LIMITATIONS OF MICROWAVE AND MILLIMETER-WAVE MIXERS DUE TO EXCESS NOISE

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Abstract:

Excess noise due to hot electrons, intervalley scattering andd traps in the diode is included in the mixer noise analysis. Its influence is discussed for room temperature as well as for cooled mixers.

Introduction

The theory of microwave and millimeter wave mixers has recently concentrated on the circuit aspects of the network. Kerr and others [1-5] developed a rather complete method of analysis from the circuit point of view. For example, the analysis of Kerr and Held [2] takes into account the finite conversion loss at the harmonic frequencies, produced by the variation of both the conductance and the capacitance of the Schottky barrier diode. Many of the results of the analysis agree quite well with experiment, but as Kerr pointed out at the 1975 International Microwave Symposium [1], conventional noise models predict considerably lower noise temperatures than those measured. An anomalous noise mechanism has to be present, especially at higher LO powers. Using a simple noise model which includes only thermal noise from the series resistance and shot noise, Held and Kerr [2] attempted to describe the anomalous noise by assuming an increase in the temperature of the series resistance. They stated however that this approach will be insufficient for describing the noise behavior of cooled mixers. Recent noise measurements on a cooled 100 GHz mixer for a wide range of diode bias current and voltage, as well as LO power [6], shown in Fig. 1 confirmed that prediction. The closed curves for constant noise temperature in this diagram can not be obtained from the standard mixer noise analysis.

At the present time, however, much more is known about other potentially important noise sources, and the main contribution of this paper is to include these in the mixer noise model. The circuit aspects of the mixer are treated in the same manner as Kerr and Held. As detailed below, a good qualitative explanation for a number of experimentally observed noise characteristics is obtained for the first time.

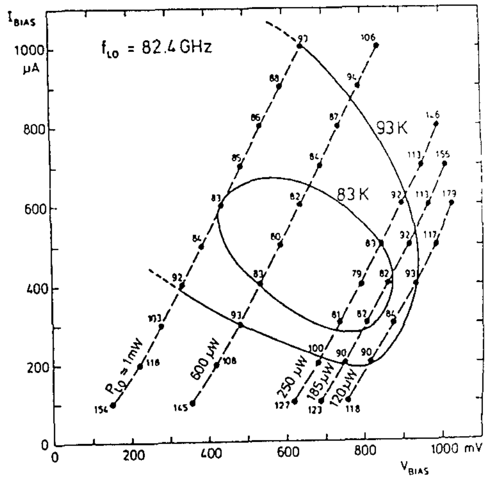

Figure 1. Measured receiver noise temperature T_{DSB} versus LO power and bias conditions (from [6]).

2. Noise in Schottky Barrier Diodes

Low conversion loss millimeter wave mixers fundamentally require relatively high current densities, and this fact points directly at other potential noise mechanisms, like the hot electron noise and intervalley scattering. Such electric field dependent noise in GaAs has been described and measured by several authors [7-8]. More recent results by Keen, Kollberg, Jelenski, Schneider and Zirath [9-11] of the noise temperature measured from dc-biased Schottky barrier diodes at different frequencies are summarized in Fig. 2. These results show that the excess noise which appears at high diode currents is due not only to hot electron effects and intervalley scattering, but is also due to some other mechanism which is frequency dependent. It was shown in [12] that shallow traps near the interface provide the mechanism which has that frequency dependence. This latter source of noise, which is well known at low frequencies, gives rise to the frequency-dependence of the noise temperature in the microwave region as well.

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Fig. 2 shows that the excess noise temperature T_e can be approximated by the formula:

$$T_e = A(f)R_{se}I_d^2 \qquad (1)$$

where A(f) is a constant dependent on the parameters of the diode, R_{se} is the resistance of the diode epilayer, and I_d is the diode current.

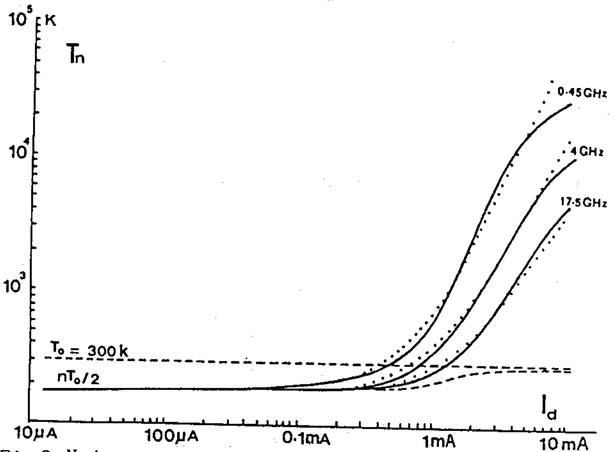

Fig 2. Noise temperature of a GaAs Schottky diode as function of the forward bias (T_o=295K) [9-11]. The broken curve shows the thermal noise at $T = T_o$, and the dotted curves are the thermal noise at the corresponding frequencies if the excess noise is given by eq. 1.

