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RADIO ELECTRONICS

1. Parametric Amplifiers

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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 theorizes 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

$$\text{(a) } \omega=\omega_1+\omega_2, \text{ (b) } \beta=\beta_1+\beta_2$$

and

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

where ω_1, ω_2, and ω are, respectively, the signal, idler, and pump frequencies, and β_1, β_2, and β 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 P. 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 ω_1 is the signal frequency and ω_2, the idler frequency. The signal and the idler circuits are assumed at the same temperature.

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 2ω is obtained by actually pumping at frequency ω, without providing any resonant circuit at 2ω. 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 $3\bar{1}0$ 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

$$Q_d=\frac{1}{\omega_1 C_0 R_s}.$$

Here ω_1 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 [Giacoletto and O'Connell, 1956; Mortenson, 1959; Jorsboe, 1959; Spector, 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 nonconducting 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 bv 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 800 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

Adler, R., G. Hrbek, and G. Wade, A low-noise electron beam parametric amplifier, Proc. IRE **46,** 1756 (1958).

Adler, R., G. Hrbek, and G. Wade, The quadruple amplifier, a low-noise parametric device, Proc. IRE **47,** 1713 (1959).

Ashkin, A., Parametric amplification of space-charge waves, J. Appl. Phys. **29,** 1646 (1958).

Ashkin, A., W. H. Louisell, and C. F. Quate, Fast wave couplers for longitudinal beam parametric amplifiers (to be published in J. Electronics and Control).

Bakanowski, A. E., N. G. Cranna, and A. Uhlir, Jr., Diffused silicon nonlinear capacitors, IRE Trans. **PGED–6,** 384 (1959).

Berk, A. D., L. Kleinman, and C. E. Nelson, Modified semistate ferrite amplifier, WESCON Conv. Record 2, pt. III, 9 (1958).

Bloom, S., and K. K. N. Chang, Parametric amplifiers using low-frequency pumping, J. Appl. Phys. **29,** 594 (1958).

Bossard, B. B., Superregenerative reactance amplifiers, Proc. IRE **47,** 1269 (1959).

Brand, F. A., W. G. Matthei, and T. Saad, The reactatron—low noise, semiconductor diode, microwave amplifier, Proc. IRE **47,** 42 (1959).

Bridges, T. J., and A. Ashkin, A microwave adler tube (to be published).

Bridges, T. J., An electron beam parametric amplifier, Proc. IRE **46,** 494 (1958).

Chang, N. C., Parametric amplification and conversion in propagating circuits using nonlinear reactances, Proc IRE **47,** 2117 (1959a).

Chang, K. K. N., and S. Bloom, Parametric amplifiers using low-frequency pumping, Proc. IRE **46,** 1383 (1958).

Chang, K. K. N., Four terminal parametric amplifier, Proc. IRE **47,** 81 (1959b).

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).

Damon, R. W., and J. R. Eshbach, Theoretical limitations to ferromagnetic parametric amplifier performance, IRE Trans. **MTT–8,** 4 (1960).

De Loach, B. C., and W. M. Sharpless, An X-band parametric amplifier, Proc. IRE **47,** 1664 (1959a).

De Loach, B. C., and W. M. Sharpless, X-band parametric amplifier noise figures, Proc. IRE **47,** 2115 (1959b).

Denton, R. T., A ferromagnetic amplifier using longitudinal pumping, Proc. IRE **48,** 937 (1960).

Endler, H., A. D. Berk, and W. L. Whirry, Relaxation phenomena in diode parametric amplifiers, Proc. IRE **47,** 1375 (1959).

Englebrecht, R. S., A low-noise nonlinear reactance traveling-wave amplifier, Proc. IRE **46,** 1655 (1958).

Firle, T. E., and O. E. Hayes, Some reactive effects in forward biased junctions, IRE Trans. **PGED–6,** 330 (1959).

Giacoletto, L. J., and J. O'Connell, A variable-capacitance germanian junction diode for UHF, RCA Rev. **17,** 68 (1956).

Gibbons, J. F., and G. L. Pearson, P–N–P variable capacitance diodes, Proc. IRE **48,** 253 (1960).

Gould, R. W., Traveling-wave couplers for longitudinal beam type amplifiers, Proc. IRE **47,** 419 (1959).

Haus, H. A., The kinetic power theorem for parametric longitudinal electron beam amplifiers, IRE Trans. **PGED–5,** 225 (1958).

Heffner, H., Stanford Univ.

Heffner, H., and K. Kotzebue, Experimental characteristics of a microwave parametric amplifier using a semiconductor diode, Proc. IRE **46,** 1301 (1958).

Heffner, H., and G. Wade, Gain, bandwith, and noise characteristics of the variable-parameter amplifier, J. Appl. Phys. **29,** 1321 (1958).

Herrmann, G. F., M. Uenohara, and A. Uhlir, Jr., Noise figure measurements on two types of variable reactance amplifiers using semiconductor diodes, Proc. IRE **46,** 1301 (1958).

Hines, M. E., Amplification with nonlinear modulators, presented at Electron Tube Research Conf., Univ. Calif, Berkeley, Calif. (June 1957).

Hogan, C. L., R. L. Jepsen, and P. H. Vartanian, A new type of parametric amplifier, J. Appl. Phys. **29,** 422 (1958).

Hsu, H., Multiple frequency parametric devices, Dig. Tech. Papers, 1959 Solid-State Circuits Conf., 12 (1959).

Johnson, C. C., Theory of fast wave parametric amplification, Tech. Memo. Hughes Aircraft Co. (1959).

Jorsboe, Helge, Space-charge capacitance of a P–N junction, Proc. IRE **47,** 591 (1959).

Kibler, L. U., Parametric oscillations with point-contact diodes at frequencies higher than pumping frequencies, Proc. IRE **48,** 239 (1960).

Knechtli, R. C., and R. D. Weglein, Low-noise parametric amplifier, Proc, IRE **47,** 585 (1959).

Landauer, Rolf., Parametric amplification along nonlinear transmission lines, J. Appl. Phys. **31,** 479 (1959).

Lombardo, P. P., Low-noise 400 Mc reactance amplifiers, Dig. Tech. Papers, 1959 Solid-State Circuits Conf., 6 (1959).

