Report on Advances in Microwave Theory and Techniques—1960*

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THIS is a compendium of the principal advances in the microwave area for the calendar year 1960; only United States journals are included in this report which is not a catalog of all published papers, but rather, is intended to be a semicritical review of the major accomplishments in the field. The report is divided into four major sections which cover, respectively, tube sources, electromagnetic devices, solid-state devices, and measurements.

The year has seen outstanding accomplishments in the realization of new types of solid-state devices such as low-noise amplifiers, tunnel-diode oscillators and amplifiers, and quantum devices. Other highlights include new structures for traveling-wave interaction, resolution of the single-mode ferrite-slab-in-guide paradox, advances in high-power component testing, and in plasma analysis/diagnostics. A major advance has occurred in the testing and operation of various low-noise systems.

This report continues a series which started with the report for 1954; 1958 was the last year covered by the series. Survey reports covering the interim that might be useful include three papers on MTT progress outside of the United States [1]–[3], and the URSI USA National Commission report to the 13th General Assembly of URSI. This last report [4], [5] covers USA progress during the triennium 1957–1959 on a variety of topics including radio measurements and standards, parametric amplifiers, masers, ferrites, microwave tubes, and plasmas.

[1] J. Brown, "Report of advances in microwave theory and techniques in Great Britain—1959," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-8, pp. 382–386; July, 1960.
[2] G. Goudet, "Report of advances in microwave theory and techniques in Western Europe—1959," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-8, pp. 387–394; July, 1960.
[3] K. Morita, "Report of advances in microwave theory and techniques in Japan—1959," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-8, pp. 395–397; July, 1960.
[4] E. A. Gerber, *et al.*, "USA National Committee URSI Report: radio measurement methods and standards," *J. Res. NBS*, vol. 64D, pp. 592–605; November–December, 1960.
[5] P. K. Tien, *et al.*, "USA National Committee URSI Report: radio electronics," *J. Res. NBS*, vol. 64D, pp. 751–767; November–December, 1960.

I. SOURCES

A. Klystrons

Large signal studies [6], [7], noise studies [8], [9], and the cascading of reflex tubes as regenerative amplifiers [10], [11] are the major areas of work. A hybrid tube has been developed [12] which is a combination of klystron and TWT. Cavities are used for bunching of the beam, and a traveling-wave section is the output coupler. Development of a Ku band electrostatically-focused tube [13] and a novel scheme for wide-band tuning using ferrite material have been reported [14].

[6] S. E. Webber, "Some calculations on the large signal energy exchange mechanisms in linear beam tubes," IRE TRANS. ON ELECTRON DEVICES, vol. ED-7, pp. 154–162; July, 1960.
[7] S. V. Yadavalli, "On the large-signal aspect of the broadband multicavity klystron problem—theory and experiment," PROC. IRE (Correspondence), vol. 48, pp. 953–954; May, 1960.
[8] G. A. Espersen, "Noise studies on two-cavity CW klystrons," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-8, pp. 474–477; September, 1960.
[9] K. Ishii, "Noise figures of reflex klystron amplifiers," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-8, pp. 291–294; May, 1960.
[10] ——, "Phase adjustment effects on cascaded reflex klystron amplifiers," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-8, pp. 445–449; July, 1960.
[11] ——, "Isolator effect on cascaded reflex klystron amplifiers," PROC. IRE (Correspondence), vol. 48, pp. 1503–1504; August, 1960.
[12] S. V. Yadavalli, "On the performance of a class of hybrid tubes," PROC. IRE (Correspondence), vol 48, p. 263; February, 1960.
[13] R. G. Rockwell, "A four-cavity, electrostatically focused, Ku-band klystron amplifier," 1960 IRE WESCON CONVENTION RECORD, pt. 3, pp. 109–113.
[14] G. R. Jones and J. C. Cacheris, "Magnetically tuned klystrons for wide-band frequency modulation applications," IRE TRANS. ON ELECTRON DEVICES, vol. ED-7, pp. 206–214; October, 1960.

B. Magnetron and Crossed-Field Tubes

Relatively little effort is being expended in this area; a new use (as a detector) of the original-type smooth-anode magnetron has appeared [15]. An analysis of the crossed-field amplifier which uses a boundary-value approach to include the effects of evanescent modes at the input boundary has been made by Hershenov [16]. Velocity sorting for secondary emission reduction is used in a crossed-field collector applicable to both TW and klystron tubes [17]. Noise measurements have been reported on "M"-type tubes [18].

[15] R. M. Hill and F. A. Olson, "Microwave oscillation and detection by a smooth anode coaxial magnetron," PROC. IRE (Correspondence), vol. 48, pp. 1906–1907; November, 1960.
[16] B. Hershenov, "A small-signal field theory analysis of crossed-field amplifiers applicable to thick beams," IRE TRANS. ON ELECTRON DEVICES, vol. ED-7, pp. 163–171; July, 1960.
[17] D. A. Dunn, *et al.*, "A crossed-field multisegment depressed collector for beam-type tubes," IRE TRANS. ON ELECTRON DEVICES, vol. ED-7, pp. 262–267; October, 1960.
[18] J. R. Anderson, "Noise measurements on an M-type backward-wave amplifier," PROC. IRE (Correspondence), vol. 48, pp. 946–947; May, 1960.

C. Traveling-Wave Tubes

Theoretical work probably represents most of the advancement in this area. A general analysis of the

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dependence of output power on various factors for dispersive structures is given by Sobol and Rowe [19]. Another analysis compares the differential and integral-equation approaches, and happily arrives at compatible results [20]. Dow has analyzed behavior near cutoff by using an expansion about cutoff frequency [21]. Another paper covers the effects of variations in dc electron velocity in electrostatically-focused tubes [22]. The space-charge-wave noise exchanger of Sturrock has been investigated further [23]; this reduces the noise temperature of the tube.

[19] H. Sobol and J. E. Rowe, "Theoretical power output and bandwidth of traveling-wave amplifiers," IRE Trans. on Electron Devices, vol. ED-7, pp. 84–94; April, 1960.
[20] J. E. Rowe, "One-dimensional traveling-wave tube analyses and the effect of radial electric field variations," IRE Trans. on Electron Devices, vol. ED-7, pp. 16–21; January, 1960.
[21] D. G. Dow, "Behavior of traveling-wave tubes near circuit cutoff," IRE Trans. on Electron Devices, vol. ED-7, pp. 123–131; July, 1960.
[22] W. W. Siekanowicz, "A small-RF-signal theory for an electrostatically focused traveling-wave tube," Proc. IRE, vol. 48, pp. 1888–1901; November, 1960.
[23] D. C Forster, "Cooling of the slow space-charge wave with application to the traveling-wave tube," 1960 IRE WESCON Convention Record, pt. 3, pp. 90–95.

Advances have also been made in new and different interaction configurations. One type, developed by Phillips, utilizes a magnetically-undulated beam reacting with the TE_{01} mode in waveguide; this is "O"-type interaction [24]. Another scheme involves a helical beam between coaxial cylinders, interacting with a TEM mode [25]. This is called an "E"-type tube. Two schemes which use cyclotron resonance interaction involve a linear-quadripole field [26] and a TE_{01} waveguide [27]. An interesting application of TWT's uses successive signal removal which converts RF to video at a number of output points and couples these into a video delay line to obtain large dynamic range [28].

[24] R. M. Phillips, "The Ubitron, a high-power traveling-wave tube based on a periodic beam interaction in unloaded waveguide," IRE Trans. on Electron Devices, vol. ED-7, pp. 231–241; October, 1960.
[25] R. H. Pantell, "Small-signal analysis of the helitron oscillator," IRE Trans. on Electron Devices, vol. ED-7, pp. 22–29; January, 1960.
[26] E. I. Gordon, "A transverse-field traveling-wave tube," Proc. IRE (Correspondence), vol. 48, p. 1158; June, 1960.
[27] K. K. Chow and R. H. Pantell, "The cyclotron resonance backward-wave oscillator," Proc. IRE, vol. 48, pp. 1865–1870; November, 1960.
[28] J. Kliger and E. J. Downey, "Extended-dynamic-range traveling-wave tubes," 1960 IRE International Convention Record, pt. 3, pp. 87–94.

Research and development in hardware have produced several interesting devices. Carlile and Sensiper use ferrite-loaded coupling apertures in a re-entrant cavity chain [29]. Hollow-beam S-band tubes using periodic focusing have been investigated with electrostatic focusing appearing most advantageous [30]. A 5-mm tube with half-watt output and bandwidth of 10 Gc has also been developed [31]. The effects of transverse-beam velocities and magnetic fields have been determined by artificially introducing these into a controlled experiment [32]. Finally, three tutorial/review articles may be mentioned [33]–[35].

[29] R. N. Carlile and S. Sensiper, "A nonreciprocal-loss traveling-wave-tube circuit," IRE Trans. on Electron Devices, vol. ED-7, pp. 289–296; October, 1960.
[30] C. C. Johnson, "A periodically focused backward-wave oscillator," IRE Trans. on Electron Devices, vol. ED-7, pp. 274–279; October, 1960.
[31] H. L. McDowell, *et al.*, "A half-watt CW traveling-wave amplifier for the 5–6 millimeter band," Proc. IRE, vol. 48, pp. 321–328; March, 1960.
[32] L. L. Maninger, "The effects of magnetic focusing fields and transverse beam velocities on spurious oscillations in backward-wave oscillators," 1960 IRE International Convention Record, pt. 3, pp. 67–77.
[33] E. J. Nalos, "Present state of art in high power traveling-wave tubes," *Microwave J.*, vol. 3, pp. 46–52; January, 1960.
[34] J. R. Hechtel, "Electrostatic focusing of microwave tubes," *Microwave J.*, vol. 3, pt. I, pp. 41–48, November; pt. II, pp. 81–86, December, 1960.
[35] C. L. Cuccia, "Lightweight very-wide-band integral package TWT's," *Microwave J.*, vol. 3, pp. 47–57; July, 1960.

D. Harmonic Generation and Millimeter Waves

Work has continued on unusual devices for the generation of millimeter waves. The megavolt Cerenkov device of Coleman follows the philosophy of building characteristic frequencies into the beam, rather than into the microwave structure [36]. The device has proproduced 3 w at 8 mm using the 13th harmonic. Another scheme shoots a highly-bunched beam into a high-mode cavitity (harmodotron concept) [37]. Anderson has recognized that the nonlinear volt-ampere characteristic of a Langmuir plasma probe can be utilized for harmonic generation [38]. However, with present configurations, efficiency is considerably below that of diode generators.

