An Integrated SIS Mixer and HEMT IF Amplifier

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Abstract—**Design details are given for a 205–270 GHz fixed-tuned SIS receiver in which the SIS mixer and HEMT IF amplifier are integrated into a single compact unit. The mixer and IF amplifier are connected with an inductor which provides the reactive part of the optimum input impedance for the HEMT. This simple coupling circuit gives an IF bandwidth of ~4 GHz. The receiver has a DSB noise temperature in the range 35–80K over the 205–270 GHz local oscillator band and 0.5–4.5 GHz IF band.**

I. Introduction

In a millimeter-wave SIS receiver, the SIS mixer and HEMT IF amplifier are usually separate units connected with a 50 Ω coaxial line. The mixer is attached to the 4 K stage of a refrigerator while the IF amplifier is typically mounted 10–20 cm away on the 12 K stage [1]. The mixer may have an isolator at its IF port or a matching network which transforms the mixer IF port impedance to 50 Ω [2]. The IF amplifier also has a matching network which transforms 50 Ω to the optimum input impedance for a HEMT.

In most SIS receivers the IF contribution to the receiver noise is significant. IF amplifier noise temperatures increase roughly linearly with frequency and low-noise amplifiers typically have bandwidths of about an octave [3]. This leads to a compromise between receiver noise and IF bandwidth which is responsible for the popularity of the 1–2 GHz IF band. Increasing the IF bandwidth without degrading the receiver noise requires a low-noise IF amplifier with a bandwidth of several octaves. This is difficult because the amplifier input matching network must simultaneously match a HEMT input to 50 Ω and provide the optimum input impedance for the HEMT over a wide range of frequencies. The isolator or matching network at the mixer IF port must also have a wide bandwidth. Increasing the mixer gain allows the use of a noisier wideband IF amplifier but SIS mixers with gain tend to saturate [4].

We have explored a new approach to increasing the IF bandwidth of an SIS receiver. The SIS mixer and the first stage of the HEMT IF amplifier are integrated into a single unit with a very simple coupling network between the two circuits. In this case there is no impedance transformation through 50 Ω. The mixer is designed to provide an IF port impedance that is real and equal to the real part of the optimum input impedance for the HEMT. The imaginary part of the required input impedance is provided by an inductor. This simple coupling network provides the HEMT with a generator impedance which is close to the minimum noise impedance (Z_{opt}) over a wide range of frequencies.

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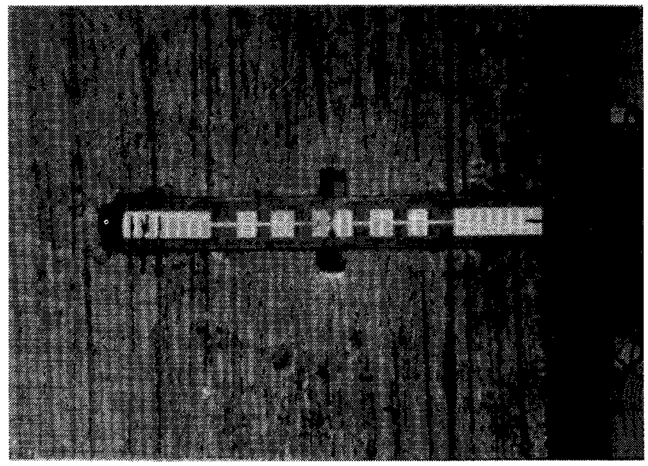

Fig. 1. Photograph of the mixer section of the integrated receiver. This is a split block with a fixed backshort in one half and a transition to the feedhorn in the other. The photograph shows the backshort block with the mixer chip suspended in a channel across the waveguide. The waveguide dimensions are 0.0092 × 0.037 inches. The block was made in a Tree 325 CNC milling machine [13], and the waveguides were punched in the same machine using a rectangular titanium-nitride-coated high-speed-steel die.

