DEVELOPMENT OF A SIDEBAND SEPARATION RECEIVER AT 100 GHZ

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I. Abstract

We have built and tested a prototype SIS receiver operating at 100 GHz to test the feasibility of sideband separation through quadrature mixing at millimeter and submillimeter wavelengths. We achieved over 40 dB of separation with no degradation of the mixer noise temperature due to the sideband separation. Both the sky signal and atmospheric noise are separated, greatly reducing the system temperature for millimeter and submillimeter observations in which spectral lines are present in only one sideband.

II. Introduction

For millimeter and submillimeter–wave astronomy low–noise flexible heterodyne receivers are required. Current receivers use broadband double-sideband mixers, which output overlapped signals and noise from both sidebands. Advances in SIS mixer technology allow these receivers to operate within a factor of a few of the photon noise limit. The atmospheric noise is now the limiting factor for many observations, so for observations in which the desired signal is only in one sideband, the noise added by the image sideband can be very significant. For many astronomical spectral line observations the image sideband may have a much higher atmospheric opacity, seriously degrading the sensitivity. As shown in Figure 1, this will greatly degrade the system temperature. Calibration of spectral line observations with a double sideband receiver is difficult. To correctly calibrate lines observed with a double sideband receiver using hot/cold loads, the sideband gain ratio, which cannot be easily measured, must be known. Astronomers commonly calibrate spectral lines against a 'standard' source, such as Orion. This does not provide an absolute scale and is not possible for less common or highly doppler shifted lines. Filters can be added in front of the mixer to select one sideband, but these must be tuned for every frequency of interest and will add considerable noise unless the image sideband is carefully terminated on a cold load. Interferometers can use quadrature phase switching to separate the two sidebands, but since the signals are from two telescopes, the atmospheric noise is uncorrelated and cannot be separated. By using two mixers in a single receiver both the signal and sky noise can be separated. A sideband separation receiver can be built so that the noise of each output port is equivalent to that of a double sideband receiver in which the image sideband is terminated in a 4° K load. For systems in which the atmosphere is the main source

