A 94 GHz BALANCED MIXER USING SUSPENDED SUBSTRATE TECHNOLOGY

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ABSTRACT

A 94 GHz balanced mixer has been developed using suspended substrate technology and advanced GaAs Beam Lead Diodes. The mixer, using a waveguide hybrid and a novel waveguide to suspended stripline transition exhibits average conversion loss of 6.5 dB and a 5.6 dB DSB noise figure including the IF contribution.

Introduction

A room temperature mixer has been designed and tested in the 91-97 GHz frequency region. This mixer, employing GaAs beam lead millimeter wave mixer diodes is easily mass produced and exhibits state of the art sensitivity over wide instantaneous bandwidths. The prototype mixer reported here, and subsequent production versions based on this technology are desirable in many applications in the 2-4 mm wavelength region. The mixer was developed through a simultaneous design of the surface-oriented millimeterwave diode[1], the low-frequency modeling of the suspended substrate used in the RF embedding network, and concurrent development of production processing technologies allowing for accurate scaling of the optimized design to frequencies in the millimeter-wavelength range.

A balanced configuration was chosen for the design to reduce the added noise contribution of typical millimeter wavelength local oscillators, and allows achievement of low overall noise temperature without the use of L.O. Injection filters. Additionally, the balanced configuration allows for a nearly constant 50Ω IF output impedance providing an optimum match to a variety of IF amplifiers. Typical conversion loss of 6 dB with an associated system noise temperature of 762°K DSB including a 170°K IF contribution at 1.0 GHz can be achieved in this design. Instantaneous IF bandwidths of greater than 900 MHz can be obtained.

Design Criteria

In order to make the 94 GHz realization of the suspended substrate mixer applicable to use in many different systems, it was decided at the onset that a broadband design based on the use of scale modeling techniques would be most likely to produce the desired results. It was felt important that a mixer developed using this technology would exhibit the following characteristics deemed desirable for systems applications:

- The mixer would achieve a SSB conversion loss of 6 dB and a SSB noise figure of less than 8 dB including a reasonable IF amplifier contribution. In addition, this noise figure would be available over at least a 1 GHz instantaneous IF bandwidth
- The mixer would be a balanced configuration providing a 50Ω IF output and needing 5-10 mW of local oscillator drive without an injection filter.
- The mixer would be virtually indestructible in severe environments, and could be reproduced in systems quantities at a very low cost per piece.

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All of the above goals were met using suspended stripline transmission line in a combination of computer aided design, empirical modeling and refinement of low frequency scaled models, and careful scaling of the design to the actual operating frequency region.

Low Frequency Model Studies

A low frequency scaled model, operating in the 2-4 GHz range was built in the laboratories of the Five College Radioastronomy Observatory, Amherst, MA. This model, was used to aid in the design of the various mixer elements. Two distinct elements were designed separately: The waveguide-to-stripline transition and the diode embedding network including the low-pass filter for the IF.

An ideal waveguide-to-stripline transition should have low loss and a wide instantaneous bandwidth. A ground return for the D.C. and I.F. was also needed, since the diodes are series connected in the stripline. The diode embedding network was experimentally optimized by adjusting the distance between the diode and a previously optimized cascaded quarter-wave lowpass filter. These elements, parts of the single-ended mixer configuration, used in the low frequency model studies are illustrated in Figure 1. As is evident, the quartz substrate passes through the upper and lower broad wall of the waveguide. After a short distance below the plane of the lower wall, a cascaded high-impedance/low-impedance low pass filter provides an RF short for the transition. Beyond this filter a ground tab supplies the IF and DC termination. The exact filter location, the conductor width and backshort position were independently varied to maximuze the return loss over a broad RF bandwidth.

