# Letters to the Editor

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## Measurement of Noise in a Maser Amplifier*

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ONE of the principle sources of interest in maser amplification[1] is the belief, based on theoretical considerations, that this type of amplification is rather free of excess noise, and can be made much more sensitive than conventional amplifiers in the microwave range. The ammonia beam maser is expected, for example, to have a limiting noise temperature near 1°K if its cavity and associated waveguide are sufficiently cold and well designed, or otherwise a noise temperature limited by the design and actual temperatures of its cavity, input, and output circuits.[2] A superregenerative amplifier of this type has been constructed and its noise figure or effective noise temperature measured under a variety of conditions. An amplifier with a noise figure of −2.0 db has been obtained. Furthermore, the measurements give an upper limit corresponding to radiation at 30°K on any noise in excess of that theoretically expected.

The ammonia beam passed through a cavity operating in the $TM_{010}$ mode which was split longitudinally and the two halves electrically separated. The beam was sufficiently intense to produce oscillations. However, when a small voltage was applied across the two halves of the cavity, the oscillations were quenched. A quenching frequency of about 600 cps was used, with zero applied voltage and hence increasing buildup of oscillations for about $\frac{1}{8}$ of the cycle. During the remainder of the cycle, about 20 volts were applied across the cavity to quench the oscillations. Any much more rapid quenching cycle would allow oscillations to begin from the previous pulses, presumably retained as a signal by the molecules, rather than from noise. The above operating conditions allowed oscillations to increase exponentially from noise by a factor of $10^6$ or $10^7$, after which they were easily amplified in a conventional 30-Mc IF amplifier.

A single coupling hole to the cavity was used, with input and output circuits separated by a T junction. A noise signal from a gas discharge tube was introduced through a calibrated attenuator, and the resulting variation in output power observed on a meter after rectification. In most cases, the increase in input signal required to double the output power was determined. Several cases were measured as follows:

1. With a coupling hole of such size that losses from the cavity through the hole were 1/2.65 as large as other losses within the cavity ($Q_1/Q_0=2.65$), and with cavity and input and output circuits at room temperature (300°). The increase in noise power required in the input waveguide to double power output from the maser was found to correspond to 1370°K, or 6.6 db above room temperature. Theoretical results predict for this case a required input of 1100°K, or a 5.6 db noise figure.

2. With $Q_1/Q_0=1.15$, and with cavity and attached circuits at room temperature. The increase in input power for doubling the output was 570°K, giving a noise figure of 2.8 db above room temperature. In this case, theory would predict 640°K or a 3.3 db noise figure.

3. With $Q_1/Q_0=0.61$, and the cavity and attached circuits at room temperature. The increase in input power for doubling the output was 510°K, giving a noise figure of 2.3 db. Theory predicts for this case 490°, or 2.1 db.

4. With $Q_1/Q_0$ approximately 0.6, and cavity and input and output loads cooled to near liquid nitrogen temperature. In this case, the actual temperature of radiation in the cavity with no beam present should have been approximately 110°K, and the theoretical noise figure −2.3 db based on room temperature. This corresponds to doubling the output power with an increase in input signal corresponding to 176°K. Experimentally it was found that an input of 187°K would double the output, giving a noise figure of −2.0 db based on room temperature (300°K). In this case, the noise signal introduced was radiation from an attenuator at room temperature rather than from the gas discharge. Table I summarizes these results.

Case 4 demonstrates an actual microwave amplifier with a noise temperature less than room temperature, which has long been taken as a type of limit for an amplifier. However, perhaps of more basic significance is the upper limit which can, as the result of the above measurements, be set on any noise generated within the maser cavity in excess of theoretical expectations.

TABLE I. Comparison of theoretical noise figures (based on 300°K) of maser amplifier and experimental results. See text for definition of noise figure.

| Case | Theoretical noise figure in db | Experimental noise figure in db |
|---|---|---|
| 1 | 5.5 | 6.6 |
| 2 | 3.3 | 2.8 |
| 3 | 2.1 | 2.3 |
| 4 | −2.3 | −2.0 |

The accuracy which results from all of these measurements is probably about 0.5 db, giving an upper limit to the excess noise of about 30°K. This is a small amount of noise and indicates that maser amplifiers can indeed be very sensitive, but it is still about 25 times the limit set by spontaneous emission.

We are indebted to J. P. Gordon for the loan of a cavity with which some of the measurements were made. We wish also to acknowledge helpful conversations with J. P. Gordon, J. C. Helmer, and M. L. Stitch, who have been engaged in somewhat similar measurements.

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[1] Increasing interest in maser-type amplification perhaps makes appropriate a brief statement of very early developments in this field. An important preliminary step was the experiment of E. M. Purcell and R. V. Pound [Phys. Rev. **81**, 279 (1951)] on nuclei oriented in magnetic fields which demonstrated "negative temperatures" and stimulated emission rather than absorption. Ideas on the use of stimulated emission for amplification have arisen independently in at least the three different places indicated below.

