XII. NOISE IN ELECTRON DEVICES

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A. AN IMPROVED MEASURE OF NOISE PERFORMANCE

We propose as a measure of the noise performance of amplifiers the expression

$$M = \frac{F - 1}{1 - \frac{1}{G}}$$

where F is the spot-noise figure and G is the available power gain. The quantity M, henceforth called the noise measure, has certain appealing properties that are stated here without proof. (Some of the proofs will appear in the IRE Convention Record, Part 2. Circuit Theory, 1956 National Convention. Another publication is being prepared in which all of the proofs will be presented.)

1. The noise measure M of an amplifier, consisting of two stages of noise measures M_1 and M_2 in cascade, has a value intermediate between M_1 and M_2. In the particular case in which $M_1 = M_2$, we have $M = M_1 = M_2$.

2. The noise measure of a cascade of amplifiers is least, if the stage with the lower noise measure is used as the input stage. (We cannot make a similar statement about the noise figure of a cascade, if the gain of either of the two stages is low.)

3. The smallest noise measure that can be achieved with a given two terminal-pair amplifier by using a lossless (reciprocal or nonreciprocal), or a lossy (reciprocal), transformation of it in order to generate a new two terminal-pair amplifier is equal to the smallest positive eigenvalue of the matrix (1)

$$-\frac{1}{2} \overline{EE^+}(Z + Z^+)^{-1}$$

where E is a column matrix that comprises the two open-circuit noise-voltage amplitudes of the amplifier, the superscript + indicates the operation of the complex-conjugate transpose of a matrix, the bar stands for an ensemble average, and Z is the impedance matrix of the network.

4. The eigenvalues of the matrix $-\frac{1}{2} \overline{EE^+}(Z + Z^+)^{-1}$ remain invariant under a lossless transformation of the amplifier (1). This fact is in agreement with the intuitive notion that a lossless transformation cannot change the inherent noise of a network. Indeed, a lossless transformation can always be removed by a realizable, inverse, lossless transformation.

5. The smallest noise measure that can be achieved with a set of n amplifiers by the most general lossless interconnection of them is equal to the noise measure achievable with the best amplifier of the set. The best amplifier is the one with the

lowest positive eigenvalue of the matrix $-\frac{1}{2}\overline{EE^{+}}(Z + Z^{+})^{-1}$. The use of lossy inter-connections cannot improve the result, even if the added loss is noise-free.

6. For the class of amplifiers with unilateral gain U greater than 1 (ref. 2), the minimum noise measure can always be achieved by using a lossless network to render the amplifier unilateral and then placing a suitable, lossless, mismatching network at the input. It is almost a certainty that unilateralization is unnecessary and that the theorem applies to any two terminal-pair amplifier with available gain; but more work must be done to complete the proof.

The authors derived the results given above after they had decided to use the noise measure, instead of the noise figure, as a measure of the noise performance of an amplifier. Since so many appealing properties of the noise measure have been found, little doubt remains that the noise measure is more suitable than the noise figure as a measure of noise performance. It should be stressed that the main difference between the two measures arises when the gain is very low.

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References

1. Quarterly Progress Report, Research Laboratory of Electronics, M. I. T. , Jan. 15, 1956, p. 46.

2. S. J. Mason, Power gain in feedback amplifiers, Technical Report 257, Research Laboratory of Electronics, M. I. T. , Aug. 25, 1953.

B. DIODE MIXER PERFORMANCE AS A FUNCTION OF TEMPERATURE

The dc characteristics of a number of commercially available germanium and silicon diodes were investigated at low temperatures in order to determine whether or not any improvement is possible in mixer conversion efficiency. All of the diodes that were tested can be placed in one of the two broad classes — "junction" or "point-contact." The junction class contains not only grown and fused junctions but also bonded-point contacts. The point-contact class includes diodes that are normally referred to as point-contact diodes, despite the fact that some process, such as welding (but not bonding), may be used in their manufacture. About thirty diodes were measured, including the following types: 1N21, 1N23, 1N34, 1N38, 1N64, 1N67, 1N82, 1N96, T7G, HD6005, and HD6007.

At room temperature (300°K), the junction diodes, and some of the bonded diodes, exhibited a reasonable fit over a moderate range to the predicted diode equation

$$I = I_{s}\left[\exp\left(\frac{qv}{kT}\right) - 1\right] \tag{1}$$

where I_{s} is the reverse saturation current and v is the applied voltage. Lowering the

temperature of a device governed by Eq. 1 produces a number of predictable effects that tend directly to increase conversion gain. The incremental forward conductance in the normal operating region and the sharpness of the "knee" of the forward characteristic are both greater at lower temperatures. The reverse conductance is reduced considerably because of the exponential decrease with temperature of the saturation current.

For example, the dc characteristic of a Transitron T7G germanium bonded diode at liquid-nitrogen temperatures predicts a conversion loss that approaches within 1 db of the theoretical minimum conversion loss (3 db) for the matched image-termination case. This result presupposes that the low-temperature increase of diode resistance can be tolerated in the mixer.

When the point-contact diodes were tested at temperatures down to that of liquid nitrogen we did not observe any improvement of the dc characteristic that would be likely to improve mixer operation. In fact, our general conclusion is that low-temperature operation results in degraded mixer performance for any point-contact diode. This result is particularly true of conventional mixers, such as types 1N21 or 1N23, wherein we suspect that considerable physical movement of the point takes place on the surface of the silicon with lowered ambient temperature.

If we assume that the dc characteristics are the major factor in determining mixer performance at high frequencies, low-temperature mixer operation appears to be effective for diodes that behave like junctions, and ineffective for point-contact diodes. Unfortunately, the foregoing assumption, and the observed data, put an upper-frequency limit on improved mixer performance if the choice of diode is limited to the junction class. The increased barrier capacitance and hole storage effects of a junction or bonded-point diode would probably place the limit of highest usable frequency at about 500 mc.

In terms of mixer performance based upon dc characteristics alone, there does not appear to be an existing commercial diode that gives promise of yielding improved high-frequency mixer efficiency at low temperatures. The possibility of making special diodes for low-temperature operation requires further study.

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