Report of Advances in Microwave Theory and Techniques—1956*

DONALD D. KING†

MICROWAVE THEORY and techniques include the transmission, control, and measurement of waves of centimeter or millimeter length. The methods applicable in this region differ sufficiently from those at lower frequency to constitute a rather well-defined discipline. This area is the subject of our review. Several subjects contiguous to the microwave domain are excluded. Thus, antenna and propagation problems do not exhibit so clearcut a change with wavelength, and are mentioned only indirectly. The electronic aspects of microwave generators are also omitted, although much work on the circuits for these generators is necessarily included.

The year 1956 in microwaves has been dominated by the continuing advance in the use of gyromagnetic media for circuit elements. What might be called the ferrite revolution is extending rapidly to embrace more and more useful devices for the control of microwaves. The host of new practical applications for ferrites has been accompanied by a corresponding advance in the basic physics of the solid state. The close community of interest of both physicists and engineers in the microwave properties of ferrites offers the best explanation for the intense and fruitful effort in this area during the year.

Less spectacular but important advances are being made on certain types of waveguides and linear circuit elements for microwaves. Measurement techniques also show steady progress during the year. Traveling wave devices of various kinds remain the most active area of research in microwave active elements. However, interest in gas discharges appears to be increasing, and this field holds some promise of new microwave active elements. The smaller scale efforts in detectors and noise sources continue unabated.

The general subjects mentioned above provide four broad headings under which the individual work is listed. These are: I. Ferrites, II. Waveguides, III. Measurements, and IV. Sources and Detectors. These are now considered in turn.

I. Ferrites

Research in ferrites follows two complementary channels: the study of ferrite materials, and the investigation of circuit elements using ferrites. In the early developments, these two aspects often could not be distinguished, since special circuit elements were needed to study the new materials. At least the more obvious circuit elements have now been realized, and in some instances have already become standard items. Progress in ferrite circuit elements continues at a rapid pace, and enjoys the advantage of many standardized ferrite materials. The need for improvement in these ferrites is basic to much of the future development of the field, and occupies the first place in this review. Following the review of materials and their properties in waveguides, the various special circuit elements utilizing ferrites are taken up.

The work being considered is confined to published papers which may be generally accessible to others active in the field. However, two important conferences must be mentioned in connection with ferrites. The first of these was held in Cambridge, Mass. on April 2–4, 1956. The papers presented at this meeting provided the most complete and unified coverage of the ferrite field to date; they included both tutorial discussions of basic theory, and detailed papers on various special applications. These papers have since been published and are included in the bibliography wherever applicable.

Another conference on ferrites took place in London on October 29–November 2, 1956. Many important contributions were made at this conference which have not yet appeared in print. A few of these papers are incorporated into the bibliography to record their significant contribution. Many of these papers will be published in the *Proceedings of the Institution of Electrical Engineers*, part B during 1957.

The success of these two conferences, both in terms of important scientific contributions, and in numbers of interested technical people attending, is a measure of the vitality of ferrite research throughout the world.

Properties of Ferrite Materials

No single figure of merit describes the quality of a given ferrite for all circuit applications. Important properties which must be considered are:

1) Tensor susceptibility.
2) Dielectric constant.
3) Ferromagnetic resonance linewidth.
4) Curie temperature.
5) Saturation magnetization.

For the circuit designer, the tensor susceptibility and dielectric constant, both complex, specify the electrical performance. The frequency dependence of the former limits the bandwidth of many ferrite devices. In particular, the magnetic loss at low frequency constitutes a basic limitation of present materials. Except for certain resonance devices, a narrow resonance line-

* Manuscript received by the PGMTT, January 25, 1957.
† Electronic Communications, Inc., Baltimore 18, Md.

width is also desirable. At present, the dielectric constant and loss are not a major limitation on ferrite performance. However, changes in ferrite composition or extension to higher frequencies may alter the situation.

At the Curie temperature, the saturation magnetization vanishes, and the ferrite properties disappear. This places an absolute limit on the operating temperature, and hence generally on the power handling capacity.

The basic theory of ferrites has been described in considerable detail by theoretical physicists in papers intended to provide the foundation for engineering applications.

[1] J. H. Van Vleck, "Fundamental theory of ferro- and ferrimagnetism," PROC. IRE, vol. 44, pp. 1248–1258; October, 1956.

[2] N. Bloembergen, "Magnetic resonance in ferrites," PROC. IRE, vol. 44, pp. 1259–1269; October, 1956

[3] J. O. Artman, "Microwave resonance relations in anisotropic single crystal ferrites," PROC. IRE, vol. 44, pp. 1284–1293; October, 1956.

[4] G. T. Rado, "On the electromagnetic characterization of ferromagnetic media: permeability tensors and spin wave equations," IRE TRANS., vol. AP-4, pp. 512–525; July, 1956.

A good start has been made at extending the analysis of ferrite behavior to high-signal levels. Important saturation effects exist on which considerable experimental data has been accumulated.

[5] H. Suhl, "The nonlinear behavior of ferrites at high microwave signal levels," PROC. IRE, vol. 44, pp. 1270–1283; October, 1956.

[6] N. G. Sakiotis, H. N. Chait, and M. L. Kales, "Nonlinearity of microwave ferrite media," IRE TRANS., vol. AP-4, pp. 111–115; April, 1956.

In the study of new ferrite materials, particular interest has been attracted to rare earth ferrites and to hexagonal crystal structures.

[7] F. Bertaut, "Structure of the ferrimagnetic ferrites of the rare earths," *Compt. Rend. Acad. Sci. Paris*, vol. 242, p. 282; April, 1956.

[8] F. Bertaut and R. Pauthenet, "Crystalline structure and magnetic properties of ferrites having the general formula 5 Fe_2O_3—$3M_2O_3$," presented at the Convention on Ferrites, October 29–November 2, 1956.

[9] E. W. Gorter, "Saturation magnetization of new ferrimagnetic oxides with hexagonal crystal structures," presented at the Convention on Ferrites, October 29–November 2, 1956.

[10] P. B. Braun, G. H. Jonker, and H. P. J. Wijn, "A new class of oxidic ferromagnetic materials with hexagonal crystal structures," presented at the Convention on Ferrites, October 29–November 2, 1956.

A few additional materials which have been examined in some detail are the following:

[11] L. G. Van Uitert, "Nickel copper ferrites for microwave applications," *J. Appl. Phys.*, vol. 27, pp. 723–727; July, 1956.

[12] P. E. Tannenwald and M. H. Seavey, "Anisotropy of cobalt-substituted Mn ferrite single crystals," PROC. IRE, vol. 44, pp. 1343–1344; October, 1956.

[13] F. Mayer, "Study of magnetic rotatory polarization in copper ferrite at 10 kmc/s," *Compt. Rend. Acad. Sci. Paris*, vol. 242, pp. 81–83; January, 1956.

Permeability and dielectric properties of ferrites have been determined by a variety of methods and in considerable detail.

