The Design, Construction and Evaluation of a 585 GHz Planar Schottky Mixer

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Abstract

The design, construction and testing of a room temperature 585 GHz fundamentally pumped planar Schottky waveguide receiver are presented. Microwave modeling of the planar diode and circuit structure are discussed. Preliminary receiver tests have yielded a double sideband receiver noise temperature of 4100 K and total conversion loss of 10.0 dB using less than 0.5 mW of LO power.

Introduction

There is a need for sensitive receivers at submillimeter wavelengths for such applications as radio astronomy, atmospheric studies, plasma diagnostics, molecular spectroscopy and compact range radars. Receivers based on SIS junctions have achieved record sensitivity to frequencies as high as about 800 GHz and are the technology of choice for radio astronomy at millimeter and submillimeter wavelengths. However, many applications, particularly those which involve space based receivers, require a technology which does not require cryogenic cooling. GaAs Schottky diodes have the advantage of operating well at either cryogenic or room temperatures, although not with the sensitivity of SIS receivers. The best reported Schottky receiver at 500 GHz has a receiver noise temperature of only 550K (DSB) at 20K operating temperature [1]. Unfortunately, the best Schottky receivers have used whisker contacted diodes, which

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makes the receiver design and assembly quite expensive, and complicates the space qualification process. This research is an investigation of the use of new planar Schottky diodes [2,3] in waveguide receivers which are optimized through the use of modern circuit simulators and design tools, with the goal of achieving the same level of performance that has already been demonstrated with whisker contacted Schottky diodes.

This paper describes our design, fabrication and initial testing of a 585 GHz waveguide receiver which utilizes state-of-the-art planar Schottky diodes. The design of the mixer, including numerical modeling of the diode and circuitry with Hewlett Packard's High Frequency Design Software is described. These design tools allow us to fully understand the mixer performance and draw important conclusions about the fundamental limits of these receivers in terms of sensitivity and maximum operating frequency. The results of preliminary testing with several mixer configurations are also presented, and future improvements to the receiver are discussed.

Mixer Configuration

The mixer block, shown schematically in Fig. 1, was originally designed for use with an SIS junction. The primary modification was the redesign of the microstrip circuitry which includes the waveguide transition, solder pads for the diode, IF filter structure and bonding pads for the IF output and DC/IF return. The LO and RF signals are coupled into an 8x16 mil waveguide by a diagonal feedhorn. The waveguide transition to microstrip was designed using a scale model at 3.3-4.9 GHz. The measured return loss of the transition was better than 25 dB over the full waveguide band. The design was also verified using Hewlett Packard's High Frequency Structure Simulator (HFSS). The IF and DC return to ground is provided by a 1 mil gold wire bonded to the microstrip which is shorted in indium at the end of a quarter wave side channel. The diode, a UVa SC1T5-S20 diode with 20 μm finger length and 1 μm anode diameter, is mounted across a gap in the microstrip. The distance between the gap and the low pass filter is used for tuning.

Diode Modeling

The equivalent circuit of Schottky junctions has been extensively investigated and is rather well understood. However, the parasitic impedances created by the diode chip structure can also have a great impact on receiver performance. To determine these circuit elements HFSS was used to solve for the fields of the diode mounted in the microstrip channel. The two port S-parameters generated by HFSS were then compared with the equivalent circuit model shown in Fig. 2. The circuit element values were determined by using the optimization routines available in Hewlett Packard's Microwave Design System (MDS) to match the S-parameters with those of the equivalent circuit.

