LOW CONVERSION LOSS MILLIMETER WAVE MIXERS

Lawrence E. Dickens
Westinghouse Defense and Electronic Systems Center
Baltimore, Maryland 21203

Abstract

To be reported in this paper are new results obtained for mixers in the frequency range up to 95 GHz. Both frequency diplexer types of mixers and those which utilize a standard directional coupler for LO injection will be discussed. The mixers use a replaceable wafer type diode holder. The replaceable wafer contains a unique Westinghouse developed double diode structure which results in very low RF losses. The diode is a GaAs Schottky barrier with zero bias frequency cut-off of over 800 GHz. Theoretically predicted values of conversion loss under 5.0 dB are attained over the frequency range.

Summary

In 1971, there was reported[1] by Westinghouse the development of a mixer and solid state LO for a 60 GHz receiver. The conversion loss of 5.0 dB therein reported represented the state-of-the-art at that time. This paper will contain the results of the continuing effort at Westinghouse to utilize the GaAs Schottky barrier and to realize the full potential of the GaAs devices.

Schottky barrier diodes are particularly advantageous for applications involving millimeter waves because of the simplicity of their fabrication. A single evaporation or electroplating operation, performed through a suitable mask, will define the active area and provide the metallic surface for lead contact. The high mobility of GaAs has made possible the design of diodes with active regions of extremely low resistance. The design and fabrication of the semiconductor element follows closely the approach previously reported[1-4] and has resulted in GaAs diodes with a varactor frequency cutoff of nominally 800 GHz, as measured at zero bias and with a measurement frequency of 70 GHz.

The diode is a planar, SiO_2 passivated device. The chips used in the wafers are .015" x .015" x .004" and have an array of 4.0 micron diameter junctions spaced on 8.0 micron centers. The junction capacitance at zero bias is nominally .03-.04 pf and the series resistance falls in the range of 5-7 ohms. The diode package developed represents one successful approach to the realization of a replaceable diode for millimeter wave mixer applications which fully utilizes the benefits of the planar passivated Schottky barrier junction.

The mixer consists of a small metallic wafer, in which are embedded the semiconductor diodes, the waveguide mount used to couple the diode wafer to the signal circuit, an RF tuning element, and a 3 mm. coaxial connector for the IF output terminal. Figure 1 is a photograph of a mixer mount for RG-98/U with the wafer diode in place. The cross-sectional dimension is that of the waveguide flange (19 mm. x 19 mm., 0.75" x 0.75"), the overall length is nominally 25 mm. (1.0").

This component is to be used as a single ended RF mixer with replacement wafers which can be installed as necessary in the field without unreasonably complex procedures, tests or equipment. This mount can be used with a simple directional coupler for LO injection or with a frequency diplexer when the LO losses of a coupler are not wanted. Figure 2 shows a photograph of a complete mixer for a 50 GHz application. In the figure is seen an RF bandpass filter, a directional filter and the mixer body. The combined insertion loss of the bandpass and directional filters is under 0.5 dB over a 2 GHz RF band. The IF port is matched better than 2:1 over the IF band 2.0-4.0 GHz <u>without</u> any special IF transformers and only by virtue of the unique double diode structure. The basic double diode structure, shown more clearly in Figure 3, is used for the advantage that it virtually eliminates RF signal and LO leakage out of the IF terminal without resorting to bypass capacitors or chokes which limit the IF band, and that a better inherent impedance match is obtained at both the RF and IF terminals. The tuned RF impedance of a typical diode (single junction) is about 160 ohms under the usual mixer operating conditions, and the IF impedance is about 90 ohms. For this double diode configuration, the two diodes are in series to the RF and thus yield a good match to the waveguide impedances. But the two diodes are in parallel to the IF yielding an effective impedance of 45 ohms which is a good match to the IF output coax. As the match to the RF and IF is simultaneously obtained, no transformers are needed. As no impedance transformer is required on the IF port, the IF terminal represents no problem on bandwidth.

This type of dual diode mixer has been developed and extensively tested in mounts designed for operation at 50, 60, 70 and 95 GHz. The 95 GHz mixer was developed for use in a 95 GHz radiometer receiver. The conversion loss, in each case, is measured by use of a klystron local oscillator for the LO, and a BWO for the sweep signal generator. A waveguide level set attenuator followed by a precision (rotary-vane) attenuator is used to obtain a precise and controllable power level. A TRG Water Calorimeter is used as an absolute RF power indicator. A General Microwaves, Thermoelectric Power Meter is used to measure the IF power. Calibration was performed before and after each measurement to ensure accuracy.

Figure 4 presents the measured results for several 95 GHz diodes. Therein is shown the range of conversion loss as a function of LO power. The plotted conversion loss includes all mount RF and IF losses. The shaded range represents that range into which fell 95% of the data taken on nine separate mixer diode wafers. The curves for eight of the nine wafers fell completely within the given area. The initial tuning was done at an LO power level of +5 dBm. The bias was optimally set and the waveguide (RF) tuner was adjusted. Then the LO power was varied and the bias adjusted for minimum conversion loss; the RF tuner was not readjusted at each LO power level. Notice that at the LO power level of about +11 dBm, the conversion loss of all nine wafers tested fell within 5.3 ± 0.5 dB.

