A Novel Planar Diode Mixer for Submillimeter-Wave Applications

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***Abstract*—A novel mixer employing a planar GaAs Schottky diode has been designed and tested over a 300–365 GHz bandwidth at the University of Virginia (UVa). Using a planar diode eliminates the disadvantages of mechanical instability and labor-intensive assembly associated with conventional whisker-contacted diodes. The mixer design process used scale model impedance measurements both for the design of individual components and for the measurement of impedances presented to the diode terminals by the mixer mount at fundamental and harmonic frequencies. Results from these impedance measurements were then used in linear and nonlinear numerical mixer analyses to predict the mixer performance. To the best of our knowledge, this represents the first attempt at using a planar diode in a submillimeter-wave mixer, and test results indicate performance comparable with the best whisker-contacted room temperature mixers for submillimeter wavelengths.**

I. Introduction

WHISKER-CONTACTED Schottky barrier diodes have been the preferred nonlinear elements for submillimeter-wave mixers for the last two decades. Planar versions of these diodes are more rugged and reliable, and can be more easily integrated into a circuit than their whisker-contacted counterparts, but they generally have had a formidable parasitic capacitance. The planar GaAs diodes used in this work, however, have an air-channel etched through the doped material between the anode and cathode bonding pads which substantially reduces this parasitic capacitance. The fabrication [1] and testing at 100 GHz [2] of these diodes have been described previously.

This paper describes a submillimeter-wave mixer designed for these diodes. A scale model was used in conjunction with the transverse resonance, finite difference, and spectral domain numerical techniques to design the individual components. The scale model was then used to measure impedances presented to the diode terminals by the mixer mount. These measured impedances were then used in nonlinear and linear mixer analyses to determine the theoretical mixer performance for two types of diodes. The intent was to present the optimum impedance to the diode terminals for each type of diode, thereby obtaining the lowest noise temperature and conversion loss, while maintaining minimal machining and fabrication requirements.

The mixer uses a novel coupling and tuning scheme from circular waveguide to shielded microstrip. Both the microstrip probe, which is printed on a quartz substrate, and the adjustable planar waveguide short circuit, which is used to tune the probe, are fabricated using photolithographic techniques. Hence they can be fabricated accurately to very small dimensions for applications at very high frequencies. The use of this coupling scheme, rather than those previously employed for waveguide mixers, reduces considerably the machining requirements for the mixer block. A target frequency range of 300–365 GHz was chosen for the design to test its feasibility in the submillimeter-wave range. The design should be useful up to a frequency at least as high as 700 GHz, when machining of the mixer block may start to present some problems.

II. Mixer Block Design

The mixer block design is shown in Fig. 1. The planar diode, shown in Fig. 2, consists of a block of semi-insulating GaAs topped with a thin doped epitaxial layer of GaAs. Two metal bonding pads are formed on top of the epitaxial layer, with a thin metal finger connecting the anode bonding pad to the Schottky anode. A channel is etched through the epitaxial layer between the two bonding pads, which substantially lowers the parasitic capacitance of the diode. The diode is mounted face down on a quartz substrate, as shown in Fig. 2(b), on which a microstrip circuit is formed in the mixer block. The externally combined local oscillator (LO) and RF signals are coupled into a circular waveguide through a dual-mode feedhorn [3], and then onto a microstrip by a waveguide probe tuned with a planar noncontacting adjustable short circuit. A noncontacting short circuit provides a more

