Limitations of Microwave and Millimeter-Wave Mixers Due to Excess Noise

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Abstract —Previous analytical work on microwave and millimeter-wave mixers concentrated on circuit aspects, utilizing for the analysis a simple noise model consisting of shot and thermal noise sources at a constant temperature. However, measurements show that the excess noise created in the diode by hot electrons, intervalley scattering, and traps at the metal–semiconductor interface can be important, especially in millimeter-wave mixers.

In this paper, the method of calculation of mixer noise performance in the presence of excess noise is given and its influence discussed for room-temperature, as well as for cooled, mixers.

I. 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 82-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 cannot 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.

Manuscript received March 14, 1985; revised June 25, 1985.

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II. 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 at low currents the measured noise is equal to the shot noise in the junction. 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. Fig. 2 shows that the excess noise temperature T_e can be approximated by the formula

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

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.

An expression of $A(f)$ can be obtained by summing the contributions of hot electron, intervalley scattering, and trap induced noise. In the current region of interest for mixer applications, below the onset of the intervalley scattering

$$A(f) = A_H + A_T \tag{2}$$

where A_H is the contribution of hot electrons

$$A_H = \frac{2}{3} \cdot \frac{\tau_\epsilon}{kN_D} \cdot \frac{1}{S \cdot d} \tag{2a}$$

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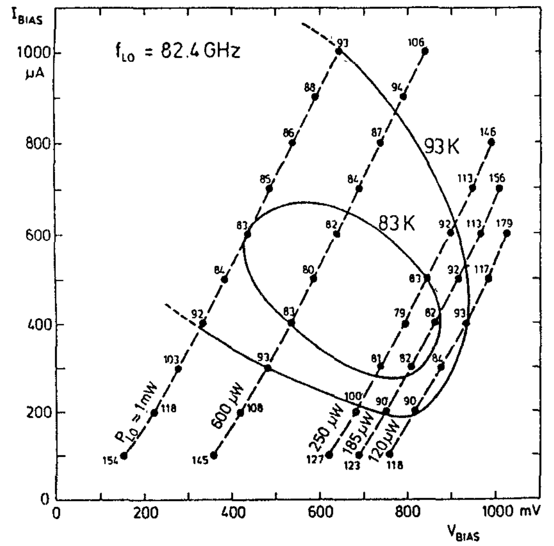

Fig. 1. Measured receiver noise temperature T_{RDSB} versus LO power and bias conditions (from [6]).

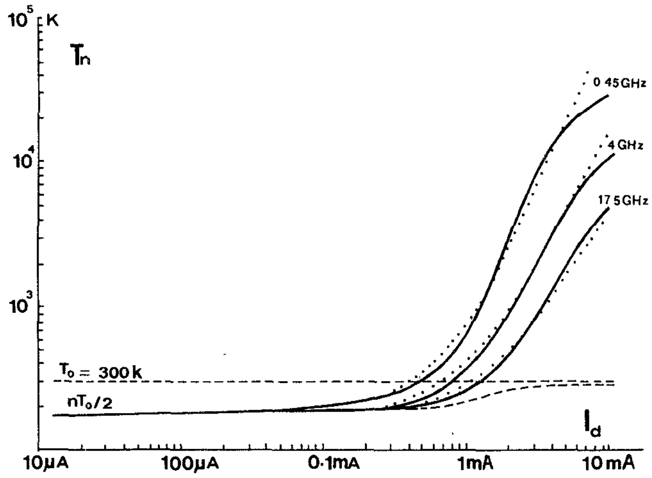

Fig. 2. Noise temperature of a GaAs Schottky diode as function of the forward bias ($T_0 = 295$ K) [9]–[11]. The broken curve shows the thermal noise at $T = T_0$, and the dotted curves are the thermal noise at the corresponding frequencies if the excess noise is given by (1).

and A_T is the contribution from shallow traps given by

$$A_T = \frac{a}{4} \frac{N_T}{N_D} \cdot \frac{\tau}{kN_D} \cdot \frac{1}{S \cdot d} \cdot \frac{1}{1+(\omega\tau)^2} \tag{2b}$$

where

- τ_ϵ energy relaxation time $\simeq 1$ ps,
- τ trapping time constant,
- N_D donor concentration in the epilayer,
- N_T trap concentration in the epilayer,
- S area of the diode (anode),
- d thickness of the epilayer,
- a constant.