The total thermal noise generated in the diode can be described by

$$T_{th} = T_o + T_e \qquad (2)$$

This more realistic noise model will be introduced in the mixer analysis.

3. Mixer Noise Theory:

To describe the influence of the current-dependent excess noise, the method proposed by Dragone [12] can be used. Because of its dependence upon current, it can be considered in any individual side-band as a white noise amplitude modulated by the LO power, and its quasi-sinusoidal components at various side band frequencies will be partially correlated. The excess noise current at the m-th side band is

$$<|i_m^2|> = \frac{e_{s_m}^2}{|Z_{e_m}+Z_{s_m}|^2} = 4\ K\ \Delta f\ \frac{T_m R_{s_m}}{|Z_{e_m}+Z_{s_m}|^2} \qquad (3)$$

where $R_{s_m} = Re(Z_{s_m})$ - is the real part of the h.f. series impedance (Z_{s_m}) of the diode at frequency f_o+mf_p.

Z_{e_m} - is the embedding impedance.

Additional terms due to the excess noise which have to be included in the correlation matrix can be calculated as

$$<|i_m|^2> = \frac{4KA_m\Delta f R_{s_m}^2 |I_m|^2}{|Z_{e_m}+Z_{s_m}|^2} \qquad (4)$$

for the diagonal elements and

$$<i_m i_n^*> = \frac{4K\Delta f R_{s_m} R_{s_n} \sqrt{A_m A_n}(I_m \cdot I_n^*)}{|Z_{e_m}+Z_{s_m}| \cdot |Z_{e_n}+Z_{s_n}|^*} \qquad (5)$$

for the off-diagonal elements. I_m and I_n are the Fourier coefficients of the total diode current, and A_m and A_n are values of A(f) at frequencies mf_p+f_o and nf_p+f_o respectively.

These elements have to be added to the elements of the correlation matrix describing the shot noise generated in the junction and the thermal noise generated in the diode series resistance and in the real part of the embedding impedance at a given side band.

4. Results:

The program of [5] was modified to include the excess noise sources as was described above. For room temperature calculations, the same data for the diode and embedding impedances as in the original program were utilized. As an important fraction of the embedding impedances comes from circuit losses, the noise generators representing these losses were also added. Fig. 3 shows the constant noise temperature contours vs LO power and bias conditions for a room temperature mixer.

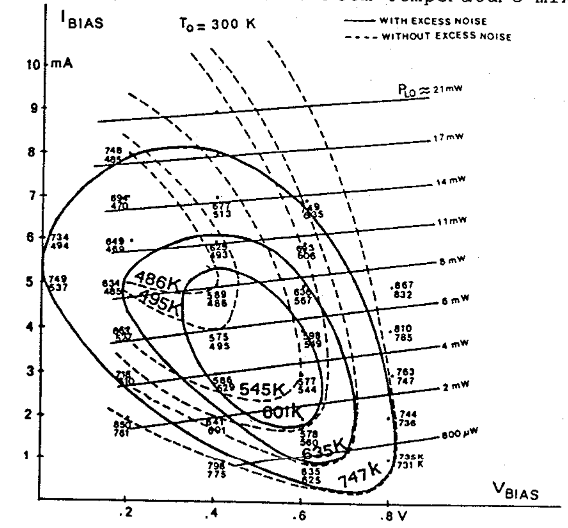

Fig 3. Calculated constant noise temperature contours vs bias conditions and LO power for the 184 GHz mixer of [5] at room temperature. The two temperature values at each point correspond to values with excess noise (upper) and without (lower). $A_{IF} = A_{RF} = 10^7$ K/W.

Without the excess noise (A=0), the contours do not close. When the excess noise is taken into account the contours close in agreement with the measurements in [6] (see Fig. 1). The results show that the calculated minimum mixer noise temperature passes through a minimum point at some LO power only if the excess noise is included, in agreement with common experience. In Fig. 4, the influence of the excess noise on the minimum noise temperature of the mixer as function of LO power is depicted. The excess noise at room temperature produces only slight increase of the minimum mixer noise temperature as was predicted in [2]. The effect of the freuqency dependence of the excess noise on the mm wave mixer noise can be seen from the broken curve of the same figure, which was plotted for the case when the RF noise temperature is ~1/10 that of its IF (0.5 GHz) value (see Fig. 2). The difference between the latter curve and the A=0 curve also gives an estimate of the relative importance of excess noise generated in the IF and RF circuits. In Fig. 5 the plot of the different components of the total mixer noise temperature is given as a function of LO power. The curves were plotted for a constant bias voltage corresponding to the minimum of the noise temperature in Fig. 3. With the inclusion of the excess noise we find that the total thermal noise increases with LO power. The shot noise increases again after a certain minimum

