Solid-State Microwave Amplifiers*

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Summary—The maser and the parametric amplifier form a new class of microwave amplifiers which can exploit the properties of bound electrons in a solid. These amplifiers have several common characteristics, among them being their very low-noise performance. This paper reviews the method of operation of these amplifiers, discusses the performance achieved and achievable by the various versions, and points up some of the difficulties involved in effectively utilizing the extremely low-noise figures obtainable. A bibliography is included in which an attempt has been made to include all published papers on masers and parametric amplifiers.

TODAY technology is pressing close on the heels of new fundamental scientific discoveries and in turn, advances in understanding nature rely heavily on the technological exploitation of yesterday's new understanding. This intertwining of physics and engineering is perhaps nowhere so vividly illustrated as in the field of microwave solid state amplifiers. Right now certain forms of the maser must be held in abeyance until we obtain a more thorough understanding of the fundamentals of paramagnetic relaxation. At the same time, the successful operation of low-noise solid-state amplifiers has influenced other fields of physics. The astronomer, Gold, has said that the maser which will soon be attached to Harvard's radio telescope should yield measurements which will prove or disprove the cosmological theory of continuous creation of hydrogen. Here the familiar process of fundamental discovery to technology to new discovery has been telescoped from the usual time interval of decades to, at most, a few years.

There are at present—and I emphasize the words "at present"—two types of solid-state amplifiers at microwave frequencies, the maser and the variable parameter or parametric amplifier. The maser is an acronym coined by Townes [35] to stand for "microwave amplification by stimulated emission of radiation." The parametric amplifier draws its name from the fact that the differential equation which governs its operation has one or more parameters which vary with time. These two amplifiers operate on entirely different principles but they do have certain features in common.

1) They draw their energy from an RF source rather than dc
2) They behave as bilateral negative resistances at the amplifying frequency.
3) They are capable of very low-noise amplification.

Before we investigate each amplifier in more detail, let us examine briefly some of the implications of their common characteristics. First consider their behavior as bilateral negative resistances. In lumped circuit terms they appear as a negative resistance across a resonant LC tank with input and output coupled in. This is shown in Fig. 1. Because this is a negative resistance amplifier, the product of the square root of the power gain and bandwidth is a constant. The magnitude of this constant depends upon the type of amplifier and the material used.

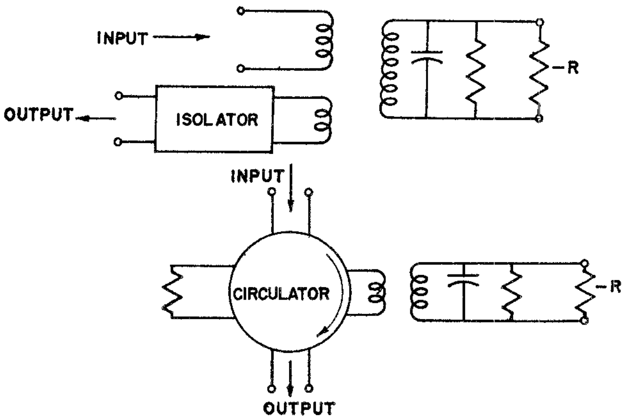

Fig. 1—Schematic representation of a solid-state amplifier as an effective negative resistance, showing its use with an isolator or circulator.

Because the negative resistance is bilateral, the magnitude of both load and source impedance will affect the gain. Thus, for stable amplification independent of the output match, some nonreciprocal element, either a circulator or isolator must be used. These elements serve another purpose also. They prevent thermal noise from a relatively hot load from entering the amplifier, there to be amplified and possibly to destroy the low noise behavior [45].

These new amplifiers, and in particular the maser, offer possibilities of low-noise amplification to a degree heretofore unattainable. The effective noise temperature of the maser can be as low as a few degrees Kelvin [52]. This low a noise temperature can be accomplished only at the expense of complicated external circuitry and use of liquid helium so that it is wise to ask whether such a low temperature is really needed.