In order to determine the effect of the diode's semi-insulating GaAs substrate, the equivalent circuit for a chip without a substrate was also determined. With the diode

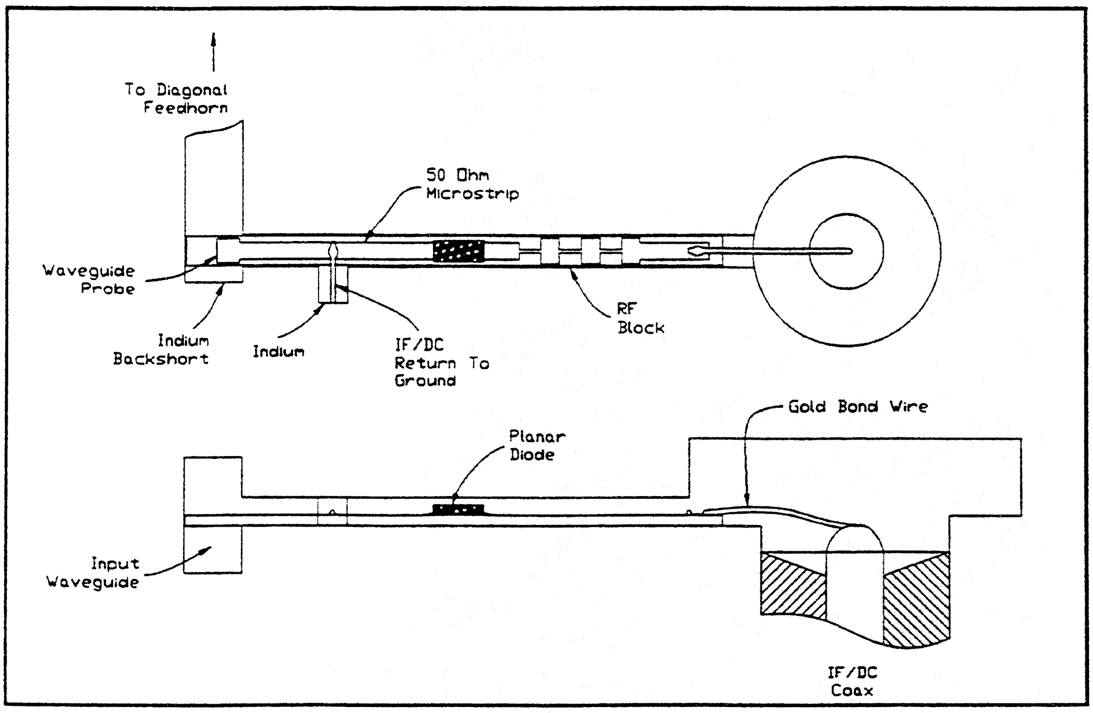

Fig. 1. Schematic of the interior of the 585 GHz mixer block, with quartz choke and diode mounted in block.

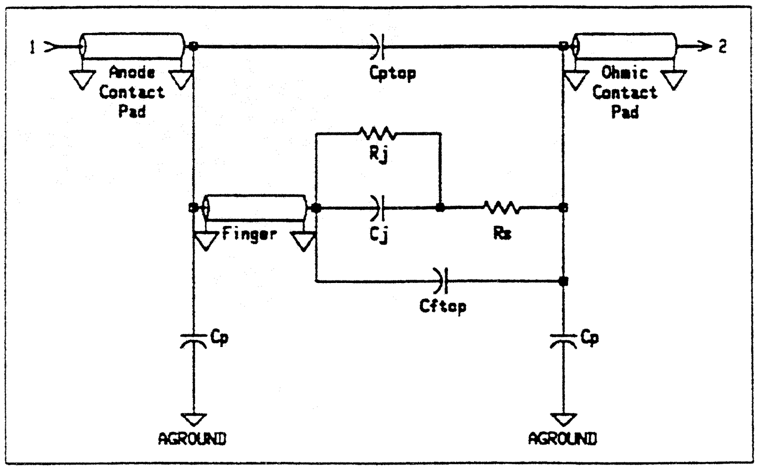

Fig. 2. Equivalent circuit model of SC1T5 planar diode.

substrate in place the pad-to-pad capacitance, C_{pp}, is the dominant parasitic capacitance. However, after substrate removal C_{pp} is significantly decreased and the finger-to-pad capacitance, C_{fp}, becomes the dominant element. Table 1 gives a summary of the equivalent circuit modeling results.

