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A COMPARISON OF THE MEASURED AND THEORETICAL PERFORMANCE OF A 140-220 GHZ SCHOTTKY DIODE MIXER

Peter H. Siegel and Anthony R. Kerr
NASA Goddard Space Flight Center, Institute for Space Studies
2880 Broadway, New York, NY 10025

Robert J. Mattauch
University of Virginia
Charlottesville, VA 22901

Summary

The results of a theoretical study of a 140-220 GHz Schottky diode mixer are described. Close agreement is obtained between the measured performance and the performance predicted by the mixer analysis program GISSMIX. The importance of making separate sideband conversion loss measurements is demonstrated. A sensitivity analysis shows the effects of various diode and mount characteristics on the mixer performance.

Introduction

At frequencies above 100 GHz, reported mixer performance varies widely from laboratory to laboratory, and in fact there is considerable variation amongst mixers produced in the same laboratory using diodes fabricated from the same semiconductor wafer. The reasons for these differences have never been adequately explained. In addition, few guidelines exist to aid researchers in their efforts to produce better mixer diodes, nor is there any clear understanding of the relationships between mixer performance and the diode mounting circuit at these frequencies. We have addressed these problems by using the computer program GISSMIX [1] to analyze a room temperature single-ended Schottky diode mixer [2] in the WR-5 (140-220 GHz) waveguide band.

In an earlier study, Held and Kerr [3] analyzed a room temperature mixer operating at 115 GHz. We have refined and extended their work to 200 GHz. Using measured diode and mount characteristics, we have been able to predict the performance of the WR-5 mixer over a wide tuning range with unprecedented accuracy. In addition, we have examined the sensitivity of the mixer performance to various diode and mount characteristics. The results of this study are presented in the hope that they may serve as a guide to future mixer designers.

Mixer Analysis

To analyze a mixer it is necessary first to determine the diode current and voltage waveforms produced by the local oscillator. These are then used to find the mixer conversion loss, input and output port impedances and noise temperature. A computer program GISSMIX [1] was written which solves the large signal problem using the multiple reflection technique [4], and performs the small-signal and noise analyses following Held and Kerr [3]. The program can be used for analyzing mixers having a single diode with any given I-V and C-V relationships once the diode mount (embedding) impedances at the LO harmonic and sideband frequencies are known.

Diode Mount Impedances

In order to perform an accurate mixer analysis we must know the diode mount impedances at a number of LO harmonic and sideband frequencies. Since it is not practical to measure these impedances directly, a 100x scale model was employed to bring the first six LO harmonic frequencies into the microwave band. A technique described by Eisenhart and Khan [5] was then used to measure the embedding impedances at the equivalent of 1 GHz intervals from 140 to 1320 GHz (the sixth harmonic of 220 GHz), as a function of mixer tuning. In this way the diode mount was characterized over the entire mixer operating range when using any desired intermediate frequency.

The measured embedding impedances (normalized to 50 ohms) at 180 GHz and five higher harmonic frequencies are shown in Fig. 1 as functions of the

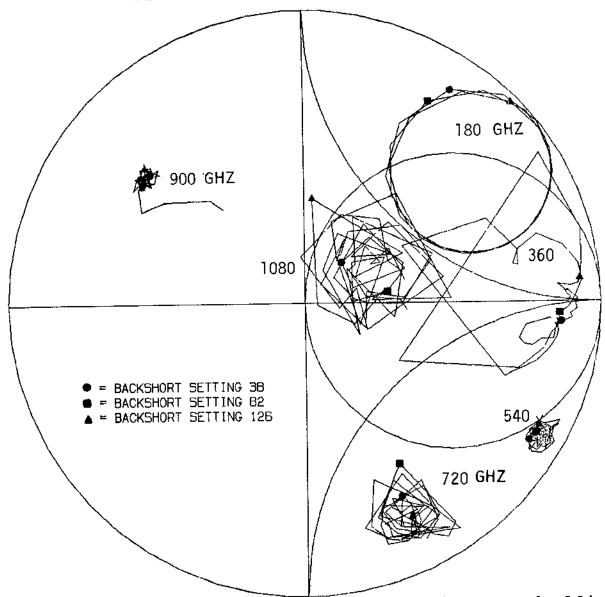

Fig. 1 Smith chart plot of the diode embedding impedances as a function of backshort position for an LO frequency of 180 GHz and five higher harmonics. The plotted symbols indicate the three backshort positions at which the mixer had the lowest conversion loss (see Fig. 3).

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mixer backshort position. Even after adding in the mean diode junction capacitance (not included in Fig. 1), the higher harmonics are neither open- nor short-circuited, contrary to the assumptions implicit in many earlier mixer analyses. Similar plots for the sideband frequencies indicate that with an IF of 4 GHz there is a considerable difference between the impedances at the upper and lower sidebands which, as we shall see, strongly affects the mixer performance.

