Design and Analysis of a Waveguide NbN-based SIS Mixer using a Tuning Circuit with Two Half-Wavelength Distributed Junctions for the 900-GHz Band

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Abstract

We designed a waveguide SIS mixer based on NbN for the 900-GHz band. The waveguide mixer block with an MgO substrate was designed using Hewlett Packard's High Frequency Structure Simulator (HFSS) and uses a waveguide-to-microstip transition. Simulation by HFSS showed that a source impedance of around 60 Ω can be achieved from 786 to 988 GHz by using an MgO substrate about 30 μm thick. The tuning circuit was proposed to reduce the current density of the NbN SIS junctions without impairing broadband operation; it consists of two half-wavelength distributed SIS junctions connected by a half-wavelength microstripline. Simulated mixer performance based on the experimental I-V curve of the NbN SIS junctions showed SSB receiver noise temperatures of below 150 K from 760 to 960 GHz, assuming a junction current density of 25 kA/cm^2.

1. Introduction

Millimeter- and submillimeter-wave SIS mixers with quantum limited noise sensitivity and wideband characteristics are needed in radio-astronomy projects such as the Atacama Large Millimeter Array (ALMA) and the Herschel space observatory. For example, the ALMA covers the fequency range from 30 to 950 GHz in ten bands. For most of the bands, waveguide Nb-based SIS mixers can be used because they satisfy demanding specifications. However, the highest band (band 10), from 787 to 950 GHz, is beyond the gap frequency of Nb (700 GHz). In band 10, Nb has a large RF loss due to pair-breaking. It would thus be very difficult to achieve the specified SSB noise temperature of about 440 K over band 10 by using conventional Nb-based SIS mixers. Although a few reported SIS mixers, consisting of Nb-based tunnel junctions and NbTiN- or Al-based tuning circuits, enable low-noise operation at frequencies above the gap frequency of Nb, they do not satisfy the specifications [1, 2].

Our approach for achieving low-noise operation above 700 GHz is to develop all-NbN SIS mixers that should in principle perform well up to a gap frequency of 1.4 THz, like all-Nb SIS mixers do. We previously developed NbN/AlN/NbN tunnel junctions and

NbN/MgO/NbN microstriplines that are epitaxially grown on single-crystal MgO substrates [3, 4, 5]. Using these technologies, we have demonstrated relatively low-noise performance and broadband operation in the 900-GHz band using a quasi-optical SIS mixer with a self-compensated distributed tunnel junction with a high current density (45 kA/cm^2) [6, 7]. To make these SIS mixers practical for such applications as the ALMA, further improvements are necessary. First, the quasi-optical coupling, which uses a self-complimentary log-periodic antenna, contributes a large input noise, as estimated using the standard technique. The coupling system must be improved to reduce this noise. Second, the high-current-density junction with usually poor quality, which is needed for broadband operation, degrades mixer performance. These junctions must be improved to obtain better performance.

We have now designed a waveguide all-NbN SIS mixer using an MgO substrate for application to ALMA band 10. We also proposed a broadband tuning circuit that enables junctions with lower current density and better I-V curve to be used. Numerical calculations of the receiver noise temperature based on Tucker's quantum theory of mixing show that broadband and low-noise characteristics can be achieved with this new mixer.

2. Waveguide design

Most of the reported SIS mixers use a waveguide coupling because of the availability of feed horns, such as corrugated horns and diagonal horns, which produce an efficient power coupling into the waveguide over a broadband and an excellent antenna beam pattern. In conventional waveguide SIS mixers, a greatly reduced-height waveguide effectively yield broadband RF matching between the waveguide and SIS junction [8]. However, it may be difficult to fabricate such a waveguide in the submillimeter-wave regime because the aperture is so small. One way to overcome this problem is to use a waveguide probe, which provides excellent power coupling using a waveguide-to-microstrip transition [9]. We designed a mixer block including a waveguide-to-microstrip transition for ALMA band 10.