The equivalent circuit model is useful because it gives insight into the relative importance of the various parasitic elements related to the diode's geometry. However, at 585 GHz the lumped element circuit model begins to break down because the geometric features of the diode (e.g. surface channel width) are significant compared to a wavelength. By adding a small coaxial probe near the anode and solving for the fields, the embedding impedance can be determined more directly. Fig. 3 shows a schematic of the area near the anode with a coaxial probe inserted to determine embedding impedance.

In order to compare the two methods, the embedding impedance at the anode is calculated by each method for the circuit of Fig. 4 with Z_{source} and Z_{match} equal to 50 Ω. Fig. 5 shows the variation in embedding impedance for both methods as the distance between the diode and the low pass filter (L_{match}) is varied.

Microstrip Circuit Design

Once the variation of the diode's embedding impedance with system parameters was determined, the harmonic balance routines in MDS were used to design RF coupling structures for the diodes. Typical diode parameters for an SC1T5 diode are: $R_s = 15\ \Omega$, $\eta = 1.16$, $I_{sat} = 3E\text{-}17$ A, and $C_{jo} = 1$ fF. The values for R_s, η and I_{sat} were determined by a least squares fit of the measured diode I-V to the non-linear diode equation. The mixer simulations include plasma resonance and skin effect by the addition of a complex series resistance. The predicted locations of the conversion loss minimum (L_{opt}) and noise temperature minimum (T_{opt}) for the SC1T5 diode with no parasitics are indicated in the impedance Smith chart shown in Fig. 6.

A schematic of the basic mixer microstrip configuration is shown in Fig. 4. On one side of the diode is a length of transmission line, L_{match}, between the diode and the low pass filter. The low pass filter presents an open circuit at its input to the LO and RF. On the other side of the diode is a length of microstrip line running to the waveguide transition. This mixer circuit design thus offers 3 main variables for tuning: Z_{source}, Z_{match} and L_{match}. Changing L_{match} loops the embedding impedance around the Smith chart in a circle (see Fig. 6). Varying Z_{match} alters the sensitivity of Z_{embed} to changes in both L_{match} and frequency. Finally, varying Z_{source} changes the size of the loop on the Smith chart. The gap which the diode is mounted across can also significantly affect the embedding impedance presented to the diode. This is because the diode's pads alter the transmission line into the nonlinear diode and thus alter Z_{embed}.

The microstrip circuit on which the diode is mounted should be designed to give the proper Z_{embed} while also being broadband in frequency and insensitive to variations in diode mounting. The designs that have been tested to date have had both Z_{source} and Z_{match} of 50 Ω. Harmonic balance simulations indicated that this mixer design is

Diode Type	C_{pp} (fF)	C_{fp} (fF)	C_p (fF)	Z_{finger} (Ω)	θ_{finger} (°)
SC1T5-S5	2.9	1.2	0.5	193	6.9
SC1T5-S5 (no substrate)	0.8	1.9	0.3	198	6.4
SC1T5-S20	1.8	1.3	1.0	194	18
SC1T5-S20 (no substrate)	0.3	1.7	0.7	199	17

Table 1. Summary of the equivalent circuit modeling results for the SC1T5 diode.