[14] E. B. Mullen and E. R. Carlson, "Permeability tensor values from waveguide measurements," PROC. IRE, vol. 44, pp. 1318–1322; October, 1956.

[15] E. G. Spencer, L. S. Ault, and R. C. LeCraw, "Intrinsic tensor permeabilities on ferrite rods, spheres, and disks," PROC. IRE, vol. 44, pp. 1311–1317; October, 1956.

[16] R. C. LeCraw and E. G. Spencer, "Tensor permeabilities of ferrites below magnetic saturation," 1956 IRE CONVENTION RECORD, Part 5, pp. 66–74.

[17] E. G. Spencer, R. C. LeCraw, and F. Reggia, "Measurement of microwave dielectric constants and tensor permeabilities of ferrite spheres," PROC. IRE, vol. 44, pp. 790–800; June, 1956.

[18] L. G. Van Uitert, "Dielectric properties of and conductivity in ferrites," PROC. IRE, vol. 44, pp. 1294–1302; October, 1956.

[19] S. Sensiper, "Resonance loss properties of ferrites in 9 kmc region," PROC. IRE, vol. 44, pp. 1323–1342; October, 1956.

The preparation and chemical aspects of ferrites have been discussed in a paper which in many respects is basic to all ferrite applications.

[20] D. L. Fresh, "Methods of preparation and crystal chemistry of ferrites," PROC. IRE, vol. 44, pp. 1303–1310; October, 1956.

Wave Propagation in Ferrites

Microwave applications inevitably involve the propagation of EM waves in ferrite materials. Here, the boundary conditions assumed are of paramount importance. Circular waveguide is perhaps the most common and useful configuration. For more complicated geometries, the mathematical complications become formidable. In spite of this, some progress has been made, both by approximation and by numerical solution.

Several reviews of the general problem have appeared which serve well to put the various problems in perspective.

[21] P. S. Epstein, "Theory of wave propagation in a gyromagnetic medium," *Rev. Mod. Phys.*, vol. 28, pp. 3–17; January, 1956.

[22] M. L. Kales, "Topics in guided-wave propagation in magnetized ferrites," PROC. IRE, vol. 44, pp. 1403–1409; October, 1956.

[23] G. H. B. Thompson, "Ferrites in waveguides," *J. Brit. IRE*, vol. 16, pp. 311–328; June, 1956.

Papers dealing with more specific waveguide cross sections containing ferrites include the following.

[24] L. R. Walker and H. Suhl, "Propagation in circular waveguides filled with gyromagnetic material," IRE TRANS., vol. AP-4, pp. 492–494; July, 1956.

[25] J. L. Melchor, W. P. Ayers, and P. H. Vartanian, "Energy concentration effects in ferrite loaded wave guides," *J. Appl. Phys.*, vol. 27, pp. 72–77; January, 1956.

[26] A. A. van Trier, "Some topics in the microwave application of gyrotropic media," IRE TRANS., vol. AP-4, pp. 502–507; July, 1956.

[27] N. Karayianis and J. C. Cacheris, "Birefringence of ferrites in circular waveguides," PROC. IRE, vol. 44, pp. 1414–1420; October, 1956.

[28] K. J. Button and Benjamin Lax, "Theory of ferrites in rectangular waveguide," IRE TRANS., vol. AP-4, pp. 531–537; July, 1956.

[29] H. Seidel, "Anomalous propagation in ferrite-loaded waveguide," PROC. IRE, vol. 44, pp. 1410–1413; October, 1956.

[30] P. H. Vartanian and E. T. Jaynes, "Propagation in ferrite-filled transversely magnetized waveguide," IRE TRANS., vol. MTT-4, pp. 140–143; July, 1956.

[31] B. J. Duncan and L. Swern, "Temperature behavior of ferrimagnetic resonance in ferrites located in waveguide," *J. Appl. Phys.*, vol. 27, pp. 209–215; March, 1956.

More general boundary conditions have also been treated, including an experimental study of radiation from ferrite-filled apertures.

[32] J. Sontif-Guichard, "Calculation of the Faraday effect in a gyroparamagnetic medium," *Compt. Rend. Acad. Sci. Paris*, vol. 242, pp. 1868–1871; April 9, 1956.

[33] J. Sontif-Guichard, "Equation of circularly polarized waves in a gyroparamagnetic medium," *Compt. Rend. Acad. Sci. Paris*, vol. 242, pp. 1418–1421; March, 1956.

[34] D. J. Angelakos and M. M. Korman, "Radiation from ferrite-filled apertures," PROC. IRE, vol. 44, pp. 1463–1467; October, 1956.

Isolators

The component which makes the most obvious use of nonreciprocal ferrite properties is the isolator. It is probably the most outstanding ferrite component, since it offers properties which cannot be attained at all with linear elements, and does so with elegance and dispatch.

The general configuration of isolators and other ferrite circuit elements involves a section of waveguide partially filled with ferrite material of a particular shape. For most circuit elements, the distribution of ferrite is uniform along the direction of propagation. The properties of these ferrite devices have been reviewed in several papers covering both the basic theory and the generally attainable performance at the present time.

[35] C. L. Hogan, "The elements of nonreciprocal microwave devices," Proc. IRE, vol. 44, pp. 1345–1367; October, 1956.
[36] B. Lax, "Frequency and loss characteristics of microwave ferrite devices," Proc. IRE, vol. 44, pp. 1368–1385; October, 1956.
[37] G. S. Heller, "Ferrites as microwave circuit elements," Proc. IRE, vol. 44, pp. 1386–1393; October, 1956.
[38] C. L. Hogan, "The low-frequency problem in the design of microwave gyrators and associated elements," IRE Trans., vol. AP-4, pp. 495–501; July, 1956.

An important contribution to the analysis of such elements has been the introduction of matrix methods for the solution of transverse propagation characteristics. This type of analysis holds promise for a number of waveguide types.

[39] J. H. Rowen, "A novel approach to the analysis of ferrite-loaded waveguide structures," presented at the London Convention on Ferrites, October 29–November 2, 1956.

An example of the possibilities for ferrite isolators in strip line was also given earlier in the year.

[40] L. Lewin, "A resonant absorption isolator in microstrip for 4 kmc/s," presented at the London Convention on Ferrites, October 29–November 2, 1956.
[41] O. A. Fix, "A balanced stripline isolator," 1956 IRE Convention Record, Part 5, pp. 99–105.

A large number of papers has appeared on various isolator designs. In many of these considerable material of importance to the basic understanding of isolator operations is included, as well as specific information on a practical engineering design.