Figure 1 shows the schematic layout of the waveguide mixer block, which we designed using Hewlett Packard's High Frequency Structure Simulator (HFSS) [10]. The mixer chip with MgO substrate, on which the SIS junctions, tuning circuit, impedance transformer, waveguide probe, and RF choke filter are integrated, is placed in a channel of the mixer block. The mixer chip is 70 μm wide, 1.4 mm long, and 32 μm thick. For simplicity, externally adjustable mechanical tuners are not used. A diagonal feed horn is buried in the block and connected to the input waveguide (0.1 mm high and 0.26 mm wide) through a tapered structure. The aperture and length are 2.5 and 16 mm, respectively.

The calculated feed-point impedance normalized to 60 Ω is shown in Fig. 2. The graph shows that an RF bandwidth of 21%, from 786 to 988 GHz, is available with our design. It also shown that ALMA band 10 is covered better than with –10 dB matching.

In designing the waveguide-to-microstrip transition, it is important to examine how the position of the waveguide probe affects the input coupling efficiency. Figure 3 shows the dependence of the S-parameters on the position of the waveguide probe. The S-parameters were calculated assuming the input port of the input waveguide and the output port of the microstrip with a characteristic impedance of 60 Ω. The solid lines in Fig. 3 show the S-parameters when the waveguide probe was shifted 10 μm from the designed position toward the IF port, and the dashed lines show the S-parameters at the designed position. The bandwidth of the RF matching was not sensitive to the position of the waveguide probe. This is a benefit of mounting the mixer chip in the mixer block.

3. Tuning-circuit design

Recently proposed distributed mixers based on the nonlinear quasi-particle tunnel current in a SIS transmission line have demonstrated low noise and good tunablity at submillimeter wavelengths. Electrically long junctions (say, a few times the guided wavelength) need low-current density but a submicron line-width to achieve reasonably high impedance for ease of matching, so that electron-beam lithography is necessary [11]. To obtain high input impedance with a wide junction width with conventional photolithographic techniques, a resonant distributed SIS mixer (say, half or one guided wavelength) was proposed [12] and tested [6, 7, 13]. However, its fractional bandwidth is narrow when low-current-density SIS junctions are used because the bandwidth is largely governed by the Q-factor of the junction, like that of a conventional lumped element mixer. Using a conventional tuning configuration, consisting of a resonant SIS junction with a quarter-wavelength impedance transformer, we can control the matching bandwidth by adjusting only the current density of the junction. In sum, high-current density-junctions are needed to obtain wideband operation at submillimeter wavelengths.

The tuning method we proposed efficiently compensates for the reactance component of distributed tunnel junctions. According to simple transmission theory, the input impedance of an open-ended distributed SIS junction is expressed by

$$Z_{in} = Z_j \coth(\gamma_j l_j), \tag{1}$$

where Z_j, γ_j ($=\alpha+j\beta$), and l_j are, respectively, the characteristic impedance, propagation constant (α is quasi-particle loss and β is the phase constant), and length of the tunnel-junction transmission line. If the transmission line is low-loss (αl_j<<1), the equation can be rewritten as

$$Z_{in} = Z_j \frac{\dfrac{Z_j}{\alpha l_j}\cos(\beta l_j) + jZ_j \sin(\beta l_j)}{Z_j \cos(\beta l_j) + j\dfrac{Z_j}{\alpha l_j}\sin(\beta l_j)}. \tag{2}$$

This equation shows that the input impedance of an open-ended SIS tunnel junction is equivalent to that of a loss-less transmission line (α=0) end-loaded with a pure resistance of $Z_j/(\alpha l_j)$. Accordingly, the frequency-varying impedance of the SIS transmission line can be simply understood as the frequency-varying reactance component yielding in the loss-less transmission line. One solution for broadbanding by efficient reactance compensation is to use a filter structure consisting of half-wavelength components, which can control the impedance characteristics to have a bandwidth within a prescribed tolerance.

The diagram in Fig. 4 is an example tuning circuit consisting of two distributed SIS junctions connected by a transmission line and an impedance transformer. The lengths of junctions and the line between them have half-guided wavelengths at the center frequency, and the length of the impedance transformer has a quarter-wavelength. The tuning circuit was designed for a source impedance of 60 Ω over ALMA band 10 centered at 870 GHz. The modeled SIS junctions and transmission lines are, respectively, the NbN/AlN/NbN tunnel junction and the NbN/MgO/NbN microstripline. These elements have been used in actual SIS mixers and have been well characterized.