The total noise generated in R_{se} can be described by the noise temperature

$$T_t = T_0 + T_e. \tag{3}$$

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

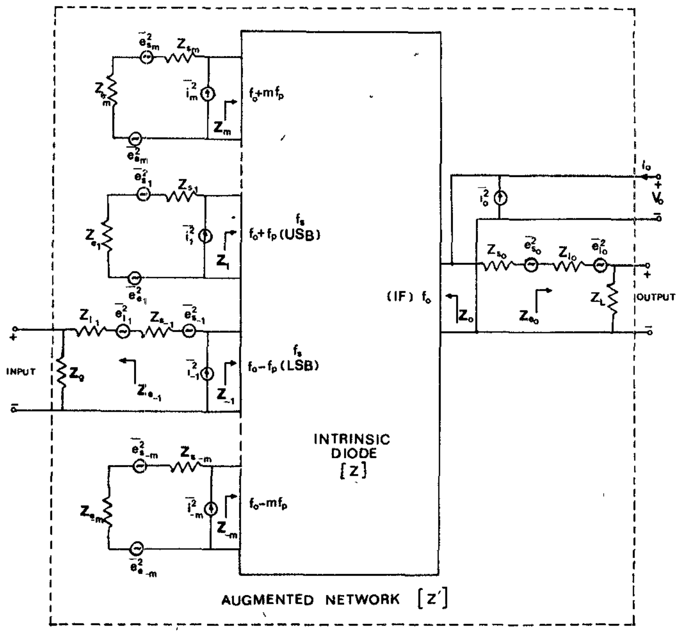

Fig. 3. The small-signal equivalent circuit for the LSB mixer. $\overline{e_{e_m}^2} = 4kT_0 \,\mathrm{Re}(Z_{e_m})\Delta f$, $\overline{e_{s_m}^2} = 4kT_t \,\mathrm{Re}(Z_{s_m})\Delta f$, and $i_g^2 = 2qI_g\Delta f$.

III. Mixer Noise Theory

A single-sideband mixer can be represented by an equivalent circuit represented in Fig. 3. In this figure, Z_{s_m}, Z_{e_m}, e_{s_m}, and e_{e_m} represent the diode series resistance, the embedding impedance, and the sources of noise related to them respectively, and i_m represents the shot noise in the frequency band around $\omega_0 + m\omega_p$. When the mixer circuit is considered lossless, and the embedding impedances are very large, then the well-known case of open-circuited sidebands at all LO harmonics will result. In this case, only shot noise from the image and sidebands of the LO harmonics will be down-converted. On the other hand, if $Z_{e_m} = 0$, sidebands at all LO harmonics are short circuited. In this case, thermal and shot noise will be down-converted from all sidebands to the output because of the finite diode series resistance.

In practice, however, it is very difficult to realize these conditions, and $Z_{e_m} \neq 0$. The real parts of Z_{e_m} representing losses of the mixer circuit at frequencies $f_0 + mf_p$ are sources of thermal noise, which can give a considerable contribution to the total noise generated in the mixer [3]. The shot noise from the mixer was calculated by Dragone [13]. He showed that when the noise sources are current-dependent, then the noise components originating from different sidebands will be partially correlated because they are modulated by the same local oscillator. The ensemble average of the noise voltage components at the output representing shot noise (see Fig. 3) is equal to

$$\left\langle |v_{s_0}|^2 \right\rangle = Z_0' \langle i_s, i_s^* \rangle Z_0'^{\dagger} \tag{4}$$

where $\langle i_s, i_s^* \rangle$ is the shot noise correlation matrix with elements equal to

$$\langle i_{s_m}, i_{s_n}^* \rangle = 2qI_{m-n}\Delta f \tag{5}$$

Z_0' is the zeroth row of the augmented impedance matrix [5], and I_{m-n} is the $m-n$th Fourier coefficient of the diode current.