The coupling circuit in the integrated receiver has lower loss than the isolator, 50 Ω line and IF amplifier input matching network in the standard receiver configuration. This reduces the IF contribution to the receiver noise in the integrated receiver. Integrating the mixer and IF amplifier substantially reduces the size of the receiver and this is an important advantage for multiple receiver systems such as dual polarization receivers and focal plane arrays. The main disadvantage of the integrated approach is that the mixer and IF amplifier cannot be tested separately with the correct load and source impedances. As a result, the development of an integrated receiver relies heavily on modeling. We used programs written by Wengler [5] to calculate admittance and noise parameters for the SIS junction and the MMICAD [6] microwave circuit design program was used to model the integrated receiver.

II. SIS Mixer

The SIS mixer is a copy of a 176–256 GHz mixer previously reported [7], but scaled for a center frequency of 245 GHz. It is a fixed-tuned waveguide design with a corrugated feedhorn and a single SIS junction. The junction is fabricated on a thin-film chip which is suspended across the waveguide as shown in Fig. 1. The chip has a waveguide to microstrip transition and a 2-section microstrip transformer followed by a short inductive line which tunes out the capacitance of the SIS junction. The original mixer achieved a DSB noise temperature of 25–35 K over the 180–250 GHz band at 1.5 GHz IF with a 1.3 μm^2 7.5 $kAcm^{-2}$ SIS junction with a normal state resistance of 22 Ω.

Bias for the SIS junction is provided through a 45 nH spiral chip inductor connected to the mixer IF port as shown in Fig. 2. The inductor is mounted on a 0.050 inch thick quartz slab to move its parallel resonant frequency above the top of the IF band. The bias network has differential connections for voltage and current monitoring and provides 20 Ω shunt resistance across the SIS junction to prevent the bias supply from oscillating when the junction has negative resistance.

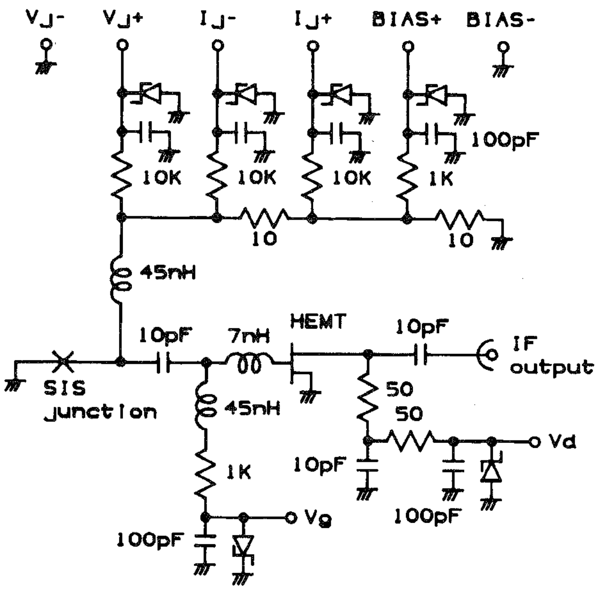

Fig. 2. Circuit diagram of the integrated receiver.

For the integrated receiver work, the SIS junction was modeled as a three-port device (signal, image and IF ports) with admittance and noise parameters computed from a typical I–V curve. MMICAD can only handle two-port noise parameters so the three-port junction was synthesized from a triangular array of two-ports. The mixer model consists of the junction, an image termination, a transformer to simulate the signal port impedance and an IF port circuit which contains the junction capacitance, the various microstrip and suspended stripline sections on the thin film chip and the bias network. The model is primarily a description of the mixer at IF but it can also be used to investigate different signal and image port impedances. For double sideband operation, an SIS junction with a normal state resistance of 22 Ω has optimum signal and image port impedances of ~13 Ω. The corresponding IF port impedance is ~200 Ω which is close to the real part of the optimum input impedance for a 250 μm HEMT at L-band.

