Present State of the Millimeter Wave Generation and Technique Art—1958*

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Summary—**Two of the few fruitful approaches to the low millimeter and submillimeter wave generation problem appear to be frequency multiplication by means of nonlinear phenomena and frequency conversion by parametric systems. Current work on frequency multiplication using relativistic megavolt beams, crystal diodes, field emitters, ferrites, etc., is reviewed. A brief account of present efforts to extend conventional tubes below wavelengths of 3 mm is presented. Waveguide components used at 1 to 2 mm are described.**

Introduction

IN SPITE of the fact that Nichols and Tear[1] succeeded in closing the gap between infrared and electric waves in 1923 using the radiation from high-pressure quartz mercury lamps, the generation of electromagnetic radiation in the wavelength range from roughly 0.1 to 3 mm remains today an unsolved practical problem. Moreover, even an idea that might lead to a prime, self-excited source of radiation has yet to be suggested as far as the authors are aware. It is somewhat annoying that of the enormous range (greater than 18 orders of magnitude) of the electromagnetic spectrum, only a small range of frequencies in the submillimeter range cannot be generated.

Most of the effort to push into this frontier region has come from the microwave side of the spectrum since microwave electronic sources are coherent generators of smooth sinusoidal signals as opposed to incoherent, continuous spectrum infrared sources. However, this progress, frequency-wise, has been rather slow.[2–7]

In 1936, Cleeton and Williams[8] achieved a wavelength of 6 mm using a magnetron. In the last 22 years, magnetrons have only been extended by a factor of two to a wavelength of 2.6 mm by a group at Columbia University.[9] The lowest wavelength commercial magnetron operates around 4.3 mm.

By 1946, Lafferty[10] had achieved a wavelength of 4.15 mm with a reflex klystron tube. Twelve years later, the highest frequency klystron available is the DX151 which operates between 4.0 and 4.5 mm wavelength.

In 1951, Millman[11] was able to build a traveling-wave tube amplifier for 6-mm wavelength. More recently, in 1957, Karp[12] produced a wavelength of 1.5 mm by means of a ladder structure backward-wave oscillator.

The preceding historical facts indicate that, frequency-wise, microwave tubes have been extended by a factor of less than five in the last two decades.

All electron tubes utilize the same basic interaction between an electron and an electromagnetic field, namely, the force equation

$$\frac{dm\bar{v}}{dt} = q\bar{E} + q(\bar{v} \times \bar{B}). \tag{1}$$

If the dot product of the velocity $\bar{v}$ on both sides of (1) is performed, then

$$\frac{dmc^2}{dt} = \frac{d\xi}{dt} = q(\bar{v} \cdot \bar{E}) = \mathcal{P} \tag{2}$$

which states that the power $\mathcal{P}$ flowing into the electromagnetic field is equal to the time rate of change of the kinetic energy ξ of the charge q, where v is the electron velocity, c is the speed of light, and $\bar{E}$ is the electric field intensity. To achieve coherence, the electron beam must be bunched or converted into an ac beam.

The problem of producing a bunched beam to interact with an RF field has been achieved in many different ways in such tubes as magnetrons, klystrons, TWT, BWO, retarding field tubes, crossed field tubes, carcinotrons, etc. However, no matter how the interaction is achieved, all these tubes encounter essentially the same fundamental problems[2] as they are pushed into the low millimeter wave region. It is always possible, but highly improbable, that a radically new method of realizing the interaction will be discovered that would permit

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[1] E. J. Nichols and J. D. Tear, "Joining the infrared and electric wave spectra," *Astrophys. J.*, vol. 61, pp. 17–37; 1925.

[2] J. R. Pierce, "Millimeter waves," *Phys. Today*, vol. 3, pp. 24–29; November, 1950.

[3] W. E. Willshaw, *et al.*, "Experimental equipment and techniques for the study of millimeter wave propagation," *Proc. IEE*, vol. 102, pt. B, pp. 99–111; January, 1955.

[4] R. Q. Twiss, "On the generation of millimeter radiation," *Services Electronics Res. Lab. J.*, vol. 2, p. 10, 1952.