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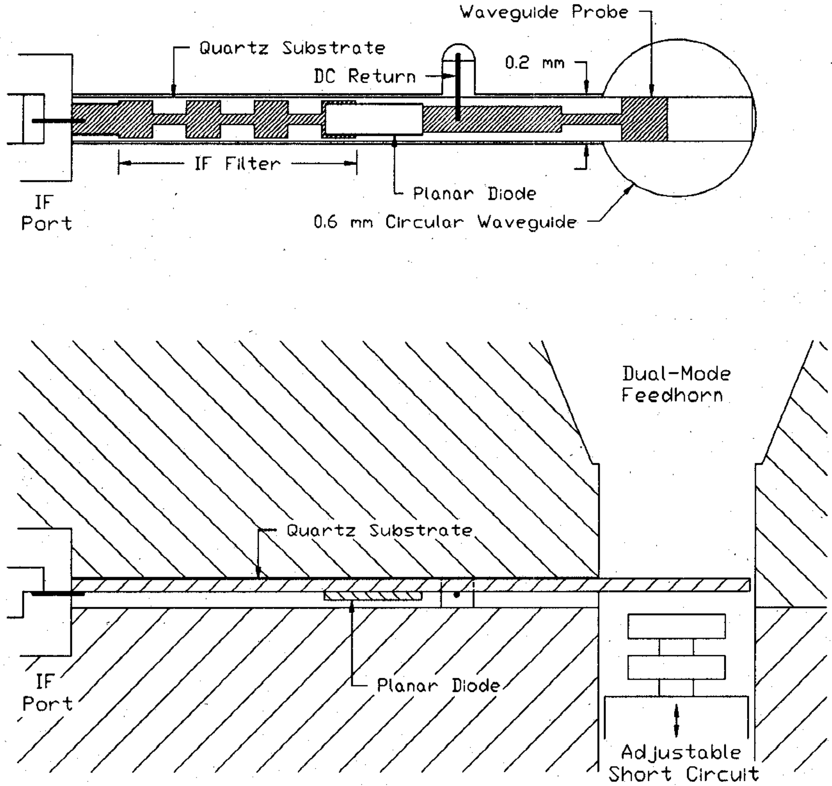


Fig. 1. Two cross sectional views of the submillimeter-wave planar diode mixer.

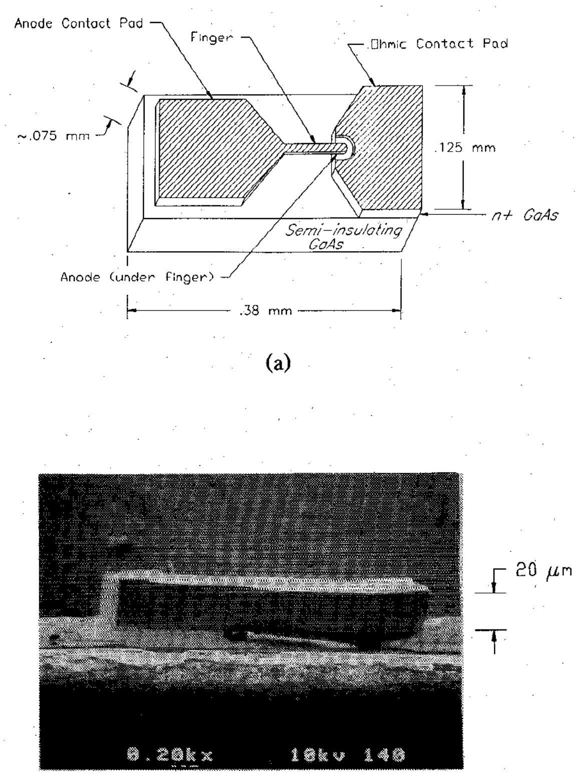
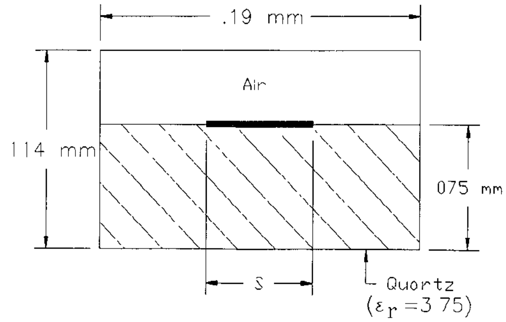


Fig. 2. (a) UVa planar diode geometry. (b) Scanning electron microscope photo of a planar diode which has been mounted face down on a quartz substrate and chemically thinned to a thickness of 0.02 mm.

repeatable short circuit than a contacting one at submillimeter wavelengths [4] and the planar version developed for this project can be accurately fabricated using photolithographic techniques. No transition to rectangular waveguide is used in the design, and no reduction in waveguide dimensions in the vicinity of the probe was found to be necessary. Using a circular waveguide and a dual-mode feedhorn allows the mixer block to be machined for use at submillimeter wavelengths but restricts the bandwidth to 25% or less. A quarter-wavelength long bond-wire connects the microstrip to ground between the diode and probe, and functions as a dc and IF return. Finally, a series of alternate high and low impedance quarter-wavelength microstrip sections between the diode and the IF port allow dc and IF power to pass through, but present nearly a short circuit in series with the diode at RF.

