Report of Advances in Microwave Theory and Techniques—1955

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THE THEORY and techniques we wish to review comprise the transmission, control, measurement, and generation of microwaves. Excluded are antenna and propagation problems, as well as the specifically electronic aspects of microwave amplifiers and generators. To order the subjects being considered we have established the following broad headings: I. Waveguides; II. Gyromagnetic Media; III. Measurements; IV. Detection; V. Sources. Within each of these, more specific subdivisions help to classify the large number of papers which have appeared.

The large quantity of papers, and the attendant number of subdivisions needed to order them, are proof of the broad activity in the microwave field. However, what was once considered a small area has thereby been subdivided into even smaller parts. In this review, we have provided many subcategories in order to show more clearly the different directions of effort in the microwave field. We hope this does not lend support to the superspecialist, interested only in say TE_{01n} mode reaction wavemeter design in the *p*-band. To the reader with such limited interests we must address a warning: our discussion is not cross-referenced, and waveguide measurements on gyromagnetic media might be listed under I, II, or III depending on relative emphasis.

I. Waveguides

The term "waveguide" is gradually being freed from its early identification with hollow metal pipes. The literal definition—anything that guides an electromagnetic wave—properly includes the variety of structures now coming into use. Some of these guides bear little resemblance to the rectangular pipes that first bore the name waveguide. However, the structure enjoying the most rapid development harks back to the period when only the principal (TEM) mode was known to transmission engineers. The terms stripline, microstrip, planar transmission line, and other similar names are applied to various modifications of a structure supporting only TEM waves between flat metal strips.

Striplines

The characteristic impedance of a line consisting of one or two long thin strips placed between two relatively broad conducting planes has been successfully calculated. The attenuation of several such structures has also been evaluated. The calculations involve suitable transformations in the complex plane of the line cross-section.

[1] D. Park, "Planar transmission lines," Trans. IRE, vol. MTT-3, pp. 8–12; April, 1955.
[2] D. Park, "Planar transmission lines—II," Trans. IRE, vol. MTT-3, pp. 7–11; October, 1955.
[3] J. M. C. Dukes, "Characteristic impedance of air-spaced strip transmission line," Proc. IRE, vol. 43, p. 876; July, 1955. (Correspondence)
[4] B. A. Dahlman, "A double-ground-plane strip-line system for microwaves," *Jour. IEE*, vol. 102, part B, pp. 488—492; July, 1955. Also Trans. IRE, vol. MTT-3, pp. 52–57; October, 1955.
[5] W. H. Hayt, Jr., "Potential solution of a homogeneous strip-line of finite width," Trans. IRE, vol. PGMTT-3, pp. 16–18; July, 1955.
[6] E. Burshtein and L. Solov'ev, "Propagation of a fundamental wave between parallel surfaces," *C. R. Acad. Sci.* (*URSS*), vol. 101, pp. 465–468; March 21, 1955. (In Russian).

The development of circuit components in striplines is proceeding rapidly. The simple structure and ease of manufacture of striplines is perhaps even more evident in the component field. Filters and directional couplers with excellent performance are very simply fabricated in strip form.

[7] M. Arditi and J. Elefant, "Microstrip applied to band-pass microwave filters," *Elec. Commun.*, vol. 32, pp. 52–61; March, 1955.
[8] S. B. Cohn, "Shielded coupled-strip transmission line," Trans. IRE, vol. MTT-3, pp. 29–38; October, 1955.

By replacing the closely confined TEM mode with the loosely bound HE_{11} or dipole mode of a dielectric rod, a millimeter-wave version of strip lines is obtained. Here, half of a dielectric rod is placed on a metal image surface. Some success at circuit components in this system is also being achieved.

[9] D. D. King, "Circuit components in dielectric image lines," Trans. IRE, vol. MTT-3, pp. 35–39; December, 1955.

Surface Waves

The wave of the image surface of the dielectric line mentioned above is a type of surface wave. The study of surface waves in general is important both for waveguide applications and for antennas. The surfaces being studied include dielectric rods and tubes, dielectric coated wires, as well as metal sheets and cylinders.

[10] P. Mallach, "Investigations on dielectric waveguides in rod or tube form," *Fernmeldetech. Z.*, vol. 8, pp. 8–13; January, 1955.
[11] G. Piefke, "Theory of the harms-goubau wire waveguide at metre wavelengths," *Arch. elekt. Übertragung*, vol. 9, pp. 81–93; February, 1955.
[12] H. E. M. Barlow and A. E. Karbowiak, "An experimental investigation of axial cylindrical surface waves supported by capactive surfaces," *Jour. IEE*, vol. 102, part B, pp. 313–322; May, 1955.
[13] G. J. Rich, "The launching of a plane surface wave," *Jour. IEE*, vol. 102, part B, pp. 237–246; March, 1955.
[14] R. S. Elliott, "Azimuthal surface waves on circular cylinders," *J. Appl. Phys.*, vol. 26, pp. 368–376; April, 1955.
[15] A. E. Karbowiak, "On the surface impedance of a corrugated waveguide," *Jour. IEE*, vol. 102, part B, pp. 501–502; July, 1955.

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The experimental investigations by Barlow and Karbowiak have produced particularly interesting results. These authors have succeeded in launching on a dielectric rod a surface wave with phase velocity greater than the velocity of light. This result tends to support the conclusion that a Zenneck wave can exist over the earth's surface. Experimental evidence for this wave has been lacking, although theoretical arguments on it date back to Zenneck's early work in 1907.