[36] P. D. Coleman and C. Enderby, "Megavolt electronics Cerenkov coupler for the production of millimeter and submillimeter waves," *J. Appl. Phys.*, vol. 31, pp. 1695–1696; September, 1960.
[37] E. Brannen, *et al.*, "Generation of millimeter waves by the electron beam of a microtron," *J. Appl. Phys.*, vol. 31, p. 1829; October, 1960.
[38] J. M. Anderson, "Microwave detection and harmonic generation by Langmuir-type probes in plasmas," Proc. IRE (Correspondence), vol. 48, pp. 1662–1663; September, 1960.

Most of the effort on harmonic generation has used the nonlinear properties of diodes. Hedderly uses a distributed transmission line loaded with diodes [39]. Johnson has made an analysis for the large-signal/high-harmonic case and has concluded that higher efficiencies are possible for it than for the small-signal case [40]. The theoretical conversion loss is 2.9 db$\times n$ for large n. A related analysis derives conversion efficiency for the case where some circuits are resistively terminated [41]. There are several papers on specific harmonic generators and their performance [42]–[46]. Conversion losses quoted are: 2.7 db/octave at an output of 1 Gc; 3.0 db/octave at 1 Gc; 3.9 db/octave at 1.6 Gc; and 9 db/octave at 48 Gc. From these limited data, little can be concluded except that losses increase with frequency.

[39] D. L. Hedderly, "A traveling wave harmonic generator," Proc. IRE (Correspondence), vol. 48, p. 1658; September, 1960.
[40] K. M. Johnson, "Large signal analysis of a parametric harmonic generator," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 525–532; September, 1960.
[41] I. Kaufman and D. Douthett, "Harmonic generation using idling circuits," Proc. IRE (Correspondence), vol. 48, pp. 790–791; April, 1960.
[42] G. F. Montgomery, "Efficient harmonic generation," Proc. IRE (Correspondence), vol. 48, pp. 251–252; February, 1960.

[43] G. H. Heilmeier, "Millimeter wave generation by parametric methods," PROC. IRE (Correspondence), vol. 48, pp. 1326–1327; July, 1960.
[44] R. Lowell and M. J. Kiss, "Solid-state microwave power sources using harmonic generation," PROC. IRE (Correspondence), vol. 48, pp. 1334–1335; July, 1960.
[45] D. Leenov and J. W. Rood, "UHF harmonic generation with silicon diodes," PROC. IRE (Correspondence), vol. 48, p. 1335; July, 1960.
[46] G. Luettgenaū, *et al.*, "High power at 1000 mc using semiconductor devices," 1960 IRE WESCON CONVENTION RECORD, pt. 3, pp. 13–26.

II. ELECTROMAGNETIC DEVICES

A. General EM Theory

1) Energy and Reciprocity: Energy-transport processes in dispersive media are still of considerable interest: witness two important papers. Tonning identifies a "dispersion energy" and calculates energy velocity and group velocity for dispersive media [47], while Sturrock treats the negative energy of a slow wave in a moving coordinate system [48]. Two papers have appeared on reciprocity theorems for nonperiodic sources. One obtains a Lorentz integral form containing cross correlations of fields [49]; the other, using the Reaction Concept, obtains general reciprocity involving electric- and magnetic-current sources and their associated fields [50]. An interesting note shows that attenuation for common types of waveguides can be written in a quasi-separable form where separate coefficients relate dielectric loss, conductor loss, and geometry; however, the cutoff wavelength common to all prevents complete separability [51].

[47] A. Tonning, "Energy density in continuous electromagnetic media," IRE TRANS. ON ANTENNAS AND PROPAGATION, vol. AP-8, pp. 428–434; July, 1960.
[48] P. A. Sturrock, "In what sense do slow waves carry negative energy?" *J. Appl. Phys.*, vol. 31, pp. 2052–2056; November, 1960.
[49] G. Goubau, "A reciprocity theorem for nonperiodic fields," IRE TRANS. ON ANTENNAS AND PROPAGATION (Communications), vol. AP-8, pp. 339–342; May, 1960.
[50] W. J. Welch, "Reciprocity theorems for electromagnetic fields whose time dependence is arbitrary," IRE TRANS. ON ANTENNAS AND PROPAGATION, vol. AP-8, pp. 68–73; January, 1960.
[51] D. K. Gannett and Z. Szekely, "A simple general equation for attenuation," PROC. IRE (Correspondence), vol. 48, pp. 1161–1162; June, 1960.

2) Obstacles: One of the more intriguing problems has been the thermodynamic paradox associated with the single surface-wave mode in a waveguide with ferrite slab. Bresler has carefully investigated this problem and has discovered that the correct secular equation obtained as the slab is moved to the wall has a different limit than the previously obtained secular equation [52]. The correct equation admits pairs of modes representing power flow in opposite directions, thereby resolving the paradox. Another unusual problem has been solved by Forrer and Jaynes, who have shown that ghost modes are resonant modes in dielectric windows in waveguide [53]. Investigation of these has led to advances in design of high-power windows. The change in parameters produced in a gas excited by acoustic waves allows the partial reflection of incident electromagnetic energy; this has been investigated by Schmitt and Sengupta [54]. Gradual-transition absorbers constitute another partial-reflection problem. Walther solved the resulting Riccati equation by the WKB method for thick layers [55]. Other general studies have included the application of Babinet's principle to transmission lines [56]. Oliner has studied, theoretically and experimentally, symmetrical discontinuities in transmission lines [57], [58]. Spruch and Bartram, in another important paper, have applied a quantum-scattering technique to three-dimensional waveguide scattering problems wherein the usual Schwinger form gives only an upper bound [59]. This new method obtains upper and lower bounds on the principal wave phase shift. Other papers include a conformal evaluation of strip-line parameters [60] and thickness corrections for strip-line structures obtained from an exact solution using semi-infinite plates [61].

[52] A. D. Bresler, "On the TE_{n0} modes of a ferrite slab loaded rectangular waveguide and the associated thermodynamic paradox, IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-8, pp. 81–95; January, 1960.
[53] M. P. Forrer and E. T. Jaynes, "Resonant modes in waveguide windows," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-8, pp. 147–150; March, 1960.
[54] H. J. Schmitt and D. L. Sengupta, "On the reflection of electromagnetic waves from a medium excited by acoustic waves," *J. Appl. Phys.*, vol. 31, pp. 439–440; February, 1960.
[55] K. Walther, "Reflection factor of gradual-transition absorbers for electromagnetic and acoustic waves," IRE TRANS. ON ANTENNAS AND PROPAGATION, vol. AP-8, pp. 608–621; November, 1960.
[56] G. H. Owyang and R. King, "Complementarity in the study of transmission lines." IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-8, pp. 172–181; March, 1960.
[57] A. A. Oliner, "Equivalent circuits for small symmetrical longitudinal apertures and obstacles," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-8, pp. 72–80; January, 1960.
[58] H. M. Altschuler and A. A. Oliner, "Discontinuities in the center conductor of symmetric strip transmission line." IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-8, pp. 328–339; May, 1960.
[59] L. Spruch and R. Bartram, "Bounds on the elements of the equivalent network for scattering in waveguides," *J. Appl. Phys.*, vol. 31, "Part I: Theory," pp. 905–913; "Part II: Application to dielectric obstacles," pp. 913–917; May, 1960.
[60] T.-S. Chen, "Determination of the capacitance, inductance, and characteristic impedance of rectangular lines," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-8, pp. 510–519; September, 1960.
[61] S. B. Cohn, "Thickness corrections for capacitive obstacles and strip conductors," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-8, pp. 638–644; November, 1960.

B. Waveguides and Filters

1) Waveguides: Strip transmission lines and associated devices have been in use now for several years; Cohn has contributed a critical reappraisal of their merits, drawbacks, and estimated future [62]. This article also contains an excellent bibliography. Tai has demonstrated that evanescent modes in a waveguide partially filled with ferrite are members of an orthogonal set although they do not carry power [63]. Corrugated waveguides have been analyzed by replacing the periodic structure with an anisotropic quasi-homogeneous medium [64]. However, this appears to be equivalent to the transverse-resonance method and does not include the effect of all evanescent modes. Other investigations include the elliptic waveguide [65], round waveguide with a double lining [66], [67] (for spurious mode suppression), and a superconductive coaxial line [68]. An interesting feature of the latter is that care must be exercised to avoid reflections, as the absence of loss eliminates sometimes-beneficial attenuation.

[62] S. B. Cohn, "A reappraisal of strip transmission line," *Microwave J.*, vol. 3, pp. 17–27; March, 1960.
[63] C. T. Tai, "Evanescent modes in a partially filled gyromagnetic rectangular wave guide," *J. Appl. Phys.*, vol. 31, pp. 220–221; January, 1960.
[64] G. Piefke, "A contribution to the theory of corrugated guides," *J. Res. NBS*, vol. 64D, pp. 533–555; September–October, 1960.
[65] G. R. Valenzuela, "Impedances of an elliptic waveguide (for the $_eH_1$ mode)," IRE Trans on Microwave Theory and Techniques, vol. MTT-8, pp. 431–435; July, 1960.
[66] H.-G. Unger, "Round waveguide with double lining," *Bell Sys. Tech. J.*, vol. 39, pp. 161–167; January, 1960.
[67] A. P. King, "The observed 50–90 kmc attenuation of two inch improved waveguide," 1960 IRE WESCON Convention Record, pt. 1, pp. 28–33.
[68] N. S. Nahman and G. M. Gooch, "Nanosecond response and attenuation characteristics of a superconductive coaxial line," Proc. IRE, vol. 48, pp. 1852–1856; November, 1960.

In the open waveguide area, further investigations have been made of trough waveguides by Cohn, *et al.* [69], [70]. Also, propagation constant curves have been given for a grounded dielectric slab with an air gap between the slab and ground plane [71].

[69] M. Cohn, *et al.*, "TE mode excitation on dielectric loaded parallel plane and trough waveguides," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 545–552; September, 1960.
[70] M. Cohn, "TE modes of the dielectric loaded trough line," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 449–454; July, 1960.
[71] J. H. Richmond, "Surface waves on symmetrical three-layer sandwiches," IRE Trans. on Microwave Theory and Techniques (Correspondence), vol. MTT-8, p. 572; September, 1960.