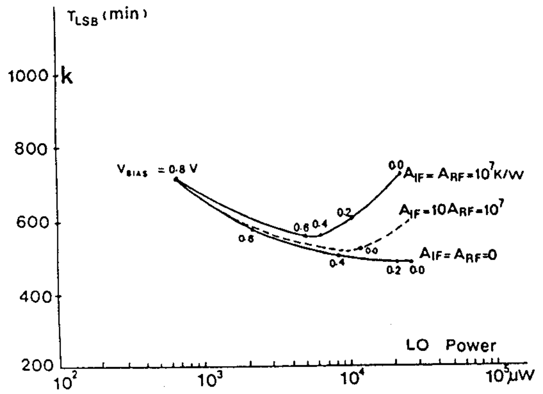

Fig 4. Calculated minimum noise temperature vs. LO power for the 184 GHz mixer of [5] at room temperature. The upper curve has A_{IF}= A_{RF}=0. The broken curve has $A_{IF} = 10^7$ and $A_{RF} = 10^6$ K/W.

because of the correlation between the shot current sources at different sidebands. That figure also shows that the effect of the embedding network losses, given by the thermal noise of the real parts of the embedding impedances at different sidebands can be quite important. An optimization procedure of the embedding impedances can be used to minimize the overall noise [13].

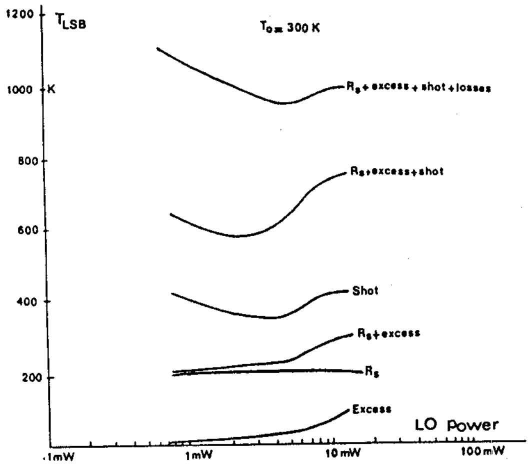

Fig 5. Different components of the total noise of the room temperature mixer.

To improve the receiver noise performance, mixers are usually cooled to cryogenic temperatures. At low temperatures the parameters of the diode change, but again one finds that inclusion of the excess noise is necessary to close the contours, in agreement with experiment.

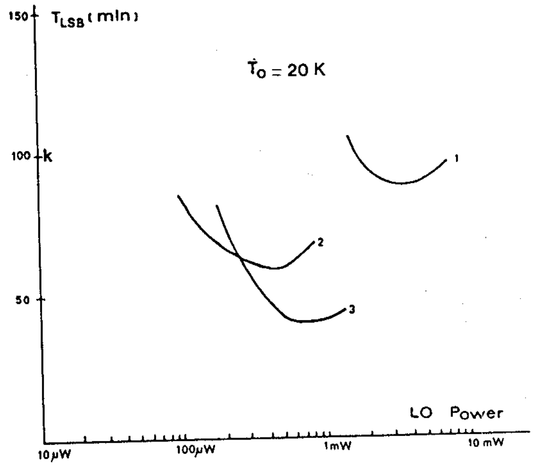

Fig 6. Calculated minimum noise temperature vs LO power at for three different diodes. Curve 1 has a diode with doping $N_D = 2 \times 10^{17}$ cm^{-3} and anode radius = 1 µm. Curve 2 diode has $N_D = 2 \times 10^{16}$ and anode radius = 1 µm. Curve 3 diode has $N_D = 2 \times 10^{16}$ and anode radius = 1.14 µm.

Noise performances of a cooled mixer for different diodes are compared in Fig. 6. This figure shows that by increasing the area of the low doped diode two times, the excess noise decreases and a lower mixer noise temperature can be obtained, although a higher LO power is needed. However the same improvement on the noise characteristics of the small area diode can be obtained at lower LO power by increasing the embedding impedances as was demonstrated by [14]. If the doping of the diode is increased from $2x10^{16}$ to $2x10^{17} cm^{-3}$, then the shot noise increases about three times from 25 to about 75 K causing a significant increase of the minimum noise temperature.

Conclusions

We presented a method to include the excess noise sources of Schottky diodes into the mixer analysis. It was shown that agreement between the measured and calculated mixer noise temperatures can be obtained only by including these sources, especialy at higher LO powers where it limits the noise performance of the mixer. The influence of excess noise is particularly pronounced in cooled mixers, in which diodes with lower doping concentrations have to be used as it was shown above. The inclusion of the excess noise in the mixer model will enable the optimization of the embedding impedances and driving conditions for a given diode, as well as the optimization of the diode for a given frequency band.

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