Artificial Dielectrics

The control of microwaves by artificial dielectrics brings us close to the border between radiation and guided waves. The applications of artificial dielectrics are probably largely in the design of horns, lenses and other antennas. However, we include references to microwave work in periodic structures.

[16] J. Brown and W. Jackson, "The properties of artificial dielectrics at centimetre wavelengths," *Jour. IEE*, vol. 102, part B, pp. 11–16; January, 1955.
[17] M. M. Z. El-Kharadly, "Some experiments on artificial dielectrics at centimetre wavelengths," *Jour. IEE*, vol. 102, part B, pp. 17–23; January, 1955.
[18] R. I. Primich, "A general experimental method to determine the properties of artificial media at centimetre wavelengths, applied to an array of parallel metallic plates," *Jour. IEE*, vol. 102, part B, pp. 26–36; January, 1955.
[19] J. Brown and W. Jackson, "The relative permittivity of tetragonal arrays of perfectly conducting thin discs," *Jour. IEE* vol. 102, part B, pp. 37–42; January, 1955.

Periodic Structures

The artificial dielectrics mentioned above are periodic structures in three dimensions. One dimensional periodicity along a waveguide also produces a new set of properties. The resulting slow waves are particularly important in electron beam devices. However, the basic theory of the isolated guide is receiving considerable attention.

[20] S. Sensiper, "Electromagnetic wave propagation on helical structures (A review and survey of recent progress)," Proc. IRE, vol. 43, pp. 149–161; February, 1955.
[21] M. Müller, "Application of recurrent-network equivalent circuit in determining the attenuation of helical transmission lines loaded by resistive coatings," *Fernmeldetech. Z.*, vol. 8, pp. 29–34; January, 1955.
[22] C. C. Grosjean and V. J. Vanhuyse, "Experimental verification of a frequency equation for corrugated waveguides," *Nuovo Cim.*, vol. 1, pp. 193–200; January 1, 1955.
[23] C. C. Grosjean, "On the theory of circularly symmetric TM waves in infinite iris-loaded guides," *Nuovo Cim.*, vol. 1, pp. 427–438; March 1, 1955. (In English).
[24] V. J. Vanhuyse, "On the (β_0, k) diagrams for circularly symmetric TM waves in infinite iris-loaded waveguides," *Nuovo Cim.*, vol. 1, pp. 447–452; March 1, 1955. (In English).
[25] V. J. Vanhuyse, "On the proper frequencies of terminated corrugated waveguides," *Physica*, vol. 21, pp. 269–280; April, 1955; *ibid.*, vol. 32, p. 603; July, 1955.
[26] A. J. Simmons, "Phase shift by periodic loading of waveguide and its application to a broadband circular polarization," Trans. IRE, vol. MTT-3, pp. 18–21; December, 1955.

Hollow Waveguides

Extensions and refinements of the theory of hollow waveguides continue to appear in large numbers. Among the most welcome refinements is an exact treatment of hollow waveguides with finite wall conductivity.

[27] A. E. Karbowiak, "Theory of imperfect waveguides: The effect of wall impedance," *Jour. IEE*, vol. 102, part B, pp. 698–708; September, 1955.

Here the fields in the guide are matched to the surface impedance of the metal at the guide wall. In addition to confirming the standard approximate results, this theory provides valuable information on mode purity in an imperfect guide. Thus, in the rectangular case, only TE_{0n} and TE_{m0} modes can propagate down a uniform imperfect guide without change in form, *i.e.*, without conversion to other modes. In circular guides the purity of both TE_{0n} and TM_{0m} is unimpaired by wall losses.

An interesting analog for the cutoff parameters of hollow guides with arbitrary cross-section has been described.

[28] P. R. Clement and W. C. Johnson, "A distributed electrical analog for waveguides of arbitrary cross section," Proc. IRE, vol. 43, pp. 89–92; January, 1955.

Here a thin parallel-plate resonator is constructed whose end plates have the shape of the guide cross section. The resonant frequency of the resonator is simply related to the cutoff frequency of the guide. Either TE and TM modes are handled by open or short circuiting the edges of the closely spaced plates.

Perturbations in the uniformity of hollow guides lead to a variety of analytical complications. A fair share of these are listed in the following references:

[29] L. Lewin, "Propagation in curved and twisted waveguides of rectangular cross-section," *Jour. IEE*, vol. 102, part B, pp. 75–80; January, 1955.
[30] M. Jouguet, "Problems of propagation in cylindrical systems," *Câbles B. Trans.*, vol. 9, pp. 3–39; January, 1955.
[31] J. Kornfeld, "Stability of the H_{01} mode in circular waveguides, and the occurrence of harmonic modes on deformation to an elliptical cylinder," *Arch. elekt. Übertragung*, vol. 9, pp. 29–38; January, 1955.
[32] P. I. Sandsmark, "Effect of ellipticity on dominant-mode axial ratio in nominally circular waveguides," Trans. IRE, vol. MTT-3, pp. 15–20; October, 1955.

Dielectric filling and end-effects are also treated in several papers.

[33] S. K. Chatterjee, "Propagation of microwave through an imperfectly conducting cylindircal guide filled with an imperfect dielectric," *Jour. Indian Inst. Sci.*, Section B, vol. 37, pp. 1–9; January, 1955.
[34] J. W. Carr, "Transverse electric Resonances in a coaxial line containing two cylinders of different dielectric constant," Trans. IRE, vol. MTT-3, pp. 41–44; July, 1955.
[35] V. Pfirrmann, "The Behavior of the Open End of a Coaxial Line," *Arch. elekt. Übertragung*, vol. 9, pp. 8–12; January, 1955.