To answer that question, let us consider the applications for which one might use a maser. Among these certainly are radio astronomy [46], radar, and scatter communications. Each of these would use a maser to amplify a signal received from an antenna. If now, the effective noise temperature of the antenna and its lead in are many tens of degrees, then an amplifier having an effective noise temperature of a few degrees is obviously of marginal utility in comparison to one ten times as noisy. Fig. 2 shows some measurements taken by J. E.

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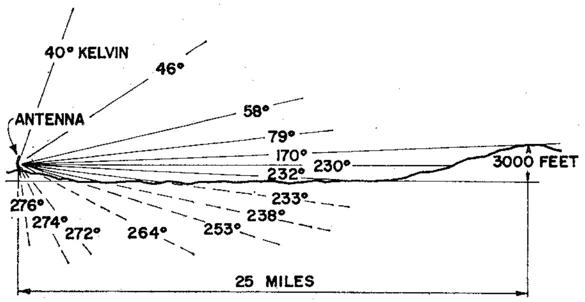


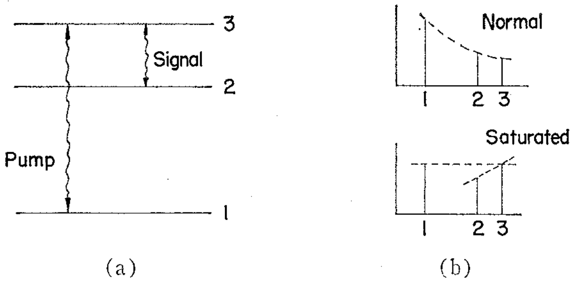
Fig. 2—Antenna temperature at 9270 mc as a function of elevation. The antenna used was an 18-inch parabola. The more-or-less horizontal line indicates the ground contour.

TABLE I*

$$M = \frac{\sqrt{B}}{F-1} \sim \frac{\sqrt{B}}{T_{\text{amp}}}$$

Type of Amplifier	T_{amp} °Kelvin	Bandwidth Mc	M
TWT	360° ($F=3.5$ db)	1000	25.4
Cavity maser	2°	0.4	91.6
Cavity parametric amp	25° (?)	1.0	11.6
TW maser	2°	20 (?)	648
TW parametric amp	25° (?)	300 (?)	201

* Amplifier figure of merit when used in a radiometer at 3000 mc. The question marks indicate reasonable but unobtained performance values.



(a) (b)

Fig. 3—Mechanism of operation of the three-level maser. (a) Energy levels. (b) Populations.

Sterrett of Stanford on antenna temperatures at X band as a function of the angle of elevation. The antenna used was an 18-inch parabola. The solid, more or less horizontal, line represents the ground surface showing a low range of hills some 25 miles away. Notice the minimum temperature measured was 40 degrees Kelvin. Most of this noise was due to side lobes seeing the earth as was shown when two large screens of chicken wire were placed beneath the antenna. With these in place the minimum noise temperature was reduced from 40 to 10 degrees. The same effect might well be achieved by placing the antenna in the center of a lake.

The antenna temperature is not the only limiting factor. If losses are present in the transmission system between antenna and amplifier, another noise source is added. If, for example, the transmission system is at room temperature and has 0.1 db loss, it is an effective noise source at about 7 degrees Kelvin, and if it has 1 db of loss its effective noise temperature is 78 degrees Kelvin.

These figures point up the very stringent requirements on any isolator or circulator which is used in conjunction with the amplifier. Perhaps, in order to make full use of the amplifier capabilities, these elements will have to be cooled also.

For many radio astronomy applications, low amplifier noise figure is not the only consideration. When using the Dicke radiometer system, what is important is the ratio of the amplifier noise temperature to the square root of the amplifier bandwidth. Table I shows a comparison of several forms of solid-state amplifiers with a particular (admittedly the best) low-noise traveling-wave tube. The column on the right gives the figure of merit, which one wants to be as high as possible. The author has marked several numbers in the chart with a question mark to indicate that these are reasonable, although as yet unobtained values. The chart shows several things: first, the relative superiority of the maser over the parametric amplifier; second, the great superiority of the traveling-wave versions of each; and third, just how good the traveling-wave tube is.

