1. Parametric Amplifiers

P. K. Tien and H. Heffner

1.1. General Theory and Historical Development

The parametric amplifier was first introduced to the microwave field in 1957 by Suhl. In his first paper [Suhl, 1957a], he proposed an equivalent circuit for a cavity type of parametric amplifier. It consists of two resonant circuits coupled to each other through a time-varying capacitor or inductor. The use of a ferromagnetic sample as a time-varying element was discussed. In his second paper [Suhl, 1957b], he theorized in great detail on three different possible operations of a ferromagnetic amplifier; namely

(a) Electromagnetic,
(b) semielectromagnetic, and
(c) magnetostatic.

Tien and Suhl [1958] then worked out the traveling wave version of the parametric amplifier. In their paper a propagating circuit loaded with time-varying reactor was studied. They found that, for optimum gain and bandwidth, the following conditions must be satisfied

(a) \( \omega = \omega_1 + \omega_2 \)
(b) \( \beta = \beta_1 + \beta_2 \)

and

(c) \( \frac{(d\omega)}{(d\beta)} \frac{1}{2} = \frac{(d\omega)}{(d\beta)} \)

where \( \omega_1, \omega_2 \), and \( \omega \) are, respectively, the signal, idler, and pump frequencies, and \( \beta_1, \beta_2 \), and \( \beta \) are their phase velocities. In a later paper, Tien [1958] investigated amplification and frequency conversion of propagating circuits including bandwidth, noise figure, and circuits of opposite group velocities. An alternative derivation of Tien’s gain expression was derived by Chang [1959a].

The basic principles of parametric interaction are the Manley and Rowe relations. They were discussed in a paper [Manley, 1956] published in 1956, actually earlier than Suhl’s invention. It stated that power at different frequencies measured at the terminals of a nonlinear reactance must obey certain relations which bear the names of the authors. Rowe [1958; Manley and Rowe, 1959] later published two papers discussing, respectively, the small signal theory and general properties of a nonlinear element. Pantell [1958] also studied the energy relations of a nonlinear resistive element. Some extensions of the Manley-Rowe relations have been made by Yeh [1960] and by A. Sturrock [1959], and alternative derivations have been presented by Salzberg [1957] and Weiss [1957a].

An important calculation was carried out [Heffner and Wade, 1958] concerning noise of the parametric amplifiers. They found that noise generated in the idler circuit adds to the noise generated in the signal circuit. Under usual operating conditions, the noise figure of the parametric amplifier is

\[ 1 + \frac{\omega_1}{\omega_2} \]

instead of 1 for a noiseless amplifier. Here \( \omega_1 \) is the signal frequency and \( \omega_2 \), the idler frequency.

The parametric amplifiers so far described require a pump source at a frequency higher than that of the signal. A scheme was described by Bloom and Chang [1958] in which an effective pump of frequency \( 2\omega \) is obtained by actually pumping at frequency \( \omega \), without providing any resonant circuit at \( 2\omega \). Another low-frequency pumping scheme was proposed by Hogan et al. [1958] and also independently by Heffner. In the latter scheme, the parametric amplifier involves four frequencies, and is sort of a modulator internally coupled with a basic amplifying unit. Those schemes are very interesting but are rather limited in practical applications.

A dispersionless parametric propagating circuit which carries an infinite number of mixed frequencies was analyzed by Roe and Boyd [1959]. They showed that when a sinusoidal signal is applied to the input end of such a circuit, the signal will contain more and more harmonics as it travels down the circuit and eventually becomes a chain of sharp pulses. Landauer [1960] also theorizes that such a dispersionless nonlinear transmission line may produce electromagnetic shock waves.

1.2. Ferromagnetic Amplifier—Theory and Experiment

A few months after Suhl’s invention, Weiss [1957b] experimentally demonstrated the electromagnetic operation of the ferromagnetic amplifier. In the next year, Poole and Tien [1958] reported a ferromagnetic resonance frequency converter and obtained a fair agreement between the theory and the measurement.
Berk et al. [1958] reported a modified operation of ferromagnetic amplifiers. In their experiment, the ferromagnetic resonance is positioned at the idler frequency instead of the pump frequency as originally proposed by Suhl.

Ferromagnetic amplifier has not been very successful in the past because of excess loss at the ferromagnetic resonance. Both Weiss and Berk have reported a pump power in the kilowatt range which is much too large for practical applications. The situation is, however, being improved lately as new techniques are developed in reducing the linewidth of yttrium iron garnet. A linewidth of less than 1 oersted has been reported up to 59 kMc/s.

Very recently, Denton [1960] has constructed a c.w. ferromagnetic amplifier which is operated in magnetostatic modes. The amplifier requires only 500 mw of pump power. The pump frequency is 9196 Mc/s and the pump field is in parallel with the d-c biasing field. The signal and idler frequencies are respectively 4626 and 4570 Mc and are the resonance frequencies of the 310 and the 310 modes (Walker's magnetostatic modes). The sample is a single crystal yttrium iron garnet sphere of 0.043 in. in diameter and has a linewidth of 0.40 oersteds. A gain of 25 db is measured and the noise figure is below 12 db. Some additional considerations of the limitations on ferromagnetic amplifier performance has been given by Damon and Eshbach [1960].

1.3. Diode Amplifiers and Noise Figure Measurements

Early in 1956, Uhlir [1956] investigated the use of p-n junction devices for frequency conversion in communication systems. The first semiconductor parametric amplifier was, however, demonstrated by Hines [1957] after Suhl's invention. In 1958, a traveling wave parametric diode amplifier was constructed by Engelbrecht [1958]. Since then, the diode amplifier has attracted much attention in the field of low-noise devices.