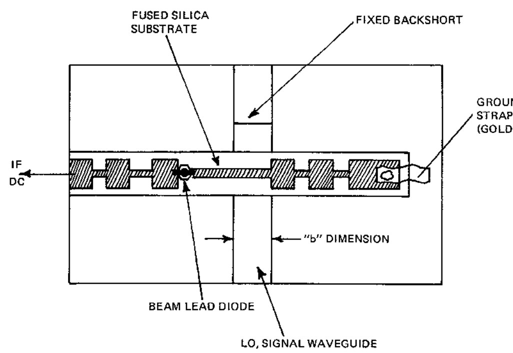

FIGURE 1 PROTOTYPE MIXER CONFIGURATION

Additionally, in Figure 2, we show the return loss from the waveguide-to-stripline transition, with the strripline terminated in a matched load. The return loss is greater than 10 dB from 2.8 to 3.9 GHz which corresponds to 75 to 105 GHz in a properly scaled mixer. It is noteworthy that this transition is accomplished using full height waveguide and a fixed backshort position.

Once in the stripline channel, the characteristic impedance is 100Ω with the diode series-connected in the line. A second low pass filter is located beyond the diode followed by the IF output port. Again, the exact location of the diode with respect to the leading edge of the second low pass filter was optimized, this time with respect to conversion loss.

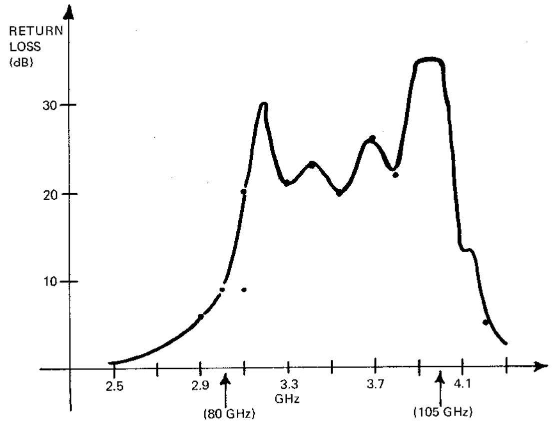

FIGURE 2 PERFORMANCE OF W/G-STRIPLINE TRANSITION – A FIXED BACKSHORT AND FULL HEIGHT WAVEGUIDE IS USED IN THIS DESIGN

The conversion loss for a fixed backshort position optimized at 3.5 GHz (93 GHz) is illustrated in Figure 3. The SSB conversion loss is seen to be 5.75 ± 0.25 dB over a 0.5 GHz (13 GHz at 94 GHz) bandwidth. This predicted loss takes into account the degredation due to the higher skin effect losses expected at millimeter wavelengths. Although all other aspects of the mixer design were faithfully scaled, the conductor resistivity was not, since copper sensing tape was used throughout these model studies.

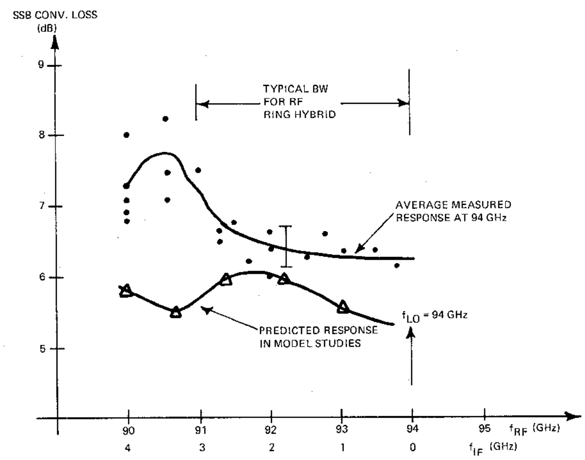

FIGURE 3 CONVERSION LOSS OF 94 GHz PROTOTYPE AND SCALE MODEL STRUCTURE

Millimeter Wave Performance

Several prototype 94 GHz balanced mixers were built and evaluated, using a 4 port ring hybrid. The hybrid operates as an in-phase/out-of-phase 3 dB power divider over a ±3 GHz bandwidth. The suspended stripline substrates are located in two arms with backshorts terminating the waveguide. Figure 4 shows the hybrid, with substrates, diodes and backshort. Tuneable backshorts are used in this prototype design, but it was found that a unique matching position exists over the 5-6 percent bandwidth defined by the ring hybrid, making adjustable shorts unnecessary in production units. The top half of the split block is not visible in this view.