[5] D. D. King, "Report of advances in microwave theory and techniques—1956," IRE Trans. on Microwave Theory and Techniques, vol. MTT-4, pp. 68–74; April, 1956.

[6] S. W. Rubin, "Millimeter waves," *Polytechnic Research and Development Co. Reps.*, vol. 4; October, 1955.

[7] R. S. Ohl, "Millimeter Wave Research," Bell Telephone Labs., Inc., New York, N. Y., Rep. No. 24261-15; October, 1955.

[8] E. E. Cleeton and N. H. Williams, "The shortest continuous radio waves," *Phys. Rev.*, vol. 50, p. 1091; 1936.

[9] Quarterly Reps., Rad. Lab., Physics Dept., Columbia University, New York, N. Y.; Contract DA-36-039 SC-64630, September, 1957.

[10] J. M. Lafferty, "Millimeter-wave reflex oscillator," *J. Appl. Phys.*, vol. 17, pp. 1061–1066; December, 1946.

[11] S. Millman, "A spatial harmonic traveling-wave amplifier for six millimeter wavelength," Proc. IRE, vol. 39, pp. 1035–1043; September, 1951.

[12] A. Karp, "Backward-wave oscillator experiments at 100 to 200 kilomegacycles," Proc. IRE, vol. 45, pp. 496–503; April, 1957.

circumventing existing tube problems.

For reasons such as those just indicated, many people now feel that conventional electron tubes have reached their practical limit somewhere around 2 to 3-mm wavelength and that in order to push on further into the submillimeter range an entirely new set of techniques will be required.

In the past several years many of the workers who have been in millimeter wave research, and especially the newer workers, are turning their attention to solid-state electronics. While the recent work on masers, ferrite multipliers, parametric oscillators, etc., has not as yet produced electromagnetic radiation of wavelengths which are not already obtainable by electron tubes, there seems to be a note of optimism that a breakthrough will come. It should be pointed out that electron tubes are an important part of the work on these solid-state devices since these devices, at present, convert energy at one RF frequency into energy at another RF frequency, thereby requiring an RF source of energy.

In this paper, an effort will be made to present, by a limited number of specific examples, some of the representative work currently in progress in the millimeter region, to point out the problems these endeavors are encountering, and to indicate the directions that research is taking either to solve the present problems or to discover new principles to circumvent the old problems.

Limitations of Conventional Electron Tubes

In a survey article in 1950, Pierce[2] discussed four fundamental problems that plague conventional tubes operating in the low millimeter range: 1) physical size and tolerance, 2) heat dissipation, 3) circuit losses, and 4) cathode and starting current densities.

The resonant element or tube structure has its cross-sectional area comparable to a half wavelength in physical size if it operates in the dominant mode. Hence, constructability in the small dimensions becomes the sole practical criterion in choosing circuit structures. In slow-wave structures, tolerance problems in maintaining periodicity are important. Reflections on the slow-wave structure result in constructive and destructive interference between the wave components, thereby causing the output power to have appreciable "fine structure" as the frequency is swept.

Circuit losses increase with frequency, thus lowering the efficiency of the tube. In order to maintain the output power constant, greater input power is necessary to compensate for the losses, with the result that more heat is dissipated in the structure. However, with the tube structure shrinking in size as the design frequency is increased, dissipation of the heat by conduction and radiation is a major problem.

In reflex klystrons, the starting current density is proportional to the five-halves power of the frequency. In backward-wave oscillators, such as those described by Karp,[12] the longitudinal electric field component E_z falls off exponentially away from the circuit, decaying to a negligible value in a distance small compared to the thickness of the beam. Thus the beam current has physical significance only when expressed as density and when considered as having a "skin effect." These current density problems place difficult requirements on cathode emission.

Fig. 1(a) shows a drawing of a reflex klystron made by Lafferty[10] in 1946. One of his tubes achieved a wavelength of 4.15 mm, a value exceeded today only by the Amperex DX151 klystron which operates in the range of 70 to 75 kmc. Lafferty comments in his paper that it is doubtful if oscillations of wavelengths appreciably shorter than 4 mm can be obtained by the velocity modulation reflex principle until new cathodes are developed with considerably higher emission current density, or some radically new gun design is invented for producing electron beams of extremely high current densities.