Lombardo, P. P., and E. W. Sard, Low-noise microwave reactance amplifiers with large gain bandwidth products, IRE WESCON Conv. Record, pt. 1, 83 (1959).

Louisell, W. H., and C. F. Quate, Parametric amplification of space-charge waves, Proc. IRE **46,** 707 (1958).

Louisell, W. H., A three frequency electron beam parametric amplifier, J. Electronics and Control **6,** 1 (1959), Proc. IRE **47,** 2016 (1959).

Manley, J. M., and H. E. Rowe, Some general properties of nonlinear elements, I. General energy relations, Proc. IRE **44,** 904 (1956).

Manley, J. M., and H. E. Rowe, General energy relation in nonlinear reactance, Proc. IRE **47,** 2115 (1959).

Moll, J., Variable capacitance with large capacity change, 1959 IRE WESCON Conv. Record, Pt. III (1959).

Mortenson, K. E., Alloyed, thin-base diode capacitors for parametric amplification, J. Appl. Phys. **30,** 1542 (1959).

Olson, F. A., C. P. Wang, and G. Wade, Parametric devices tested for phase distortionless limiting, Proc. IRE **47,** 587 (1959).

Pantell, R. H., General power relationships for positive and negative nonlinear resistive elements, Proc. IRE **46,** 1910 (1958).

Pfann, W. G., and C. G. B. Garrett, Semiconductor varactors using surface space-charge layers, Proc. IRE **47,** 2011 (1959).

Poole, K. M., and P. K. Tien, A ferromagnetic resonance frequency converter, Proc. IRE **46,** 1387 (1958).

Roe, G. M., and M. R. Boyd, Parametric energy conversion in distributed systems, Proc. IRE **47,** 1213 (1959).

Rowe, H. E., Some general properties of nonlinear elements. II. Small signal theory, Proc. IRE **46,** 850 (1958).

Salzberg, B., Masers and reactance amplifier—basic power relations, Proc. IRE **45,** 1544 (1957).

Salzberg, B., and W. E. Sard, A low-noise wide-band reactance amplifier, Proc. IRE **46,** 1303 (1958).

Seidel, H., and G. F. Herrmann, Circuit aspects of parametric amplifiers, IRE WESCON Conv. Record, Pt. II, 83 (1959).

Sharpless, W. M., High frequency gallium arsenide point-contact rectifiers, BSTJ **38,** 259 (1959).

Siegman, A. E., Phase-distortionless limiting by a parametric method, Proc. IRE **47,** 447 (1959).

Siegman, A. E., The waves on a filamentary electron beam in a transverse field slow wave circuit, Stanford Electron. Lab. Tech. Rept. (1959).

Spector, C. J., A design theory for the high-frequency P-N junction variable capacitor, IRE Trans **PGED–6,** 347 (1959).

Sturrock, P. A., Action-transfer and frequency-shift relations in the nonlinear theory of waves and oscillations, Tech. Note, Stanford Univ. Microw. Lab. Rept. 625 (1959).

Suhl, H., A proposal for a ferromagnetic amplifier in the microwave range, Phys. Rev. **106,** 384 (1957a).

Suhl, H., Theory of the ferromagnetic microwave amplifier, J. Appl. Phys. **28,** 1225 (1957b).

Tien, P. K., Parametric amplification and frequency mixing in propagating circuits, J. Appl. Phys. **29,** 1347 (1958).

Tien, P. K., and H. Suhl, A traveling-wave ferromagnetic amplifier, Proc. IRE **46,** 700 (1958).

Uenohara, M., and A. E. Bakanowski, Low-noise parametric amplifier using GE P-N junction diode at 6 kmc, Proc. IRE **47,** 2113 (1959).

Uenohara, M., and N. M. Sharpless, An extremely low-noise 6 kmc parametric amplifier using gallium arsenide point-contact diodes, Proc. IRE **47,** 2114 (1959).

Uenohara, M., Noise consideration of the variable capacitance parametric amplifier, Proc. IRE **48,** 169 (1960).

Uhlir, A., Jr., Two terminal p-n junction devices for frequency conversion and computation, Proc. IRE **44,** 1183 (1956).

Wade, G., and R. Adler, A new method for pumping a fast space-charge wave, Proc. IRE **47,** 79 (1959).

Wade, G., and H. Heffner, Gain, bandwidth and noise in a cavity-type parametric amplifier using an electron beam, J. Electron. Control **5,** 497 (1958).

Weiss, M. T., Quantum derivation of energy relations analogous to those for nonlinear reactances, Proc. IRE **45,** 1012 (1957a).

Weiss, M. T., Solid-state microwave amplifier and oscillator using ferrites, Phys. Rev. **107,** 317 (1957b).

Wolf, A. A., and J. E. Pippin, A passive parametric limiter, Dig. Tech. Papers, 1960 Solid-State Circuits Conf., 90 (1960).

Yeh, Chai, Generalized energy relation of nonlinear reactive elements, Proc. IRE **48,** 253 (1960).

Younger, J. J., A. G. Little, H. Heffner, and G. Wade, Super-regenerative operation of parametric amplifiers and detectors, IRE WESCON Conv. Record, Pt. 1, 108 (1959b).

Younger, J. J., A. G. Little, H. Heffner, and G. Wade, Parametric amplifiers as superregenerative detectors, Proc. IRE **47,** 1271 (1959a).

2. Microwave Properties of Ferrites

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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 peak power without breakdown. *Y* circulators in the 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 ½ 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].

Beside 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 $4\pi M_s \cong 1700$ gauss
(b) resistivity in the order of 10^6 ohm-cm,
(c) anisotropy at room temperature $\cong 90$ oersteds,
(d) linewidths at room temperature less than 10 oersteds, and
(e) spectroscopic splitting factor$=2.005 \pm 0.002$ 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, Spencer, 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 by Clogston et al. [1956], to be inhomogeneities of M or H of long wavelengths by Geschwind et al. [1957], and to be microcrystal effects in polycrystalline materials by Schlomann [1958]. Those theories appear to explain satisfactorily the order of magnitude of linewidth more than 25 oersteds found in spinel ferrites, but obviously not the kind of linewidth obtained in polished garnet spheres.