The diodes, having C_{jo} = 0.008 pfd, $C_p \sim$ 0.010 pfd and R_s (DC) ≅ 4Ω were mounted on the fused silica substrates with opposite polarities. A small section of coaxial line connected the output of the low pass filter to a microstrip circuit on the back side of the split block. There each diode was individually DC biased with the IF outputs paralleled. No attempt was made to do any IF matching on the microstrip.

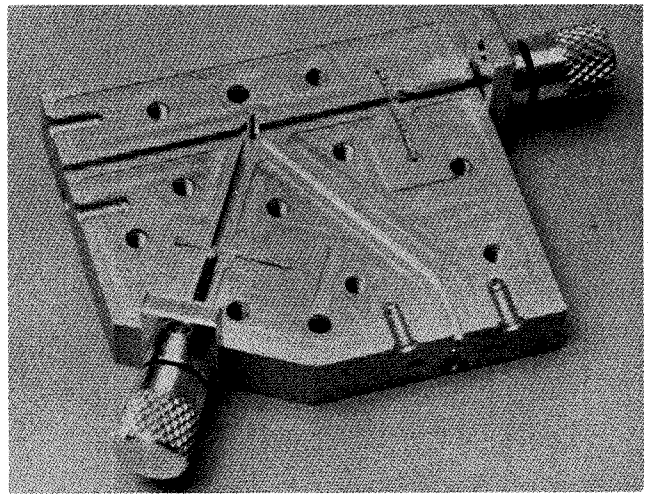

FIGURE 4 PHOTOGRAPH OF PROTOTYPE STRUCTURE

Two types of measurements were made. First, SSB conversion loss measurements were obtained with a tuneable IMPATT sweeper as signal source, attenuated to approximately -15 dBm. The SSB conversion loss as a function of signal frequency is shown in Figure 3. A triple stub tuner was used to minimize the conversion loss at each signal frequency. Typical errors for any single data point are at least ±0.25 dB. The average conversion loss is seen to be ~6.5 dB. These data should be considered typical, as optimization of the mixer at one frequency often lowers the conversion loss by 0.5-0.7 dB. The LO to RF isolation was measured to be 23 dB at a LO frequency of 94 GHz.

Second, a horn antenna was placed on the signal port and pieces of lossy dielectric at 295K and 77K served as broadband thermal sources. Y-factor measurements were taken. Additionally, by calibrating the IF system, the double sideband system temperature, double sideband conversion loss and mixer noise temperature could be calculated. The method and definitions of mixer noise parameters as described by Carlson[2] were used throughout. These results, summarized in Table I along with data on other room temperature mixers operating near 94 GHz, clearly establish the use of suspended substrate technology as an important and useful approach to the realization of millimeter wave low noise downconverters. In Appendix I we outline details of the measurement system and noise calculations.

TABLE 1

Conversion Loss and Mixer Noise Temperature of Various Mixers in the 70-110 GHz Range

	F(GHz)	SSB L_c	T_m(K)†	F_R (dB)	IF Freq.
THIS DESIGN (TRG)	94	6.0	760 ± 50	5.6 (DSB)	.75-1.5 GHz
Linke[3] (BTL)	72	6.2	700	--	4.5-5.0
Zimmerman and Haas[4] (MPIfR)	112	6.1	760		
Kerr[5] (NRAO)	85	4.6	420		1.4
Schneider[2] (BTL)	94	6.5	710 ± 60	7.8 (SSB)	1.4
Kramer[6] (HAC EDD)	94	–	–	6.5 (DSB)	0.1-0.7

†T_m is SSB Intrinsic Mixer Noise Temperature

There are several aspects of this prototype mixer which are not optimum. Excess loss of 0.9 dB due to the ring hybrid, unnecessary IF line lengths and an unmatched IF combining network can be reduced in production versions by using a folded tee hybrid and a more efficient IF combining circuit. SSB conversion loss of 5.0-5.5 dB, a mixer temperature of less than 500K and RFand IF bandwidths of 10 GHz and 1 GHz respectively should be attained at 94 GHz.

Environmental Reliability

The prototype mixer has been subjected to various environmental tests to determine the overall reliability of the suspended substrate medium. These tests, summarized in Table II demonstrate the reliability and applicability of this medium to operation in severe environmental conditions.