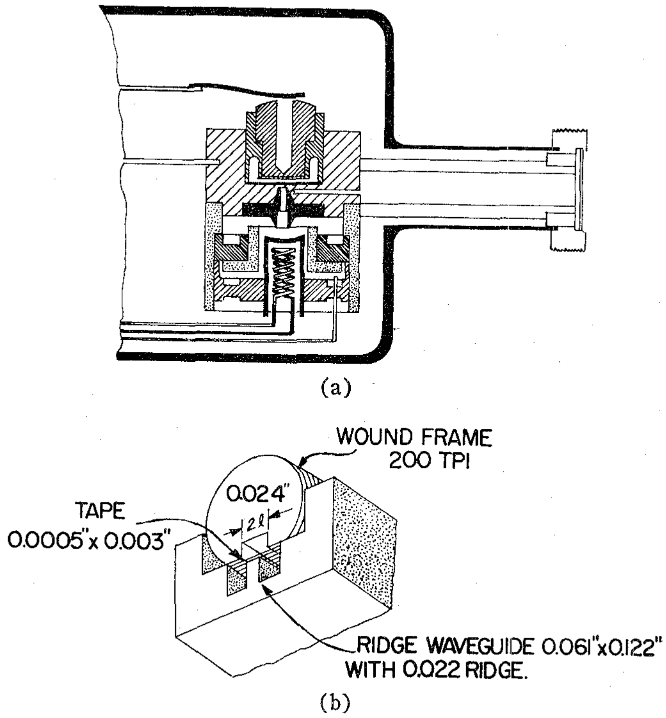


Fig. 1—Millimeter wave tubes. (a) Lafferty (1946) reflex klystron 4.15–5.80 mm. (b) Karp (1957) ladder structure 1.5–1.7 mm.

Fig. 1(b) is a schematic drawing of the "ladder structure" BWO as described by Karp.[12] This tube has produced oscillations as low as 1.5 mm, the shortest wavelength produced thus far with an electronic self-excited oscillator. Karp comments that the circuit parameter of almost overwhelming importance is the circuit "cold" loss and that recognition of the dominating influence of the loss should govern future work. Reduction of the loss is a very urgent need in trying to reach still shorter wavelengths.

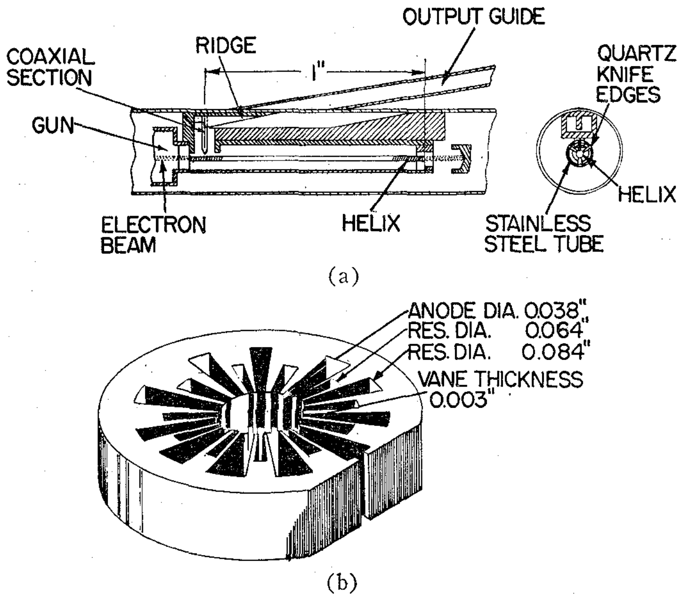


Fig. 2—Millimeter wave tubes. (a) Christensen-Watkins helix BWO tube (1955) 4.5–6.0 mm. (b) Bernstein-Kroll Columbia magnetron (1954) 2.6 mm.