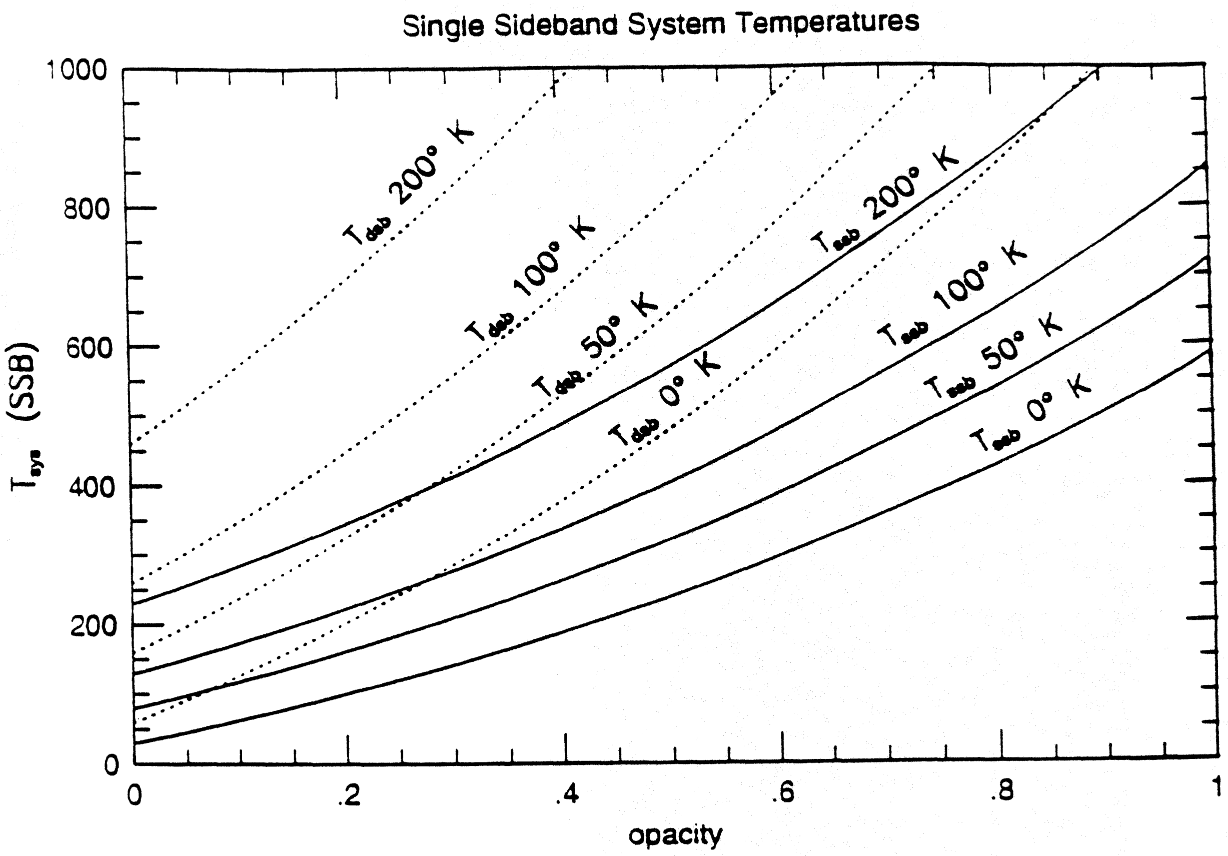

Figure 1: The single sideband system temperature referred to outside the atmosphere is shown as a function of atmospheric optical depth and the double and single sideband receiver temperatures. The beam transfer and spillover losses are assumed to be 10%. Note that the sensitivity of a single sideband system is considerably better than the double sideband system with comparable mixers for large opacities. (e.g. comparing a 50° K DSB system with a 100° K SSB system at an opacity of 0.4, the system temperature for the SSB system is 36% lower.)

of noise the single sideband receiver sensitivity is increased by up to a factor of two over a double sideband receiver with balanced sideband gains. The increase in sensitivity is even higher if the atmospheric opacity is larger in the image sideband.

III. Design

In order to test the feasibility of quadrature mixing at millimeter wavelengths with low noise SIS mixers, we built a sideband separation receiver which operates at 3 mm. This prototype uses waveguide components for convenience, though they are more lossy than other design methods. As illustrated in Figure 2, the incoming sky signal is received by a feedhorn and split by a Magic-'T'. This device equally