In 1959, Dillion and Nielson [1960] discovered that the peak of the linewidth and the anomalous anisotropy reported previously by Dillion at low temperature, are the effects of the rare earth impurities contained in the crystal. He 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 line width 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).

Bertant, F., and F. Forrat, Structure des ferrites ferrimagnetiques des terres rares, Compt. Rend. **242**, 382 (1956).

Bertant, F., and R. Pauthenet, Crystalline structure and magnetic properties of ferrites having the general formula $5Fe_2O_3 3M_2O_3$, Proc. IRE **104B,** 261 (1956).

Bloembergen, N., and S. Wang, Relaxation effects in para- and ferromagnetic resonances, Phys. Rev. **93,** 72 (1954).

Boyet, H., S. Weisbaum, and I. Gerst, Design calculations for UHF ferrite circulators, IRE Trans. PGMTT **7,** 4 (1959).

Buffler, C. R., Ferromagnetic resonance near the upper limit of the spin wave manifold, J. Appl. Phys. Supp. **30** (1959).

Button, K. J., Theoretical analysis of the operation of the field-displacement ferrite isolator, IRE Trans. PGMTT **6,** 303 (1958a).

Button, K. J., Theory of nonreciprocal ferrite phase shifter in dielectric loaded coaxial line, J. Appl. Phys. **29,** 998 (1958b).

Clarricoats, P. J. B., A. G. Hayes, and A. T. Harvey, A survey of the theory and applications of ferrite at microwave frequencies, Proc. IRE **104B,** 267 (1956).

Clavin, A., Reciprocal ferrite phase shifters in rectangular waveguide, IRE, Trans. PGMTT **6,** 3 (1958).

Clogston, A. M., N. Suhl, L. R. Walker, and P. W. Anderson, Possible source of linewidth in ferromagnetic resonance, Phys. Rev. **101,** 903 (1956).

Davis, L., U. Milano, and J. Saunders, A strip line L-band compact circulator, Proc. IRE **48,** 115 (1960).

deGennes, P. G., C. Kittel, and A. M. Portis, Theory of ferromagnetic resonance in rare earth garnets II. Line widths, Phys. Rev. **116,** 323 (1959).

Dillion, J. F., Jr., Ferromagnetic resonance in yttrium-iron at liquid helium temperatures, Phys. Rev. **111,** 1476 (1958).

Dillion, J. F., Jr., Ferromagnetic resonance in yttrium-iron garnet, Phys. Rev. **105,** 759 (1957).

Dillion, J. F., and J. W. Nielson, Effects of rare earth impurities on ferromagnetic resonance in yttrium-iron garnet, Phys. Rev. Letters **3,** 30 (1960).

Duncan, B. J., L. Swern, and K. Tonisyasu, Design considerations for broadband ferrite coaxial line isolators, Proc. IRE **45,** 483 (1957).

Farrar, R. T., Spin-lattice relaxation time in yttrium-iron garnet, J. Appl. Phys. **30,** 425 (1959).

Fleri, D., and G. Hanley, Nonreciprocity in dielectric loaded TEM mode transmission lines, Trans. IRE PGMTT **7,** 23 (1959).

Fletcher, R. C., and H. Seidel, Limitations of elementary mode considerations in ferrite loaded waveguide, J. Appl. Phys. **30,** 1475 (1959).

Fletcher, P. C., and I. H. Solt, Coupling of magnetostatic modes, J. Appl. Phys. **30,** 1815 (1959).

Fox, A. G., S. E. Miller, and M. T. Weiss, Behavior and application of ferrites in the microwave region, BSTJ **34** (1955).

Geller, S., and M. A. Gilleo, Structure and ferromagnetism of yttrium and rare earth iron garnets, Acta Cryst. **10,** 239 (1957).

Geller, S., and M. A. Gilleo, J. Phys. Chem. Solids **3,** 20 (1957).

Geschwind, S., and A. M. Clogston, Phys. Rev. **108,** 49 (1957).

Hogan, C. L., The ferromagnetic faraday effect at microwave frequencies and its applications, Rev. Mod. Phys. **25,** 253 (1953).

Hogan, C. L., The elements of nonreciprocal microwave devices, Proc. IRE **44,** 1368 (1956).

Kales, M. L., Propagation of fields through ferrite loaded waveguides, Proc. Symp. Mod. Adv. Microw. Tech. Polytech. Inst. of Brooklyn, Brooklyn, N.Y., 215 (1954).

Kittel, C., Theory of ferromagnetic resonance in rare earth garnets, I. g-values, Phys. Rev. **115,** 1587 (1959).

Kravitz, L. C., and G. S. Heller, Resonance isolator at 70 kmc, Proc. IRE **47,** 2 (1959).

Lax, B., Fundamental design principles of ferrite devices, Proc. Symp. Mod. Adv. Microw. Tech. Polytech. Inst. of Brooklyn, Brooklyn, N.Y., 229 (1954).

Lax, B., Frequency and ton characteristics of microwave ferrite devices, Proc. IRE **44,** 1368 (1956).

Lax, B., The status of microwave application of ferrites anP semiconductors, Trans. IRE PGMTT **6,** 5 (1958).

LeCraw, R. C., E. G. Spencer, and C. S. Porter, Ferromagnetic resonance and nonlinear effects in yttrium-iron garnet, J. Appl. Phys. **29,** 326 (1958a).

LeCraw, R. C., E. G. Spencer, and C. S. Porter, Ferromagnetic resonance linewidth in yttrium-iron garnet single crystals, Phys. Rev. **110,** 1131 (1958b).

LeCraw, R. C., and E. G. Spencer, Surface independent spin-wave relaxation in ferromagnetic resonance of yttrium-iron garnet, J. Appl. Phys. **30,** 1855 (1959).

Melcher, J. L., W. P. Ayres, and P. H. Vartanian, Microwave frequency doubling from 9 to 18 kmc in ferrites, Proc. IRE **45,** (1957).

Pippin, J. E., Frequency doubling and mixing in ferrites, Proc. IRE **44,** 1054 (1956).

Rowen, J. H., Ferrites in microwave applications, BSTJ **32,** 1333 (1953).

Schlomann, E., Spin wave analysis of ferromagnetic resonance in polycrystalline ferrites, J. Phys. Chem. Solids **6,** 242 (1958).