This chart does not tell the whole story, however, because, first of all, the noise introduced by antenna side-lobes and lossy lead in, as indicated, sets a lower limit on useful amplifier temperature; and, second, for many radio astronomy applications a narrow bandwidth is required to pick out a particular spectral line. For this last reason, the apparent advantage in favor of the traveling-wave tube and the traveling-wave versions of the maser and parametric amplifier which result because of their increased bandwidth can often not be used.

Let us turn now to a brief discussion of the three-level maser [39]–[44]. The general way the maser operates is illustrated in Fig. 3, where three paramagnetic energy levels are shown with their normal populations given by Boltzmann distribution shown in the upper right hand corner. A strong microwave signal at the pump frequency corresponding to the energy difference between levels one and three saturates the resonance by bringing the populations of these two levels into equality. Under these conditions the population diagram can look somewhat as shown in the lower right hand corner. The population of the highest energy level, three, is greater than that of a lower energy level, two. This situation could be described by a Boltzmann distribution only if the temperature were taken to be a negative quantity. This negative temperature population distribution is now capable of emitting rather than absorbing energy. The magnitude of the negative temperature is also the effective noise temperature of the maser material [27–32].

Cavity-type masers using this principle have been built by the Bell Telephone Laboratories, Lincoln Laboratory, Harvard University, Columbia University, Hughes Aircraft Company, M.I.T., Ewen-Knight Com-

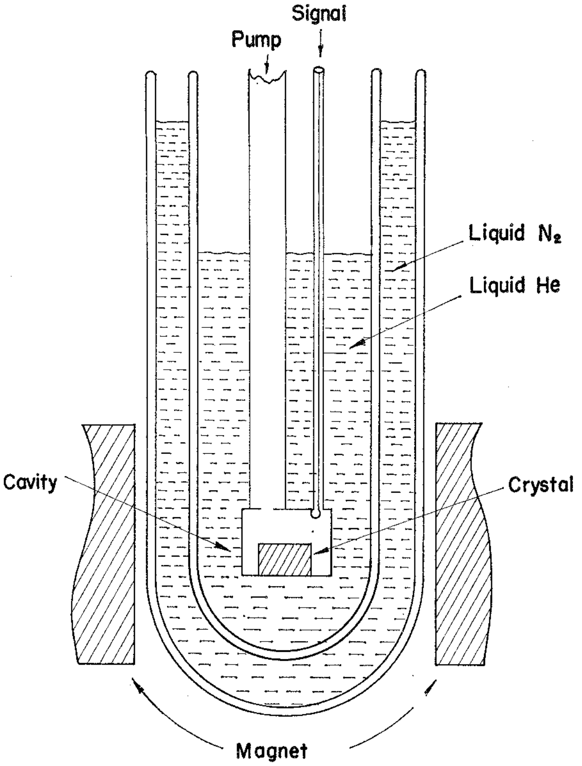


Fig. 4—Diagram of a three-level solid-state maser

pany, Michigan University, A.F.C.R.C., and Stanford University. They have operated at 300, 1400, 3000, 7000, and 10,000 mc, all at liquid helium temperatures. A schematic drawing of a cavity maser is shown in Fig. 4. Here between the pole-pieces which supply the dc magnetic field is an outer Dewar or vacuum flask which contains liquid nitrogen to aid in keeping heat away from the inner Dewar containing liquid helium. Immersed in the liquid helium is a cavity resonant to both the pump and amplifying frequencies containing the paramagnetic crystal. A waveguide supplies the pump power which saturates the upper and lower energy level resonance, and in this drawing a coax serves to feed the incoming signal and return the amplified reflected signal. A circulator (not shown) would be necessary of course to make a practical amplifier.

Typical cavity maser performance has been obtained using a pump power of 1 to 10 mw supplied at 9000 mc. Thirty-db gain at a signal frequency of 3000 mc results with a bandwidth of about 200 kc and a maximum power output of 1 to 10 μw. The noise figure is 0.04 db corresponding to a noise temperature of 3 degrees Kelvin.