The same analysis applies if the thermal noise contains a current-dependent part, as is the case in Schottky diodes when the excess noise is present.

Without the excess noise, the thermal noise correlation matrix has only diagonal elements. They are

$$\langle |i_m^2|\rangle = \frac{e_{s_m}^2 + e_{e_m}^2}{|Z_{e_m} + Z_{s_m}|^2}$$

$$= 4k\,\Delta f \frac{T_0(R_{e_m} + R_{s_m})}{|Z_{e_m} + Z_{s_m}|^2} \qquad \text{for} \quad m \neq 0$$

$$\langle |i_m^2|\rangle = 4k\,\Delta f \frac{T_0(R_s)}{|Z_{e_0} + Z_{s_0}|^2} \qquad \text{for} \quad m = 0 \tag{6}$$

where $R_{s_m} = \mathrm{Re}(Z_{s_m})$ and $R_{e_m} = \mathrm{Re}(Z_{e_m})$ are the real part of the h.f. series impedance (Z_{s_m}) of the diode and of the embedding impedance (Z_{e_m}) at frequency $f_0 + mf_p$.

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

$$\langle |i_m|^2\rangle = \frac{4kA_m\,\Delta f R_{s_m}^2 |I_m|^2}{|Z_{e_m} + Z_{s_m}|^2} \tag{7}$$

for the diagonal elements and

$$\langle i_m i_n^* \rangle = \frac{4k\,\Delta f R_{s_m} R_{s_n} \sqrt{A_m A_n}\,(I_m \cdot I_n^*)}{|Z_{e_m} + Z_{s_m}| \cdot |Z_{e_n} + Z_{s_n}|^*} \tag{7a}$$

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 $mf_p + f_0$ and $nf_p + f_0$, respectively.

The elements given by (5)–(7) have to be added to obtain the total correlation matrix describing the shot noise generated in the junction and the total noise generated in the diode series resistance, the thermal noise generated in the real part of the embedding impedance at a given sideband.

The input noise temperature of the mixer is calculated by multiplying the output noise power by the conversion loss from signal to IF. L is defined as

$$L = \frac{\text{available power at signal port}}{\text{delivered power to output (IF)}}$$

$$= \frac{P_{\mathrm{av}}(f_s)}{P_{\mathrm{del}}(\mathrm{IF})}. \tag{8}$$

The single-sideband input noise temperature is

$$T_{\mathrm{LSB}} = \frac{P_{\mathrm{del}} \cdot L}{k\,\Delta f} = \frac{\langle |v_n|^2\rangle |Z_{e_1} + R_{s_1}|^2}{4k\,\Delta f |Z_{0,-1}'|^2 R_e[Z_{e_1}]} \tag{9}$$

where $Z_{0,-1}'$ is an element of the augmented impedance matrix Z' [5].