Fig. 2(a) illustrates a helix millimeter-wave tube described by Christensen and Watkins.[13] This tube operates in the range 4.5 to 6.0-mm wavelength. They comment that the CW power output of their present design is limited by helix dissipation (the helix temperature is 1300°C). They calculate that increased circuit loss plus reduction in beam current due to the decrease in cross section would place a lower limit on the wavelength of 2.4 mm using the current density and beam voltage employed in their tube.

Fig. 2(b) shows a rising-sun type magnetron structure which Bernstein and Kroll[14] have pushed to a wavelength of 2.6 mm. These tubes have been designed for "low field" operation. They report a peak power output of 1 and 2 kw with an efficiency of 1 per cent and a lifetime of several hours.

The above examples clearly illustrate the four fundamental problems encountered by conventional tubes as their wavelength is pushed into the low millimeter range.[15] Improvement in the art will undoubtedly permit the wavelengths of present tubes to be reduced still further, but what is really needed is a new generation principle or science to reach 1 mm and lower wavelengths.

Examples of Commercially Available Millimeter Wave Tubes

In Figs. 3–5, a representative list of unclassified tubes in the 20 to 90-kmc range is presented for the benefit

[13] W. V. Christensen and D. A. Watkins, "Helix millimeter-wave tube," Proc. IRE, vol. 43, pp. 93–96; Janury, 1955.

[14] M. J. Bernstein and N. M. Kroll, "Magnetron research at Columbia Radiation Laboratory," IRE Trans. on Microwave Theory and Techniques, vol. MTT-2, pp. 33–37; September, 1954.

[15] R. L. Bell and M. Hillier, "An 8-mm klystron power oscillator," Proc. IRE, vol. 44, pp. 1155–1159; September, 1956.

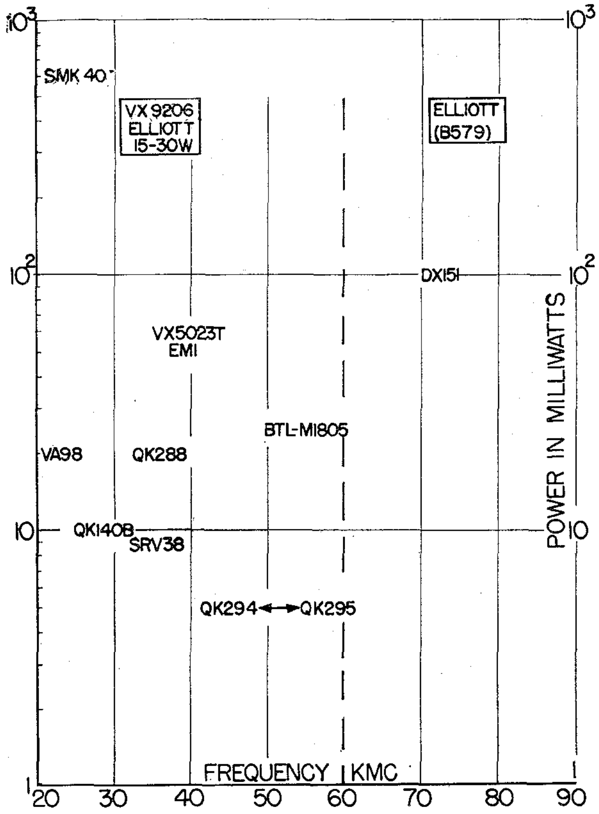


Fig. 3—Klystrons (representative list).