Ridges and Steps

An important variant of rectangular guide is ridge guide. More precise calculations of its parameters and continued favor in practical applications are shown by the references below.

[36] H. G. Unger, "Calculations for ridge waveguides," *Arch. elekt. Übertragung*, vol. 9, pp. 157–161; April, 1955.
[37] S. Hopfer, "The design of ridged waveguides," Trans. IRE, vol. MTT-3, pp. 20–29; October, 1955.
[38] T. G. Mihran, "Impedance of open- and closed-ridge waveguide," Proc. IRE, vol. 43, p. 1014; August, 1955. (Correspondence.)
[39] T. N. Anderson, "Double-ridge waveguide for commercial airlines weather radar installation," Trans. IRE, vol. MTT-3, pp. 2–9; July, 1955.

Proceeding from a ridge along the guide axis to transverse steps, we encounter two papers which fill a long standing need.

[40] R. E. Collin, "Theory and design of wide-band multisection quarter-wave transformers," PROC. IRE, vol. 43, pp. 179–185; February, 1955.
[41] S. B. Cohn, "Optimum design of stepped transmission-line transformers," TRANS. IRE, vol. MTT-3, pp. 16–21; April, 1955.

The authors here independently arrive at an optimum design for quarter-wave transformers. As might be suspected, Tchebycheff distributions appear in the result instead of the previously accepted binomial steps.

However, the binomial rule is still useful. Thus, a skillful application of modified binomial stepping to twists has resulted in tremendous savings in space and bandwidth for this waveguide component.

[42] H. A. Wheeler and H. Schwiebert, "Step-twist waveguide components," TRANS. IRE, vol. MTT-3, pp. 44–52; October, 1955.

Directional Couplers, Junctions, and Other Circuit Elements in Waveguide

Significant advances are being made in the methods of coupling two guides. By tapering the phase velocity in the coupled guides, efficient directional couplers have been built covering three or more octaves. A more general method of coupling involves periodically varying both the velocities and the coupling. If such a coupler can be many wavelengths long, it can be made completely insensitive to frequency.

[43] J. S. Cook, "Tapered velocity couplers," *Bell Sys. Tech. Jour.*, vol. 7, pp. 807–822; July, 1955.
[44] A. G. Fox, "Wave coupling by warped normal modes," *Bell Sys. Tech. Jour.*, pp. 823–852; July, 1955.
[45] W. H. Louisell, "Analysis of the singe tapered mode coupler," *Bell. Sys. Tech. Jour.*, pp. 853–870; July, 1955.

Another type of broadband coupler has been devised for dominant mode waveguides. Here the field is gradually concentrated on ridges or fins in the guide, and then transferred to the coupled guide.

[46] S. D. Robertson, "The ultra-bandwidth fineline coupler," PROC. IRE, vol. 43, pp. 739–741; June. 1955.

Analysis of more conventional couplers has also proceeded apace.

[47] G. D. Monteath, "Coupled transmission lines as symmetrical directional couplers," *Jour. IEE*, vol. 102, part B, pp. 383–392; May, 1955.
[48] R. C. Knechtli, "Further analysis of transmission-line directional couplers," PROC. IRE, vol. 43, pp. 867–869; July, 1955.
[49] P. Andrews, "A simple waveguide directional coupler," *Jour. Brit. IRE*, vol. 15, pp. 112–116; February, 1955.

Directional couplers are a special class of junctions. Some work on other junction types in hollow waveguide has also been published.

[50] W. K. Kahn, "*E*-plane forked hybrid-T junction," TRANS. IRE, vol. MTT-3, pp. 52–58; December, 1955.
[51] M. A. Meyer and H. B. Goldberg, "Applications of the turnstile junction," TRANS. IRE, vol. MTT-3, pp. 40–45, December, 1955.
[52] A. F. Harvey, "Standard waveguides and couplings for microwave equipment," *Jour. IEE*, vol. 102, part B, pp. 493–500; July, 1955.

The need for more complex junctions is one aspect of the trend toward higher modes and multiple modes of polarizations in hollow guides. More convenient application of microwave filter design is another evidence of this trend.

[53] H. N. Dawirs, "Graphical filter analysis," TRANS. IRE, vol. MTT-3, pp. 15–21; January, 1955.
[54] H. N. Dawirs, "A chart for analyzing transmission-line filters from input impedance characteristics," PROC. IRE, vol. 43, part I, pp. 436–443; April, 1955.

Resonant cavities are an important element both in microwave circuits and oscillators. A more complete analysis of radial and reentrant resonators has taken place during the year.

[55] J. R. Whinnery and D. C. Stinson, "Radial Line discontinuities," PROC. IRE, vol. 43, pp. 46–51; January, 1955.
[56] D. C. Stinson, "Resonant frequencies of higher-order modes in radial resonators," TRANS. IRE, vol. MTT-3, pp. 18–23; July, 1955.
[57] E. L. Ginzton and E. J. Nalos, "Shunt impedance of klystron cavities," TRANS. IRE, vol. MTT-3, pp. 4–7; October, 1955.

A basic mathematical point in the theory of cavity resonators has also been clarified. This concerns the completeness of the set of modes used to describe the field in a resonator. The need for including the dc (irrotational) field is often overlooked. Only under special conditions is this permissible.

[58] S. A. Schelkunoff, "On representation of electromagnetic fields in cavities in terms of natural modes of oscillation," *J. Appl. Phys.*, vol. 26, pp. 1231–1234; October, 1955.

