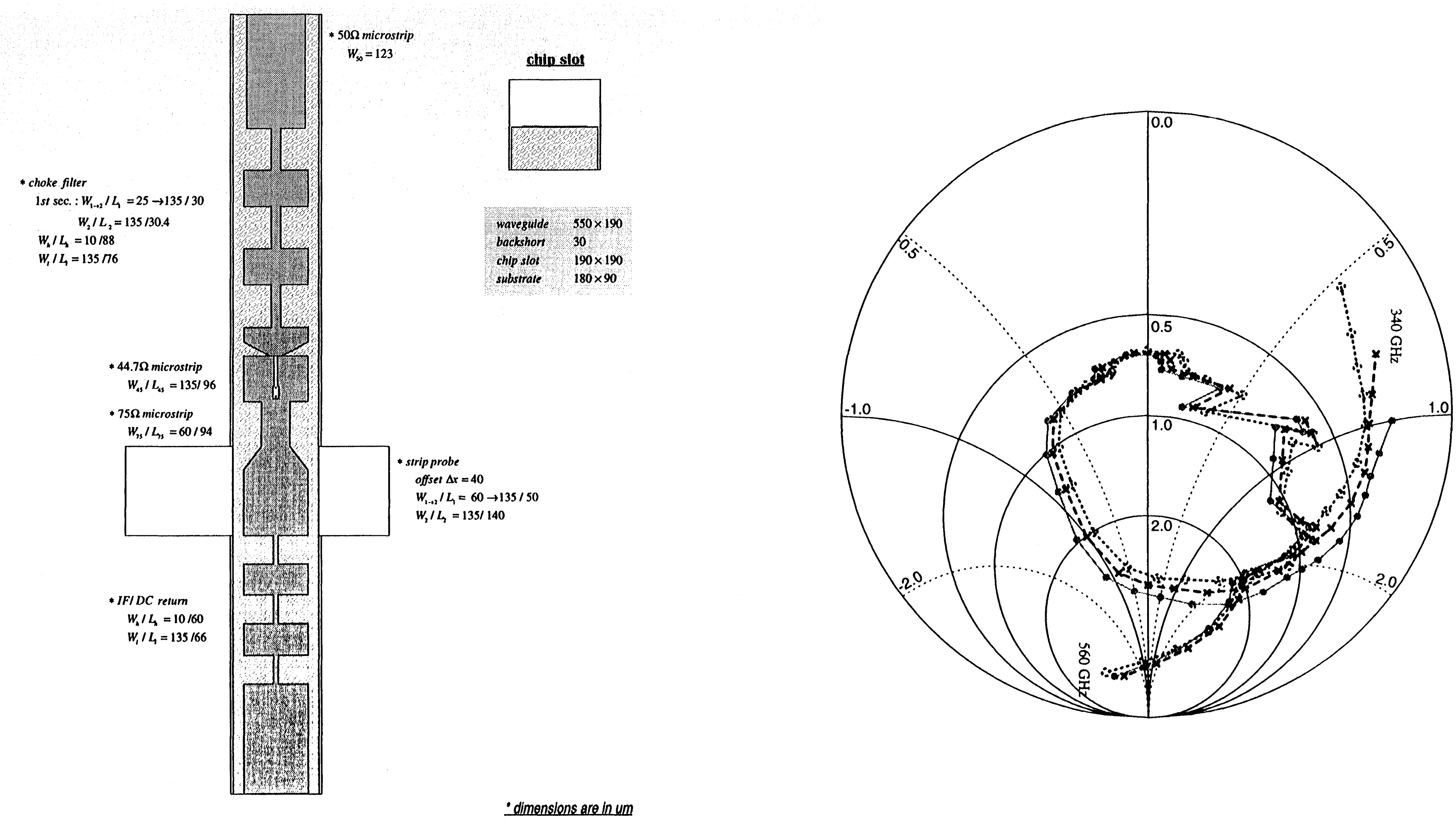


Fig. 2 (a) Cross-sectional view of a 470-GHz tuneless waveguide SIS mixer; (b) Embedding impedance of the 470-GHz mixer mount (seen from the distributed junction array), plotted on a Smith impedance chart for the two-, five-, and ten-junction arrays.