Three paramagnetic materials which have been successfully used in three-level masers are single crystals of lanthanum ethyl sulphate $[La(C_2H_5SO_4)_3]$ doped with gadolinium [57], potassium cobalticyanide $[K_3Co(CN)_6]$ [10],[50] and sapphire $[Al_2O_3]$, both doped with chromium [55]. Fig. 5 illustrates the typical variation of the magnetic energy levels of chromium in $K_3Co(CN)_6$.

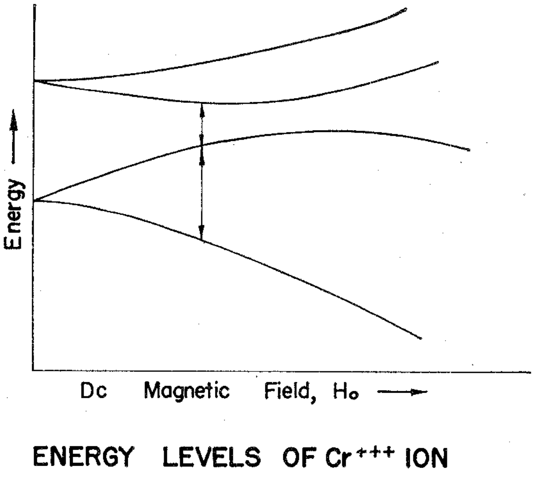


Fig. 5—Typical variation of energy levels of Cr^{+++} in $K_3Co(CN)_6$ with varying dc magnetic field.

These materials are by no means the only ones capable of being used. The double nitrates appear attractive as host crystals and other dopants in sapphire may have advantages. Of the three materials which have been used, the chromium doped sapphire (ruby) seems to be the best. It has favorable relaxation times and has the largest zero field splitting, which is a measure of how high in frequency the maser can operate.

As can be seen, there are three big disadvantages of this amplifier; first, it must be operated at liquid helium temperatures; second, it has an exceedingly small bandwidth; third, energy must be supplied at a higher frequency than that which is amplified. Can we reasonably expect that future developments will overcome these drawbacks?

The answer to whether we can eliminate the liquid helium is still unclear. We can not operate at much higher temperatures with the materials we now know, but the ultimate answer must await better understanding of the spin-lattice relaxation process—the way that microwave energy ultimately is transferred to heat. Possibly, if our paramagnetic crystals achieve the same degree of purity as transistor materials, we might be able to operate at higher temperatures.

The answer to the question of whether we can increase the bandwidth is an unqualified, "yes." The method is simple and involves merely the use of a traveling-wave circuit rather than a cavity. To see why this improves bandwidth, consider the cavity as simply a circuit which allows a wave to bounce back and forth between the walls many times before it dies out. Each time the wave passes through the crystal it is amplified very slightly; but if the cavity Q is high, it makes a sufficient number of passages through the crystal that the small amplitude increments of each passage add up to large gain. The price one pays is, of course, a very small frequency range over which the waves can bounce back and forth without phase interference effects destroying them.

In a wave guide filled with crystal, the wave passes through the crystal only once so the gain is low but the bandwidth can be the full bandwidth of the paramagnetic resonance line, typically 20 to 50 mc. We can increase the gain per unit length by decreasing the group velocity, which can be looked upon as providing the wave with a certain amount of bouncing back and forth as it achieves its net forward progress. The noise figure of the traveling wave version should be the same as that of the cavity maser.

The gain in db of such a traveling wave maser can be written as

$$G = \frac{27N}{Q_m(v_g/c)}$$

where N is the length of the structure in free space wavelengths, Q_m is the magnetic Q, and v_g/c is the ratio of group velocity to velocity of light. The magnetic Q is a function of the properties of the paramagnetic material and the filling factor, *i.e.* how effectively the RF magnetic field fills the crystal. The value of Q_m is typically 500–2000.

Recently Scovil[1] reported a traveling-wave maser using gadolinum doped ethyl sulphate in a filter structure composed of an array of wires shorted along one edge and placed between the two broad faces of a waveguide. The amplifier operated at 6.3 kmc with pumping power supplied at 9 kmc and had a gain of 30 db in about 7-cm length. The bandwidth was 10 mc with the center frequency capable of being tuned over a 350-mc band. The addition of garnet allowed nonreciprocal propagation so that the amplifier had 40-db loss in the reverse direction. One of the most interesting properties of this amplifier was its large signal behavior. The amplifier did not saturate until the output power was 30 milliwatts!