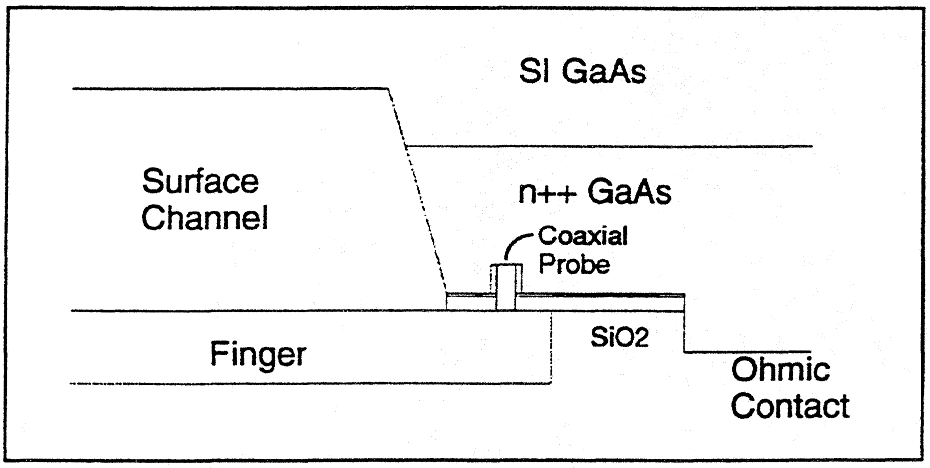

Fig. 3. Schematic of diode near anode for coaxial probe method.

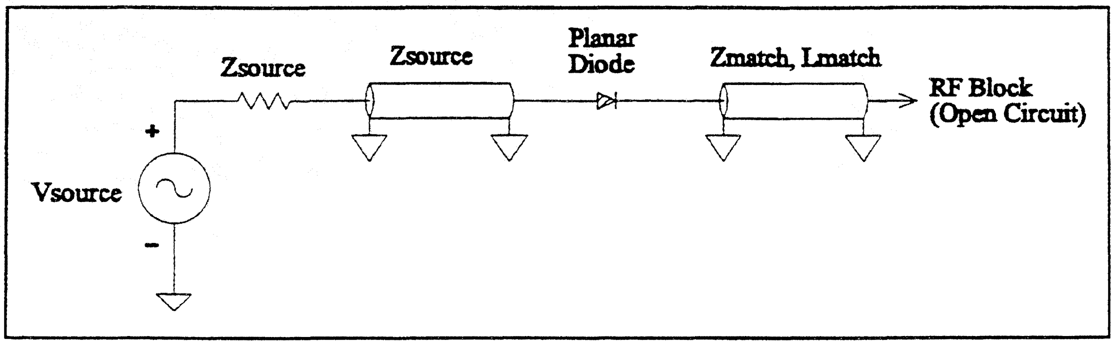

Fig. 4. Simplified schematic of the mixer microstrip configuration.

