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An Empirical Probe to the Operation of SIS Receivers — Revisiting the Technique of Intersecting Lines

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***Abstract*— An alternate formulation is derived for the technique of intersecting lines which is a well established tool for the analysis of the performance of SIS receivers. This newer formulation is easier to use and provides an estimate of possible experimental error. The significance of the intersecting temperature, T_X, is discussed. Our experiments suggest that both quantum noise and the input match of the SIS mixer contribute to the value of the intersecting temperature.**

I. INTRODUCTION

The theory of operation and the technique of implementation of the Superconductor-Insulator-Superconductor (SIS) receiver are now well established. Many tools are available for use to design an SIS mixer [1, 2]. The technique of intersecting lines, introduced by Blundell et al [3], is one such empirical method, put forth to facilitate the analysis of the different constituents of the measured receiver noise temperature. Ke and Feldman [4, 5] developed the theoretical foundation for this technique. In this paper, we revisit the basis of this technique, and discuss an alternate formulation of the method, which is simpler to use. This version of the formulation has been established by the authors many years ago and was communicated to colleagues in the field in private. Both the original formulation and the alternate formulation have been cited in the literature [6,7]. A formal derivation will be presented in this paper.

A range of measurement data on SIS mixers have been examined using our technique. The results further allow us to understand the composition of noise in a practical SIS receiver with optical losses in front of the mixer.

II. TECHNIQUE OF INTERSECTING LINES

The starting point of the technique is a series of hot/cold load measurements performed on an SIS receiver, at various levels of Local Oscillator (LO) drive. For each incident LO power, we can draw a straight line in a plot of receiver output power (P_{out}) versus load temperature (T_{in}). These lines are found to intersect at a point ($-T_X$, P_X). This technique is illustrated in Fig. 1 with a data set for an SIS receiver operating at 225 GHz.

Using calculations based on the theory of quantum mixing, Ke and Feldman [4] found that the value of T_X given by the intersecting point is simply "***the equivalent input noise temperature of the RF input section of the receiver***", which they refer to as T_{RF}. Their foundation to this argument is: "***the SIS mixer output noise temperature is largely independent of mixer gain for low local oscillator power.***"

However, the original form of the technique of intersecting lines is difficult to implement. Firstly, for a set of *N* hot/cold load measurements, we have *N(N-1)/2* intersection points. In general, the intersection points obtained from the higher LO drive measurements are not as clustered together as the ones for lower LO drive. It is difficult to determine the boundary between the low and high LO drive, so the value of T_X is hard to pin down.

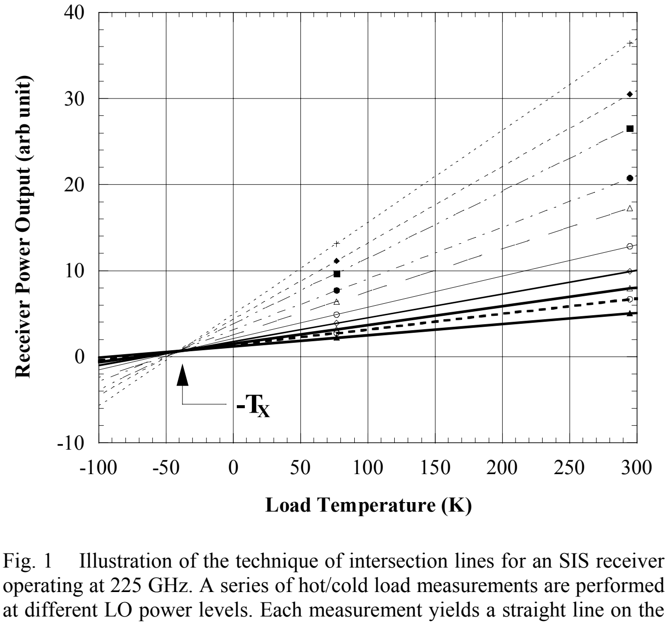

Fig. 1 Illustration of the technique of intersection lines for an SIS receiver operating at 225 GHz. A series of hot/cold load measurements are performed at different LO power levels. Each measurement yields a straight line on the

power output versus input load temperature plot. The lines are found to intersect at a point $T_{in} = -T_X$.