2) Periodic Structures: An excellent review article on guiding structures has been written by Harvey [72]. The article develops the theory of dispersive structures, pass and stop bands, forward and backward waves, etc. Extensive descriptions and analyses are given of the many slow-wave structures including dielectric structures with and without metal, corrugated surfaces, ladders, coupled cavities, and helices; the bibliography contains nearly 300 references. Allen and Kino have obtained field distributions and dispersive characteristics of strongly-coupled cavities [73]. Variational principles have been developed for ω and β for periodic structures using closed-cavity modes as trial functions [74], [75]. Additional papers are a general analysis of periodic circuits [76] and an experimental description of a block-loaded guide [77].

[72] A. F. Harvey, "Periodic and guiding structures at microwave frequencies," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 30–61; January, 1960.
[73] M. A. Allen and G. S. Kino, "On the theory of strongly coupled cavity chains," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 362–372; May, 1960.
[74] T. J. Goblick, Jr., and R. M. Bevensee, "Variational principles and mode coupling in periodic structures," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, p. 500–509; September, 1960.
[75] R. M. Bevensee, "Misconceptions about equivalent circuits for periodic microwave structures," 1960 IRE WESCON Convention Record, pt. 1, pp. 3–10.
[76] R. N. Carlile, "General properties of the propagation constant of a nonreciprocal iterated circuit," Proc. IRE (Correspondence), vol. 48, pp. 1162–1163; June, 1960.
[77] W. B. Mims, "The block loaded guide as a slow wave structure," Proc. IRE (Correspondence), vol. 48, pp. 1176–1177; June, 1960.

3) Nonuniform and Coupled Guides: An interesting validation of coupled transmission-line theory has been provided by Bahiana and Smullin [78]. They analyzed a waveguide filled with two dielectrics by coupling the modes individually existing in each dielectric. The phase constant using this approach was found to compare favorably with that using exact theory. Cohn has derived even- and odd-characteristic impedances for closely-coupled strip lines of the type useful in coupled filters, 3-db couplers, etc. [79]; the Schwartz-Christoffel transformation was used. Other work includes a study of multi-element transmission lines by superposition of virtual two-element pairs [80], and a derivation of the higher-mode indicial equation in coaxial helices [81]. General analyses of transmission lines include a variational integral for propagation constant of a lossy line assuming only axial current [82], and an analysis of the pulse response of several hybrids in nondispersive line [83]. Finally, Sugai has attempted to fit specialized solutions of Riccati equations to the nonuniform transmission-line problem [84].

[78] L. C. Bahiana and L. D. Smullin, "Coupling of modes in uniform, composite waveguides," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 454–458; July, 1960.
[79] S. B. Cohn, "Characteristic impedances of broadside-coupled strip transmission lines," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 633–637; November, 1960.
[80] H. Kogo, "A study of multi-element transmission lines," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 136–142; March, 1960.
[81] R. E. Hayes, "Higher order modes in coupled helices," IRE Trans. on Microwave Theory and Techniques (Correspondence), vol. MTT-8, pp. 119–120; January, 1960.
[82] R. E. Collin, "A variational integral for propagation constant of lossy transmission lines," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 339–342; May, 1960.
[83] W. J. Getsinger, "Analysis of certain transmission-line networks in the time domain," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 301–309; May, 1960.
[84] I. Sugai, "The solutions for nonuniform transmission line problems," Proc. IRE (Correspondence), vol. 48, pp. 1489–1490; August, 1960.

C. Isotropic Devices

As might be expected in a rapidly growing hardware field, there have been many advances in components. These are grouped into six categories: switches and duplexers, mixers and modulators, filters, phase shifters, transformers and baluns, and junctions. However, several developments do not readily fit in these categories. Sooy, *et al.*, developed a microwave Meacham bridge oscillator where, in a fashion analogous to that at audio frequencies, the resonant feedback element is incorporated into a bridge circuit, thereby multiplying Q and providing exceptional stability [85]. Gradual mode transducers have been designed by determining the appropriate eigenfunction from the input and output modes [86]. Design equations and curves for broad-band chokes have also appeared [87].

[85] W. R. Sooy, *et al.*, "A microwave Meacham bridge oscillator," Proc. IRE, vol. 48, pp. 1297–1306; July, 1960.
[86] L. Solymar and C. C. Eaglesfield, "Design of mode transducers," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 61–65; January, 1960.
[87] H. E. King, "Broad-band coaxial choked coupling design," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 132–135; March, 1960.

1) Switches and Duplexers: Harvey has prepared an excellent survey article covering all aspects of microwave duplexers, both ferrite and gaseous; a large bibliography is included [88]. Hill and Ichiki have developed hot-cathode gas switches [89], [90]. Two schemes have appeared for increasing average-power capabilities of gas duplexers by reducing gas volume and using silica tubes [91], [92].

[88] A. F. Harvey, "Duplexing systems at microwave frequencies," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 415–431; July, 1960.
[89] R. M. Hill and S. K. Ichiki, "Microwave switching with low-pressure arc discharge," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 628–633; November, 1960.
[90] S. J. Tetenbaum, *et al.*, "Arc discharge, microwave switch tube," 1960 IRE WESCON Convention Record, pt. 3, pp. 96–102.
[91] D. W. Downton and P. D. Lomer, "A pre-TR tube for high mean power duplexing," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 654–659; November, 1960.
[92] R. S. Braden, "A new concept in microwave gas switching elements," IRE Trans. on Electron Devices, vol. ED-7, pp. 54–59; January, 1960.

Garver, *et al.*, have shown experimentally that germanium diodes follow the majority-carrier theory of Lawson whereas silicon diodes follow Shockley's minority-carrier theory [93]. This accounts for the switching action which is noted in germanium diodes, but is not observed in those of the silicon type. Finally, another ring waveguide switch has appeared [94].

[93] R. V. Garver, *et al.*, "Theory of the germanium diode microwave switch," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 108–111; January, 1960.
[94] R. C. Johnson, *et al.*, "A waveguide switch employing the offset ring-switch junction," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 532–537; September, 1960.

2) Mixers and Modulators: Advances in crystal mixers have largely been concerned with operational problems. Garver and Rosado have analyzed the equivalent circuit for a microwave diode and conclude that a three-arm circuit is needed [95]. Two papers concern the optimum operating conditions. Mohr and Okwit give curves showing the proper RF drive [96]; Staniforth and Craven indicate that a 100-μa bias and low-video load resistance give an optimum dynamic square-law range for 1N23B mixers [97]. Other papers cover a broad-band mount (with dimensions) [98], and temporary deterioration of silicon diodes due to high-power ionization at the barrier [99].

[95] R. V. Garver and J. A. Rosado, "Microwave diode cartridge impedance," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 104–107; January, 1960.
[96] R. J. Mohr and S. Okwit, "A note on the optimum source conductance of crystal mixers," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 622–627; November, 1960.
[97] A. Staniforth and J. H. Craven, "Improvement in the square law operation of 1N23B crystals from 2 to 11 kmc," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 111–115; January, 1960.
[98] A. Staniforth, "A broad-band crystal mount 10.5 kmc to 20 kmc," IRE Trans. on Microwave Theory and Techniques (Correspondence), vol. MTT-8, pp. 464–465; July, 1960.
[99] P. P. Lombardini and R. J. Doviak, "Temporary and permanent deterioration of microwave silicon crystal diodes," Proc. IRE (Correspondence), vol. 48, pp. 119–120; January, 1960.

Microwave modulators (for modulation or attenuation) have been developed. These use semiconductor wafers across the waveguide [100], [101].

[100] F. C. De Ronde, *et al.*, "The *p-i-n* modulator, an electrically controlled attenuator for mm and sub-mm waves," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 325–327; May, 1960.
[101] H. Jacobs, *et al.*, "A new semiconductor microwave modulator," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 553–559; September, 1960.

3) Filters: Matthaei has contributed an important paper on the theory and design of microwave filters using the insertion-loss principle [102]. This allows the designer to use either equal-ripple or maximally-flat insertion loss. Cohn has treated these two cases where isolation rather than bandwidth narrowing is desired [103]. He shows that for this case the equal-ripple design is superior to the maximally flat. Others have used an analog computer for cascading klystron cavities [104].

[102] G. L. Matthaei, "Design of wide-band (and narrow-band) band-pass microwave filters on the insertion loss basis," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 580–593; November, 1960.
[103] S. B. Cohn, "Phase shift and time-delay response of microwave narrow-band filters," *Microwave J.*, vol. 3, pp. 47–51; October, 1960.
[104] A. Norris and D. M. Byck, "Analog simulation: a network method for solving microwave problems," *Microwave J.*, vol. 3, pp. 43–48; June, 1960.

In the cavity area, Kotzebue discusses broad-band circuits in coax and waveguide for a tuned filter using a YIG sphere [105]. A detailed design of temperature-compensated cavities is given by Cogdell, *et al.* [106]. Other papers include an analysis of a transmission cavity wavemeter which is treated as a lossy transmission line [107], peak fields in cavity filters [108], and the effects of refractive index variations in limiting refractometer resolution [109]. An interesting development uses two quarter-wave lines coupled together to provide a linear tuning-range resonator [110]. As one quarter-wave line is lengthened the other is shortened, so that the nonlinearities cancel.

[105] K. L. Kotzebue, "Broadband electronically-tuned microwave filters," 1960 IRE WESCON Convention Record, pt. 1, pp. 21–27.
[106] J. R. Cogdell, *et al.*, "Temperature compensation of coaxial cavities," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 151–155; March, 1960.
[107] L. Young, "Analysis of a transmission cavity wavemeter," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 436–439; July, 1960.
[108] ——, "Peak internal fields in direct-coupled-cavity filters," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 612–616; November, 1960.
[109] W. J. Hartman, "Limit of spatial resolution of refractometer cavities," *J. Res. NBS*, vol. 64D, pp. 65–72; January–February, 1960.
[110] B. H. Wadia and R. L. Sarda, "UHF resonator with linear tuning," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 66–72; January, 1960.