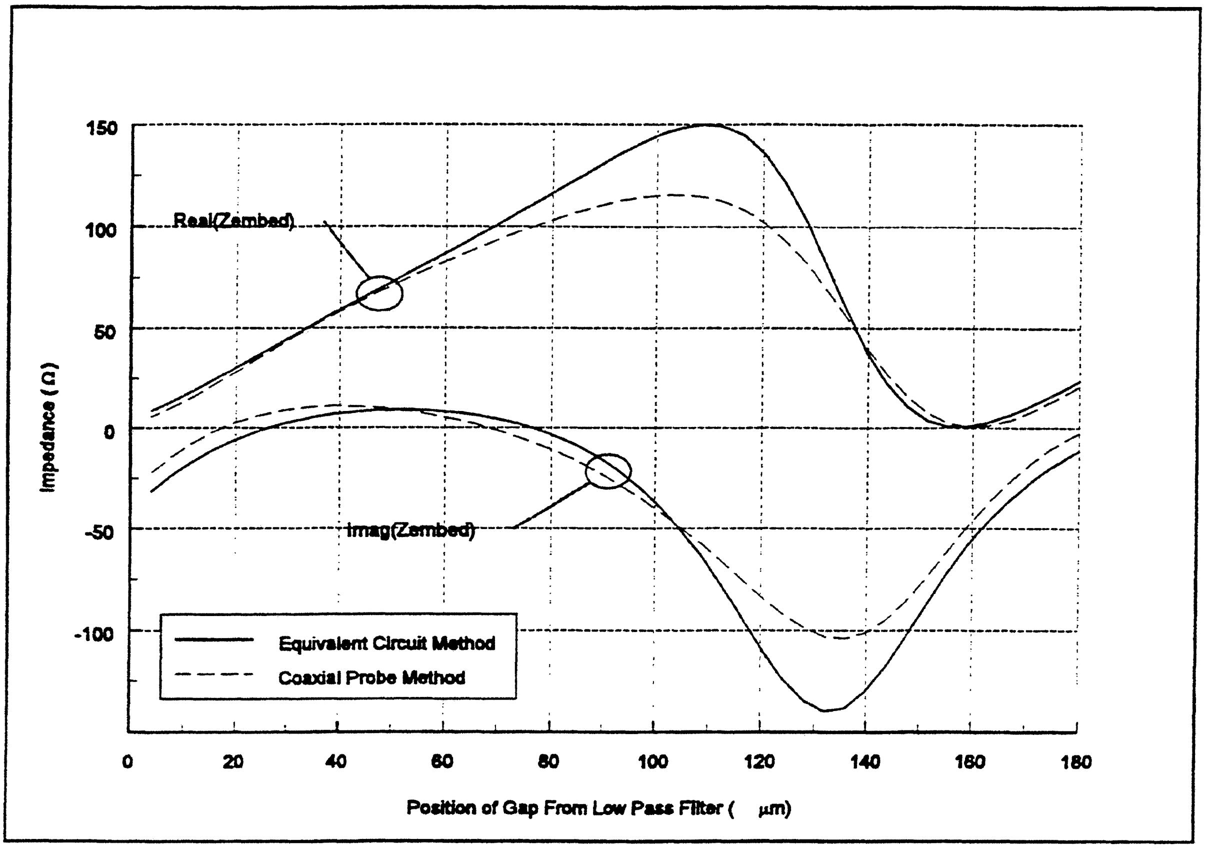

Fig. 5. Variation of embedding impedance with distance between the diode and the low pass filter for equivalent circuit and coaxial probe methods. The curves shown are for a choke with Z_{source} and Z_{match} equal to 50 Ω.

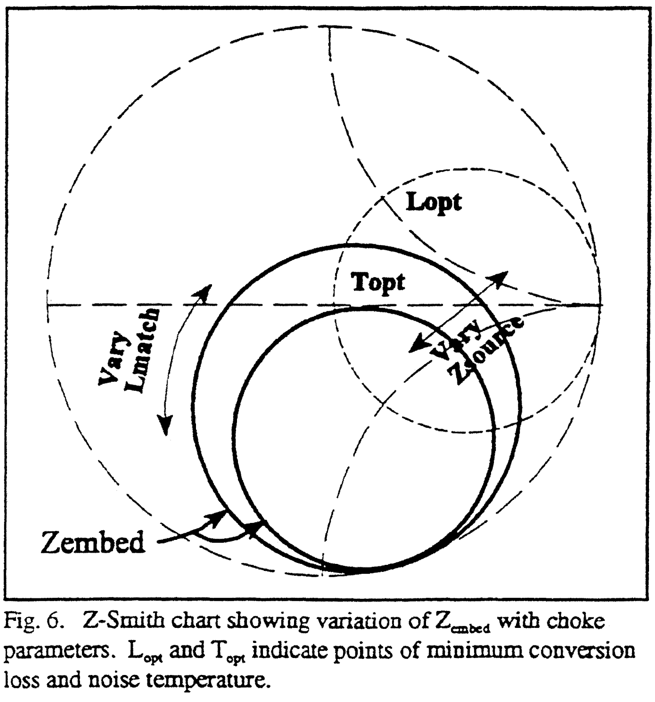

Fig. 6. Z-Smith chart showing variation of Z_{embed} with choke parameters. L_{opt} and T_{opt} indicate points of minimum conversion loss and noise temperature.

broadband, with a 3 dB conversion loss bandwidth of approximately 160 GHz.

The microstrip circuits were fabricated on 1.5 mil quartz substrates. The thin quartz wafer was mounted with wax on a silicon support wafer, allowing the use of standard photolithography techniques to fabricate the circuitry. The quartz wafer was then diced into individual circuits before being removed from the silicon carrier. The IF/DC connection wires were then bonded onto the choke and the diode was soldered across the gap. Finally the quartz structure was mounted into the mixer block and held in place by the wires which were pressed into indium. A picture of a quartz choke mounted in a mixer block is shown in Fig. 7.