What about the final disadvantage, that of requiring pump power at a frequency higher than the signal? Can this restriction be eliminated? The answer is, "yes." For certain special materials with many energy levels it appears possible to pump up stairstep-wise and then fall back many levels to amplify at a higher frequency.

Let us turn now to the parametric amplifier. Unlike the maser, this amplifier operates on purely classical principles. As a matter of fact, the device which we would now call a parametric oscillator was studied by Lord Rayleigh in the last century. We can illustrate how it works quite simply by Fig. 6. Here is a simple LC resonant circuit in which we imagine we can physically grasp the condenser plates and pull them apart. At the upper right is shown the voltage across the condenser as a function of time. Imagine that when the voltage is a maximum, we suddenly pull the plates apart. We work to separate the charge and to increase the voltage. Now, just as the voltage goes through zero and there is no charge on the plates, we push them back to their original position. No work is done and the voltage is unchanged. When the voltage is a negative maximum, we again pull the plates apart, and so on. In this way a signal at the resonant frequency is amplified by the changing capacitance. By coupling in an input circuit and a load, we have a parametric amplifier. Note the following three points, however.

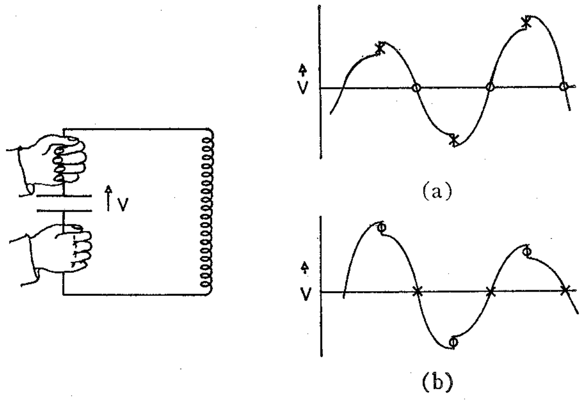


Fig. 6—Illustration of a parametric amplifier. The crosses indicate the sudden pulling apart of the capacitor plates, and the circles, the sudden pushing together. (a) Illustration of the phase relations suitable for growth of the voltage across the capacitor. (b) The attenuating effect of the opposite phase relations.

First, our pushing or pulling, that is the capacitance variation, must be at a frequency which is twice that of the resonant frequency of the LC circuit.

Second, in order to amplify, we must be careful to pull apart when the voltage is maximum and push together when it is zero. If we do the opposite, the signal is attenuated. Another way of saying this is that this amplifier is phase sensitive. The phase of the capacitance variation frequency (we shall call this the pumping frequency) must be adjusted relative to the phase of the signal in order to amplify.

Third, we might just as well have varied the inductance, rather than the capacitance, and achieved the same result.

This circuit is often called a two-frequency parametric amplifier. Its phase sensitivity is usually a drawback, but for certain applications it can be turned into an advantage.

As an example, consider what happens when we introduce a signal whose frequency is slightly different from ω, the value which is just half the pumping frequency. We can treat this signal as though it were at the exact half frequency ω but had a time varying phase at the difference frequency. Thus, as the phase changes, the amplifier, as we have seen, alternately amplifies and attenuates. The output then is an amplified signal, amplitude modulated at the difference frequency. Another way of describing this is that if the incoming signal is treated as a single sideband, the amplifier inserts the other sideband. This behavior, coupled with low-noise characteristics, makes this form of the amplifier attractive for use in doppler radar receivers and in recep-

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[1] H. E. D. Scovil, "Some performance characteristics of a solid state maser," presented at the Congres Internationale sur la Physique de l'Etat Solide et ses Applications à l'Electronique et aux Telecommunications, Brussels, Belgium; June, 1958.

tion of single sideband transmission, as employed in scatter communications.

Since the device either amplifies or attenuates, depending upon the phase relations between pump and signal, it can be looked upon as a two-state element, making it suitable for computer use. Indeed, Japanese workers have recently used a low-frequency version in an experimental computer [98].

