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Characterization of submillimetre quasi-optical twin-slot double-junction SIS mixers

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Abstract. We report on the continuing development of submillimetre quasi-optical slot antenna SIS mixers, which use two-junction tuning circuits. Direct and heterodyne Fourier transform spectrometer measurements have been performed to compare device performance with predictions. Demonstrated double-sideband receiver noise temperatures of better than 540 K at 808 GHz make these SIS mixers substantially better than GaAs Schottky receivers for the astronomically important CI and CO transitions near 810 GHz.

1. Introduction

Quasiparticle SIS mixers with Nb-trilayer tunnel junctions have demonstrated excellent performance at frequencies below ~ 800 GHz [1]. There is strong motivation in the field of submillimetre astronomy to extend the low-noise performance of SIS mixers into the atmospheric window at ~ 850 GHz. To achieve this, one requires a receiver design which extends straightforwardly to such high frequencies, and one requires a means of accurately designing mixers for optimal performance in the desired passband. The quasi-optical receiver configuration we use is detailed elsewhere [1, 2], and should permit straightforward scaling to the highest frequencies at which Nb-trilayer devices are useful.

To design and simulate our twin-slot two-junction mixers [3], we employ a program that we developed in-house for microwave circuit analysis. This program allows us to include the effects of lossy Nb microstrip lines, such as are used for the antenna-to-junction transformers, and for the inductor used to tune out the junction capacitance. The inclusion of loss is particularly important for simulations of device response at frequencies above the Nb gap, where Cooper pair breaking becomes significant. To date, we have achieved reasonable success in generating mixer designs for optimized operation between 400 and 800 GHz. As determined from comparison with results of Fourier transform spectroscopy (FTS), the simulation of at least one mixer significantly underestimates the measured loss at frequencies above ~ 800 GHz [1]. The use of FTS has proven to be a valuable tool in increasing our understanding of the nature of our SIS mixers, thus greatly decreasing the time between device generations.

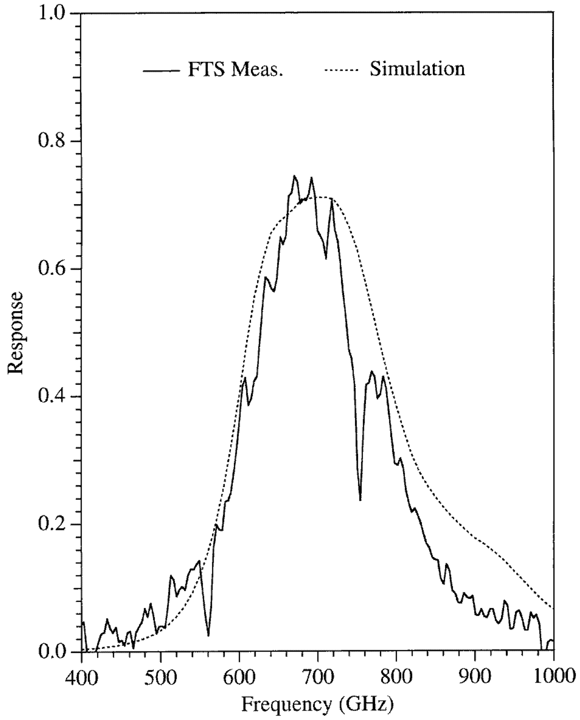

Figure 1. FTS measurements and computer simulation of the direct response of a device optimized for 700–800 GHz operation.

2. Fourier transform spectroscopy

Figure 1 shows the predicted and measured direct response of a mixer optimized for operation in the 700–800 GHz

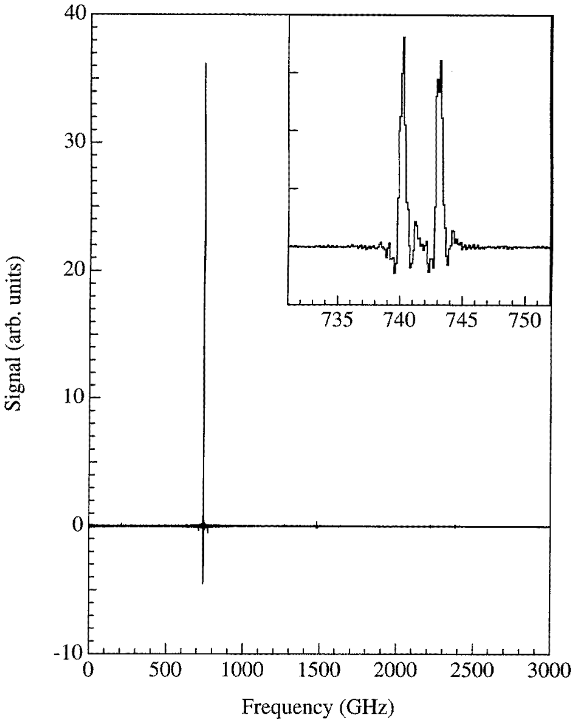

Figure 2. Heterodyne FTS measurement performed with 742 GHz LO, 500 MHz IF bandwidth and 3 GHz sideband separation.