4) *Phase Shifters:* A novel phase shifter, developed by Augustine and Cheal, consists of a helix wound of coaxial line with the portion of the outer conductor that faces inward in the helix removed [111]. Insertion of a dielectric slug produces the variable phase shift. Another scheme in this paper is a coaxial 3-db coupler with ganged shorts. This is similar to the waveguide short-slot coupler with ganged shorts that has become so popular. A related scheme terminates the coupler with diodes, thereby allowing the phase shift to be electronically controlled [112]. Wide-band phase shifters have been produced by using three half-wave anisotropic plates at appropriate angles [113], and by an iterative calculation to obtain a dispersionless dielectric quarter-wave plate [114]. Another scheme uses a feedback scheme similar to the single-sideband phase cancellation technique [115].

[111] C. F. Augustine and J. Cheal, "The design and measurement of two broad-band coaxial phase shifters," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-8, pp. 398–402; July, 1960.
[112] R. H. Hardin, *et al.*, "Electronically-variable phase shifters utilizing variable capacitance diodes," PROC. IRE (Correspondence), vol. 48, pp. 944–945; May, 1960.
[113] S. Adachi and E. M. Kennaugh, "The analysis of a broad-band circular polarizer including interface reflections," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-8, pp. 520–525; September, 1960.
[114] R. D. Tompkins, "A dispersionless dielectric quarter-wave plate in circular waveguide," PROC. IRE (Correspondence), vol. 48, pp. 1171–1172; June, 1960.
[115] A. A. Ahmed, "A wide band phase shifter," PROC. IRE (Correspondence), vol. 48, p. 945; May, 1960.

5) *Transformers and Baluns:* Young has derived an improved quarter-wave transformer by making the matching section less dispersive [116], [117], and has shown the relation between the quarter-wave transformer and a directly-coupled cavity [118]. Riblet considers the binomial transformer of equal quarter-wavelength steps, and derives a sort of "physical limitations" theorem stating that only minor improvement can be made without increasing the transformer length [119]. This is for monotonic, maximally-flat transformers. Another work gives the design for equal-ripple transformers in coax and in double-ridged waveguide [120].

[116] L. Young, "Optimum quarter-wave transformers," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-8, pp. 478–482; September, 1960.
[117] ——, "Inhomogeneous quarter-wave transformers of two sections," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-8, pp. 645–649; November, 1960.
[118] ——, "The quarter-wave transformer prototype circuit," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-8, pp. 483–489; September, 1960.
[119] H. J. Riblet, "A general theorem on an optimum stepped impedance transformer," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-8, pp. 169–170; March, 1960.
[120] D. J. Sullivan and D. A. Parkes, "Stepped transformers for partially filled transmission lines," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-8, pp. 212–217; March, 1960.

Duncan and Minerva have developed a wide-band balun where a smooth transition is made from the outer-coax conductor to one twin-line conductor [121]. This device can have impedance bandwidths of 100:1. Other work includes an impedance analysis of the split coaxial or British dipole balun [122], and two strip-line baluns which can be used with printed antennas, *e.g.*, spiral antennas [123], [124]. It has been remarked that a balun is just a hybrid with special terminations and, in fact, one of these printed baluns is just a strip-line rat race.

[121] J. W. Duncan and V. P. Minerva. "100:1 bandwidth balun transformer," PROC. IRE, vol. 48, pp. 156–164; February, 1960.
[122] H. Kogo, "Analysis of split coaxial line type balun," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES (Correspondence), vol. MTT-8, pp. 245–246; March, 1960.
[123] R. Bawer and J. J. Wolfe, "A printed circuit balun for use with spiral antennas," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-8, pp. 319–325; May, 1960.
[124] J. H. Craven, "A novel broad-band balun," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES (Correspondence), vol. MTT-8, pp. 672–673; November, 1960.

6) *Junctions:* Several interesting hybrid junction developments have appeared. Jones has developed a wide-band distributed circuit hybrid in strip-line using two coupled strip-line filters [125]; a coaxial version of this has also been in use [126]. Multiple hybrid power dividers are of interest for such applications as antenna array feeding; a multi-terminal hybrid which is a modified rat race has appeared [127]. A novel directional coupler for TE_{01} circular-electric mode in round waveguide has been developed [128]. This uses two coaxial waveguides with two bifurcations; the coupling exists in the space between the two bifurcations.

[125] E. M. T. Jones, "Wide-band strip-line magic-T," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-8, pp. 160–168; March, 1960.
[126] S. J. Robinson, "Broad-band hybrid junctions," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES (Correspondence), vol. MTT-8, pp. 671–672; November, 1960.
[127] E. J. Wilkinson, "An N-way hybrid power divider," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-8, pp. 116–118; January, 1960.
[128] B. Oguchi, "Circular electric mode directional coupler," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-8, pp. 660–666; November, 1960.

D. Plasmas

Several books could and have been written just listing references in the plasma field. From this vast science, of particular interest to the microwave area are the microwave properties of the atmosphere, and microwave diagnostic techniques.

In the first category, Bachynski, *et al.* [129], have given propagation parameters for high-temperature air for the frequency range 1 to 100 Gc with temperatures up to 12×10^3 °K. Phelps has analyzed the errors inherent in the use of an energy independent collision frequency [130]. The conductivity tensor is derived using a linear dependence of electron collision frequency on electron energy, with the result that errors are comparable to the experimental errors in ionospheric observations. Kelly and Margenau postulate by kinetic theory that the major electron loss for a moving antenna is caused by sweeping [131]. This paper gives voltage breakdown plots. Another paper investigates electron-ion recombination in water vapor [132].

[129] M. P. Bachynski, *et al.*, "Electromagnetic properties of high-temperature air," PROC. IRE, vol. 48, pp. 347–356; March, 1960.

[130] A. V. Phelps, "Propagation constants for electromagnetic waves in weakly ionized, dry air," *J. Appl. Phys.*, vol. 31, pp. 1723–1729; October, 1960.
[131] D. Kelly and H. Margenau, "High-frequency breakdown of air," *J. Appl. Phys.*, vol. 31, pp. 1617–1620; September, 1960.
[132] S. Takeda and A. A. Dougal, "Microwave study of afterglow discharge in water vapor," *J. Appl. Phys.*, vol. 31, pp. 412–416; February, 1960.

Microwave absorption for the case where collisions can be neglected has been investigated by Cullen [133]. The absorption is obtained in closed form for the extraordinary wave from electron dynamics. Other work concerns particle densities behind hypersonic shock waves [134], and on a precise definition of average electron collision frequency [135].

[133] A. L. Cullen, "Propagation of microwaves through a magneto-plasma, and a possible method for determining the electron velocity distributions," *J. Res. NBS*, vol. 64D, pp. 509–513; September–October, 1960.
[134] C. A. Roberts, *et al.*, "Theory of equilibrium electron and particle densities behind normal and oblique hypersonic shock waves in air," IRE Trans. on Antennas and Propagation (Communications), vol. AP-8, pp. 102–103; January, 1960.
[135] J. M. Anderson, "A note on the relation between the "exact" and "simplified" theories for EM wave propagation in ionized gases," IRE Trans. on Antennas and Propagation (Communications), vol. AP-8, pp. 337–338; May, 1960.

Diagnostic papers include plane wave reflection and scattering by a plasma sheet [136], a microwave interferometer technique [137], and a heuristic derivation of an absorption spectrum [138].

[136] R. G. Buser and P. Wolfert, "Microwave interaction with plasmas," 1960 IRE International Convention Record, pt. 3, pp. 146–154.
[137] C. B. Wharton and D. M. Slager, "Microwave determination of plasma density profiles," *J. Appl. Phys.*, vol. 31, pp. 428–430; February, 1960.
[138] W. D. Hershberger, "Absorption and reflection spectrum of a plasma," *J. Appl. Phys.*, vol. 31, pp. 417–422; February, 1960.

III. Solid-State Devices

A. Parametric Amplifiers

1) General: An interesting history of parametric transducers is given by Mumford [139] which includes a 200-item bibliography dating from Faraday's work in 1831 to Chang's in 1959. A very complete bibliography is provided by Mount and Begg [140] which covers both parametric devices and masers.

[139] W. W. Mumford, "Some notes on the history of parametric transducers," Proc. IRE, vol. 48, pp. 848–853; May, 1960.
[140] E. Mount and B. Begg, "Parametric devices and masers: an annotated bibliography," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 222–243; March, 1960.

Numerous general theoretical papers have been published including generalizations of the Manley-Rowe relations [141], [142], an important correction to the Heffner-Wade paper [143], and new formulations of the bandwidth and noise theory [144]–[149]. An important theoretical discussion of a parametric amplifier having a resonance at idler but not at the signal frequency is given by Fisher [150].

[141] C. Yeh, "Generalized energy relations of nonlinear reactive elements," Proc. IRE (Correspondence), vol. 48, p. 253; February, 1960.
[142] H. Iwasawa, "The extended theory of the Manley-Rowe's energy relations in nonlinear elements and nonlinear lossless medium," IRE Trans. on Microwave Theory and Techniques (Correspondence), vol. MTT-8, pp. 459–460; July, 1960.
[143] H. Heffner and G. Wade, "Noise figure and gain of parametric converters," *J. Appl. Phys.*, vol. 31, p. 2316; December, 1960.
[144] S. T. Fisher, "Bandwidth of lower sideband parametric up-converter and parametric amplifiers," Proc. IRE (Correspondence), vol. 48, p. 946; May, 1960.
[145] S. Deutsch, "Symmetrical matrix analysis of parametric amplifiers and converters," Proc. IRE, vol. 48, pp. 1595–1602; September, 1960.
[146] D. K. Adams, "An analysis of four-frequency nonlinear reactance circuits," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 274–283; May, 1960.
[147] G. Herrmann, "Idler noise in parametric amplifiers," Proc. IRE (Correspondence), vol. 48, pp. 2021–2022; December, 1960.
[148] J. C. Greene and E. W. Sard, "Optimum noise and gain-bandwidth performance for a practical one-port parametric amplifier," Proc. IRE, vol. 48, pp. 1583–1590; September, 1960.
[149] K. L. Kotzebue, "Optimum noise performance of parametric amplifiers," Proc. IRE (Correspondence), vol. 48, pp. 1324–1325; July, 1960.
[150] S. T. Fisher, "Theory of single-resonance parametric amplifiers," Proc. IRE, vol. 48, pp. 1227–1232; July, 1960.