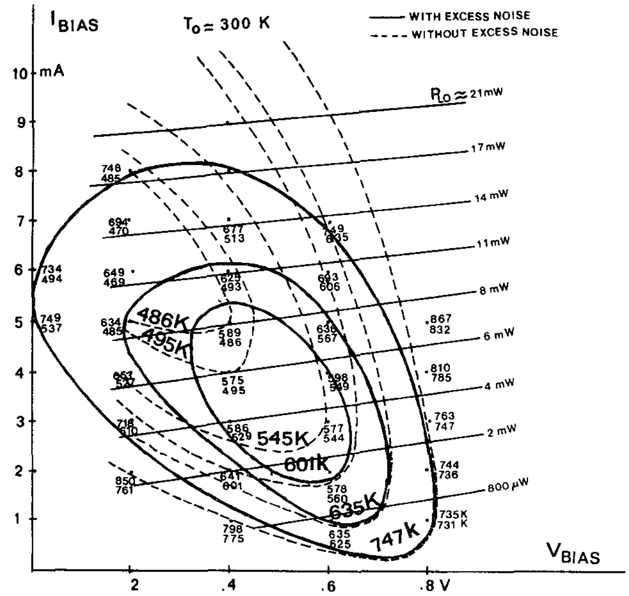

Fig. 4. Calculated constant noise temperature contours versus bias conditions and LO power for the 184-GHz mixer of [5] at room temperature. The two temperature values at each point correspond to values with excess noise (upper) and without (lower). $A_{\mathrm{IF}} = A_{\mathrm{RF}} = 10^7$ K/W. The exponential characteristic is $i = I_0(\exp(qV/nkT)-1)$ with $n = 1.18$, $I_0 = 3.77\times10^{-17}$ A, $R_s = 6.3$ Ω, $C_0 = 6.2\times10^{-15}$ f, anode radius = 1 μm, $N_D = 2\times10^{17}\,\mathrm{cm}^{-3}$.

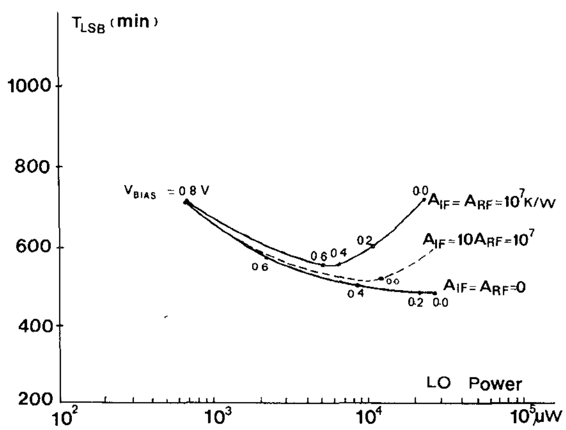

Fig. 5. Calculated minimum noise temperature versus LO power for the 184-GHz mixer of [5] at room temperature.

IV. 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 losses caused by the embedding impedances comes from circuit losses, the noise generators representing these losses were also added. Fig. 4 shows the constant noise temperature contours versus LO power and bias conditions for a room-temperature mixer. 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). Fig. 5 shows that the calculated minimum mixer noise temperature passes through a minimum point

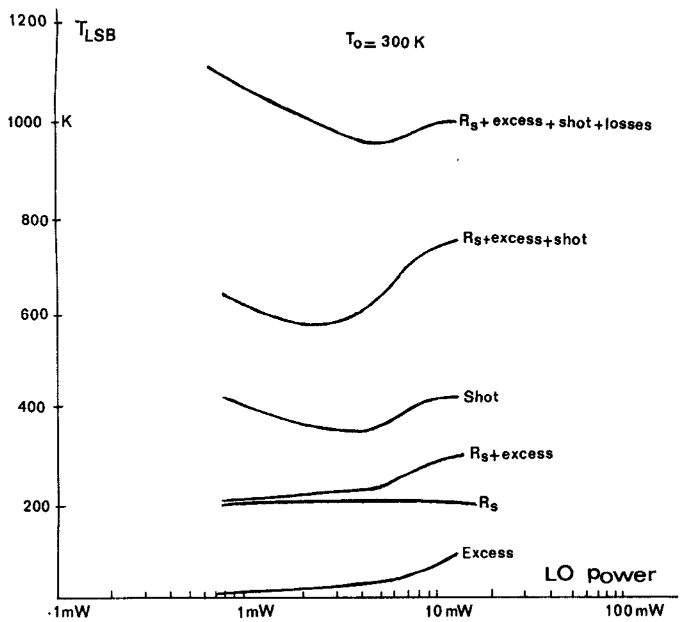

Fig. 6. Different components of the total noise at room temperature for the same mixer.