Seidel, H., Anomalous propagation in ferrite-loaded waveguide, Proc. IRE **44,** 1410 (1956).

Seidel, H., The character of waveguide modes in gyromagnetic media, BSTJ **36,** No. 2 (1957).

Seidel, H., Ferrite slabs in transverse electric mode waveguide, J. Appl. Phys. **28,** 216 (1957).

Seidel, H., and R. C. Fletcher, Gyromagnetic modes in waveguide partially loaded with ferrite, BSTJ **38,** 1427 (1959).

Seiden, P. E., and H. J. Shaw, High power effects in ferromagnetic resonance, J. Appl. Phys. **31,** 432 (1960).

Skomal, E. N., and M. A. Medina, Study of a microwave ferromagnetic multiple signal conversion process, J. Appl. Phys. Supp. **30,** no. 4, (1959).

Solt, I. H., W. L. White, and J. E. Mercereau, Multiplicities of the uniform processional mode in ferromagnetic resonance, J. Appl. Phys. **29,** 324 (1958).

Sparks, M., and C. Kittel, Ferromagnetic relaxation mechanism for M_s in yttrium-iron garnet, Phys. Rev. Letters **4,** 232 (1960).

Spencer, E. G., and R. C. LeCraw, Spin-lattice relaxation in yttrium-iron garnet, Phys. Rev. Letters **4,** 130 (1960).

Spencer, E. G., R. C. LeCraw, and A. M. Clogston, Low temperature linewidth maximum in yttrium-iron garnet, Phys. Rev. Letters **3,** 32 (1960).

Spencer, E. G., R. C. LeCraw, and C. S. Porter, Ferromagnetic resonance in yttrium-iron garnet at low frequencies, J. Appl. Phys. **29,** 429 (1958).

Stern, E., and P. Persham, Harmonic generation in ferrites, Presented at Symp. on the Role of Solid-State Phenomena in Electric Circuits, Polytech. Inst. of Brooklyn, Brooklyn, N.Y. (1957).

Sucher, M., and H. J. Carlin, Coaxial line nonreciprocal phase shifters, J. Appl. Phys. **28,** 921 (1957).

Suhl, H., The nonlinear behavior of ferrites at high microwave signal levels, Proc. IRE **44,** 1270 (1956).

Suhl, H., The theory of ferromagnetic resonance at high power signal powers, J. Phys. Chem. Solids **1,** 209 (1957).

To Tai Chen, Evanescent modes in a partially filled gyromagnetic rectangular waveguide, J. Appl. Phys. **31,** No. 1, 220 (1960).

Thaxter, J. B., and G. S. Heller, Circulators at 70 and 140 kmc, Proc. IRE **48,** 110 (1960).

Turner, E. H. (unpublished work) Bell Telephone Labs., Holmdel, N.J.

Van Uitart, L. G., R. C. LeCraw, E. G. Spencer, and R. L. Martin, Proposed means of realizing high power stability in magnetic oxides, J. Appl. Phys. **30,** 1623 (1959).

Walker, L. R., Magnetostatic modes in ferromagnetic resonance, Phys. Rev. **105,** 390 (1957).

Walker, L. R., Ferromagnetic resonance: line structures, J. Appl. Phys. **29,** 318 (1958).

3. Progress in Solid-State Masers

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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 (Al_2O_3) containing a small amount of chromium, was soon introduced by the University of Michigan and has become probably the most widely used maser material. [Makhov, 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 McAvoy, 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, 1958; 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, 1958; Feynman, Vernon, and Hellwarth, 1957; Heffner, 1957; Javan, 1958; King, Birko, and Makhov, 1959; Mims and McGee, 1959; Scovil and Schulz-DuBois, 1959; Yatsiv, 1959]. The circulator is a vital component in the reflection-type cavity maser, and one paper discussing this topic has appeared. In addition, proposals have been made for a circulatorless amplifier using two balanced maser cavities and a magic tee, and for nonreciprocal cavity masers without circulators using the nonreciprocal nature of the maser interaction process itself [Arams and Krayer, 1958; Autler, 1958; Strandberg and Kyhl]. Proposals have also been made for radiofrequency masers using nuclear spin levels, although the numerical calculations are not encouraging, particularly at lower frequencies [Braunstein, 1957; Donovan and Vuylsteke, 1960].

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, Makhov, 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 [Burkhardt, 1959; Chester and Bolef, 1957; Chester, Wagner, and Castle, 1958; Feher, Gordon, Buehler, Gere, and Thurmond, 1958; Hoskins, 1959; Wagner, Castle, and Chester, 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; Senitzky, 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].

3.6. Traveling Wave Masers

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 MELabs 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 temperature of ~1 ° 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 ° 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 ° K for the maser and associated circuitry, and to as low as ~18 ° K 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 (~2 ° 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. Schwalow 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 (~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

Alsop, L. E., J. A. Giordmaine, C. H. Mayer, and C. H. Townes, Observations using a maser radiometer at 3 cm wavelength, Astronom. J. **63,** 301 (1958).

Alsop, L. E., J. A. Giordmaine, C. H. Mayer, and C. H. Townes, Observation of discrete radio sources at 3 cm wavelength using a maser, Paris Symp. on Radio Astron. R. N. Bracewell (ed.), Stanford Univ. Press, Stanford, Calif., p. 69 (1959).

Alsop, L. E., J. A. Giordmaine, C. H. Townes, and T. C. Wang, Measurement of noise in a (*n* ammonia) maser amplifier, Phys. Rev. **107,** 1450 (1957).

Anderson, P. W., The reaction field and its use in some solid-state amplifiers, J. Appl. Phys. **28,** 1049 (1957).

Arams, F. R., Low-field X-band ruby maser, Proc. IRE **47,** 1373 (1959).

Arams, F. R., Maser operation with signal frequency higher than pump frequency, Proc. IRE **48,** 108 (1960).

Arams, F. R., and G. Krayer, Design considerations for circulator maser systems, Proc. IRE **46,** 912 (1958).

Arams, F. R., and S. Okwit, Tunable L-band ruby maser, Proc. IRE **47,** 992 (1959).