2) Diode Type: A number of papers discuss theoretical and experimental results on various diode parametric amplifiers [151]–[153]. The highest-frequency amplifier reported is a 30-Gc degenerate amplifier by DeLoach [154]. Results of an X-band amplifier using the unique silver-bonded diode were reported by Kita and Obata [155]. Bossard, *et al.* [156] discuss a super-regenerative amplifier. The use of diodes as subharmonic oscillators [157] is well known but Kibler [158] reports on diode oscillations at frequencies higher than the pump. At low microwave frequencies the parametric up-converter is of importance and is discussed in several papers [159]–[161].

[151] M. Uenohara, "Noise consideration of the variable capacitance parametric amplifier," Proc. IRE, vol. 48, pp. 169–179; February, 1960.
[152] R. C. Knechtli and R. D. Weglein, "Low-noise parametric amplifier," Proc. IRE, vol. 48, pp. 1218–1226; July, 1960.
[153] I. Goldstein and J. Zorzy, "Some results on diode parametric amplifiers," Proc. IRE (Correspondence), vol. 48, p. 1783; October, 1960.
[154] B. C. DeLoach, "17.35 and 30-kmc parametric amplifiers," Proc. IRE (Correspondence), vol. 48, p. 1323; July, 1960.
[155] S. Kita and F. Obata, "An X-band parametric amplifier using a silver-bonded diode," Proc. IRE (Correspondence), vol. 48, pp. 1651–1652; September, 1960.
[156] B. B. Bossard, *et al.*, "X-band super-regenerative parametric amplifier," Proc. IRE (Correspondence), vol. 48, pp. 1329–1330; July, 1960.
[157] A. H. Solomon and F. Sterzer, "A parametric subharmonic oscillator pumped at 34.3 kmc," Proc. IRE (Correspondence), vol. 48, pp. 1322–1323; July, 1960.
[158] L. U. Kibler, "Parametric oscillations with point contact diodes at frequencies higher than pumping frequency," Proc. IRE (Correspondence), vol. 48, pp. 239–240; February, 1960.
[159] R. Pettai, *et al.*, "Single-diode parametric up-converter with large gain-bandwidth product," Proc. IRE (Correspondence), vol. 48, pp. 1323–1324; July, 1960.
[160] A. K. Kamal and A. J. Holub, "Gain inconsistencies in low-frequency reactance parametric up-converters," Proc. IRE (Correspondence), vol. 48, pp. 1784–1785; October, 1960.
[161] A. K. Kamal and M. Subramanian, "Gain optimization in low-frequency parametric up-converters by multidiode operation," Proc. IRE (Correspondence), vol. 48, pp. 2020–2021; December, 1960.

Several papers [162]–[164] discuss the appropriate definition of a figure of merit for a varactor diode while one paper [165] expands the capacitance coefficients in terms of the hypergeometric function. Attention is also given to the anomalous reverse current in diodes and its effect on amplifier performance [166], [167]. Measurement techniques of diode Q are described in two papers [168], [169] while contradictory results on the frequency dependence of the equivalent series resistance are also discussed [170].

[162] R. C. Knechtli and R. D. Weglein, "Diode capacitors for parametric amplification," *J. Appl. Phys.*, vol. 31, pp. 1134–1135; June, 1960.
[163] K. E. Mortenson, "Parametric diode figure of merit and optimization," *J. Appl. Phys.*, vol. 31, pp. 1207–1212; July, 1960.
[164] C. R. Boyd, "Noise figure measurements relating the static and dynamic cutoff frequencies of parametric diodes," Proc. IRE (Correspondence), vol. 48, pp. 2019–2020; December, 1960.
[165] S. Sensiper and R. D. Weglein, "Capacitance and charge coefficients for parametric diode devices," Proc. IRE (Correspondence), vol. 48, pp. 1482–1483; August, 1960.
[166] R. D. Weglein, "Some limitations on parametric amplifier noise performance," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 538–544; September, 1960.
[167] K. Siegel, "Anomalous reverse current in varactor diodes," Proc. IRE (Correspondence), vol. 48, pp. 1159–1160; June, 1960.
[168] N. Houlding, "Measurement of varactor quality," *Microwave J.*, vol. 3, pp. 40–45; January, 1960.
[169] R. I. Harrison, "Parametric diode Q measurements," *Microwave J.*, vol. 3, pp. 43–46; May, 1960.
[170] S. T. Eng and R. Solomon, "Frequency dependence of the equivalent series resistance for a germanium parametric amplifier diode," Proc IRE (Correspondence), vol. 48, pp. 358–359; March, 1960.

Two unusual uses of parametric amplifiers as a limiter [171] and as a nonreciprocal element [172] are to be noted as well as the use of space-charge capacitors for parametric amplifiers [173]. A new development which may prove to be of importance is the "parametric mode" of operation of transistors [174] which significantly increases the amplification and oscillation frequency of transistors.

[171] A. D. Sutherland and D. E. Countiss, "Parametric phase distortionless L-band limiter," Proc. IRE (Correspondence), vol. 48, pp. 938–939; May, 1960.
[172] A. K. Kamal, "A parametric device as a nonreciprocal element," Proc. IRE, vol. 48, pp. 1424–1430; August, 1960.
[173] J. R. Macdonald, "Space-charge capacitors for parametric amplifiers," Proc. IRE (Correspondence), vol. 48, pp. 1483–1485; August, 1960.
[174] R. Zuleeg and V. W. Vodicka, "Parametric amplification properties in transistors," Proc. IRE (Correspondence), vol. 48, pp. 1785–1786; October, 1960.

3) Traveling-Wave Parametric Amplifiers: A number of theoretical papers [175]–[180] appeared giving a rigorous analysis of the traveling-wave parametric amplifier taking into account the nonlinear, parasitic, or lossy elements as well as the more usual simple time varying characteristics previously analyzed. A method for keeping the pump, signal, and idler in synchronism over a broadband is also discussed [181] in a theoretical paper. A detailed theoretical and experimental treatment of a coupled-cavity amplifier is given in two companion papers [182], [183]. Several other papers [184]–[186] present a theoretical and experimental discussion of various traveling-wave amplifiers in the UHF and S-band regions. One paper [187] describes an unusual amplifier structure using a helix.

[175] R. Landauer, "Parametric amplification along nonlinear transmission lines," *J. Appl. Phys.*, vol. 31, pp. 479–484; March, 1960.
[176] ——, "Parametric standing wave amplifiers," Proc. IRE (Correspondence), vol. 48, pp. 1328–1329; July, 1960.
[177] D. Fleri and J. Sie, "The effect of parasitic diode elements on traveling-wave parametric amplification," Proc. IRE (Correspondence), vol. 48, pp. 1330–1331; July, 1960.
[178] W. Jasinski, "Gain of a traveling-wave parametric amplifier using nonlinear lossy capacitors," Proc. IRE (Correspondence), vol. 48, pp. 2018–2019; December, 1960.
[179] K. Kurokawa and J. Hamasaki, "An extension of the mode theory to periodically distributed parametric amplifiers with losses," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 10–18; January, 1960.
[180] K. K. N. Chang. "Theory of a negative-resistance transmission line amplifier with distributed noise generators," *J. Appl. Phys.*, vol. 31, pp. 871–875; May, 1960.
[181] H. Boyet and D. Fleri, "A method for broad-banding synchronism in traveling-wave parametric devices," Proc. IRE (Correspondence), vol. 48, pp. 1331–1333; July, 1960.
[182] M. R. Currie and R. W. Gould, "Coupled-cavity traveling-wave parametric amplifiers: part I—analysis," Proc. IRE, vol. 48, pp. 1960–1973; December, 1960.
[183] K. P. Grabowski and R. D. Weglein, "Coupled-cavity traveling-wave parametric amplifiers: part II—experiments," Proc. IRE, vol. 48, pp. 1973–1987, December, 1960.
[184] R. C. Honey and E. M. T. Jones, "A wide-band UHF traveling-wave variable reactance amplifier," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 351–361; May, 1960.
[185] Clinton G. Shafer, "Design and operation of an S-band traveling-wave diode parametric amplifier," 1960 IRE WESCON Convention Record, pt. 1, pp. 49–54.
[186] C. V. Bell and G. Wade, "The noise figure of iterative traveling-wave parametric amplifiers," 1960 IRE WESCON Convention Record, pt. 1, pp. 55–60.
[187] G. Conrad, *et al.* "The diode-loaded helix as a microwave amplifier," Proc. IRE (Correspondence), vol. 48, pp. 939–940; May, 1960.

4) Electron-Beam Parametric Amplifiers: There has been apparently little experimental activity in electron-beam parametric amplifiers except for the Adler quadrupole type. Bridges and Ashkin [188] give experimental results on an Adler tube operating at 4140 Mc with 24-db gain, 67-Mc bandwidth, and 2.5-db double-channel noise figure. Possible causes of excess noise in Adler tubes are discussed [189] and analytical descriptions of various electron-beam amplifiers are given [190]–[193]. A novel dc-pumped quadrupole amplifier which needs no RF pump and has no idler is analyzed by Siegman [194]. Kino [195] gives a theoretical discussion of plasma and electron-beam parametric amplifiers.

[188] T. J. Bridges and A. Ashkin, "A microwave Adler tube," Proc. IRE (Correspondence), vol. 48, pp. 361–363; March, 1960.
[189] C. P. Lea-Wilson, "Some possible causes of noise in Adler tubes," Proc. IRE (Correspondence), vol. 48, pp. 255–256; February, 1960.
[190] C. C. Johnson, "Theory of fast-wave parametric amplification," *J. Appl. Phys.*, vol. 31, pp. 338–345; February, 1960.
[191] H. Sobol, "Extension of longitudinal-beam parametric-amplifier theory," Proc. IRE (Correspondence), vol. 48, pp. 792–793; April, 1960.
[192] B. J. Udelson, "An electrostatically focused electron beam parametric amplifier," Proc. IRE (Correspondence), vol. 48, pp. 1485–1486; August, 1960.
[193] Y. Matsuo, "New microwave tube devices 'Fawshmotron' using the fast electron wave," Proc. IRE (Correspondence), vol. 48, p. 1908; November, 1960.
[194] A. E. Siegman, "The dc pumped quadrupole amplifier—a wave analysis," Proc. IRE, vol. 48, pp. 1750–1755; October, 1960.
[195] G. S. Kino, "Parametric amplifier theory for plasmas and electron beams," *J. Appl. Phys.*, vol. 31, pp. 1449–1458; August, 1960.