For most applications, however, this phase sensitivity is a disadvantage. We can overcome this sensitivity by adding another resonant circuit, termed the idling circuit. This is shown in Fig. 7. Here we have a circuit resonant at the signal frequency ω_1 and a circuit resonant at the idling frequency ω_2. The two circuits are coupled together by a capacitance which is varied at a frequency ω_3, which is the sum of the two resonant frequencies ω_1 plus ω_2. The presence of the idling circuit introduces another degree of freedom, and the voltage developed across it will adjust itself in phase so that work is done by the capacitance variation causing both the signal and idling voltages to grow. Again, by coupling an input circuit and load into the signal circuit, we can make an amplifier. Also, by coupling a load into the idling circuit we can make an amplifying frequency converter.

So far, nothing has been said about how one obtains the variable capacitance or, what is equivalent, a variable inductance at microwave frequencies. The original microwave parametric amplifier proposed by Suhl [90] used ferrite as the variable element. Since then, others have proposed and successfully built parametric amplifiers using electron beams [93], [94], [108], [109] and back-biased semiconductor diodes [98], [99]–[102]. Other proposals for the variable element have been the use of ferroelectric materials and cyclotron resonance in semiconductors. Independent of the particular embodiment, however, one can write a general noise figure and gain-bandwidth expression for the amplifier [83], [84].

The sources of noise are threefold: thermal noise, shot noise, and random capacitance or inductance fluctuations in the variable element. Of these three, only the thermal noise appears to be of any importance in the solid-state versions of the parametric amplifier.

With only thermal noise, the noise figure for a parametric amplifier with circulator may be written

$$F = \frac{\omega_p}{\omega_i} \frac{Q_{\text{ext}}}{Q_l},$$

where

ω_p = pump frequency
ω_i = idling frequency
Q_{ext} = the external Q
Q_l = the loaded Q.

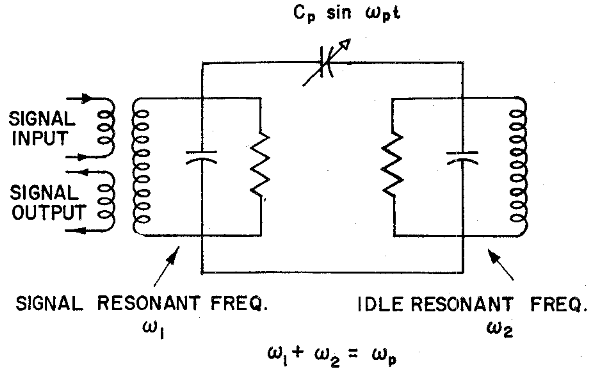


Fig. 7—A two-tank parametric amplifier.

Thus, for a low-noise figure, one wants a low ratio of pumping-to-idling frequency, a high ratio of pumping-to-signal frequency, and close coupling of load to cavity. In the limit of negligible cavity and variable element losses, this Q ratio goes to unity and the minimum noise figure is then

$$F_{\min} = \frac{\omega_p}{\omega_i}.$$

Both of these expressions assume all elements are at the same standard temperature. If the cavity is cooled the appropriate temperature ratios must be employed.

The power-gain, fractional bandwidth product of the cavity version can in most cases be written as

$$G^{1/2} \frac{\Delta f}{f} \cong \frac{\omega_i}{\omega_s} \frac{1}{Q_i},$$

where

ω_i = idling frequency
ω_s = signal frequency
Q_i = idling circuit Q.

(If a circulator is employed, the gain-bandwidth is improved by a factor of two.)

This expression points up the desirability of having a large ratio of idling-to-signal frequency not only for low noise behavior, but also for large gain bandwidth.

As an example of the performance to be expected, this last expression would indicate that for a gain of 20 db, a parametric amplifier having an idling circuit Q of 100 would have a bandwidth of the order of a few tenths of a per cent.

Let us now turn to a discussion of the characteristics of the ferrite and semiconductor diode versions of the parametric amplifier. Hogan has already discussed in detail the characteristics of ferrites which make them suitable for use in these amplifiers, and so the author shall attempt only to assess their advantages and drawbacks relative to the semiconductor diode.