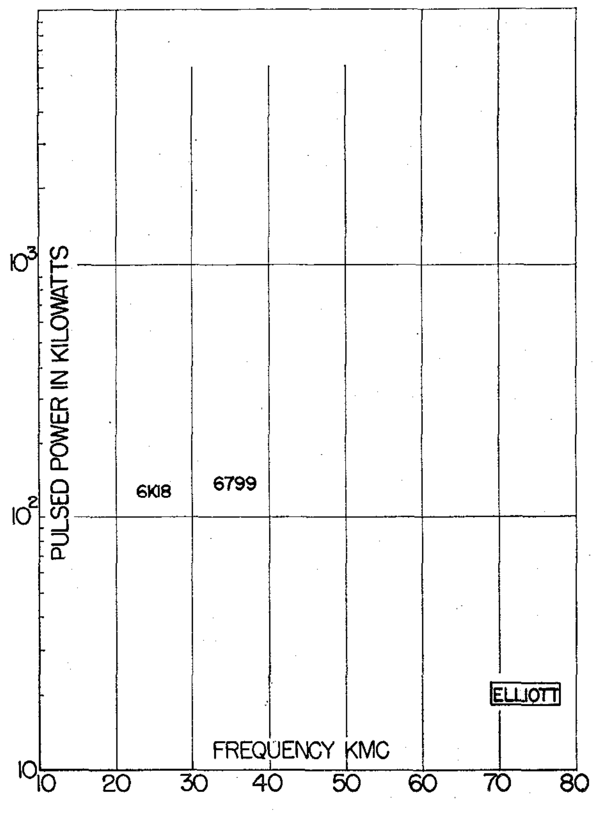


Fig. 4—Magnetrons (representative list).

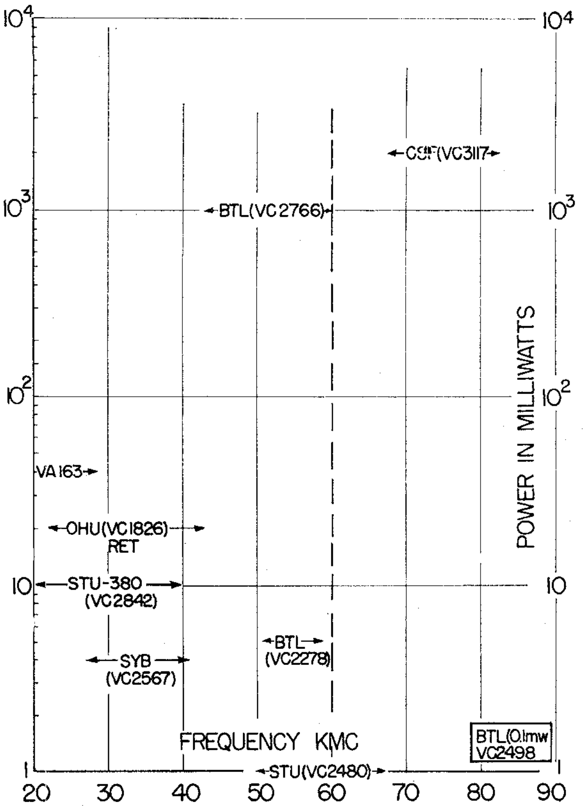


Fig. 5—Backward-wave tubes (representative list).

of those persons who may be considering work in the millimeter range for the first time. These tubes were taken from a special list of microwave tubes supplied by the Advisory Group on Electron Tubes.[16] This Group follows the progress of electron tubes both under development or in production in the U.S.A. By establishing a "need-to-know," the Advisory Group will supply a list of both classified and nonclassified tubes to all interested persons. The VC number indicated for the tube is the Advisory Group's index number for that particular item.

It will be observed that above 60 kmc (5-mm wavelength) about the only available commercial tube is the Amperex DX151. Elliott Brothers, England, plans to bring out a 20-watt magnetron in the range 70 to 75 kmc, perhaps within the next year. The status of the CSF French tube, listed as Advisory Group No. VC3117, is not known.

Waveguides—Connectors

Attempts to extend microwave components and techniques into the low millimeter or submillimeter range is almost as difficult as extending microwave tubes into the same range. It may well be that around 1-mm wavelength both microwave tubes and techniques will be abandoned and replaced by hybrid microwave-physical optics methods. However, there is considerable advantage in extending techniques as far as practical.

JAN rectangular waveguides for the 30 to 300-kmc range are given in the Armed Services Index of RF Transmission Lines and Fittings. Table I lists the RG-96, 97, 98, and 99/U sizes that have been in use for many years. They can be obtained from a number of manufacturers. Unfortunately, the RG-135, 136, 137, 138, and 139/U guides are not commercially available at the present time. These smaller guides are planned to have a circular exterior geometry and are envisioned to be made by electroforming as opposed to being extruded or drawn.