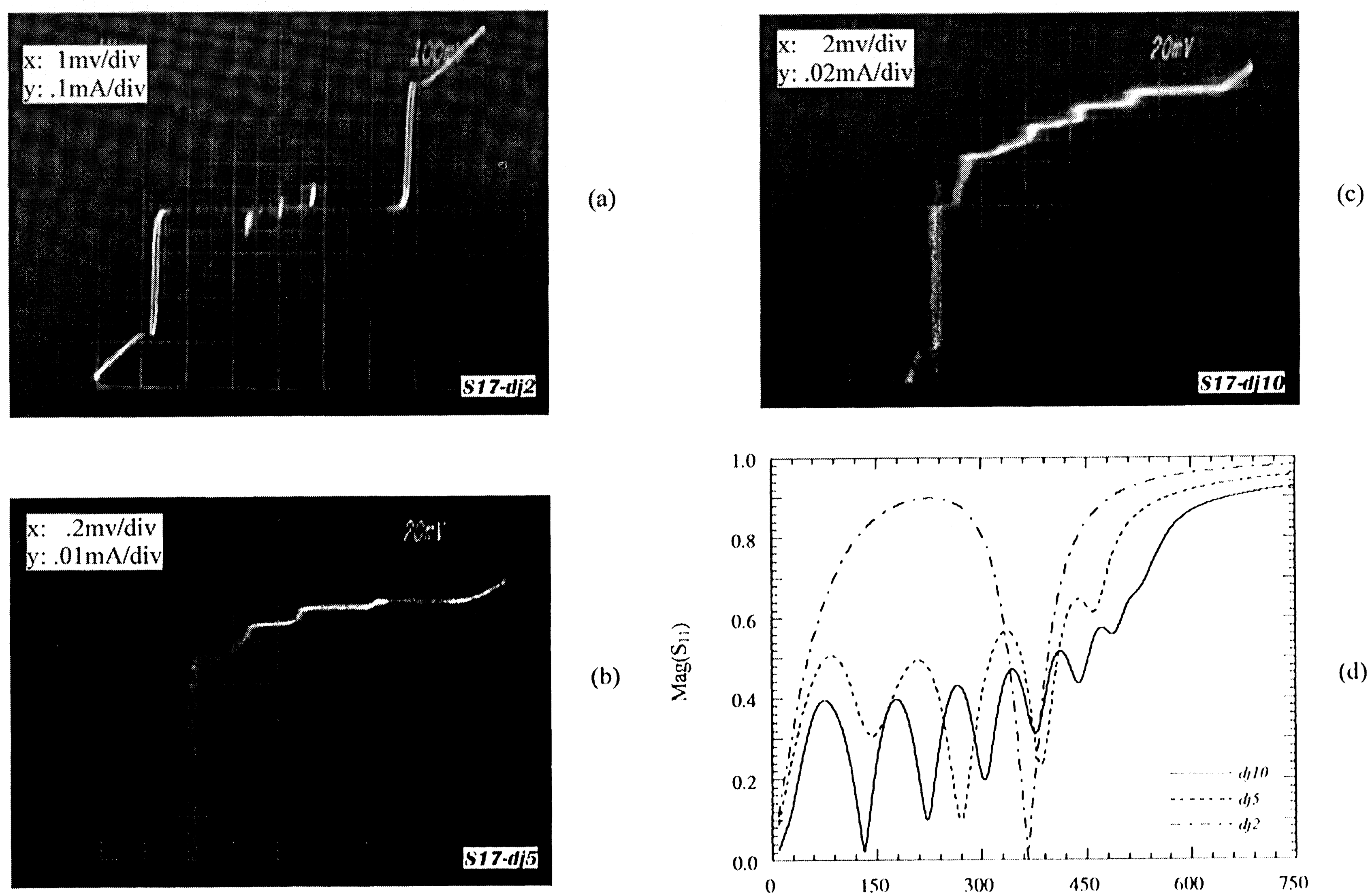
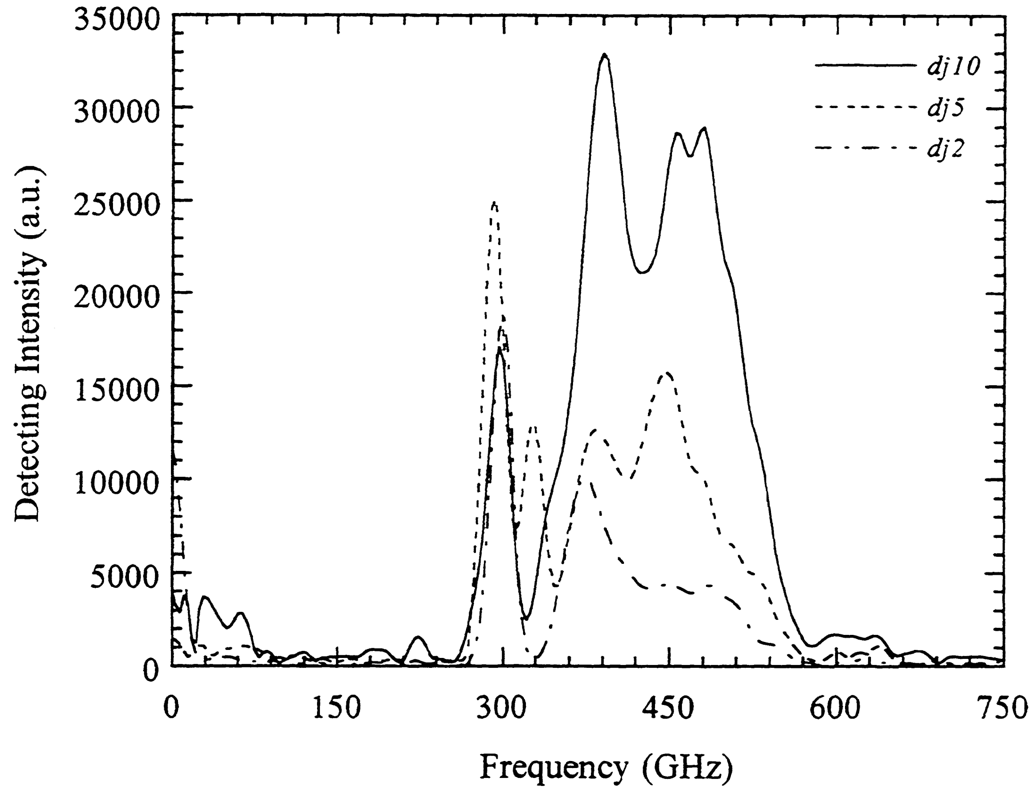