A. Microstrip Enclosure Design

An analysis was performed using transverse resonance and spectral domain techniques [5] to find a single mode microstrip enclosure with the largest possible cross sectional dimensions. The transverse resonance analysis was used to calculate the cutoff frequencies of waveguide modes with no metal strip present, and the more complex spectral domain technique was used to calculate cutoff frequencies with a metal strip present. Fig. 3 shows good agreement between the two analyses for narrow strips and shows the importance of using the spectral domain analysis in specifying enclosure dimensions when wide mi-



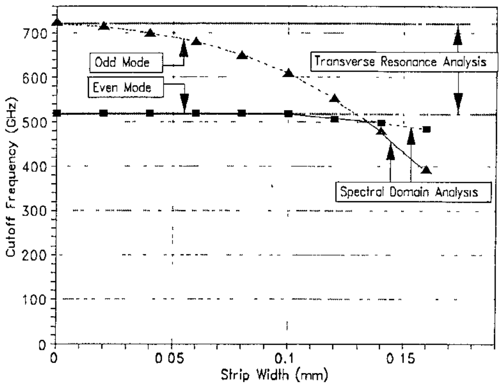


Fig. 3. Cutoff frequencies of the fundamental even and odd modes in shielded microstrip plotted as a function of strip width in an enclosure 0.19 mm wide by 0.114 mm high with a 0.075 mm thick quartz substrate.

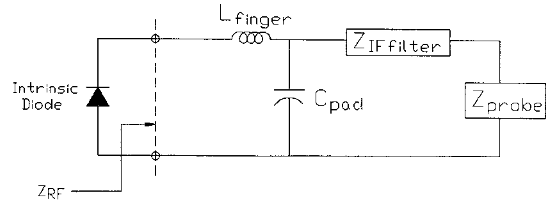


Fig. 4. RF circuit model used to obtain the impedance seen from the diode terminals. Z_{IFfilter} and Z_{probe} represent respectively the impedances of the IF filter and probe transition into the input waveguide.

crostrips are required. Cutoff frequencies are shown for two types of modes: 1) the lowest order even mode, which has a symmetric strip current distribution and becomes the LSM_{11} mode when there is no strip, and 2) the lowest order odd mode, which has an antisymmetric strip current distribution and becomes the LSE_{01} mode when there is no strip. In the present mixer, a quartz substrate of thickness 0.075 mm in a 0.114 mm×0.19 mm enclosure with a 0.16 mm wide metal strip will support only a single mode for frequencies up to 390 GHz.

Maintaining single mode propagation in the shielded microstrip region is the prime determinant of the upper frequency limit for the design. Machining and handling will limit us to a 0.05 mm thick quartz substrate and a 0.07 mm×0.135 mm enclosure, ie., a milled slot 0.135 mm wide by 0.07 mm deep. Using this geometry with a 0.11 mm wide microstrip and with the GaAs layer thinned to 10 μm using the techniques described in [6], the upper useful frequency for this design should be ~ 700 GHz.

B. Chemical Thinning of Planar Diodes

Because the diode length is approximately one wavelength in the microstrip enclosure, the diode bonding pads should be considered as transmission line segments, rather than lumped impedances. The high dielectric constant of the GaAs substrate has the undesirable effect of lowering the cutoff frequencies of higher order modes which may propagate through the diode region. However, by mounting the diode face down firmly onto a lower dielectric constant material such as quartz and etching most of the GaAs substrate from the back of the diode, the cutoff frequencies of the higher order modes were raised without compromising the physical integrity of the diode. Chemical etching has been used [6] to thin GaAs diodes to less than 5 μm thick, but a thickness of 12 μm was found to be sufficient to keep higher order modes from propagating. Before chemical etching could begin, the sides of the diode had to be covered to prevent the etchant from attacking the active material around the Schottky contact. This was accomplished with Apiezon-W black wax [7] which was thinned with the solvent, trichloroethane, to the point that, when a drop was brought into contact with the diode, it flowed around all four sides of the diode but not over its top, forming a meniscus due to surface tension. Once the wax had dried it was impervious to most peroxide GaAs etchants and, after etching was completed, the wax was removed with TCE. A mounted and chemically thinned planar diode is shown in Fig. 2(b).