Arditi, M., and T. R. Carver, A gas call 'atomic clock' using optical pumping and optical detection, 1958 IRE Natl. Conv. Rec., pt. 1, 3.

Artman, J. O., N. Bloembergen, and S. Shapiro, Operation of a three-level solid-state maser at 21 centimeters, Phys. Rev. **109,** 1392 (1958).

Autler, S. H., Proposal for a maser amplifier system without non-reciprocal elements, Proc. IRE **46,** 1880 (1958).

Autler, S. H., Superconducting electromagnets, Bull. Am. Phys. Soc. **II 4,** 413 (1959); Rev. Sci. Instr. (to be published).

Autler, S. H., and M. McAvoy, A 21-centimeter solid-state maser, Phys. Rev. **110,** 280 (1958).

Barnes, F. S., Operating characteristics of an ammonia beam maser, Proc. IRE **47,** 2085 (1959).

Bell, W. E., A. Bloom, and R. Williams, A microwave frequency standard employing optically pumped sodium vapor, IRE Trans. **MIT–7,** 95 (1959).

Bergmann, S. M., Three-level solid-state maser, J. Appl. Phys. **30,** 35 (1959).

Bergmann, S. M., Submillimeter wave maser, J. Appl. Phys. **31,** 275 (1960).

Bloembergen, N., Proposal for a new type solid-state maser, Phys. Rev. **104,** 324 (1956).

Bloembergen, N., Electron spin and phonon equilibrium in masers, Phys. Rev. **109,** 2209 (1958).

Bloembergen, N., Solid-state infrared quantum counters, Phys. Rev. Letters **2,** 84 (1959a).

Bloembergen, N., Noise characteristics of infrared quantum counters, (abstract only), Bull. Am. Phys. Soc. **II, 4** 165 (1959b).

Bolef, D. I., and P. F. Chester, Some techniques of microwave generation and amplification using electron spin states in solids, IRE Trans. **MIT–6,** 47 (1958).

Braunstein, R., Proposal for a nuclear quadruple maser, Phys. Rev. **107,** 1195 (1957).

Burkhardt, J. L., et al., Theory of two-level masers, Final Report, ONR Contract Nonr 2254(00), Hycon Eastern, Inc. (now Hermes Electronics), Cambridge Parkway, Cambridge 42, Mass., Feb. 3, 1958.

Burkhardt, J. K., Inversion of paramagnetic resonance lines in irradiated calcite, Phys. Rev. Letters **2,** 149 (1959).

Chang, W. S. C., J. Cromack, and A. E. Siegman, Cavity and traveling-wave masers using ruby at S-band, IRE Wescon Conv. Rec., pt. 1, 142 (1959a).

Chang, W. S. C., J. Cromack, and A. E. Siegman, Cavity maser experiments using ruby at S-band, J. Electron. Control **6,** 508 (1959b).

Chang, W. S., and A. E. Siegman, Characteristics of potassium Chromicyanide for Zeeman transitions, Tech. Rep. No. 156–1, Stanford Electronics Lab., Stanford Univ., Stanford, Calif. (May 16, 1958).

Chang, W. S., and A. E. Siegman, Characteristics of ruby for maser applications, Tech. Rep. No. 156–2, Stanford Electronics Lab., Stanford Univ., Calif. (Sept. 30, 1958); also published as a special appendix to "Masers" by J. Weber, Rev. Mod. Phys. **31,** 681 (1959).

Chester, P. F., and D. I. Bolef, Superregenerative masers, Proc. IRE **45,** 1287 (1957).

Chester, P. F., P. E. Wagner, and J. G. Castle, Two-level solid-state maser, Phys. Rev. **110,** 281 (1958).

Clogston, A. M., Susceptibility of the three-level maser, J. Phys. Chem. Solids **4,** 271 (1958).

Collins, S. A., Jr., R. I. Kyhl, and M. W. P. Strandberg, Spin-lattice relaxation from state of negative susceptibility, Phys. Rev. Letters **2,** 88 (1959).

DeGrasse, R. W., Slow-wave structures for unilateral solid-state maser amplifiers, IRE Wescon Conv. Rec. pt. 3, 29 (1958).

DeGrasse, R. W., D. C. Hogg, E. A. Ohm, and H. E. D. Scovil, Ultra-low noise measurements using a horn reflector antenna and a traveling-wave maser, J. Appl. Phys. **30,** 2013 (1959).

DeGrasse, R. W., E. O. Schulz-DuBois, and H. E. D. Scovil, The three-level solid-state traveling-wave maser, BSTJ **39,** 305 (1959).

DeGrasse, R. W., and H. E. D. Scovil, Noise temperature measurement on a traveling-wave maser preamplifier, J. Appl. Phys. **31,** 443 (1960).

Ditchfield, C. R., and P. A. Forrester, Maser action in the region of 60 °K, Phys. Rev. Letters **1,** 448 (1958).

Donovan, R. E., and A. A. Vuylsteke, On the possibility of maser action in nuclear quadruple systems, J. Appl. Phys. **31,** 614 (1960).

Ewen, H. I., A thermodynamic analysis of maser systems, Microw. J. **3,** 41 (1959).

Feher, G., J. R. Gordon, E. Buehler, E. A. Gere, and C. D. Thurmond, Spontaneous emission of radiation from electron spin system, Phys. Rev. **109,** 221 (1958).

Feynman, R. P., F. L. Vernon, Jr., and R. W. Hellwarth, Geometrical representation of the Schrodinger equation for solving maser problems, J. Appl. Phys. **28,** 49 (1957).

Foner, S., J. Phys. Radium **20,** 336 (1959).

Foner, S., L. R. Momo, and A. Mayer, Multilevel pulsed field maser for generation of high frequencies, Phys Rev. Letters **3,** 36 (1959).

Forward, R. L., F. E. Goodwin, and J. E. Kiefer, Application of a solid-state ruby maser to an X-band radar system, IRE Wescon Conv. Rec. **pt. 1,** 119 (1959).

Friedburg, H., General amplifier noise limit, Quantum Electronics, ed. by C. H. Townes, Columbia Univ. Press, to be published in 1960.

Garstens, M. A., Method for calculating simultaneous resonance conditions in a three-level ruby maser, J. Appl. Phys. **30,** 976 (1959).