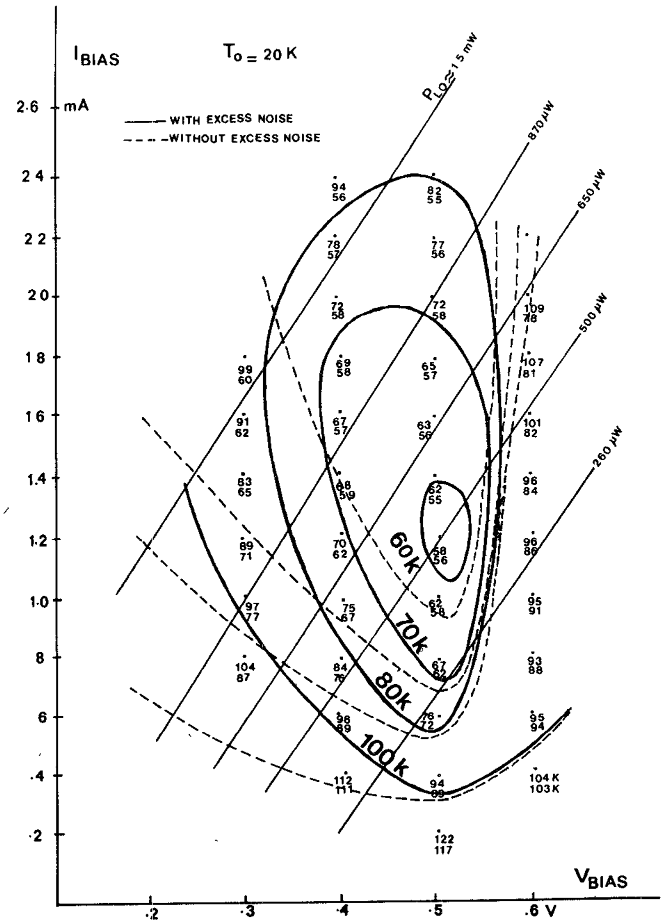

Fig. 7. Calculated constant noise temperature contours versus bias conditions and LO power for the same mixer of Fig. 4 but at 20 K and with a different diode. The diode parameters are: $N_D = 2\times10^{16}$ cm^{-3}, $n = 5$, $I_0 = 3\times10^{-35}$ A, $R_s = 14$ Ω, anode radius = 1 μm. The two temperature values at each point correspond to values with excess noise (upper) and without (lower). $A_{IF} = A_{RF} = 9\times10^8$ K/W.

at some LO power only if the excess noise is included, in agreement with common experience. The excess noise at room temperature produces only a slight increase of the minimum mixer noise temperature as was predicted in [2]. The effect of the frequency-dependence of the excess noise on the millimeter-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 $\sim 1/10$ 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. 6, 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. 4. With the inclusion of the excess noise, the total noise in R_s increases with LO power. The shot noise increases again after a certain minimum because of the correlation between the shot current sources at different sidebands. This 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 [14].

To improve the receiver noise performance, mixers are usually cooled to cryogenic temperatures. At low temperatures, the parameters of the diode change. The parameters of a typical diode utilized in the millimeter-wave mixer at 20 K are given in Fig. 7, in which the plot of the contours of constant noise temperatures is presented as a function of LO power and bias conditions. Again, one finds that inclusion of the excess noise is necessary to close the contours, in agreement with experiment. The different components of the total mixer noise temperature are shown in Fig. 8 as a function of LO power. The excess noise increases considerably, and is solely responsible for the increase of the total mixer noise with LO power. The shot noise is lower than the total noise in R_s because of the low doping of the diode, but is still more important than the thermal noise of the diode series resistance. However, in a more realistic case, in which the real parts of the embedding impedances at the different sidebands are mainly due to circuit losses, noise generated in these losses has to be taken into account. These losses are very important in Fig. 8, but the embedding impedances were not optimized for a low-temperature operation of the mixer. This shows that cooling of the mixer can be much more effective than predicted from the direct comparison between the noise generated by the diode series resistance and the shot noise, especially in mixers where the signal is fed through a bandpass filter.

Noise performances of a cooled mixer for different diodes are compared in Fig. 9. 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 characteris-

