Low-Noise Slot Antenna SIS Mixers

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Abstract—**We describe quasi-optical SIS mixers operating in the submillimeter band (500-750 GHz) which have very low noise, around 5 $h\nu/k_B$ for the double-sideband receiver noise temperature. The mixers use a twin-slot antenna, Nb/Al-Oxide/Nb tunnel junctions fabricated with optical lithography, a two-junction tuning circuit, and a silicon hyperhemispherical lens with a novel antireflection coating to optimize the optical efficiency. We have flown a submillimeter receiver using these mixers on the Kuiper Airborne Observatory, and have detected a transition of $H_2{}^{18}O$ at 745 GHz. This directly confirms that SIS junctions are capable of low-noise mixing above the gap frequency.**

I. Introduction

Over the past several years, there have been dramatic advances in SIS mixers operating in the submillimeter band. The upper frequency limit has been pushed from around 250 GHz to beyond 700 GHz, with the best double-sideband receiver noise temperatures scaling roughly as 5 $h\nu/k_B$. These SIS receivers are now deployed at a number of astronomical observatories, and the field of submillimeter astronomy is advancing rapidly. References [1], [2] are good review articles on SIS mixers; however, there has been much progress since these were published, e.g. [3]–[12].

These advances were made possible through the development of high quality, high current density (10 kA cm^{-2}), small-area ($\lesssim 1\ \mu m^2$) Nb/Al-Oxide/Nb tunnel junctions. Furthermore, the RF loss of Nb thin films appears to be quite low below the gap frequency (700 GHz), and so integrated tuning circuits can be fabricated which match the highly capacitive junction impedance. Examples of these tuning circuits can be found in [3]-[9]; a discussion of the fundamental limitations of such circuits is given in [10].

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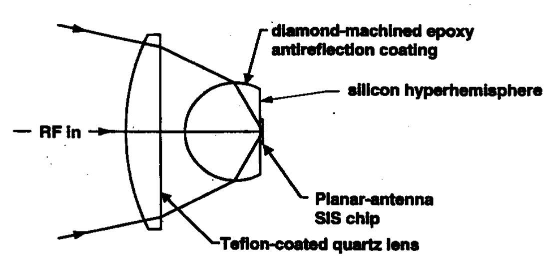

Fig. 1. The mixer optics include an epoxy-coated hyperhemispherical silicon lens and a plastic lens or a Teflon-coated quartz lens.

The mixer type can either be waveguide (e.g. [4], [6], [9], and [11]) or quasi-optical (e.g. [3], [5], [7], and [12]–[15]). The waveguide mounts are tunable, highly efficient, and were better understood initially. The quasi-optical mixers are much easier to fabricate, especially at higher frequencies, but are fixed tuned and can suffer from low efficiencies. Fortunately, there has been much recent progress in the understanding of planar antennas on dielectric lenses [15]–[17], and there seems to be no fundamental reason that a quasi-optical mixer cannot have high efficiency and low noise. Indeed, our paper will describe the quasi-optical mixer we have developed whose sensitivity exceeds that of any other quasi-optical mixer demonstrated to date, and is fully competitive with the best waveguide receivers.

II. Mixer Optics

Figure 1 shows the optical layout of our mixer. The SIS chip is mounted on a silicon hyperhemispherical lens, which concentrates the incident radiation onto an antenna fabricated lithographically on the SIS chip. Hyperhemispherical lenses with planar antennas were introduced by Rutledge and Muha [18], and were first used with SIS mixers by Wengler *et al.* [12]. The hyperhemispherical lens simulates a semi-infinite dielectric, and thereby avoids the leakage of radiation into substrate modes which occurs when planar antennas are mounted on a finite thickness substrate. Another benefit of this approach is that the

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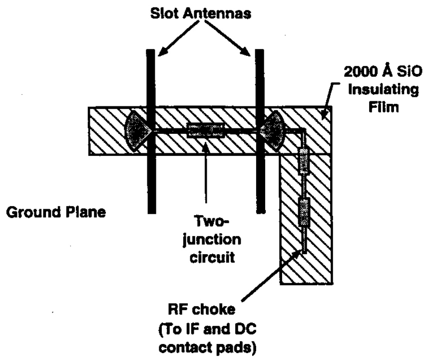

Fig. 2. A diagram of the layout of our mixer chip. The two SIS junctions are placed symmetrically about the center; their separation along with the width of the microstrip line joining them controls the tuning inductance. The center of the circuit is a voltage null, or virtual ground.