Geschwind, S., R. J. Collins, and A. L. Schwalow, Optical detection of paramagnetic resonance in an excited state of Cr^{3+} in Al_2O_3, Phys. Rev. Letters **3,** 545 (1959).

Gerritsen, H. J., and H. R. Lewis, Operation of a chromium doped titania maser, J. Appl. Phys. **31,** 608 (1960).

Gianino, P. D., and F. J. Dominick, A tunable X-band ruby maser, Proc. IRE **48,** 260 (1960).

Giordmaine, J. A., L. E. Alsop, C. H. Mayer, and C. H. Townes, A maser amplifier for radio astronomy at X-band, Proc. IRE **47,** 1062 (1959).

Goodwin, F. E., Duplexing a solid-state ruby maser in an X-band radar system, Proc. IRE **48,** 113 (1960).

Gordon, J. P., and K. D. Bowers, Microwave spin echoes from donor electrons in silicon, Phys. Rev. Letters **1,** 368 (1958).

Gordon, J. P., and L. D. White, Experimental determination of the noise figure of an ammonia maser, Phys. Rev. **107,** 1728 (1957).

Gordon, J. P., and L. D. White, Noise in (ammonia) maser amplifiers—theory and experiment, Proc. IRE **46,** 1588 (1958).

Gross, L. G., Silvered ruby maser cavity, J. Appl. Phys. **30,** 1459 (1959).

Hawkins, W. B., and R. H. Dicke, The polarization of sodium atoms, Phys. Rev. **91,** 1008 (1953).

Heffner, H., Maximum efficiency of the solid-state maser, Proc. IRE **45,** 1289 (1957).

Helmer, J. C., Maser oscillators, J. Appl. Phys. **28,** 212 (1957).

Helmer, J. C., (Ammonia) maser noise measurement, Phys. Rev. **107,** 902 (1957).

Helmer, J. C., and M. W. Muller, Calculation and measurement of the noise figure of a(*n* ammonia) maser amplifier, IRE Trans. **MIT–6,** 210 (1958).

Hoskins, R. H., Two-level maser materials, J. Appl. Phys. **30,** 797 (1959).

Hoskins, R. H., Spin-level inversion and spin-temperature mixing in ruby, Phys. Rev. Letters **3,** 174 (1959).

Javan, A., Theory of a three-level maser, Phys. Rev. **107,** 1579 (1957).

Javan, A., Multiple quantum transitions and maser amplification in two-level systems (in French), J. Phys. Radium **19,** 802 (1958).

Javan, A., Possibility of production of negative temperature in gas discharge, Phys. Rev. Letters **3,** 87 (1959).

Kaplan, D. E., and M. E. Browne, Electron free precession in paramagnetic free radials, Phys. Rev. Letters **2,** 454 (1959).

Kemp, J. D., Theory of maser oscillation, J. Appl. Phys. **30,** 1451 (1959).

Kikuchi, C., J. Lambe, G. Makhov, and R. W. Terhune, Ruby as a maser material, J. Appl. Phys. **30,** 1061 (1959).

King, J. E., A. Birko, and G. Makhov, A double pumping scheme applicable to low-frequency masers, Proc. IRE **47,** 2025 (1959).

King, J. E., and R. W. Terhune, Operation of a zero-field X-band maser, J. Appl. Phys. **30,** 1844 (1959).

Kingston, R. H., A UHF solid-state maser, Proc. IRE **46,** 916 (1958).

Kingston, R. H., A UHF solid-state maser, IRE Trans. **MIT–7,** 92 (1959).

Maiman, T. E., Maser behavior: temperature and concentration effects, J. Appl. Phys. **31,** 222 (1960).

Mainberger, M., and A. Orenberg, The atomichron—an atomic frequency standard: operation and performance, 1958 IRE Nat. Cov. Rec., pt. 1, 14.

Makhov, G., C. Kikuchi, J. Lambe, and R. W. Terhune, Jr., Maser action in ruby, Phys. Rev. **109,** 1399 (1958).

McCoubry, A. O., The atomichron—an atomic frequency standard: physical foundations, 1958 IRE Natl. Conv. Rec., pt. 1, 10.

McWhorter, A. L., and F. E. Arams, System noise measurement of a solid-state maser, Proc. IRE **46,** 913 (1958).

McWhorter, A. L., and J. W. Meyer, Solid-state maser amplifier, Phys. Rev. **109,** 312 (1958).

McWhorter, A. L., J. W. Meyer, and P. D. Strum, Noise temperature measurement on a solid-state maser, Phys Rev. **108,** 1642 (1957).

Mims, W. B., and J. D. McGee, Spin-spin energy transfer and the operation of three-level masers, Proc. IRE **47,** 2120 (1959).

Momo, L. R., R. A. Meyers, and S. Foner, Pulsed field millimeter wave maser, J. Appl. Phys. **31,** 443 (1960).

Morris, R. J., R. I. Kyhl, and M. W. P. Strandberg, A tunable maser amplifier with large bandwidth, Proc. IRE **47,** 80 (1959).

Muller, M. W., Noise in a molecular amplifier, Phys. Rev. **106,** 8 (1957).

Norton, L. E., Coherent spontaneous microwave emission by pulsed resonance excitation, IRE trans. **MIT–5,** 262 (1957).

Pound, R. V., Spontaneous emission and the noise figure of maser amplifiers, Ann. Phys. **1,** 24 (1957).

Price, R., et al., Radar echoes from Venus, Science **129,** 751 (1959).

Robinson, W. A., Infrared quantum converter, Bull. Am. Phys. Soc. II, **5,** 15 (1960).

Sanders, J. H., Optical maser design, Phys. Rev. Letters **3,** 86 (1959).

Schulz-DuBois, E. O., H. E. D. Scovil, and R. W. DeGrasse, Use of active material in three-level solid-state masers, BSTJ **38,** 335 (1959).

Schwalow, A. L., and C. H. Townes, Infrared and optical masers, Phys. Rev. **112,** 1940 (1958).

Scovil, H. E. D., The three-level solid-state maser, IRE Trans. **MIT–6,** 29 (1958).

Scovil, H. E. D., G. Feher, and H. Seidel, The operation of a solid-state maser, Phys. Rev. **105,** 762 (1957).