Most of the noise figure measurements were made on the cavity type of diode amplifier, and may be outlined briefly below: A noise figure of about 3 db (double side-band operation) was reported by Herrmann, Uenohara, and Uhlir [1958] using silicon and germanium diffused p-n junction diodes and also gold bond germanium diodes. They also reported a noise figure of 2.5 db for up-frequency conversion from 460 to 9375 Mc/s. At the same time, Heffner and Kotzebue [1958] reported a noise figure of less than 4.8 db about 2 kMc/s using Western Electric 427A diodes. Salzberg and Sard [1958] reported an excess noise temperature of 30°K for up-frequency conversion from 1 to 21 Mc/s using Hoffman 1N470 silicon diodes. In 1959, Knechtli and Weglein [1959] reported an excess noise temperature of 50 °K (double side-band operation) at 3 kMc/s using gold bond germanium diodes refrigerated to liquid nitrogen temperature (78 °K). Lately, a noise figure of 0.6 db (or an excess noise temperature of 44 °K) was reported by Uenohara and Bakanowski [1959] at 6 kMc/s using germanium diffused mesa-type p-n junction diodes refrigerated to 87 °K. The best noise figure so far measured is 0.3 db or 21 °K excess noise temperature for double side-band operation. This was obtained by Uenohara and Sharpless [1959] at 6 kMc/s using Ga-As point contact diodes refrigerated to 90 °K. Gallium arsenide diodes have many good features [Sharpless, 1959] including higher energy gap, larger electron mobility, and lower dielectric constant.

Other work on diode parametric amplifiers at various frequencies and with various noise figures have been reported by Brand et al. [1959], by Chang [1959], by Hsu [1959], by De Loach and Sharpless [1959a], by Lombardo [1959], by Lombardo and Sard [1959], and Kibler [1960]. The highest frequency amplifier reported up to now also used a Ga-As diode operated in a degenerate mode at a signal frequency of 11.55 kMc/s with a gain of 10 db, a bandwidth of 53 Mc/s and a measured double channel noise figure of 3.2 db. This was reported by De Loach and Sharpless [1959b].

The major noise in diode comes from the spreading resistance. With a spreading resistance, $R_s$, and an average shunt capacitance across the diode, $C_0$, the figure of merit of the diode as a parametric amplifier element is

$$Q_d = \frac{1}{\omega_0 C_0 R_s}.$$ 

Here $\omega_0$ is the signal frequency. Uenohara in a recent paper [1960] has shown experimentally and theoretically that larger gains and lower noise figures are obtained with diodes of larger $Q_d$'s. From the definition of $Q_d$ we may easily see that, for a particular diode, the noise figure of the amplifier increases linearly with the frequency. It may, therefore, take years of research in material and fabrication technique before diode amplifiers may be used in millimeter wave regions as low-noise devices.

Several papers have investigated certain interesting relaxation oscillations which occur in diode amplifiers at very high pump powers. These oscillations make possible their operation as self-quenched superregenerative amplifiers. These properties have been discussed in papers by Bossard [1959], by Younger et al. [1959a; b], and by Endler et al. [1959]. There has also been an investigation of the saturation characteristics of cavity-type diode amplifiers with possible applications for phase distortionless limiting by Olson et al. [1959].

In addition to this work on various ways of using diodes in amplifiers, there has also been considerable effort devoted to investigating the properties of diodes as parametric elements and the design and characteristics which optimize the performance of these diodes [Giaccoletto and O'Connell, 1956; Mortenson, 1959; Jorsboe, 1959; Specter, 1959; Firle and Hayes, 1959; Bakanowski, 1959]. Along with this work should be mentioned the development of two new types of variable capacitance diodes. One of these
employs a $p$-$n$-$p$ configuration which gives a symmetrical capacity voltage characteristic and hence can produce capacity changes at a frequency twice that of the pump. This was developed by Gibbons and Pearson [1960]. The second type involves a thin nonconductive layer of oxide sandwiched between a metal on one side and a thin layer of lightly doped semiconductor on the other side. These devices can give extremely large changes of capacity with bias though they are somewhat more lossy than the normal junction diodes. The invention seems to have been made independently by Moll [1959] and by Pfann and Garrett [1959].

Among other investigations involving diode parametric amplifiers might be mentioned a significant improvement in the bandwidth of the cavity-type amplifier which was obtained by use of a filter structure as a signal and idle frequency circuit instead of single-tuned resonant cavities. This technique is described by Seidel and Herrmann [1959]. With this technique the authors have constructed a diode amplifier at UHF with a 40 percent bandwidth. Another interesting application involves using the parametric principle for a limiter. This is described by Siegman [1959]. If the parametric element is ideal, the limiting is phase distortionless. Experimental results on a limiter of this type are presented by Wolf and Pippin [1960].

1.4. Electron Beam Parametric Amplifier—
Space-Charge Wave Parametric Amplifier and Adler’s Tube

The first electron-beam parametric amplifier was demonstrated by Bridges [1958]. The beam is premodulated by a pump and then exposed to signal field of a double gap cavity specially designed to reduce noise. Later, Louisell and Quate [1958] suggested the use of space-charge waves in an electron beam as a variable reactance element. Such tubes have been constructed by Ashkin [1958] and show large amplification both at the lower and upper sidebands. Since the phase velocities of space-charge waves vary slowly with frequency, many sidebands are generated in the electron beam. As each sideband may be considered as separate idler circuit and all the idlers introduce additional noise, those tubes are relatively noisy. The problem has also been studied by many others [Cook and Louisell, 1958; Louisell, 1959; Haus, 1958; Wade and Adler, 1959; Wade and Heffner, 1958].

A much better noise figure is obtained from a tube which utilizes cyclotron motion of electrons. This type of tube was first proposed by Adler et al. [1958, 1959] and has been extensively studied by many others [Johnson, 1959; Siegman, 1959].

The Adler tube consists of three sections. The first section is a fast wave coupler which has been studied by Cuccia [1949], Ashkin, Louisell, and Quate [1960], and Gould [1959]. In the coupler, a signal fast cyclotron wave is excited and noise of the same wave in the electron beam is stripped. The electron beam then enters the next section know as the pump cavity in which a quadrupolar electric field is excited by a local oscillator of the pump frequency. As the signal is amplified after the electron beam passes through the pump cavity, it finally reaches another coupler (the third section of the tube) where the electromagnetic power of the amplified signal is extracted.

A noise figure of 1.4 db has been obtained by Adler et al. [1959] in the 400 and 500 Mc/s region. A microwave version of the Adler tube was constructed by Bridges and Ashkin [1960], and a noise figure of 2.5 db was measured at 4 kMc/s.

