COOLED LOW NOISE GaAs MONOLITHIC MIXERS AT 110 GHz*

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ABSTRACT

We describe the fabrication and testing of GaAs monolithic integrated circuit mixers which have liquid nitrogen double sideband (DSB) mixer noise temperatures in the range 50-200 K and conversion losses of 4.0-5.0 dB.

Introduction

We have previously reported[1] the room temperature performance of a novel GaAs monolithic integrated circuit mixer at 110 GHz. In this paper we report the improved noise performance which is obtained in cooling these mixers to 77 K. This performance is in general agreement with the predictions of other investigators[2,3]. The monolithic mixers differ from more conventional mixers as a result of the unique way in which the signal and local oscillator energy are coupled into the device. This results in the monolithic mixer being intrinsically more stable during cooling, and hence in contrast with many whisker contacted mixers the monolithic mixer may be repeatedly cycled between room and cryogenic temperatures with no ill effects. The mixer circuit is fabricated using photolithographic techniques, and consequently should be scalable into the submillimeter wave region with only slight degradation in performance.

Monolithic Integrated Circuit Mixer

In this mixer the radiation propagates through the semi-insulating GaAs to a slot coupler fabricated photolithographically in a metallic ground plane on the surface of the GaAs. The slot coupler is connected to a diode by a section of coplanar line, and an integrated bypass capacitor completes the mixer circuit providing a short circuit to millimeter wave frequencies and an open circuit at the IF (Fig. 1). The heart of the integrated mixer is the surface-oriented Schottky barrier diode (Fig. 2) which is made on material having epitaxial layers of n on n^+ GaAs grown upon a semi-insulating substrate. The n^+ layer is approximately 3 µm thick with a carrier concentration of 3×10^{18} cm^{-3} while the n layer is 0.1-0.2 µm thick with a concentration of $1-2 \times 10^{17}$ cm^{-3}. The diode ohmic contact region is defined on the surface of the n^+ GaAs by alloying an evaporated Au-Ge ohmic contact metallization into the n^+ layer. The Schottky barrier is a stripe of Ta-Au which is defined on the surface of the n-GaAs using optical projection lithography and metallization liftoff. Proton bombardment is used to isolate the diode conducting area by converting the surrounding unprotected epitaxial layers to high resistivity material. A final overlay circuit metallization contacts the Schottky barrier stripe and forms a bypass capacitor around the periphery of the ohmic contact. The module dimensions are chosen to be slightly less than the inside dimension of WR-10 waveguide and the module thickness is approximately 125 µm.

Each module is a complete integrated mixer, but for convenience is mounted in a larger structure

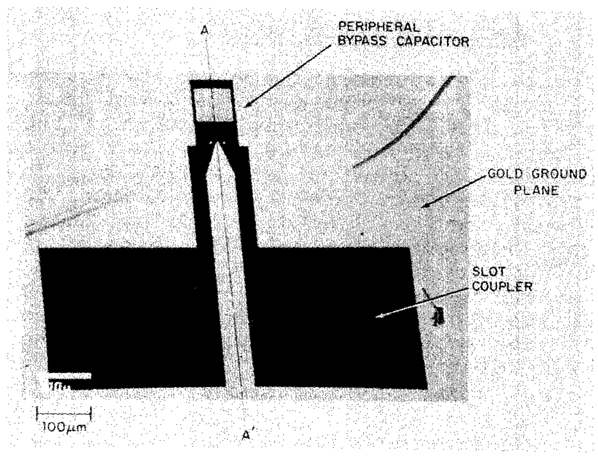

Figure 1. 110 GHz monolithic integrated circuit mixer.