First, we can say that the usual ferrites are not attractive in this application. Their large line widths necessitate the use of unreasonably large amounts of pumping power, of the order of kilowatts. It is the newer garnets, with their narrow line widths, to which we must turn for practical amplifier materials. Even here, it is only the single crystal form which allows the pumping power to be reduced below several tens of watts.

The single crystal garnet, when used in the electromagnetic version, that is when both amplifying and idling modes are cavity resonances, still requires several watts of pumping power. It is only the semi-static or magnetostatic forms, in which one or both resonances are internal spin-wave resonances [115], [116], which allow the pumping power to be reduced below the watt level. It is still probably too early to assess the noise and gain-bandwidth capabilities of these versions. The nature of the loss mechanism of the spin-wave resonances is only imperfectly understood. It is fair to say, however, that the single-crystal garnet amplifier using spin-wave resonances is the only attractive form of the ferrimagnetic version, and that in the present state of the art it offers no advantages over the semiconductor diode. It is possible that as our knowledge improves, we shall find ways of making ferrimagnetic amplifiers with lower noise figures than those of the diode versions. To date, this is not the case.

Let us now consider the diode amplifier. A point contact or junction diode when back-biased has an equivalent circuit shown in Fig. 8. It is composed of a barrier capacitance C_D, which is voltage sensitive in series with a constant spreading resistance R_s. The voltage sensitive barrier resistance, which shunts the barrier capacitance, is so large in the back-biased condition that it can be neglected. Typically the barrier capacitance varies as the square root or cube root of the voltage across it, as is shown in the figure.

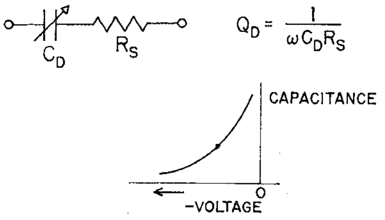


Fig. 8—The equivalent circuit and capacitance variation for a back-biased semiconductor diode.

The Q of the diode, the measure of energy stored to power dissipated, is $1/\omega CR$. It is this quantity which determines the noise performance of the amplifier. If the diode Q is low, the ratio of external Q to loaded Q can not be made small and, as we saw, the noise figure is directly proportional to this quantity.

To give an idea of the sort of performance which has been obtained, the characteristics of a diode parametric amplifier which was constructed a few months ago is mentioned [99]. This amplifier used a rectangular brass box as a cavity whose cross section is shown in Fig. 9. A photograph of this amplifier appears in Fig. 10. A germanium junction diode was supported between two posts in the center of the cavity, and by means of tuning screws, the cavity was made resonant at 1200, 2300, and at the sum frequency 3500 mc. A loop shown on the right of Fig. 10 served to couple in pumping power at 3500 mc causing the diode capacitance to vary at this frequency. With about 70 mw of pumping power, the device would oscillate at 1200 and 2300 mc with an output power of about 2 mw. With slightly reduced pumping power, we were able to amplify at either of the two frequencies. Using it as an amplifier at the lower frequency, we obtained a bandwidth of about 1 mc for 20-db net gain. At 16-db gain, the measured noise figure was less than 4.8 db.

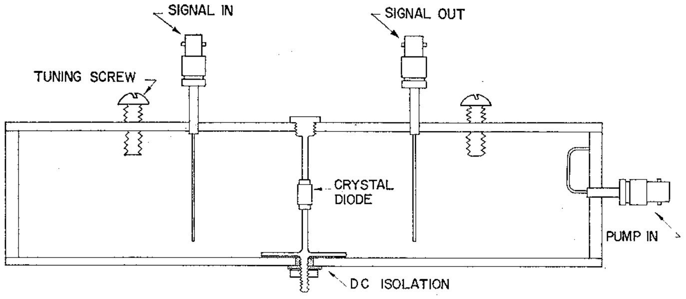


Fig. 9—Cross section of an experimental parametric amplifier.