The material parameters of the junctions and microstriplines used for the calculation are summarized in Table 1. The characteristic impedance of the 0.6-μm-wide SIS junctions with a symmetrical counter-electrode overhang of 1 μm on either side was about 2 Ω. The quasi-particle loss in the half-wavelength line (αl_j in equation (2)) for the given current density was of the order of 10^{-1}, so we can apply the model described by equation (2) to this circuit. The characteristic impedance of the microstripline between the SIS lines was about 27 Ω.

To match the impedance of the tuning circuit, which has a filter structure, to the source impedance, they are connected using a quarter-wavelength impedance transformer. A broadband matching of below –10 dB was obtained at frequencies ranging from 750 to 1000 GHz (fractional bandwidth of about 29%), as shown in Fig. 4. Also shown in the figure are the impedance loci toward the load at each position of the circuit. One can see that the reactance component was well compensated for with this tuning circuit. Compared to a roughly estimated fractional bandwidth of 10% from the $\omega C_j R_N$ products for a conventional mixer design, the improvement in matching was about three times.

4. Simulated noise performance

We numerically simulated the mixing properties of our distributed SIS mixer using Tucker's quantum theory of mixing [14]. Equivalent large and small signal models for the mixer were established by replacing the model of inhomogeneous junction arrays based on lumped elements [15] with a distributed element model as described by Tong et al. [16]. Each section of the tunnel junctions was divided into 16 cells, sufficient for analyzing quasi-particle nonlinear transmission lines [16]. In these lines, each cell must be driven by a different LO phase and amplitude. We assumed an LO drive strength with the zero phase at the open end of the mixer, then derived the conversion admittance matrices for each cell recursively according to transmission theory. The correlation matrices was derived from the LO amplitude only for each cell, based on the assumption that shot noise created at any point along a nonlinear transmission line is not correlated with shot noise generated at any other point [16]. We used a quasi-five-port approximation in which the fundamental frequency sidebands, the second harmonic sidebands, and IF frequency were taken into account [17]. The IF frequency was assumed to be 1.5 GHz, and the IF termination was 50 Ω. The dc characteristic of an actual

NbN SIS junction was used, as shown in Fig. 5. The subgap-to-normal state-resistance ratio at 4 mV was about 11.

We used simplified model without a quarter-wavelength transformer to calculate the mixing properties of the mixer. A constant source impedance of 5 Ω was assumed across the entire frequency band for a circuit consisting of half-wavelength components because the quarter-wavelength microstripline transforms a waveguide source impedance of 60 Ω to about 5 Ω at the center frequency. Figure 6 shows the calculated SSB receiver noise temperature. Note that the dc bias and LO strength across the last cell were optimized with respect to the receiver noise temperature at each simulated frequency by assuming a noise temperature of the IF amplifier of 2 K. One can see that there are two noise ripples, one at around 800 GHz, and another at around 930 GHz. In our simulation, this could be reduced by assuming a lower source impedance of 2 Ω, as shown in the figure, but the bandwidth became a bit narrow because the matching became worse. If we use junctions with a different width, the ripples can be reduced without impairing broadband matching.

To compare the performance of our mixer with that of other type mixers, we simulated the mixing properties of a full-wavelength resonant distributed SIS mixer with the same current density, 25 kA/cm^2. As shown in Fig. 6, the receiver noise bandwidth of our proposed SIS mixer was broader than that of the conventional mixer, as predicted from the design, whereas the total length of the distributed junction was the same. Thus, this tuning method using effective reactance compensation can reduce the current density and obtain broadband characteristics.