References

Bakanowski, A. E., N. G. Canna, and A. Uhli.r, Jr., Diffused silicon nonlinear capacitors, IRE Trans. PGED-6, 384 (1959).
Cook, J. S., and W. H. Louisell, Traveling-wave tube equations including the effect of parametric pumping.
Cuccia, C. L., The electron coupler, RCA Rev. 10, 270 (1949).
2. Microwave Properties of Ferrites

P. K. Tien and B. Lax

2.1. Finite Waveguide Components, Frequency Doubler and Mixer, and Ferromagnetic Amplifiers

Ferrite waveguide components have attracted much attention in the past. They may be classified in four groups:

- a. Devices using Faraday relation phenomenon,
- b. the nonreciprocal phase shifter in rectangular waveguide,
- c. the resonance isolator,
- d. the field-displacement isolator.

Major advancements in those devices were made between 1952–1956 and have been reviewed by many authors [Hogan, 1953; Rowan, 1953; Kales, 1954; Lax, 1954; Fox et al., 1955; Hogan, 1956; Lax, 1956; Clarricoats et al., 1956; Lax, 1958].

One of the important developments in nonreciprocal devices after 1956 is the coaxial line resonance isolator reported by Duncan et al. [1957]. They obtained more than 10.5-db isolation over 2–4 kMc/s with a forward loss of less than 0.8 db. In addition to broad banding, the coaxial configuration permits the construction of very compact devices. Usually ferrite effects in TEM propagating waves are reciprocal. Here a section of coaxial line is partially filled with dielectric. An almost true sense of circular polarization is created at the air-dielectric interface where two transversely magnetized ferrite rods provide nonreciprocal resonant elements. Obviously this new device offers many possibilities. A coaxial line nonreciprocal phase shifter is discussed by Sucher and Carlin [1957] and also by Button [1958]. Nonreciprocity in dielectric loaded strip line is investigated by Fleri and Hanley [1959].

There have been further investigations of phase shifters and isolators by various investigators [Boyet et al., 1959; Kravitz and Heller, 1959; Clavin, 1958; Seidel, 1957].

Another important development is the Y circulator reported by Chait and Curry [1959]. Such circulators are simple in construction and require little d-c magnetic field. They obtained 0.75-db insertion loss and more than 18-db isolation between 9200–9500 Mc/s. The circulator has been operated at 50 kMc/s in millimeter wave range have been constructed by Thaxter and Heller [1960]. The 70-kMc/s circulator has an insertion loss about 1 db with a maximum isolation more than 40 db. The 140 kMc/s circulator has the insertion loss less than 1/4 db with isolation about 20 db. The applied magnetic field in both cases is about 20 gauss.

There has been an application to strip line by Davis et al. [1960]. There have also been a series of investigations on the nature of the various modes in a ferrite filled or partially filled waveguide [Angelakas 1959; Button, 1958; to Taichen, 1960]. A particularly interesting set of problems have arisen in connection with anomalous modes of propagation which apparently can exist in ferrite filled waveguides of arbitrarily small cross section [Seidel, 1957, 1956; Seidel and Fletcher, 1959; Fletcher and Seidel, 1959].

Besides waveguide components, the nonlinear property of the ferrites has been used for frequency doubling and mixing. The phenomenon can easily be analyzed from the equation of motion of the magnetization vector and has been investigated by Pippin [1956] and Stern and Persham [1957]. For the frequency doubler, the conversion efficiency is about −30 db at relatively low power levels. With a 30-kMc/s peak power at 9 kMc/s, Melcher, Ayres, and Vartanian [1957] were able to obtain 8-kw output at 18 kMc/s with an impressive conversion-efficiency of −6 db. A millimeter wave frequency doubler is reported by Ayres [1959]. He obtained more than 10-w output peak power at 2 mm.

Some work on generation of the third harmonic has also been reported [Skomal and Medins, 1959]. The ferromagnetic amplifiers are discussed under the topic "Parametric Amplifiers" and will not be repeated here.

2.2. Linewidth of Single Crystal Yttrium-Iron Garnet-Surface Imperfections and Rare Earth Impurities

The loss of a magnetized ferrite sample is measured by the linewidth at the resonance. It is therefore essential to have ferrites of narrow linewidths in order to reduce loss in devices. The linewidths of usual spinel ferrites are more than 25 oersted. The search for materials of better linewidths had not been successful until the discovery of a new class of magnetic oxides of cubic symmetry-yttrium-iron and rare earth iron garnets.

Yttrium-iron and rare earth iron garnets were discovered by Bertant and Forrat [1956] [Bertant and Pauthenet, 1956], and also independently though somewhat later by Geller and Gilleo [1957]. As first reported by Dillion [1957], this material has the following general properties:

(a) Saturation magnetization 4πM_s ≈ 1700 gauss
(b) resistivity in the order of 10^6 ohm-cm,
(c) anisotropy at room temperature ≈ 90 oersteds,
(d) linewidths at room temperature less than 10 oersteds, and
(e) spectroscopic splitting factor = 2.005 ± 0.002 at the room temperature.

Data reported by Dillion were taken at two frequencies, 9300 and 2400 Mc/s, and at various temperatures from 2.85 to about 540 °K. He found
that the linewidth increases as temperature decreases from the room temperature and reaches to a peak between 20 and 65 °K. The linewidth then decreases to about 5 oersteds at 2.85 °K. The behavior of the magnetocrystalline anisotropy is also very complex at low temperature. A more detailed report was given in one of his later papers [Dillion, 1958].

A major advance in linewidth of yttrium-iron garnet was achieved by LeCraw, Spence, and Porter [1958a, b]. They polished the surfaces of single crystal garnet spheres, using polishing papers of different mean grit sizes. They found that the linewidth in spherical samples decreases by over a factor of 20, as the samples are polished by successively finer grit sizes. They finally obtained a linewidth of about ½ oersted using a mean grit size in the order of 1 μ. The measurement was made at 9300 Mc/s.

The question now is, "What is the intrinsic linewidth of the garnet?" There were at that time several papers discussing the sources of the linewidth. The linewidth was calculated by studying the rate at which the uniform procession is dissipated into disturbances of shorter wavelengths by scattering due to various mechanisms. For example, the scattering perturbation has been taken to be magnetic ion randomness of interatomic wavelengths. They found that the linewidth peak at about 90 °K becomes much more prominent with the crystals doped with terbium. Spencer, LeCraw, and Clogston [1960] also found that with a specially purified crystal (the rare earth impurities less than 0.1 ppm), the maximum linewidth is reduced from 6 oersteds (normal crystal) to slightly over 0.1 oersted (purified crystal), a factor of 50:1. Kittel [1960] has forwarded a possible mechanism for such anomalous effects.