The analysis of microwave circuits often proceeds most conveniently by matrix methods. A particularly effective example of this appeared in the study of circular polarization in a cavity.

[59] M. Tinkham and M. W. P. Standberg, "The excitation of circular polarization in microwave cavities," PROC. IRE, vol. 43, pp. 734–738; June, 1955.
[60] E. W. Matthews, Jr., "The use of scattering matrices in microwave circuits," TRANS. IRE, vol. MTT-3, pp. 21–26; April, 1955.
[61] B. Beghlin, "The matrix equation of loss-free exponential lines," *Compt. Rend. Acad. Sci.* (Paris), vol. 240, pp. 168–170; January 10, 1955.

II. GYROMAGNETIC MEDIA

The introduction of gyromagnetic media has produced a revolution in microwave circuits. A new class of components has become possible, based on the usual equivalent circuit elements plus a new one, the gyrator. The nonreciprocal components based on the gyrator are, perhaps, the most spectacular. However, a new class of both reciprocal and nonreciprocal circuit elements is emerging. In addition to performing hitherto impossible functions, these devices are often susceptible to convenient electrical control through the applied magnetic field.

The central problem in the field of gyromagnetic microwave circuits is the behavior of a waveguide containing gyromagnetic material. The analysis of this problem, usually in terms of a ferrite, is proceeding actively.

[62] M. A. Gintsburg, "The anisotropic waveguide," *Zh. Tekh, Fiz.*, vol. 25, pp. 358–363; February, 1955.
[63] A. Chevalier, T. Kahan, and E. Polacco, "Propagation of electromagnetic waves in an anisotropic gyromagnetic medium in a rectangular waveguide," *Compt. Rend. Acad. Sci.* (Paris), vol. 240, pp. 1323–1324; March 21, 1955.
[64] L. M. Vallese, "Understanding the gyrator," PROC. IRE, vol. 43, part I, p. 483; April, 1955. (Correspondence.)
[65] N. G. Sakiotis, H. N. Chait, and M. L. Kales, "Nonlinearity of propagation in ferrite media," PROC. IRE, vol. 43, p. 1011; August, 1955. (Correspondence.)

[66] B. Laux and K. J. Button, "Theory of new ferrite modes in rectangular wave guide," *J. Appl. Phys.*, vol. 26, pp. 1184–1185; September, 1955. (Correspondence.)
[67] B. Lax and K. J. Button, "New ferrite mode configurations and their applications," *J. Appl. Phys.*, vol. 26, pp. 1186–1187; September, 1955. (Correspondence.)
[68] A. D. Berk and B. A. Lengyel, "Magnetic fields in small ferrite bodies with applications to microwave cavities containing such bodies," Proc. IRE, vol. 43, pp. 1587–1591; November, 1955.

Some of the practical results of the ferrite revolution in circuit elements are described in the papers listed below. These include circulators, isolators, attenuators, couplers, and switches.

[69] C. Stewart, "Some applications and characteristics of ferrite at wavelengths of 0.87 cm and 1.9 cms," Trans. IRE, vol. MTT-3, pp. 27–31; April, 1955.
[70] J. A. Rich and S. E. Webber, "Ferrite atttenuators in helixes," Proc. IRE, vol. 43, pp. 100–101; January, 1955. (Correspondence.)
[71] J. B. Gunn and C. A. Hogarth, "A novel microwave attenuator using germanium," *J. Appl. Phys.*, vol. 26, pp. 353–354; March, 1955.
[72] R. W. Damon, "Magnetically controlled microwave directional coupler," *J. Appl. Phys.*, pp. 1282–1283; October, 1955. (Correspondence.)
[73] R. F. Sullivan and R. C. LeCraw, "New type ferrite microwave switch," *J. Appl. Phys.*, pp. 1282–1283; October, 1955. (Correspondence.)

Basic to the success of these devices are the properties of the ferrite material itself. New data on the characteristics of various ferrites as a function of frequency has been gathered by several observers.

[74] A. Nishioka and H. Okamoto, "Measurement of the complex permeability of carbonyl iron powders at 4,000 mc/s," *J. Phys. Soc. Japan*, vol. 10, p. 79; January, 1955.
[75] H. Suhl, "Ferromagnetic resonance in nickel ferrite between one and two kilomegacycles (per second)," *Phys. Rev.*, vol. 97, pp. 555–557; January 15, 1955.
[76] H. Suhl, L. G. Van Uitert, and J. L. Davis, "Ferromagnetic resonance in magneisum-manganese aluminum ferrite between 160 and 1,900 mc," *J. Appl. Phys.*, vol. 26, pp. 1180–1182; September, 1955. (Correspondence.)
[77] B. Lax, "Figure of merit for microwave ferrites at low and high frequencies," *J. Appl. Phys.*, vol. 26, p. 919; July, 1955. (Correspondence.)

The losses observed in ferromagnetic resonance are particularly important, both theoretically and in applications. The absorption losses and domain motion have been studied and a theory developed to account for the observed effects.

[78] A. M. Cloyston, "Relaxation phenomena in ferrites," *Bell Sys. Tech. Jour.*, pp. 739–760; July, 1955.
[79] F. Brown and C. L. Gravel, "Direct observation of domain rotation in ferrites," *Phys. Rev.*, vol. 98, pp. 442–448; April 15, 1955.
[80] J. Smit and H. G. Beljers, "Ferromagnetic resonance absorption in $BaFe_{12}O_{19}$ a highly anisotropic crystal," *Phillips Res. Rep.*, vol. 10, pp. 113–130; April, 1955.