[42] S. Weisbaum and H. Seidel, "The field displacement isolator," *Bell Sys. Tech. J.*, vol. 35, pp. 877–898; July, 1956.
[43] S. Weisbaum and H. Boyet, "A double-slab ferrite field displacement isolator at 11 kmc," Proc. IRE, vol. 44, pp. 554–555; April, 1956.
[44] M. T. Weiss, "Improved rectangular waveguide resonance isolators," IRE Trans., vol. MTT-4, pp. 240–243; October, 1956.
[45] P. H. Vartanian, J. L. Melchor, and W. P. Ayres, "Broadband ferrite microwave isolator," IRE Trans., vol. MTT-4, pp. 8–13; January, 1956.
[46] P. H. Vartanian, J. L. Melchor, and W. P. Ayres, "Broadbanding ferrite microwave isolators," 1956 IRE Convention Record, Part 5, pp. 79–83.
[47] A. Langley Morris, "The 45° rotation ferrite isolator," presented at the London Convention on Ferrites, October 29–November 2, 1956.
[48] R. F. Sullivan, "A miniaturized high temperature isolator," 1956 IRE Convention Record, Part 5, pp. 75–78.
[49] W. Eichin, "A unidirectional attenuator with delay line and ferrite element for the 4-kmc/s frequency band," *Nachrichtentech Z.*, vol. 9, pp. 168–172; April, 1956.
[50] B. N. Enander, "A new ferrite isolator," Proc. IRE, vol. 44, pp. 1421–1430; October, 1956.

Modulators

Control of attenuation by means of the external magnetic field is easily achieved in ferrite devices. The resulting possibilities for modulation and gain control are very attractive. A number of papers have reported successful devices of this type.

[51] P. Fire and P. H. Vartanian, "An amplitude regulator for microwave signal sources," 1956 IRE Convention Record, Part 5, pp. 166–171.
[52] W. W. H. Clarke, W. M. Searle, and F. T. Vail, "A ferrite microwave modulator employing feedback," *Proc. IEE*, vol. 103, Part B, pp. 485–490; July, 1956.
[53] J. C. Cacheris and H. A. Dropkin, "Compact microwave single-sideband modulator using ferrites," IRE Trans., vol. MTT-4, pp. 152–155; July, 1956.
[54] H. G. Beljers, "Amplitude modulation of centimetre waves by means of ferroxcube," *Philips Tech. Rev.*, vol. 18, pp. 82–86; September, 1956.
[55] J. P. Vinding, "Automatic gain control system for microwaves," IRE Trans., vol. MTT-4, pp. 244–245; October, 1956.

Frequency modulation is also possible by means of cavity tuning. An example of this has been given.

[56] G. R. Jones, J. C. Cacheris, and C. A. Morrison, "Magnetic tuning of resonant cavities and wideband frequency modulation of klystrons," Proc. IRE, vol. 44, pp. 1431–1438; October, 1956.

A rather different action, namely frequency doubling, has also been obtained in ferrites. Although not modulation in the usual sense, this important effect is listed here for want of a better heading.

[57] W. P. Ayres, P. H. Vartanian, and J. L. Melchor, "Frequency doubling in ferrites," *J. Appl. Phys.*, vol. 27, pp. 188–189; February, 1956.

Circulators and Directional Couplers

A circulator may be defined as a device in which energy is transferred from port to port without amplitude change. Phase shifts may be tolerated, and energy need not return from a port by the same path as it came to that port. Such a device in nonreciprocal form is only practicable with ferrite elements. The network properties of circulators have been analyzed very effectively in terms of group theory and topology. In terms of the former, a circulator is defined as a device whose scattering matrix operates on the incident voltages so as to produce the same result as the operation of a cyclic substitution. In the language of topology, a circulator is any structure which may be represented by an "oriented 1-circuit."

With the aid of these concepts, possible symmetries for circulators can be specified, and rules for determining the results of complicated interconnections of circulators can be set up.

[58] Milton A. Treuhaft, "Network properties of circulators based on the scattering concept." Proc. IRE, vol. 44, pp. 1394–1402; October, 1956.

Several circulator schemes have been developed with widely differing physical arrangements.

[59] E. A. Ohm, "A broad-band microwave circulator," IRE Trans., vol. MTT-4, pp. 210–217; October, 1956.
[60] P. J. Allen, "The turnstile circulator," IRE Trans., vol. MTT-4, pp. 223–227; October, 1956.

A directional coupler based on the nonreciprocal scattering from a ferrite post has also been developed. This device is closely related to circulators.

[61] A. D. Berk and E. Strumwasser, "Ferrite directional couplers," Proc. IRE, vol. 44, pp. 1439–1445; October, 1956.

Phase Shifters

The differential phase shifts which underlie the operation of the ferrite devices mentioned so far may be used explicitly in phase shifters. Both reciprocal and nonreciprocal types are possible, and offer new possibilities in electrical control of transmission characteristics over broad bands.

[62] S. Weisbaum and H. Boyet, "Broad-band nonreciprocal phase shifts—analysis of two ferrite slabs in rectangular waveguide," *J. Appl. Phys.*, vol. 27, pp. 519–524; May, 1956.
[63] H. Scharfman, "Three new ferrite phase shifters," Proc. IRE, vol. 44, pp. 1456–1459; October, 1956.
[64] H. N. Chait and N. C. Sakiotis, "The design of nonreciprocal phase shift sections," 1956 IRE Convention Record, Part 5, pp. 58–65.
[65] R. F. Sookov, "Ferrite microwave phase shifters," 1956 IRE Convention Record, Part 5, pp. 84–98.

Filters

The insertion of a ferrite post into a resonant cavity permits electrical tuning over a considerable bandwidth. The basic theory of a ferrite post in a section of waveguide has been analyzed in general terms and applied to this problem.

[66] P. S. Epstein and A. D. Berk, "Ferrite post in a rectangular waveguide," *J. Appl. Phys.*, vol. 27, pp. 1328–1334; November, 1956.

Several specific filter designs and their capabilities have been described during the year. These are evidently the forerunners of a family of devices for electrical frequency control over the entire microwave spectrum.

[67] C. E. Fay, "Ferrite-tuned resonant cavities," Proc. IRE, vol. 44, pp. 1446–1448; October, 1956.
[68] C. E. Nelson, "Ferrite-tunable microwave cavities and the introduction of a new reflectionless, tunable microwave filter," Proc. IRE, vol. 44, pp. 1449–1455; October, 1956.
[69] James H. Burgess, "Ferrite-tunable filter for use in S-band," Proc. IRE, vol. 44, pp. 1460–1462; October, 1956.

After reviewing the ferrite contributions in the various areas of development, it appears that not only new elements are being created: operations which have been successfully performed by linear elements are being accomplished with ferrites to considerable advantage. It may not be too extravagant a prediction to state that within a few years most microwave circuit elements will rely on ferrites in one way or another.

II. Waveguides

The bandwidth and attenuation requirements for waveguides are becoming increasingly severe. As a result, strong effects are underway to improve the performance of TEM lines, whose bandwidth is inherently greater than that of hollow guides. Where allowable transmission loss does not permit the use of such lines, extremely high frequencies and precise mode control must be relied on to produce adequate bandwidth and attenuation characteristics. The trend to broad-band systems increases the importance of filters, transformers, and other elements suitable for separating and controlling various portions of the spectrum being transmitted. Most of the published work on waveguides is concerned with these aspects of the field.