Scovil, H. E. D., and E. O. Schulz-DuBois, Three-level masers as heat engines, Phys. Rev. Letters **2,** 262 (1959).

Senitzky, I. R., Behavior of a two-level solid-state maser, Phys. Rev. Letters **1,** 167 (1958).

Serber, R., and C. H. Townes, Limits on electromagnetic amplification due to complementarity, Quantum electronics, ed. by C. H. Townes, Columbia Univ. Press, to be published in 1960.

Shimoda, K., H. Takahasi, and C. H. Townes, Fluctuations in amplification of quanta, J. Phys. Soc. Japan **12,** 686 (1957).

Siegman, A. E., Gain-bandwidth and noise in maser amplifiers, Proc. IRE **45,** 1737 (1957).

Siegman, A. E., P. N. Butcher, J. Cromack, and W. S. C. Chang, Traveling wave solid-state masers, Proc. Brit. IRE **105,** pt. B, Suppl. No. 11, 711 (1958).

Siegman, A. E., and R. J. Morris, Proposal for a "staircase" maser, Phys. Rev. Letters **2,** 302 (1959).

Singer, J. R., Proposal for a tunable millimeter wave molecular oscillator and amplifier, IRE Trans. **MIT–7,** 268 (1959).

Stitch, M. L., Maser amplifier characteristics for transmission and reflection cavities, J. Appl. Phys. **29,** 782 (1958).

Strandberg, M. W. P., Computation of noise figure for quantum mechanical amplifiers, Phys. Rev. **107,** 1483 (1957).

Strandberg, M. W. P., C. F. Davis, B. W. Faughnan, R. W. Kyhl, and G. J. Wolga, Operation of a solid-state quantum mechanical amplifier, Phys. Rev. **109,** 1988 (1958).

Strandberg, M. W. P., and R. L. Kyhl, Nonreciprocal cavity masers, Various unpublished technical reports, MIT.

Tenney, H. D., R. W. Roberts, and P. H. Vartanian, An S-band traveling-wave maser, 1959 IRE Wescon Conv. Rec. pt. 1, 151.

Theissing, H. H., P. J. Caplan, F. A. Dieter, and N. Rabbiner, Optical pumping in crystals, Phys. Rev. Letters **3,** 460 (1959).

Theissing, H. H., F. A. Dieter, and P. J. Caplan, Analysis of the emissive phase of a pulsed maser, J. Appl. Phys. **29,** 1673 (1958).

Wagner, P. E., J. G. Castle, Jr., and P. F. Chester, Electron spin-lattice relaxation in dilute potassium chromicyanide, Bull. Am. Phys. Soc. **II–4,** 21 (1959).

Weber, J., Maser noise considerations, Phys. Rev. **108,** 537 (1957).

Wells, W. H., Maser oscillator with one beam through two cavities, J. Appl. Phys. **29,** 714 (1958).

Wessel, G. K., A UHF ruby maser, Proc. IRE **47,** 590 (1959).

Wieder, I., Solid-state, high intensity, monochromatic light sources, Rev. Sci. Instr. **30,** 995 (1959).

Wieder, I., Optical detection of paramagnetic resonance saturation in ruby, Phys. Rev. Letters **3,** 468 (1959).

Yariv, A., J. R. Singer, and J. Kemp, Radiation damping effects in two-level maser oscillators, J. Appl. Phys. **30,** 265 (1959).

Yatsiv, S., Role of double-quantum transitions in masers, Phys. Rev. **113,** 1538 (1959).

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 π/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 π/S were specified at some point beyond the virtual cathod. Experimental studies had demonstrated the invariance of S and π/S in some 3-region guns.

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

A summary of the state of the art to about 1958 is presented in L. D. Smullin and H. A. Haus, "Noise in Electron Devices," John Wiley & Sons, MIT., Technology Press, 1958.

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 π 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 π 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. A 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 $\frac{1}{2}$ 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 π 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 $\lambda_q/4$ apart to separately determine the noise excitation of the fast and slow space charge waves. Saito found a positive correlation, $\pi/S\approx0.2$—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 $\pi/S\approx0$ 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 π/S. His values show $\pi/S\approx0.2$. 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 [1]

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 1½ 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

Coulton, M., and G. E. St. John, S-band traveling wave tube with noise figure below 5 db, Proc. IRE **46,** No. 5 (1958).

Currie, M. R., A new type of low-noise electron gun for microwave tubes, Proc. IRE **46** No. 5, (1958).

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

Currie, M. R., and D. C. Forster, Conditions for minimum noise generation in backward wave amplifiers, IRE Trans. **ED–5,** No. 1, 88 (1958).

Currie, M. R., and D. C. Forster, New mechanism of noise reduction in electron beams, J. Appl. Phys. **30,** No. 1 (1959).

Echenbaum, A. E., and R. W. Peter, The exponential gun—a low-noise gun for traveling wave tube amplifiers, RCA Rev. **XX,** No. 1 (1959).

Hammer, J. M., J. P. Laico, H. J. Holvorsen and E. G. Olsen, Low-noise C-band traveling-wave tube, IRE, 1959 Electron Devices Meeting, Oct. 29–30, Washington, D.C.

Haus, H. A., and R. B. Adler, Optimum noise performance of linear amplifiers, Proc. IRE **46,** 1517 (1958a).

Haus, H. A., and R. B. Adler, Canonical form of linear noisy networks, IRE Trans. **CT–5,** No. 3, 161 (1958b).

Haus, H. A., and R. B. Adler, Circuit theory of linear noisy networks, John Wiley and Sons, MIT Technol. Press (1959).

Jory, H. R., Noise in backward wave amplifiers, Ph.D. Thesis in Electrical Engineering, Univ. Calif. (1960).

Kinaman, E. W., and M. Magid, Very low-noise traveling wave amplifier, Proc. IRE **46,** No. 5 (1958).

Knechtli, R. C., Effect of electron lenses on beam noise, IRE Trans. **PGED–5,** No. 2, 84 (1958).

Muller, W. M., and M. R. Currie, Noise propagation in uniformly accelerated multivelocity electron beams, J. Appl. Phys. **30,** No. 12 (1959).

Nevins, J. E., Jr., A 5 db noise figure backward wave amplifier at X-band, IRE, 1959 Electron Devices Meeting, Oct. 29–30, Washington, D.C.