III. ALTERNATE FORMULATION

In Fig. 2, two of the intersecting lines are drawn on a plot of P_{out} versus T_{in}. These lines pass through the points (T_h, P_h) and (T_c, P_c) which represent the data for the hot and cold load measurements respectively. A property of these lines is that their horizontal intercept is simply $-T_R$, where T_R is the receiver noise temperature. For any given line, we can derive the following equation by writing its slope in two different ways and obtain

$$\text{slope} = \frac{P_h - P_c}{T_h - T_c} = \frac{P_X}{T_R - T_X}$$

$$T_R = \frac{(T_h - T_c)P_X}{P_h - P_c} + T_X \qquad (1)$$

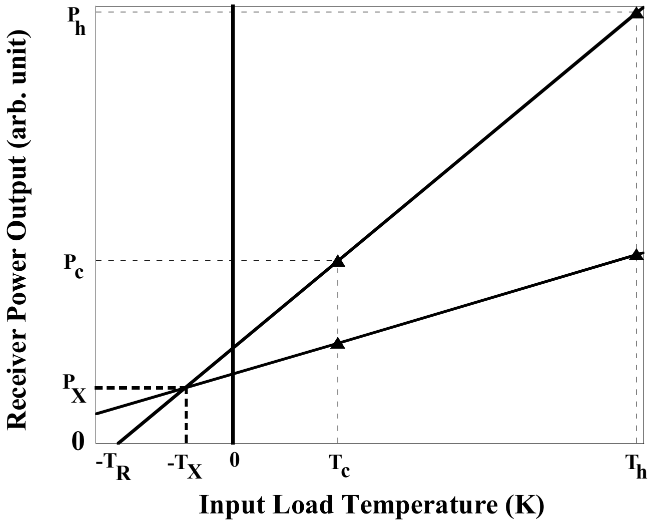

Fig 2 Relation between the intersecting point and the measured hot/cold load data lines. The lines intersect at the point *(*$-T_X$*,* P_X*)*. Each line intercepts the horizontal axis at $T = -T_R$, where T_R is the receiver noise temperature corresponding to that hot/cold load measurement.

Since (P_h-P_c) is proportional to the conversion gain of the receiver, G_C, we can conclude that when T_R is plotted against $1/G_C$ (or equivalently the conversion loss, L_C), a straight line should be obtained for low LO drive and the *y*-intercept of this line is T_X. In other words, we have,

$$T_R = \frac{m}{G_C} + T_X = mL_C + T_X \qquad (2)$$

where *m* is the slope of the fitted line.

An example of such linear fitting is given in Fig. 3. In this figure, the conversion loss of the receiver is normalized to that of the data point with the lowest loss. Excluding the first data point which shows significant deviation from linearity, a value of 40.8 K is obtained for T_X, the standard deviation of the fit being 0.6 K. This example demonstrates two desirable properties of the alternate formulation. First, the boundary between low and high LO drive is easily identified by noting the departure from linearity. Furthermore, the approach also gives an indication of the confidence for the value of T_X.

From equation (2), we note that T_X can be interpreted as the part of the measured receiver noise temperature that is independent of the mixer conversion loss. Obviously, this points to noise introduced in front of the SIS mixer, in line with the theory of Ke and Feldman. However, we can also argue that there may be some residual contribution from the mixer itself. To follow this argument, we break the mixer noise temperature, T_M, into a part that is invariant with conversion loss and a part that is linearly dependent on conversion loss:

$$T_M = T_M^{(0)} + L_C T_M^{(1)} \qquad (3)$$

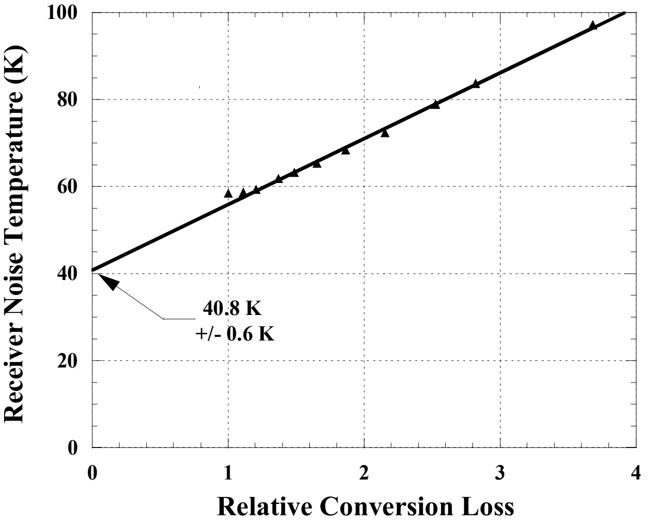

Fig 3 Use of alternate formulation of the technique of intersecting lines. Receiver noise temperature is plotted against conversion loss, with the conversion loss normalized to the first data point. A straight line is fitted to the data points except the first point which shows significant deviation from linearity. The error of the intersecting temperature is estimated by computing the root-mean deviation of the data from the fitted line.

