Report of Advances in Microwave Theory and Techniques in U.S.A.—1958*

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Introduction

THIS report on advances in microwave theory and techniques is based on papers appearing in American journals. Advances in the realm of sources and detectors, transmission lines, circuits and circuit elements, components, and measurements are reported. No attempt is made to cover advances in the realm of antennas and wave propagation.

Advances in 1958 were dominated by extensions in knowledge and understanding of solid-state phenomena and by the application of solid-state materials for sources, detectors, and microwave components. Methods of inducing emission of internal molecular energy to achieve microwave amplification have been studied intensively and extensively.

Molecular beam types of masers have characteristics which are serious limitations to extensive practical utilization except for very specialized application requiring very small noise figures. One of the greatest disadvantages is the requirement for operation at liquid helium temperatures; a second serious disadvantage is the very narrow bandwidth; and a third is the requirement of pumping power, usually at frequencies higher than the signal frequency.

These disadvantages are not as great for the new solid-state masers which have received a greater measure of attention during the past year. New materials such as ruby and garnet have been studied. The promise of large scale improvements is not great.

Parametric amplifiers which utilize nonlinear reactances appear to offer significant advantages over masers. Following Suhl's proposal for a ferromagnetic amplifier in the microwave range utilizing a ferrite to obtain, in effect, a time-varying inductance, interest in parametric amplifiers, in general, increased. The well-known nonlinear capacitance characteristic of semiconductor diodes led to considerable efforts to utilize them and to improve their characteristics for such microwave applications. The future of parametric amplifiers utilzing semiconductor diodes at microwave frequencies as low-noise devices appears to be very bright. Traveling-wave forms of parametric amplifiers are considered by some to be very promising. Since low noise figures (as low as can be justified for most applications) are realizable in a simple manner by parametric means without cooling, the great interest in them seems justified.

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The interest in, and development of, traveling-wave tubes as versatile sources of microwave energy having unequaled gain-bandwidth products continued unabated. These efforts have resulted in much smaller, lighter, and more easily adjustable tubes of low, medium, and high power capabilities. Commercial use of these tubes will undoubtedly increase significantly as the result of recent advances.

Klystrons remain the work horses of the microwave tubes and as such are of great importance and have received considerable study. Of especial significance among the developments of the year is the clarification of the low noise-figure potentialities of kylstrons as amplifiers with wide dynamic range for application in RF amplifiers of microwave receivers. Microwave receivers having high sensitivity, high gain, and great dynamic range now appear to be feasible.

It is interesting to note that both traveling-wave tubes and reflex klystrons, respectively, have been operated in a parametric fashion with pumping signals to achieve operation over an extended frequency band and to achieve regenerative amplifier action with the aid of isolators or circulators.

Magnetrons, *per se*, and ordinary vacuum tubes for microwave use received comparatively little study.

Transmission lines and components for transmission systems were investigated extensively. Investigations of TEM lines continue to be dominated by such needs as wider operating bandwidths and smaller size. The large circular waveguide operating in the low-attenuation TE_{01} mode continued to attract study. Mode-purity problems hinder commercial application of these large waveguides. Interest in open or surface waveguides was dominated by their potential usefulness at millimeter wavelengths. Launching methods for surface waves were studied.

Transmission lines containing anisotropic media and microwave components utilizing such media accounted for much activity. The theory of wave propagation in anisotropic waveguides of various geometries, the development of such components as isolators, circulators, and phase shifters, and the search for new anisotropic materials were areas of major interest. Study of the utility of yttrium garnet in components for operation at lower frequencies than are possible with ferrites is noteworthy.

Advances in microwave measurements were principally of the nature of refinements of well-established techniques.

The individual work on the subjects mentioned above is listed in the following three sections; Sources and Detectors, Transmission Lines, and Measurements. Studies of microwave components and devices which utilize anisotropic materials are also listed in these sections.

Sources and Detectors

Activity in the field of sources of microwave energy has been extensive. Well-established types continue to receive attention. Traveling-wave-tube studies were especially numerous and have resulted in tubes with characteristics which should make them acceptable for field use.

Interest in masers has continued but has been greatest in solid-state rather than in gaseous-state types. The principal advance in sources appears to be in the field of cavity and traveling-wave types of parametric amplifiers, especially those using semiconductor diodes as nonlinear reactive elements.

The results of recent studies of semiconductor diodes indicate that greatly improved diodes for microwave applications will be forthcoming.

Parametric Amplifiers

Most devices which amplify at microwave frequencies use dc sources of power, however, the required power can be supplied from a CW source. The CW source, or "pump," functions to vary the reactance of a circuit. Amplifiers which depend upon the variation of a circuit parameter for their operation are called parametric amplifiers. A parametric amplifier, utilizing a ferromagnetic sample in a microwave cavity for amplification of microwaves, was proposed about two years ago by Suhl. He showed that if the ferromagnetic sample is placed in a cavity which is resonant at three frequencies such that one of the frequencies is equal to the sum of the other two, amplification may occur at either of the two lower frequencies. The simplest case is that for which the RF power source is operated at twice the frequency of the signal to be amplified.

Suhl's proposal and the availability of suitable nonlinear reactances for microwave operation supplied a great stimulus to the development of parametric amplifiers utilizing nonlinear reactances in cavity and traveling-wave structures. Another important stimulus is the promise of low noise figures without cooling since variable-reactnace amplifiers do not depend upon resistive elements for their operation.

A critical evaluation of the relative merits of masers and parametric amplifiers was favorable to the parametric amplifier. Traveling-wave types were considered the most promising of all. Ferrite parametric amplifiers require high pumping powers for reasonably large gain-bandwidth products and strong static magnetic fields. These characteristics place ferrite amplifiers in a poor competitive position relative to semiconductor-diode and electron-beam types of parametric amplifiers.

[1] H. Heffner, "Masers and parametric amplifiers—introduction," 1958 IRE WESCON Convention Record, pt. 3, pp. 3–8.

A basic study of the general energy relations for nonlinear lumped circuit elements was published by Manley and Rowe two years ago. In a continuation of this study the simplest types of nonlinear capacitor modulators, demodulators, and negative conductance amplifiers in which components at two signal frequencies are present were studied by the methods of small-signal theory.

[2] H. E. Rowe, "Some general properties of nonlinear elements. II. Small signal theory," Proc. IRE, vol. 46, pp. 850–860; May, 1958.

A generalization of the Manley-Rowe relations to include power flow in systems involving nonlinear anisotropic electric and magnetic media and nonreciprocal circuits was reported.

[3] H. A. Haus, "Power-flow relations in lossless nonlinear media," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 317–324; July, 1958.

An analysis of the variable reactance amplifier in terms of a low-frequency analog in which a variable energy storage is coupled to two resonant circuits looks promising as a simple guide for a parametric amplifier design.

[4] H. Heffner and G. Wade, "Gain, bandwidth, and noise characteristics of the variable-parameter amplifier," *J. Appl. Phys.*, vol 29, pp. 1321–1331; September, 1958.

The principles of a ferromagnetic resonance frequency converter which are those of the Suhl amplifier were described and checked experimentally. The results obtained are pertinent to the original amplifier as well as to the frequency converter.

[5] K. M. Poole and P. K. Tien, "A ferromagnetic resonance frequency converter," Proc. IRE, vol. 46, pp. 1387–1396; July, 1958.

A mode of operation which is characterized by the use of the uniform precession in a ferrite as the idling magnetostatic mode was described. Although this mode is similar to Suhl's semistatic mode, it differs in that the biasing field is tuned to the difference between the pump and signal frequencies rather than to the pump frequency.

[6] A. D. Berk, L. Kleinman, and C. E. Nelson, "Modified semistatic ferrite amplifier," 1958 IRE WESCON Convention Record, pt. 3, pp. 9–12.

As an indication of the advances in the use of semiconductors, a back-biased germanium junction diode was used in a rectangular cavity which was resonant at 3500, 2300, and 1200 mc. Values of gain as high as 40 db were obtained at 1200 and 2300 mc with a pump frequency of 3500 mc. At 16-db gain, a noise figure of less than 4.8 db was observed.

[7] H. Heffner and K. Kotzebue, "Experimental characteristics of a microwave parametric amplifier using a semiconductor diode," Proc. IRE, vol 46, p. 1301; June, 1958.

The following studies indicate that operation with lower-frequency pumping instead of with higher-frequency pumping is possible and that lower noise figures are to be achieved by this type of operation.

[8] S. Bloom and K. K. N. Chang, "Parametric amplification using low-frequency pumping," *J. Appl. Phys.*, vol. 29, p. 594; March, 1958.
[9] K. K. N. Chang and S. Bloom, "A parametric amplifier using lower-frequency pumping," Proc. IRE, vol. 46, pp. 1383–1386; July, 1958.
[10] K. K. N. Chang and S. Bloom, "A parametric amplifier using lower-frequency pumping," 1958 IRE WESCON Convention Record, pt. 3, pp. 23–27.
[11] C. L. Hogan, R. L. Jepsen, and P. H. Vartanian, "A new type of ferromagnetic amplifier," *J. Appl. Phys.*, vol. 29, pp. 422–423; March, 1958.
[12] G. F. Herrmann, M. Uenohara, and A. Uhlir, Jr., "Noise figure measurements on two types of variable reactance amplifiers using semiconductor diodes," Proc. IRE, vol. 46, pp. 1301–1303; June, 1958.

An analysis of the traveling-wave type of parametric amplifier which is based on a low-frequency model was made. The existence of a growing wave was demonstrated. The amplifying system consisted of two coupled transmission lines with time-dependent coupling. A theory was then developed for a structure which consisted of four parallel wires imbedded in a ferrite rod.

[13] P. K. Tien and H. Suhl, "A traveling-wave ferromagnetic amplifier," Proc. IRE, vol. 46, pp. 700–706; April, 1958.

A closely related study, which expands the general theory and cites applications to broad-band frequency converters, frequency channel selectors, wide-band amplifiers, tunable narrow-band amplifiers and oscillators, was described.

[14] P. K. Tien, "Parametric amplification and frequency mixing in propagating circuits," *J. Appl. Phys.*, vol. 29, pp. 1347–1357; September, 1958.

Somewhat pertinent to the study of traveling-wave parametric amplifiers is a discussion of the solution of Maxwell's equations for media in which the permittivity and permeability vary independently with time.

[15] F. R. Morgenthaler, "Velocity modulation of electromagnetic waves," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 167–172; April, 1958.

The results obtained with an experimental UHF traveling-wave parametric amplifier utilizing diffused-junction silicon diodes as nonlinear capacitors were summarized in the following paper. A noise figure of 3.5 db, a bandwidth of 10 to 20 mc, a forward gain of about 12 db for a signal frequency of 380 mc were reported.

[16] R. S. Engelbrecht, "A low-noise nonlinear reactance traveling-wave amplifier," Proc. IRE, vol. 46, p. 1655; September, 1958.

It was suggested early in 1958 that an electron beam be used instead of the ferrite to vary the reactance of a microwave cavity for parametric amplification. A tube for a signal frequency of 4130 mc, and a pump frequency of 8300 mc was constructed and tested. This amplifier was of the regenerative type utilizing the electronic reactance of a double-gap cavity to give parametric excitation. Results obtained were substantially as predicted.

[17] T. J. Bridges, "A parametric electron beam amplifier," Proc. IRE, vol. 46, pp. 494–495; February, 1958.

A distributed parametric amplifier, using an electron beam and deriving its power from a CW source equal to twice the operating frequency, was described. It was found that the normal space-charge waves in a drifting electron beam will convert to exponentially growing waves if one modulates the beam with a pumping frequency equal to twice the signal frequency. Either the fast or slow space-charge wave can be made to grow. Previous microwave amplifiers have amplified only the slow wave and theorems on minimum noise figure for slow-wave tubes are not valid for fast-wave amplifiers. Emphasis is placed on the fast wave.