Performance of the Diagonal Feed Horn

A diagonal feed horn based on the design discussed in [4] is used to couple power into the mixer block. With proper quasi-optical design this horn should capture 84% of the power from a Gaussian beam. Fig. 8 shows a contour plot of the measured antenna pattern of the diagonal feed horn. This pattern was measured using the video response of a diode mounted in the block. Using this data we calculated the beam waist to be 0.67 mm, which is very close to the design value of 0.7 mm.

Receiver Measurements

A schematic of the receiver test setup is shown in Fig. 9. A Martin-Puplett diplexer [5] and an off-axis parabolic mirror with a focal length of 60 mm are used to couple the LO and RF power into the feed horn. The LO power is supplied by an FIR gas laser which is in turn pumped by a CO_2 gas laser.

The first mixer block tested was made at NRAO, and the best results to date in this block are 4400K double sideband receiver temperature and 10.1 dB conversion loss. A new mixer block with a shorter input waveguide and an integrated feedhorn was fabricated by Rutherford Appleton Laboratory (RAL). Preliminary testing in the RAL block has yielded a slight improvement in performance. The best results to date with this block are a double sideband receiver noise temperature of 4100 K and total conversion loss of 10.0 dB. The mixer required less than 0.5 mW of LO power to achieve this performance. Fig. 10 shows a plot of receiver temperature versus LO power incident on the parabolic mirror. These results are discussed in further detail in the next section.

Comparison of Simulations with Measured Results

The harmonic balance simulations indicated that the double sideband conversion loss for the SC1T5-S20 diode mounted on a choke with Z_{source} and Z_{match} equal to 50 Ω should be 3.4 dB, not including waveguide and horn conductor losses. Conductor losses are hard to estimate for real waveguide surfaces which have significant roughness. To approximate these losses we have chosen to assume that they are twice as large as would be measured with ideal smooth surfaces but finite conductivity. For the NRAO block, the losses are: 1.8 dB for microstrip channel, 1.2 dB for the waveguide, and 1.0 dB for

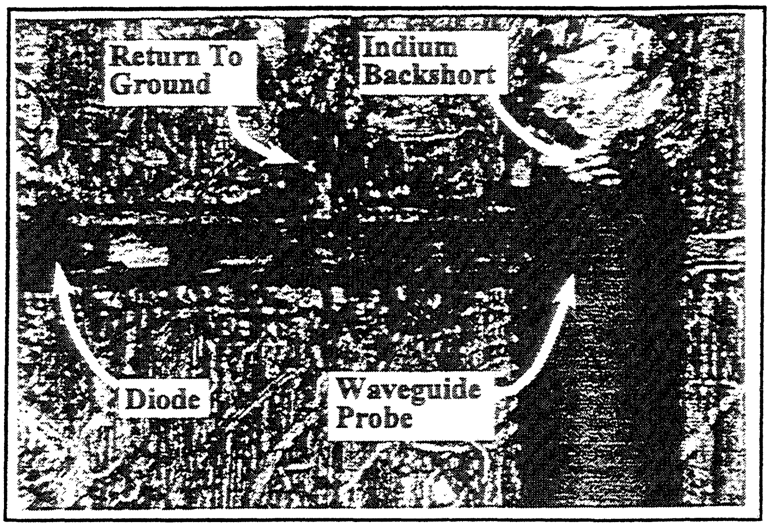

Fig. 7. Choke mounted in mixer block channel.