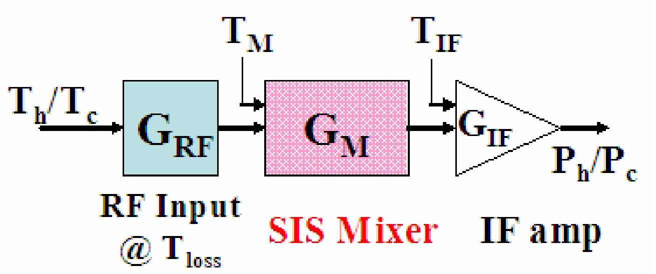

Fig. 4 Schematic of an SIS receiver with RF losses in front of the mixer.

Fig. 4 is a schematic representation of an SIS receiver with a lossy optical element, at a temperature of T_{loss}, in front of the mixer. The receiver noise temperature of such a receiver can be written as:

$$T_R = \left(\frac{1}{G_{RF}} - 1\right)T_{loss} + \frac{T_M}{G_{RF}} + \frac{T_{IF}}{G_{RF}G_M} \qquad (4)$$

After substituting equation (3) and noting that $G_C = G_{RF} G_M G_{IF}$, we obtain

$$T_R = (\frac{1}{G_{RF}} - 1)T_{loss} + \frac{T_M^{(0)} + L_C T_M^{(1)}}{G_{RF}} + \frac{G_{IF} T_{IF}}{G_C} \tag{5}$$

Comparing with equation (2), we can conclude that

$$T_X = (\frac{1}{G_{RF}} - 1)T_{loss} + \frac{T_M^{(0)}}{G_{RF}} \tag{6}$$

IV. DETERMINING OPTICAL LOSSES

In general, optical losses are incurred at different points along the beam of the receiver, such that noise is injected from noise sources at different temperatures. It is, therefore, quite difficult to derive a model of the overall optical losses in front of an SIS receiver based on a set of simple Y-factor measurements. However, using a set of measurements with and without an optical element, we would be able to deduce the losses incurred by that particular optical element. Let G_{optics} be the insertion gain introduced by an optical element placed in front of the hot/cold input loads, and let T_{optics} be the physical temperature of the element. Equation (6) can be generalized to accommodate such a situation:

$$T_X^{'} = (\frac{1}{G_{optics}} - 1)\, T_{optics} + (\frac{1}{G_{RF}} - 1)\, \frac{T_{loss}}{G_{optics}} + \frac{T_M^{(0)}}{G_{optics}\, G_{RF}} \tag{7}$$

$T_X^{'}$ represents the intersecting temperature obtained by the technique of intersecting lines in the presence of the added optics element, while T_X is the intersecting temperature without the added optics element. On substituting (6) into (7), and after some manipulations, we obtain an expression for the insertion gain of the optics element.

$$G_{optics} = \frac{T_X + T_{optics}}{T_X^{'} + T_{optics}} \tag{8}$$

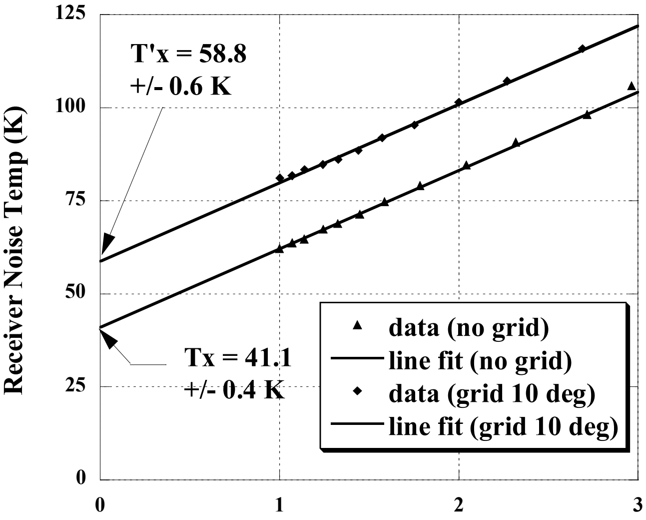

Fig 5 Determination of the optical loss introduced by an optical element using the method of intersecting lines through equation (8).