[18] W. H. Louisell and C. F. Quate, "Parametric amplification of space charge waves," Proc. IRE, vol. 46, pp. 707–716; April, 1958.

An experimental fast-wave amplifier utilizing double-gap cavities as fast-wave couplers was proposed and built. A gain of 30 db was measured. A gain of 13 db per plasma wavelength for a pump frequency of 8400 mc and a signal frequency of 4200 mc was obtained by utilizing a demountable tube with a fixed input and pump cavities but movable signal pick-up cavity. It was also demonstrated that parametric amplification of space-charge waves is possible with the pump frequency lower than the signal frequency or with the pump frequency slightly different from twice the signal frequency.

[19] A. Ashkin, T. J. Bridges, W. H. Louisell, and C. F. Quate, "Parametric electron beam amplifiers," 1958 IRE WESCON Convention Record, pt. 3, pp. 13–22.
[20] A. Ashkin, "Parametric amplification of space charge waves," *J. Appl. Phys.*, vol. 29, pp. 1646–1651; December, 1958.

In principle fast-wave amplifiers should be less noisy than slow-wave amplifiers because noise cancellation is possible for the fast electron wave. A device was described which employs fast-wave interaction in its input and output sections and in which the amplitude of the transverse motion of the electrons is increased by parametric amplification between its input and output sections. It was reported that a gain of 20 db was easy to obtain with a few milliwatts of pump power and that a noise figure of 1.3 db was measured.

[21] R. Adler, "Parametric amplification of the fast electron wave," Proc. IRE, vol. 46, pp. 1300–1301; June, 1958.
[22] R. Adler, G. Hrbek, and G. Wade, "A low-noise electron-beam parametric amplifier," Proc. IRE, vol. 46, pp. 1756–1757; October, 1958.

Chu's kinetic power theorem which provided the key to the solution of noise problems in conventional longitudinal beam amplifiers was not general enough to apply to the parametric beam amplifier. This power theorem was generalized to apply to parametric beam amplifiers.

[23] H. A. Haus, "The kinetic power theorem for parametric, longitudinal, electron-beam amplifiers," IRE Trans. on Electron Devices, vol. ED-5, pp. 225–232; October, 1958.

An interesting development which may well include the parametric effects in electron beams was that of the utilization of a high-level pumping signal to extend the frequency range of amplification in a traveling-wave tube. The small signal gain of an S-band tube operating at L band was increased by 33 db by adding a saturating S-band signal to the input of the tube.

[24] L. D. Buchmiller and G. Wade, "Pumping to extend traveling-wave-tube frequency range," Proc. IRE, vol. 46, pp. 1420–1421; July, 1958.

Nonlinear Devices

The need for extending the frequency range, in which the detection sensitivity is good, and for improving nonlinear capacitors for parametric amplifiers has had considerable influence in the study of methods of improving solid-state diodes. The upper frequency limit of operation of semiconductor diodes is being increased; the Q, decreased; new materials are being used; new design techniques are being developed; and an appreciation of their potential fields of usefulness is developing. The following papers are representative of those which treated some aspect of solid-state diodes.

[25] A. Uhlir, "The potential of semiconductor diodes in high-frequency communications," Proc. IRE, vol. 46, pp. 1099–1155; June, 1958.
[26] G. C. Messenger, "New concepts in microwave mixer diodes," Proc. IRE, vol. 46, pp. 1116–1121; June, 1958.
[27] C. T. McCoy, "Present and future capabilities of microwave crystal receivers," Proc. IRE, vol. 46, pp. 61–66; January, 1958.
[28] D. A. Jenny, "A gallium arsenide microwave diode," Proc. IRE, vol. 46, pp. 717–722; April, 1958.
[29] L. K. Anderson and A. Hendry, "An investigation of the properties of germanium mixer crystals at low temperatures," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 393–398; October, 1958.
[30] S. M. Bergmann, "One aspect of minimum noise figure microwave mixer design," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 324–326; July, 1958.
[31] S. Kita, "A harmonic generator by use of nonlinear capacitance of germanium diode," Proc. IRE, vol. 46, p. 1307; June, 1958.
[32] K. K. N. Chang, "Harmonic generation with non-linear reactances," *RCA Rev.*, vol. 19, pp. 455–464; September, 1958.
[33] J. L. Moll, A. Uhlir, Jr. and B. Senitzky, "Microwave transients from avalanching silicon diodes," Proc. IRE, vol. 46, pp. 1306–1307; June, 1958.
[34] W. T. Read, Jr., "A proposed high-frequency, negative-resistance diode," *Bell. Sys. Tech. J.*, vol. 37, pp. 401–446; March, 1958.

The use of the nonlinear characteristics of ferrites and similar materials for detection, harmonic generation, frequency conversion and related functions, has continued. The following papers are indicative of experimental investigations in this area.

[35] D. Jaffe, J. C. Cacheris and N. Karayianis, "Ferrite microwave detector," Proc. IRE, vol. 46, pp. 594–601; March, 1958.
[36] E. N. Skomal and M. A. Medina, "Microwave frequency conversion studies in magnetized ferrites," *J. Appl. Phys.*, vol. 29, pp. 423–424; March, 1958.

Masers

The utilization of direct interaction of microwave fields with the molecules in uncharged matter has received much study during this year. Emphasis has been placed on the three-level solid-state maser rather than the ammonia-beam type. New paramagnetic materials such as cobalticyanide, ruby, and yttrium-iron garnet have been introduced, and traveling-wave propagating structures have been used instead of cavities. Methods of increasing gain and bandwidth and of decreasing the lower limit on operating frequency have been sought. A unidirectional quantum-mechanical amplifier which affords a natural isolation of output and input without the use of isolators or circulators was described, and the results of gain and noise measurement were recorded. The amplifying medium consisted of a prestimulated beam of ammonia molecules which was first passed through a state selector where only the excited or upper state molecules were retained. The beam was then passed, in turn, through two cavities which were resonant at the same frequency (23.87 kmc). Beyond-cut-off-waveguide sections were used to prevent RF leakage at the beam entrance and exit points and between the cavities.

[37] N. Sher, "A two-cavity unilateral maser amplifier," 1958 IRE National Convention Record, pt. 1, pp. 27–35.

In another study of two cavity masers a method which involves a geometrical representation of the Schroedinger equation was found especially useful in finding the approximate behavior of a complicated maser system. The theory of an experimental observation by Higa was developed. In this experiment the two cavities were tuned to the molecular frequency under such conditions that each maintained oscillations without the other. The first cavity, A, through which the beam passed, was then detuned. Oscillations in the second cavity, B, were observed to follow the frequency of A up to the critical point, a few kilocycles from the molecular frequency. Without further detuning of A, cavity B began to oscillate simultaneously at the molecular frequency to which it was tuned and at the frequency of A.

[38] W. H. Wells, "Maser oscillator with one beam through two cavities," *J. Appl. Phys.*, vol. 29, pp. 714–717; April, 1958.

The results of a theoretical analysis of the respective merits of reflection-type and transmission-type cavities for use in maser amplifiers were reported. Consideration was given to noise temperature, bandwidth, and gain modulation characteristics. The reflection type of maser was shown to be superior in most respects to the transmission type. However, they are limited by the isolation obtainable from available circulators. A figure of merit for both types was included.

[39] M. L. Stich, "Maser amplifier characteristics for transmission and reflection cavities," *J. Appl. Phys.*, vol. 29, pp. 782–789; May, 1958.

The three-level, solid-state maser has received considerable study during the past year. The theoretical principles of operation were discussed; the relevant physical properties of paramagnetic salts were elucidated, and a 6-kmc maser using lanthanum ethylsulphate crystals containing one-half per cent cerium was described in the following paper.

[40] H. E. D. Scovil, "The three-level solid-state maser," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 29–38; January, 1958.

In this investigation a gain of 20 db with a bandwidth of approximately 100 kc and an effective noise temperature of about 150°K were obtained experimentally. The stability margin was small. Both bandwidth and stability, it was claimed, could be improved if an appropriate unidirectional slow-wave structure were employed.

Solid-state masers using potassium cobalticyanide with one-half per cent chromicyanide as the paramagnetic salt received appreciable attention. This material is considered to be well-suited for maser application because it has a long spin-lattice relaxation time; a value of 0.2 seconds at 1.25°K was reported. This salt was used in cavities with dual resonant frequencies to obtain S-band and L-band amplification and oscillation.

[41] A. L. McWhorter and J. W. Meyer, "Solid-state maser amplifier," *Phys. Rev.*, vol. 109, pp. 312–318; January 15, 1958.
[42] A. L. McWhorter and F. R. Arams, "System-noise measurement of a solid-state maser," Proc. IRE, vol. 46, pp. 913–914; May, 1958.
[43] J. O. Artman, N. Bloembergen, and S. Shapiro, "Operation of a three-level solid-state maser at 21 cm," *Phys. Rev.*, vol. 109, pp. 1392–1393; February 15, 1958.
[44] S. H. Autler and N. McAvoy, "21-centimeter solid-state maser," *Phys. Rev.*, vol. 110, pp. 280–281; April 1, 1958.

A UHF maser which had two separate resonant structures instead of the usual one was described. A cavity, which was resonant at the pumping frequency, and a lumped circuit, which was resonant at the amplifying frequency, were used. The paramagnetic material was potassium cobalticyanide.

[45] R. H. Kingston, "A UHF solid-state maser," Proc. IRE, vol. 46, p. 916; May, 1958.

To prevent noise from being fed back into the resonant cavities, ferrite circulators have been widely used. For lower microwave frequencies, such as 300 mc and 1380 mc, satisfactory circulators were not available. To eliminate the circulator, a system involving two matched masers coupled to the side arms of a magic T was proposed.

[46] S. H. Autler, "Proposal for a maser-amplifier system without nonreciprocal elements," Proc. IRE, vol. 46, pp. 1880–1881; November, 1958.

The application of three-level solid-state masers is hindered by the limited number of suitable paramagnetic materials, and by the requirement for pumping signal powers at frequencies above the signal frequency. Therefore the two-level solid-state maser, even though basically intermittent in operation instead of continuous as is the three-level one, was carefully examined for possible modes of continuous operation. In principle, it was concluded that a continuous two-level maser which would have some advantage over the three-level maser was possible using paramagnetic materials and the principle of nonadiabatic field reversal.

[47] D. I. Bolef and P. F. Chester, "Some techniques of microwave generation and amplification using electron spin states in solids," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp 47–52; January, 1958.

In another paper on two-level solid-state masers, an analysis of the emission from a matched cavity at paramagnetic resonance was given.

[48] H. H. Theissing, F. A. Dieter, and P. J. Caplan, "Analysis of the emissive phase of a pulsed maser," *J. Appl. Phys.*, vol. 29, 1673–1678; December, 1958.

Cavity-type masers are quite limited in bandwidth and gain. Greatly improved performance was obtained by using a slow-wave propagation structure instead of a cavity; wider amplifying bandwidth, high gain, and unidirectional amplification resulted. As representative of the results obtained, a ruby traveling-wave maser gave a net gain of 23 db, a bandwidth of 25 mc, and a tuning range of 350 mc centered about 5900 mc.

[49] R. W. DeGrasse, "Slow-wave structures for unilateral solid-state maser amplifiers," 1958 IRE WESCON Convention Record, pt. 3, pp. 29–35.

Noise in maser amplifiers was the object of considerable study. One study resulted in a theoretical treatment and experimental data on the noise of an ammonia-beam maser. An equivalent circuit was developed, and expressions for the gain and effective noise input temperature were derived for both transmission and reflection types of masers.

[50] J. P. Gordon and L. D. White, "Noise in maser amplifiers—theory and experiment," Proc. IRE, vol. 46, pp. 1588–1594; September, 1958.
[51] J. C. Helmer and M. W. Muller, "Calculation and measurement of the noise figure of a maser amplifier," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 210–214; April, 1958.
[52] F. R. Arams and G. Krayer, "Design considerations for circulator maser systems," Proc. IRE, vol. 46, pp. 912–913; May, 1958.