band. The FTS data are scaled to fit the computer-simulated coupling of RF into the junction resistance. For this mixer there is some discrepancy above the gap, but the measurement is otherwise quite close to prediction. The deviation may be due in part to antenna losses which are not included in our simulation. Alternatively, the surface resistance of the Nb films above 700 GHz may be larger than theoretically predicted. Other apparent non-idealities present in the measured data are water absorption lines at 557 and 752 GHz, and Fabry–Perot resonances spaced by $\sim$ 50 GHz, caused by internal reflection in the 2.5 mm thick quartz IR filter on the dewar's 77 K stage.

The predicted response of the device does not approach the ideal of 1.0, as we have optimized for best response in the 700–800 GHz band and have therefore sacrificed response below the gap. The response above the gap is degraded primarily by losses in the Nb microstrip inductor used to resonate the junction capacitance. We have also designed similar mixers for slightly lower-frequency bands, where the simulator predicts near-unity response over 100 GHz bandwidths.

We have also, for the first time, measured the heterodyne response of a mixer at sufficiently high resolution to resolve the local oscillator (LO) and sideband frequencies. This measurement verifies that our devices do in fact perform as mixers. Figure 2 shows the FTS response of the device characterized in figure 1, but in heterodyne mode, with a 742 GHz LO illuminating the device during the FTS measurement. The figure clearly shows significant response only near the LO frequency. The IF bandwidth (1.25 to 1.75 GHz) and double-sideband operation are apparent in the inset. The negative-going portion of the signal results from ringing in the Fourier-transforming procedure. Presumably the upper-sideband peak is weaker than the lower-sideband peak because of absorption near the 752 GHz water line.

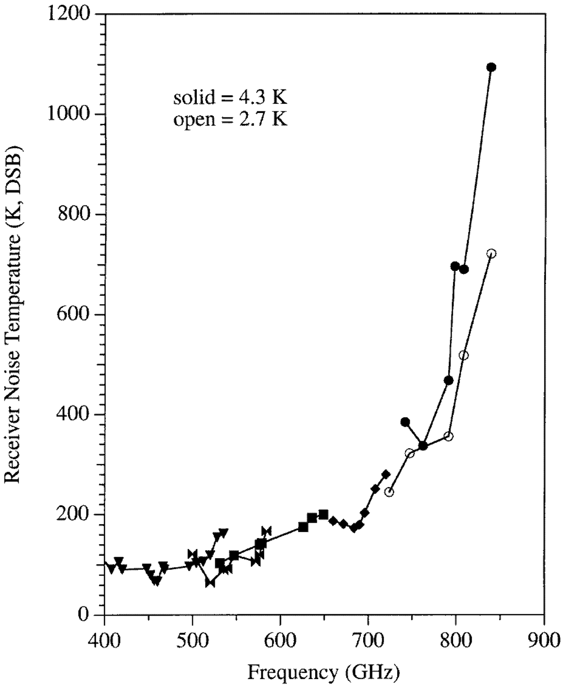

Figure 3. Measured noise temperatures for several of our quasi-optical twin-slot double-junction mixers.

3. Noise temperatures

We have characterized several quasi-optical twin-slot double-junction mixers with heterodyne noise temperature measurements using the Y-factor method. All noise temperatures presented are referred to the input of the beamsplitter, and no corrections have been made for beamsplitter or other losses. In figure 3 we present measured noise temperatures for five different mixer designs, optimized for the frequency bands 400–500, 500–600, 550–650, 650–750 and 700–800 GHz, where each device is represented by a different marker. The high-frequency device was also tested at a pumped-He temperature of 2.7 K, with resulting noise temperatures displayed with open markers. To our knowledge, the receiver noise temperatures presented in figure 3 are the best, or comparable to the best, reported to date for any broadband heterodyne receiver. The 800 GHz results are particularly impressive when compared with the nearest competitor, namely GaAs Schottky corner-cube receivers at 1500 K (*after* correcting for the $\sim$ 50% corner-reflector antenna efficiency) [4].