5. Conclusion

We designed a waveguide SIS mixer with an MgO substrate on which NbN-based SIS and microstrip are epitaxially grown in the 900-GHz band of the Atacama Large Millimeter Array. Simulation using Hewlett Packard's High Frequency Structure Simulator showed that the waveguide source impedance was around 60 Ω when a 32-μm-thick substrate was used. To achieve performance better than the previous results using high current density junction of 45 kA/cm^2, we proposed a broadband tuning circuit that enables the use of lower current density junctions, resulting in a smaller leakage current. It utilizes the efficient reactance compensation produced by two half-wavelength distributed junctions connected by a half-wavelength microstripline. Based on the design and simulated noise performance, we predict that a tuning circuit using NbN junctions with a current density of 25 kA/cm^2 can cover the whole 900-GHz band with a SSB receiver noise temperature below 150 K.

Acknowledgements

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Table 1. Parameters used in design.

NbN upper electrode thickness:	400 nm
NbN lower electrode thickness:	200 nm
MgO insulator thickness:	180 nm
NbN/AlN/NbN junction width:	0.6 μm
current density:	25 kA/cm^2
$J_C R_N A$ products	380 kVμm^2/cm^2
Specific capacitance:	120 fF/μm^2
AlN barrier thickness:	1 nm
$\omega C_J R_N$ products:	10 @870 GHz

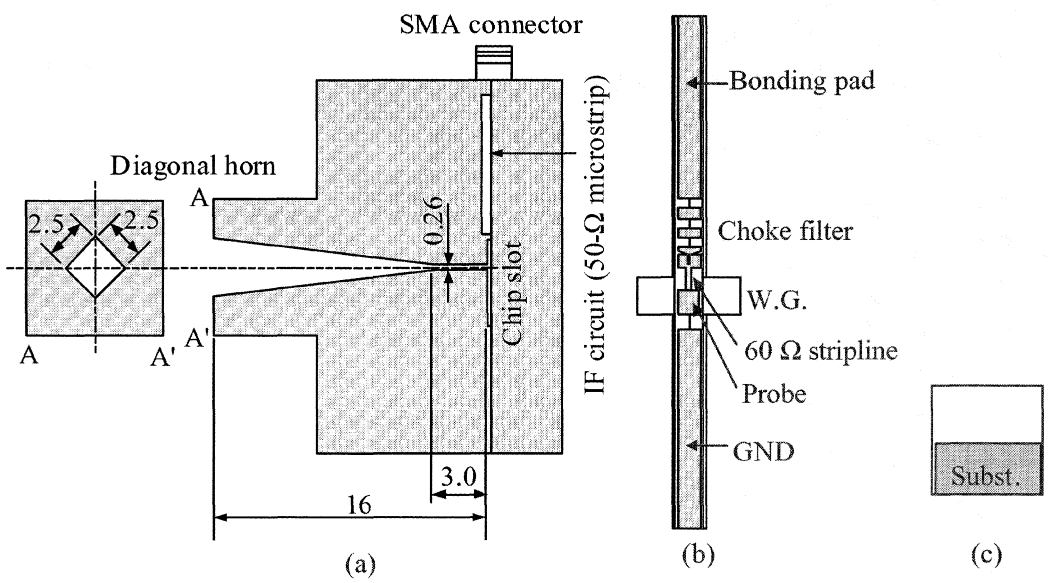
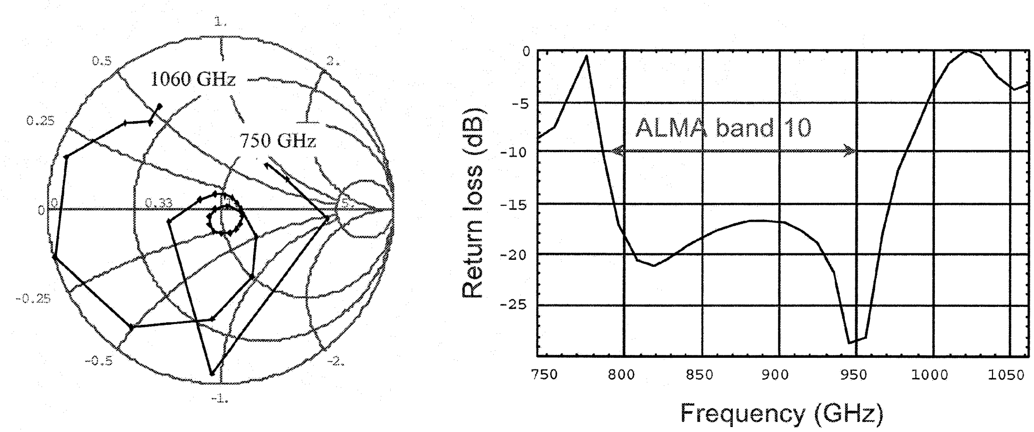