In another endeavor to find paramagnetic materials suitable for masers, the spin properties of ruby (Al_2O_3:Cr) were investigated. Using the regenerative cavity system, K- and X-band absorption lines characteristic of the ruby were observed; no interaction between the two bands was detected. Net gain as high as 20 db was observed at 9300 mc for a pumping frequency of 24,000 mc.

[53] G. Makhov, C. Kikuchi, J. Lambe, R. W. Terhune, "Maser action in ruby," *Phys. Rev.*, vol. 109, pp. 1399–1400; February 15, 1958.

The spin-lattice relaxation time of yttrium-ion garnet was measured and found to be 7×10^{-8} second. The ferromagnetic resonance line width was 2.3 oersteds at 9300 mc, reportedly the narrowest line width of any known ferromagnetic material. Low-frequency resonances at frequencies as low as 44 mc, for an applied field of 1000 oersteds, was observed in another investigation.

[54] R. C. LeCraw, E. G. Spencer, and C. S. Porter, "Ferromagnetic resonance and nonlinear effects in yttrium iron garnet," *J. Appl. Phys.*, vol. 29, pp. 326–327; March, 1958.
[55] E. G. Spencer, and R. C. LeCraw, C. S. Porter, "Ferromagnetic resonance in yttrium garnet at low frequencies," *J. Appl. Phys.*, vol. 29, pp. 429–430; March, 1958.

Traveling-wave Tubes

Taveling-wave tubes operate over a wide band of frequencies and provide appreciable gain. These characteristics are desirable ones for application in systems requiring frequency diversification. The use of heavy, power-thirsty electromagnets for focusing the electron beam has been the greatest factor limiting their application. Other factors include the need for precise alignment of the focusing structure, the large size, the fragility, and the cost. The size and weight were considerably reduced by the use of convergent flow shielded electron guns and by the imposition of proper relationships upon beam diameter, beam current, and magnetic field to produce a balance between the magnetic force on the electrons and the forces due to space-charge and centrifugal acceleration. Periodic-permanent-magnet focusing was then developed to obtain further reductions. The need for accurate alignment of the focusing structure with the axis of the tube remained. To achieve further reductions in size and weight and the elimination of the alignment problem, studies of periodic electrostatic focusing were initiated. These means of focusing are still being studied.

A new traveling-wave tube, called the Estiatron, was announced. Instead of one helix, this tube utilizes two helices which are interwound in a bifilar manner, imbedded in the glass envelope, and operated at different potentials to produce periodic electrostatic focusing of the electron beam. A continuous-wave output in excess of 9 watts over the frequency range from 2000 to 3000 mc and a maximum gain of 25 db were reported. The weight of the tube was less than 1 pound.

[56] D. Blattner and F. Vaccaro, "The Estiatron—an electrostatically focused medium-power traveling-wave tube," 1958 IRE National Convention Record, pt. 3, pp. 101–105.

A new traveling-wave tube which utilizes an annular gun and a pair of concentric bifilar helices in a biperiodic electrostatic focusing system was also described. An experimental tube had a gain of 10 db at a power level of 100 milliwatts at a frequency of 2970 mc.

[57] K. K. N. Chang, "An electrostatically focused traveling-wave-tube amplifier," *RCA Rev.*, vol. 19, pp. 86–97; March, 1958.

A new type of voltage-tuned microwave oscillator, called the Helitron, was described. It employs an electron beam which travels in a helical path around a four-conductor transmission line. The beam interacts on a radial and angular basis with a TEM wave on the line in such a way as to lose potential energy to the wave. The interaction is similar to that in an M-type traveling-wave tube. Electron focusing is accomplished by balancing centrifugal force against a radial electric-field force; no focusing magnets are required. Continuous voltage tuning over the frequency range from 1200 to 2400 mc with a change in tuning voltage from 650 to 1700 volts and power output between 1 and 10 milliwatts were reported.

[58] D. A. Watkins and G. Wada, "The helitron oscillator," Proc. IRE, vol. 46, pp. 1700–1705; October, 1958.

Design considerations for traveling-wave tubes for use in airborne equipment were surveyed and examples of current tubes with desirable characteristics were given.

[59] M. Nowogrodzki, "Design of traveling-wave tubes for airborne applications," 1958 IRE WESCON Convention Record, pt. 3, pp. 66–71.

Factors affecting the design of a high-power traveling-wave tube using periodic magnetic focusing were described in another paper. The design considerations, construction, and performance were given for an *S*-band tube which yielded a saturated power gain of 30 db, a 3-db bandwidth of 2200–4000 mc, a mid-band peak power of about 2 kw, good reproducibility characteristics, and a weight of about 17 pounds.

[60] O. T. Purl, J. R. Anderson, and G. R. Brewer, "A high-power periodically focused traveling-wave tube," Proc. IRE, vol. 46, pp. 441–448; February, 1958.

Another study of periodic magnetic focusing structures yielded charts to facilitate the design of periodic permanent magnets for focusing electron beams in tubes with parallel-flow guns.

[61] J. E. Sterrett and H. Heffner. "The design of periodic magnetic focusing structures," IRE Trans on Electron Devices, vol. ED-5, pp. 35–42; January, 1958.

Formulas and graphs which describe the distribution of leakage flux around a tubular permanent magnet were also discussed.

[62] M. S. Glass, "Distribution of leakage flux around a TWT-tron focusing magnet—a graphic analysis," Proc. IRE, vol. 46, pp. 1751–1756; October, 1958.

There is a growing need for permanent magnets of higher coercive force for focusing of electron beams. An appraisal of such materials and some design techniques which enable the use of materials with relatively low remanence for compact tubular magnets for strong focusing fields were given.

[63] M. S. Glass, "Appraisal of permanent magnet materials for magnetic focusing of electron beams," *J. Appl. Phys.*, vol. 29, pp. 403–404; March, 1958.

Periodic electrostatic focusing of a hollow electron beam was studied in an attempt to obtain useful design information. The system studied was one in which combined uniform radial electric and periodic radial and longitudinal electric fields were used to focus the hollow beam. The beam was confined between an inner cylinder and a concentric outer series of focusing rings whose potentials were alternated.

[64] C. C. Johnson, "Periodic electrostatic focusing of hollow electron beam," IRE Trans. on Electron Devices, vol. ED-5, pp. 233–243; October, 1958.

The practical realization of improved signal-to-noise ratios in traveling-wave tubes stimulate considerable activity. Improvements in design and techniques which have lowered the noise figure of a developmental traveling-wave tube from 9 db to 6 db and which have resulted in noise figures as low as 4.8 db in selected tubes were discussed. The most important factor contributing to the smaller noise figure was claimed to be a smooth and highly-emissive dense-oxide cathode operating at about 600°C.

[65] E. W. Kinaman and M. Magid, "Very low-noise traveling-wave amplifier," Proc. IRE, vol. 55, pp. 861–867; May, 1958.

A study has shown that backward-wave tubes are capable of very low noise figures and experimental *S*-band tubes with special low-noise guns have yielded noise figures of less than 4.5 db for a 25 per cent tuning range.

[66] M. R. Currie and D. C. Forster, "Low noise tunable preamplifiers for microwave receivers," Proc. IRE, vol. 46, pp. 570–579; March, 1958.

Measured noise figures in the vicinity of 3.5 db were reported for backward-wave tubes. Features of the low-noise gun are that emission originated predominately from the edge and side of the cathode and that the potential profile in the cathode region departed drastically from the usual approximate Fry-Langmuir distribution.

[67] M. R. Currie, "A new type of low-noise electron gun for microwave tubes," Proc. IRE, vol. 46, p. 911; May, 1958.

In another experiment it was demonstrated that the nature of the potential profile in the vicinity of the cathode is the important factor in achieving a low-noise electron gun. Tests on a conventional low-noise traveling-wave tube which had the usual circular-disk type of emitting surface, but the new potential profile also yielded noise figures as low as 3.5 db.

[68] M. Caulton and G. E. St. John, "S-band traveling-wave tube with noise figure below 4 db," Proc. IRE, vol. 46, pp. 911–912; May, 1958.

The minimum noise-power output of traveling-wave tubes is a unique function of the noise pattern in the electron beam. Achievement of minimum noise-power output involves optimizing the standing-wave ratio and position in the vicinity of the potential minimum. Calculations of optimum noise parameters for common types of backward wave tubes were presented along with a discussion of noise reduction as the pass bands of these tubes are tuned in frequency.

[69] M. R. Currie and D. C. Forster, "Conditions for minimum noise generation in backward-wave amplifiers," IRE Trans. on Electron Devices, vol. ED-5, pp. 88–98; April, 1958.

In a study of the noise characteristics of a backward-wave oscillator, it was shown that a backward-wave oscillator is representable as a CW generator in which both amplitude and frequency are simultaneously modulated by noise in a partially correlated manner. It was also demonstrated that there is a rough correspondence between the regions of high slope of the power and frequency vs beam current curves and the regions of high AM and FM noise. The noise modulation was found to be influenced principally by variations in the beam and magnet currents.

[70] J. B. Cicchetti and J. Munushian, "Noise characteristics of a backward-wave oscillator," 1958 IRE National Convention Record, pt. 3, pp. 84–100.

Other papers of interest on noise in traveling-wave tubes include the following:

[71] R. C. Knechtli, "Effect of electron lenses on beam noise," IRE Trans. on Electron Devices, vol. ED-5, pp. 84–88; April, 1958.
[72] R. P. Little, H. M. Ruppel, and S. T. Smith, "Beam noise in crossed electric and magnetic fields," *J. Appl. Phys.*, vol. 29, pp. 1376–1377; September, 1958.
[73] S. Saito, "New method of measuring the noise parameters of an electron beam," IRE Trans. on Electron Devices, vol. ED-5, pp. 264–275; October, 1958.

There was considerable study directed towards improving the power output and efficiency of traveling-wave tubes. A general design procedure for high-efficiency, large-signal amplifiers involving design curves was described. The procedure facilitates the design of tubes with near-maximum power output and efficiency at any frequency range. The chief limiting assumption is that the electric field is constant across the stream radius.

[74] J. E. Rowe and H. Sobol, "General design procedure for high-efficiency traveling-wave amplifiers," IRE Trans. on Electron Devices, vol. ED-5, pp. 288–300; October, 1958.

The improvement of traveling-wave-tube efficiency by adjustment of collector potential was studied. By using single-stage and double-stage collectors which can be operated at depressed potentials, over-all efficiencies of 46 and 57 per cent respectively, were obtained.

[75] F. Sterzer, "Improvement of traveling-wave tube efficiency through collector potential depression," IRE Trans. on Electron Devices, vol. ED-5, pp. 300–305; October, 1958.

In a related paper it was shown that it is necessary to inhibit secondary electron emission to achieve higher efficiency by reduction of collector potential. The application of this and other results increased collector efficiency to about 35 per cent.

[76] H. J. Wolkenstein, "Effect of collector potential on the efficiency of traveling-wave tubes," *RCA Rev.*, vol. 19, pp. 259–282; June, 1958.

In achieving high-power traveling-wave tubes, loaded waveguide circuits are of particular interest. The interaction of an electron beam with a chain of coupled resonators was studied. Other topics considered were impedance matching, frequency dependence of the gain, and the transition from backward-wave oscillation to forward-wave oscillation as the operating voltage is varied.

[77] R. W. Gould, "Characteristics of traveling-wave tubes with periodic circuits," IRE Trans. on Electron Devices, vol. ED-5, pp. 186–195; July, 1958.
[78] E. Belohoubek, "Propagation characteristics of slow-wave structures derived from coupled resonators," *RCA Rev.*, vol. 19, pp. 283–310; June, 1958.

Attempts to extend the tuning range and the upper limit of operating frequency of traveling-wave tubes have continued. The feasibility of obtaining voltage-tunable backward-wave oscillators having useful power output over very wide frequency ranges at millimeter wavelengths was demonstrated. The possibility of obtaining useful powers at frequencies as high as 150,000 mc was indicated.