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

Rigrod, W. W., and J. R. Pierce, Space charge wave excitation in solid cylindrical Brillouin beams, BSTJ **38** No. 1 (1959).

Rockwell, R. G., Low noise klystron amplifiers, IRE Trans. **PGED–6,** 428 (1959).

Saito, S., New method of measuring the noise parameters of an electron beam, IRE Trans. **PGED–5** No. 4 (1958).

Shaw, A. W., A. E. Siegman, and D. A. Watkins, Reduction of electron beam noisiness by means of a low-velocity drift region, Proc. IRE **47** 2 (1959).

Siegman, A. E., Analysis of multivelocity electron beams by the density function method, J. Appl. Phys. **28,** No. 10 (1957).

Siegman, A. E., and S. Bloom, An equivalent circuit for microwave noise at the potential minimum, IRE Trans. **PGED–4,** No. 4 (1957).

Siegman, A. E., D. A. Watkins, and Hsung-Cheng Hsieh, Density function calculations of noise propagation on an accelerated multivelocity electron stream, J. Appl. Phys. **28,** No. 10 (1957).

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 Symposia 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 ω_p and ω_b 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. Haeff. 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, monotrons, 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

Allis, W. P., and R. J. Papa, MIT Research Lab. Electron Quart. Prog. Rept. No. **54,** 5 (1959).

Allis, W. P., and R. J. Papa, MIT Research Lab. Electron. Quart. Prog. Rept. No. **55,** 19 (1959).

Auer, P. L., H. Hurwitz, Jr., and R. D. Miller, Phy. of Fluids, **1,** 501 (1958).

Bernstein, I. B., Waves in a plasma in a magnetic field, Phys. Rev. **109,** 10 (1958).

Bernstein, I. B., J. M. Greene, and M. D. Kruskal, Exact nonlinear plasma oscillations, Phys. Rev. **108,** 546 (1957).

Boyd, G. D., Experiments on the interaction of a modulated electron beam with a plasma, Tech. Rept. No. 11, Electron Tube and Microw. Lab., Cal.Tech. (1959).

Boyd, G. D., L. M. Field, and R. W. Gould, interaction between an electron stream and an arc discharge plasma, Proc. Symp. Electron. Waveguides, 367, Polytech. Press of Polytech. Inst. of Brooklyn, Brooklyn, N.Y. (1958a).

Boyd, G. D., L. M. Field, and R. W. Gould, Excitation of plasma oscillations in growing plasma waves, Phys. Rev. **109,** 1393 (1958b).

Brown, S. C., Basic data of plasma physics, The Technology Press, Cambridge (1959).

Buneman, O., Instability, turbulence and conductivity in current-carrying plasma, Phys. Rev. Letters, **1,** 8 (1958).

Buneman, Nonlinear calculation of plasma oscillations, Proc. Conf. Plasma Oscillations, Speedway Research Lab., Linde Co., Indianapolis, Ind., June 8–10 (1959).

Chorney, P., Electron-stimulated ion oscillations, Tech. Rept. 277, Research Lab. Electron., MIT (1958).

Clauser, F. H., Plasma dynamics, Addison-Wesley, Reading, Mass. (1960).

Dawson, J., and C. Oberman, Oscillations of a finite cold plasma in a strong magnetic field, Phys. of Fluids **2,** 103 (1959).

Goldstein, L., Nonreciprocal electromagnetic wave propagation in ionized gaseous media, IRE Trans. **MIT-6,** 19 (1958).

Gould, R. W., and A. W. Trivelpiece, A new mode of wave propagation on electron beams, Proc. Symp. Electron. Waveguides, 215–228, Polytech. Press of Polytech. Inst. of Brooklyn, Brooklyn, N.Y. (Apr. 1958).

Haus, H. A., MIT, Research Lab. of Electron. Quart. Prog. Rept. 46 (1959).

Jepsen, R. L., Ion oscillations in electron beam tubes; ion motion and energy transfer, Proc. IRE **45,** 1069 (1957).

Kino, G. S., A parametric amplifier theory for plasmas and electron beams, M. L. Rept. 636, Stanford Univ. (1959).

Kino, G. S., A proposed millimeter-wave generator, M. L. Rept. 609, Stanford Univ. (1959) (paper submitted to Proc. Symp. Polytech. Inst. Brooklyn (1960)).

Landshoff, R. K. M., Magnetohydrodynamics, A symposium, Stanford Univ. Press, Palo Alto, Calif. (1957).

Landshoff, R. K. M., The plasma in a magnetic field, Symp. Magnetohydrodynam. Stanford Univ. Press, Palo Alto, Calif. (1958).

Lichtenberg, A. J., Plasma waveguides as high-Q structures, Univ. California, Series No. 60, Issue No. 247 (1959).

Longmire, C., J. L. Tuck, and W. B. Thompson (editors) Progress in nuclear energy, Ser. XI Plasma Physics and Thermonuclear Research (Pergamon Press, Inc., New York, N.Y., 1959).

MIT Summer Course notes on Plasma dynamics (1959) (out of print).

Smullin, L. D., and P. Chorney, Properties of plasma-filled waveguides, Proc. IRE **46,** 360 (1958a).

Smullin, L. D., and P. Chorney, Propagation in ion loaded waveguides, 229, Polytech. Press of Polytech. Inst. of Brooklyn, N.Y. (1958b), Proc. of Symp. Electron. Waveguides.

Stix, Thomas H., Oscillations of a cylindrical plasma, Phys. Rev. **106,** No. 6 1146 (1957).

Sturrock, P. A., Kinematics of growing waves, Phys. Rev. **112,** 1488 (1958).

Symposium on Electronic Waveguides, Electronic waveguides, Microw. Research Inst. Symp. Ser. Vol. VIII, Polytech. Press of Polytech. Inst. of Brooklyn (1958).

Trivelpiece, A. W., Slow wave propagation in plasma waveguides, Tech. Rept. No. 7, Electron Tube and Microw. Lab. Calif. Inst. Technol. (1958).

Trivelpiece, A. W., and R. W. Gould, Space charge waves in cylindrical plasma columns, J. Appl. Phys. **30,** 1784 (1959).

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