Most workers in the millimeter field are presently using the nonstandard G, F, and E rectangular guides[17] made by Horton-Angell Company of Attleboro, Mass.

Essentially two problems are encountered in millimeter waveguides: 1) small physical size, and 2) excessive attenuation. The modes used on the common waveguides are shown in Fig. 6 and attenuation characteristics are compared in Fig. 7, where all dimentions are given in inches.

It is seen that F-band guide operating in the TE_{10} mode has a theoretical attenuation of the order of 8 to 9 db per meter, a value so large as to severely limit its uses in many practical situations. The use of a TE_{11} mode in a cylindrical guide has a similar attenuation. However the TE_{01} mode in cylindrical guide has an attenuation which decreases indefinitely with increasing frequency since the currents in the guide walls approach zero. For this reason, the TE_{01} mode has been studied rather intently by workers seeking to propagate millimeter waves over long distances.[7] One of the difficulties with this mode is that any asymmetry or bending of the guide produces currents in the walls with a corresponding attenuation. However, a reduction of the TE_{01} transmission loss in a bend can be realized by adding suppressors for the unwanted TM_{11} mode generated in the bend region.[18]

Hybrid modes on dielectric rods and tubes have been under study for some time.[19–21] These modes have longitudinal components of both $\overline{E}$ and $\overline{H}$ and are designated as HEM modes. In addition, these modes are sometimes called HE_{mn} or EH_{mn}, depending upon whether they resemble more strongly an H(TE) mode or an E(TM) mode, respectively. The attenuation of the hybrid

[16] Advisory Group on Electron Tubes, 346 Broadway, New York 13, N. Y.

[17] W. Gordy, *et al.*, "Microwave Spectroscopy," John Wiley and Sons, Inc., New York, N. Y., ch. 1; 1953.

[18] S. E. Miller, "Notes on methods of transmitting circular electric waves around bends," Proc. IRE, vol. 40, pp. 1104–1113; September, 1952.

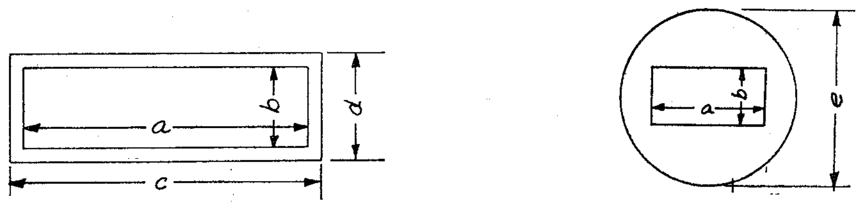
[19] W. M. Elsasser, "Attenuation in a dielectric rod as wave guide," *J. Appl. Phys.*, vol. 20, pp. 1193–1196; December, 1949.

[20] C. Chandler, "An investigation of dielectric circular rod as wave guide," *J. Appl. Phys.*, vol. 20, pp. 1188–1193; 1949.

[21] R. E. Beam *et al.*, "Investigation of Multi-Mode Propagation in Waveguides and Microwave Optics," Northwestern University, Evanston, Ill., performed under U. S. Army Signal Corps Contract No. W36-039, sc-38240; May 1, 1949 to November, 1950.