Fig. 5 illustrates how equation (8) was used to derive the insertion gain of a wire grid placed at 45 degrees to the input beam of a 270 GHz SIS receiver, the grid having been rotated by 10 degrees from the position of minimum loss, which yields an effective projected angle of 14 degrees. From the pair of fitted lines, the insertion loss of the wire grid was found to be 0.950(±0.005), compared to a theoretical value of 0.941(±0.007). It can be argued that the insertion gain of optical components can be determined more simply by a pair of Y-factor measurements with and without the element. However, the simple Y-factor measurement does not afford an estimation of error. Furthermore, the two measurements need to be done at the same bias current, which could be tricky if the optical component under test has poor reflection.

V. NATURE OF THE INTERSECTING TEMPERATURE

When the technique of intersecting lines is applied to a higher frequency SIS receiver, it is found that that the value of T_X generally increases. Fig. 6 shows the data from the measurement of a 678 GHz SIS receiver in the lab [8]. T_X was found to be about 82 K. If this is completely attributed to room temperature optical losses, then it will require more than 1 dB of losses and if such losses occurred at a lower temperature, the hypothetical insertion loss would become even higher. This projection is not compatible with the experimental setup, which consisted of very simple optics setup.

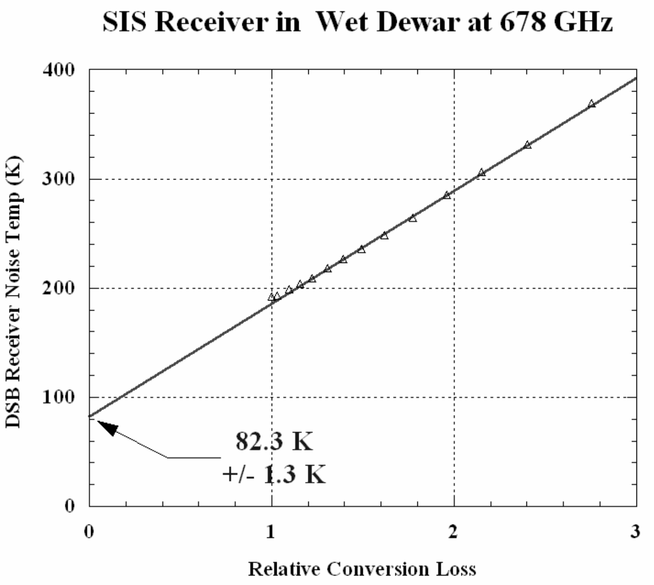

Fig 6 Determination of the intersecting temperature for a 678 GHz SIS receiver.

Since the technique of intersecting line is based upon the Rayleigh-Jean method, quantum noise is included in the measured receiver noise temperature. As the quantum noise is invariant with the mixer conversion efficiency, it is clear that the quantum noise contributes to the intersecting temperature. Contrary to the current belief that the quantum noise comes from outside the receiver, we argue that since optical elements can be added in front of any SIS mixer, the quantum noise should be accounted for at the input of the mixer, and be included in the mixer noise temperature. Thus equation (6) can be written as:

$$T_X = (\frac{1}{G_{RF}} - 1)T_{loss} + \frac{1}{G_{RF}}\left[T_M^{(0)} + \frac{h\nu}{2k}\right] \qquad (9a)$$

The introduction of $h\nu/2k$ would partially explain why the intersecting temperature is higher for high frequency SIS receiver.

Another important consideration is that for noise measurements, the result is affected by the average match of components. Bearing in mind that SIS mixers do not generally have very good match for both the signal port or LO port, and that lossy optical elements introduce additional reflection, the components of noise temperature may have to be corrected for reflection effects.