Specific properties such as temperature dependence and saturation have direct application to component design. These, of course, are also being studied.

[81] B. J. Duncan and L. Swern, "Temperature dependence of the microwave properties of ferrites in waveguide," Proc. IRE, vol. 43, pp. 623–624; May, 1955. (Correspondence.)
[82] L. G. Van Uitert, "Low magnetic saturation ferrites for microwave applications," *J. Appl. Phys.*, vol. 26, pp. 1289–1290; November, 1955.

III. Measurements

The number of quantities which can be measured to advantage in the microwave region has not increased in the past year. However, the techniques for performing the measurements continue to advance and multiply. In all of the classes of measurements we shall consider, we are potentially better instrumented than ever before.

Impedance Measurement

Point-by-point impedance data is inadequate for most broad-band components and systems. Perhaps the most desirable display of data for the engineer is a locus plotted on the reflection-coefficient plane or Smith chart. A very elegant solution of this problem was described during 1955. The waveguide equipment makes use of square-law product detectors to multiply unknown and reference signals. Output voltages are placed on the deflection plates of an oscilloscope to trace the desired locus of z in the ρ-plane. The compact system utilizes five hybrid junctions in standard waveguide form. The 12 per cent band of the X-band guide is covered without need for adjustment.

[83] Henry L. Bachman, "A waveguided impedance meter for the automatic display of complex reflection coefficient," Trans. IRE, vol. MTT-3, pp. 22–30; January, 1955.

Two rather comprehensive surveys of special impedance measuring methods also appeared during the year.

[84] A. Lebrun, "Techniques for the measurement of impedances at Metre and decimetre wavelengths and their use for studying the dielectric properties of solids and liquids," *Ann. Phys.* (Paris), vol. 10, pp. 16–70; January/February, 1955.
[85] H. Severin, "The squeeze section, a simple and universal measurement apparatus for centimetre wavelengths," *Tech. Mitt. schweiz Telegn-Teleph. Verw*, vol. 33, pp. 130–135; March 1, 1955. (In German.)

Power Measurement

Bolometers and thermistors are the principal means for measuring microwave power. Improvements in their calibration and performance continue to be recorded.

[86] M. Sucher and H. J. Carlin, "The operation of bolometers under pulsed power conditions," Trans. IRE, vol. MTT-3, pp. 45–52; July, 1955.
[87] J. A. Lane, "The measurement of power at a wavelength of 3 cm by thermistors and bolometers," Proc. IRE, part B, vol. 102, pp. 819–824; November, 1955.

A new self-balancing bridge for these elements is also reported.

[88] Glenn F. Engen, "A Self-Balancing D-C Bolometer Bridge," presented at URSI meeting, Washington, D. C., May 4, 1955.

A different approach to power measurement in the milliwatt region relies on a differential air thermometer coupled to the standard and unknown power absorbers. Glass cells containing carbon strips serve to dissipate the power. These are joined through a capillary containing a liquid pellet. The position of the pellet registers differential pressure and hence differential power.

[89] A. C. Gordon-Smith, "A milliwattmeter for centimetre wavelengths," *Jour. IRE*, vol. 102, part B, pp. 685–686; September, 1955.

For high power measurements, a calorimeter is required. A new load for this service has been developed.

[90] W. Hersch, "A very wide-band dummy load for measuring power at very-high and ultra-high frequencies," *Jour. IEE*, vol. 102, part B, pp. 96–98; January, 1955.

Amplitude and Phase Measurements

Although often combined in impedance data, the amplitude and phase of a signal are often sought separately. The near field of a radiator or the field within a resonator are examples of a situation where such data is desirable. Probe methods as well as indirect scattering techniques have been described for this problem.

[91] J. H. Richmond and T. E. Tice, "Probes for microwave near-field measurements," TRANS. IRE, vol. MTT-3, pp. 32–34; April, 1955.

[92] J. S. Ajioka, "A microwave phase contour plotter," PROC. IRE, vol. 43, pp. 1088–1090; September, 1955.

[93] J. H. Richmond, "A modulated scattering technique for measurement of field distributions," TRANS. IRE, vol. MTT-3, pp. 13–15; July, 1955.

[94] J. G. Linhart and T. H. B. Baker, "A method of measuring the intensity distributions of radio-frequency electric and magnetic fields in resonant cavities," *Brit. J. Appl. Phys.*, vol. 6, pp. 100–103; March, 1955.

[95] S. W. Kitchen and A. D. Schelberg, "Resonant-cavity field measurements," *J. Appl. Phys.*, vol. 26, pp. 618–621; May, 1955.

Another application of phase and amplitude methods is in permittivity measurements.

[96] T. J. Buchanan and E. H. Grant, "Phase and amplitude balance methods for permittivity measurements between 4 and 50 cm," *Brit. J. Appl. Phys.*, vol. 6, pp. 64–66; February, 1955.

A single rotating probe can combine the amplitude and phase measurements to yield standing-wave data.

[97] F. J. Tischer, "Rotatable inductive probe in waveguides," PROC. IRE, vol. 43, pp. 974–980; August, 1955.

Direct determination of amplitude and phase by coherent detection in a hybrid junction is also conveniently accomplished.

[98] J. H. Richmond, "Measurement of time-quadrature components of microwave signals," TRANS. IRE, vol. MTT-3, pp. 13–15; April, 1955.