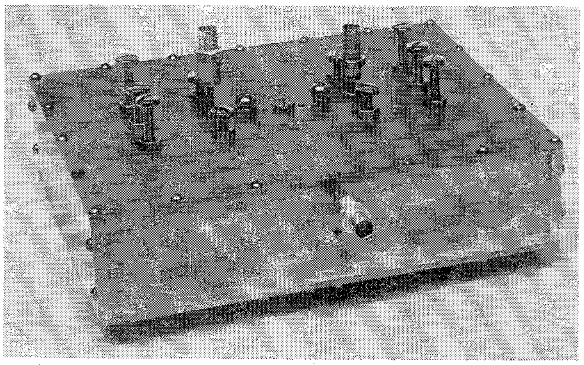


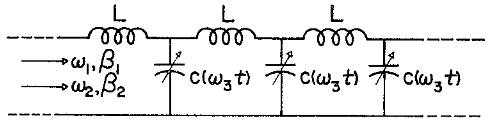
Fig. 10—Photograph of the parametric amplifier shown in Fig. 9.

This noise figure by no means represents the best that one can do. The diode which we employed has a Q of only 30 at the amplifying frequency. Using known techniques to produce better diodes, a better cavity design, and a higher pumping frequency, a noise figure at 1000 mc of about four tenths of a db can be achieved corresponding to an effective noise temperature of 30 degrees Kelvin, and all this without cooling.

It is obvious that the parametric amplifier is a strong adversary to the maser for low-noise amplification. Its one large advantage is that it can be operated at room temperature. Like the cavity maser, the cavity parametric amplifier has the disadvantages of narrow bandwidth and the necessity of pumping at a higher frequency than that to be amplified. As in the maser, these disadvantages can be overcome.

Hogan [85], at Harvard, Bloom and Chang [97], at R.C.A., and the author seem to have all simultaneously hit upon the fact that if one introduces still another resonant circuit to make a four-frequency parametric amplifier, the pump frequency can be made less than the signal frequency. This indicates that its minimum noise figure is likely to be considerably higher than that of the three frequency scheme.

The disadvantage of narrow bandwidth can be overcome, as it was in the maser, by going to a traveling-wave circuit rather than a cavity [95], [96]. A schematic representation is shown in Fig. 11. Here we consider a transmission line with constant series inductance per unit length and time varying shunt capacitance per unit length. Tien [96] has analyzed such a configuration in detail and has shown that exponential gain can be obtained if the sum of the signal and idling frequencies is equal to the pumping frequency of the capacitance variation and also if the phase constants of the waves are related in the same fashion. One of the outstanding advantages of the traveling-wave parametric amplifier over its maser counterpart is that it is inherently nonreciprocal due to the relations which the phase constants must obey.



Amplification IF:

$$\omega_1 + \omega_2 = \omega_3$$
$$\beta_1 + \beta_2 = \beta_3.$$

Fig. 11—Schematic diagram of a traveling-wave parametric amplifier.

Recently, R. S. Englebrect reported an experimental traveling-wave parametric amplifier using four diodes, which amplified at 400 mc with 10 db gain and had a 25 per cent bandwidth. The amplifier was pumped at 900 mc and had an effective noise temperature in the vicinity of 50 degrees Kelvin.

And now, let us sum up the main points. The first is, that of the solid-state microwave amplifiers we now know, the maser has by far the lowest noise figure, which it achieves at the expense of requiring liquid helium. It is so low in fact, that it may not be effectively utilized in many systems where antenna and lead-in noise may be ten to thirty times that introduced by the maser. In these cases, the parametric amplifiers operating at room temperature with noise figures of one db or less, may be completely satisfactory.

The second point to emphasize is the great advantage of the traveling-wave versions of both the maser and parametric amplifier. To date these forms have not been fully exploited and there is a great deal of room for ingenuity in both their design and in their application.

Finally, it should be made clear that this whole field of microwaves and the solid state is in its infancy but it is a rapidly growing infant. Every month some new idea or technique or measurement comes along. New devices are invented before old ones are tested. The author suspects that a few years from now the forms of the amplifiers mentioned here and the performances will be as obsolete as the Stutz-Bearcat.

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