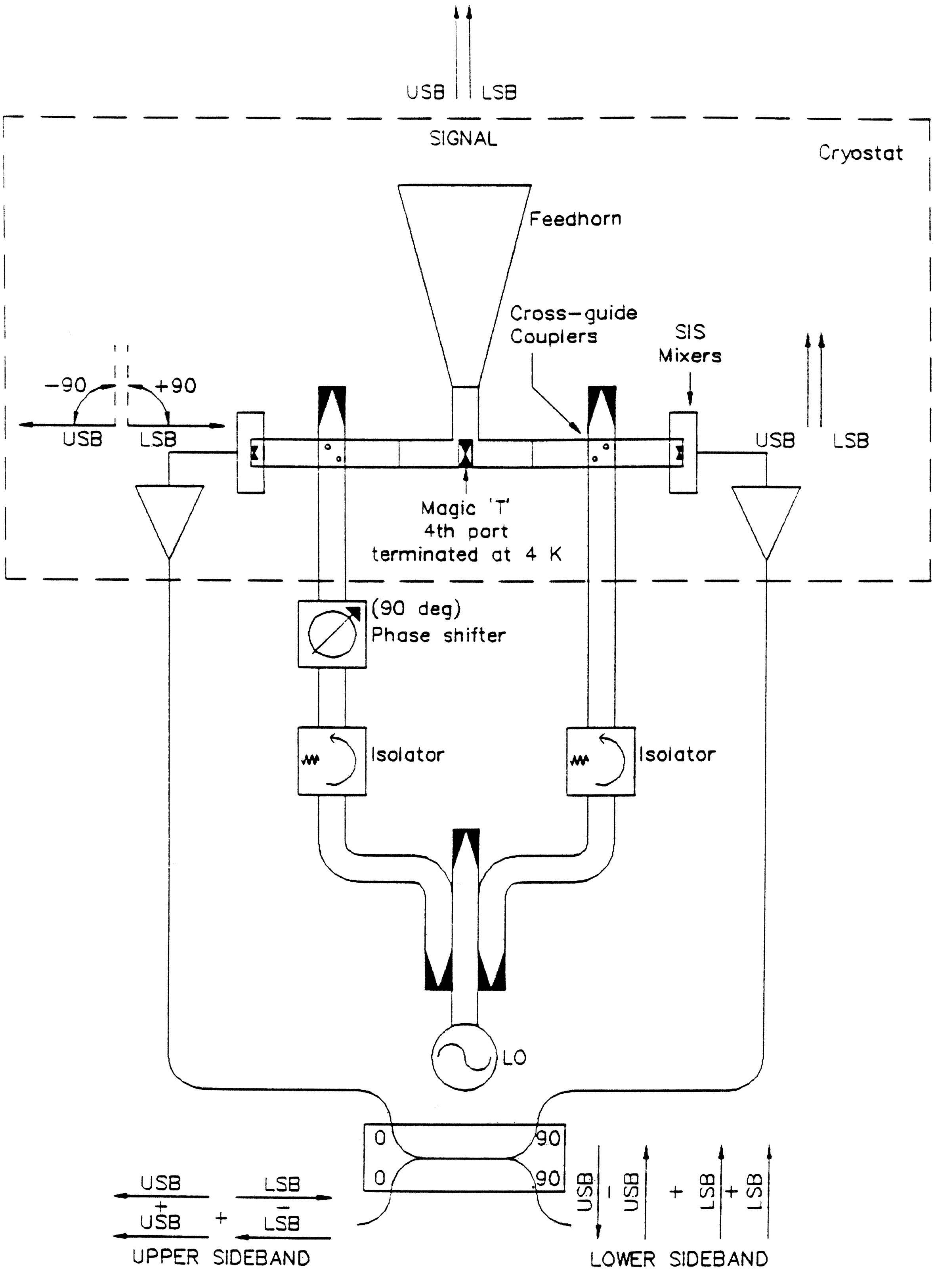

Figure 2: Prototype Sideband Separation Receiver

splits the signal from the first port into the two output ports in phase. The output ports also receive half of the power from the 4th port, which is terminated at 4° K. Any signal reflected from the output ports will be split between the feedhorn and the 4° K termination, minimizing cross talk between the mixer ports which would contaminate the separation. A Gunn oscillator provides the LO signal which is injected through isolators into two 20 dB cross guide couplers. A variable phase shifter in one of the LO paths introduces a 90° phase shift between the sky signal and LO at one mixer relative to the other. This causes a 90° phase shift in the signal received at one mixer relative to the other mixer; the relative phase shift is in the opposite sense for the two downconverted sidebands.

In this prototype, as in the next generation of receiver, we use SIS mixers. Our two mixers are integrated, tunerless devices with four Nb-AlOx-Nb junctions, developed by A.R. Kerr at NRAO with junctions made by Kelin Wan at the University of Illinois (Kerr and Pan 1990). Having two well-matched, tunerless mixers greatly simplifies operation. After the mixers, each signal is amplified by a 3 stage, FET amplifier with a 500 MHz bandpass. The two IF amplifiers were carefully tuned to be well-matched, with less than 0.5 dB difference in gain across the 1.25 to 1.75 GHz passband. They are relatively noisy with noise temperatures ~10° K. All components up to this stage were liquid helium cooled. Coaxial extenders were added to the IF paths so that small phase corrections could be made to compensate for the different IF pathlengths. The two IF signals pass through a quadrature hybrid coupler. Unshifted signal from one port is combined with 90° shifted signal from the other port. Each output consists of signals from only one of the sidebands, up to the level of separation.

IV. Results

The maximum Y factor, the ratio of the output power of the receiver seeing an ambient temperature load to that when seeing an liquid nitrogen cooled load, achieved at the output of a single mixer was 1.5, (DSB temperature = 360° K) although a more typical value was 1.45. Recall that in our receiver the effective temperature that a single mixer sees is half or less of the actual temperature. A second Gunn oscillator, matched to the input, served as an artificial source. The coaxial extenders were adjusted to compensate for the difference in IF pathlengths such that signals in the upper and lower sideband had maximum separation at the same position of the LO phase shifter. With the individual amplitudes from the mixers equalized by adjusting the IF amplifiers, the separation exceeded 40 dB. However, when the signal was switched to the lower sideband without any other adjustments, the separation was only 23 dB. This was due to unequal signal IF amplitudes, resulting from the slightly different sideband gain ratios of the two mixers. The separation in this sideband could be improved to 40 dB by equalizing the amplitudes with the IF amplifiers. Adjusting for equal signal amplitudes at a mid-IF frequency, where the IF amplifiers had matched gains, the separation across the entire IF passband was greater than 25 dB. There was no degradation of the mixer noise temperature measured at one port of the hybrid coupler compared to the noise temperature from a single IF port, demonstrating that the noise is completely separated.

The mixer and IF contributions to the receiver noise temperature were found by analyzing the IV curve and the receiver output power when the mixers were biased above the band gap (Woody *et al.* 1985). We also measured, at room temperature, the additional loss of the Magic-'T' and cross guide couplers to be 1 dB per mixer port. The cross guide couplers were surprisingly lossy, accounting for 0.4 dB of the RF loss. After correcting for these losses we found that the mixer temperatures were 87° K and 78° K. When initially tested, these mixers had noise temperatures near 60° K, but our operating temperature was about half a degree higher. The RF losses add ~40° K to the receiver temperature. With better IF amplifiers and colder operating temperatures, the SSB receiver temperature for our prototype should be around 200° K. However, with the best available mixers and IF amplifiers and lower RF losses, we should be able to achieve single sideband temperatures around 100° K while still separating sidebands.