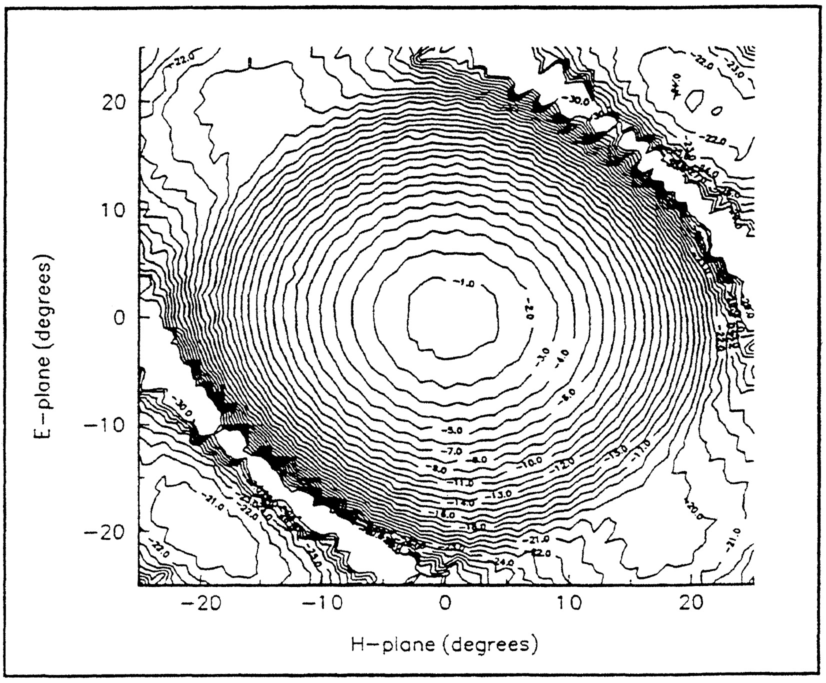

Fig. 8. Antenna map of diagonal feed horn.

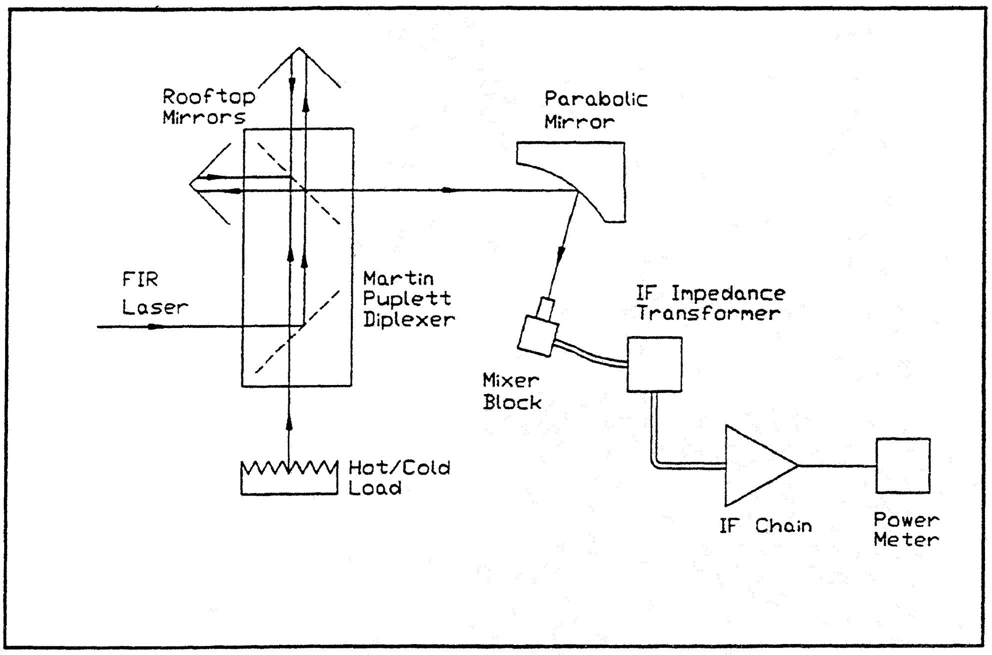

Fig. 9. Schematic of quasi-optical receiver test setup.