5) *Ferrite Amplifier:* The most significant development in ferrite parametric amplifiers is Denton's [196] longitudinal-pumped magnetostatic amplifier which requires only fractional watt pump power for amplification at 4600 Mc. Thomson [197] also describes a longitudinal-pumping experiment in which subharmonic spin-wave excitation is observed. Damon and Eshbach [198] discuss the theoretical limitations to ferrite amplifier performance due to spin-wave instabilities.

[196] R. T. Denton, "A ferromagnetic amplifier using longitudinal pumping," Proc. IRE (Correspondence), vol. 48, pp. 937–938; May, 1960.
[197] A. F. H. Thomson, "Ferromagnetic amplifiers," Proc. IRE (Correspondence), vol. 48, p. 259; February, 1960.
[198] R. W. Damon and J. R. Eshbach, "Theoretical limitations to ferromagnetic parametric amplifier performance," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 4–9; January, 1960.

B. Tunnel Diodes

An excellent review of the properties, principle of operation, and applications of the tunnel diode is given by Hall [199]. Remarkable progress has been made in raising the frequency of oscillation of tunnel diodes [200] with the highest frequency reported [201] being 103 Gc. The power output varied from several milliwatts in the UHF [202] to 2 μw [201] at 90 Gc. The effect of voltage on the frequency of oscillation has also been investigated [203].

[199] R. N. Hall, "Tunnel diodes," IRE Trans. on Electron Devices, vol. ED-7, pp. 1–9; January, 1960.
[200] R. Trambarulo and C. A. Burrus, "Esaki diode oscillators from 3 to 40 kmc," Proc. IRE (Correspondence), vol. 48, pp. 1776–1777; October, 1960.
[201] C. A. Burrus, "Millimeter wave Esaki diode oscillators," Proc. IRE (Correspondence), vol. 48, p. 2024; December, 1960.
[202] D. E. Nelson and F. Sterzer, "Tunnel-diode microwave oscillators with milliwatt power outputs," 1960 IRE WESCON Convention Record, pt. 1, pp. 68–73.
[203] J. K. Pulfer, "Voltage tuning in tunnel diode oscillators," Proc. IRE (Correspondence), vol 48, p. 1155; June, 1960.

Progress has also been made in the use of tunnel diodes in amplifiers both in attaining unusual bandwidths [204] (210–625 Mc) and in reaching 26 Gc [205]. The noise figures, however, have not yet reached an attractively low level, with reports of 7 db at 4.5 Gc [206] to 10 db at X band. The tunnel diode has also been used as a down converter with gain [207], [208]. The use of distributed tunnel diodes which lend themselves naturally to microwave applications is discussed in an important paper by Hines [209].

[204] J. S. Sie, "Absolutely stable hybrid coupled tunnel-diode amplifier," Proc. IRE (Correspondence), vol. 48, p. 1321; July, 1960.
[205] R. F. Trambarulo, "Esaki diode amplifiers at 7, 11, and 26 kmc," Proc. IRE (Correspondence), vol. 48, pp. 2022–2023; December, 1960.
[206] A. Yariv, *et al.*, "Operation of an Esaki diode microwave amplifier," Proc. IRE (Correspondence), vol. 48, p. 1155; June, 1960.
[207] K. K. N. Chang, *et al.*, "Low-noise tunnel-diode down converter having conversion gain," Proc. IRE, vol. 48, pp. 854–858; May, 1960.
[208] W. J. Robertson, "A broad-band hybrid coupled tunnel diode down converter," Proc. IRE (Correspondence), vol. 48, pp. 2023–2024; December, 1960.
[209] M. E. Hines, "High-frequency negative-resistance circuit principles for Esaki diode applications," *Bell. Sys. Tech. J.*, vol. 39, pp. 477–513; May, 1960.

Great interest [210]–[218] has also been shown in theoretical calculations of the noise performance of tunnel-diode amplifiers and in design procedures for optimizing the amplifier noise performance.

[210] K. K. N. Chang, "The optimum noise performance of tunnel-diode amplifiers," Proc. IRE (Correspondence), vol. 48, pp. 107–108; January, 1960.
[211] M. E. Hines and W. W. Anderson, "Noise performance theory of Esaki (tunnel) diode amplifiers," Proc. IRE (Correspondence), vol. 48, p. 789; April, 1960.
[212] A. van der Ziel and J. Tamiya, "Note on the noise figure of negative conductance amplifiers," Proc. IRE (Correspondence), vol. 48, p. 796; April, 1960.
[213] D. I. Breitzer, "Noise figure of tunnel diode mixer," Proc. IRE (Correspondence), vol. 48, pp. 935–936; May, 1960.
[214] A. van der Ziel, "Noise of measure of lossy tunnel diode amplifiers," Proc. IRE (Correspondence), vol. 48, pp. 1321–1322; July, 1960.
[215] J. J. Tiemann, "Shot noise in tunnel diode amplifiers," Proc. IRE, vol. 48, pp. 1418–1423; August, 1960.
[216] P. Penfield, Jr., "Noise performance of tunnel-diode amplifiers," Proc. IRE (Correspondence), vol. 48, pp. 1478–1479; August, 1960.
[217] E. G. Nielsen, "Noise performance of tunnel diodes," Proc. IRE (Correspondence), vol. 48, pp. 1903–1904; November, 1960.
[218] R. La Rosa and C. R. Wilhelmsen, "Theoretical justification for shot-noise smoothing in the Esaki diode," Proc. IRE (Correspondence), vol. 48, p. 1903; November, 1960.

The use of metal and insulator films as a tunnel-emission amplifier has been proposed [219] though not specifically for microwave applications.

[219] C. A. Mead, "The tunnel-emission amplifier," Proc. IRE, vol. 48, pp. 359–361; March, 1960.

C. Masers

Solid-state masers have received continuing attention with two papers [220], [221] discussing the progress that has been made in packaging masers and making them suitable for low-noise-system applications. In radar applications [222], conventional duplexers cannot adequately prevent degradation of maser performance due to the saturation effects of the leakage spike. However, in ruby masers, a desaturation pulsing technique is described [223] which significantly reduces the maser recovery time. Several tunable masers are described [224], [225] and a novel broad-banding technique is described [226] which makes use of the fact that a maser has a negative L and C characteristic. Another paper [227] gives a thorough discussion of the parameters entering the design of masers of the unidirectional type which do not require circulators. A 70 Gc-pulsed-field maser [228] and several titania masers are also discussed [229]–[231]. The technique of noise temperature measurement of a traveling-wave maser is described by DeGrasse and Scovil [232].

[220] H. R Senf, "Masers for systems applications," 1960 IRE WESCON Convention Record, pt. 1, pp. 43–48.
[221] F. R. Arams and S. Okwit, "Packaged tunable L-band maser system," Proc. IRE, vol. 48, pp. 866–874; May, 1960.
[222] J. L. Carter, *et al.*, "Use of an X-band solid-state ruby maser with a conventional duplexing system," *Microwave J.*, vol. 3, pp. 43–46; July, 1960.
[223] G. K. Wessel, "Recovery technique for saturated masers," IRE Trans. on Electron Devices, vol. ED-7, pp. 297–302; October, 1960.
[224] P. D. Gianino and F. J. Dominick, "A tunable X-band ruby maser," Proc. IRE (Correspondence), vol. 48, p. 260; February, 1960.

[225] S. Okwit, *et al.*, "Electronically-tunable traveling-wave masers at L and S bands," PROC. IRE (Correspondence), vol. 48, pp. 2025–2026; December, 1960.
[226] R. L. Kyhl, "Negative L and C in solid-state masers," PROC. IRE (Correspondence), vol. 48, p. 1157; June, 1960.
[227] M. W. P. Strandberg, "Unidirectional paramagnetic amplifier design," PROC. IRE, vol. 48, pp. 1307–1320; July, 1960.
[228] L. R. Momo, *et al.*, "Pulsed field millimeter wave maser," *J. Appl. Phys.*, vol. 31, p. 443; February, 1960.
[229] S. Foner and L. R. Momo, "CW millimeter wave maser using Fe^{3+} in TiO_2," *J. Appl. Phys.*, vol. 31, pp. 742–743; April, 1960.
[230] H. J. Gerritsen and H. R. Lewis, "Operation of a chromium doped titania maser," *J. Appl. Phys.*, vol. 31, pp. 608–609; March, 1960.
[231] H. J. Gerritsen, *et al.*, "Chromium-doped titania as a maser material," *J. Appl. Phys.*, vol. 31, pp. 1566–1571; September, 1960.
[232] R. W. DeGrasse and H. E. D. Scovil, "Noise temperature measurement on a traveling-wave maser preamplifier," *J. Appl. Phys.*, vol. 31, pp. 443–444; February, 1960.

The possibility of amplifying signals at frequencies higher than the pump is described by Arams [233] who uses harmonic-spin coupling to amplify a 10,590-Mc signal using a 9595-Mc pump. Another paper [234] shows that maser action in nuclear-quadrupole systems is unlikely to result in net gain, although it is shown [235] that by applying an RF field near the frequency of the quadrupole resonance of the Al nuclei, increased gain of a ruby maser results. Proposals are also made for millimeter-wave oscillators using a beam-type gas maser [236] or Na atoms in a cavity [237]. Theoretical expressions for the emitted power and frequency pulling in an ammonia-beam maser are given [238] while the productizing of an ammonia maser as a frequency standard is also described [239]. The problem of beam formation for a gas maser is discussed in two papers [240], [241].

[233] F. R. Arams, "Maser operation with signal frequency higher than pump frequency," PROC. IRE (Correspondence), vol. 48, p. 108; January, 1960.
[234] R. E. Donovan and A. A. Vuylsteke, "On the possibility of maser action in nuclear quadrupole systems," *J. Appl. Phys.*, vol. 31, pp. 614–615; March, 1960.
[235] G. Makhov, *et al.*, "Effect of nuclear polarization on the behavior of solid state masers," *J. Appl. Phys.*, vol. 31, pp. 936–938; May, 1960.
[236] W. Gordy and M. Cowan, "Proposed molecular amplifier and coherent generator for millimeter and submillimeter waves," *J. Appl. Phys.*, vol. 31, pp. 941–942; May, 1960.
[237] S. M. Bergmann, "Submillimeter wave maser," *J. Appl. Phys.*, vol. 31, pp. 275–276; February, 1960.
[238] H. G. Venkates and M. W. P. Strandberg, "Operating characteristics of a molecular-beam maser," *J. Appl. Phys.*, vol. 31, pp. 396–399; February, 1960.
[239] S. Hopfer, "Design considerations for a self-contained ammonia maser oscillator," 1960 IRE INTERNATIONAL CONVENTION RECORD, pt. 3, pp. 78–86.
[240] J. C. Helmer, *et al.*, "Focusing molecular beams of NH_3," *J. Appl. Phys.*, vol. 31, pp. 458–463; March, 1960.
[241] J. A. Giordmaine and T. C. Wang, "Molecular beam formation by long parallel tubes," *J. Appl. Phys.*, vol. 31, pp. 463–471; March, 1960.