V. Future Developments

Despite the losses of the waveguide components, this prototype demonstrated the feasibility of a sideband separation receiver. The current separation is limited by the unequal response of the mixers across the IF band. Our easily constructed design is suitable for applications that require high separation but not extremely low noise, such as atmospheric line observations. The separation achieved was more than enough to separate the sky noise and so is already sufficient for interferometric observations. For single-dish spectral line surveys a factor of 25 dB separation is very helpful and it is possible to do much better with a more optimized system. The IF noise can be reduced by state of the art IF amplifiers, which have noise temperatures of 2-4° K and 1 GHz passbands. For applications that demand low noise as well as separation, the lossy waveguide components should be improved or replaced. The Magic-'T' and cross guide coupler could be designed and built to have much lower loss, even at higher frequencies. The design we will pursue in the next generation of receiver is a quasi-optical system (Figure 3). In the sideband separation mode the LO signal passes through a quarter-wave plate and is injected with a beam splitter. A wire grid polarizer splits the signal to the mixers. This design has the additional advantage of being easily converted to a dual polarization double sideband receiver by removing the first polarizing grid.

References

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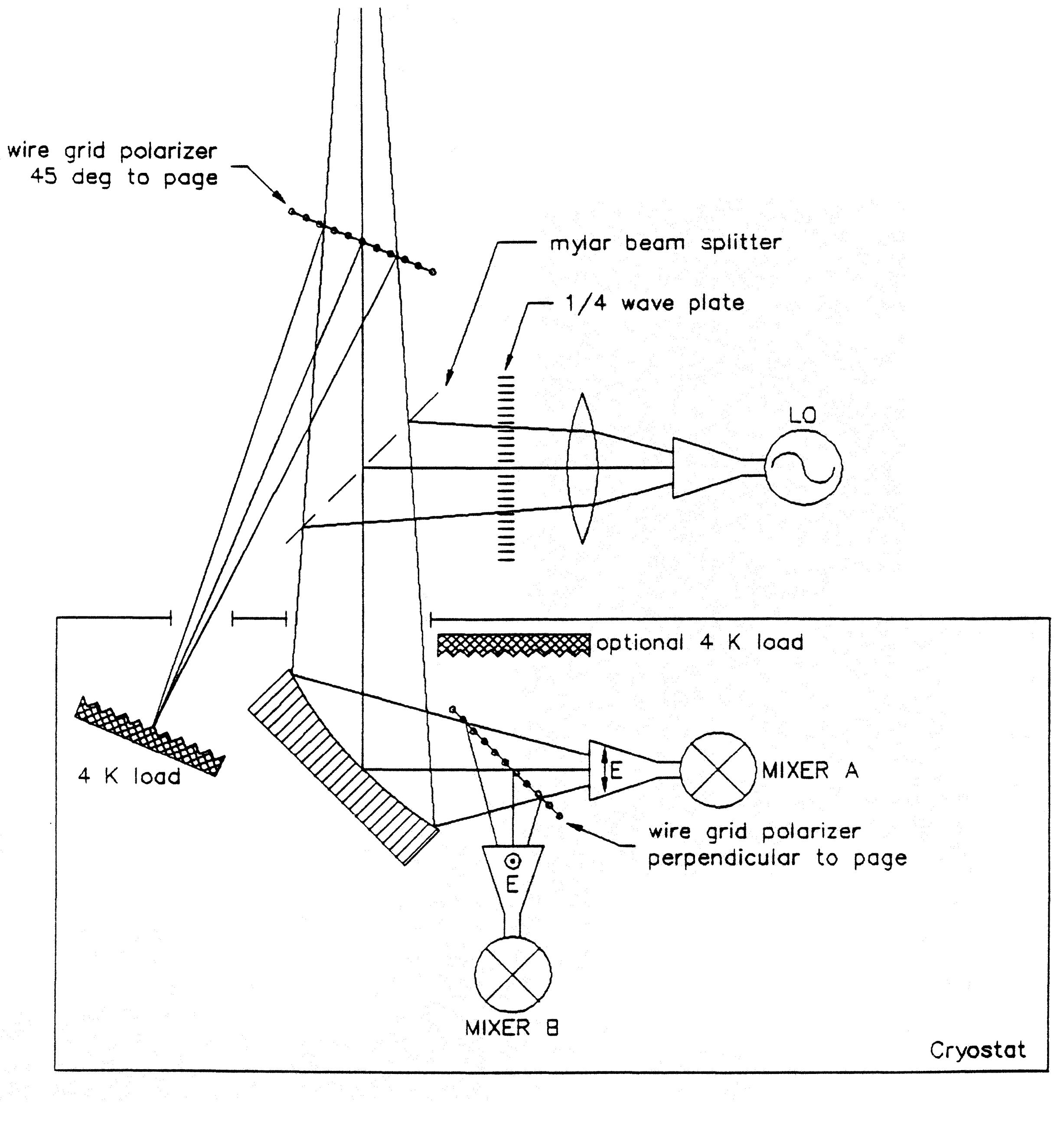

Figure 3: Quasi–optical Sideband Separation Receiver