III. Scale Model Design of Components

Large scale models of submillimeter-wave circuits allow measurement and optimization of the circuit using a microwave network analyzer. In scaling the dimension of a circuit by a factor S, the electrical characteristics of the circuit are shifted by $1/S$ in frequency (this is not generally true of conductor or dielectric loss). In the present work a scale factor $S = 45$ was used. The scale model design of the probe transition from the circular waveguide to the 50 Ω shielded microstrip, as shown in Fig. 1, was described in [8] and updated in [9], where the model design for the IF filter is also presented. The IF filter consists of a microstrip with alternating quarter-wavelength high and low impedance sections achieved by varying the microstrip width. Each section was shortened by 4% from the nominal quarter-wavelength to compensate for the fringing inductance associated with the abrupt change in width. Values were also obtained for the major parasitic elements associated with the planar diode geometry, namely the capacitance between the bonding pads, C_{pad}, and the inductance of the finger connecting the pads, L_{finger}. The results of the scale model measurements were used to derive values for the RF circuit model

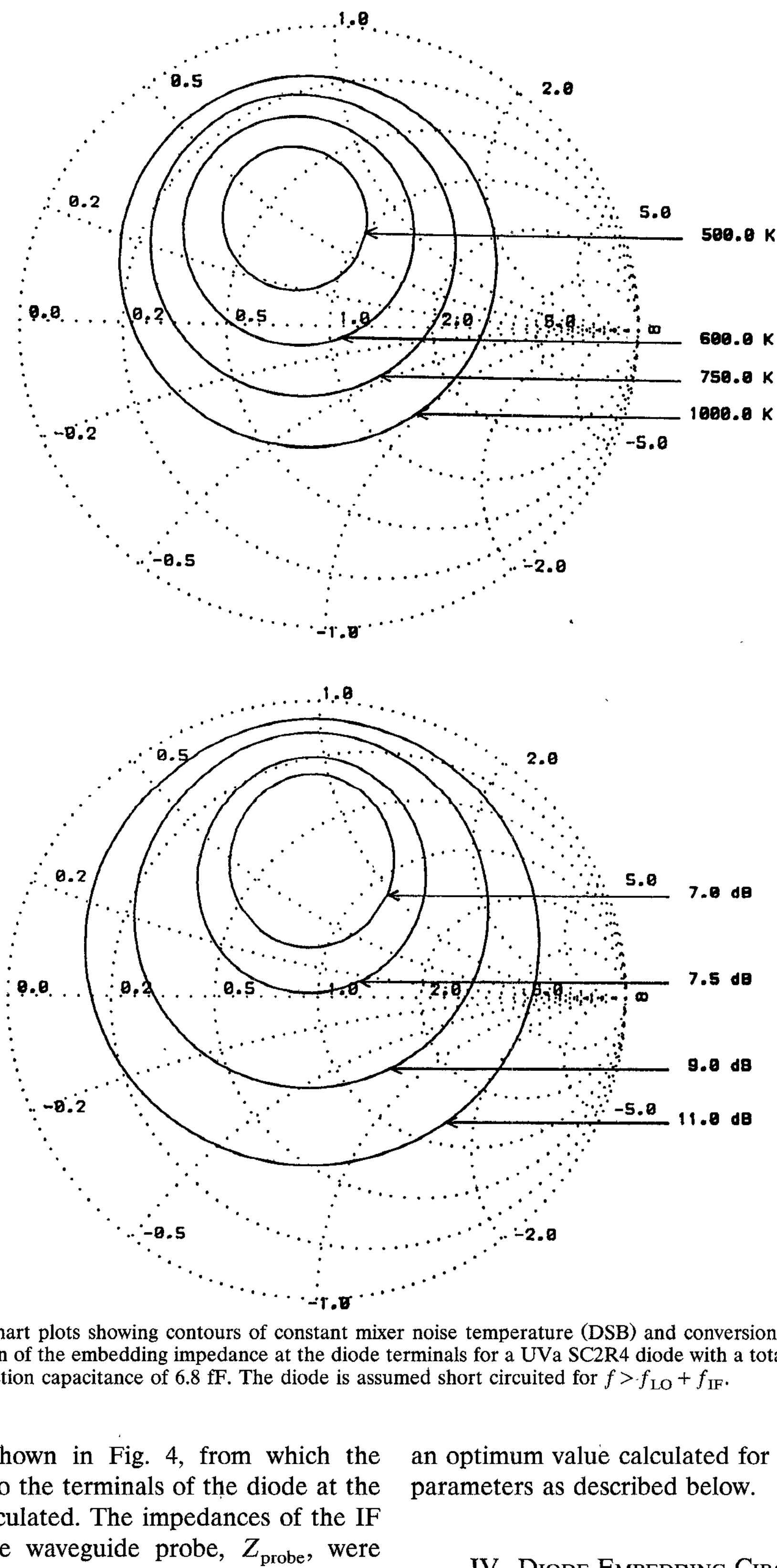