The most significant development in the whole field of quantum electronics is of course the first realization of the optical maser by Maiman [242]. This development opens up a whole new area of technology of great importance. Though perhaps not properly falling into the field of microwave theory and techniques, the optical maser is certainly the child of the microwave maser and can indeed profit from the application of microwave techniques as evidenced in the Fox and Li [243] paper.

[242] T. H. Maiman, "Optical maser action in ruby," *British Commun. and Electronics*, vol. 7, pp. 674–675; September, 1960. See also, R. J. Collins, *et al.*, "Coherence, narrowing, directionality, and relaxation oscillations in the light emission from ruby," *Phys. Rev.*, vol. 5, pp. 303–305; October, 1960.
[243] A. G. Fox and T. Li, "Resonant modes in an optical maser," PROC. IRE (Correspondence), vol. 48, pp. 1904–1905; November, 1960.

D. Ferrites

1) General Microwave Properties: There is a very extensive literature on fundamental investigations of ferrites, particularly on ferrimagnetic resonance, magnetostatic modes, high-power studies, magnetic structure and chemistry, and anisotropy. A good many of these papers are included in the *Proceedings of the Fifth Symposium on Magnetism and Magnetic Materials* published as a supplement to the May, 1960, *Journal of Applied Physics*. In order to make the present review of manageable size, most of the papers which deal with ferrites from the fundamental physics point of view rather than from the point of view of microwave applications are not included. It is hoped that the availability of the above *Proceedings* in the *Journal of Applied Physics* will serve as an adequate bibliographical source for those interested in the areas not covered by this review.

An excellent historical sketch of the ferrite field together with an 82-item bibliography is given by Button [244]. Button and Lax [245] have also published an outstanding three-part review paper on the microwave properties and applications of ferrites. Magnetostatic modes are reviewed by White [246], while Morgenthaler [247] gives a brief theoretical survey of ferrimagnetic resonance in ellipsoids. A review of resonance phenomena at high-power levels is given by Schlömann, *et al.* [248], who also give a detailed discussion of subsidiary absorption obtained with a microwave magnetic field applied parallel to the dc field. New methods for growing large single crystal garnets are given by Nielsen [249]. The progress made in the theory of propagation in ferrite-loaded structures has been discussed in Section II-A, 2) of the present review.

[244] K. J. Button, "Historical sketch of ferrites and their microwave applications," *Microwave J.*, vol. 3, pp. 73–79; March, 1960.
[245] B. Lax and K. J. Button, "Electromagnetic properties of ferrimagnets and their applications from UHF to millimeter waves," *Microwave J.*, vol. 3, pt. I, pp. 43–49; September; pt. II, pp. 52–62, October; pt. III, pp. 49–56, November, 1960.
[246] R. L. White, "Use of magnetostatic modes as a research tool," *J. Appl. Phys.*, vol. 31, pp. 86S–94S; Supplement to May, 1960.
[247] F. R. Morgenthaler, "Survey of ferromagnetic resonance in small ferrimagnetic ellipsoids," *J. Appl. Phys.*, vol. 31, pp. 95S–97S; Supplement to May, 1960.
[248] E. Schlömann, *et al.*, "Recent developments in ferrimagnetic resonance at high power levels," *J. Appl. Phys.*, vol. 31, pp. 386S–395S; Supplement to May, 1960.
[249] J. W. Nielsen, "Improved method for the growth of yttrium-iron and yttrium-gallium garnets," *J. Appl. Phys.*, vol. 31, pp. 51S–52S; Supplement to May, 1960.

High-power effects have been studied extensively and a representative list of papers should include the following [250]–[254]. An experimental study of the linewidth of high-anisotropy materials is given by Bady, *et al.* [255].

[250] E. Schlömann, *et al.*, "L-band ferromagnetic resonance experiments at high peak power levels," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 96–100; January, 1960.
[251] J. J. Green and E. Schlömann, "High power ferromagnetic resonance at X-band in polycrystalline garnets and ferrites," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 100–103; January, 1960.
[252] P. E. Seiden and H. J. Shaw, "High-power effects in ferrite devices," Proc. IRE (Correspondence), vol. 48, p. 122; January, 1960.
[253] M. T. Weiss, "High power effects on ferrimagnetic resonance," *J. Appl. Phys.*, vol. 31, pp. 778–782; May, 1960.
[254] F. C. Rossol, "Subsidiary resonance in the coincidence region in yttrium iron garnet," *J. Appl. Phys.*, vol. 31, pp. 2273–2275; December, 1960.
[255] Isidore Bady, *et al.*, "Ferrimagnetic linewidth of single crystals of barium ferrite ($B_aF_{e12}O_{19}$)," Proc. IRE (Correspondence), vol. 48, p. 2033; December, 1960.

2) Ferrite Devices: For commercial purposes, the *Y* circulator has become of very great importance and a number of papers are devoted to the design of such devices [256]–[258]. *Y* circulators have now been developed in most frequency ranges from 360 Mc [259] to 140 Gc [260]. A similar device, called the three-port ring circulator [261], which makes use of nonreciprocal phase shifters, has also been developed.

[256] U. Milano, *et al.*, "A *Y*-junction strip-line circulator," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 346–351; May, 1960.
[257] L. Freiberg, "Lightweight *Y*-junction strip-line circulator," IRE Trans. on Microwave Theory and Techniques (Correspondence), vol. MTT-8, p. 672; November, 1960.
[258] S. Yoshida, "Strip-line *Y* circulator " Proc. IRE (Correspondence), vol. 48, pp. 1337–1338; July, 1960.
[259] ——, "*J*-band strip line *Y* circulator," Proc. IRE (Correspondence), vol. 48, p. 1664; September, 1960.
[260) J. B. Thaxter and G. S. Heller, "Circulators at 70 and 140 kmc," Proc. IRE (Correspondence), vol. 48, pp. 110–111; January, 1960.
[261] M. Grace and F. R. Arams, "Three-port ring circulators," Proc. IRE (Correspondence), vol. 48, pp. 1497–1498; August, 1960.

A detailed theoretical discussion of resonance isolators is given by Schlömann [262], while an analytical and experimental study of the field displacement isolator is presented by Comstock and Fay [263]. In the UHF region, there is a need for avoiding coincidence of main and subsidiary resonance in a resonance isolator and a method for accomplishing this is described [264].

[262] E. Schlömann, "On the theory of the ferrite resonance isolator," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 199–206; March, 1960.
[263] R. L. Comstock and C. E. Fay, "Operation of the field displacement isolator in rectangular waveguide," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 605–611; November, 1960.
[264] E. Stern, "Ferrite shape considerations for UHF high-power isolators," IRE Trans. on Microwave Theory and Techniques (Corresponcence), vol. MTT-8, p. 565; September, 1960.

Several new ferrite switches are described including one making use of the zero-permeability condition of the ferrite as a reflective switch [265], one using ferrite toroids [266], and one using multimode propagation [267] with a 3000-Mc bandwidth at *X* band. Weiss [268], [269] describes the tetrahedral junction as a switch. This device consists of two waveguides which are mutually cross-polarized and loaded by a longitudinally-magnetized ferrite rod. The use of a quadruply-ridged waveguide in the Faraday rotators and a doubly-ridged rectangular waveguide in an isolator is described by Grimes *et al.* [270], and in a single-ridge waveguide by Chen [271]. Higher-order modes and temperature sensitivity in the Reggia-Spencer phase shifter are discussed [272] and a wide ferrite-slab phase shifter is described [273].

[265] C. M. Johnson and J. C. Wiltse, "A broad-band ferrite reflective switch," IRE Trans. on Microwave Theory and Techniques (Correspondence), vol. MTT-8, pp. 466–467; July, 1960.
[266) L. Levey and L. M. Silber, "A fast-switching *X*-band circulator utilizing ferrite toroids," 1960 IRE WESCON Convention Record, pt. 1, pp. 11–20.
[267] J. E. Tompkins, *et al.*, "Multimode propagation in gyromagnetic rods and its application to traveling-wave devices," *J. Appl. Phys.*, vol. 31, pp. 176S–177S; Supplement to May, 1960.
[268] J. A. Weiss, "The tetrahedral junction as a waveguide switch," IRE Trans. on Microwave Theory and Techniques (Correspondence), vol. MTT-8, pp. 120–121; January, 1960.
[269] ——, "Tetrahedral junction," *J. Appl. Phys.*, vol. 31, pp. 168S–169S; Supplement to May, 1960.
[270] E. S. Grimes, *et al.*, "Broad-band ridge waveguide ferrite devices," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 489–492; September, 1960.
[271] T. S. Chen, "Nonreciprocal attenuation of ferrite in single-ridge waveguide," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 247–248; March, 1960.
[272] A. Clavin, "Reciprocal ferrite phase shifters," IRE Trans. on Microwave Theory and Techniques (Correspondence), vol. MTT-8, pp. 254–255; March, 1960.
[273] T. D. Geiszler and R. A. Henschke, "Broadband reciprocal ferrite phase shifters," *J. Appl. Phys.*, vol. 31, pp. 174S-175S; Supplement to May, 1960.

Two papers [274], [275] describe Faraday-rotation structures while Coale [276] discusses a novel rotating half-wave plate which uses a four-wire transmission line for generating both the rotating microwave fields and the rotating low-frequency magnetizing fields. The use of single crystal garnets in microwave filters is discussed in three papers [277], [278], [105]. Several papers [279]–[281] treat the problem of microwave generation by pulsed-magnetic fields.