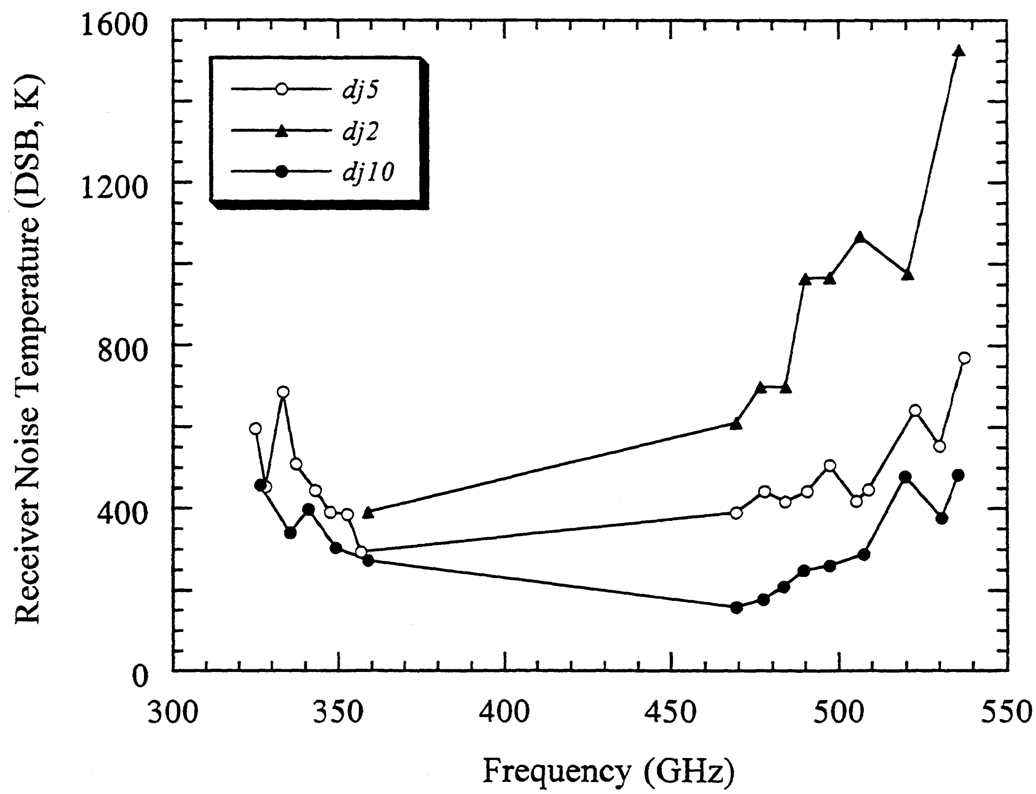