III. IF Amplifier

The IF amplifier circuit is shown in Fig. 2. The input network is just a dc blocking capacitor and a 7 nH spiral chip inductor. This inductor and the mixer IF port resistance provide close to the optimum input impedance for the HEMT. The bandwidth of the amplifier is determined by the inductor which forms a low-pass filter with the HEMT gate capacitance. A 250 μm HEMT has a gate capacitance of ~200 fF so a 7 nH gate inductor gives a bandwidth of ~4 GHz. With the 7 nH inductor the impedance at the HEMT gate is slightly less reactive than optimum, but this gives a good compromise between IF amplifier bandwidth and noise. Below ~500 MHz, the increasing reactance of the dc blocking capacitor reduces the gain of the IF amplifier and moves the HEMT input impedance far from optimum. With just a single inductor at the HEMT gate, deviations from optimum input impedance increase with the mixer IF port capacitance. To reduce this capacitance, the dc blocking capacitor and chip inductor are mounted on the 0.050 inch thick quartz slab which supports the 45 nH inductor in the SIS junction bias circuit. The mixer IF port capacitance is then dominated by the microstrip transformers on the mixer chip. The quartz slab also serves as a thermal shunt to prevent the HEMT from heating the SIS junction. The HEMT drain has a 50 Ω shunt resistor which guarantees unconditional stability and provides a convenient connection for the drain bias. The source is connected directly to ground with short wirebonds.

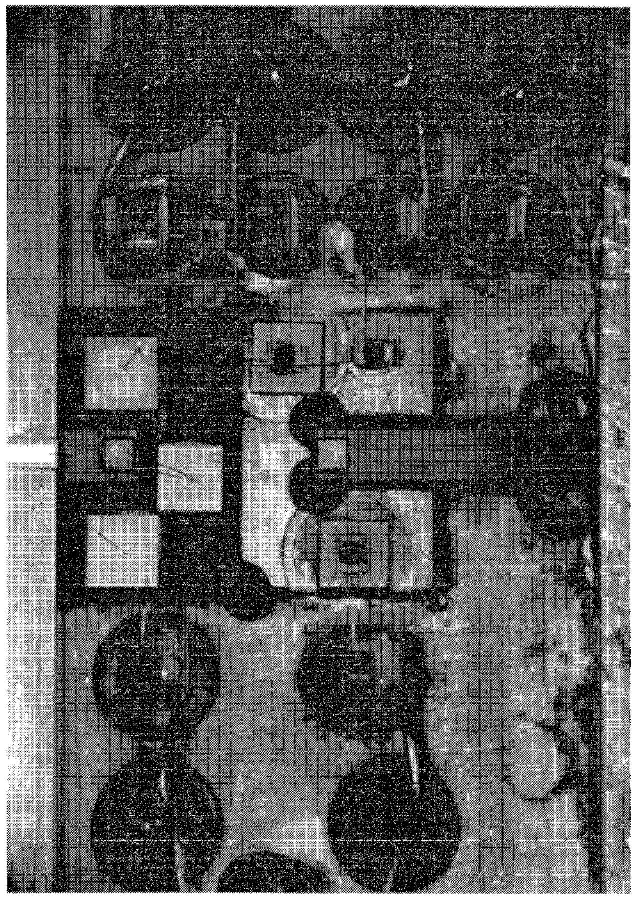

Fig. 3. Photograph of the IF section of the integrated receiver. The HEMT is glued to the pedestal in the center of the photograph. On the left is the 0.050 inch thick quartz slab which carries the input network and the 45 nH inductors in the gate and SIS junction bias circuits. The SIS junction bias circuit is at the top of the photograph and the HEMT bias circuit is at the bottom. The small black rectangles with metallized pads at each end are chip resistors. These have a wrap-around contact on one side so they can be glued directly to chip capacitors or to the block. The cylindrical components at the top and bottom of the block are the zener diodes in the bias circuits.

The IF amplifier and SIS junction bias network are built on a separate subblock in the integrated receiver. This is shown in Fig. 3. The chip components are soldered to the block or glued with conductive epoxy and connected with 0.001 inch aluminum wirebonds. Wirebonded chip construction was chosen to minimize parasitics with a view to making the integrated receiver model easier to construct and more accurate. The IF subblock can be tested in a 50 Ω system and while this presents a lower impedance than the mixer IF port the test provides a useful comparison with the IF section of the receiver model. To facilitate testing, a plate with a coaxial connector can be attached to the IF subblock in place of the mixer. Fig. 4 shows the gain and noise temperature for IF blocks with FHR02X [8] and 300 μm InP [9] HEMT's along with predictions from the receiver model. The measurements were made at 12 K using a cooled 20 dB attenuator at the input of the IF block.