Fig. 5. Smith chart plots showing contours of constant mixer noise temperature (DSB) and conversion loss (SSB) at 345 GHz as a function of the embedding impedance at the diode terminals for a UVa SC2R4 diode with a total series resistance of 13 Ω and junction capacitance of 6.8 fF. The diode is assumed short circuited for $f > f_{LO} + f_{IF}$.

of the mixer block, shown in Fig. 4, from which the impedance presented to the terminals of the diode at the RF, Z_{RF}, could be calculated. The impedances of the IF filter, $Z_{IFfilter}$, and the waveguide probe, Z_{probe}, were modified to account for the transmission line length of the diode bonding pads and microstrip lines in front of these elements. Adjustments were made to the circuit elements by varying the diode geometry i.e., changing L_{finger} and C_{pad}, and by changing the length of the microstrip transmission line between the diode and the IF filter. In this way the design was tuned to match Z_{RF} to an optimum value calculated for a set of measured diode parameters as described below.

IV. Diode Embedding Circuit Optimization

Providing the correct embedding impedance, Z_{RF}, seen from the intrinsic diode terminals is of primary importance in mixer design. The analysis method described in [10], [11] was employed for calculating mixer noise temperature and conversion loss as functions of Z_{RF}. This analysis includes the effects of nonlinear diode junction