Other contributions to the theory of ferromagnetic resonance in garnets and to the relaxation mechanism have been made by Spencer and LeCraw [1960], and by Kittel and various co-workers [Sparks and Kittel, 1960; Kittel, 1959; de Gennes et al., 1959].

Recently, Turner reported linewidth measurements in a range from 9 kMc/s up to 59 kMc/s. The linewidth varies almost linearly with frequency, from about 0.3 oersted at 9 kMc/s to slightly less than 1 oersted at 59 kMc/s. The linewidth therefore varies little with frequency; the future applications of ferrite in millimeter wave region seem to be unlimited.

2.3. Instabilities and Magnetostatic Modes

It was first reported by Bloembergen and Wang [1954] that the linewidth of a ferrite sample broadens at high microwave signal levels and in some cases subsidiary absorption peaks are observed. Such instabilities were later analyzed by Suhl [1956a, b, 1957] and his theory agrees quite well with the experiments.

Suhl found two types of instability:
(a) Spin waves directed in parallel with the magnetizing field,
(b) Spin waves not directed in parallel with the magnetizing field. In this case, subsidiary absorption peak appears at a magnetizing field lower than that required for the resonance.

In both cases, the spin waves are coupled to the uniform procession and instabilities are produced by the second order small quantities in the equation of the motion of magnetization. In the latter case, however, when the subsidiary absorption peak coincides with the main resonance line, the instability involves first order small quantities and the critical field for the onset of the instability is very low.

According to Suhl's theory, the critical field at which the instability starts, depends on the linewidth associated with the spin waves. Attempts have been made by LeCraw, Spencer, and Porter [1958a, b; LeCraw and Spencer, 1959] to determine the intrinsic line width by measuring the critical field. They indeed found that the line width thus determined is independent of the surface conditions of the sample, and is of a magnitude comparable to the spin-lattice relaxation time measured by Farrar by a different method [Farrar, 1959].

Instability at a power level much higher than Suhl's threshold has recently been studied by Seiden and Shaw [1960].

At the bottom of the spin-wave spectrum, the wavelength becomes so long that the effect of exchange force may be neglected. The electromagnetic fields satisfying proper boundary conditions are then the magnetostatic modes.

There have been some experimental studies of these modes made back in 1956 by White, Solt, and Mercereau and also by Dillion. An excellent theory was given by Walker [1957, 1958]. Coupling of the magnetostatic modes have been studied by Fletcher and Solt [1959].

Additional studies on behavior of spin waves have been published by Buffler [1959], Solt, White, and Mercereau [1958]. Van Uitert et al. [1959] have proposed a method for varying the composition of a ferromagnetic material so as to increase the spin wave linewidth.

References

Angelakos, D. J., Transverse electric field distributions in ferrite loaded waveguide, IRE Trans. PGMTT 7, 390 (1959).
Ebert, F., and R. Pauherhen, Crystalline structure and magnetic properties of ferrites having the general formula 5Fe₂O₃·2MnO₃, Proc. IRE 104B, 261 (1956).
Button, K. J., Theoretical analysis of the operation of the field-displacement ferrite isolator, IRE Trans. PG-MTT 6, 303 (1958).
Fox, A. G., S. E. Miller, and M. T. Weiss, Behavior and application of ferrites in the microwave region, BSTJ 34 (1955).
Hogan, C. L., The ferromagnetic faraday effect at microwave frequencies and its applications, Rev. Mod. Phys. 25, 253 (1953).
Rowen, J. H., Ferrites in microwave applications, BSTJ 32, 1333 (1953).
Suhl, H., The nonlinear behavior of ferrites at high microwave signal levels, Proc. IRE 44, 1270 (1956).
3. Progress in Solid-State Masers

A. Siegman

During the past three years an important accomplishment in masers has been the development of the solid-state maser and most of the recent work has been concerned with this device.

Although most of this review will be devoted to this work on the solid-state maser, we may mention some research concerned with ammonia beam masers [Barnes, 1959; Helmer, 1957; Wells, 1958]. There has also been some work on the so-called atomic clock. This is not really a maser device since it only involves absorption on a resonance line and not emission. However, it is a competitor of the ammonia maser as a time-keeper, and there have been a number of papers on such atomic clocks [Arditi, 1958; Bell, 1959; Mainberger and Orenberg, 1958; McCoubry, 1958].

Most of the recent work in masers is a consequence of Bloembergen's original proposal for a three-level solid-state maser [Bloembergen, 1956]. The same three-level pumping scheme had also been independently proposed earlier by the Russians in connection with gas masers, but the proposal had not been exploited. Bloembergen's proposal was very rapidly verified in every essential through the experimental work of Scovil et al. [Scovil, Feher, and Seidel, 1957]. The rapid development which ensued can be judged from the work which will be described below.

3.1. Cavity-type Solid-state Masers: Experimental Results

Three-level solid-state masers have now been operated in many laboratories mostly at helium temperatures at frequencies ranging from 350 to 35,000 Mc/s. Shortly after the initial maser operation mentioned above, definitive measurements on an S-band maser using potassium chromocyanide as the maser crystal were made by a group at Lincoln Laboratories [McWhorter and Meyer, 1958]. The maser material ruby, i.e., sapphire (Al₂O₃) containing a small amount of chromium, was soon introduced by the University of Michigan and has become probably the most widely used maser material. [Makov, Kikuchi, Lambe, and Terhune, 1958]. A number of groups have developed masers in the UHF region and in L-band, the latter frequency band containing the important hydrogen emission line at 1420 Mc/s [Arams and Okwit, 1959; Artman, Bloembergen, and Shapiro, 1958; Autler and McAvoys, 1958; Butler and McAvoys, 1958; Kingston, 1958, 1959; Wessel, 1959]. An S-band maser (approximately 3000 Mc/s) with a large gain bandwidth has been reported by Stanford University and many tunable high-performance masers have been reported at X-band (about 10,000 Mc/s) [Chang, Cromack, and Siegman, 1959; Arams, 1959; Gionino and Dominick, 1960; King and Terhune, 1959; Morris, Kyhl, and Strandberg, 1959; Strandberg, Davis, Faughnan, and Kyhl, 1958]. A group at RCA has used titania (rutile) as a high-frequency maser material [Gerritsen and Lewis, 1960]. Three-level maser operation at liquid nitrogen temperature (with a considerable sacrifice in performance over helium temperature) has been achieved in England and at the Hughes Aircraft Co. [Ditchfield and Forrester, 1958; Maiman, 1960].