Four-Pole Measurements

The four-pole is the basic element for transmission networks. Direct measurement of four-pole parameters is therefore of the greatest importance. The treatment of loss in a four-pole has been the subject of several papers. In one of these, the general dissipative four-pole is represented by a new equivalent circuit consisting of a lossy section of transmission line with ideal transformers at each end. This representation is particularly well adapted to precise analysis by the methods of Weissfloch (tangent method) and Deschamps.

[99] H. M. Altschuler, "A method of measuring dissipative four-poles based on a modified Wheeler network," TRANS. IRE, vol. MTT-3 pp. 30–36; January, 1955.

The preceding method is well adapted to networks having considerable loss. Where very small losses are encountered, the measuring procedure can be modified to advantage by the inclusion of a lossy shunt element. This reduces the standing waves to more convenient values for measurement. Proper analysis of the data permits extraction of the original low-loss parameters.

[100] H. M. Altschuler and A. A. Oliner, "A shunt technique for microwave measurements," TRANS. IRE, vol. MTT-3, pp. 24-30; July, 1955.

Four-pole techniques are also well adapted to measuring insertion loss, the location of discontinuities, and dielectric constants.

[101] K. Tomiyasu, "Intrinsic insertion loss of a mismatched microwave network," TRANS. IRE, vol. MTT-3, pp. 40–44; January, 1955.

[102] O. T. Neau, "A practical method of locating waveguide discontinuities," TRANS. IRE, vol. MTT-3, pp. 45–46; January, 1955. (Correspondence.)

[103] A. A. Oliner and H. M. Altschuler, "Methods of measuring dielectric constants based upon a microwave network viewpoint," *J. Appl. Phys.*, vol. 26, pp. 214–219; February, 1955.

A new class of four-poles, the nonreciprocal, has also made its appearance in circuit components. Preliminary work shows that extension of present methods to this type of four-pole should proceed without difficulty.

[104] A. C. Macpherson, "Measurement of microwave nonreciprocal four-poles," PROC. IRE, vol. 43, p. 1017; August, 1955.

Cavity Techniques

Resonant cavities have long been used with success in measuring magnetic properties. Refinements in this technique are continuing.

[105] E. G. Spencer and R. C. LeCraw, "Wall effects on microwave measurements of ferrite spheres," *J. Appl. Phys.*, vol. 2, p. 250; February, 1955. (Correspondence.)

[106] J. Uebersfeld, "Various ways of using cavity resonators in paramagnetic resonance," *J. Phys. Rad.*, vol. 16, pp. 78–79; January, 1955.

Sending an electron beam through a cavity alters its electrical properties. Although this effect is fairly obvious, the magnitude of the tuning range obtainable with adequate Q has probably been unsuspected. An analysis of the problem and extensive supporting data have been presented in a paper.

[107] F. R. Arams and H. K. Jenny, "Wide-range electronic tuning of microwave cavities," PROC. IRE, vol. 43, pp. 1102–1110; September, 1955.

Special Techniques

The use of higher modes or of several polarizations of one mode in the same guide is becoming increasingly common. At the terminals of such a guide the proper separation of modes must then be accomplished. Several papers have appeared which describe successful attacks on this problem. From the present trend it appears that we shall be able to overcome most of the problems which have so far prevented exploitation of the full capacity of a hollow waveguide.

[108] A. C. Beck, "Measurement techniques for multimode waveguides," TRANS. IRE, vol. MTT-3, pp. 35–41; April, 1955.

[109] H. P. Raabe, "A rotary joint for two microwave transmission channels of the same frequency band," TRANS. IRE, vol. MTT-3, pp. 30–41; July, 1955.

[110] P. A. Crandell, "A turnstile polarizer for rain cancellation," TRANS. IRE, vol. MTT-3, pp. 10–15; January, 1955.

Circular polarization in a round guide induced by helices has been used to provide a convenient high-speed phase shifter. Here, the phase shift is proportional to the angular position of the helices.

[111] W. Sichak and D. J. Levine, "Microwave high-speed continuous phase shifter," PROC. IRE, vol. 43, pp. 1661–1663; November, 1955.

Millimeter wave techniques are also steadily advancing. Papers on this subject and the related problem of surface roughness in metal guides are listed below.

[112] W. E. Willshaw, H. R. L. Lamont, and E. M. Hickin, "Experimental equipment and techniques for a study of millimetre-wave propagation," *Jour. IEE*, vol. 102, part B, pp. 99–111; January, 1955.
[113] W. W. Balwanz, "A method of wavelength measurement for the microwave and millimeter wave regions," presented at URSI meeting, Washington, D. C., May 4, 1955.
[114] A. F. Harvey, "The electroforming of components and instruments for millimetre wavelengths," *Jour. IEE*, vol. 102, part B, pp. 223–230; March, 1955.
[115] A. F. Harvey, "A surface-texture comparator for microwave structures," *Jour. IEE*, vol. 102, part B, pp. 219–222; March, 1955.
[116] J. Allison and F. A. Benson, "Surface roughness and attenuation of precision-drawn, chemically polished, electropolished, electroplated, and electroformed waveguides," *Jour. IEE*, vol. 102, part B, pp. 251–252; March, 1955.

IV. Detection and Noise Sources

The principal microwave detector is the crystal diode. Improved schemes for measuring its noise temperature and optimizing mixer performance have been advanced during the year.

