Report of Advances in Microwave Theory and Techniques—1954

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THE FIELD OF interest indicated by the title includes the transmission, control, measurement, and generation of microwaves. We shall consider transmission only in the form of guided waves, leaving antenna and propagation problems as a subject deserving of a review in its own right. Similarly, we shall take note of the circuit aspects of microwave amplifiers and generators. Space charge, focusing, and noise problems associated with microwave oscillators are probably best considered separately, since they often require very different theoretical approaches and experimental techniques. With these boundaries to our review established, we must proceed to subdivide the area of interest for detailed discussion. We follow here a somewhat arbitrary set of headings which aim to clarify and codify the material without duplication.

Waveguides

The dominant characteristic of microwaves is their length, which permits a variety of convenient waveguide structures to be designed for scientific and engineering applications. The potentialities of *conventional hollow waveguide* have by no means been exhausted. Efforts at realizing the favorable attenuation and bandwidth characteristics of the TE_{01}° mode continue with increasing success, as indicated in the following papers:

(1) L. S. Sheingold and J. E. Storer, "Circumferential gap in circular waveguide excited by a dominant circular-electric wave," *Jour. Appl. Phys.*, vol. 25, pp. 545–552; May, 1954.
(2) S. E. Miller, "Waveguide as a communication medium," *Bell Sys. Tech. Jour.*, vol. 33, pp. 1209–1265; November, 1954.
(3) D. A. Lanciani, "H_{01} mode circular waveguide components," Trans. IRE, vol. MTT-2, pp. 45–51; July, 1954.
(4) G. A. Grinberg and B. E. Bonshtedt, "Foundations of an exact theory of the wave field of a transmission line," *Zh. tekh. Fiz.*, vol. 24, pp. 67–95; January, 1954.
(5) F. J. Tischer, "Transmission and matching theory of homogeneously guided waves," *Arch. elekt. Übertragung*, vol. 8, pp. 8–14 and 75–84; January/February, 1954.

The propagation of *pulses in hollow waveguide* has received special attention.

(6) M. Cotte, "Propagation of a pulse in a waveguide," *Onde élect.*, vol. 34, pp. 143–146; February, 1954.
(7) P. Poincelot, "Time constant of a cylindrical electric guide," *Compt. Rend. Acad. Sci.* (*Paris*), vol. 238, pp. 2394–2395; June 21, 1954.

Modified guides involving dielectric or periodic loading, steps, or curved surfaces have been studied in considerable variety.

(8) R. N. Bracewell, "Step discontinuities in disk transmission lines," Proc. IRE, vol. 42, pp. 1543–1547; October, 1954.
(9) D. Graffi, "Waveguides with nonhomogeneous dielectric," Proc. IRE, vol. 42, pp. 1449–1450; September, 1954.
(10) K. S. Kunz, "Propagation of microwaves between a parallel pair of doubly curved conducting surfaces," *Jour. Appl. Phys.*, vol. 25, pp. 642–653; May, 1954.
(11) D. J. Angelakos, "A coaxial line filled with two nonconcentric dielectrics," *Trans. IRE*, vol. MTT-2, pp. 39–44; July, 1954.
(12) S. B. Cohn, "Characteristic impedance of the shielded-strip transmission line," *Trans. IRE*, vol. MTT-2, pp. 52–57; July, 1954.
(13) M. DeSocio, "Representation of the electromagnetic field in a waveguide with absorbent walls," *R.C. Acad. naz. Lincei*, vol. 16, pp. 63–68; January, 1954.
(14) R. Combe, "Pass band and dispersion of waveguides loaded with circular irises," *Compt. Rend. Acad. Sci.* (*Paris*), vol. 238, pp. 1697–1699; April 26, 1954.
(15) H. Weber, "The dimensioning of loaded waveguides for the H_{10} mode," *Telefunken Ztg.*, vol. 27, pp. 44–53; March, 1954.
(16) H. Uchida, Y. Mushiake, and S. Nishida, "Transmission Loss of the Waveguide having Thin Dielectric Film on its Inner Wall," Sci. Rep. Res. Inst., Tohoku Univ., Japan, Ser. B, vol. 4, pp. 287–298; March, 1953.
(17) S. K. Chatterjee, "Propagation of microwaves through cylindrical metallic guide filled coaxially with two different dielectrics: part 5," *Jour. Indian Inst. Sci.*, sec. B, vol. 36, pp. 48–58; April, 1954.
(18) R. Combe, "Attenuation coefficient of waveguides loaded with circular irises," *Compt. Rend. Acad. Sci.* (*Paris*), vol. 238, pp. 2063–2065; May 24, 1954.
(19) G. N. Rapoport, "Some results of the general theory of waveguides with diaphragms," *Radioteknika* (*Moscow*), vol. 9, pp. 79–80; May/June, 1954.