The principle of harmonic pumping offers considerable future promise for masers amplifying at higher than the pumped frequency. The principle has been successfully demonstrated by Arams [1960]. An ingenious and very useful practical development has been the use of superconducting solenoids immersed in a helium bath to supply the masers' d-c magnetic field [Autler, 1959]. Fields up to 5,000 gauss were obtained with a flashlight battery as power supply or even with no power supply by setting up a persistent current in the solenoid. Other useful practical developments included techniques for orienting ruby boules and making silver-plated ruby maser cavities [Mattuck and Strandberg, 1959; Gross, 1959].

3.2. Applications of Solid-State Masers

Several important applications of the solid-state maser to radio astronomy and radar astronomy have already been made. The first use of a maser was by Lincoln Laboratories in contacting the planet Venus by radar at a frequency of 440 Mc/s [Price, 1959]. A group from Columbia and the Naval Research Laboratory have used a maser as a preamplifier for an X-band radiometer, obtaining a substantial increase in sensitivity. Thermal emission from Venus and Jupiter was detected, as well as radio emissions from several radio stars [Alsop, Giordmaine, Mayer, and Townes, 1959; Giordmaine, Alsop, Mayer, and Townes, 1959; Alsop, Giordmaine, Mayer, and Townes, 1959]. A maser has also been tested as the first-stage receiver for an X-band radar system, with again a substantial increase in performance. However, special measures were required to obtain satisfactory duplexing in the system [Forward, Goodwin, and Kiefer, 1959; Goodwin, 1960].

3.3. Solid-State Masers: Theory and Analysis

Numerous papers devoted to aspects of maser theory and analysis have appeared since Bloembergen's paper cited earlier. Detailed quantum-mechanical analyses of the solid-state maser have been carried out by several workers [Anderson, 1957;
Clogston, 1958; Javan, 1957]. Analyses of the solid-state maser at somewhat less rarefied levels can be found in several review papers and also in the following [Bergman, 1959; Burkhart, 1958; Schulz-DuBois, Scovil, and DeGrasse, 1959; Scovil, 1958; Siegman, 1957; Stitch, 1958]. More specialized problems such as the reaction field, maser efficiency, phonon effects, double-quantum transitions, and others have also been considered [Bloembergen, 1956; Fleischmann, 1957; King, Birko, and Therhune, 1959]. The above work all uses adiabatic fast passage to obtain the population inversion. An MIT group has successfully used the rather more difficult 180° pulse technique [Collins, Kyhl, and Standberg, 1959]. A staircase scheme involving two successive adiabatic-fast-passage inversions has been suggested as a means for generating higher frequencies [Siegman and Morris, 1959]. Two other groups have generated high microwave frequencies by a “brute force” approach; that is, by inverting a spin population at a relatively low frequency and then rapidly pulsing the magnetic field to a high value to obtain a high output frequency [Foner, 1959; Foner, Momo, and Mayer, 1959; Momo, Mayer, and Foner, 1960; Hoskins, 1959]. Momo et al., in particular, have obtained output at frequencies up to 70 kMc/s by pulsing the magnetic field up to 30 kilogauss.

Immediately after the spin population in a maser cavity is inverted, intermittent or relaxation-type oscillations are often obtained instead of a continuous oscillation. The explanation of these effects in terms of the dynamics of the spin system and the cavity fields has occupied several workers [Kemp, 1959; Sendzky, 1958; Theissing, Dieter, Caplan, 1958; Yariv, Singer, and Kemp, 1959]. Finally, the topics of electron free precession and spin echoes from electron spins are at least distantly related to masers, and some work on these topics has been reported [Gordon and Bowers, 1958; Kaplan and Browne, 1959; Norton, 1957].

### 3.4. Maser Materials

Ruby is probably the most widely used maser material at present. The properties of ruby as a maser material have been summarized by the University of Michigan group [Kikuchi, Lambe, Makrov, and Terhune, 1959]. Extensive tabulations of the energy levels and transition probability matrix elements for ruby and potassium chromicyanide have been given in reports from Stanford University [Chang and Siegman, 1958, 1959] and from the Royal Radar Establishment in England. Garstens [1959] has also given a method for finding an operating point, given the desired pump and signal frequencies.

#### 3.5. Pulsed and Two-Level Masers

There exists a variety of methods for obtaining population inversion in a material having only two energy levels, although nearly all of these methods permit only intermittent or pulsed amplification. The two-level maser may nonetheless have certain advantages over the three-level maser, and work on the former has been carried out in several places. The various possible two-level schemes, including one as yet untried scheme for a CW two-level maser, are summarized by Bolef and Chester [1958]. Experimental work carried on via two-level masers has included the measurement of relaxation times and the study of paramagnetic levels in irradiated crystals of various sorts [Burkhart, 1959; Chester and Bolef, 1957; Chester, Wagner, and Castle, 1958; Feher, Gordon, Buehler, Gere, and Thurmond, 1958; Hoskins, 1959; Wagner, Castle, and Chester, 1959].

In the traveling wave type of maser, the active maser material is distributed along a low-group-velocity slow-wave circuit, rather than being concentrated in a resonant cavity. As a result, the traveling wave maser achieves broader bandwidth, easier frequency tuning, much better gain stability, and built-in nonreciprocity. Although the traveling wave maser would appear to hold much more promise than the cavity type, only a few groups have so far constructed traveling wave masers. At the Bell Telephone Laboratories, the comb slow-wave structure has been used with good results in a traveling wave maser at 6000 Mc/s [DeGrasse, 1958; DeGrasse, Schulz-DuBois, and Scovil, 1959]. Another slow-wave structure, the so-called meander line, has been developed at Stanford University and used in an S-band traveling wave maser [Chang, Cromack, and Siegman, 1959]. A ME Labs group has also worked at 3000 Mc/s, exploring various modifications of the comb circuit [Tenney, Roberts, and Vartanian, 1959]. Various general discussions of the traveling wave maser have also been published [Siegman, Butcher, Cromack, and Chang, 1958].