In Fig. 7, we show two sets of measurement data obtained from the same measurement setup but using 2 different SIS mixer chips with slightly different tuning circuits. At the LO frequency of 270 GHz, both chips produce a noise temperature as low as 60 K. However, the values of T_X derived from the 2 sets of data are different. In order to explain this phenomenon, we propose that the input reflection coefficient of the mixer should be included in equation (9a). The proposed modification is given as follows:

$$T_X = (\frac{1}{G_{RF}} - 1)T_{loss} + \frac{1}{G_{RF}} \cdot \frac{1}{1-\left|\Gamma_{in}\right|^2} \cdot \left[T_M^{(0)} + \frac{h\nu}{2k}\right] \qquad (9b)$$

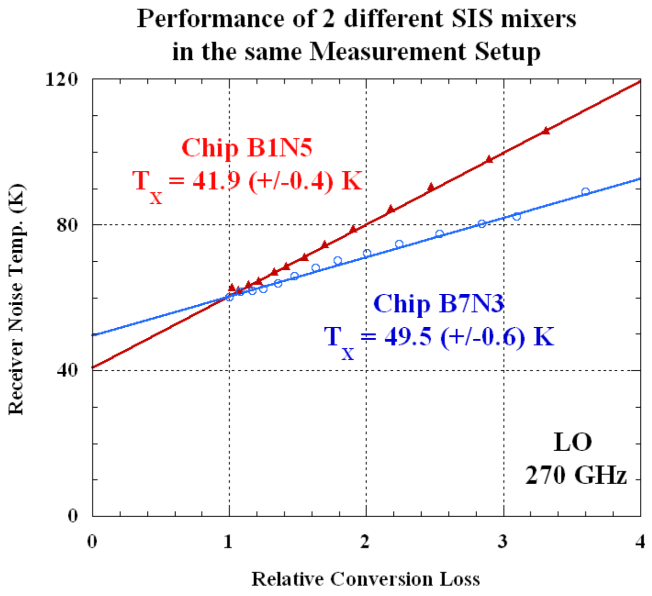

Fig. 7 Applying the technique of intersecting lines to two sets of receiver noise measurement data involving 2 different mixer chips mounted in an identical setup. Both chips show similar optimal noise performance but they yield different intersecting temperature.

Finally, we have studied the effect of dark current on the value of T_X . One of the SIS mixer chips mentioned above was cooled to a lower temperature by pumping on the helium bath. The leakage current at the bias point was reduced from 5.2 µA to 3.4 µA as the helium bath temperature was lowered from 4.2 K to 2.5 K. The leakage ratio of the device changed from 14 to a ratio in excess of 20. As can be seen in Fig. 7, this reduction in dark current does not translate into any significant reduction of the value of T_X. This suggests that $T_M^{(0)}$, the residual value of mixer noise temperature which is invariant with conversion loss, may be quite small.

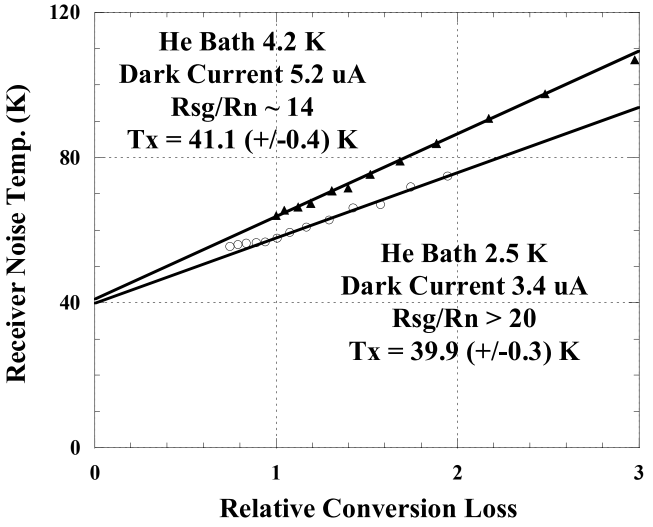

Fig. 8 Effect of dark current on the intersecting temperature. The temperature of the Helium bath of the cryostat was lowered to change the dark current of the SIS junction at the operating point. While an improvement of both the conversion loss and receiver noise temperature was observed, the change in the intersecting temperature is small.

CONCLUSIONS

An alternate formulation for the Technique of Intersecting Lines has been proposed and derived formally. Our approach generally yields a very good linear fit in a plot of receiver noise temperature versus mixer conversion loss, with the intersecting temperature, T_X, appearing as the y-intercept of the fitted line. This new formulation also provides an indication of experimental error.

The intersecting temperature, T_X, arises in part from optical losses in front of mixer and the part of mixer noise temperature, T_M, that is independent of conversion gain. Furthermore, we have shown that the magnitude of optical losses may be estimated from T_X.

From our experimental investigations, we propose that quantum noise is a constituent of T_X, and suggest that the return loss of the mixer can affect T_X, whereas leakage current does not. An equation embodying these results is proposed. Therefore, the intersecting temperature may provide us with useful information on the operation of the SIS receiver.

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