Junctions between various guides have also been considered.

(20) J. D. Pearson, "A contribution to the theory of right-angled junctions in waveguides," *Quart. Jour. Mech. Appl. Math.*, vol. 7, part 2, pp. 194–202; June, 1954.
(21) E. G. Solov'ev, "Conical joint," *Radioteknika* (*Moscow*), vol. 9, pp. 76–78; May/June, 1954.
(22) B. A. Dahlman, "Application of Brewster's angle to the design of coaxial-line components for microwaves," *RCA Rev.* XV, pp. 239–251; June, 1954.

The *helical line or waveguide* occupies a particularly important place since the advent of traveling-wave tubes. Traveling-wave tube applications continue to stimulate much of the research on helical guides. However, the general circuit properties have also received attention, particularly their advantages for broadband applications.

(23) V. J. Fowler, "Analysis of helical transmission lines by means of the complete circuit equations," *Trans. IRE*, vol. AP-3, pp. 132–143; October, 1954.
(24) W. Sichak, "Coaxial line with helical inner conductor," Proc. IRE, vol. 42, pp. 1315–1319; August, 1954.
(25) L. Stark, "Lower modes of a concentric line having a helical inner conductor," *Jour. Appl. Phys.*, vol. 25, pp. 1155–1162; September, 1954.
(26) R. C. Honey, "A traveling-wave electron deflection system," *Trans. IRE*, vol. MTT-2, pp. 2–9; July, 1954.
(27) J. H. Bryant, "Some wave properties of helical conductors," *Elec. Commun.*, vol. 31, pp. 50–56; March, 1954.
(28) D. A. Watkins and E. A. Ash, "The helix as a backward-wave circuit structure," *Jour. Appl. Phys.*, vol. 25, pp. 782–790; June, 1954.
(29) J. R. Pierce and P. K. Tien, "Coupling of modes in helixes," Proc. IRE, vol. 42, pp. 1389–1396; September, 1954.
(30) P. K. Tien, "Bifilar helix for backward-wave oscillators," Proc. IRE, vol. 42, pp. 1137–1143; July, 1954.

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The interaction of several waves along a single line or on adjacent lines is of basic importance to traveling-wave devices, whether they be amplifiers, oscillators, or couplers. The general *theory of coupled waves* has been carefully studied by a number of authors. Their results lead to a better understanding of multimode guides, directional couplers, and other circuit elements. A now well-established proposition is the following: no interaction takes place when either the attenuation or phase constants of the two waves differ significantly. This result is easy to grasp and powerful in its application.

(31) J. R. Pierce, "Coupling of modes of propagation," *Jour. Appl. Phys.*, vol. 25, pp. 179–183; February, 1954.
(32) B. M. Oliver, "Directional electromagnetic couplers," Proc. IRE, vol. 42, pp. 1686–1692; November, 1954.
(33) W. L. Firestone, "Analysis of transmission line directional couplers," Proc. IRE, vol. 42, pp. 1529–1538; October, 1954.
(34) S. E. Miller, "Coupled wave theory and waveguide applications," *Bell Sys. Tech. Jour.*, vol. 33, pp. 661–719; May, 1954.

Waveguides are usually thought of in terms of an enclosure completely confining the wave. However, propagation along a suitable surface is also possible. Here the binding of the wave is accomplished through a layer providing a reduced velocity of propagation. This layer may consist of dielectric material or of regular corrugations on a metal or dielectric surface. *Surface waves* are particularly useful where the ultimate purpose is to couple to an extended radiating element. By virtue of the large area occupied by the wave, low dissipation losses may also be realized, albeit at the expense of some radiation loss.