TEM Lines

As in previous years, various types of strip or planar lines are being developed as compact broad-band transmission systems. Refinements in characteristic impedance determination are the principal contribution being made.

[70] R. H. Bates, "The characteristic impedance of the shielded slab line," IRE Trans., vol. MTT-4, pp. 28–33; January, 1956.
[71] R. M. Chisholm, "The characteristic impedance of trough and slab lines," IRE Trans., vol. MTT-4, pp. 166–172; July, 1956.
[72] J. M. C. Dukes, "An investigation into some fundamental properties of strip transmission lines with the aid of an electrolytic tank," *Proc. IEE*, vol. 103, Part B, pp. 319–333; May, 1956.

An important application of TEM lines is coupling to various types of radiators. Here, a better understanding of both strip and coaxial line coupling has been achieved.

[73] A. D. Frost, C. R. McGeoch, and C. R. Mingins, "The excitation of surface waveguides and radiating slots by strip-circuit transmission lines," IRE Trans., vol. MTT-4, pp. 218–223; October, 1956.
[74] R. E. Collin, "The characteristic impedance of a slotted coaxial line," IRE Trans., vol. MTT-4, pp. 4–8; January, 1956.

Tapered TEM lines have long served as transformers. This subject, which received considerable attention in 1955, has been examined further. As a result, the various Fourier and Tchebycheff formulations have been brought more clearly into focus, and several useful, practical formulas and charts have been published.

[75] R. W. Klopfenstein, "A transmission line taper of improved design," Proc. IRE, vol. 44, pp. 31–35; January, 1956.
[76] R. E. Collin, "The optimum tapered transmission line matching section," Proc. IRE, vol. 44, pp. 539–548; April, 1956. (Also p. 1055; August, 1956.)
[77] J. Willis and N. K. Sinha, "Non-uniform transmission lines as impedance transformers," *Proc. IEE*, vol. 103, Part B, pp. 166–172; March, 1956.
[78] J. Willis and N. K. Sinha, "Impedance transformers," *Wireless Eng.*, vol. 33, pp. 204–208; September, 1956.
[79] E. F. Bolinder, "Fourier transforms and tapered transmission lines," Proc. IRE, vol. 44, p. 557; April, 1956.

Hollow Waveguides

The TE_{01} circular mode provides minimum theoretical attenuation in hollow pipes. To achieve this, an ingenious helical guide has been developed: by replacing the cylindrical conductor of a circular waveguide with a helical coil of fine wire, only circular components of current can be supported. Consequently, only the TE_{0n} type modes are sustained by the guide. Other modes penetrate the guide wall and are absorbed by a lossy outer coating.

[80] S. P. Morgan and J. A. Young, "Helix waveguide," *Bell Sys. Tech. J.*, vol. 35, pp. 1347–1385; November, 1956.

The problem of unwanted mode control in large guides is being attacked very effectively. By making the guide lossy for undesired modes, their amplitudes are kept low; the interaction with the transmission mode is thereby reduced. Conversion to other modes occurs primarily in bends and discontinuities, hence particular attention must be concentrated here.

[81] A. P. King and E. A. Marcutili, "Transmission loss due to resonance of converted modes," *Bell Sys. Tech. J.*, vol. 35, pp. 899–906; July, 1956.

Techniques for evaluating the performance of low-loss guide are now highly refined. The use of very short pulses for transmission is particularly effective.

[82] A. P. King, "Observed 5–6 mm. attenuation for the circular electric wave in small and medium-sized pipes," *Bell Sys. Tech. J.*, vol. 35, pp. 1115–1128; September, 1956.
[83] A. Sander, "The excitation and propagation of E_{0n} modes in a circular waveguide with coaxial lines at input and output," *Arch. Elekt. Übertragung*, vol. 10, pp. 77–85; March, 1956.
[84] W. Schaffeld and H. Bayer, "Propagation of electromagnetic waves in circular waveguides with finite wall conductivity at frequencies near cut-off," *Arch. Elekt. Übertragung*, vol. 10, pp. 89–97; March, 1956.
[85] A. S. Beck, "Waveguide investigations with millimicrosecond pulses," *Bell Sys. Tech. J.*, vol. 35, pp. 35–66; January, 1956.
[86] O. E. DeLange, "Experiments on the regeneration of binary microwave pulses," *Bell Sys. Tech. J.*, vol. 35, pp. 67–90; January, 1956.

Several extensions of existing theory on circular guides complete the contributions noted on hollow waveguides.

[87] A. D. Berk, "Variational principles for electromagnetic resonators and waveguides," IRE Trans., vol. AP-4, pp. 104–111; April, 1956.
[88] M. Handelsman, "The susceptance of a circular iris to the dominant TE_{11} mode in circular waveguide," 1956 IRE Convention Record, Part 5, pp. 133–140.

Surface Waves and Periodic Structures

Various structures have been used as surface waveguides. Perhaps the simplest of these is the dielectric-coated wire. Coupling phenomenon for lines of this type have been studied.

[89] D. Marcuse, "Investigation of the energy exchange and the field distribution for parallel surface-wave transmission lines," *Arch. Elekt. Übertragung*, vol. 10, pp. 117–124; March, 1956.

A method for confining a wave between two strips with the aid of a small dielectric spacer has been described. The resulting structure has a cross section resembling the letter H, and offers very low attenuation for loosely-bound waves.

[90] F. J. Tischer, "H-guide—a waveguide for microwaves," 1956 IRE Convention Record, Part 5, pp. 44–47.

The use of periodic structures as waveguides continues to grow. The most generally useful of these is the helix. Several papers extend the theoretical treatment of this structure so common in traveling-wave tubes.

[91] N. N. Smirnov, "Propagation of waves along an infinitely long helix," *Compt. Rend. Acad. Sci. U.R.S.S.*, vol. 108, pp. 243–246; May 11, 1956.
[92] S. Kh. Kogan, "Theory of helical lines," *Compt. Rend. Acad. Sci. U.R.S.S.*, vol. 107, pp. 541–544; April, 1956.
[93] C. P. Allen and G. M. Clarke, "Interpretation of wavelength measurements on tape helices," *Proc. IEE*, vol. 103, Part C, pp. 171–176; March, 1956.

When used to support the inner conductor of coaxial cables, the helix appears in a different role. The physical conditions needed to provide good support with a dielectric helix result in well defined stop bands at higher frequencies.

[94] J. W. E. Griemsmann, "An approximate analysis of coaxial line with helical dielectric support," IRE Trans., vol. MTT-4, pp. 13–23; January, 1956.

Diaphragms or irises in tubes provide another common method of obtaining relatively slow guided waves. Theoretical work continues here, with emphasis on formulating a more exact analysis for lossy structures and on representation for measurements.

