A WIDE-BANDWIDTH, LOW-NOISE SIS RECEIVER DESIGN FOR MILLIMETER AND SUBMILLIMETER WAVELENGTHS

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ABSTRACT

In principle, millimeter and submillimeter heterodyne receivers using state-of-the-art SIS detectors are capable of extremely large instantaneous bandwidths with noise temperatures within a few Kelvin of the quantum limit. We are applying modern design tools, such as 3D electromagnetic simulators and Caltech's *SuperMix* SIS analysis package, to develop a new generation of waveguide SIS mixers with very broad RF and IF bandwidths. Our initial design consists of a double-sideband mixer targeted for the 180 – 300 GHz band that uses a single SIS junction excited by a full bandwidth, fixed-tuned waveguide probe on a silicon substrate. The IF output band, limited by the MMIC low-noise IF preamplifier, is 6 – 18 GHz, providing an instantaneous RF bandwidth of 24 GHz (double-sideband). The SIS mixer conversion loss is predicted to be no more than 1 – 2 dB (single-sideband) with mixer noise temperatures across the band within 10 Kelvin of the quantum limit. The single-sideband receiver noise temperature goal is 70 Kelvin. The wide instantaneous bandwidth and low noise will result in an instrument capable of a variety of important astrophysical observations beyond the capabilities of current instruments. Lab testing of the receiver will begin in the summer of 2002, and a demonstration on the CSO should occur in the spring of 2003.

INTRODUCTION

Heterodyne receivers currently in use on major telescopes typically offer an IF bandwidth of a few GHz, although some recent designs have achieved 8 GHz.[1] Extending this bandwidth even further would be highly desirable, as several applications would benefit greatly from this improvement.

Surveys using submillimeter cameras (such as SCUBA and MAMBO) have resulted in the discovery of roughly 200 very luminous galaxies. These sources appear to be at high redshifts, although only a handful have been precisely measured.[2] The redshifts can be determined using the spectral lines of several molecules (particularly CO) that can be observed in the millimeter band. However, the high redshifts of these objects make it difficult to predict the observed line frequencies, and the lines can only be found by searching a large fraction of the 190 – 320 GHz atmospheric window. Since these are such faint sources, each observation requires several, or even tens, of hours per LO frequency, even with a sensitive receiver. A wide-bandwidth receiver decreases the required number of LO settings, greatly reducing the total observing time and making it practical to build up a statistical sample of redshifts. Spectral line surveys of star-forming regions would also benefit from expanded receiver bandwidths.

In the Earth Sciences community, broadband receivers would be very useful for studying the Earth's atmosphere. The atmospheric abundances of several important molecules can be mapped by detecting their spectral-line emissions at millimeter wavelengths (near 230 GHz). Two generations of satellites have been built that use this technique to provide considerable information on atmospheric chemistry, ozone depletion, and the global effects of pollution.[3] As the next step in this research, a new satellite mission, the Scanning Microwave Limb Sounder (SMLS), has been proposed that would provide a much larger data rate, allowing for higher resolution and better coverage. A receiver with a large bandwidth and low noise would be required to allow the satellite to measure multiple spectral lines accurately and rapidly with each pointing of the antenna.

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RECEIVER DESIGN

In order to address some of these needs, we have developed a new receiver design with an eye toward maximizing the bandwidth while maintaining a low noise temperature. Our initial design consists of a double-sideband receiver using a single SIS junction. Intensive simulations, combined with preliminary measurements, indicate that the design will offer a 12 GHz IF bandwidth (6 – 18 GHz), corresponding to a double-sideband RF bandwidth of 24 GHz, while maintaining a noise temperature that is competitive with narrower bandwidth designs.