(35) A. E. Karbowiak, "Theory of composite guides: stratified guides for surface wave," *Jour. IEE*, part III, vol. 101, pp. 238–242; July, 1954.
(36) A. L. Cullen, "The excitation of plane surface waves," *Jour. IEE*, part III, vol. 101, pp. 276–277 (Abstract); July, 1954.
(37) H. E. M. Barlow and A. E. Karbowiak, "An experimental investigation of the properties of corrugated cylindrical surface waveguides," *Jour. IEE*, part III, vol. 101, pp. 182–188; May, 1954.
(38) H. Ataka, "A series laminated conductor for high frequencies," Proc. IRE, vol. 42, pp. 1527–1529; October, 1954.
(39) L. Hatkin, "Analysis of propagating modes in dielectric sheets," Proc. IRE, vol. 42, pp. 1565–1568; October, 1954.
(40) E. H. Scheibe, B. G. King, and D. L. Van Zeeland, "Loss measurements of surface transmission lines," *Jour. Appl. Phys.*, vol. 25, pp. 790–797; June, 1954.
(41) M. T. Weiss and E. M. Gyorgy, "Low-loss dielectric waveguides," *Trans. IRE*, vol. MTT-2, pp. 33–37; September, 1954.
(42) H. G. Unger, "Dielectric tubes as waveguides," *Arch. elekt. Übertragung*, vol. 8, pp. 241–252; June, 1954.
(43) T. E. Roberts, Jr., "An experimental investigation of the single-wire transmission line," *Trans. IRE*, vol. AP-2, pp. 46–56; April, 1954.
(44) M. D. Karasev and V. A. Apanasenko, "Surface waves propagated along a single cylindrical conductor," *Zh. Tekh. Fiz.*, vol. 24, pp. 662–666; April, 1954.

Strip lines ("microstrip") are also playing an increasing role as compact microwave transmission lines. Twenty-two papers on this subject were presented at a Symposium on Microwave Strip Circuits at Tufts College, Medford, Mass., on October 11 and 12, 1954. They have been published in a special issue of the Transactions of the IRE, vol. MTT-3, No. 2; March, 1955. The papers are listed below.

(45) M. Arditi, "Characteristics and application of microstrip for microwave wiring."
(46) E. N. Torgow and J. E. Griemsmann, "Miniature strip transmission line for microwave applications."
(47) K. E. Zublin, "Strip type components for 2,000-mc receiver head end."
(48) R. M. Barrett, "History of microwave strip circuits."
(49) A. D. Frost, "Activity on microwave strip circuits at Tufts College."
(50) W. E. Fromm, "Characteristics and some applications of stripline components."
(51) N. R. Wild, "Photoetched microwave transmission lines."
(52) D. D. King, "Properties of dielectric image lines."
(53) T. N. Anderson, "Practical dielectric-filled waveguide."
(54) K. G. Black and T. J. Higgins, "Rigorous determination of the parameters of microstrip transmission lines."
(55) W. H. Hayt, Jr., "The input and mutual impedance of dipole strips between parallel planes."
(56) S. B. Cohn, "Problems in strip transmission lines."
(57) N. A. Begovich, "Characteristic impedance of strip transmission lines."
(58) A. A. Oliner, "Theoretical considerations in strip lines."
(59) R. L. Pease, "Characteristic impedance of shielded strip-transmission lines."
(60) E. G. Fubini, "Stripline antennas."
(61) D. J. Sommers, "Slot array employing photoetched tri-plate transmission lines."
(62) E. H. Bradley, "Bandpass filters using strip-line techniques."
(63) J. F. Moore and Max Michelson, "Design for a high-*Q* reference cavity."
(64) E. Carlson, "Broadband microstrip crystal mixer with integral dc return."

Gyromagnetic Media

The development of a nonreciprocal circuit element, the gyrator, has opened new possibilities in component development. Research in microwave circuits using gyromagnetic media continues on an expanded scale. Several studies of various *ferrite materials* and of the theoretical aspects of *nonreciprocal elements* are listed below:

(65) A. Cunliffe, R. N. Gould, and K. D. Hall, "On cavity resonators with nonhomogeneous media," *Jour. IEE*, part III, vol. 101, p. 192 (Abstract); May, 1954.
(66) T. H. Crowley, "On reciprocity theorems in electromagnetic theory," *Jour. Appl. Phys.*, vol. 25, pp. 119–120; January, 1954.
(67) H.-T. Hsieh, J. M. Goldey, and S. C. Brown, "A resonant cavity study of semiconductors," *Jour. Appl. Phys.*, vol. 25, pp. 303–307; March, 1954.
(68) L. G. Van Uitert, J. P. Schafer, and C. L. Hogan, "Low-loss ferrites for application at 4,000 megacycles per second," *Jour. Appl. Phys.*, vol. 25, pp. 925–926 (Letter); July, 1954.
(69) A. G. Redfield, "An electrodynamic perturbation theorem with application to nonreciprocal systems." *Jour. Appl. Phys.*, vol. 25, pp. 1021–1024; August, 1954.
(70) H. G. Beljers, "Faraday Effect in Magnetic Materials with Traveling and Standing Waves," Philips Res. Rep. 9, pp. 131–139; April, 1954.
(71) K. M. Polivanov, "Theory of measurement of μ and ϵ of semiconducting ferromagnetics," *Compt. Rend. Acad. Sci.* (*URSS*), vol. 95, pp. 61–64; March 1, 1954. In Russian.
(72) G. S. Sanyal and J. S. Chatterjee, "Measurement of ferromagnetic permeability at microwave frequencies," *Indian Jour. Phys.*, vol. 27, pp. 328–339; June, 1953.
(73) T. R. McGuire, "Microwave resonance absorption in nickel ferrite-aluminate," *Phys. Rev.*, vol. 93, pp. 682–686; February 15, 1954.

The general theory of *ferrite-loaded waveguides* and the development of components taking advantage of the gyrator property is advancing rapidly, as indicated by the following work:

(74) H. Suhl and L. R. Walker, "Topics in guided wave propagation through gyromagnetic media I, II, III," *Bell Sys. Tech. Jour.*, vol. 33, pp. 579–660, 939–986, 1133–1194; May, July, and September, 1954.
(75) B. Lax, K. J. Buttom, and L. M. Roch, "Ferrite phase shifters in rectangular waveguide," *Jour. Appl. Phys.*, vol. 25, pp. 1413–1421; November, 1954.
(76) J. Cacheris, "Microwave single-sideband modulator using ferrites," Proc. IRE, vol. 42, pp. 1242–1247; August, 1954.
(77) E. Albers-Schoenberg, "Ferrites for microwave circuits and

digital computers," *Jour. Appl. Phys.*, vol. 25, pp. 152–154; February, 1954.

(78) M. A. Gintsburg, "Gyrotropic waveguide," *Compt. Rend. Acad. Sci. (URSS)*, vol. 95, pp. 489–492; March 21, 1954. In Russian.

Measurements

Progress in the art of measurement includes exploitation of standard microwave techniques as well as adaptation to new waveguides and circuit elements. *Impedance measurement* on hollow waveguides has been advanced by several extensions of earlier work.

(79) W. F. Gabriel, "An automatic impedance recorder for X-band," Proc. IRE, vol. 42, pp. 1410–1421; September, 1954.

(80) S. B. Cohn, "Impedance measurement by means of a broadband circular polarization coupler," Proc. IRE, vol. 42, pp. 1554–1558; October, 1954.

(81) T. Junction, A. Cunliffe, and D. P. Saville, "Measurement of waveguide impedance," *Wireless Eng.*, vol. 31, pp. 115–118; May, 1954.

(82) A. A. Oliner, "The calibration of the slotted section for precision microwave measurements," *Rev. Sci. Instr.*, vol. 25, pp. 13–20; January, 1954.

(83) J. Smidt, "A reflectionless waveguide termination," *Appl. Sci. Res.*, vol. B3, pp. 465–476; 1954.

(84) E. J. Nalos, "Measurement of circuit impedance of periodically loaded structures by frequency perturbation," Proc. IRE, vol. 42, pp. 1508–1511; October, 1954.

Two careful *determinations of conductivity and loss* in waveguide walls at short wavelengths were reported.

(85) F. A. Benson, "Attenuation in nickel and mild-steel waveguides at 9 375 mc/s," *Jour. IEE*, part III, vol. 101, pp. 38–41; January, 1954.

(86) J. S. Thorp, "RF conductivity in copper at 8 mm wavelength," *Jour. IEE*, part III, vol. 101, pp. 357–359; November, 1954.

Extension of *absolute power measurements to the millimeter* region has also been accomplished, as well as the application of *correlation techniques* to the microwave spectrum.

(87) R. H. Wilcox, "A simple microwave correlator," Proc. IRE, vol. 42, pp. 1512–1515; October, 1954.