[95] E. G. Solov'ev, "Propagation of electromagnetic waves between two circular cylindrical surfaces in the presence of longitudinal, periodically spaced diaphragms," *Radiotekhnika Moscow*, vol. 11, pp. 57–60; January, 1956.
[96] P. N. Butcher, "A new treatment of lossy periodic waveguides," *Proc. IEE*, vol. 103, Part B, pp. 301–306; May, 1956.
[97] R. L. Kyhl, "The use of non-Euclidean geometry in measurements of periodically loaded transmission lines," IRE Trans., vol. MTT-4, pp. 111–115; April, 1956.

The use of current sheets to provide slow guided waves has also been proposed.

[98] F. Bertein and W. Chahid, "Production of slow electromagnetic waves by means of cylindrical current sheets," *Compt. Rend. Acad. Sci. Paris*, vol. 242, pp. 2918–2920; June 18, 1956.

The launching of surface waves over corrugated or dielectric coated surfaces is being accomplished with surprising efficiency with dipole radiators. Calculations based on Sommerfeld's integrals and comparative measurements on smooth and reactive surfaces confirm efficiencies up to 80 per cent for the radially symmetric surface wave.

[99] W. M. G. Fernando and H. E. M. Barlow, "An investigation of the properties of radial cylindrical surface waves launched over flat reactive surfaces," *Proc. IEE*, vol. 103, Part B, pp. 307–318; May, 1956.

The theoretical treatment of propagation in periodic structures is facilitated by considering an infinite medium. A number of interesting periodic structures can then be studied with a view to obtaining a quantitative understanding of their propagation characteristics.

[100] R. I. Primich, "A semi-infinite array of parallel metallic plates of finite thickness for microwave systems," IRE Trans., vol. MTT-4, pp. 156–166; July, 1956.
[101] Z. A. Kaprielian, "Electromagnetic transmission characteristics of a lattice of infinitely long conducting cylinders," *J. Appl. Phys.*, vol. 27, pp. 1491–1502; December, 1956.
[102] H. T. Ward, W. D. Puro, and D. M. Bowie, "Artificial dielectrics utilizing cylindrical and spherical voids," Proc. IRE, vol. 44, pp. 171–175; February, 1956.
[103] I. Kay and H. E. Moses, "Reflectionless transmission dielectrics and scattering potentials," *J. Appl. Phys.*, vol. 27, pp. 1503–1508; December, 1956.
[104] Ya. N. Fel'd, "Paired systems of infinite linear algebraic equations, linked with infinite periodic structures," *Compt. Rend. Acad. Sci. U.R.S.S.*, vol. 106, pp. 215–218; January, 1956.

Filters

The impact of Striplines on microwave filter design has been very significant. The possibilities of filters using multiple combinations of Stripline elements are surprisingly great. In addition to providing flexible filter elements, the Stripline components are easily designed and built. Several papers have dealt rather extensively with this subject; practical designs as well as the theory are tabulated and discussed.

[105] S. B. Cohn and F. S. Coale, "Directional channel-separation filters," Proc. IRE, vol. 44, pp. 1018–1024; August, 1956.
[106] E. H. Bradley, "Design and development of stripline filters," IRE Trans., vol. MTT-4, pp. 86–93; April, 1956.

Waveguide filters are the subject of a number of papers. Several new ideas have been advanced, including the use of circular polarization and symmetry to increase power capability and efficiency at constant input resistance.

[107] R. W. Klopfenstein and J. Epstein, "The polarguide—a constant resistance waveguide filter," PROC. IRE, vol. 44, pp. 210–218; February, 1956.
[108] E. M. T. Jones, "Synthesis of wide-band microwave filters to have prescribed insertion loss," 1956 IRE CONVENTION RECORD, Part 5, pp. 119–128.
[109] P. A. Rizzi, "Microwave filters utilizing the cut-off effect," IRE TRANS., vol. MTT-4, pp. 36–40; January, 1956.
[110] M. H. N. Potok, "Waveguide filters," *Wireless Eng.*, vol. 33, pp. 79–82; April, 1956.
[111] G. Craven and L. Lewin, "Design of microwave filters with quarter-wave couplings," *Proc. IEE*, vol. 103, Part B, pp. 173–177; March, 1956.

Two new tunable filters have been described. One of these uses two crossed modes in a square-cylinder resonator. A double tuned response is thereby obtained with only a single resonator. The second device is electrically tunable over a 10:1 frequency range starting at 600 mc. The paramagnetic resonance of hydrazyl provides the tuning element.

[112] N. A. Spencer, "Crossed-mode tunable selector for microwaves," 1956 IRE CONVENTION RECORD, Part 5, pp. 129–132.
[113] P. H. Vartanian and J. L. Melchor, "Broad-band microwave frequency meter," PROC. IRE, vol. 44, pp. 175–178; February, 1956.

A microwave filter has been developed which relies on a traveling-wave resonance rather than the conventional standing wave. A closed transmission line loop supports the traveling wave. Two directional couplers provide coupling to four output terminal pairs. The device is a constant resistance circuit with very low input standing-wave ratio. The traveling-wave filter seems particularly well-suited to multiplexing applications because of its terminal arrangement and low reflection.

[114] F. S. Coale, "A traveling-wave directional filter," IRE TRANS., vol. MTT-4, pp. 256–260; October, 1956.

Directional Couplers and Junctions

Directional couplers are easily realized in Striplines. Because of the simple structures involved, tuned elements can be combined easily with directional coupling to yield a variety of useful response patterns.

[115] E. M. T. Jones and J. T. Bolljahn, "Coupled-strip-transmission-line filters and directional couplers," IRE TRANS., vol. MTT-4, pp. 75–81; April, 1956.

Lumped-element couplers for lower frequencies have been reviewed and new data provided.

[116] P. Lombardini, R. F. Schwartz, and P. J. Kelly, "Criteria for the design of loop-type directional couplers for the L band," IRE TRANS. vol. MTT-4, pp. 234–239; October, 1956.

The recently developed finline circuits offer interesting possibilities in a variety of functions. Directional couplers, twists, bends, and hybrid junctions have been described for use with hollow waveguide carrying one or several modes.

[117] S. D. Robertson, "Recent advances in finline circuits," IRE TRANS., vol. MTT-4, pp. 263–267; October, 1956.

Several papers have appeared on waveguide junctions and the systematic representation of their properties.

[118] R. S. Potter, "A trimode turnstile waveguide junction," 1956 IRE CONVENTION RECORD, Part 5, pp. 36–43.
[119] J. A. Ortusi, "The amplitude concept of an electromagnetic wave and its application to junction problems in waveguides," IRE TRANS. vol. AP-4, pp. 156–162; April, 1956.
[120] P. A. Loth, "Recent advances in waveguide hybrid junctions," IRE TRANS., vol. MTT-4, pp. 268–271; October, 1956.
[121] J. Reed and G. J. Wheeler, "A method of analysis of symmetrical four-port networks," IRE TRANS., vol. MTT-4, pp. 246–252; October, 1956.