Fig. 3 Josephson resonance effects of three distributed (a. two-, b. five-, and c. ten-) junction arrays of a ~66% enlarged junction area and a current density of 3.4 kA/cm^2; (d) Simulated S_{11} parameters for the three junction arrays, shown as a function of frequency. Note that each SIS junction is assumed as a parallel combination of its normal-state resistance and geometric capacitance (i.e., 22 Ω and 90 fFx1.66).



(a)



(b)

Fig. 4 (a) Measured FTS responses and (b) measured receiver noise temperatures (DSB), for the two-, five-, and ten-junction arrays of a ~66% enlarged junction area and a current density of 3.4 kA/cm^2

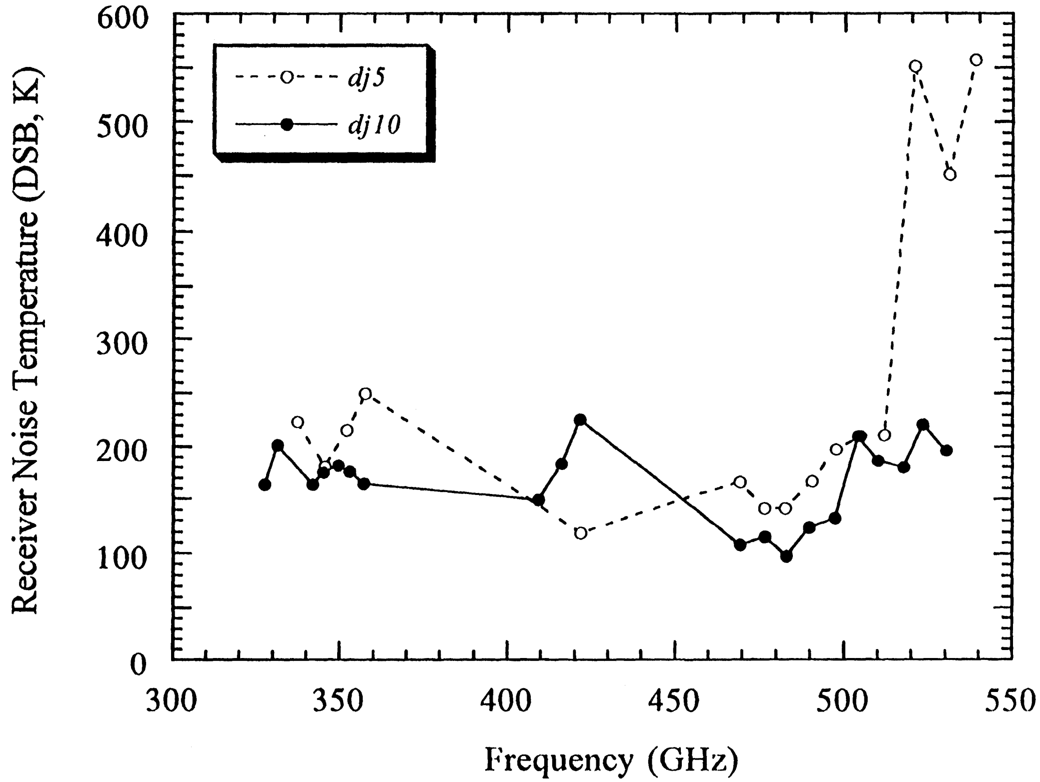


Fig. 5 Measured receiver noise temperature (DSB) as a function of frequency. Results are shown for a five- and a ten-junction array of a corrected junction area and a critical current density equal to 3.8 kA/cm^2.