[79] D. J. Blattner and F. Sterzer, "Two backward-wave oscillator tubes for the 29,000 to 74,000 megacycle frequency range," *RCA Rev.*, vol. 19, pp. 584–597; December, 1958.
[80] R. W. Grow, D. A. Dunn, J. W. McLaughlin, and R. P. Lagerstrom, "A 20 to 40-KMC backward-wave oscillator," IRE Trans. on Electron Devices, vol. ED-5, pp. 152–156; July, 1958.

As the frequency of operation of conventional low-voltage helix-type backward-wave oscillators is decreased, a rapid rise in starting current has been observed. Theory indicates that the low-frequency end of the tuning range can be extended by creating the proper velocity distribution across the electron beam. The high-frequency end of the tuning range of such an oscillator is usually limited by the crossover of the forward- and backward-wave interactions. The upper end is controlled by such factors as tube dimensions and dielectric loading of the helix. The design, construction, and experimental results on modified conventional L- and S-band oscillators were given. Significant extensions of tuning range resulted.

[81] L. Maninger, "A low voltage helix type backward wave oscillator with extended tuning range," 1958 IRE WESCON CONVENTION RECORD, pt. 3, pp. 42–54.

Electron beam and circuit interaction phenomena, including such topics as thermal velocity effects, beam dynamics, current and charge distributions, spurious oscillations, efficiency of conversion, and power output were studied extensively. These studies are applicable to most types of microwave tubes and are not limited to traveling wave tube designs.

[82] G. Herrmann, "Optical theory of thermal velocity effects in cylindrical electron beams," *J. Appl. Phys.*, vol. 29, pp. 127–136; February, 1958.
[83] A. Szabo, "Thermal velocity effects in magnetically confined beams," IRE TRANS. ON ELECTRON DEVICES. vol. ED-5, pp. 183–185; July, 1958.
[84] A. Ashkin, "Dynamics of electron beams from magnetically shielded guns," *J. Appl. Phys.*, vol. 29, pp. 1594–1604; November, 1958.
[85] M. Chodorow, H. J. Shaw, and D. A. Winslow, "Current distribution in modulated magnetically focussed electron beams," *J. Appl. Phys.*, vol. 29, pp. 1525–1533; November, 1958.
[86] J. W. Gewartowski, "Velocity and current distributions in the spent beam of the backward-wave oscillator," IRE TRANS. ON ELECTRON DEVICES, vol. ED-5, pp. 215–222; October, 1958.
[87] T. T. Kirstein and G. S. Kino, "Solutions to the equations of space-charge flow by the method of the separation of variables," *J. Appl. Phys.*, vol. 29, pp. 1758–1767; December, 1958.
[88] I. P. Shkarofsky, "A symmetry property of space-charge waves in accelerated electron beams," IRE TRANS. ON ELECTRON DEVICES, vol. ED-5, pp. 283–288; October, 1958.
[89] M. Chodorow and C. Susskind, "Space-charge-balanced hollow beam with uniform charge distribution," PROC. IRE, vol. 46, pp. 497–498; February, 1958.
[90] H. G. Kosmahl, "Influence of magnetic focusing fields and transverse electron motion on starting conditions for spurious oscillations in O-type backward-wave oscillators," IRE TRANS. ON ELECTRON DEVICES, vol. ED-5, pp. 252–257; October, 1958.
[91] W. E. Waters, "Rippling of thin electron ribbons," *J. Appl. Phys.*, vol. 29, pp. 100–104; January, 1958.
[92] W. W. Rigrod, "Space-charge waves along magnetically-focused electron beams," PROC. IRE, vol. 46, pp. 358–359; January, 1958.
[93] D. V. Geppert, "Analysis of traveling-wave tubes with tapered velocity parameter," PROC. IRE, vol. 46, p. 1658; September, 1958.
[94] W. H. Louisell, "Approximate analytic expressions for TWT propagation constants," IRE TRANS. ON ELECTRON DEVICES, vol. ED-5, pp. 257–259; October, 1958.
[95] A. Kiel, M. Scotto, and P. Parzen, "Propagation in a crossed field periodic structure," IRE TRANS. ON ELECTRON DEVICES, vol. ED-5, pp. 76–84; April, 1958.
[96] A. Yariv, "On the coupling coefficients in the coupled-mode theory," PROC. IRE, vol. 46, pp. 1956–1957; December, 1958.

Klystrons

The great practical importance of klystrons continues to provide considerable motivation for improving their performance and for gaining a better understanding of their potential. Higher operating frequencies, wider operating bandwidths, higher efficiencies, greater power outputs, and lower noise levels are representative of the areas in which studies have been made.

Much of the work listed under other headings in this review might well have been listed under this heading; examples include studies of electron guns, beam and circuit interaction, and noise. Of course the resemblance between a traveling-wave tube with periodic circuits and a klystron is very great. If the resonator coupling coefficient is small, and the ratio of the power flowing along the slow-wave circuit to the power dissipated in a resonator is much less than unity, the traveling-wave device becomes a klystron. The results of an analysis of traveling-wave amplifiers were extended to klystron amplifiers in the following paper.

[97] R. W. Gould, "Characteristics of traveling-wave tubes with periodic circuits," IRE TRANS. ON ELECTRON DEVICES, vol. ED-5, pp. 186–195; July, 1958.

Klystrons are usually considered to be inherently noisy with noise figures of the order to 25 to 40 db. Actually low-noise amplifiers can be built. A klystron amplifier with a noise figure of 6.7 db was reported. It was found that to achieve low-noise operation much higher beam currents were required than for low-noise traveling-wave tubes. The greater dynamic range of klystrons as compared with traveling-wave tubes and parametric amplifiers was also emphasized.

[98] R. G. Rockwell, "Are klystron amplifiers inherently noisy?" 1958 IRE WESCON CONVENTION RECORD, pt. 3, pp. 55–59.

An investigation of millimeter-wave klystron power amplifiers demonstated that it is possible to obtain CW powers of at least 75 watts in the 8-mm wave band. Cathode emission densities of 1.5 amperes per square centimeter in an electron gun with a density multiplication of 100 was required.

[99] T. J. Bridges and H. J. Curnow, "Experimental 8-mm klystron power amplifiers," PROC. IRE, vol. 46, pp. 430–432; February, 1958.

Another investigation of millimeter-wave klystrons was concerned with double-cavity designs for the ranges, 4.3 to 5.2 mm, 5.0 to 6.4 mm, and 5.8 to 6.8 mm. All three were operated at 800 volts or less. An output of 175 mw at a wavelength of 6.0 mm was reported. An X-band design which gave 20 mw output for an operating voltage of 200 volts was described in the same paper.

[100] C. J. Carter and W. H. Cornetet, Jr., "Low voltage operation of the retarding-field oscillator at X band and in the millimeter wavelength region," IRE TRANS. ON ELECTRON DEVICES, vol. ED-5, pp. 139–143; July, 1958.

Bunching in two-cavity and multicavity klystrons in the presence of space charge was studied. Computed results were synthesized to provide a qualitative picture of the manner in which bunching velocity spread and circuit efficiency contribute to the efficiency of energy conversion at the output gap.

[101] S. E. Webber, "Ballistic analysis of a two-cavity finite beam klystron," IRE TRANS. ON ELECTRON DEVICES, vol. ED-5, pp. 98–108; April, 1958.
[102] S. E. Webber, "Large signal analysis of the multicavity klystron," IRE TRANS. ON ELECTRON DEVICES, vol. ED-5, pp. 306–315; October, 1958.

The successful operation of a reflex klystron as a narrow-band regenerative parametric amplifier at 11,000 mc was reported. The performance was predicted quite accurately from simple theory. A circulator was used to separate input from output.

[103] C. F. Quate, R. Kompfner, and D. A. Chisholm, "The reflex klystron as a negative resistance type amplifier," IRE TRANS. ON ELECTRON DEVICES, vol. ED-5, pp. 173–179; July, 1958.

General formulas for calculating the equivalent circuit constants of reentrant cavities were derived using the theory of Green's function. A very impressive number of resonant cavity dimensions were given for a number of resonant frequencies.

[104] K. Fujisawa, "General treatment of klystron resonant cavities," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-6, pp. 344–358; October, 1958.

A 10-kw six-cavity klystron was described. By the use of double-tuned coupled circuits at the gaps of the cavities it was possible to obtain a 3-db band-width of 20 mc at the frequency of 840 mc.

[105] H. Goldman, L. F. Gray, and L. Pollack, "Wideband uhf klystron amplifier," 1958 IRE NATIONAL CONVENTION RECORD, pt. 3, pp. 114–123.

A brief, but helpful, discussion was presented of the conditions under which broad-band operation of multicavity klystrons is profitable.

[106] S. V. Yadavalli, "Effect of beam coupling coefficient on broad band operation of multi-cavity klystrons," PROC. IRE, vol. 46, pp. 1957–1958; December, 1958.

At present little data are available on the velocity spread and the current distribution for practical klystron beams. If such data were known, it is possible to determine their effect on the fundamental component of the beam current by a method reported in the following paper:

[107] L. A. Harris, "The effect of an initial velocity spread on klystron performance," IRE TRANS. ON ELECTRON DEVICES, vol. ED-5, pp. 157–160; July, 1958.

Instead of the usual bunching theory of an electron beam in transit through an accelerating aperture of such velocity modulation devices as klystrons, another theory which is based upon a potential-well model was presented. An expression for the radiated power resulting from the acceleration of the electrons was developed from this model.

[108] L. Gold, "Potential well theory of velocity modulation," PROC. IRE, vol. 46, p. 1952; December, 1958.

The generation of second harmonic in a velocity-modulated beam of a klystron was analyzed. The analysis gave results which were consistent with the experimental observations that the second harmonic current is not a periodic function of distance; that the maxima of the second harmonic current are closer to the input cavity than are the corresponding maxima of the fundamental; and that the second harmonic current grows with distance for thin beams.

[109] F. Pasche, "Generation of second harmonic in a velocity-modulated electron beam of finite diameter," *RCA Rev.*, vol. 19, pp. 617–627; December, 1958.

Barkhausen-Kurz oscillators *per se* have received very little attention during recent years. The necessity for an accelerating grid mesh has hindered commercial development. The Osaka tube in which the grid mesh is replaced by the interaction gap of a resonant cavity has resulted in an efficient oscillator. A magnetically-focused Barkhausen-Kurz oscillator which is an improved version of the Osaka tube for operation at centimeter or millimeter wavelengths received attention. At *K*-band, 430 mw of power, and an efficiency of 12.2 per cent were reported. The results give promise that a high-power tube with high efficiency may be possible.

[110] E. M. Boone, M. Uenohara, and D. T. Davis, "A Barkhausen-Kurz oscillator at centimeter wavelengths," IRE TRANS. ON ELECTRON DEVICES, vol. ED-5, pp. 196–205; July, 1958.

The need for pulsed signals with minimum possible sideband energy in air navigation systems resulted in a method of generation in which the anode of a klystron final amplifier is modulated by a special modulating circuit.

[111] D. H. Preist, "The generation of shaped pulses using microwave klystrons," 1958 IRE NATIONAL CONVENTION RECORD, pt. 3, pp. 106–113.

The problem of generation of appreciable amounts of power at millimeter and submillimeter wavelengths is one of the most difficult and challenging problems facing designers of energy sources. Several new types of coupling structures for extracting energy from a megavolt electron beam at a harmonic of the frequency used to modulate the beam were described. Emphasis was placed on the use of dielectric-tubes as coupling structures and Cerenkov radiations.

[112] R. H. Pantell, P. D. Coleman, and R. C. Becker, "Dielectric slow-wave structures for the generation of power at millimeter and submillimeter wavelengths," IRE TRANS. ON ELECTRON DEVICES, vol. ED-5, pp. 167–173; July, 1958.