(88) W. M. Sharpless, "A calorimeter for power measurements at millimeter wavelengths," Trans. IRE, vol. MTT-2, pp. 45–54; September, 1954.

Dielectric and magnetic properties of material have been determined by improved procedures. *Microwave spectroscopy* continues to be an active field of physics, and microwave measurements of the *velocity of light* are still the most accurate available. These various physical measurements are reported below:

(89) T. E. Talpey, "Optical methods for the measurement of complex dielectric and magnetic constants at centimeter and millimeter wavelengths," *Trans. IRE*, vol. MTT-2, pp. 1–12; September, 1954.

(90) M. P. W. Strandberg, H. R. Johnson, and J. R. Eshbach, "Apparatus for microwave spectroscopy," *Rev. Sci. Instr.*, vol. 25, pp. 776–792; August, 1954.

(91) O. Huber, "Two new methods of determining the electrical constants of liquids in the decimetre waveband," *Z. Angew. Phys.*, vol. 6, pp. 9–14; January, 1954.

(92) K. D. Froome, "Interferometer for determining the velocity of electromagnetic waves," *Proc. Roy. Soc. A.*, vol. 223, pp. 195–215; April 27, 1954.

Four *terminal networks* have been the object of special measurement methods. Additional progress in this field emphasizes particularly the flexibility of the circuit representations used.

(93) L. B. Felsen and A. A. Oliner, "Determination of equivalent circuit parameters for dissipative circuits microwave structures," Proc. IRE, vol. 42, pp. 477–483; February, 1954.

(94) H. F. Mathis, "Experimental procedures for determining the efficiency of four-terminal networks," *Jour. Appl. Phys.*, vol. 25, p. 982; August, 1954.

(95) A. Weissfloch, "Use of short-circuiting pistons in the study of junctions and directional couplers," *Ann. Télécommun.*, vol. 9, pp. 81–92; March, 1954.

Attacks on the *resonant cavity* problem have been continued by both analog and perturbation methods.

(96) S. Bertram, "Calculation of the resonant properties of electrical cavities," Proc. IRE, vol. 42, pp. 579–585; March, 1954.

(97) A. Gilardini, "The measurement of electromagnetic field in resonant cavities by introduction of small metallic rings," *Jour. Appl. Phys.*, vol. 25, pp. 1064–1065 (Letter); August, 1954.

Detection and Noise

The detection of microwaves is accomplished chiefly in crystal mixers, and these continue to receive attention both in a checker and at millimeter wavelength.

(98) P. D. Strum, "Crystal checker for balanced mixers," *Trans. IRE*, vol. MTT-2, pp. 10–15; July, 1954.

(99) J. Taub and P. J. Giordano, "Use of crystals in balanced mixers," *Trans. IRE*, vol. MTT-2, pp. 26–38; July, 1954.

(100) C. M. Johnson, "Superheterodyne receiver for the 100 to 150 kc region," *Trans. IRE*, vol. MTT-2, pp. 27–32; September, 1954.

A new method of detection has also been described. Here, the large transit angle of vacuum diodes is turned to advantage in novel microwave detector whose sensitivity compares favorably with crystals.

(101) A. B. Bronwell, T. C. Wang, I. C. Nitz, J. Mays, and H. Wachowski, "Vacuum-tube detector and converter for microwaves using large electron transit angles," Proc. IRE, vol. 42, pp. 1117–1123; July, 1954.

Interest in the field of noise in microwave devices is increasing rapidly. Evidence of this is found in the Symposium held on Fluctuation Phenomena in Microwave Sources in New York, N. Y., on November 18 and 19, 1954. The papers have been published in a special issue of the Transactions of the IRE, vol. ED-1, No. 4; December, 1954. They are listed below.

(102) J. B. Wiesner, "Relation of noise in microwave sources to system requirements."

(103) W. W. McLeod, Jr., "Microwave oscillator requirements for cw radar."

(104) W. L. Pritchard and K. I. Larkin, "Influence of noisy components on microwave receivers."

(105) E. J. Shelton, "Stabilization of microwave oscillators."

(106) H. Mueller, "Noise measurements of local oscillators."

(107) G. C. Dalman and A. S. Rhoads, Jr., "Microwave oscillator noise spectrum measurements."

(108) D. Middleton, "Theory of phenomenological models and direct measurements of the fluctuating output of cw magnetrons."