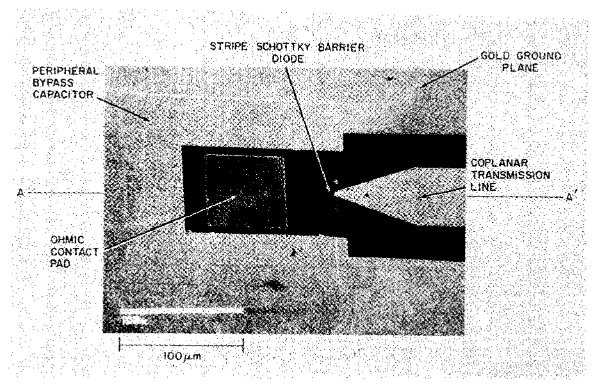

Figure 2. Detail of surface-oriented Schottky diode.

(Fig. 3) for use. The mixer module is alloy bonded to the ground plane metallization on the back surface of a ceramic substrate. A gold ribbon thermocompression bonded to the ohmic contact pad on the mixer module passes through a hole in the ceramic and is bonded to a 50 ohm microstrip line defined on the front surface of the ceramic. The integrated mixer module is located in the end of a WR-10 TE_{10} waveguide horn, and a bellows spring-contact to the microstrip line on the ceramic substrate provides an IF output connection to an SMA connector (Fig. 4). The quasi-optical spherical reflector located behind the slot coupler refocuses the power radiated through the hole in the ceramic back onto the slot coupler giving a slight improvement in conversion loss.

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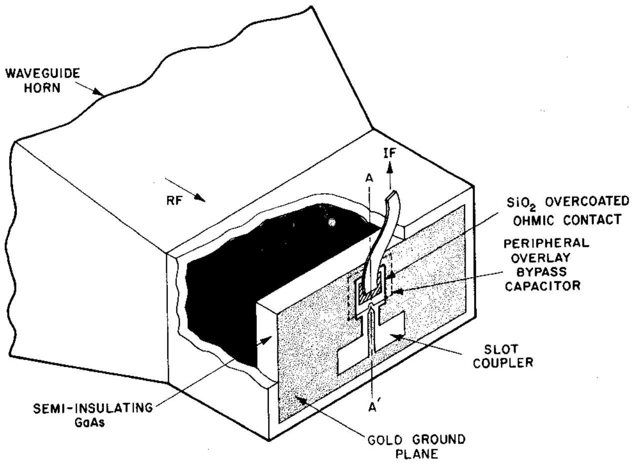

Figure 3. Monolithically integrated circuit mixer mounted in TE_{10} waveguide horn.

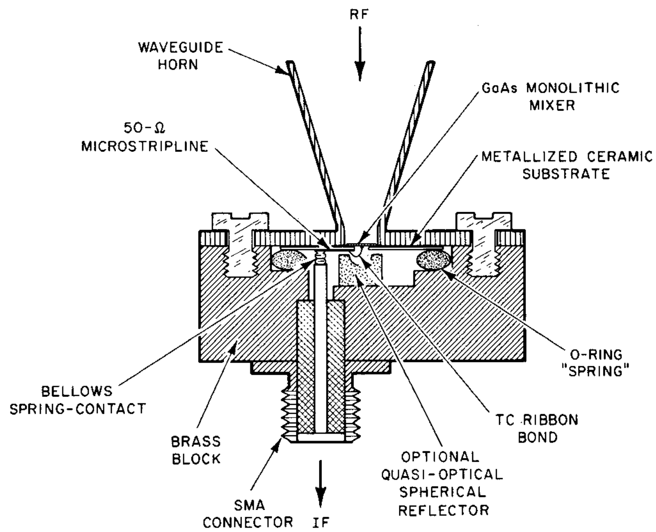

Figure 4. 110 GHz monolithic mixer mount.