Diode Equivalent Circuit

To perform the mixer analysis we must have an accurate characterization of the diode's I-V and C-V relationships. In the analysis presented here, we have assumed that conduction is due only to thermionic emission, and we have used the usual abrupt junction C-V law. The GaAs Schottky diodes used in the actual mixer were made by one of the authors [R.J.M] and we have derived for them the equivalent circuit shown in Fig. 2. R_s, c_0, and i_s were measured, γ was taken to be 0.5 according to the abrupt junction approximation and the value of ϕ_{bi} was suggested by measurements made at U. Va. on similar diodes. The value of η was initially obtained from the diode DC I-V curve and was then adjusted (within the error limits of the initial measurement) to obtain a best fit between the measured and computed mixer performance. It should be pointed out that we were not able to measure either γ or ϕ_{bi} directly; however the excellent agreement obtained between the measured and computed mixer performance over the whole of the mixer tuning range supports our choice of values for these variables.

Comparison of Computed and Measured Results

The mixer embedding impedances and diode electrical properties were used in the mixer analysis program [1] to compute the upper and lower sideband conversion loss, equivalent input noise temperature, output noise temperature ratio, and IF output VSWR at each of 65 backshort positions. The results, for an LO frequency of 180 GHz and a 4 GHz IF, are shown in Fig. 3. The discrete points in the figure were measured as follows.

The individual sideband conversion losses were determined from direct RF and IF power measurements using the test setup depicted in Fig. 4. Measurement uncertainty due to power meter calibration and mismatch was estimated to be ±1.0dB. This uncertainty was reduced to ±0.5dB by a double-sideband conversion loss measurement using thermal RF noise sources (ambient and liquid nitrogen temperature loads) with an IF radiometer/reflectometer similar to that of [6]. Knowing the conversion loss in each sideband, the equivalent input noise temperature of the mixer was determined from the mixer's output noise temperature measured, as described in [6], with a room-temperature RF load. These measurements are described in more detail in [7].

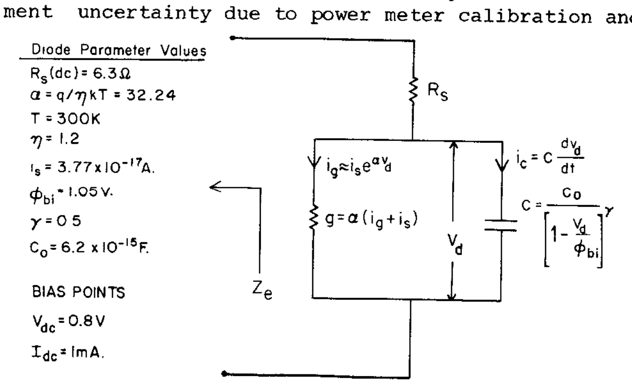

Fig. 2 The diode equivalent circuit with the derived parameter values used in the mixer analysis program.

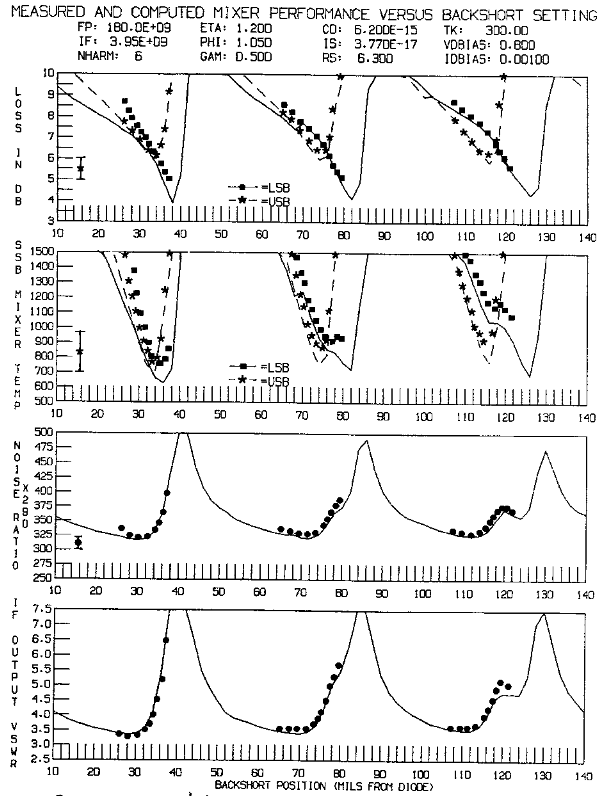

Fig. 3 A comparison of the measured (points) and computed (lines) mixer performance at 180 GHz. The output noise temperature ratio (third graph) has been multiplied by 290 for convenience. Error bars are shown at the left.

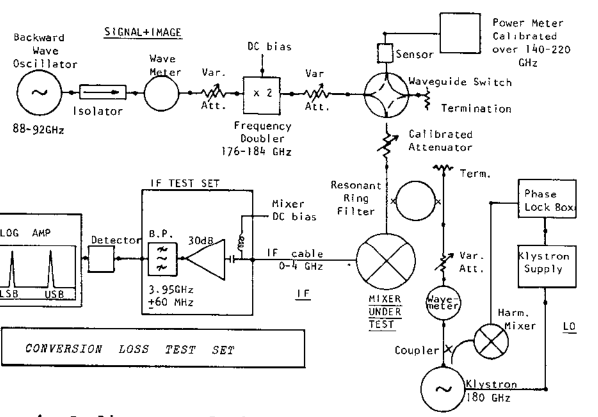

Fig. 4 A diagram of the measurement test set used to determine the upper (USB) and lower (LSB) sideband conversion losses of a mixer under fixed bias conditions. The IF test set gain and RF waveguide component losses are measured beforehand.