TRANSMISSION LINES

The accepted definition of transmission lines encompasses ordinary transmission lines, closed waveguides, and surface-wave structures. The large amount of literature on transmission lines containing anisotropic media has led to the division of the references in this section into those in which isotropy prevails and those in which anisotropy plays a dominant role. Isotropic lines are reviewed first.

TEM Lines

The broad bandwidth characteristics and mechanical simplicity of various types of strip and planar lines continue to stimulate the development of components for such lines, and the study of methods of improving their characteristics. Specialized aspects of coaxial lines were also studied.

The field configuration in a duo-dielectric parallel-plane waveguide was discussed qualitatively in an effort to clarify a point of confusion associated with the field configuration for a particular mode in a coaxial line which was filled throughout 180° of arc with a low-loss material of high dielectric constant. A more exact analysis of the parallel-plane guide yielded results which partially contradict the field structure previously described.

[113] B. J. Duncan, L. Swern, K. Tomiyasu, "Microwave magnetic field in dielectric loaded coaxial line," PROC. IRE, vol. 46, pp. 500–502; February, 1958.
[114] M. Cohn, "Parallel plane waveguide partially filled with a dielectric," PROC. IRE, vol. 46, pp. 1952–1953; December, 1958.

The same structure and a double-slab version were studied for application at millimeter wavelengths. For this application, the important mode is one in which the E field is parallel to the walls. Low attenuation was observed. The use of laminated dielectrics was suggested.

[115] F. J. Tischer, "Properties of the H-guide at microwaves and millimeter waves," 1958 IRE WESCON CONVENTION RECORD, pt. 1, pp. 4–12.

Other structures which were investigated are the shielded balanced pair, the double-slotted coaxial line, and the slab line. The shielded balanced pair was studied experimentally over a range of variables to evaluate the relative merit of each of three different formulas for the capacitance. The use of the simplest of these formulas was recommended.

[116] B. G. King, J. McKenna, and G. Raisbeck, "Experimental check of formulas for capacitance of shielded balanced-pair transmission line," PROC. IRE, vol. 46, pp. 922–923; May, 1958.

The double-slotted coaxial lines can support two types of TEM waves; approximate formulas for the characteristic impedance for each type of wave were derived by a conformal mapping method.

[117] J. Smolarska, "Characteristic impedances of the less slotted coaxial line," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-6, pp. 161–166; April, 1958.

Slab lines, consisting of a circular inner conductor between two parallel planes, were studied to determine the breakdown conditions. The power handling capacity was found to be on the order of 60 to 96 per cent of an equivalent coaxial line.

[118] G. M. Badoyannis, "The power handling capacity of slab lines," 1958 IRE WESCON CONVENTION RECORD, pt. 1, pp. 35–38.

Further advances were reported in the use of nonuniform transmission lines as broad-band terminations. It was shown that if the fractional change in shunt admittance was maintained constant, a fixed length of line can lead to an arbitrarily large effective length without destroying the match at the input. The analysis was applied to the problem of broad-band terminations.

[119] I. Jacobs, "The nonuniform transmission line as a broadband termination," *Bell Sys. Tech. J.*, vol. 37, pp. 913–924; July, 1958.

The design of monotonic stepped transmission-line transformers for prescribed reflection coefficients and bandwidth ratio was studied. A design method was evolved which for a specified number of steps provides the maximum possible bandwidth for a specified reflection coefficient, or the minimum possible reflection coefficient for a given bandwidth.

[120] L. Solymar, "Some notes on the optimum design of stepped transmission-line transformers," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-6, pp. 373–378; October, 1958.

The inherent wide bandwidth of TEM lines was utilized for the design of broad-band baluns. A balun with ferrite loading to obtain high permeability was analyzed and constructed. The insertion loss fluctuated between 1 and 2 db over the frequency range of 5 to 1000 mc. Another design, using coaxial cavities was operated over a 13-to-1 frequency range. The nondispersive nature of TEM lines was also used for circuits with constant phase shift over a five-to-one frequency range.

[121] T. M. O'Meara and R. L. Sydnor, "A very-wide band balun transformer for VHF and UHF," PROC. IRE, vol. 46, pp. 1848–1860; November, 1958.
[122] J. W. McLaughlin, D. A. Dunn, and R. W. Grow, "A wide-band balun," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-6, pp. 314–316; July, 1958.
[123] B. M. Schiffman, "A new class of broad-band microwave 90-degree phase shifters," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-6, pp. 232–237; April, 1958.

Isotropic Hollow Waveguides

The low-attenuation and wide-bandwidth characteristics of large circular waveguides have stimulated further study of the problems which have delayed their practical application. These difficulties are principally due to the excitation of spurious modes.

A study of the effect of random geometric imperfections upon mode conversion in circular cylindrical waveguides was reported. It was shown that coupling to spurious modes caused by random deviations of the guide axis from a straight line is more serious than that caused by joints and by small deviations of the cylinders from circularity.

[124] W. D. Warters and H. E. Rowe, "The effects of mode conversion in long circular waveguide," 1958 IRE WESCON CONVENTION RECORD, pt. 1, pp. 13–20.

In the study of conically tapered transition sections, both constant and variable cone angle designs were investigated. In constant angle types, it was found that the magnitude of the next higher mode caused significant reflections. An improved design, in which the cone angle was gradually varied, exhibited reduced reflection. A 3-foot transition, using a variable cone angle, was found to be as effective as a 58-foot transition with constant cone angle.

[125] L. Solymar, "Design of a conical taper in circular waveguide system supporting H_{01} mode," PROC. IRE, vol. 46, pp. 618–619; March, 1958.
[126] H. G. Unger, "Circular waveguide taper of improved design," *Bell Sys. Tech. J.*, vol. 37, pp. 899–921; July, 1958.

It was noted that the mode conversion effects are much less significant in helical waveguides, operating in a TE_{01} mode, than in solid waveguides. This aspect of helical waveguides prompted an extensive examination of other effects in this structure. The power loss is one effect which was studied. When the wires of the helix are in contact, the loss is 8.5 per cent higher than the loss in the equivalent circular waveguide. When the wires are separated by a distance equal to their diameter, the loss is increased to 22.5 per cent more than that for a smooth surface.

[127] J. A. Morrison, "Heat loss of circular electric waves in helix waveguides," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 173–177; April, 1958.

Another helical waveguide structure that appears promising as a solution to the difficulties of solid-wall waveguides, is the helix with a jacket of lossy material. The principal effect of the lossy jacket is to attenuate spurious modes. The structure was evaluated for use as mode filters between sections of solid waveguide, as mode suppressors in bends, and as a substitute for the solid waveguide in transmission systems. Sections of helix waveguides with lossy jackets and diametral resistance sheets were found to be effective mode filters for all spurious modes including the TE_{12} mode. At sharp bends, the most effective construction was found to be a low-loss dielectric jacket within a coaxial shield. As a replacement for solid circular waveguide, the preferred design is a helix within a jacket of medium loss surrounded by a metal shield. Examples of different constructions and their characteristics were presented.

[128] W. D. Warters, "The effects of mode filters on the transmission characteristics of circular electric waves in a circular waveguide," *Bell Sys. Tech. J.*, vol. 37, pp. 657–677; May, 1958.
[129] H. G. Unger, "Helix waveguide theory and application," *Bell Sys. Tech. J.*, vol. 37, pp. 1599–1647; November, 1958.
[130] D. Marcuse, "Continuation of the TE_{01} wave within the curved helix waveguide," *Bell Sys. Tech. J.*, vol. 37, pp. 1649–1662; November, 1958.
[131] C. F. E. Rose, "Research models of helix waveguide," *Bell Sys. Tech. J.*, vol. 37, pp. 679–688; May, 1958.

An interesting component, a phase shifter using coupling between coaxial helical waveguides operating in a lower mode, was reported. The phase shifter had a trombone-like shape.

[132] P. A. Crandall and F. J. Dominick "A helical phase shifter for VHF," *Microwave J.*, pp. 29–32; January, 1958.

The attenuation of waveguides for frequencies far above cut off and approaching the frequencies of visible light were studied. It was found that the attenuation of transverse magnetic waves (including TEM waves) increased for a limited range of frequencies above cut off and then decreased. The attenuation of the TE_{on} modes always decreased with higher frequency. In the visible region, the attenuation of TE waves was lower than that of TM waves.

[133] A. E. Karbowiak, "Guided wave propagation in submillimetric region," Proc. IRE, vol. 46, pp. 1706–1711; October, 1958.

The effect of geometrical and electrical imperfections on the propagation of energy through a waveguide was studied. In the immediate vicinity of localized imperfections, such as irregularities in the wall of a waveguide, higher mode fields which do not propagate are excited. These "ghost" modes behave like resonant structures. The finite conductivity of the walls affects the propagation of a pulse-modulated wave in a waveguide. Assuming small losses, it was shown that the damping factor for a pulse is the same as for the carrier.

[134] E. T. Jaynes, "Ghost modes in imperfect waveguides," Proc. IRE, vol. 46, pp. 416–418; February, 1958.
[135] G. Ryszard, "Influence of wall losses on pulse propagation in waveguides," *J. Appl. Phys.*, pp. 22–24; January, 1958.

The design of transitions between waveguides of different characteristics was the subject of continuing study. Cohn's design procedure for Tchebycheff-stepped transformers was used to design a transformer for coupling a rectangular to a double-ridged waveguide and for coupling an air-filled to a dielectric-filled rectangular waveguide. Linear and sinusoidal E-plane tapers for coupling rectangular waveguides were also studied and convenient design curves were presented. Formulas for the complex reflection coefficient were derived.

[136] E. S. Hensperger, "Broad-band stepped transformers from rectangular to double-ridged waveguide," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 311–314; July, 1958.
[137] R. W. Whiteman, H. Zucker, C. M. Knop, "A low reflection dielectric waveguide stepped taper," *Proc. Natl. Electronics Conf.*, vol. 14; 1958.
[138] K. Matsumaru, "Reflection coefficient of E-plane tapered waveguides," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 143–149; April, 1958.

The harmonic power present in high-power waveguides of rectangular cross section was studied experimentally. The relative amplitudes of the higher modes was determined. A 31-kw x-band signal was observed in the radiation from a 5-mgw S-band magnetron.

[139] M. P. Forrer and K. Tomiyasu, "Determination of higher order propagating modes in wave-guide systems," *J. Appl. Phys.*, vol. 29, pp. 1040–1045; July, 1958.

The power handling capacity of a rectangular waveguide, with a centered dielectric slab and sides parallel to the E-plane, was related to the dielectric constant and the thickness of the slab. For realizable values of dielectric constant and thickness, the power handling capacity could be made twice that of the empty guide.

[140] P. H. Vartanian, W. P. Ayres, and A. L. Holgesson, "Propagation in dielectric slab loaded rectangular waveguide," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 215–222; April, 1958.

It was shown that breakdown of high power waveguides may be initiated by cosmic rays.

[141] S. W. Lichtman, "Influence of sea level cosmic radiation on power breakdown of air filled waveguide," *Proc. Natl. Electronics Conf.*, vol. 14; 1958.

Surface Waves

Surface waves may be defined as waves which propagate without radiation along the interface between two media and which have an evanescent field structure over an equiphase surface. A brief survey of the characteristics of surface waves was published. Attention was focused on the inhomogeneous plane wave (Zenneck wave), the radial surface wave, and the axially propagating cylindrical wave (Goubau wave).

[142] H. M. Barlow, "Surface waves," Proc. IRE, vol. 46, pp. 1413–1417; July, 1958.

The need for supporting dielectric-rod waveguides in space at some distance from objects has led to the investigation of waveguides consisting of half-round dielectric rods mounted on conducting image planes. The use of the image plane permits transmission of the low-loss hybrid mode but excludes certain other modes.

Field purity predictions were verified experimentally, and the effects of dielectric geometry and dielectric constant on field extension, loss, and dispersion were discussed. The case in which the dielectric was partially submerged in the ground plane was also considered.