From the point of view of fabrication, waveguide junctions are often clumsy and space-consuming. An interesting scheme of construction has been proposed in which guides are arranged in a single plane with adjacent walls common. Considerable simplification in construction results from this arrangement.

[122] L. Lewin, "Miniaturization of microwave assemblies," IRE TRANS., vol. MTT-4, pp. 261–262; October, 1956.

A variety of articles on transitions and joints have appeared during the year. One of the most interesting of these is an annular rotary joint with coupling through an array of slots forming an extended directional coupler between two waveguide rings.

[123] K. Tomiyasu, "A new annular waveguide rotary joint," PROC. IRE, vol. 44, pp. 548–553; April, 1956.

A somewhat related device is the serrated choke proposed by the same author for broad-band applications.

[124] K. Tomiyasu and J. J. Bolus, "Characteristics of a new serrated choke," IRE TRANS., vol. MTT-4, pp. 33–36; January, 1956.

Another ingenious device is a high-speed phase shifter utilizing circular polarization and rotating helical coupling units.

[125] W. Sichak and D. J. Levine, "Microwave high-speed continuous phase shifter," *Elec. Communication*, vol. 33, pp. 224–227; September, 1956.

Several transitions and a switching tee complete the circuit elements noted in this review.

[126] R. D. Tompkins, "A broad-band dual-mode circular waveguide transducer," IRE TRANS., vol. MTT-4, pp. 181–183; July, 1956.
[127] F. Mayer, "Transitions from the TE_{01} mode in a rectangular waveguide to the TE_{11} mode in a circular waveguide," *J. Phys. Radium*, vol. 17, Suppl. 3 Phys. Appl., pp. 52A-53A; March, 1956.
[128] R. L. Fogel, "An orthogonal mode transducer," 1956 IRE CONVENTION RECORD, Part 5, pp. 53–57.
[129] J. W. E. Griemsmann and S. S. Kasai, "Broad-band waveguide series T for switching," IRE TRANS., vol. MTT-4, pp. 252–255; October, 1956.

As can be seen from the papers listed, the designers of waveguides and linear circuit elements have been both active and ingenious during 1956.

III. MEASUREMENTS

Progress in measurements for the most part reflects a continuing refinement and extension of proven techniques. However, some basically new approaches have appeared during the year, both in technique and representation. The impact of advances in solid-state physics are now beginning to be felt in the measurements field; in future years, this influence will undoubtedly grow.

Impedance Measurements

The techniques of impedance measurements rest on long-established foundations. As can be seen from their titles, the papers in this field belong largely in the category of reports on refinements and extensions of the art.

[130] A. C. MacPherson and D. M. Kerns, "A new technique for the measurement of microwave standing wave ratios," Proc. IRE, vol. 44, pp. 1024–1030; August, 1956.
[131] E. E. Conrad, C. S. Porter, N. J. Doctor, and P. J. Franklin, "Extension of the 'thin-sample method' for measurement of initial complex permeability and permittivity," *J. Appl. Phys.*, vol. 27, pp. 346–350; April, 1956.
[132] H. L. Bachman, "Automatic plotter for waveguide impedance," *Electronics*, vol. 29, pp. 184–187; March, 1956.
[133] J. P. Vinding, "The Z-Scope, an automatic impedance plotter," 1956 IRE Convention Record, Part 5, pp. 178–183.
[134] W. R. Thurston, "A transadmittance meter for vhf-uhf measurements," 1956 IRE Convention Record, Part 5, pp. 3–7.
[135] M. M. Zimet and S. Friedman, "Measurement of electron tube admittance matrix parameters at ultra high frequencies," 1956 IRE Convention Record, Part 5, pp. 8–14.
[136] C. Polk, "Standing-wave ratio of inaccessible load," *Comm. and Elect.*, No. 23, pp. 9–11; March, 1956.
[137] D. M. Bowie and K. S. Kelleher, "Rapid measurement of dielectric constant and loss tangent," IRE Trans., vol. MTT-4, pp. 137–140; July, 1956.

Power Measurement

In the domain of power measurement, the Hall effect has been put to use for microwave power measurement. By mounting *n*-type germanium in a slot-excited cavity, sufficient magnetic field at 4000 mc was obtained to give about 5 μv/watt Hall output. The resulting directional wattmeter offers great promise as a sensitive power indicator.

[138] H. E. M. Barlow and L. M. Stephenson, "The Hall effect and its application to power measurement at microwave frequencies," *Proc. IEE*, vol. 103, Part B, pp. 110–112; January, 1956. (Also Monograph No. 191R, August, 1956.)

Two other wattmeters of novel design have also been described.

[139] R. A. Bailey "A resonant cavity torque-operated wattmeter for microwave power," *Proc. IEE*, vol. 103, Part C, pp. 59–63; March, 1956.
[140] J. A. Lane, "A film radiometer for centimetre wavelengths," *Nature*, Lond., vol. 177, p. 392; February 25, 1956.

Four-Pole Methods

Determination of the properties of a four-pole can be achieved by several elegant methods. The mathematical representation of four poles is particularly important to the measuring procedure, and hence is included at this point in the review. One of the most interesting advances in this area has been a proposed representation for nonreciprocal two-ports. A modified Wheeler form is used in which the nonreciprocal properties appear in two bilaterally matched elements: a one-way phase-shifter and a one-way attenuator.

[141] H. M. Altschuler and W. K. Kahn, "Nonreciprocal two-ports represented by modified Wheeler networks," IRE Trans., vol. MTT-4, pp. 228–233; October, 1956.

Graphical representations of four-poles by various formalisms have been extended by a number of investigators.

[142] F. L. Wentworth and D. R. Barthel, "A simplified calibration of two-port transmission line devices," IRE Trans., vol. MTT-4, pp. 173–175; July, 1956.
[143] H. F. Mathis, "Some properties of image circles," IRE Trans., vol. MTT-4, pp. 48–50; January, 1956.
[144] E. F. Bolinder, "Impedance and polarization ratio transformations by a graphical method using isometric circles," IRE Trans., vol. MTT-4, pp. 176–180; July, 1956.
[145] H. Schering, "The mean geometrical distances of a circle," *Elektrotech. Z.*, Edn. A, vol. 77, pp. 12–13, January, 1956.

Resonators and Related Measurements

Cavity resonators are an important tool for many microwave measurements. Perhaps the most direct application of cavity techniques is in the measurement of dielectric and magnetic properties of materials. Several papers have appeared describing improvements and extensions of these techniques to new materials and geometries.