Fig. 1. Mixer mount layout showing diagonal horn section and mixer back piece. (b) View of chip slot from side of back piece. Waveguide is 0.1 × 0.26 mm, substrate is 0.07 × 1.4 × 0.032 mm. (c) Sectional view of chip slot, which is 0.073 × 0.073 mm.



(a) (b)

Fig. 2. (a) Calculated feed-point impedance normalized to 60 Ω. (b) Return loss characteristics between feed-point and 60 Ω.

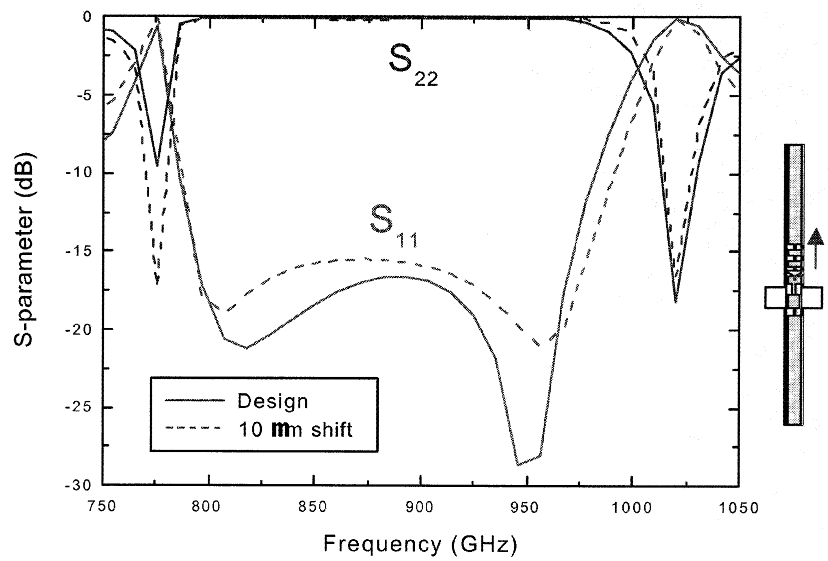


Fig. 3. Dependence of S-parameters on waveguide probe position. The 10-μm shift toward the IF port from the original position did not affect the characteristics.