#### 3.7. Noise in Masers

So far as noise in masers is concerned, one can say in general that the inherent noise in a maser amplifier is extremely small, corresponding to a noise tem-
perature of $\sim 1^\circ$ K for typical microwave masers at helium temperature. The fundamental source of noise in masers is spontaneous emission from spins in the upper amplifying level. However, one can show by heuristic arguments that the noise generation in a maser material is given by ordinary thermal noise formulas, providing that one is willing to tolerate the idea of a negative resistance with a negative temperature (the spin temperature). This viewpoint has been used by many workers to analyze maser noise [Ewen, 1959; Gordon and White, 1958; Pound, 1957; Strandberg, 1957a, b; Weber, 1957]. The results of these analyses are in agreement with more rigorous analyses which have been carried out. [Muller, 1957; Shimoda, Takahasi, and Townes, 1957].

Because of the small noise output of masers, accurate noise measurements are quite difficult. Moreover, the inherent maser noise is generally masked by extraneous noise sources. Small losses in the input cables and connections of the maser are a particularly troublesome noise source and generally determine the overall system noise figure in practical maser amplifiers. Nonetheless, all the noise measurements which have been made are in excellent agreement with theory and give strong support to the noise analyses listed above. Measurements have been made on ammonia beam maser amplifiers by several groups [Alsop, Giordmaine, Townes, and Wang, 1957; Gordon and White, 1957; Helmer, 1957; Helmer and Muller, 1958]. The first and still one of the definitive noise measurements on a cavity-type solid-state maser was made by the Lincoln group, who achieved a system noise figure of $20^\circ$ K in good agreement with theory [McWhorter, Meyer, and Strum, 1957; McWhorter and Arams, 1958]. More recent measurements at the Bell Telephone Laboratories on a traveling wave maser have shown that the noise in a carefully engineered maser system can be reduced to as low as $10^\circ$ K for the maser and associated circuitry, and to as low as $18^\circ$ K in including noise contributions from the antenna and the sky noise. In addition, the accuracy of the measurement was such as to permit careful verification of the maser's intrinsic noise ($\sim 2^\circ$ K in this case) by subtracting out the known extraneous noise sources [DeGrasse and Scovil, 1960; DeGrasse, Hogg, Ohn, and Scovil, 1959].

The maser is certainly the lowest noise amplifier obtainable in practice. Is it also the lowest noise amplifier that one can conceive in principle, and is there any fundamental limitation on amplifier noise figure? These two questions have been recently considered in two very stimulating papers apparently developed simultaneously and independently [Friedburg, 1960; Serber and Townes, 1960]. The gist of the papers is that the uncertainty principle of quantum theory sets a lower limit on the noise figure of an amplifier, with an ideal maser just attaining this theoretical limit. The lower limit corresponds to an uncertainty of one quantum per resolution time. Certain devices such as the quantum counter mentioned in the next section appear to be completely noiseless since they can detect incident photons with no inherent noise or error. However, the uncertainty principle then requires that they lose all ability to measure the phase of an incident signal. These latter devices might better be called counters or detectors than true amplifiers.

### 3.8. Infrared and Optical Masers

With the microwave-frequency solid-state maser now fairly well under control, considerable attention is turning to possibilities for application of the maser principle at optical and infrared frequencies. There have been a number of proposals for optical or optically pumped masers, but as yet no successful experiments. Schwalo and Townes have summarized the problems involved [Schwalow and Townes, 1958]. Several proposals involve the use of energy levels in gases, with excitation at optical frequencies, and amplification or oscillation at optical, infrared, or microwave frequencies [Bergmann, 1960; Hawkins and Dicke, 1953; Singer, 1959]. Two authors have pointed out that it may also be possible to excite or pump a gaseous optical maser by electron impact [Javan, 1959; Sanders, 1959]. Another technique, proposed in Russia, would use impact ionization to excite holes or electrons to higher levels in impurity-doped semiconductors. The possibilities of optical pumping in crystals have been discussed, and an interaction between optical and microwave radiation in ruby has been observed successfully (although no maser operation was obtained) first by Wieder and then by a Bell Laboratories group [Theissing, Caplan, Dieter, and Rabbiner, 1959; Wieder, 1959; Geschwind, Collins, and Schwalow, 1959]. As a pump source for his optical experiments in ruby, Wieder developed a very interesting narrowband high-power ($\sim 100$ milliwatts) light source using the fluorescence of the $R_1$ and $R_2$ optical lines in a second piece of ruby [Wieder, 1959]. An alternative type of maser-like device for infrared frequencies called the quantum counter has been proposed by Bloembergen and also by Robinson [Bloembergen, 1959a, b, Robinson, 1960]. The quantum counter operates in a fashion similar to the Geiger counter or other particle detectors. As mentioned in the previous section, the quantum counter has the advantage in comparison with the maser of having no inherent noise even at high frequencies if operated at a very low temperature.

### References


4. Low-Noise Beam-Type Microwave Tubes

L. Smullin

At the time of the last URSI meeting in Boulder, Colo. (September 1957), theory and experiment on low-noise, beam-type microwave amplifier had reached the following stage: Traveling wave tubes with noise figures for 4–5 db had been produced in the 3,000 megacycles per second region. The noise in an electron beam was described theoretically in terms of two basic parameters $S$ and $\pi/S$. These parameters had been shown to be invariant under ordinary beam accelerations so long as the average beam velocity was large compared with thermal fluctuations. Thus, it was possible to predict the optimum attainable noise performance of a tube if the quantities $S$ and $\pi/S$ were specified at some point beyond the virtual cathode. Experimental studies had demonstrated the invariance of $S$ and $\pi/S$ in some 3-region guns.

Thus the outstanding theoretical problems were the determination of the ultimate values of $S$ and $\pi/S$ and thus of noise figure, and the determination of the factors that governed these two parameters.


4.1. Progress During the Past 3 Years

a. Design of Solid-Beam, Low-Noise Guns

Further progress was made in the design of low-noise guns previously described by R. W. Peter. The analysis of noise transformation within a multi-anode gun was analyzed in terms of a tapered transmission line [Echenbaum and Peter, 1959]. The deleterious effect on noise of very rapid accelerations has been pointed out. This arises from the strong transverse focusing action accompanying such accelerations in gridless gaps [Knechtli, 1958].