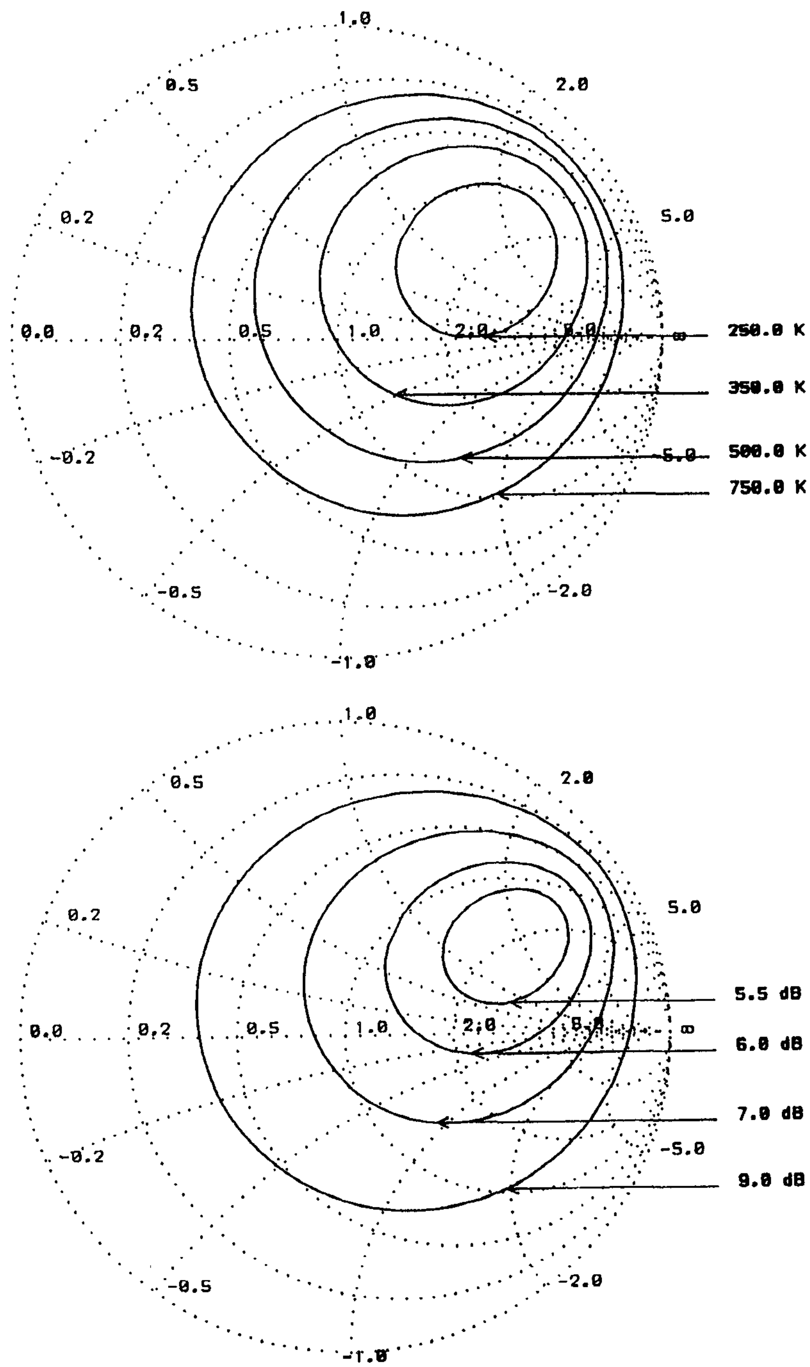


Fig. 6. Smith chart plots showing contours of constant mixer noise temperature (DSB) and conversion loss (SSB) at 345 GHz as a function of the embedding impedance at the diode terminals for a UVa SC2T1 diode with a total series resistance of 23 Ω and junction capacitance of 2.4 fF. The diode is assumed short circuited for $f > f_{LO} + f_{IF}$.

capacitance and resistance as well as shot and thermal noise generated in the diode. For analysis purposes, the diode was assumed to be terminated with short circuits at the LO harmonics and at harmonic sidebands, $nf_{LO} \pm f_{IF}$. Also the fundamental sideband impedances, $Z_{RF}(f_{LO} \pm f_{IF})$, were assumed equal, and the IF load impedance was assumed perfectly matched to the IF port. Figs. 5 and 6 show Smith chart plots of calculated contours of constant mixer noise temperature (double sideband, DSB) and conversion loss (single sideband, SSB) over all possible values of Z_{RF}. The analysis was performed at a frequency of 345 GHz for two UVa diode types designated as SC2R4, which has a 2.5 μm anode diameter, and SC2T1, which has a 1.5 μm anode diameter. The SC2R4 diodes have a dc series resistance of 8 Ω and zero-bias junction capacitance of 6.8 fF, and the SC2T1 diodes have a dc series resistance of 15.5 Ω and zero-bias junction capacitance of 2.4 fF. An additional series resistance calculated in [12] was added to account for the skin effect in the GaAs chip at 345 GHz, which amounts to 5 Ω for the SC2R4 diodes and 7.5 Ω for the SC2T1 diodes. It is seen that the lower junction capacitance SC2T1 diodes have less noise and higher conversion efficiency than the SC2R4 diodes.

The element values needed to produce an optimum embedding impedance, Z_{RF} in Fig. 4, for a particular type of diode were then determined. A 50 μm finger length between diode bonding pads was found necessary for both diode types. The cathode bonding pads of the SC2R4 diodes (used as the first low impedance section of the IF filter) were reduced from 0.10 mm to 0.035 mm to give the desired impedance of 30+j40 Ω. This was accomplished by trimming the length of the bonding pad with a dicing saw. No such modification of bonding pad length for the SC2T1 diodes was required to give the desired impedance of 110+j115 Ω.