Mixer Circuit Design

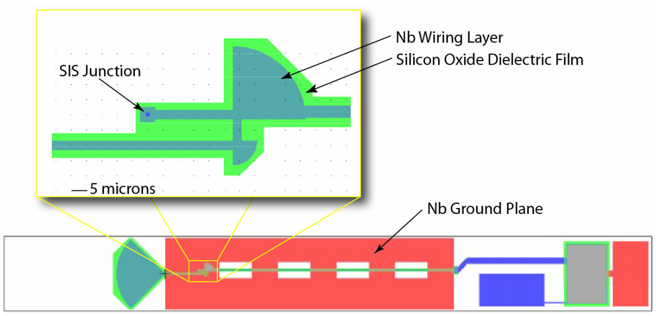
The heart of the RF mixer is an Nb-AlN-Nb SIS junction. We expect the 1.3 × 1.3 micron junction to have a critical current density (J_c) of 14 kA/cm^2, resulting in a normal resistance (R_n) of 8.5 Ω, and a junction capacitance of 144 fF. The junction size is suitable for UV contact lithography, and the R_nC product corresponds to a frequency of 130 GHz. Current technology at JPL can produce such junctions with very high quality, and subgap-to-normal resistance ratios in excess of 20 should be attainable.

The SIS junction is coupled to the waveguide probe using a thin-film, superconducting microstrip matching network consisting of a ¼-wave transformer followed by a two-section LC ladder (see Figure 1-a). The RF network tunes out the junction capacitance and matches the 36 Ω probe to the 9 Ω junction impedance. The IF output is extracted from the low impedance, fan end of the large radial-stub capacitor.

The IF output then passes through a CPW/microstrip filter ladder that provides RF isolation and matches the junction to the 50 Ω IF amplifier. The IF signal is coupled to the amplifier via a DC blocking capacitor just before IF wirebond pad at the right side of Figure 1-a. DC bias for the SIS junction is provided through a separate wirebond pad to the left of the DC blocking capacitor.

The niobium ground plane is 0.2 microns thick, and the niobium wiring thickness is 0.4 microns. The conductors are separated by a 0.35 micron thick SiO layer. The layout is suitable for UV contact lithography and uses a minimum wire width of 3.0 microns in the RF section. The ground plane extends just to the waveguide wall and is shorted to the waveguide block along each edge of the substrate using thick gold pads which contact the upper half of the split waveguide block when the block is assembled.

The entire circuit has been modeled and optimized by C++ programs using the *SuperMix* library. Figure 1-b shows the modeled performance of the optimized mixer chip design. Clearly, powerful software tools like *SuperMix* and *Ansoft HFSS* can improve the performance and lower the technical risk of current design efforts.



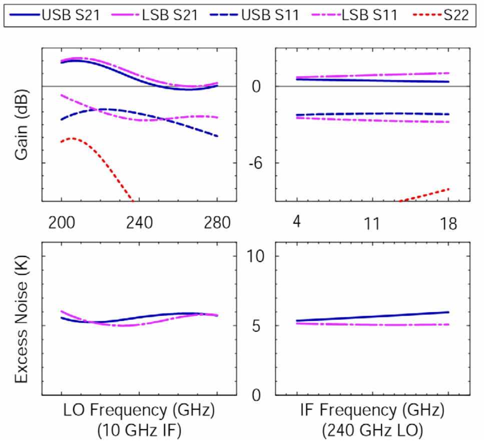
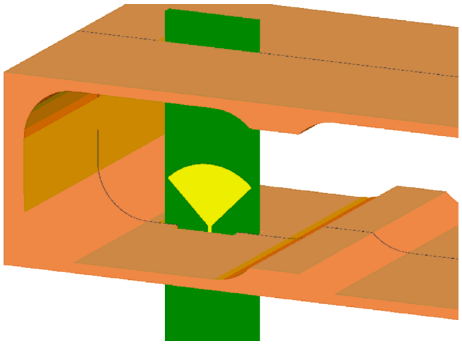


Figure 1-a (left): *Preliminary mask layout for the SIS mixer chip. The broadband radial-stub probe (at left) couples the signal from the waveguide into the RF matching network (shown in the enlargement). The IF output is picked off from the low-impedance, outer edge of the radial-stub capacitor (at the right side of the inset). The IF signal then travels through a CPW/microstrip filter ladder (for RF isolation) to the bonding pad at the far right end of the chip. DC bias is provided through the bonding pad just to the left of the large DC blocking capacitor.*