Mixer Performance Predictions

The monolithic mixer, although elegant and simple in concept, is extremely complex to analyze theoretically as a result of the mixed dielectric media and the complicated boundary conditions imposed by the circuit metallization. However, low-frequency scale modelling allows a realistic and complete investigation of circuit parameter effects and provides a convenient tool for circuit optimization. We have modelled the mixer at 4.8 GHz in WR-229 waveguide using a scale factor of 22.9. The GaAs is simulated by machinable ceramic with a dielectric constant of 13 and the integrated circuit pattern is formed by using conductive adhesive copper tape. Scaled planar diodes have been fabricated but adequate modelling can be obtained by using commercial silicon or GaAs Schottky barrier mixer diodes with the appropriate junction capacitance. Single sideband (SSB) conversion loss measurements for both upper and lower signal sidebands as a function of intermediate frequency for a number of local oscillator frequencies are performed under computer control. Also measured are return loss at both the signal and image frequencies. Complete characterization of the mixer performance as a function of the important design parameters is therefore possible. Scaling the results to WR-10 waveguide allows for prediction of mixer performance and a comparison with actual measured performance. The predicted dependence of double sideband (DSB) conversion loss in WR-10 waveguide on GaAs substrate thickness is illustrated in Fig. 5 for an IF frequency of 1.1 GHz. The sharp falloff in conversion loss evidenced in the thicker substrates at higher LO frequencies is due to an undesired surface wave propagating on the GaAs[1]. Also evident are both the degree of circuit tuning afforded by thinning the GaAs substrate and the relatively broad bandwidth provided by the nominal 125 μm thick substrate. Two measured room temperature data points for a monolithic mixer in WR-10 waveguide are shown for comparison. All the data of Fig. 5 are taken without the optional spherical reflector indicated in Fig. 4. Fig. 6 shows the predicted SSB conversion loss at the upper and lower signal sidebands for the nominal 125 μm thick substrate both with and without the spherical reflector. Local oscillator drive and diode bias were adjusted for flatness over the band rather than minimum conversion loss. The improvement given by the spherical reflector is clearly evident.

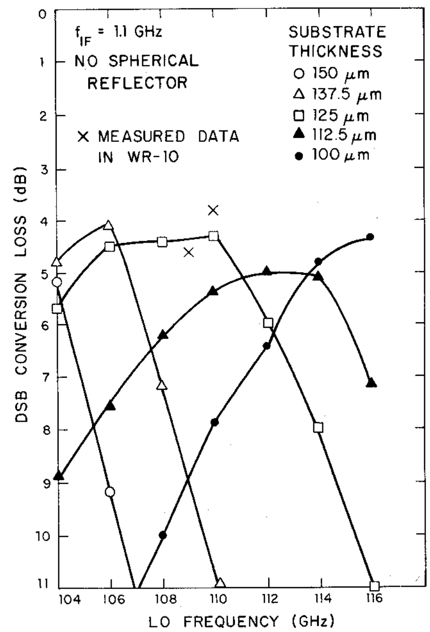

Figure 5. Predicted conversion loss vs LO frequency as a function of substrate thickness from scale model measurements.

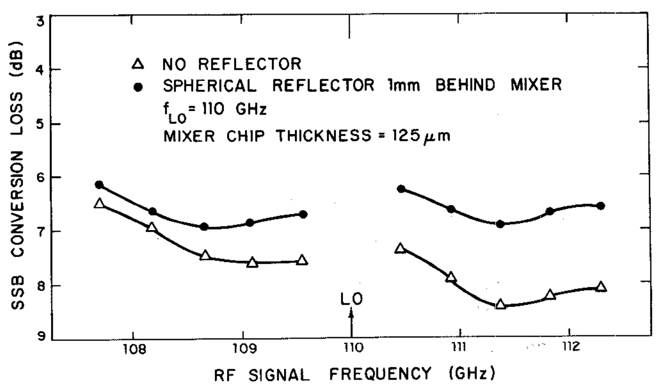

Figure 6. Predicted conversion loss vs RF signal frequency based on scale model measurements

Although all modelling is performed at room temperature, the performance of cooled monolithic mixers may be predicted by applying conventional cooled mixer theory[2,3] to the room temperature predicted performance. Viola and Mattauch[3] have considered the dominant transport mechanisms of the Schottky barrier to calculate the decrease in diode noise temperature on cooling. Weinreb and Kerr[2], in considering the cryogenic cooling of millimeter wave mixers use the predicted decrease in diode noise temperature to calculate the decrease in mixer noise temperature. They also show that the conversion loss and impedance levels should be invariant on cooling if the LO power and diode dc current are reduced accordingly. Thus a mixer circuit that is optimum at room temperature should also be optimum at cryogenic temperatures provided the LO power and dc bias are reduced accordingly. However, since in the monolithic mixer the signal and local oscillator energy propagate through the semi-insulating GaAs substrate any change in substrate propagation parameters as a function of temperature should also be considered.