[274] W. Beust and E. G. Johnson, "High average power rotator," *Microwave J.*, vol. 3, pp. 55–57; May, 1960.
[275] S. J. Lewandowski and J. Konopka, "On some problems in designing microwave Faraday-rotation devices," IRE Trans. on Microwave Theory and Techniques (Correspondence), vol. MTT-8, pp. 249–251; March, 1960.
[276] F. S. Coale, "High-speed ferrite rotating half wave plate," *J. Appl. Phys.*, vol. 31, pp. 170S–171S; Supplement to May, 1960.
[277] P. S. Carter, Jr., "Magnetically tunable microwave filters employing single crystal garnet resonators," 1960 IRE International Convention Record, pt. 3, pp. 130–135.
[278] —— and C. Flammer, "Unloaded *Q* of single crystal yttrium-iron-garnet resonator as a function of frequency," IRE Trans. on Microwave Theory and Techniques (Correspondence), vol. MTT-8, pp. 570–571; September, 1960.
[279] B. J. Elliot, *et al.*, "Pulsed ferrimagnetic microwave generator," *J. Appl. Phys.*, vol. 31, pp. 400S–401S; Supplement to May, 1960.
[280] T. Schaug-Pattersen, "Growing spin waves in ferrites in unstable equilibrium," *J. Appl. Phys.*, vol. 31, pp. 372S–383S; Supplement to May, 1960.
[281] M. R. Stiglitz and F. R. Morgenthaler, "Resonance experiments with single crystal YIG in pulsed magnetic fields," *J. Appl. Phys.*, vol. 31, pp. 37S–38S; Supplement to May, 1960.

3) Ferroelectrics: Gemulla and Hall [282] review the field of ferroelectrics at microwave frequencies and point out the many problems yet to be solved before extensive applications become practical. Two other papers discuss the use of the nonlinear properties of ferroelectrics as microwave mixers [283] and parametric amplifiers [284].

[282] W. J. Gemulla and R. D. Hall, "Ferroelectrics at microwave frequencies," *Microwave J.*, vol. 3, pp. 47–51; February, 1960.
[283] I. Goldstein, "Interaction of two microwave signals in a ferroelectric material," Proc. IRE (Correspondence), vol. 48, p. 1665; September, 1960.
[284] Y. Aoki, "Proposed parametric amplifier utilizing ferroelectric substance," IRE Trans. on Microwave Theory and Techniques, (Correspondence) vol. MTT-8, pp. 465–466; July, 1960.

IV. Measurements and Microwave Systems

A. Systems

Microwave and millimetric radiometry has again been prominent in the microwave field. An excellent review paper is by Harris [285]; Richter has described a 33-Gc radiometer [286]. The microwave aspects of particle accelerators have been covered in three articles: Barrington, *et al.*, discuss the RF system for a synchrotron [287]; Robinson discusses the Cambridge electron accelerator [288]; a review paper on linear accelerators has also appeared [289]. The problems of duplexing a ruby maser in a radar have been examined [290]. Finally, a frequency control system using a reference cavity has been patterned after an ac carrier servo by using a 100-kc crystal to modulate the reference cavity [291].

[285] D. B. Harris, "Microwave radiometry," *Microwave J.*, vol. 3, pt. I, pp. 41–46, April; pt. II, pp. 47–54, May, 1960.
[286] E. W. Richter, "Millimeter radiometers," *Microwave J.*, vol. 3, pp. 63–66; October, 1960.
[287] A. E. Barrington, *et al.*, "Model studies of a strongly coupled synchrotron RF system," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 597–604; November, 1960.
[288] K. W. Robinson, "Radio-frequency system of the Cambridge electron accelerator," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 593–596; November, 1960.
[289] A. E. Barrington, "Microwave engineering aspects of electron linear accelerators," *Microwave J.*, vol. 3, pt. I, pp. 35–40, April; pt. II, pp. 54–58, June, 1960.
[290] F. E. Goodwin, "Duplexing a solid-state ruby maser in an X-band radar system," Proc. IRE (Correspondence), vol. 48, p. 113; January, 1960.
[291] J. R. Singer, "A new automatic frequency regulation system," IRE Trans. on Microwave Theory and Techniques (Correspondence), vol. MTT-8, p. 249; March 1960.

B. High-Power Resonators

Resonant ring circuits for testing of high-power components have arrived at a high degree of perfection. Tomiyasu has given curves relating ring gain, coupling, and ring attenuation [292]. Golde has presented a derivation of loaded and unloaded Q and gives parametrically the ratio of these vs gain [293]. Miller has considered, in addition, impedance mismatch effects [294]. This last paper also gives sample waveforms and includes photographs of breakdown phenomena.

[292] K. Tomiyasu "Attenuation in a resonant ring circuit," IRE Trans. on Microwave Theory and Techniques (Correspondence), vol. MTT-8, pp. 253–254; March, 1960.
[293] H. Golde, "Theory and measurement of Q in resonant ring circuits," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 560–564; September, 1960.
[294] S. J. Miller, "The traveling wave resonator and high power microwave testing," *Microwave J.*, vol. 3, pp. 50–58; September, 1960.

C. Dielectric Measurements

One method of measuring constitutive parameters involves filling a length of transmission line or waveguide with the dielectric material. Sharpe terminates the transmission line with a sliding short and uses a bilinear transformation to derive the constants [295]. He shows that for a TEM line the transformation leads to an immediate solution via the Smith chart. A similar technique has been used on single crystals of barium titanate, measuring transmission resonances through a section of filled waveguide [296]. Another method uses a resonant dielectric cylinder between metal plates, where the Q and two resonant frequencies are measured [297]. Culshaw has developed a Fabry-Perot interferometer at 6 mm [298].

[295] C. B. Sharpe, "A graphical method for measuring dielectric constants at microwave frequencies," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 155–159; March, 1960.
[296] A. Lurio and E. Stern, "Measurements of the dielectric constant of $B_aT_iO_3$ single crystals in the paraelectric region at X-band," *J. Appl. Phys.*, vol. 31, pp. 1805–1809; October, 1960.
[297] B. W. Hakki and P. D. Coleman, "A dielectric resonator method of measuring inductive capacities in the millimeter range," IRE Trans. on Microwave Theory and Techniques vol. MTT-8, pp. 402–410; July, 1960.
[298] W. Culshaw, "High resolution millimeter wave Fabry-Perot interferometer," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 182–189; March, 1960.

D. Noise Temperature

Low-noise systems have continued to be of great interest. Haun calculates single- and double-sideband noise figures for parametric amplifiers for the general case where gain is different at the two sidebands [299]. The often quoted difference of 3 db is only correct if the gain is the same at both sidebands. Hogg, in a pair of papers, has reported on investigations of sky temperature [300], [301]. At 6 Gc the sky temperature during a storm may be as high as 120°K. Extensive nonstormy data are given on sun temperature, galactic noise, atmospheric-absorption noise, etc., for a wide range of frequencies. Finally, detailed calculations for the performance of a low-noise radar at 5 Gc have been made [302].

[299] R. D. Haun, Jr., "Summary of measurement techniques of parametric amplifier and mixer noise figure," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 410–415; July, 1960.
[300] D. C. Hogg and R. A. Semplak, "The effect of rain on the noise level of a microwave receiving system," Proc. IRE (Correspondence), vol. 48, pp. 2024–2025; December, 1960.
[301] D. C. Hogg and W. W. Mumford, "The effective noise temperature of the sky," *Microwave J.*, vol. 3, pp. 80–84; March, 1960.
[302] R. L. Forward and F. Richey, "Effects of external noise on radar performance," *Microwave J.*, vol. 3, pp. 73–80; December, 1960.

E. Miscellaneous Measurements

A general method for analyzing microwave measurements using flow graphs has been proposed by Hunton [303]. This procedure takes the place of the scattering matrix solution, and for some purposes it is simpler. Lerner and Wheeler measure filter bandwidths by adjusting amplitude modulation of the signal until a 45° phase shift is realized across the filter [304]. Q is then simply given by the ratio of carrier frequency to twice modulation frequency. Finnila, *et al.*, have developed a technique for measuring relative microwave phase shift in cases where a wide difference in signal amplitudes exists [305]. They use a Serrodyne technique to translate both signals to audio, where wide differences in level can readily be handled. Another analysis compares phase-shift mismatch errors for several choices of reference wave [306]. Hu has extended the modulated dipole scatterer method for measuring electric field to the case of a modulated loop scatterer for measuring magnetic field [307]. Other devices include a calorimeter with an absorptive harmonic filter for multimode power measurements [308], and a bridge-type impedance meter [309].

[303] J. K. Hunton, "Analysis of microwave measurement techniques by means of signal flow graphs," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-8, pp. 206–212; March, 1960.
[304] D. S. Lerner and H. A. Wheeler, "Measurement of bandwidth of microwave resonator by phase shift of signal modulation," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-8, pp. 343–345; May, 1960.
[305] C. A. Finnila, *et al.*, "Measurement of relative phase shift at microwave frequencies," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-8, pp. 143–147; March, 1960.
[306] G. E. Schafer, "Mismatch errors in microwave phase shift measurements," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-8, pp. 617–622; November, 1960.
[307] M.-K. Hu, "On measurements of microwave $\bar{E}$ and $\bar{H}$ field distributions by using modulated scattering methods," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-8, pp. 295–300; May, 1960.
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Several new techniques have appeared for measuring specific devices or material characteristics. In the Doppler method for measuring back scatter, the sample (in this case absorber) is nutated by means of counter-rotating eccentric disks in a ground plane [310]. This imparts an audio modulation to the scattered return, thereby allowing greater suppression of extraneous signals. A nanosecond-pulse radar has been useful in identifying internal reflections of TWT's [311]. Several papers relate to excess carrier lifetime in semiconductor materials [312]–[314]. The technique (see Section IV-C) uses a section of waveguide filled with the material; incident light pulses create excess carriers whose lifetime is determined from measurements of the microwave power absorption through the sample.

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The Short Pulse Behavior of Lossy Tapered Transmission Lines*

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Summary—**An analytic method is given which allows the design engineer to assess rapidly the short pulse characteristics of any given tapered-transmission-line type of pulse transformer. The method allows inclusion of both skin-effect losses and losses which are independent of frequency. The effects of mismatching at either end are shown to be as important as the taper function of the line itself. The results of this approximate method are expressed as simple integrals and matching terms to which it is easy to attach physical significance.**

The method is applied to the analysis of two tapered-line pulse transformers which are geometrically uniform coaxial structures with tapered dielectric constants. The line whose nominal characteristic impedance is an exponential function of electrical position is shown to have a good rise time and tilt distortion characteristics.

INTRODUCTION

IN the already extensive literature on the tapered-transmission-line pulse transformer,[1] there has been little investigation of the pulse-distorting effects of losses in the tapered line. That such distortions must exist is evident, for even the lossy uniform line can be

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