IV. Integrated Receiver Performance

The integrated receiver was tested at 4.2 K in a cryostat with a closed-cycle helium refrigerator [10]. Signals enter this cryostat through an expanded polyethylene vacuum window with an expanded

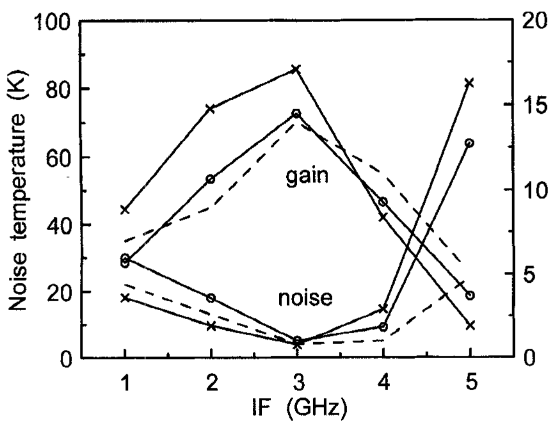

Fig. 4. IF block gain and noise temperature measured with 50 Ω input impedance. The circles are for an FHR02X 250 μm GaAs HEMT and the crosses are for a 300 μm InP HEMT. Noise and gain measurement errors are ~2K and ~0.2 dB. The dashed lines are model predictions for an FHR02X HEMT.

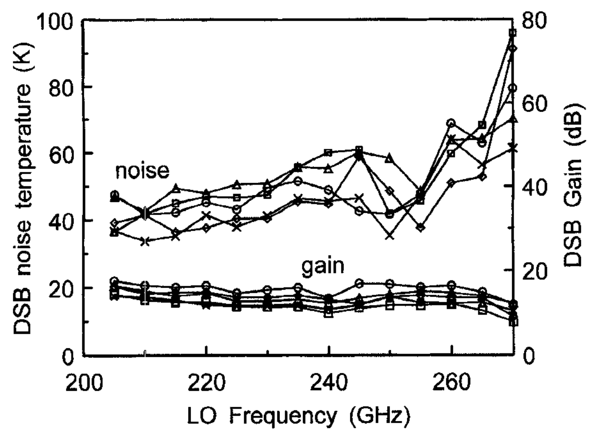

Fig. 5. Noise temperature and gain for several different integrated receivers at 3 GHz IF. The circles indicate a receiver with a 300 μm InP HEMT. All the other receivers have FHR02X HEMT's. The noise contribution from the second IF amplifier has been subtracted and noise and gain measurement errors are ~5K and ~0.2 dB.

Styrofoam infrared block. The local oscillator was injected using a 0.001 inch thick mylar beam splitter outside the cryostat. Receiver noise temperature measurements were made using room and liquid nitrogen temperature loads. The receiver gain and second IF amplifier noise contribution were obtained from additional measurements with room and liquid nitrogen temperature coaxial loads at the input to the second IF amplifier.

Fig. 5 shows the noise temperature and gain for several different integrated receivers at 3 GHz IF. The noise temperature increases from about 35–80 K across the 205–270 GHz band. Measurements of the IF output power with hot and cold loads at the receiver input and different local oscillator power levels were used to calculate the noise contribution due to optical and RF coupling losses [11]. For all the receivers measured, the input noise is ~20K at 230 GHz. Fig. 6 shows the receiver noise temperature and gain across the IF band for receivers with FHR02X and InP HEMT's. The receiver with an InP HEMT has approximately flat gain and noise at IF's down to ~0.5 GHz but the receiver with an FHR02X HEMT shows a significant increase in noise at the bottom of the IF band. This is because the mixer IF port resistance is much lower than predicted so at low IF the impedance presented to the HEMT gate is far from optimum. Fig.