[143] S. P. Schlesinger and D. D. King, "Dielectric image lines," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 291–299; July, 1958.

In order to excite the surface waves, it is necessary that the fields of the launching structure conform with the field distribution of the surface waves. Horns have been widely used for launching waves on dielectric rods. Other launching devices, such as wires, rings, and slots were investigated for exciting image lines.

[144] C. M. Angulo and W. S. C. Chang, "The excitation of a dielectric rod by a cylindrical waveguide," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 389–393; October, 1958.
[145] R. H. DuHamel and J. W. Duncan, "Launching efficiency of wires and slots for a dielectric rod waveguide," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 277–284; July, 1958.

A theoretical study of surface wave phenomena was concerned with the problem of propagation of electromagnetic waves produced by a line source of magnetic dipoles located at the corner of a right-angle wedge. An impedance-type boundary condition was prescribed on the surface of the wedge.

[146] S. N. Karp and F. C. Karal, Jr., "Surface waves on a right angled wedge," 1958 IRE WESCON Convention Record, pt. 1, pp. 101–103.

Artificial Dielectrics

If the elements of an artificial dielectric forms a cubic lattice and the lattice is small compared with the wavelength, the structure behaves isotropically. A change in structure or an enhanced behavior of the elements in a specific direction leads to a dielectric with anisotropic properties. Several studies of artificial dielectrics were reported. The anisotropy, which arises in a cubic lattice when the inter-element spacing is large, was investigated, and an anisotropy tensor was derived. An experimental investigation of planar arrays of thin metallic rectangles was made. The anomalous dispersion was strongly affected by lateral interaction between the elements of the array. Another structure, which consisted of thin dielectric sheets separated by thin sheets of different dielectric constant, was investigated theoretically. To obtain an isotropic dielectric of light weight, a random array of concentric metal and dielectric shells was suggested.

[147] Z. A. Kaprielian, "Anisotropic effects in geometrically isotropic lattices," *J. Appl. Phys.*, vol. 29, pp. 1052–1063; July, 1958.
[148] A. F. Wickersham, Jr., "Anomalous dispersion in artificial dielectrics," *J. Appl. Phys.*, vol. 29, pp. 1537–1542; November, 1958.
[149] R. E. Collin, "A simple artificial anisotropic dielectric medium," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 206–209; April, 1958.
[150] M. K. Hu and D. K. Cheng, "A new class of artificial dielectrics," 1958 IRE WESCON Convention Record, pt. 1, pp. 21–25.

In a related area, the problem of propagation through a random distribution of dielectric spheres was considered. Time-averaged attenuation and phase shift were measured for foamed dielectric spheres suspended by a turbulent air column.

[151] C. I. Beard and V. Twersky, "Propagation through random distributions of spheres," 1958 IRE WESCON Convention Record, pt. 1, pp. 87–100.

Junctions

Several studies of junctions, directional couplers, and hybrid structures were reported.

An analysis of two-part networks utilized a stereographic mapping of the output and input parameters on the Reimann sphere.

[152] E. F. Bolinder, "General method of analyzing bilateral two port networks from three arbitrary impedance or reflection coefficient measurements," *Proc. Natl. Electronics Conf.*, vol. 14; 1958.

Multiple-branch couplers are most useful for applications requiring tight coupling. A design method which is based on the use of n series branches in rectangular waveguide was presented. In another paper, distributed coupling between strip lines was studied. Couplings over one-quarter and three-quarter wavelengths were treated in detail. The former gave almost constant coupling over a two-to-one frequency band while the latter gave a similar result over a five-to-one frequency band.

[153] J. Reed, "The multiple branch waveguide coupler," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 398–403; October, 1958.
[154] J. K. Shimizu and E. M. T. Jones, "Coupled-transmission-line directional couplers," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 403–410; October, 1958.

A broad-band coaxial hybrid ring which has excellent isolation and balance characteristics was described. An equivalent admittance circuit was developed and used as a basis for the determination of the admittance and VSWR at the input arms. An isolation of 13.5 db or better was observed over a 50 per cent bandwidth.

[155] V. J. Albanese and W. P. Peyser, "An analysis of a broad-band coaxial hybrid ring," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 369–373; October, 1958.

Resonators and Filters

Accurate methods of measuring the characteristics of resonators were subjects of considerable study in 1958. It was shown that a graph of susceptance vs frequency is a straight line with a slope related to the Q. In this way, all of the impedance-frequency data is averaged so that a more accurate value for the Q is obtained. In another report, the phase shift introduced by a small perturbing element was used to determine the shunt impedance.

[156] A. Singh, "An improved method for the determination of Q of cavity resonators," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 155–160; April, 1958.
[157] K. B. Mallory, "Measurement of shunt impedance of a cavity," *J. Appl. Phys.*, vol. 29, p.p. 790–793; May, 1958.

The problems associated with the measurements of the Q of the resonators in the presence of coupling losses were studied. The analysis demonstrated that series losses were separable from cavity losses. Shunt losses, however, could not be distinguished from the cavity losses without separate measurements of the coupling network.

[158] E. L. Ginzton, "Microwave Q measurements in the presence of coupling losses," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 383–389; October, 1958.

A discussion of the case in which the resonant frequencies of two or more modes are sufficiently close to affect the observed impedance loci was presented.

[159] M. G. Keeney, "On the measurement of resonant cavity Q," *Proc. Natl. Electronics Conf.*, vol. 13, pp. 442–451; 1957.

A contribution to the theoretical analysis of cavity resonators was made which clarified the assumptions underlying Slater's analysis. By expanding the fields in terms of complete orthonormal functions and determining the expansion coefficients, the input impedance of the cavity could be determined. A corrected set of functions for the expansion was presented.

[160] K. Kurokawa, "The expansions of electromagnetic fields in cavities," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 178–187; April, 1958.

A traveling-wave resonator, a ring circuit directionally coupled to the main guide, has the property that fields within the ring are larger than the fields in the main guide. This property was employed to obtain higher powers for testing microwave components. An effective power of 8 mgw was obtained from an 800 kw source.

[161] L. J. Milosevic and R. Vautey, "Traveling-wave resonators," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 136–143; April, 1958.

The general synthesis procedure for high-Q waveguide filters was further clarified. The approximations required for synthesis based upon a ladder-network prototype were placed upon a formal basis.

[162] H. J. Riblet, "A unified discussion of high-Q waveguide filter design theory," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 359–368; October, 1958

A number of papers giving examples of specific designs appeared.

[163] S. B. Cohn, "Parallel-coupled transmission-line-resonator filters," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 223–231; April, 1958.
[164] G. L. Matthaei, "Direct-coupled, band-pass filters with $\lambda_0/4$ resonators," 1958 IRE National Convention Record, pt. 1, pp. 98–111.
[165] A. I. Grayzel, "A band separation filter for the 225–400 mc band," 1958 IRE National Convention Record, pt. 1, pp. 91–97.
[166] J. H. Vogelman, "High power microwave filters," 1958 IRE National Convention Record, pt. 1, pp. 84–90.
[167] R. E. Saxe "Analysis of a lossy transmission line filter," *Proc. Natl. Electronics Conf.*, vol. 13, pp. 470–481; 1957.
[168] D. Alstadter and E. O. Houseman, Jr., "Some notes on strip transmission line and waveguide multiplexers," 1958 IRE WESCON Convention Record, pt. 1, pp. 54–69.

Microwave components

Advances in switching techniques, matched windows, and absorbing materials were prominent among the reports on microwave components.

At low-power levels, semiconductor diodes in novel circuits were used for rapid switching. The equivalent circuit of the diode as a function of bias was analyzed to to predict the switching behavior. Germanium diodes were found to be preferable to silicon diodes since they have lower spreading resistance and higher nonlinear resistance with reverse bias. A millimicrosecond switching time appears to be feasible. The RF power that can be switched depends upon the Zener voltage and the resistivity of the crystal. The control of powers up to 50 mw were reported. The diodes were mounted across the waveguide in single and cascade arrangements. A hybrid-T configuration produced an insertion loss of 0.7 db with an isolation of 50 db.

[169] M. R. Millet, "Microwave switching by crystal diodes," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 284–290; July, 1958.
[170] R. V. Garver, E. G. Spencer, and M. A. Harper, "Microwave semiconductor switching techniques," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 378–383; October, 1958.

For rapid switching of high-power levels, the duplexer is the accepted component. A new duplexer, consisting of a microwave bridge and a power sensitive phase shifter was reported to be capable of handling twice the power of conventional balanced duplexers.

[171] P. D. Lomer and R. M. O'Brien, "A new form of high-power microwave duplexer," IRE Trans. on Microwave Theory and Technique, vol. MTT-6, pp. 264–267; July, 1958.

Dielectric windows for low- and high-power operation were described. The matching of the low-power window was accomplished by recessing the dielectric slab into the walls of the waveguide and using a matching iris. For high-power applications, a ceramic slab was used as one element of a three-element filter. This structure was successfully operated at powers in excess of one mgw over a 15 per cent bandwidth at X band.

[172] H. Zucker and C. M. Knop "A low reflections dielectric waveguide window for X band," *Proc. Natl. Electronics Conf.*, vol. 13, pp. 254–268; 1957.
[173] H. J. Shaw and L. M. Winslow, "A broad-band high-power vacuum window for X band," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 326–330; July, 1958.

Further work on the properties of single layer microwave absorbing materials was carried out. The effects of magnetic and electric losses were studied as well as the design of the material for greatest bandwidth and minimum thickness.

[174] D. L. Waidelich, "The design of a single-layer microwave absorbing material," *Proc. Natl. Electronics Conf.*, vol. 14; 1958.

A rotary joint for use with mast-mounted antennas was developed.

[175] W. E. From, E. G. Fubini, and H. S. Keen, "A new microwave rotary joint," 1958 IRE National Convention Record, pt. 1, pp. 78–72.

Anisotropic waveguides

With the development of ferrite materials, a new dimension was added to the field of microwave engineering. The ferrites are characterized by large spin resonances and low conductivity. The existence of a large number of uncoupled electron spins results in a tensor permeability with a strong anisotropy. Although other ferromagnetic materials are anisotropic, the low conductivity of ferrites has resulted in their wide application to microwaves.

Developments in the theory and application of waveguides loaded with anisotropic media proceeded rapidly during the year. The general theory of wave propagation in waveguides of various geometries was discussed; isolators, circulators, and other microwave components were studied; and new materials were introduced. Ferrites were most widely used, but other anisotropic materials and gas plasmas increased in importance.

A comprehensive survey of recent developments in ferrites and semiconductors was published early in 1958. Emphasis was placed on the application of nonreciprocal devices at low frequencies and at high-power levels. The study of nonlinear behavior in ferrites for frequency doubling, mixing, and amplification was reviewed. In other semiconductors, experiments in cyclotron resonance and spin resonance were reported.

[176] B. Lax, "The status of microwave applications of ferrites and semiconductors," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 5–18; January, 1958.

The theory of propagation in anisotropic media was expanded by the derivation of orthogonality properties of uniform waveguides filled with this material. Specific orthogonality relationships were derived which permit the expansion of the field components in terms of a complete set of waveguide modes.

[177] A. D. Bresler, G. H. Joshi, and N. Marcuvitz, "Orthogonality properties for modes in passive and active uniform waveguides," *J. Appl. Phys.*, vol. 29, pp. 794–799; May, 1958.

Early ferrite devices employed Faraday rotation in circular waveguide. Later discoveries of nonreciprocal effects in rectangular waveguides loaded with transversely magnetized ferrite slabs stimulated investigations of this preferred structure. The propagation constants and field configurations in the region of resonance were presented, and confirming measurements of the distribution of the transverse electric field were reported. The conditions for cut off of slab-loaded and completely filled rectangular guide were established and verified experimentally.