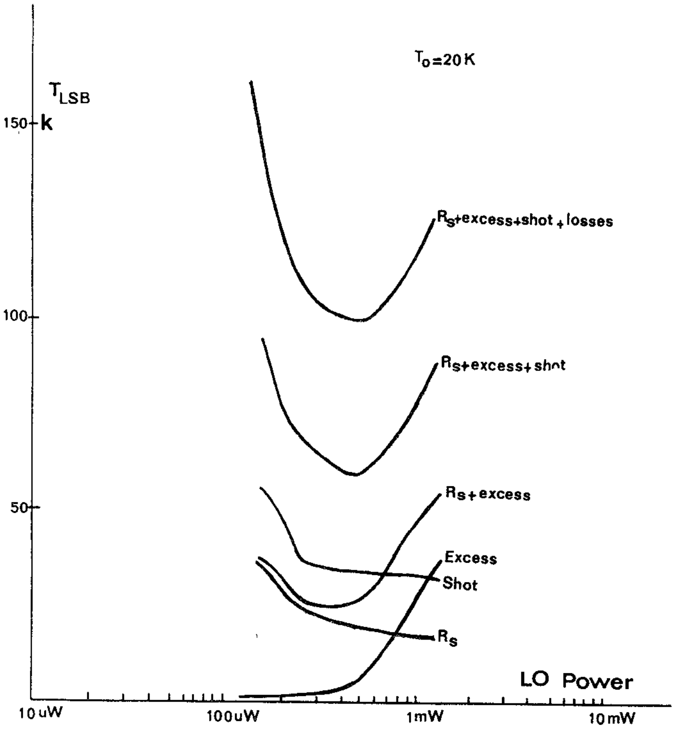

Fig. 8. Different components of the total noise of the cooled mixer. The diode has the same parameters as Fig. 7.

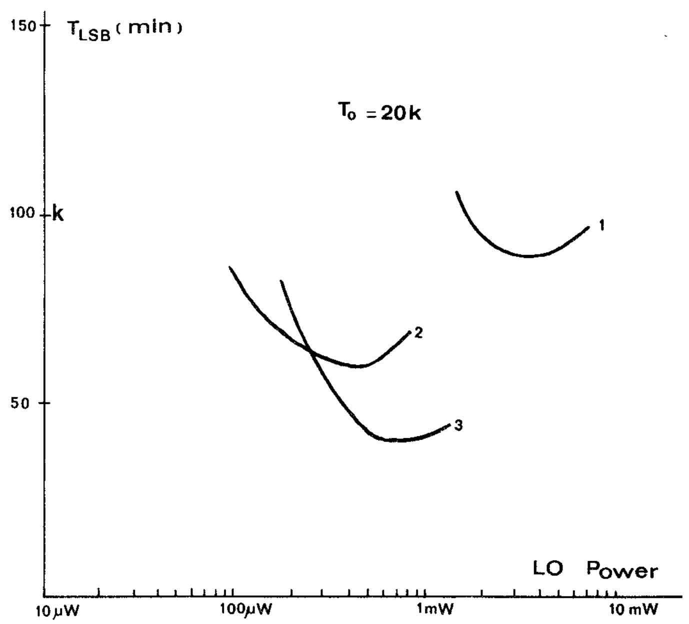

Fig. 9. Calculated minimum noise temperature versus LO power at 20 K for three different diodes. Curve 1 has a diode with doping $N_D = 2\times10^{17}\,\mathrm{cm}^{-3}$ and anode radius = 1 μm. Curve 2 diode has $N_D = 2\times10^{16}$ and anode radius = 1 μm. Curve 3 diode has $N_D = 2\times10^{16}$ and anode radius = 1.41 μm.

tics of the small area diode can be obtained at lower LO power by increasing the embedding impedances as was demonstrated by [15]. If the doping of the diode is increased from 2×10^{16} to $2\times10^{17}\,\mathrm{cm}^{-3}$, then the shot noise increases about three times from 25 to about 75 K causing a significant increase of the minimum noise temperature.

V. 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, especially at higher LO powers where it limits the noise performance of the mixer. The results also show that the procedure of matching the diode to the circuit by increasing the forward bias will not give the optimum mixer performance because of the excess noise. The optimum noise performance can be achieved only if the diode current is limited below the onset of the excess noise, while low conversion loss is maintained by increasing the embedding impedances. The influence of excess noise is particularly pronounced in cooled mixers, in which diodes with lower doping concentrations have to be used, as 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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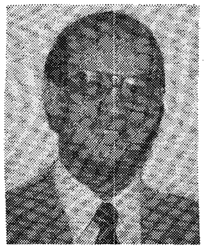

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