At high frequencies (> 700 GHz), our Gunn/multiplier LO chains have relatively low output powers. To couple large enough LO powers to run the device optimally, we are forced to use thick beamsplitters, resulting in a loss

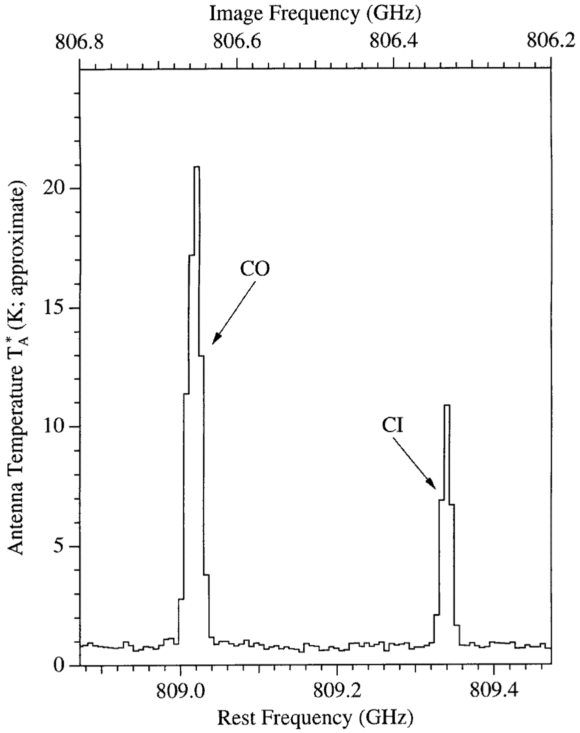

Figure 4. Observed emission from the CO(7–6) and the CI($^3P_2$–$^3P_1$) transitions in M17.

of signal. At the highest frequencies, even our thickest available beamsplitter does not couple in enough LO, and dark current noise becomes quite significant (the 4.2 K dark current is ~ 40% of the total pumped bias current). By reducing the bath temperature to 2.7 K, we reduce the dark current and slightly increase the Nb gap, thus resulting in improved receiver noise temperatures.

The anomalously low noise temperature of the 4.2 K device at 761 GHz results from a more powerful LO. At this frequency, we were able to use an FIR laser LO source, which output a good deal more power than our standard LO chain. A thinner beamsplitter was employed, resulting in improved signal coupling efficiency.

4. Astronomy

We have recently been able to take advantage of the low 800 GHz receiver noise temperatures during observing runs aboard NASA's Kuiper Airborne Observatory (KAO). We detected the CO(7–6) and CI($^3P_2$–$^3P_1$) transitions in the M17 HII region/molecular cloud complex. Figure 4 shows the data obtained with the double-sideband receiver, with an LO frequency of 807.8 GHz and an IF bandwidth from 1 to 2 GHz. The CI line lies in the upper sideband, at 809.3 GHz, while the CO line is found in the lower (image) sideband at 806.7 GHz. The non-zero baseline is indicative of dust continuum emission from M17.

Unfortunately, we were not able to use our best device at this frequency for these observations. Nonetheless, we achieved complete system (including telescope and atmosphere) noise temperatures of better than 2000 K. Judging from laboratory measurements with a better device, we should be able to reduce this system temperature to below 1200 K.

5. Conclusions

We have demonstrated for the first time that all-Nb SIS receivers can have substantially better performance than GaAs Schottky receivers for the astrophysically important CI and CO transitions near 808 GHz. These receivers utilize a quasi-optical configuration, which allows on-chip broad-band lithographic tuning elements, natural adaptation to focal-plane imaging arrays and straightforward scaling to yet higher frequencies.

The use of computer simulations has advanced the design of these mixers such that we can confidently predict device response up to 800 GHz. Fourier transform spectroscopy provides a powerful tool upon which we can rely to select useful devices and optical configurations. We have also used heterodyne FTS measurements to verify the mixing behaviour of SIS devices well into the submillimetre region.

Future work will concentrate on understanding the apparently excessive losses above 800 GHz. In an effort to further increase the operating frequencies of Nb-trilayer devices to take advantage of atmospheric windows at ~ 850 and ~ 1050 GHz; we have also begun work on replacing the Nb microstrip tuning elements with lower-loss normal metals.

Acknowledgments

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