[178] W. J. Crowe, "Behavior of the T.E. modes in ferrite loaded rectangular waveguide in the region of ferri-magnetic resonance," *J. Appl. Phys.*, vol. 29, pp. 397–398; March, 1958.
[179] T. M. Straus, "Field displacement effects in dielectric and ferrite loaded waveguides," 1958 IRE WESCON Convention Record, pt. 1, pp. 135–146.
[180] R. F. Soohoo, "Cutoff phenomena in transversely magnetized ferrites," Proc. IRE, vol. 46, pp. 788–789; April, 1958.

The theory of the field displacement isolator was studied, and it was found that a thick slab placed close to a side wall produced the maximum ratio of reverse to forward attenuation.

[181] K. J. Button, "Theoretical analysis of the operation of the field displacement ferrite isolator," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 303–308; July, 1958.

The theoretical determination of reflection from an air-to-ferrite interface was presented. The transversely magnetized ferrite completely filled the waveguide, and the components of the equivalent circuit representation for the interface were calculated.

[182] C. B. Sharpe and D. S. Heim, "A ferrite boundary-value problem in a rectangular waveguide," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 42–46; January, 1958.

In cylindrical waveguide, a thick axially-magnetized rod and a circumferentially magnetized cylinder were studied. The propagation constants for the rod structure are well-known for the case of thin rods, and have been computed by approximate methods. The propagation constants for the thick rod were found by machine computation. The boundary value problem for the circumferentially magnetized ring was solved. It was found that the E-field displacement for a TE_{01} mode was suitable for an isolator.

[183] J. E. Tompkins, "Energy distribution in partially ferrite-filled waveguides," *J. Appl. Phys.*, vol. 29, pp. 399–400; March, 1958.
[184] N. Kumagai and K. Takeuchi, "Circular electric waves propagating through the circular waveguide containing a circumferentially magnetized ferrite cylinder," 1958 IRE WESCON Convention Record, pt. 1, pp. 123–130.

Ferrite-loaded TEM lines (microstrip and coaxial lines) were also studied to determine their reciprocal and nonreciprocal properties. The theoretical analysis of infinite parallel plane waveguide filled with longitudinally magnetized ferrite was applied to the microstrip structure. The reciprocal behavior was verified and the predicted variation of propagation constant with applied magnetic field was observed. The problem of the coaxial line, with transversely magnetized ferrite, was approached by the analysis of the equivalent parallel-plane structure. The geometry consisted of a dielectric slab between ferrite slabs; the differential phase shift was calculated.

[185] M. E. Brodwin, "Propagation in ferrite-filled microstrip," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 150–155; April, 1958.
[186] K. J. Button, "Theory of non-reciprocal ferrite phase shifters in dielectric-loaded coaxial line," *J. Appl. Phys.*, vol. 29, pp. 998–1000.

Reciprocity was investigated to determine how the impedance, admittance and scattering matrices were affected by reversal of the dc magnetic field. It was found that the usual reciprocity relations hold when the source and load are interchanged if the field is reversed.

[187] R. F. Harrington and A. T. Villeneuve, "Reciprocity relationships for gyrotropic media," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 308–310; July, 1958.

Isolators and Circulators

Improvements in the design of isolators consisted of new techniques for increasing bandwidth and for reducing the low-frequency limit. The bandwidth of isolators in rectangular waveguide was increased by using ferrites with different saturation magnetizations located at different positions in the wave-guide. The result is equivalent to cascaded narrow band isolators. Another approach to this problem was the use of inherently wide-band structures with the ferrite as a coupling medium. Devices operating over 6–11 kmc were reported.

[188] B. J. Duncan and B. Vafiades, "Design of a full waveguide bandwidth high-power isolator," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 411–414; October, 1958.
[189] E. M. T. Jones, S. B. Cohn and J. K. Shimizu, "A wideband nonreciprocal tem-transmission-line network," 1958 IRE WESCON Convention Record, pt. 1, pp. 131–134.

Factors affecting the low-frequency limit of operation were shown to be functions of the ferrite material and the geometry. Materials with small saturation magnetization and narrow line width are desireable. The optimum arrangement is thin ferrite slabs placed along the broad walls of the waveguide.

[190] F. O. Schulz-DuBois, G. J. Wheeler, and M. H. Sirvetz, "Development of a highpower L-band resonance isolator," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 423–428; October, 1958.
[191] G. S. Heller and G. W. Catuna, "Measurement of ferrite isolation at 1300 mc," IRE Trans. on Microwave Theory and Technique, vol. MTT-6, pp. 97–100; January, 1958.

A new circulator design was reported in which a ferrite rod was placed along an axis of symmetry of an H-plane waveguide junction.

[192] W. E. Swanson and G. J. Wheeler, "Tee circulator," 1958 IRE WESCON Convention Record, pt. 1, pp. 151–156.

Switches, Filters, and other Components

The effects of anisotropy were the principal features of a number of components; switches, attenuators, phase shifters, and a power limiter. The principal problem in rapidly switching ferrite devices is the high power requirements of the external magnet. One reported solution is to use a thin-walled waveguide to reduce eddy-current loss but with sufficient thickness for low-loss wave propagation. Another solution is to place the entire magnetic circuit within the waveguide structure and use an internal conductor to control the magnetic properties. Switching times of 0.1 μsec and with a power of 50 watts were reported.

[193] E. H. Turner, "A fast ferrite switch for use at 70 kmc," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 300–303; July, 1958.
[194] M. A. Treuhaft and L. M. Silber, "Use of microwave ferrite toroids to eliminate external magnets and reduce switching power," Proc. IRE, vol. 46, p. 1538; August, 1958.

Ferrites were used to control the characteristics of filters by using the ferrite as an integral part of a cavity, and by employing isolators to prevent interaction between networks.

[195] W. L. Whirry and C. E. Nelson, "Ferrite-loaded, circularly polarized microwave cavity filters," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 59–65; January, 1958.
[196] H. Rapaport, "A microwave ferrite frequency separator," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6; pp. 53–58; January, 1958.

A reciprocal phase shifter which operated at a power of 15 kw and a ferrite attenuator for compensating the gain variation of traveling wave tubes were also reported.

[197] W. H. Hewitt Jr. and W. H. VonAulock, "A reciprocal ferrite phase shifter for X band," *Proc. Natl. Electronics Conf.*, vol. 13, pp. 459–469; 1957.
[198] F. Fleri and B. J. Duncan, "Reciprocal ferrite devices in TEM mode transmission lines," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 91–96; January, 1958.

The saturation effects in ferrites were used to limit high microwave powers. At high levels, spin wave effects produce an anomalous absorption on the low field side of the main ferromagnetic resonance. This effect was used to construct a simple limiter with a threshold of 300 watts.

[199] R. F. Soohoo, "Power limiting using ferrites," 1958 IRE National Convention Record, pt. 1, pp. 36–47.

Radiation from Ferrite Filled Apertures

Ferrite properties were employed to control the phase and amplitude distribution of radiating apertures. Rectangular, square and circular apertures were investigated. The previously reported experimental investigations of ferrite-filled rectangular waveguide apertures were analyzed. The contributions of higher modes were considered and the far-field behavior was related to the aperture distribution.

[200] B. Tyras and G. Held, "Radiation from a rectangular waveguide filled with ferrite," IRE Trans. on Microwave Theory and Techniques. vol. MTT-6, pp. 268–277; July, 1958.

Experimental investigations of the radiation from square and circular apertures were reported. Beam displacements of $\pm 30°$ were observed for the completely-filled square aperture and a system was devised for sequential lobing. The circular aperture containing a ferrite ball was studied for possible application to conical scanning.

[201] D. B. Medved, "An electronic scan using a ferrite aperture Luneberg lens system," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 101–103; January, 1958.
[202] M. S. Wheller, "Nonmechanical beam steering by scattering from ferrites," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 38–42; January, 1958.

Measurement of Ferrite Properties

When the sample is placed in an inhomogeneous RF magnetic field, anomalous resonances were observed. The origin of these anomalies was studied; it was shown that they are caused by the free modes of the magnetic dipoles in the material.

[203] L. R. Walker, "Ferro-magnetic resonance: line structure," *J. Appl. Phys.*, vol. 29, pp. 318–322; March, 1958.

Cavity techniques for the measurement of disc and rod samples were reported. In one paper, the frequency shift, produced by a ferrite disc in a cavity of generalized cross section, was related to the tensor components. For rod-shaped samples, the solution to the boundary value problem in cylindrical waveguide was used for the measurement. A different approach to this problem employed a bimodal cavity. A relationship was derived for the coupling between the modes and the properties of the material.

[204] H. Seidel and H. Boyet, "Frequency shifts in cavities with longitudinally magnetized small ferrite discs," *Bell Sys. Tech. J.*, vol. 37, pp. 637–655; May, 1958.
[205] H. E. Bussey and L. A. Steinert, "Exact solution for a gyromagnetic sample and measurements on a ferrite," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-6, pp. 72–76; January, 1958.
[206] A. M. Portis, and D. Teaney, "Microwave Faraday rotation: design and analysis of a bimodal cavity," *J. Appl. Phys.*, vol. 29, pp. 1692–1698; December, 1958.

A technique for the measurement of line width which is insensitive to the sample size was developed. It was found that the surface finish had a strong effect on the measured line width.

[207] D. C. Stinson, "Experimental techniques in measuring ferrite line widths with a cross-guide coupler," 1958 IRE WESCON CONVENTION RECORD, pt. 1, pp. 147–150.

The use of ring circuits for the measurement of ferrite properties led to a theoretical analysis of the effects of ferrites on the resonant frequency and Q.

[208] F. J. Tischer, "Resonant properties of nonreciprocal ring circuits," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-6, pp. 66–71; January, 1958.

For the measurement of ferrite parameters at low frequencies, a new technique was developed and results of measurements on foreign materials were given.

[209] P. P. Lombardini, R. F. Schwartz, and R. J. Doviak, "Measurement of the properties of various ferrites used in magnetically tuned resonant circuits in the 2.5–45 mc. region," *J. Appl. Phys.*, vol. 29, pp. 395–296; March, 1958.

Ferrite Materials

The search for improved materials included an examination of polycrystalline rare earth garnets as possible solutions to the low-frequency ferrite problem. The desired characteristics are narrow line width and low saturation magnetization.

Different compositions were examined and their application to L-band and S-band isolators was reported.

[210] B. Ancker-Johnson and J. J. Rowley, "Mixed garnets for nonreciprocal devices at low microwave frequencies," PROC. IRE, vol. 46, pp. 1421–1422; July, 1958.

The effect of partial substitution of gadolinium for yttrium in rare earth garnets was determined and it was shown that the gadolinium reduces the saturation magnetization with a small effect on line width.

[211] H. R. Sirvetz and J. E. Zniemer, "Microwave properties of polycrystalline rare earth garnets," *J. Appl. Phys.*, vol 29, pp. 431–434; March, 1958.

The behavior of materials of different compositions were reported in the following papers:

[212] J. E. Pippin and C. L. Hogan, "Resonance measurements on nickel-cobalt ferrites as a function of temperature and on nickel ferrite-aluminates," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-6, pp. 77–82; January, 1958.
[213] G. P. Rodrique, J. E. Pippin, W. P. Wolf, and C. L. Hogan, "Ferrimagnetic resonance in some polycrystalline rare earth garnets," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-6, pp. 83–91; January, 1958.

Ionized Gases and Hall Effect

Ionized gases were investigated and nonreciprocal effects were reported. Among other reports on gaseous media were improvements in discharge tubes and noise sources. A Hall effect circulator was described.

A valuable survey was presented which outlined the present knowledge of the application of gas plasmas to microwave propagation. The paper discussed the isotropic gas plasma and the anisotropy produced by a static magnetic field. The problem of guided-wave propagation was reviewed and data were presented on resonant phenomena in the gyromagnetic plasma.

[214] L. Goldstein, "Nonreciprocal electromagnetic wave propagation in ionized gaseous media," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-6, pp. 19–29; January, 1958.