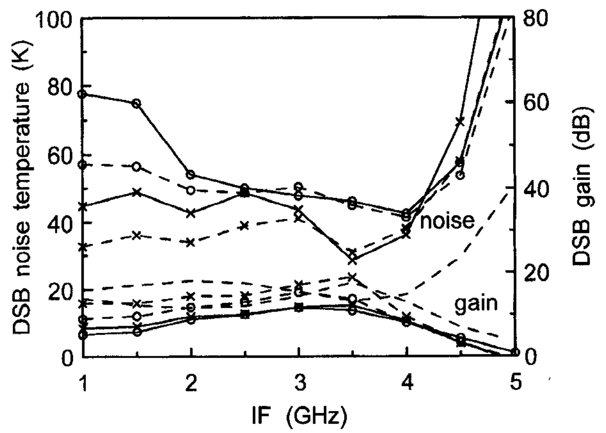

Fig. 6. Receiver noise temperature and gain across the IF band at 230 GHz (circles) and 250 GHz (crosses). The solid lines are for an FHR02X HEMT and the dashed lines are for a 300 μm InP HEMT. The same mixer was used for all the measurements so these results provide a direct comparison of the different IF amplifiers. The noise contribution from the second IF amplifier has been subtracted and noise and gain measurement errors are ~5K and ~0.2 dB. The dashed lines without symbols are model predictions. Note that these do not include the mixer input loss which contributes ~20K at 230 GHz.

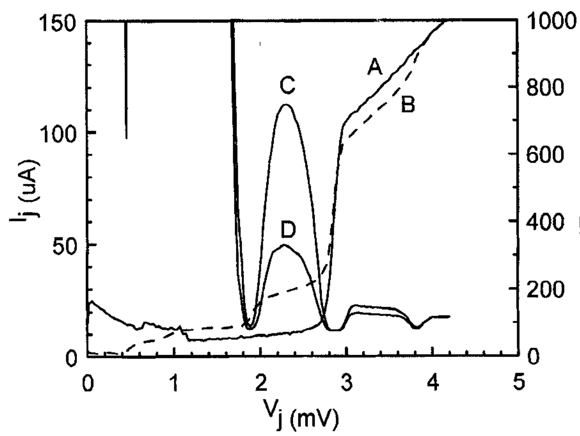

Fig. 7. I–V and IF power curves for a typical integrated receiver. A is the dc I–V response of the unpumped SIS junction and B is for the junction pumped at 230 GHz with the optimum LO power. The junction normal state resistance is 25 Ω and the resistance on the first photon step is 79 Ω. C and D show the IF response (arbitrary units) at 1.5 GHz with room temperature (295 K) and cold (74 K) loads.

7 shows typical I–V curves for a receiver. On the first photon step, where the junction is generally biased, the resistance is only ~80 Ω instead of the expected ~200 Ω. As a result, the IF amplifier noise is similar to that measured with a 50 Ω input instead of being roughly constant across the IF band. Fig. 4 shows much better performance for an InP HEMT IF amplifier with a 50 Ω input and this explains the lower noise temperature at low IF for the receiver with the InP HEMT. The low mixer IF port resistance is probably a result of the junction capacitance not being completely tuned out at the signal frequency.

V. Conclusion

We have demonstrated an integrated SIS mixer and HEMT IF amplifier with good noise performance over a 4 GHz IF bandwidth. In addition to being sensitive, the receiver is fixed-tuned, small and easy to construct, all of which are big advantages for systems with many receivers. The present version of the integrated receiver has just a single IF stage so the gain is small and the receiver must be followed by a low-noise amplifier. A second integrated IF stage could be included and the inter-IF coupling network designed to compensate the passband variations in the single IF stage receiver. The IF bandwidth could also be increased further. This would require a smaller HEMT with a lower gate capacitance to increase the cut-off frequency of the low-pass filter at the IF amplifier input. Providing the optimum input impedance for the smaller HEMT would require a mixer with a very low IF port capacitance so the tuning structures would not use microstrip. With a 50 μm InP HEMT and a coplanar waveguide mixer chip designed by Kerr [12], our receiver model predicts an IF bandwidth of $\sim$8 GHz.

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