Cooled Quasi-Optical Receiver and Noise Measurements

Low-loss beam optics and a quasi-optical diplexer are used to combine signal and local-oscillator energy into a single beam and an off-axis parabolic mirror is used to focus the beam energy through a low-loss quartz window in the dewar wall and into the waveguide horn (Fig. 7). The mixer is located on a liquid-nitrogen cold finger. The noise measurement was performed by using a calibrated noise tube with a ferrite modulator used as an isolator feeding a scalar feed horn at the focus of another off-axis parabolic mirror. Switching the noise power beam on and off at port 1 of the diplexer and measuring the noise power at the output of the 30 MHz IF amplifier on a digital power meter provides a precise measurement of system Y-factor. The noise tube is calibrated against room and liquid-nitrogen temperature absorber loads placed alternately at port 1 of the diplexer. Since IF responses from both upper and lower signal sidebands were thus obtained, DSB parameters were measured and only these are reported. Measurement of the system Y-factor as a function of IF noise figure allows calculation of both the DSB mixer noise temperature and conversion loss.

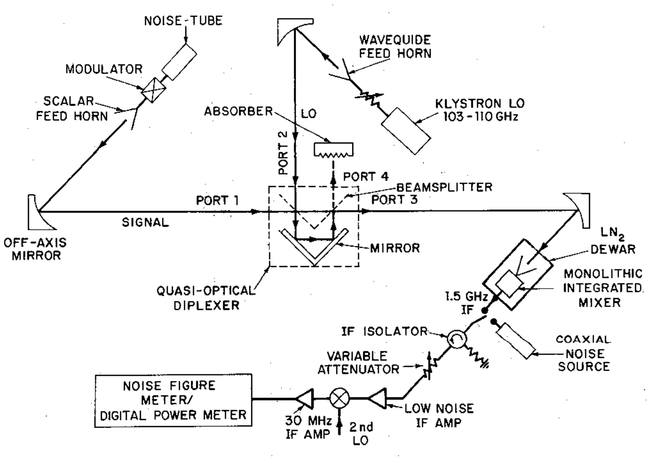

Figure 7. Quasi-optical receiver for noise figure and conversion loss measurements.

Results and Discussion

Several monolithic mixer modules have been cooled and have shown DSB mixer noise temperatures in the range 50-200 K and conversion losses of 4.0-5.0 dB. One cooled mixer module had a DSB mixer noise temperature of 50 K and conversion loss of 4.5 dB. We believe this is the lowest noise temperature ever reported for any mixer at 110 GHz. Mixer performance depends upon material quality, the presence of epitaxial material which has not been converted to high resistivity, module thickness, circuit metallization dimensions and diode parameters. Some material has shown evidence of an unconverted region extending into the original semi-insulating substrate material. Such material effectively adds an attenuating layer in front of the monolithic mixer which manifests itself in increased conversion loss and noise temperature. Cooling such material can drastically reduce the attenuation, presumably by trapping of free carriers, and produce a considerable decrease in measured conversion loss. Diodes with good room temperature performance, and presumably no unconverted layer, show little change in conversion loss on cooling in agreement with theory.

Measurements indicate that state-of-the-art mixer performance can be obtained from cooled monolithic mixers mounted in the end of a waveguide horn. The mixers are rugged and can be cycled between room and liquid-nitrogen temperatures repeatedly with no change in characteristics. The mixers have an inherently large RF bandwidth and the potential for low-cost mass production. The integrated circuit monolithic mixer is scalable to higher frequencies and should provide reliable low-loss cooled integrated mixers for the millimeter through the submillimeter wave regions.

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