[146] S. Saito and K. Kurokawa, "A precision resonance method for measuring dielectric properties of low-loss solid materials in the microwave region," Proc. IRE, vol. 44, pp. 35–42; January, 1956.
[147] R. A. Waldron, "Ferrites in resonant cavities," *Brit. J. Appl. Phys.*, vol. 7, p. 114; March, 1956.
[148] V. L. Patrushev, "Calculation of the natural frequency for a single reentrant cavity partly filled with an absorbing dielectric," *Compt. Rend. Acad. Sci. U.R.S.S.*, vol. 107, pp. 409–412; March 21, 1956.
[149] J. G. Linhart, I. M. Templeton, and R. Dunsmuir, "A microwave resonant cavity method for measuring the resistivity of semi-conducting materials," *Brit. J. Appl. Phys.*, vol. 7, pp. 36–38; January, 1956.
[150] F. Gross, "Temperature dependence of loss angle and dielectric constant of solid insulating materials in the 4 kmc/s range," *Nachrichtentech. Z.*, vol. 9, pp. 124–128; March, 1956.
[151] R. Servant and J. Gougeon, "Birefringence and rectilinear dichroism of paper at 9350 mc/s," *Compt. Rend. Acad. Sci. Paris*, vol. 242, pp. 2318–2320; May 7, 1956.
[152] I. Bady, "Measurement of the complex dielectric constant of materials from 100 to 1200 mc over a wide range of temperature," 1956 IRE Convention Record, Part 5, pp. 172–177.

The cavity itself remains an object of interest for several investigators.

[153] G. Boudouris, "Spherical-frustrum cavities," *Ondé Elect.*, vol 36, pp. 104–121; February, 1956.
[154] H. Urbarz, "Measurement of the Q-factor of cavity resonators using a straight test line," *Nachrichtentech. Z.*, vol. 9, pp. 112–118; March, 1956.
[155] U. Adelsberger, "The rod wavemeter for the frequency range 180–80,000 mc/s—construction and measurement results," *Arch. Elect. Übertragung*, vol. 10, pp. 51–57; February, 1956.
[156] J. R. G. Twisleton, "An X-band magnetron Q-measuring apparatus," *Proc. IEE*, vol. 103, Part B, pp. 339–342; May, 1956.
[157] E. O. Bowers and C. W. Curtis, "A resonant cavity frequency duplexer," 1956 IRE Convention Record, Part 5, pp. 113–118.
[158] C. Colani, "A simple microwave discriminator," *Frequenz*, vol. 10, pp. 25–26; January, 1956.
[159] D. W. Fraser and E. G. Holmes, "Frequency control in the 300–1200 mc region," Proc. IRE, vol. 44, pp. 1531–1541; November, 1956.

Optical techniques occupy a definite place at the upper end of the microwave spectrum. Two papers of particular interest on spectroscopic methods complete the measurements portion of this review.

[160] C. A. Burrus and W. Gordy, "Millimeter and submillimeter wave spectroscopy," *Phys. Rev.*, vol. 101, pp. 599–602; January 15, 1956.
[161] P. H. Sollom and J. Brown, "A centimetre-wave parallel-plate spectrometer," *Proc. IEE*, vol. 103, Part B, pp. 419–428; May, 1956.

IV. Sources and Detectors

The available sources and detectors determine the usable microwave spectrum. Of these, the former constitute the principal limitation today. Both traveling-wave devices, and more conventional klystrons, and magnetrons are being actively improved. In recent years, the primary effort has been concentrated on traveling-wave tubes of various types. This trend is continuing, both in improving existing types, and in the development of new principles of operation.

Much original work is also underway in gas discharges and related problems in physical electronics with microwave applications. These include both oscillators and noise sources. The crystal diode remains preeminent in the detector field, but some potential competition may be in sight.

Traveling-Wave Devices

The characteristics of transverse current traveling-wave tubes have been studied both theoretically and experimentally. The most unusual feature of this type of tube is its large signal behavior: output independent of input level over a 20–30 db range has been attained. This is attributed to the presence of many individual beam elements along the axis of the helix. Saturation for different power levels occurs at different positions along the helix. However, the particular beam element which saturates is immaterial to the output of the entire tube. Hence, a uniform limiting action over a wide range is achieved.

[162] D. A. Dunn, W. A. Harman, L. M. Field, and G. S. Kino, "Theory of the transverse-current traveling-wave tube," Proc. IRE, vol. 44, pp. 879–887; July, 1956.
[163] D. A. Dunn and W. A. Harman, " An experimental transverse-current traveling-wave tube," Proc. IRE, vol. 44, pp. 888–896; July, 1956.

A different transverse type tube has been developed with novel focusing elements. Two flat helices confine an electron sheet between them. The helix elements are bifilar, and provide a steady periodic focusing field. The resulting tube appears well suited to low-noise amplification in the uhf region.

[164] R. Adler, O. M. Kromhout, and P. A. Clavier, "Transverse-field traveling-wave tubes with periodic electrostatic focusing," Proc. IRE, vol. 44, pp. 82–89; January, 1956.

The Carcinotron continues in the forefront of microwave oscillators, as evidenced by the continuing studies on this configuration.

[165] P. Palluel and A. K. Goldberger, "The O-type carcinotron tube," Proc. IRE, vol. 44, pp. 333–345; March, 1956.
[166] P. Palluel, "Recent developments of O-type carcinotrons," *Ondê Elect.*, vol. 36, pp. 318–335; April, 1956.
[167] A. Bobenrieth and O. Cahen, "Travelling-wave valves for 4-cm waves: Research and development at the Centre National d'Etudes des Telecommunications," *Ondê Elect.*, vol. 36, pp. 307–317; April, 1956.

High power developments are also recorded.

[168] W. W. Siekanowicz and F. Sterzer, "A developmental wide-band, 100-watt, 20 db S-band traveling-wave amplifier utilizing periodic permanent magnets," Proc. IRE, vol. 44, pp. 55–61; January, 1956.
[169] M. Chodorow and E. J. Nalor, "The design of high-power traveling-wave tubes," Proc. IRE, vol. 44, pp. 649–659; May, 1956.
[170] J. P. Laico, H. L. McDowell, and C. R. Moster, "A medium power traveling-wave tube for 6000 mc radio relay," *Bell Sys. Tech. J.*, vol. 35, pp. 1285–1346; November, 1956.

A few circuit applications of traveling-wave tubes should also be mentioned.

[171] P. D. Lacy, "Microwave spectrum synthesis with the traveling-wave tube," 1956 IRE Convention Record, Part 5, pp. 48–52.
[172] N. Sawazaki and T. Honma, "New microwave repeater system using traveling-wave tubes," Proc. IRE, vol. 44, pp. 19–24; January, 1956.

Klystrons and Magnetrons

The klystron has been the object of several investigations.