Figure 1-b (right): *Simulated performance of mixer circuit showing the gain and the noise in excess of the quantum limit (which is approximately 10 – 15 K at these frequencies). The circuit is expected to achieve a noise temperature less than twice the quantum limit.*



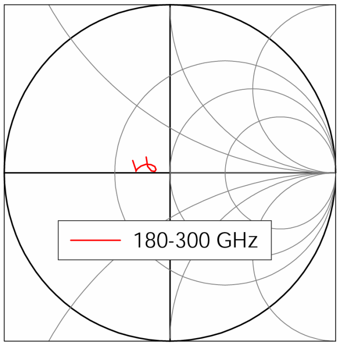


Figure 2-a (left): *Broadband probe and mixer chip shown in relation to waveguide (also see Figure 1-a). The faint line indicates the split plane in the mixer block. The small tuning step upstream of the probe and the fixed backshort were optimized using HFSS and SuperMix.*

Figure 2-b (right): *Predicted performance of probe based on HFSS model, plotted on a 50 Ω Smith chart. The probe offers an almost real impedance of (36 + j 2) Ω over the 180 – 300 GHz range of the receiver.*

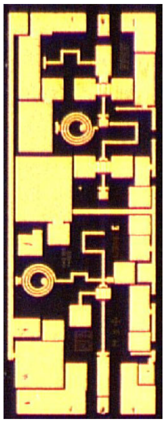
Broadband Probe

The RF signal is coupled to the SIS device through a radial-stub waveguide probe that covers the receiver's 180 – 300 GHz operating range. As shown in Figure 2-b, the probe impedance remains essentially constant and very nearly real over the 1.7:1 frequency range, with an approximate value of 36 Ω.

The waveguide includes a fixed backshort and a small capacitive tuning step just upstream of the probe (Figure 2-a). The configuration was designed by modeling the individual components in *Ansoft HFSS* and importing their behaviors into a C++ circuit model based on the *SuperMix* library, which was used to optimize the backshort and tuning step. The results shown were generated from an *HFSS* model of the entire probe and waveguide structure. These results have been validated for a very similar design by comparing the *HFSS* results to scale-model measurements.

Cryogenic Low-Noise Preamplifier

The IF output of the mixer must be amplified using a low-noise preamplifier with bandwidth and noise characteristics that will not compromise the overall performance of the receiver. Microwave monolithic integrated circuit (MMIC) technology employing indium phosphide (InP) high electron mobility transfer (HEMT) active elements has been identified as the most promising route to achieving these goals. We are currently refining a design, based on the JPL/TRW WBA8T MMIC, that uses a 75 micron thick substrate with three 200 micron InP HEMT stages (Figure 3-a). The latest iteration of this design uses inductive feedback to minimize noise, and preliminary measurements of its performance at 4 K indicate that it offers at least 20 dB of gain with a noise temperature below 10 K from 6 to 10 GHz (Figure 3-b). These measurements are consistent with simulations that predict similar performance across the entire 6 – 18 GHz IF band of the receiver.



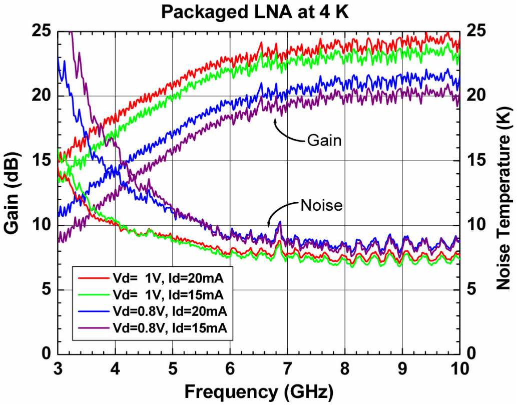


Figure 3-a (left)*:* *Picture of the IF preamplifier circuit. This version, based on the JPL/TRW WBA8T MMIC, uses three InP HEMT stages and inductive feedback to minimize noise.*