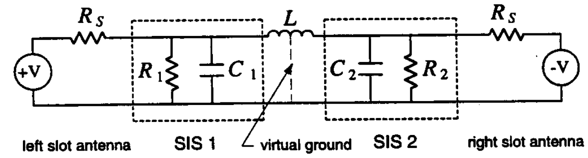

Fig. 3. A schematic of our two-junction tuning circuit. The circuit is driven antisymmetrically by the two slot antennas because the radial stubs are placed on opposite sides of the slots, and this produces a virtual ground at the center of the circuit. The SIS junctions are represented by parallel RC networks.

planar antenna radiates preferentially into dielectric material. The use of high-resistivity silicon ($\epsilon_r = 11.5$; [22]) as the dielectric results in a calculated forward efficiency (for our antenna design) of 90%, compared to a 9% loss due to backward radiation into free space. This compares quite favorably to the 70% forward efficiency quartz ($\epsilon_r = 4.5$), which we had used in previous generations of our mixers [3], [15]. However, this improvement would be largely canceled by the increased Fresnel reflection at the surface of the silicon lens. We have therefore developed an anti-reflection coating for the silicon lens, which consists of epoxy loaded with alumina powder [19]. The alumina powder is necessary to obtain a dielectric constant of $\epsilon_r \approx 4$, and the coating has reasonably low loss ($< 2\%$) [20], good adhesion, and is cryogenically recyclable. The epoxy is applied and allowed to cure, and is then diamond machined [21] to yield a very smooth coating with precisely the correct ($\lambda/4$) thickness. In order to achieve good registration, the spherical surface of the silicon lens is first diamond machined, and the coating is subsequently applied without removing the lens from the diamond-turning machine. In comparison to uncoated quartz lenses which have a reflection loss of about 15%, the overall improvement is a factor of $0.9/(0.85 \times 0.7) \approx 1.5$. An additional improvement of about 10% can be obtained by replacing the polyethylene lens in front of the hyperhemisphere with a Teflon-coated quartz lens as is shown in Fig. 1. We have obtained such lenses, and have verified the cryogenic durability of the Teflon coatings, but we have not yet used these lenses in a mixer. Another possibility would be to omit the second lens entirely by using an ellipsoidal lens in place of the hyperhemisphere, but this gives less flexibility in the choice of the beam characteristics of the mixer.

III. Twin-slot mixer chips

A. Antenna design

Our mixer uses a twin-slot antenna (Figure 2) to receive the radiation. As discussed by Zmuidzinas *et al.* [15], this antenna has a number of desirable properties, including linear polarization, a symmetric beam with low sidelobes, a low antenna impedance, and an octave bandwidth. The antenna dimensions used for the silicon substrates are as follows: the slot length is $L = 0.33\lambda$, the width is $W = 0.05L$, and the separation is $S = 0.17\lambda$. Here λ is the free-space wavelength at the center frequency, which is chosen to be the frequency at which the antenna reactance vanishes. At the center frequency, the antenna impedance is real and has a value of $Z_a = 33\Omega$.

The antenna properties were calculated using the method described in [15]; briefly, this is a spectral-domain Galerkin moment-method solution which accounts for the mutual interaction of the two slots. This calculation yields the antenna impedance as a function of frequency, the radiation pattern, and the fraction of power which is radiated into the dielectric (90%). The beam pattern radiated into the dielectric is slightly asymmetric; the FWHM of the power pattern is 26.5° in the E-plane and 23° in the H-plane. This 15% asymmetry can be reduced by increasing the slot separation S, but this also increases the strength of the E-plane grating sidelobes. With our chosen separation, the fraction of power radiated into these sidelobes is about 1%.

B. Circuit design

The radiation received by the slot antennas is coupled into the SIS junctions with superconducting microstrip lines. The properties of the superconducting microstrip lines were calculated using our previously described method [15]. Microstrip radial stubs [15] are used to effect the coupling to the slot antennas, by providing an RF short-circuit between the microstrip and one side of the slot antenna. A novel two-junction circuit [3] is used to tune out the SIS junction capacitance. The operation of this circuit is shown schematically in Fig. 3. The symmetry of the circuit produces a virtual ground at the midpoint of the circuit; therefore, the short section of microstrip which connects the two junctions behaves as two inductive shunts which cancel the junction capacitances. A quarter-wave impedance transformation section is inserted between the junctions and the slot antennas to match the junction resistance to the antenna impedance. However, the length of these sections is not sufficient to allow the junctions to meet at the center, so two additional short sections of microstrip are placed between the slots and the $\lambda/4$ sections in order to obtain a total microstrip length equal to the slot spacing S. Although this results in an aesthetically pleasing configuration, the performance of the circuit could be better optimized by removing this length constraint, and replacing these "extensions" with $\lambda/4$ sections, and taking up the excess length with 90° bends in the microstrip. We plan to incorporate this improvement in our next chip design. The circuit is analyzed and optimized using the HP/EESOF "Touchstone" microwave circuit analysis program. The circuit model includes all of the transmission line sections, our calculated frequency-dependent antenna impedance, and a parallel RC network representation of the SIS junction, but neglects the discontinuity effects associated with the step changes in microstrip width and the dimensional mismatch between the SIS junction and the microstrip. For these calculations, we have assumed a junction area-resistance product of $R_N A = 20\,\Omega\,\mu\text{m}^2$ and a capacitance C which gives $\omega R_N C = 5$ at 500 GHz; these are the values we believe to be representative of Nb/Al-Oxide/Nb junctions whose current density is $J_c = 10\,\text{kA}\,\text{cm}^{-2}$. The optimized circuits typically achieve better than -6 dB return loss (> 75% coupling efficiency) over $\gtrsim$ 140 GHz bandwidth.