The theoretical limitations of these diodes as developed from GaAs, and the limitations that would exist if comparable processing technology were utilized to make silicon mixer diodes can be seen from the following considerations. Reliable passivated Schottky barrier diodes can be made from GaAs that can have a frequency cutoff, f_{co}, as measured at zero bias of about 800 GHz. Without the use of very special (any very expensive) techniques such as ion implantation, one is limited to an $f_{co} \cong 250$ GHz at zero bias for silicon Schottky barrier diodes of similar dimensions.

Barber[5] has presented an analysis of microwave mixers and has shown that the pulse duty ratio (PDR) of the Schottky diode current waveform is the most fundamental parameter for defining mixer operations because the diode current pulse retains its typical (switched) shape even when the voltage waveform becomes highly nonsinusoidal.

It can be shown that most microwave mixer diodes (adjusted for lowest conversion loss) behave as though the barrier itself were switched on and off at the LO rate; and that the resistance in the ON state is just that of the limiting series resistance (R_s), and the impedance in the OFF state is just that expected of the series resistance, R_s, in series with the barrier capacitance, C_b. Of course the barrier capacitance is a function of voltage and time, but good correlation with measured results are obtained if the zero bias capacitance value is used. Thus, the frequency cutoff is $f_{co} = (2\pi R_s C_b)^{-1}$; and takes the 800 GHz and 250 GHz values for GaAs and Si as given above.

Using these considerations, an extension of Barber's analysis has allowed the calculation of the conversion loss as a function of the PDR and as limited by the operating frequency to cutoff frequency ratio (f/f_{co}). Figure 5 shows the expected mixer conversion loss that would obtain for the broadband case (wherein the image termination equals the signal termination). Figure 6 shows the computed mixer conversion loss for the case wherein the image is short-circuited.

To understand the effects of f_{co} more clearly, we compute the performance expected both for an X-band image enhanced case[6] (shorted image) and the 60 GHz broadband case; computed both for GaAs and silicon. Now with GaAs at X-band (10 GHz) the $(f/f_{co}) \cong 0.0125$ and taking a PDR $\cong 0.15$ (a reasonable value which keeps the terminal impedance low enough to handle) then the conversion loss, L_c, takes a value of 2.4 dB which is very close to the measured value. With Si, $(f/f_{co}) \cong 0.04$ and with the same PDR, $L_c \cong 2.7$ dB - only a 0.3 dB difference.

However, at 60 GHz, the results diverge appreciably. With GaAs, $(f/f_{co}) \cong 0.075$; and taking a PDR $\cong 0.2$, the broadband mixer conversion loss is about 4.9 dB which is about as measured. With Si, $(f/f_{co}) \cong 0.24$; and taking PDR $\cong 0.3$ (at which PDR minimum L_c obtains), a conversion loss of 8.0 dB minimum is found. Now a 3.1 dB difference is encountered.

Note that in figures 5 and 6, minima occur in the curves of L_c vs. PDR. Figure 7 presents the minimum mixer conversion loss for both the image shorted and image terminated cases as a function of f/f_{co}. Note that with GaAs at 60 GHz there is a possible 1.6 dB improvement in L_c by using image enhancement techniques (i.e., $L_c \rightarrow 3.3$ dB). For the silicon diodes, only an 0.8 dB improvement is possible (i.e., $L_c \rightarrow 7.2$ dB) which does not even get the image enhanced value down to the broadband value for GaAs.

Noise figure of the single-ended mixer was measured at 60 GHz (IF of 1-2 GHz) and for several mixer diodes. The results of this test and others confirm the fact that the mixer noise figure is essentially that due to the conversion loss, and hence, that the noise ratio of the mixer (t_m) is close to unity. That the f_{co} of 800-1000 GHz has been attained has been well demonstrated by these results herein presented and further supported by the fact that similar GaAs diodes have been used in the varactor mode in a parametric amplifier application for which paramp[7,8] was obtained an uncooled excess noise temperature of 62°K (0.85 dB noise figure).

Acknowledgments

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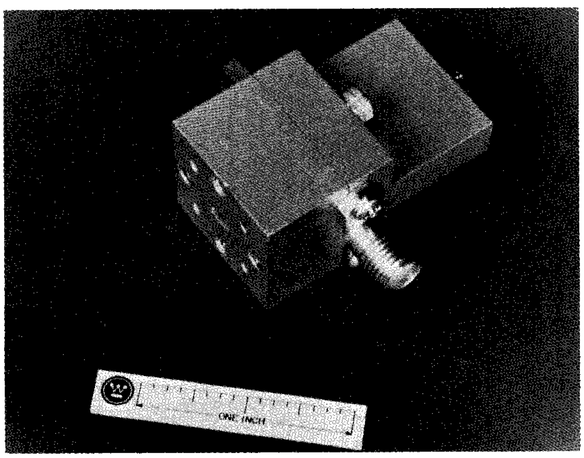