To verify that the impedance presented to the diode terminals was equal to that calculated from the RF circuit model at both the fundamental and higher harmonic frequencies, measurements were made on the mixer scale model. Scale models used to design individual mixer components (i.e., IF filter, waveguide probe, and dc return) were constructed in a modular fashion to allow subsequent coupling together for assessment of the interactions between them. The technique of Eisenhart and Kahn [13] was used in which a miniature coaxial cable was positioned to run into the model as the dc return line and then along the microstrip to the gap between the diode bonding pads. The outer conductor of the cable was soldered to the microstrip up to one bonding pad and its inner conductor was soldered to the other bonding pad. No actual diode was used. A network analyzer was then connected to the coaxial cable with the reference plane extended to the end of the coaxial shield (the position of the diode junction in the actual mixer), and measurements were made of Z_{RF}. After making a correction to the measured data to account for a difference in the capacitance of the opened coaxial line and the capacitance of the junction region of the mounted diode, good agreement (within 10 Ω) was found between Z_{RF} calculated from the RF circuit model and Z_{RF} measured directly from the mixer scale model. Impedances at the second and third harmonic frequencies were then measured and the mixer analysis in [11] was carried out to determine their effects on the conversion loss and noise temperature. This analysis revealed that the impedances at frequencies above the fundamental play a relatively minor role in this mixer's performance. In the worst case, with the impedances at the second and third harmonics representing 50 Ω terminations, there is an increase of approximately 1 dB in noise temperature and conversion loss over the values shown in Figs. 5 and 6 which were calculated with these impedances as short circuits.

V. Mixer Performance

The mixer block was constructed of brass in two 0.25 × 1.0 × 1.0 inch halves. Details on the construction are described in [14]. Noise temperature and conversion loss of the mixer were measured from 300 to 365 GHz at room temperature for two types of diodes, SC2R4 and SC2T1. The measurement arrangement is shown in Fig. 7. A carcinotron [15] was used as the LO and a Martin–Puplett interferometer was used as a quasioptical diplexer [16], [17]. Noise temperature and conversion loss measurements were made with room temperature and liquid nitrogen temperature black body sources. The 1.4 GHz IF portion of the test system is similar to that used in [2]. Optimal LO pumping was found to be obtained at about 1.4 mW measured at the mixer feedhorn position with a quasioptical power meter [18], and optimal dc biasing was obtained for both diodes at about 0.8 V and 1.5 mA. Fig. 8 shows the typical relation between noise temperature (DSB) and LO power. The mixer response in both sidebands was assumed equal in calculating the SSB conversion loss. A 3:1 IF impedance transformer was used to match the IF output impedance to the IF test system. The IF mismatch factor was calculated from measurements on noise power reflected at the IF output, and was used to correct the measured mixer performance data. Additional corrections were made to the data to account for a 0.4 dB RF optical path loss due to the teflon lens, and for the discrepancy of 8° K between Planck's radiation law and the Rayleigh–Jeans approximation at 345 GHz in specifying the power radiated from the black body sources.

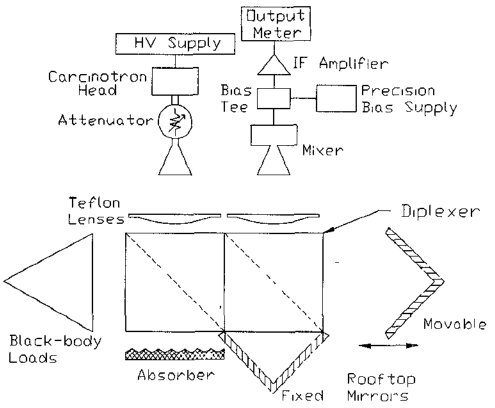


Fig. 7. Measurement set-up for 300–360 GHz mixer.

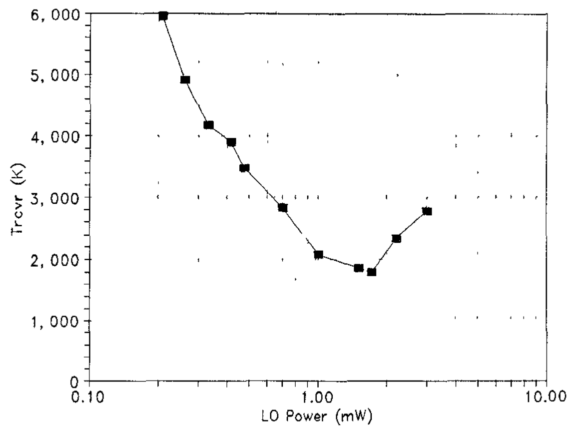


Fig. 8. Typical relation between noise performance (DSB) and LO pump power.