TABLE II

Environmental Testing Done on Suspended Substrate Mixer

TEST	STANDARD
VIBRATION	MIL-E-5400N Figure 2 curve Ia 3 axes
SHOCK	MIL-E-5400N 3 axes 30 g
TEMPERATURE	Cycling from 77K to 400K ten times. Shock Cooling through rapid immersion in LN_2
CW RF POWER	150 MW Continuous RF Power Input for 168 hours continuous
PULSED RF POWER	1.5 Watts 50 nsec 40 KHz (Pulsed Impatt Transmitter) for 168 hours continuous

At the conclusion of these tests, the mixers exhibited no measurable degradation in noise figure or conversion loss.

Conclusion

The use of advanced beam-lead diodes coupled with quality manufacture and careful scientific design have allowed the realization of a high quality millimeter wavelength mixer for commercial applications. The prototype mixers described in this paper have demonstrated both low noise performance and a high degree of reliability for application at frequencies in the short millimeter portior of the spectrum. They are designed for mass-production, and form an important adjunct to advances made in recent years in solid-state power generation and transmission. The system designer can now apply the optimum performance of these devices to many emerging radar and communications applications. Most importantly, the use of advanced beam-lead diodes, eliminates the costly and labor intensive steps associated with diodewhiskering in pervious designs.

Acknowledgement

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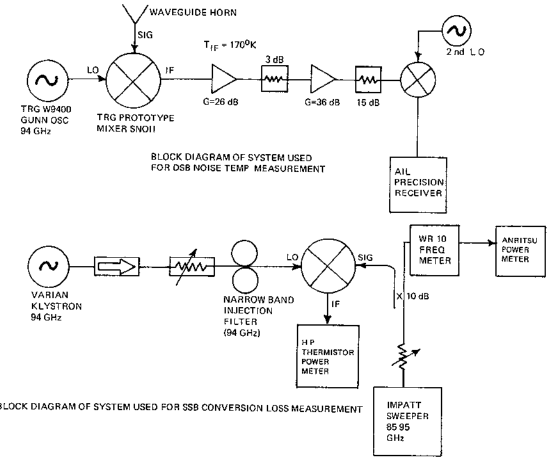
APPENDIX I

Noise Measurements & Calculations



$$\langle T_R \text{ (DSB)} \rangle = 762\text{K}$$
$$\langle L_{SIG} \rangle = 6.5 \text{ dB}$$
$$\langle L_{image} \rangle = 6.5 \text{ dB}$$
$$T_{IF} = 170\text{K}$$

therefore

$$T_R \text{ (SSB)} = (1 + \frac{L_s}{L_i}) [T_R \text{ (DSB)}] = 1524\text{K}$$

$$T_M \text{ (SSB)} = T_R \text{ (SSB)} - (L_{signal}\, T_{IF}) = 765^{\circ}\text{K}$$

where we have assumed

$$T_R \text{ (DSB)} = \frac{290\text{K} \cdot \text{Y (77K)}}{\text{Y-1}}$$

and

Y is the measured Y factor expressed as a ratio

References

1. Cardiasmenos, A.G. "New Diodes cut the cost of Millimeter Wave Mixers" MICROWAVES September 1978 pp. 78-88

2. Carlson, E.R., M.V. Schneider and T.F. McMaster "Subharmonically Pumped Millimeter-wave mixers" IEEE Transactions on MTT Vol. MTT-26 pp. 706

3. R.A. Linke, M.V. Schneider in workshop on mixers for millimeter wavelengths Max Plank Institut fur Radioastronomie, Bonn April 26-28 1977

4. P. Zimmerman and R. Haas "A broadband Low noise mixer for 106-116 GHz" Nachrichtentech Z Vol 30 pp. 721-722 September 1977

5. Kerr, A.R. "Low noise room temperature and Cryogenic mixers for 80-120 GHz" IEEE Transaction on MTT MTT-23 pp. 781-787 October 1975

6. Kramer, N.B. "Millimeter wave semiconductor devices" IEEE Special Issue Vol MTT-24 Number 11 pp 658-692 November 1976