The case of an ion-filled rectangular waveguide with an axial magnetic field was investigated and the propagation characteristics determined.

[215] L. D. Smullin and P. Chorney, "Properties of ion-filled waveguides," PROC. IRE, vol. 46, pp. 360–361; January, 1958.

Advances in gas discharge switching included the use of a magnetic field and cyclotron resonance phenomena to control the firing of a discharge tube, and the application of a shaped pulse to the keep-alive electrode to modify the electron density.

[216] S. J. Tetenbaum and R. M. Hill, "High power, broadband, microwave gas discharge switch tube," 1958 IRE NATIONAL CONVENTION RECORD, pt. 1, p. 83.
[217] R. E. Hovda and E. R. Roehl, "Characteristics and control of gas tube duplexers during their recovery time," 1958 IRE WESCON CONVENTION RECORD, pt. 3, pp. 105–114.

Close agreement was found between the noise temperature and the electron temperature for argon tubes at 3000 mc; it was recommended that these tubes be adopted as standard noise sources.

[218] E. W. Collings, "Noise and electron temperatures of some cold cathode argon discharges," *J. Appl. Phys.*, vol. 29, pp. 1215–1219; August, 1958.

An unusual device was reported for the production of high-power noise. An impulse generator was described with significant power output in the 200-to-7000 mc frequency range. The output power varied from 120 to 145 db above KTB.

[219] R. H. George and H. J. Heim, "Recent developments with spark gap impulse noise generators" *Proc. Natl. Electronics Conf.* vol. 13, pp. 287–295; 1957.

The Hall effect was studied to determine possible applications to circulators. A three-port device was constructed consisting of a slab of germanium with six wire connections. Although this design is expected to operate between dc and 100 mc, the principle could be extended to the microwave region.

[220] W. J. Grubbs, "The Hall effect circulator—a passive transmission device," 1958, IRE WESCON CONVENTION RECORD, pt. 3, pp. 83–93.

MEASUREMENTS

Advances in measurements include the use of the Hall effect and the use of the torque developed on thin metal vanes to measure microwave power; improved design methods for broad-band calorimeters as standards for microwave power measurements; the development of semiautomatic techniques for broad-band measurements; the design of new atomic frequency standards; and a more comprehensive treatment of considerations which limit the sensitivity of microwave radiometers.

Power Measurements

The Hall effect was applied to the measurement of power with the noteworthy result that the technique is independent of standing-wave ratio. A device is described which has a sensitivity of 50 mw.

[221] H. M. Barlow, "The Hall effect and its application to microwave power measurement," Proc. IRE, vol. 46, pp. 1411–1413; July, 1958.

Another novel technique employed a thin metallic vane suspended in the waveguide. The electric field produces a torque tending to rotate the vane in line with the unperturbed field. The device shows promise as a primary standard.

[222] A. L. Cullen, B. Rogal, and S. Okamura, "A wide-band double-vane torque-operated wattmeter for 3-cm microwaves," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 133–136; April, 1958.

The present primary standard of power measurement is still the calorimeter. A commercial dry calorimeter was described.

[223] M. Sucher and H. J. Carlin, "Broad-band calorimeters for the measurement of low and medium level microwave power. I. Analysis and design," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 188–194; April, 1958.
[224] A. V. James and L. O. Sweet, "Broad-band calorimeters for the measurement of low and medium level microwave power. II. Construction and performance," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 195–202; April, 1958.

With the increased use of broad-band components, rapid, convenient measurements over a wide frequency band becomes increasingly important. Automatic techniques for measuring phase and amplitude were described, and the use of a magnetically-controlled ferrite attenuator for amplitude stabilization was outlined.

[225] J. B. Linker, Jr. and H. H. Grimm, "Wide-band microwave transmission measuring system," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 415–418; October, 1958.
[226] Herbert A. Dropkin, "Direct reading microwave phase-meter," 1958 IRE National Convention Record, pt. 1, pp. 57–63.
[227] G. F. Engen, "Amplitude stabilization of a microwave signal source," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 202–206; April, 1958.

Other developments in measurement techniques were presented in the following papers.

[228] G. E. Schafer and R. W. Beatty, "A method for measuring the directivity of directional couplers," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 419–422; October, 1958.
[229] J. I. Gaicoya, "Tuning a probe in a slotted line," Proc. IRE, vol. 46, pp. 787–788; April, 1958.
[230] K. G. Beauchamp, "A phase sensitive detector for indicating VSWR," *Electronic Industries*, vol. 17, pp. 74–77; February, 1958.
[231] G. Richard Blair, "An ultra-precise microwave interferometer," 1958 IRE National Convention Record, pt. 1, pp. 48–56.

Radiometry

Recent advances in radiometry were reported in the Radio Astronomy Issue of the Proceedings of the IRE in January, 1958. Some of the papers of specific interest to those in microwaves are noted below.

Attention was focused on the sensitivity of the receiver, and the angular resolution of the receiving system. In highly sensitive radiometers, with temperature thresholds less than 1°K, internal receiver noise establishes an absolute limit. Other factors which limit the system sensitivity are background radiation, atmospheric absorption, and fluctuations in the characteristics of the receiving system. The most sensitive radiometers use a switching technique to compare the received noise with a known standard. An evaluation of the sensitivity of different systems was reported as well as a study of the ultimate sensitivity of superheterodyne receivers. Improvements of angular resolution by the use of interferometers were also discussed. The theory of radio interferometry was related to previous work in the optical region. An important theorem on the optimum spacing of the antennas for a given angular resolution was derived. It was shown that current practice is too conservative.

[232] P. D. Strum, "Considerations in high-sensitivity microwave radiometry," Proc. IRE, vol. 46, pp. 43–53; January, 1958.
[233] C. T. McCoy, "Microwave crystal receivers," Proc. IRE, vol. 46, pp. 61–66; January, 1958.
[234] R. N. Bracewell, "Radio interferometry of discrete sources," Proc. IRE, vol. 46, pp. 97–105; January, 1958.

Knowledge of the polarization of the received wave yields valuable information about the Faraday rotation in the ionosphere. Various techniques for measuring polarization in terms of total intensity, orientation, polarization fraction, and axial ratio, were discussed. Three systems for determining these parameters were compared: two antennas, for the measurement of intensity, phase difference, and correlation function; three antennas, with phase measurements; four antennas, with intensity measurements. The two antenna system was described in detail.

[235] M. H. Cohen, "Radio astronomy polarization measurements," Proc. IRE, vol. 46, pp. 172–183; January, 1958.
[236] M. H. Cohen, "The Cornell radio polarimeter," Proc. IRE, vol. 46, p. 183–190. January, 1958.

Specific examples of radiometric devices appeared in the following papers.

[237] F. D. Drake and H. I. Ewen, "A broad-band microwave source comparison radiometer for advanced research in radio astronomy," Proc. IRE, vol. 46, pp. 53–60; January, 1958.
[238] M. Graham, "Radiometer circuits," Proc. IRE, vol. 46, p. 1966; December, 1958.
[239] J. Goodman and M. Lebenbaum, "A dynamic spectrum analyzer for solar studies," Proc. IRE, vol. 46, pp. 132–135; January, 1958.
[240] J. P. Wild and K. V. Sheridan, "A swept-frequency interferometer for the study of high-intensity solar radiation at meter wavelengths," Proc. IRE, vol. 46, pp. 160–171; January, 1958.
[241] J. S. Hey and V. A. Hughes, "A method of calibrating centimetric radiometers using a standard noise source," Proc. IRE, vol. 46, pp. 119–121; January, 1958.

Frequency Measurements

Resonances in alkali metal vapors, oxygen, and paramagnetic materials were used for accurate stable sources and for frequency measurements.

Atomic resonances were applied to the problem of developing a convenient primary frequency standard. Low-frequency crystal oscillators were locked in frequency to an atomic transition by a servo system. It was shown that frequency stability depends upon the width of the resonance and the signal to noise ratio of the detected transition. Experiments were carried out using the magnetic hyperfine transitions in sodium and caesium. Productions units, with a guaranteed accuracy of 1 part in 10^9 and a minimum stability of 5 parts in 10^{10} were described.

[242] M. Arditi and T. R. Carver, "A gas cell 'atomic clock' using optical pumping and optical detection," 1958 IRE National Convention Record, pt. 1 pp. 3–9.
[243] A. O. McCoubry, "The atomichron—an atomic frequency standard: physical foundations," 1958 IRE National Convention Record, pt. 1, pp. 10–13.
[244] W. Mainberger and A. Orenberg, "The atomichron—an automatic frequency standard: operation and performance," 1958 IRE National Convention Record, pt. 1, pp. 14–18.

The possible use of an absorption line of oxygen for a frequency standard was also investigated.

[245] J. M. Richardson, "Experimental evaluation of the oxygen microwave absorption as a possible atomic frequency source," *J. Appl. Phys.*, vol. 29, pp. 136–145; February, 1958.

Paramagnetic resonance was combined with nuclear magnetic resonance for the calibration of a microwave cavity. The nuclear resonance was used to accurately determine the magnetic field. With a known field, the paramagnetic resonant frequency could be calculated to an accuracy of one part in 10^7.

[246] P. A. Crandell, "An accurate frequency measuring technique using paramagnetic resonance phenomena in the *X*-band region," 1958 IRE WESCON Convention Record, pt. 1, pp. 26–34.

Conclusion

Advances in Microwave Theory and Techniques in 1958 tended to center around direct interaction of microwaves and anisotropic media. Much information on masers, parametric amplifiers, and nonreciprocal and nonlinear devices was accumulated. Important improvements were also made in conventional sources, detectors, and transmission lines. The inference drawn from the recent trend is that classical approaches offer little promise for great forward steps. New concepts, new knowledge, and new approaches are necessary. A great challenge is before us.

Report of Advances in Microwave Theory and Techniques in Great Britain—1958*

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TEM Lines

THE characteristic impedances of a coaxial type line in which the inner conductor is a flat strip and of a triplate strip line have been calculated.

J. C. Anderson, "The calculation of characteristic impedance by conformal transformation," *J. Brit. IRE*, vol. 18, pp. 49–54; January, 1958.
K. Foster, "The characteristic impedance and phase velocity of high-Q triplate line," *J. Brit. IRE*, vol. 18, pp. 715–723; December, 1958.

Further numerical work has been carried out on estimating the probability of a specified over-all reflection coefficient caused by a number of known mismatches of random spacing.

J. H. Craven, "The probability of specified losses at mismatched junctions," *J. Brit. IRE*, vol. 18, pp. 293–296; May, 1958.

Transient conditions have also been considered.

K. W. H. Foulds, "Transmission line discontinuities," *Electronic Radio Engr.*, vol. 35, pp. 263–267; July, 1958.

* Manuscript received by the PGMTT, March, 1959.
† Dept. of Elec. Engrg., University College, London, Eng.

A study of irregularities in cable characteristic impedances has been made.

J. Allison, "Variations of characteristic impedance along short coaxial cables," *Proc. IEE*, vol. 105, pt. C, pp. 169–176; March, 1958.

Hollow Waveguides

Interest in the properties of the low-loss TE_{01} mode in circular waveguide continues and a survey of the waveguide requirements has been made.

A. E. Karbowiak, "Microwave aspects of waveguides for long-distance transmission," *Proc. IEE*, vol. 105, pt. C, pp. 360–369; September, 1958.

The use of dielectric filling has been suggested as a means of minimizing the losses at bends.

H. M. Barlow "Propagation Around Bends in Waveguides," IEE Mono. No. 113R, September, 1958; will be republished in *Proc. IEE*, vol. 106, pt. C; March, 1959.

A general treatment of helical coordinate systems can be applied to helical waveguides.

R. A. Waldron, "A helical coordinate system and its applications in electromagnetic theory," *Quart. J. Mech. and Appl. Math.*, vol. 11, pp. 438–461; November, 1958.