C. Mixer chip fabrication

The mixer chip fabrication was performed at the JPL Center for Space Microelectronics Technology, using their standard Nb/Al-Oxide/Nb trilayer process. This is essentially the same process which was used in our previous generation chips [3], [15], and uses only optical lithography. A 2000Å thick SiO insulating film was used for junction isolation and for the microstrip dielectric. A total of 720 chips are fabricated on a single 50 mm diameter, 250 μm thick high-resistivity silicon wafer. There are a total of 30 different chip designs, corresponding to two antenna center frequencies (550 and 650 GHz), three junction areas (1.0, 1.44, and 2.25 μm^2), and five variations of the tuning circuit.

IV. Mixer performance

Figure 4 shows the double-sideband receiver noise temperature as a function of frequency which we measured for two of the mixer chips. The measured noise temperatures represent averages over our 1-2 GHz IF band.

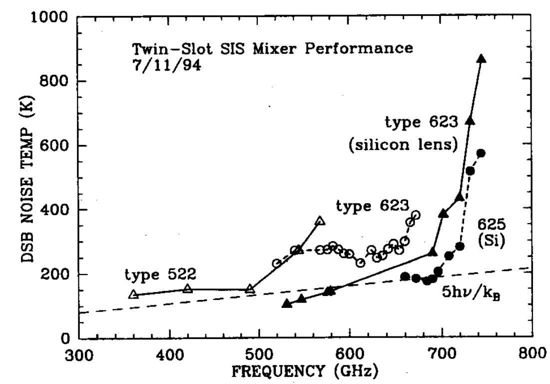

Fig. 4. Measured DSB receiver noise temperature as a function of frequency. The curves with the solid points are the measurements for the silicon-based mixers; for comparison, the performance obtained previously with quartz-based mixers is shown by the curves with the open points. Each curve represents the frequency response obtained with a single mixer chip. These measurements have not been corrected for the loss and thermal noise associated with the beamsplitter used for the local oscillator injection, or other optical losses. The junction areas for the silicon-based mixers are nominally 1.44 μm^2.

For comparison, we also show the performance previously obtained with quartz-based devices [3]; the silicon mixers outperform the quartz devices by about a factor of 2. The noise temperatures are not corrected for the local oscillator injection beamsplitter (typically 12 μm or 25 μm thick mylar film). The local oscillators (LO) used for these measurements are Gunn oscillators followed by frequency multipliers. Three multipliers were used for these tests: a 500-580 GHz quadrupler, and $\times 2 \times 3$ cascaded units covering 580-660 GHz and 650-750 GHz. The envelope of the lowest noise temperatures measured is well described by the line $T_{RX} = 5h\nu/k_B$; note that this corresponds to about 55 K (DSB) at 230 GHz. However, the noise temperatures rise rather steeply above about 700 GHz, which is the gap frequency of niobium. We believe that this behavior is caused by the large increase in circuit losses due to the onset of pair-breaking above the gap frequency. It may be possible to overcome this problem by fabricating Nb/Al-Oxide/Nb junctions with normal-metal tuning circuits.

We have attempted to use the shot-noise method to separately determine the mixer noise temperature and conversion loss; however, we do not trust the results since the IF impedance of the pumped SIS mixer is typically a factor of 10 higher than the normal-state resistance. The results we obtain with this method typically indicate rather high IF noise temperatures ($\sim$ 20 K) and low mixer conversion losses ($\sim$ 6 dB). To obtain reliable data, we plan to make measurements with a calibrated IF system.

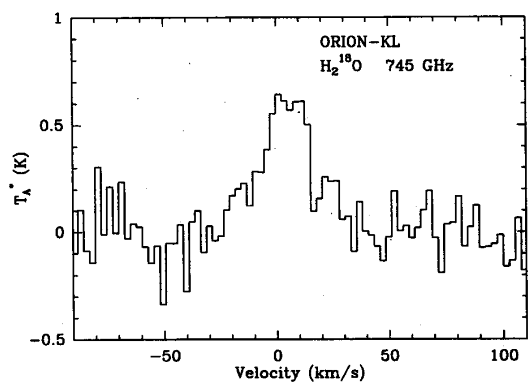

Fig. 5. Detection of the 745 GHz $2_{11} \rightarrow 2_{02}$ transition of para-$H_2{}^{18}O$ in the Orion-KL molecular cloud. This detection was obtained in a flight aboard the NASA Kuiper Airborne Observatory in February, 1994. The total integration time was 36 minutes.

V. Astronomical Demonstration

The silicon-based mixers have been used in a submillimeter receiver system which flies aboard the NASA Kuiper Airborne Observatory. During a flight series in February, 1994, we detected the 745 GHz transition of $H_2{}^{18}O$; the spectrum is shown in Fig. 5. To our knowledge, this is the first astronomical verification of SIS mixing above the gap frequency. In addition, we also obtained a detection of the 547 GHz transition with a much higher signal-to-noise ratio than the 745 GHz spectrum, and transitions of numerous other species as well.

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