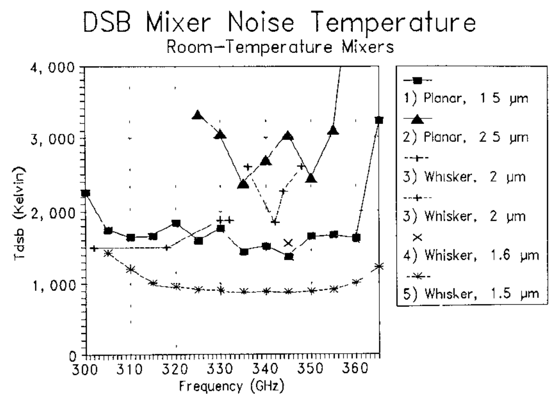


Fig. 9. Double sideband mixer noise temperature for the planar diode mixers using 1) SC2T1 diodes and 2) SC2R4 diodes. Also shown are mixer noise temperatures for other room-temperature Schottky barrier diode mixers: 3) two mixers using diodes with ~ 2 μm anodes [20]; 4) a mixer using a diode with a 1.6 μm anode [21]; and 5) a mixer using a diode with a 1.5 μm anode [22].

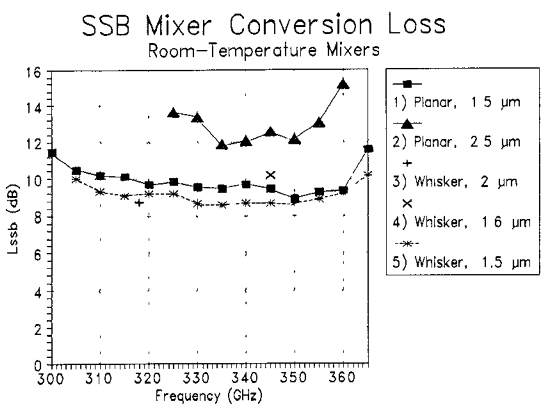


Fig. 10. Single sideband conversion loss for the planar diode mixers using 1) SC2T1 diodes and 2) SC2R4 diodes. Also shown are conversion losses for other room-temperature Schottky barrier diode mixers: 3) two mixers using diodes with ~ 2 μm anodes [20]; 4) a mixer using a diode with a 1.6 μm anode [21]; and 5) a mixer using a diode with a 1.5 μm anode [22].

Figs. 9 and 10 show the noise temperature and conversion loss of the mixer measured at room temperature. The difference between the SC2R4 diode mixer and the SC2T1 diode mixer is about 900 K in noise temperature and 2.5 dB in conversion loss. The tunable bandwidth is much wider for the SC2T1 diode mixer due to the compensation technique used to impedance match the SC2R4 diode mixer. This resulted in a larger variation in IF filter impedance over frequency. At 345 GHz the SC2T1 diode exhibits an equivalent input noise temperature of 1370 K DSB and a conversion loss of 9.5 dB SSB. The mixer shows a useful tunable frequency range of over 20%. Both mixers exhibit about 5 dB higher noise temperature and conversion loss than the theoretical optimum values shown in Figs. 5 and 6. Up to a 1 dB increase is expected from the non-zero impedance of the higher order harmonics. An additional ~1 dB increase is due to losses in the waveguide and microstrip. A further ~1 dB increase is due to the noise contribution from the LO at the signal and image frequencies. The remaining discrepancy is probably due to the omission of hot electron noise, intervalley scattering, and high frequency transport effects in the theoretical analysis [19]. Also shown in Fig. 9 are some of the best room-temperature mixer results reported for this frequency range [20]–[22]. These earlier results were obtained with whisker-contacted diodes in substantially different mounts, all using UVa diodes. These results show that the performance of the planar diode mixer is comparable with the best room temperature whisker-contacted diode mixers.

VI. Conclusion

Numerical analyses and scale model measurements have been combined effectively to yield a useful, rugged submillimeter-wave mixer design whose performance at 300–365 GHz is competitive with the best whisker-contacted type mixers made to date. This marks the first time a submillimeter-wave mixer has been designed and tested using a planar diode. The mixer block design is scalable to ~ 700 GHz with the same machining techniques used here for 365 GHz.

Acknowledgment

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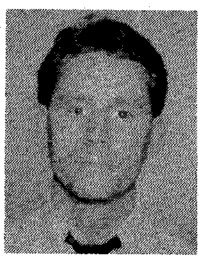

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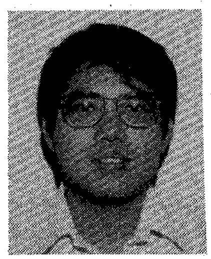

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