The measured and computed mixer performance are very close over the whole of the wide range of tuning positions shown. Notice that the upper and lower sideband performance is quite different, indicating the importance of independent measurements at both frequencies. The mixer performance was also measured and computed for an LO frequency of 150 GHz, with comparable agreement.

Sensitivity Analysis

Having demonstrated that our program correctly predicts the performance of the WR-5 mixer, we have used it to study the sensitivity of the mixer to various diode and mount characteristics. Fig. 5 summarizes the effects of 7 diode parameters on the mixer performance. Note that, in actuality, these parameters are not all independent. The extreme sensitivity to some diode parameters may explain the wide variations observed between mixers, even when using diodes made from the same semiconductor wafer.

Fig. 6 shows the changes in mixer performance when the embedding impedances above the upper sideband are either short circuited, open circuited, or set to 50 ohms. For this mixer circuit, the higher harmonic terminations have a fairly small effect. The sensitivity of the mixer performance to other parameters such as LO power level, bias voltage and rectified current are reported in [6].

Conclusions

Measurements of the performance of a WR-5 mixer show excellent agreement with the predictions of the mixer analysis program GISSMIX. Our results suggest that at room temperature and up to at least 200 GHz, the current transport processes in these diodes can be described accurately by the thermionic emission theory. No account has been taken of intervalley scattering or hot electron effects, nor have plasma resonance, dielectric relaxation or scattering effects [8] been considered. The results also demonstrate the necessity of separate sideband measurements of the mixer conversion loss and noise temperature. The sensitivity analysis indicates which diode parameters have the most effect on the mixer performance and may serve as a guide for future research.

% increase in diode parameter → (max-min)/min	η 1.16-1.24	ϕ 1.01-1.10	γ .3-.5	R_s(dc) 3 - 12Ω	T 295-310K	c_0 4-8 fF	i_s 2-6x10^{-17}
Associated change in mixer performance ↓	+7%	+9%	+67%	+300%	+5%	+100%	+200%
% Change in LOSS	-32%	0%	-10%	+44%	-20%	+29%	+14%
% Change in T_{SSB}	+55%	-43%	+58%	+84%	+47%	+130%	-14%
% Change in T_o	+38%	-23%	+18%	0%	+30%	+12%	-11%
% Change in $\lvert\Gamma\rvert$, $\lvert\Gamma\rvert = \frac{VSWR-1}{VSWR+1}$	+12%	+1%	-4%	+11%	+8%	-13%	-5%

Fig. 5 Table summarizing the effects of 7 diode parameters on the performance of the 180 GHz mixer. The numbers show whether an increase in the particular diode parameter increases (+) or decreases (-) the mixer conversion loss (LSB), equivalent input noise temperature (LSB), output noise temperature (t*290) and VSWR at the IF port (referred to 50Ω).

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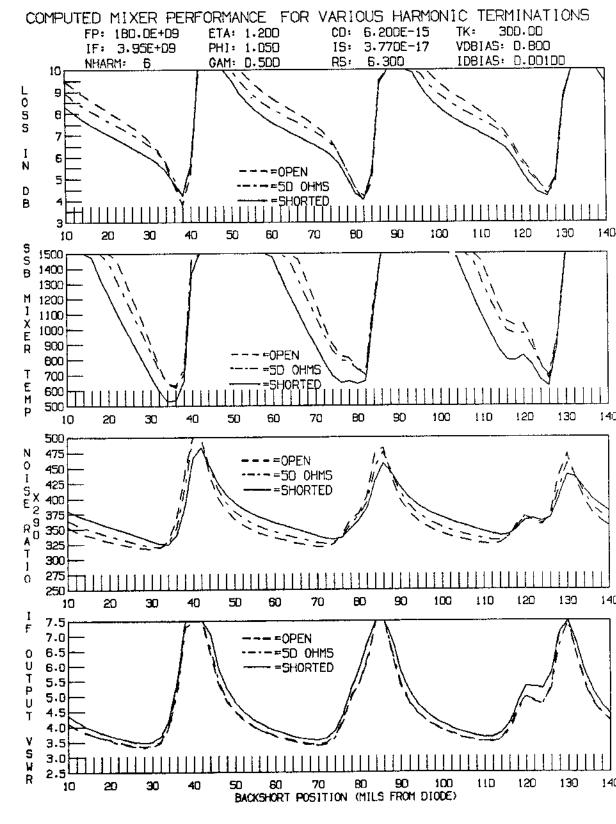

Fig. 6 Computed mixer performance at 180 GHz when the embedding impedances above the upper sideband are (i) open circuited, (ii) set to 50 ohms and (iii) short circuited. In the top two graphs only the lower sidebands are compared.