[173] I. L. Bershtein, "Fluctuation of oscillations of a klystron generator," *Compt. Rend. Acad. Sci. U.R.S.S.*, vol. 106, pp. 453–456; January, 1956.
[174] R. L. Bell and M. Hillier, "An 8-mm klystron power oscillator," Proc. IRE, vol. 44, pp. 1155–1159; September, 1956.
[175] J. R. M. Vaughan, "Klystron modulators and Schlömilch series," *J. Electronics*, vol. 1, pp. 430–438; January, 1956.
[176] J. I. Davis, "Technique of pulsing low power reflex klystrons," IRE Trans., vol. MTT-4, pp. 40–47; January, 1956.
[177] Y. Matsuo, "Multi-beam velocity-type frequency multiplier," Proc. IRE, vol. 44, pp. 101–106; January, 1956.

Two papers of particular interest have appeared on circuit applications of klystrons and magnetrons. One deals with the use of precision quench frequencies to produce a series of standard frequencies from a klystron. The other presents a simplified theory of the long-lines effect in magnetrons.

[178] N. Sawazaki and T. Honma, "A new microwave frequency standard by quenching oscillator control," IRE Trans., vol. MTT-4, pp. 116–121; April, 1956.
[179] W. L. Pritchard, "Long-line effect and pulsed magnetrons," IRE Trans., vol. MTT-4, pp. 97–110; April, 1956.

Other Electronic Sources

Plasma oscillations are an interesting potential source of microwaves. The immediate prospects for practical generators are dim. However, investigation continues actively, and all avenues have not yet been fully explored.

[180] M. A. Lampert, "Plasma oscillations at extremely high frequencies," *J. Appl. Phys.*, vol. 27, pp. 5–11; January, 1956.
[181] F. Diamand, A. Gozzini, and T. Kahon, "Interaction of centimeter waves with a plasma in the presence of magnetic field," *Compt. Rend. Acad. Sci. Paris.*, vol. 242, pp. 90–93; January, 1956.
[182] D. Gabor, "Plasma oscillations," IRE Trans. vol. AP-4, pp. 526–530; July, 1956.
[183] J. Corte and J. L. Delcroix, "Plasma oscillations and resonance frequencies in a magnetron in the Brillouin state," *Compt. Rend. Acad. Sci. Paris*, vol. 242, pp. 57–90; January 4, 1956.

Cerenkov radiation is another potential source of millimeter waves which is under study.

[184] H. Lashinsky, "Cerenkov radiation from extended electron beams near a medium of complex index of refraction," *J. Appl. Phys.*, vol. 27, pp. 631–635; June, 1956.
[185] M. A. Lampert, "Incidence of an electromagnetic wave on a 'Cerenkov electron gas,' " *Phys. Rev.*, vol. 102, pp. 299–304; April 15, 1956.

Gas discharges have long been used as noise sources and switches and considerable effort is noted in this area.

[186] R. I. Skinner, "Wide-band noise sources using cylindrical gas-discharge tubes in two-conductor lines," *Proc. IEE*, vol. 103, Part B, pp. 491–495; July, 1956.
[187] G. K. Hart, F. R. Stevenson, and M. S. Tanenbaum, "High-power breakdown of microwave structures," 1956 IRE CONVENTION RECORD, Part 5, pp. 199–205.
[188] R. H. Geiger and P. E. Dorney, "Coaxial components employing gaseous discharges at microwave frequencies," 1956 IRE CONVENTION RECORD, Part 5, pp. 193–198.
[189] G. M. Pateyuk, "Investigation of the high-frequency discharge," *Th. Eksp. Teor. Fiz.*, vol. 30, pp. 12–17; January, 1956.

Even the spark serves as an often unwelcome microwave source. Its potential as a useful generator has been studied systematically.

[190] M. H. N. Potok, "Researches into spark generation of microwaves," *Proc. IEE*, vol. 103, Part B, pp. 781–786; November, 1956.

Detection

Noise measurements are basic to receiver development, and continue to be refined.

[191] W. Klein and W. Friz, "The gas-discharge tube as a device for noise measurement in the centimetre wave-band," *J. Electronics*, vol. 1, pp. 589–600; May, 1956.
[192] C. H. Mayer, "Improved microwave noise measurements using ferrites," IRE TRANS., vol. MTT-4, pp. 24–28; January, 1956.
[193] E. Maxwell and B. J. Leon, "Absolute measurement of receiver noise figures at uhf," IRE TRANS., vol. MTT-4, pp. 81–85; April, 1956.
[194] Peter D. Strum, "A note on noise temperature," IRE TRANS., vol. MTT-4, pp. 145–151; July, 1956.
[195] V. A. Hughes, "Absolute calibration of a standard temperature noise source for use with S-band radiometers," *Proc. IEE*, vol. 103, Part B, pp. 669–672; September, 1956.
[196] H. Sutcliffe, "Noise measurements in the 3-cm band using a hot source," *Proc. IEE*, vol. 103, Part B, pp. 673–676; September, 1956.

Several important advances in microwave detectors and receivers have been recorded. First among these is an electron beam device with sensitivity comparable to a crystal and extremely wide bandwidths. This device utilizes the stop-band phenomenon of periodic magnetic focusing to sort the electrons in the beam according to their rf velocity modulation.

[197] J. T. Mendel, "Microwave detector," PROC. IRE, vol. 44, pp. 503–508; April, 1956.

Two superheterodyne systems of unusual capability have been realized. The first utilizes multiple coherent local oscillator signals to cover wide band continuously. Injection of both a microwave and a vhf signal into the mixer produces the desired spectrum.

The second scheme actually synchronizes two swept oscillators to produce a broad-band response with full superheterodyne sensitivity.

[198] M. Cohn and W. C. King, "A sideband-mixing superheterodyne receiver," PROC. IRE, vol. 44, pp. 1595–1599; November, 1956.
[199] D. L. Favin, "A swept, broad band microwave double detection system with automatic synchronization," 1956 IRE CONVENTION RECORD, Part 5, pp. 184–192.

In the field of crystals, the technique of fabricating and mounting millimeter detector elements has been perfected to the point where performance comparable to that at lower frequencies is achieved.

[200] W. M. Sharpless, "Wafer-type millimeter wave rectifiers," *Bell Sys. Tech. J.*, vol. 35, pp. 1385–1402; November, 1956.

The last reference under detectors, and in the entire review, concerns the effects of microwaves on the human body. Fortunately, the prognosis is generally favorable: at frequencies above 3000 mc, only superficial heating is to be expected, with adequate sensory perception to provide warning. Only at lower frequencies is there danger of damage to tissues from exposure to radiation.

[201] H. P. Schwan and K. Li, "Hazards due to total body irradiation by radar," PROC. IRE, vol. 44, pp. 1572–1581; November, 1956.

CONCLUSION

The number of papers and their titles give only a poor estimate of the progress made in microwave theory and techniques. More important, the quality of work has been almost uniformly high, insofar as it is possible to determine at this time. The results of future years, built on the achievements of the present, will prove the importance of the advances made during the year 1956.

ACKNOWLEDGMENT

The assistance of Dr. H. Scharfman and Dr. D. Angelakos in providing valuable information, particularly on the London Conference on Ferrites, is gratefully acknowledged.