The manufacturing experience with an S-band low-noise amplifier, employing a 3 region, solid-beam gun has been summarized in a recent article. Of 53 tubes, 4 had noise figures below 5 db, the mean value was about 5.5 db. Life test data and performance curves are given [Kinaman and Magid, 1958].

In an attempt to get even better control over the acceleration of the beam, a gun was built with many closely spaced anodes, whose potential could be separately adjusted. A noise figure of 6.5 db was obtained at X-band; and subsequently, S-band noise figures of 3.5 db were obtained. There is some evidence that this gun may be operating in the mode of the hollow beam, magnetron injection gun (see sec. III) [Shaw, Siegman, and Watkins, 1959].

b. Theory of Noise on Beams and Low-Noise Amplification

Theoretical studies have included an examination of the higher order azimuthal modes in Brillouin focused beams, the coupling between such modes and an external circuit, and the intercoupling between the modes in a finite beam were computed. The derived theory helps to explain some hitherto anomalous experiments [Rigrod and Pierce, 1959; Rigrod, 1959].

A detailed analysis of the various parameters for best noise performance of a beam type backward wave amplifier has been carried out more or less similarly to such analysis for traveling wave amplifiers [Currie and Forster, 1958].

The general theory of low-noise, linear amplifiers (noisy 4 pole networks) has received renewed attention. Optimum circuit arrangements for both positive- and negative-resistance amplifiers are described [Haus and Adler, 1958a, 1958b, 1959].

c. Hollow Beam Low-Noise Guns

An interesting new development in low-noise performance is a gun that appears to behave in a different way from the solid beam low-noise gun, and $S$- and $C$-band noise figures of 3.5 db have been achieved [Currie, 1958; Coulton and St. John, 1958].

The guns described in these two letters produced hollow beams with a system of anodes near the cathode that had potentials such as to give a strong radial field and an extended region in which the axial field was small, and the space potential also was low. The noise reducing mechanism in these guns is still not fully understood, but it may be related to the mechanism described by Siegman et al. (sec. IV). Because of the method of beam formation, they have been called "magnetron injection" guns. Best performance is achieved with a strong magnetic focusing field at the cathode. A field of about 1,100 gauss was used.

Low noise tubes incorporating such guns have been described recently. One of these was a $C$-band traveling-wave amplifier that had a noise figure below 4 db. The other was an X-band backward wave amplifier whose noise figure was about 4.5 db [Hammer, Laico, Holvorsen, and Olsen, 1959; Nevins, 1959].
d. Theory of Noise in Multivelocity Electron Beams

The work of H. A. Haus, F. N. Robinson, and others had predicted the invariance of two basic noise parameters $S$ and $\pi$ in an electron beam, so long as accelerations were slow and the drift velocity was large compared to thermal fluctuations. Thus it is possible to predict the best noise figure obtainable if $\pi$ and $S$ are specified for a given cathode.

In the period covered by this report, some progress has been made in the theory of the multivelocity region extending from the cathode to a point where the space potential is of the order of a volt or more [Siegman and Bloom, 1957]. This paper is an attempt to explain some of the numerical results obtained earlier by Tien and is concerned with the region between cathode and virtual cathode. The resonant peak in shot-noise is predicted in the neighborhood of the plasma frequency of the virtual cathode. There is still no experimental verification of this prediction.

The region just beyond the virtual cathode has been studied theoretically [Siegman, 1957; Siegman and Watkins, 1957]. In these two papers the analysis is carried out for the region just beyond the virtual cathodes of a parallel plane diode, and it is shown that even if the initial noise excitation at the virtual cathodes has zero correlation between density and velocity fluctuations, a finite, positive correlation ($\pi/S>0$) is produced as the beam is accelerated through the first $1/2$ to 1 v, and $S$ is simultaneously lowered.

Although the model was highly idealized, the results indicated a way of possibly controlling (reducing) the noise in the beam by extending the region in which the beam drifts at low voltage. The multianode gun previously described was built with this idea in mind [Shaw, Siegman, and Watkins, 1959].

The exact reason for the improved noise performance of the magnetron injection gun is not understood. The Siegman type of analysis, if applicable, might explain it; however, the magnetic field strength plays an important role in determining the actual noise figure, and no theory has so far completely accounted for it [Currie and Forster, 1959; Muller and Currie, 1959].

e. Fundamental Noise Measurements

Several measurements of the noise quantities $S$ and $\pi$ generated in low-noise guns of the solid-beam and of the magnetron injection type have been made [Saito, 1958; Zacharias and Smullin, 1960; Jory, 1960]. Saito and Zacharias used two cavities spaced $\lambda_0/4$ apart to separately determine the noise excitation of the fast and slow space charge waves. Saito found a positive correlation, $\pi/S=0.2-0.3$ in solid beam guns. This value was essentially independent of the way in which the beam was accelerated in the fun so long as strong lens effects were avoided.

In contrast, Zacharias made similar measurements on a magnetron injection gun and found $S$ to be a sensitive function of the voltage applied to the first anode and to the focusing electrode; but $\pi/S\approx 0$ for all settings. If true, these data indicate a difference in the operating mode of the two types of guns.

Jory also made measurements on a magnetron injection gun; but he used a backward wave amplifier with an axially movable gun. By measuring noise figure at various settings, he was able to determine $S$ and $\pi/S$. His values show $\pi/S=0.2$. Thus there appears to be a serious discrepancy between these results and those of Zacharias and Smullin. Further experiments are in progress.

f. Electron Beam Parametric Amplifiers

Considerable work and some success has been achieved in the design and construction of parametrically excited, low-noise, beam-type amplifiers. Earlier attempts were based on the use of space charge waves. Although it proved possible to build tubes that amplified, little success has so far been achieved in getting low-noise performance.

The principal difficulty in making low-noise, space charge wave, parametric amplifiers lies in the small separation between the fast- and slow-waves. As a result, it has so far proven practically impossible to strip the noise from the fast-wave and then to amplify it, only, without getting major contamination from slow-wave noise.

The theoretical basis of beam-parametric amplification seems firmly established; and there are now power conservation theorems, and analysis by coupling-of-modes just as for conventional beam-type amplifiers.

The use of cyclotron waves and transverse deflection allowed a great separation in velocity between the fast and slow waves (at $\omega=\omega_c=eB|m|$, the fast wave has infinite phase velocity). A UHF tube was built, using a quadrupole section excited at $2\omega_c$ for parametric amplification, and Cuccia couplers for input and output circuits. This tube has a noise figure of less than 2 db and a gain of 30 db over a 10 o/o bandwidth in the range of 400 to 800 Mc/s.