(109) W. M. Gottschalk, "Direct detection measurements of the output of cw magnetrons."

(110) R. A. LaPlante, "The development of a low-noise X-band cw klystron power oscillator."

(111) B. R. Mayo, H. H. Grim, and J. K. Records, "The measurement and sources of short time angular instabilities."

(112) E. F. McClain and W. R. Ferris, "A technique for measuring FM noise in microwave oscillators."

(113) C. R. Greenhow, "National Bureau of Standards noise comparator."

(114) H. Ayres, "A magnetron test set."

(115) J. R. Pierce, "The general sources of noise in vacuum tubes."

(116) L. D. Smullin, "Noise measurements in long electron beams."

(117) R. Warnecke, "Noise characteristics of carcinotrons."

(118) L. H. VonOhlsen, "Noise signal performance of the 416B planar triode."

(119) G. E. St. John, "Noise figures in traveling-wave tubes."

(120) J. Boyd, "Noise characteristics of a voltage tunable magnetron."

(121) W. A. Harris, "Measurement and analysis of triode noise."

(122) W. E. Danielson, "Space charge waves on an accelerating stream of uniformly charged square laminae."

(123) W. E. Waters, "Observations on ion oscillations in a cylindrical-beam tetrode under hard vacuum conditions."

(124) J. R. Whinnery, "Noise phenomena in the region of the potential minimum."

(125) H. A. Haus, "Noise in electron beams."
(126) C. G. Lehr and A. L. Collins, "Physical mechanisms of noise generation in magnetrons."

Sources

Concentration of effort on *traveling-wave amplifiers and oscillators* continues at an increasing pace. Backward-wave oscillators with an electronic tuning range of about 5:1 are perhaps the most startling product of this work. However, higher power, lower noise figure, and lighter magnets are equally rewarding achievements as tremendous bandwidths at high gain. Several summary "state of the art" papers on traveling-wave tubes as well as some of the original work are listed below:

(127) J. R. Pierce, "The wave picture of microwave tubes," *Bell. Sys. Tech. Jour.*, vol. 33, pp. 1343–1372; November, 1954.
(128) J. R. Pierce, "Some recent advances in microwave tubes," Proc. IRE, vol. 42, pp. 1735–1747; December, 1954.
(129) M. Muller, "Traveling-wave amplifiers and backward-wave oscillator," Proc. IRE, vol. 42, pp. 1651–1658; November, 1954.
(130) W. Siekanowicz, "A development medium-power traveling-wave tube for relay service in the 2,000-megacycle region," Proc. IRE, vol. 42, pp. 1091–1097; July, 1954.
(131) H. Heffner, "Analysis of the backward-wave traveling-wave tube," Proc. IRE, vol. 42, pp. 930–937; June, 1954.
(132) C. K. Birdsall, "Rippled wall and rippled stream amplifiers," Proc. IRE, vol. 42, pp. 1628–1636; November, 1954.
(133) J. W. Sullivan, "A wide-band voltage-tunable oscillator," Proc. IRE, vol. 42, pp. 1658–1665; November, 1954.
(134) S. D. Robertson, "An experimental broadband helix traveling-wave amplifier for millimeter wavelengths," *Trans. IRE*, vol. MTT-2, pp. 48–54; September, 1954.

Except at millimeter wavelengths, *magnetron research* seems to be very limited.

(135) M. J. Bernstein and N. M. Kroll, "Magnetron research at Columbia Radiation Laboratory," *Trans. IRE*, vol. MTT-2, pp. 33–37; September, 1954.

Some effort at improved stabilization of *klystron oscillators* should be noted. With higher frequencies, the problem of stabilization becomes increasingly severe.

(136) J. L. Altman, "A technique for stabilizing microwave oscillators," *Trans. IRE*, vol. MTT-2, pp. 16–25; July, 1954.
(137) S. J. Rabinowitz, "Stabilization of reflex klystrons by high-Q external cavities," *Trans. IRE*, vol. MTT-2, pp. 23–26; September, 1954.

Although traveling-wave tubes are making a strong bid to dominate the entire microwave spectrum, they have not yet reached full development in the *millimeter region*. Perhaps by default, *harmonic generators* continue to be the principal practical source of millimeter waves. The designs described below are the outgrowth of spectroscopic experiments.