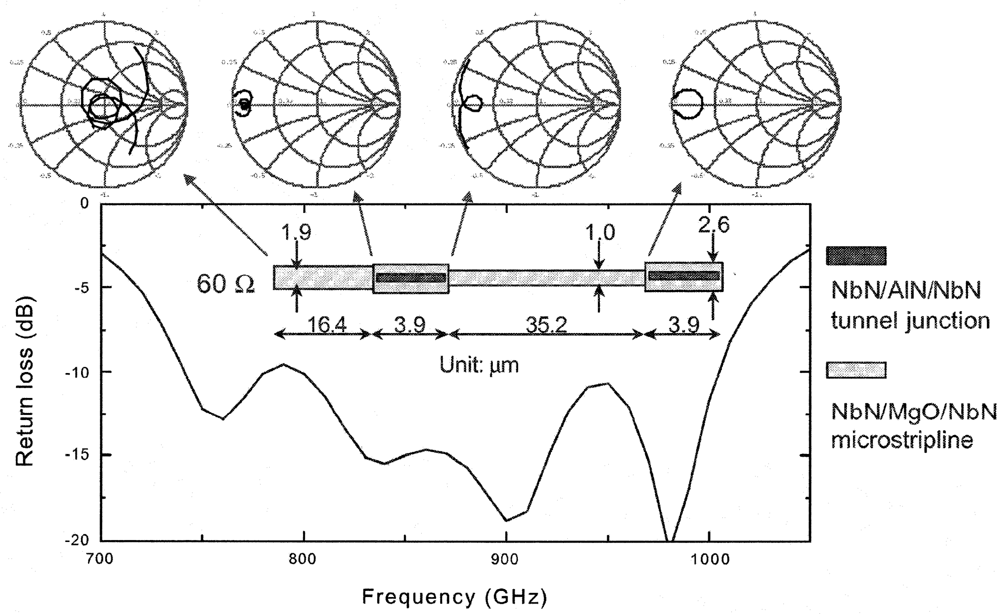


Fig. 4. Layout, theoretical return loss of tuning circuit, and impedance loci toward load at each position, normalized to 60 Ω.

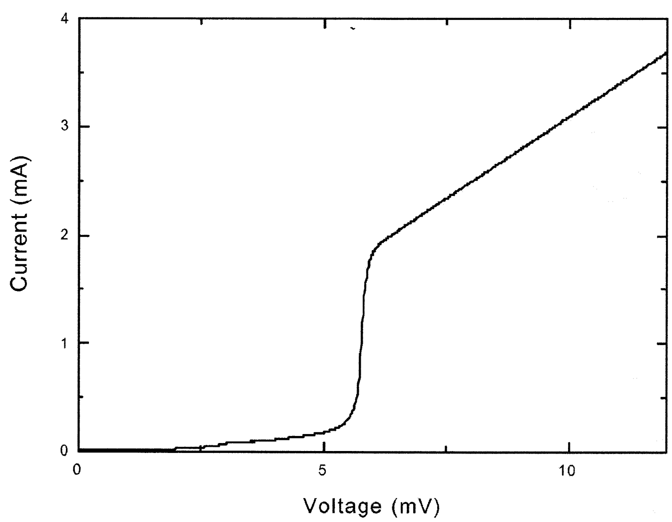


Fig. 5. Experimental I-V characteristics of NbN-based SIS junction. Subgap-to-normal state-resistance ratio was about 11.

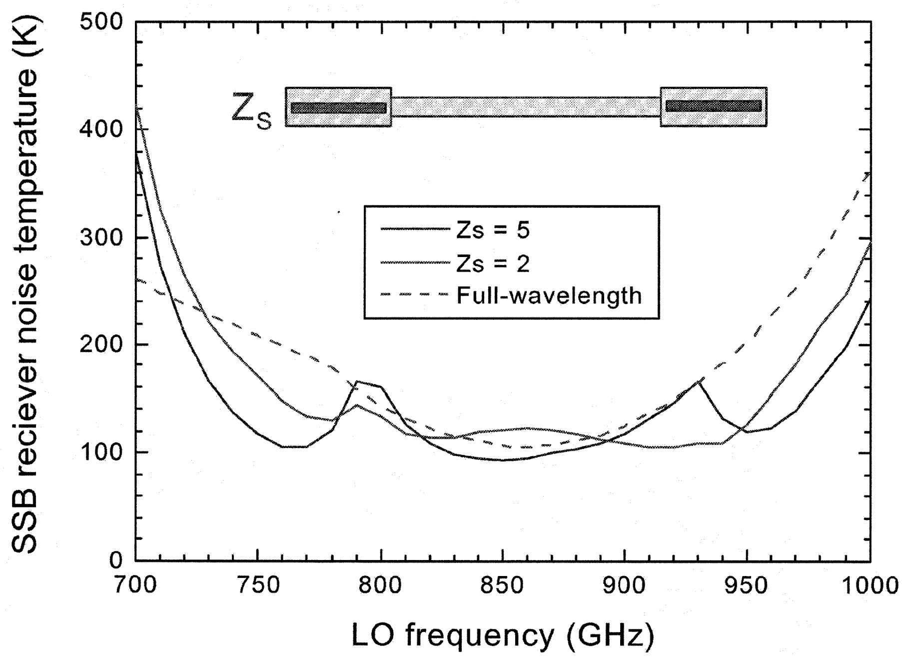


Fig. 6. Simulated SSB receiver noise temperature of two half-wavelength distributed junctions mixer. Also shown is the noise temperature of a conventional full-wavelength SIS mixer with the same current density.