Recently, a similar type tube has been built for operation at 4 kMc/s. Its double channel noise figure was about 2.5 db with a gain of 24 db, over about a 1 1/2 o/o bandwidth.

g. Low-Noise Klystrons

Two low-noise tubes have been built for operation at $S$- and $C$-bands. They employ "conventional" solid cylindrical beam low-noise guns. Noise figures of 6 to 7 db and gains of 11.5 were attained [Rockwell, 1959].

References


1 Detailed references are included in a section of this report concerned with the whole class of parametric amplifiers.


Rigrod, W. W., Space charge wave harmonics and noise propagation in rotating electron beams, BSTJ 38 No. 2 (1959).


5. Interaction Between Plasmas and Electromagnetic Fields

L. Smullin

5.1. Introduction

As a result of the intense interest in such diverse subjects as thermonuclear generation of power, ion-propulsion of rockets, and direct generation of electricity from furnace heat by MHD generators, the volume of literature on plasmas has grown enormously within the last few years.

In this review, a brief survey is made of a narrow branch of plasma physics: the interaction between plasmas and electromagnetic waves, and the coulomb interaction between interpenetrating plasma streams. As evidence of the growing interest in this field, the following books have appeared recently in the United States [Landshoff, 1957; Landshoff, 1958; Proc. of Symposium on Electronic Waveguides, Microwave Research Institute Symposium Series, Vol. VIII, Polytechnic Press, 1958; Brown, 1959; Notes or MIT Summer Course, 1959; Longmire, Tuck, and Thompson, 1959; Clauser, 1960].

5.2. Propagation of Electromagnetic Waves in Unbounded Plasmas—Small Signal Theory

The propagation of plane waves of arbitrary polarization in an ideal unbounded plasma (no collisions or thermal fluctuations) has been studied in three recent papers. Dispersion characteristics have been plotted, and the possible wave surfaces have been mapped on a chart relating applied frequency to plasma and cyclotron frequency. The wave surface contour plotted in various regions of the chart represents the phase velocity of each possible wave as a function of the angle between the d-c magnetic field and the direction of propagation. [Auer, Hurwitz, and Miller, 1958; Allis, 1959; Allis and Papa, 1959.]

The same problem has been attacked for a fully ionized plasma in which the random motion of the charged particles is included. The approach is through the Boltzmann equation [Bernstein, 1958].

5.3. Plasma Waveguides

Recently, there has been considerable interest in the study of plasma columns as electromagnetic waveguides. A number of authors have studied the problem of propagation along an ideal plasma column either in free space, or coaxial with an outer metal tube. The effect of a superimposed, axial magnetostatic field is considered. For the cases in which \( \omega_c \) and \( \omega_s \) are small compared to the cutoff frequency of the outer metal tube, relatively simple, approximate solutions to the dispersion equations have been found. These predict the existence of several passbands with both positive- and negative-dispersion and phase velocity small compared with \( c \).

Experiments have confirmed the theoretical predictions and both the positive- and negative-dispersion regions have been observed [Stix, 1957; Smullin and Chorney, 1958a; Chorney, 1958; Gould and Trivelpiece, 1958; Trivelpiece, 1958; Trivelpiece and Gould, 1959; Lichtenberg, 1959].

The previous papers all confine their attention to reciprocal modes of propagation. The gyroelectric, or nonreciprocal modes, have also been studied and nonreciprocal phase shifters and polarizers have been demonstrated experimentally [Goldstein, 1958].

The scattering of electromagnetic waves from an infinitely long plasma column in a strong magnetic field has been studied [Dawson and Oberman, 1959].

Much of the theoretical work now going on is aimed at finding methods of solving the less restricted problem of plasma within a metal cylinder (cavity) of arbitrary size. The earlier works of Van Trier, Suhl and Walker, and Gamo on ferrites has laid the foundation for the solution of these problems, but much remains to be done in this area.

5.4. Electron Stimulated Plasma Oscillations

The system consisting of an electron beam drifting through a stationary plasma has been studied by several authors. This is an old problem, and in a sense, it is a direct descendent of the double-stream amplifier of A. F. Haefl. For some time the primary interest in this type of interaction, except for vacuum tubes, lay in the hope that it might explain some of the phenomena of solar flares and similar astronomical occurrences. More recently, double-stream interaction has been studied as a possible means of heating a plasma and as a possible origin of some of the experimentally observed instabilities in the various large-scale plasma machines built for thermonuclear research.

Small signal analyses have been carried out for various geometrical arrangements in which an electron beam is allowed to drift through a stationary plasma. Modes of interaction have been discovered that are similar to those of traveling wave tubes, klystrons, monotronics, backward wave oscillators, and reactive-medium amplifiers (Easytrons). Direct experimental evidence has already established
the reality of several of these modes [Jepsen, 1957; Boyd, Field, and Gould, 1958a; Smullin and Chorney, 1958; Boyd, Field, and Gould, 1958b; Sturrock, 1958; Boyd, 1959; Smullen and Getty, 1960].

A study of large signal effects in electron-stimulated plasma oscillations has been carried out for a one-dimensional system, and klystron-type "Applegate" diagrams are plotted showing the overtaking of particles and the randomization of the original coherent oscillation [Buneman, 1958, 1959].

### 5.5. Large Signal Oscillations

The possible parametric instabilities of a plasma confined by a strong rf field have been studied theoretically. It is shown that under certain conditions, the parametrically induced oscillations may destroy the confining action of the rf field [Haus, 1959]. The use of a plasma column as a nonlinear medium for parametric amplification has been discussed. Pumping by both electromagnetic and acoustic waves is considered [Kino, 1959, 1960].

An exact solution for one-dimensional electrostatic oscillations of a collisionless plasma has been found for arbitrary large variations of electrostatic potential. It is shown that the general solution for the traveling potential wave includes a large class of waveforms, both periodic and aperiodic [Bernstein, 1957].

### References

Dawson, J., and C. Oberman, Oscillations of a finite cold plasma in a strong magnetic field, Phys. of Fluids 2, 103 (1959).  
MIT Summer Course notes on Plasma dynamics (1959) (out of print).  
(Paper 64D6–96)