J. Weber, of the University of Maryland, discussed the possibility of amplification by stimulated emission at the Institute of Radio Engineers Electron Tube Conference in Ottawa, June, 1952. His paper on this subject in 1953 [Trans. Inst. Radio Engrs. Prof. Group on Electron Devices **3**, 1 (1953)] gives some of the basic theoretical ideas, and several interesting suggestions concerning this type of amplification. N. G. Basov and A. M. Prokhorov of the Lebedev Institute mention [Doklady Akad. Nauk S.S.S.R.) **101**, 47 (1955)] having pointed out "the theoretical possibility of constructing a molecular generator" at an All-Union Conference on Radio-Spectroscopy in May, 1952. In 1954, they gave a number of design considerations for a beam-type device [J. Exptl. Theoret. Phys. U.S.S.R. **27**, 431 (1954)]. The possibility of a maser oscillator was also discussed by A. H. Nethercot of Columbia on behalf of one of the authors (C.H.T.) at a Symposium on Sub-Millimeter Waves at the University of Illinois in May, 1951. Design of a beam-type device was outlined in the Columbia Radiation Laboratory Quarterly Progress Report, December 31, 1951 (unpublished). Subsequent issues contain further information on its development, and successful operation was reported in 1954 by Gordon, Zeiger, and Townes [Phys. Rev. **95**, 282 (1954)].

[2] Gordon, Zeiger, and Townes, Phys. Rev. **99**, 1264 (1955); Shimoda, Takahasi, and Townes, J. Phys. Soc. Japan **12**, 686 (1957); M. Muller, Phys. Rev. **106**, 8 (1957); R. V. Pound, Ann. Phys. **1**, 24 (1957); M. W. P. Strandberg, Phys. Rev. **106**, 617 (1957).

## Three-Dimensional Potential Well*

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In the study of high-frequency gas discharges at very low pressures, this laboratory has come upon an interesting and perhaps very useful phenomenon. A three-dimensional potential well has been created for positive charges.

The mechanism by which a potential well is established is as follows. Consider the idealized situation of Fig. 1 which is meant to represent multipacting between two disk electrodes. Here the electrons which cross the electrode separation in one-half cycle of the applied rf power are shown as a thin disk of charge.[1] The magnitude and frequency of the applied rf power are such that the motion of the ions is negligible due to this cause alone. It can be seen that if an ion is found displaced from the center plane toward either electrode, then the field due to the disk of electrons will exert a force on the ions which when averaged over a complete cycle will be directed toward the center position. It can also be seen that if an ion is displaced radially from the axis of the cylinder, the force exerted on it by the disk of electrons will be toward the axis. Thus, a three-dimensional potential well is formed, the depth of which depends upon the magnitude of the multipacting electron current. Utilizing the above picture, force and

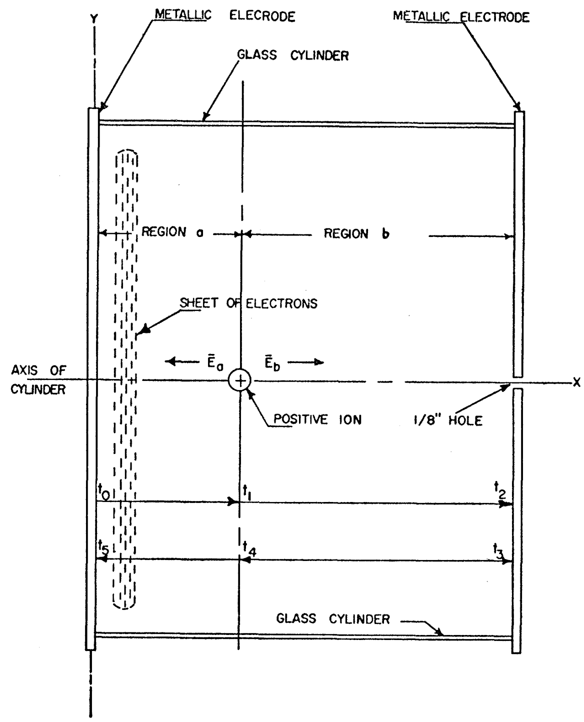


FIG. 1. Idealized representation of electron multipacting between two metallic disk electrodes. Electrons and ions which issue from the ⅛-inch hole have been studied with an energy filter.

potential functions have been calculated and plotted as shown in Fig. 2. Measurements made on apparatus in this laboratory show that there is a 10-microampere electron current through the ⅛-in. hole cut in one of the electrodes when the rf power input was 20 watts. Upon utilizing this 10-microampere figure and the other necessary parameters,[2] a value of the order of 100 electron volts was computed for the potential obtained.

The above calculations neglect the self-potential of the positive ions and can be used only when the pressure in the chamber is very low. If the potential of the ions is to be considered, we may proceed as follows. The time average of the charge density of an elemental