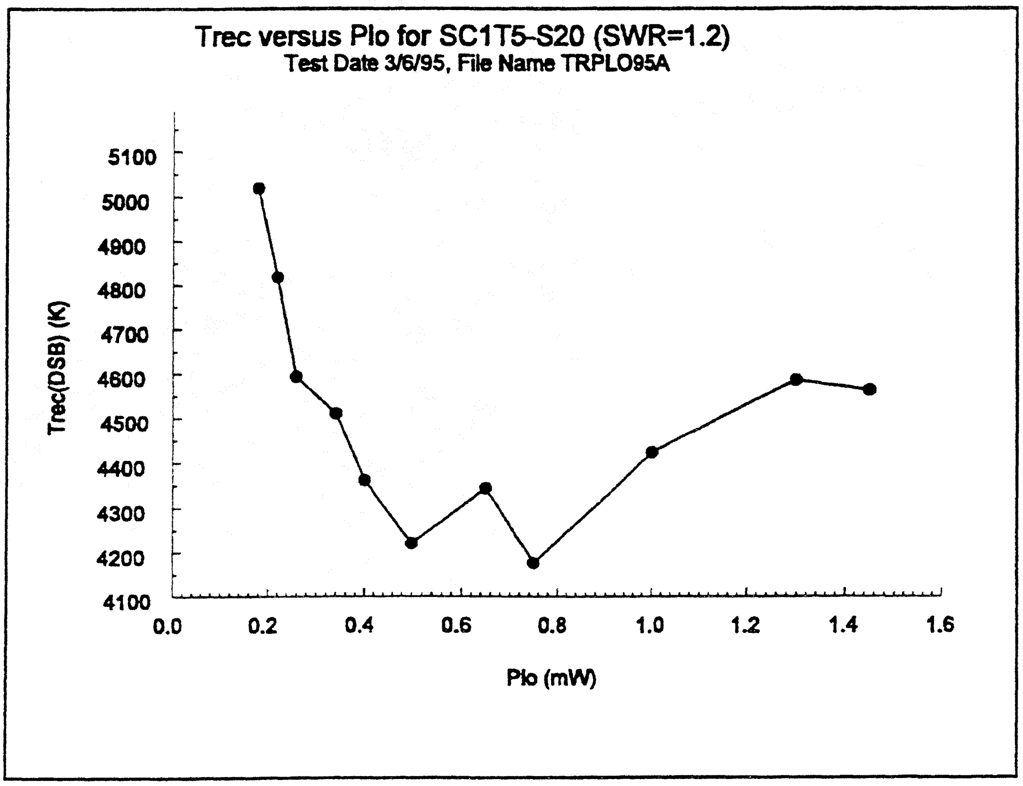

Fig. 10. T_{rec} versus P_{LO} for the SC1T5-S20 diode.

horn. The total expected loss for the receiver with this diode in the NRAO block is 7.4 dB. The RAL block has similar losses, except that the 1.2 dB waveguide loss is eliminated, yielding a predicted conversion loss of 6.2 dB. The measured conversion loss of 10.0 dB leaves a 2.6 dB discrepancy for the NRAO block, and 3.8 dB for the RAL block. These discrepancies may be attributed to problems with either the design or the assembly of the mixer.

We have performed extensive testing with the NRAO block, and have tested a number of diodes mounted on the same choke design. We have not tested the RAL block as extensively. Also, the microstrip channel on the RAL block was machined deeper than expected, thus making choke mounting difficult. Future testing using quartz chokes with the proper thickness is expected to show the improvement in mixer performance that should occur because of the reduced waveguide loss of the RAL block.

Future testing will also be performed with diodes that have their semi-insulating GaAs substrate removed after mounting on the circuit. This will reduce the shunt capacitance, and according to the harmonic balance simulations could reduce the diode's conversion loss by an additional 1.0 - 1.5 dB. Finally, testing with new choke structures with different Z_{source} will be performed. It is our expectation that with these improvements the performance of this receiver will approach that of the best whisker contacted diode receiver at this frequency.

Acknowledgments

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