(138) W. C. King, "Millimeter wave spectroscopic components," *Trans. IRE*, vol. MTT-2, pp. 13–16; September, 1954.
(139) A. H. Nethercot, Jr., "Harmonics at millimeter wavelengths," *Trans. IRE*, vol. MTT-2, pp. 17–20, September, 1954.
(140) C. M. Johnson, D. Slayer, and D. D. King, "Millimeter waves from harmonic generators," *Rev. Sci. Instr.*, vol. 25, pp. 213–217; March, 1954.

A *gas discharge* forms another source in the millimeter region, although its use is largely restricted to receiver noise-figure measurements.

(141) T. J. Bridges, "Gas discharge noise source for eight-millimeter waves," Proc. IRE, vol. 42, pp. 818–819; May, 1954.

Probably the first true *molecular oscillator* has also been reported.

(142) J. P. Gordon, H. J. Zeiger, and C. H. Townes, "Molecular microwave oscillator and new hyperfine structure in the microwave spectrum of NH_3," *Phys. Rev.*, vol. 95, p. 282; July, 1954.

By using a molecular beam technique the authors separated the upper inversion levels from the lower in NH_3, and by sending this beam of excited molecules into a cavity they were able to produce self-sustained oscillations at the molecular transition frequency. They report powers of the order of 10^{-8} watts and claim the frequency stability compares favorably with other varieties of atomic clocks.

The use of *Cerenkov radiation* to produce millimeter waves has not yet approached the realm of practical sources, but work continues on this method.

(143) M. Danos and H. Lashinsky, "Millimeter wave generation by Cerenkov radiation," *Trans. IRE*, vol. MTT-2, pp. 21–22; September, 1954.

Techniques

On November 8, 9 and 10, a Symposium on Modern Advances in Microwave Techniques was held as part of the 100th Anniversary Program of the Polytechnic Institute of Brooklyn. The papers given will be published in a book which will be available this spring at the Institute. They are listed below.

(144) E. Weber, "Historical Notes on Microwaves and Techniques."
(145) J. R. Pierce, "Recent Developments in Microwave Tubes."
(146) A. G. Clavier, "New Advances in Guided Propagation."
(147) D. A. Watkins, "Traveling-Wave Tubes and Backward-Wave Tubes."
(148) O. Doehler, "Space-Charge Effects in Traveling-Wave Tubes Using Crossed E-H Fields."
(149) G. C. Dalman, "Developments in Broadband and High-Power Klystrons."
(150) D. A. Wilbur, "New Principles of Magnetrons."
(157) G. E. Mueller, "Millimeter Tubes."
(152) R. W. Peter, "Problems of Producing Low-Noise Electron Beams."
(153) H. J. Carlin, "Principles of Gyrator Networks."
(154) F. K. DuPre, "Experiments on the Faraday and Cotton-Mouton Effects in Ferrites."
(155) M. L. Kales, "Propagation of Fields Through Ferrite-Loaded Guides."
(156) B. Lax, "Fundamental Design Principles of Ferrite Devices."
(157) E. F. Barnett, P. D. Lacy, and B. M. Oliver, "Principles of Directional Coupling in Reciprocal Systems."
(158) H. M. Altschuler and L. B. Felsen, "Network Methods in Microwave Measurements."
(159) M. Sucher, "A Comparison of Microwave Power Measurement Techniques."
(160) A. C. Beck, "Measurement Techniques for Multi-Mode Lines."
(161) H. A. Wheeler, "Tuning of Waveguide Filters by Pretuning of Individual Sections."
(162) R. G. Fellers, "Special Millimeter Techniques."
(163) S. Hopper, "Techniques Utilizing Flat and Ridged Waveguides."
(164) A. A. Oliner, "Theoretical Developments in Symmetric Strip Line."
(165) F. J. Zucker, "Guiding and Radiation of Surface Waves."
(166) J. W. E. Griemsmann, "Propagation in Helically-Supported Coaxial Lines."
(167) S. B. Cohn, "Artificial Dielectrics for Microwaves."

Having run the gamut from rectangular waveguides at 9 kc to Cerenkov radiation at several hundred kc, we now conclude our summary. Perhaps a key to microwave progress, as indicated by the scope of the papers listed, is the continuing close interplay between basic physics and engineering application. This relationship has long characterized the microwave field, and no doubt accounts in large measure for the high rate of progress.