[117] R. E. Davis and R. C. Dearle, "A method for the accurate measurement of the noise temperature ratio of microwave mixer crystals," Trans. IRE, vol. MTT-3, pp. 27–35; December, 1955.
[118] W. L. Pritchard, "Notes on a crystal mixer performance," Trans, IRE, vol. MTT-3, pp. 37–39; January, 1955.

The thermionic diode serving as a microwave detector has been analyzed in a new manner. Here it is shown that the space-charge limited diode can be considered as a velocity modulated detector when operated at microwaves.

[119] P. A. Redhead, "Microwave detection in a thermionic diode," Proc. IRE, vol. 43, pp. 995–1000; August, 1955.

The noise figures of radiometer circuits have been analyzed. Here, it appears that the use of two separate receivers with cross-correlated outputs provides somewhat better sensitivity than the original Dicke system.

[120] S. J. Goldstein, "A comparison of two radiometer circuits," Proc. IRE, vol. 43, pp. 1663–1666; November, 1955.

Noise sources are used principally to measure the noise figure of receivers. Of course, the physics of gas discharges is an interesting and important subject in itself. However, the papers on this subject listed below are largely concerned with the practical problem of obtaining an accurately known and useful noise output from a discharge.

[121] M. I. Skolnik and H. R. Puckett, Jr., "Relaxation oscillations and noise from low-current arc discharges," *J. Appl. Phys.*, vol. 26, pp. 74–79; January, 1955.
[122] W. H. Bostick and M. A. Levine, "Experiments on the behavior of an ionized gas in a magnetic field," *Phys. Rev.*, vol. 97, pp. 13–21; January 1, 1955.
[123] L. W. Davies and E. Cowcher, "Microwave and metro-wave radiation from the positive column of a gas discharge," *Aust. J. Phys.*, vol. 8, pp. 108–128; March, 1955.
[124] W. W. Mumford and R. L. Schafersman, "Data on the temperature dependence of X-band fluorescent lamp noise sources," Trans. IRE, vol. MTT-3, pp. 12–17; December, 1955.
[125] E. Maxwell and B. J. Leon, "Noise measurements in the UHF range," Trans. IRE, vol. MTT-3, p. 62; December, 1955.

V. Generators

Oscillators and amplifiers of the future will cover broad bands. This is evident from the research now underway. The newer electron beam devices show the greatest promise in this respect, and are receiving a proportionate share of the total effort.

Electron Beam Devices

The interaction of an electron beam with a periodic structure is being studied from several points of view. Specific structures have been analyzed and built to provide oscillators and amplifiers. Most important among these at present is the backward wave oscillator or carcinotron. The crossed-field or M-type carcinotron is capable of powers in the hundreds of watts, electronically tunable over wide bands. The conventional backward-wave oscillator or O-type carcinotron exhibits excellent local oscillator characteristics over the same tuning range.

[126] R. R. Warnecke, P. Guenard, O. Doehler, and B. Epsztein, "The 'M'-type carcinotron tube," Proc. IRE, vol. 43, part I, pp. 413–424; April, 1955.
[127] H. R. Johnson, "Backward-wave oscillators," Proc. IRE, vol. 43, pp. 684–697; June, 1955.
[128] R. W. Grow and D. A. Watkins, "Backward-wave oscillator efficiency," Proc. IRE, vol. 43, pp. 848–856; July, 1955.
[129] W. V. Christensen and D. A. Watkins, "Helix millimeter-wave tube," Proc. IRE, vol. 43, pp. 93–96; January, 1955.

Traveling-wave amplifiers with minimum noise figure are also the object of numerous investigations.

[130] H. A. Haus and F. N. H. Robinson, "A minimum noise figure of microwave beam amplifiers," Proc. IRE, vol. 43, pp. 981–991; August, 1955.
[131] S. W. Harrison, "On the minimum noise figure of traveling-wave tubes," Proc. IRE, vol. 43, p. 227; February, 1955. (Correspondence.)
[132] T. E. Everhart, "Concerning the noise figure of a backward-wave amplifier," Proc. IRE, vol. 43, part I, pp. 444–449; April, 1955.

The use of dispersive backward-wave amplifiers for narrow-band service has been described. By cascading several dispersive amplifiers a high gain, narrow band, voltage tuned amplifier can be obtained. Recirculation schemes for higher gain have also been used successfully with broad band amplifiers.

[133] M. R. Currie and J. R. Whinnery, "The cascade backward-wave amplifier: A high-gain voltage-tuned filter for microwaves," Proc. IRE, vol. 43, pp. 1617–1631; November, 1955.
[134] F. R. Arams, "Traveling-wave tube system having multiplied gain," Proc. IRE, vol. 43, p. 102; January, 1955. (Correspondence.)

More general studies of the interaction between microwave circuits and electron beams include helical, hairpin, and other circuit designs.

[135] M. Chodorow and E. L. Chu, "Cross-wound twin helices for traveling-wave tubes," *J. Appl. Phys.*, vol. 26, pp. 33–43; January, 1955.
[136] A. Karp, "Traveling-wave tube experiments at millimeter wavelengths with a new, easily built, space harmonic circuit," Proc. IRE, vol. 43, pp. 41–46; January, 1955.
[137] J. R. Pierce, "Interaction of moving charges with wave circuits," *J. Appl. Phys.*, vol. 26, pp. 627–638; May, 1955.
[138] H. Heffner, "A coupled mode description of beam-type amplifiers," Proc. IRE, vol. 43, pp. 210–217; February, 1955.
[139] W. H. Louisell and J. R. Pierce, "Power flow in electron beam devices," Proc. IRE, vol. 43, part I, pp. 444–449; April, 1955.