Figure 3-b (right)*:* *Preliminary measurements of the preamplifier's performance at 4 K. These results are consistent with simulations predicting that the preamplifier can achieve over 20 dB of gain with a noise temperature below 10 K across the entire 6 – 18 GHz IF band of the receiver. (The limited frequency range and the "ripple" that can be seen in the data are limitations of the test setup and will be corrected in future measurements.)*

IF System and Wideband Spectrometer

For astrophysical observations at the CSO, the receiver will be used with the WASP2 spectrometer to search for spectral lines from submillimeter sources. Developed at the University of Maryland, WASP2 is a wideband lag correlation spectrometer offering a 3.6 GHz bandwidth.[4] To match this bandwidth, the room-temperature IF system will consist of several down-converters that will divide the IF signal into four bands. Each band will be analyzed by a WASP2 unit, allowing us to utilize the entire 12 GHz bandwidth of the receiver.

The IF system will also include a wideband amplifier that has been developed for this purpose. The device, consisting of three commercial MMIC amplifiers, offers 30 dB gain over a 2 – 20 GHz bandwidth. The amplifier has been designed, built, and tested (Figure 4).

SUPERMIX

The design of this receiver has relied heavily on the use of *SuperMix*, a software package developed at Caltech that provides a complete set of circuit elements suitable for frequency-domain simulations from DC to THz frequencies. The library allows for accurate modeling of superconducting transmission line elements and predicts the nonlinear SIS mixing performance using Tucker's quantum mixing theory. In addition, the *SuperMix* package includes a sophisticated multi-parameter optimizer that can be used to refine a circuit design by modifying any device characteristics. For more information, visit *http://www.submm.caltech.edu/supermix*.

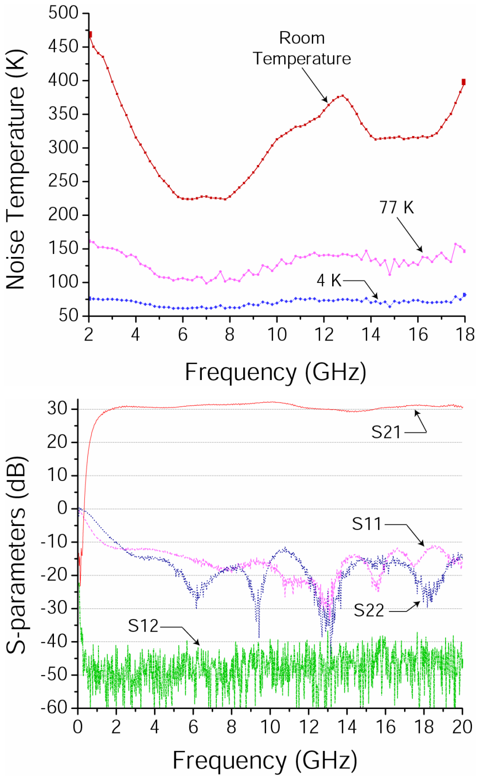


Figure 4: *Measured performance of room-temperature IF amplifier. The design offers low-noise (top) and a 30 dB gain (bottom) across the IF bandwidth of the receiver.*

SUMMARY

We present the design for a low-noise receiver that has been optimized to provide a wide IF bandwidth (6 – 18 GHz) in the 180 – 300 GHz range. The initial design consists of a double-sideband receiver that will offer an instantaneous RF bandwidth of 24 GHz, with a single-sideband receiver noise temperature goal of 70 Kelvin. Already, some elements have been built, and lab testing of the full receiver should begin in a few months. While our initial demonstration of this new design will focus on redshift surveys in the 180 – 300 GHz range, we plan to push this design to higher frequencies in the future. Such wide-bandwidth mixers will be very useful for our CASIMIR instrument for SOFIA.

ACKNOWLEDGEMENTS

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