FIG. 1: Mixer Mount for RG-98/U Applications

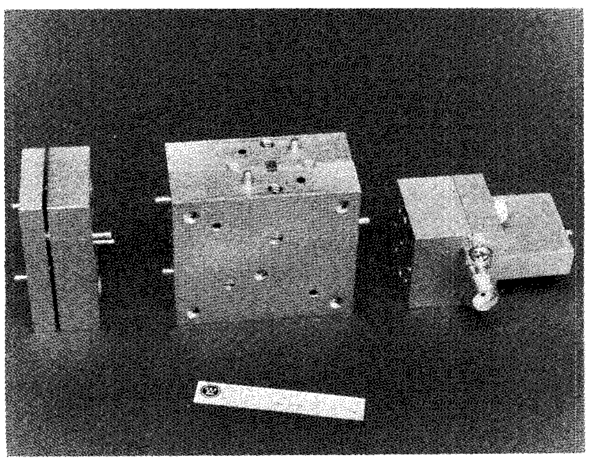

FIG. 2: Complete 50 GHz mixer with frequency diplexer and signal bandpass filter.

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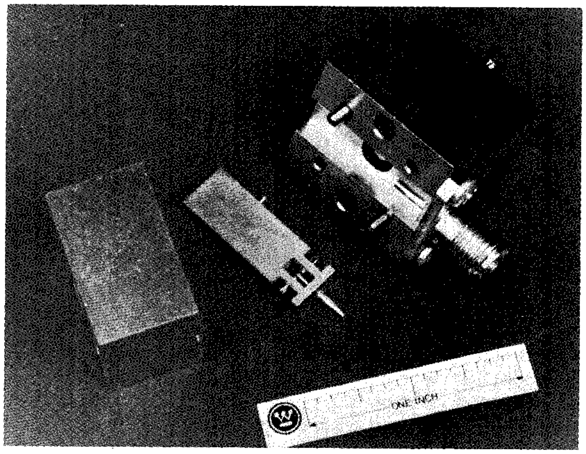

FIG. 3: A balanced pair of GaAs Schottky Barrier Junctions

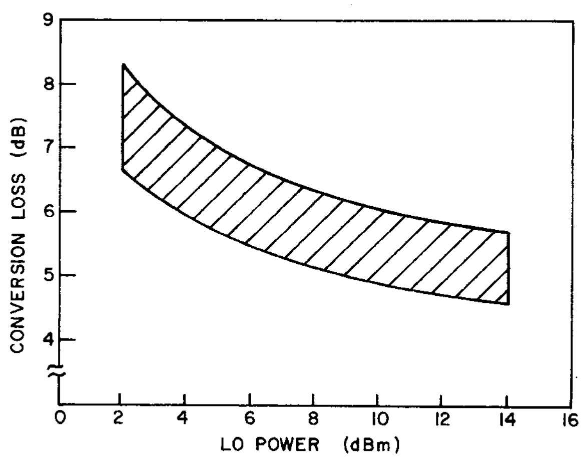

FIG. 4: Conversion Loss of 95 GHz Mixers

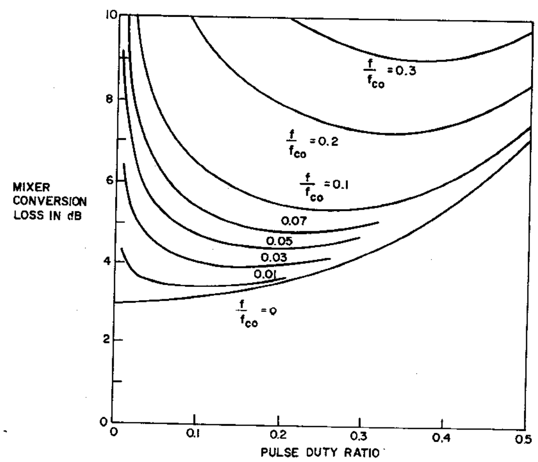

FIG. 5: Computed Mixer Conversion Loss for the Broadband Case (Image Termination Equals Signal Termination)

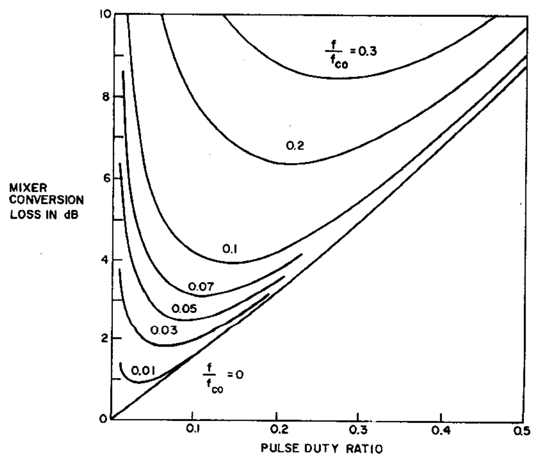

FIG. 6: Computed Mixer Conversion Loss for Short Circuited Image