New and sometimes radically different schemes for electron beam devices are being advanced. Two of these are listed below.

[140] Walter R. Beam, "On the possibility of amplification in space-charge-potential-depressed electron streams," Proc. IRE, vol. 43, pp. 454–462; April, 1955.
[141] H. Heffner, "The practicality of E-type traveling-wave devices," Proc. IRE, vol. 43, pp. 1007–1008; August, 1955.

Many of the new schemes are most promising for millimeter wave generation. The potential activity in this portion of the spectrum is very great; the precursors of this development are appearing in increasing numbers. Unfortunately, the efficiency of many of the proposed schemes is notoriously low.

[142] J. L. Farrands, "The generation of millimetre waves," *Jour. IEE*, vol. 102, part B, p. 264; March, 1955.
[143] H. Motz and K. B. Mallory, "Generation of submillimeter waves," *J. Appl. Phys.*, vol. 26, p. 1384; November, 1955. (Correspondence.)
[144] P. D. Coleman and M. D. Sirkis, "Harmodotron—A beam harmonic, higher-order mode device for producing millimeter and submillimeter waves," *J. Appl. Phys.*, vol. 26, pp. 1385–1386; November, 1955. (Correspondence.)
[145] J. G. Linhart, "Čerenkov radiation of electrons moving parallel to a dielectric boundary," *J. Appl. Phys.*, vol. 26, pp. 527–533; May, 1955.

In the related field of short-millimicrosecond-pulses, traveling tubes have been very successfully exploited. Earlier regenerative systems using traveling-wave tubes have been supplemented by a much simpler generator in which the proper transients are applied directly to the helix and focusing electrode of the traveling wave tube.

[146] A. C. Beck and G. D. Mandeville, "Microwave traveling-wave tube millimicrosecond pulse generators," Trans. IRE, vol. MTT-3, pp. 48–51; December, 1955.

The regenerative scheme is, however, being developed further for repeater purposes. A method for regenerating binary pulses directly at microwave frequencies is being tried with considerable success.

[147] O. E. DeLange, "The regeneration of binary microwave pulses," Trans. IRE, vol. MTT-3, p. 62; December, 1955.

Magnetrons, Klystrons, and Triodes

In the rivalry of broad band electronically tunable oscillators, the interdigital magnetron is a strong competitor. A voltage tunable magnetron covering the 1.5–3.5 kmc band has been developed. In local oscillator service, this tube exhibits only a 3 db higher noise figure than the reflex klystron. Its structure is extremely simple and compact when compared with backward wave oscillators.

[148] J. A. Boyd, "The Mitron—an interdigital voltage-tunable magnetron," Proc. IRE, vol. 43, pp. 332–338; March, 1955.
[149] A. Singh, "Modes and operating voltages of interdigital magnetrons," Proc. IRE, vol. 43, pp. 470–476; April, 1955.

An outstanding reflex klystron oscillator for the 50–60 kmc band has also been developed. Although quite straightforward in design, the performance of this tube far exceeds previous achievements.

[150] E. D. Reed, "A tunable, low voltage reflex klystron for operation in the 50 to 60-kmc band," *Bell. Sys. Tech. Jour.*, pp. 563–600; May, 1955.

Full exploitation of planar electrode structures has also produced relatively conventional triodes capable of oscillator service up to 10 kmc. At 1.2 kmc a noise figure of 7 db is quoted.

[151] J. E. Beggs and N. T. Lavoo, "A triode useful to 10,000 mc," Proc. IRE, vol. 43, pp. 15–19; January, 1955.

The output spectra attainable with conventional oscillators have received considerable attention. Most noteworthy is the development of a system for phase stabilization of microwave oscillators. The phase locking of a microwave oscillator to the harmonic of a crystal has been accomplished. This reduces the spectrum width of the stabilized oscillator to the width of the reference signal. When used in reverse, a system of this type can function as a frequency divider in the microwave region, where no other kind is presently available.

[152] M. Peter and M. W. P. Standberg, "Phase stabilization of microwave oscillators," Proc. IRE, vol. 43, pp. 869–873; July, 1955.

Other reports on stabilization and studies of output spectra are given below.

[153] L. Jampierre, "Study of the relative frequency fluctuations of two reflex klystrons stabilized by different methods," *Ann. Telecommun.*, vol. 10, pp. 65–78, 87–99; March/April, 1955.
[154] R. E. Wall, Jr. and A. E. Harrison, "A method of forming a broad-band microwave frequency spectrum," Trans. IRE, vol. MTT-3, pp. 4–10; January, 1955.
[155] T. Moreno and R. L. Jepsen, "Hysteresis in klystron oscillators," Proc. IRE, vol. 43, p. 344; March, 1955. (Correspondence.)
[156] P. D. Strum, "Klystron noise," Trans. IRE, vol. MTT-3, p. 45; January, 1955. (Correspondence.)

Conclusion

The summary of microwave progress just given is fragmentary in two senses. First, it is incomplete, particularly with regard to some of the less accessible foreign periodicals. Second, it does not hang together as well as might be hoped. Both of these features have a significance beyond simply proving the inadequacy of the author. Thus, we are much in need of closer contacts with other workers who publish in foreign journals and languages. We are also being drawn into many new and diverse areas of science and its application. The first of these can be remedied by a special effort to look at foreign progress. The second, our growing diversification, is a sign of natural growth and vigor. We can take satisfaction from the expansion of microwave theory and techniques during 1955 and in preceding years, even though this may tax our learning capacity in new fields.