TABLE I

Millimeter Waveguides



Type	Operating Range		Inside Dimensions		Outside Dimensions			Material	Distributor
	Frequency (kmc)	Wavelength (mm)	a (inch)	b (inch)	c (inch)	d (inch)	e (inch)		
RG-96/U	26.50– 40.00	11.30–7.50	0.280	0.140	0.360	0.220		Silver Copper	Demornay Bonardi Carl Schutter
RG-97/U	33.00– 50.00	9.09–6.00	0.224	0.112	0.304	0.192		Silver	Demornay Bonardi Carl Schutter
RG-98/U	50.00– 75.00	6.00–4.00	0.148	0.074	0.228	0.154		Silver	Demornay Bonardi Carl Schutter
RG-99/U	60.00– 90.00	5.00–3.30	0.122	0.061	0.202	0.141		Silver Copper	Demornay Bonardi Carl Schutter
RG-138/U	90.00–140.00	3.30–2.14	0.080	0.040			0.156		
G	100.00–150.00	3.00–2.00	0.075	0.034	0.135	0.094		Silver Copper	Horton Angell
RG-136/U	110.00–170.00	2.73–1.77	0.0650	0.0325			0.156		
RG-135/U	140.00–220.00	2.14–1.36	0.0510	0.0255			0.156		
F	150.00–230.00	2.00–1.30	0.049	0.022	0.107	0.080		Silver Copper	Horton Angell
RG-137/U	170.00–260.00	1.77–1.15	0.0430	0.0215			0.156		
RG-139/U	220.00–325.00	1.36–0.92	0.0340	0.0170			0.156		
E	230.00–350.00	1.30–0.85	0.033	0.016	0.097	0.080		Silver Copper	Horton Angell

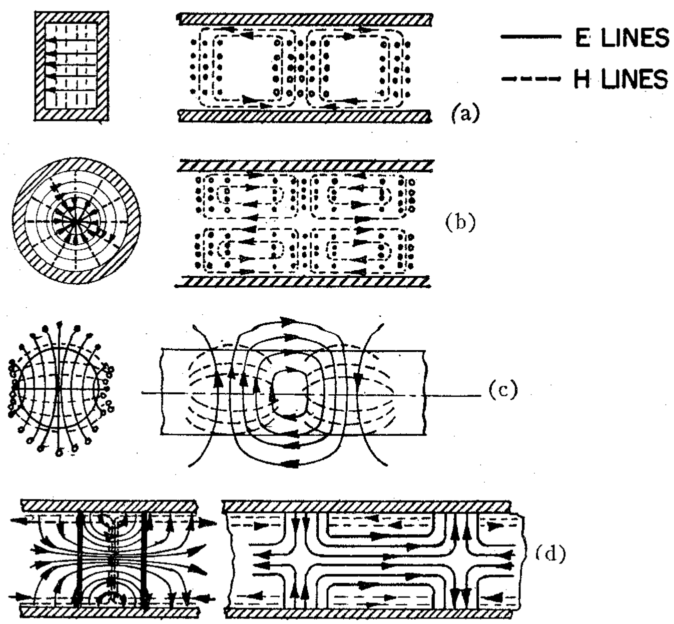


Fig. 6—Field patterns for waveguide modes. (a) Rectangular waveguide—TE_{10} mode. (b) Circular waveguide—TE_{01} mode. (c) Dielectric rod waveguide—HEM_{11} mode. (d) *H*-type waveguide—HEM_{11} mode.

HEM_{11} "dipole" mode of the dielectric rod is plotted in Fig. 7. This mode has no cutoff frequency and is preferred from the mode conversion point of view.

As is seen from the figure, a dielectric rod can provide a much smaller attenuation than metal guides, except for the TE_{01} mode in cylindrical guide. However, the problems of supports, bends, and shielding are not easily solved. Moreover, the lower the loss, the more difficult these problems become. Dielectric image lines[22,23] show promise of convenient application in bends and straight sections in the millimeter range but their cross-sectional area decreases rapidly with decreasing wavelength. Single-conductor, surface-wave transmission lines,[24–26] which have an attenuation which is less than

[22] D. D. King, "Properties of dielectric image lines," IRE Trans. on Microwave Theory and Techniques, vol. MTT-3, pp. 75–81; March, 1955.

[23] J. C. Wiltse, "Some characteristics of dielectric image lines at millimeter wavelengths," presented at MTT Symp., Stanford, Calif.; May, 1958.

[24] G. Goubau, "Single-conductor surface-wave transmission lines," Proc. IRE, vol. 39, pp. 619–624; June, 1951.

[25] G. Goubau, "Surface waves and their application to transmission lines," *J. Appl. Phys.*, vol. 21, pp. 1119–1128; November, 1950.

[26] W. Rotman, "A study of single-surface corrugated guides," Proc. IRE, vol. 39, pp. 952–959; August, 1951.

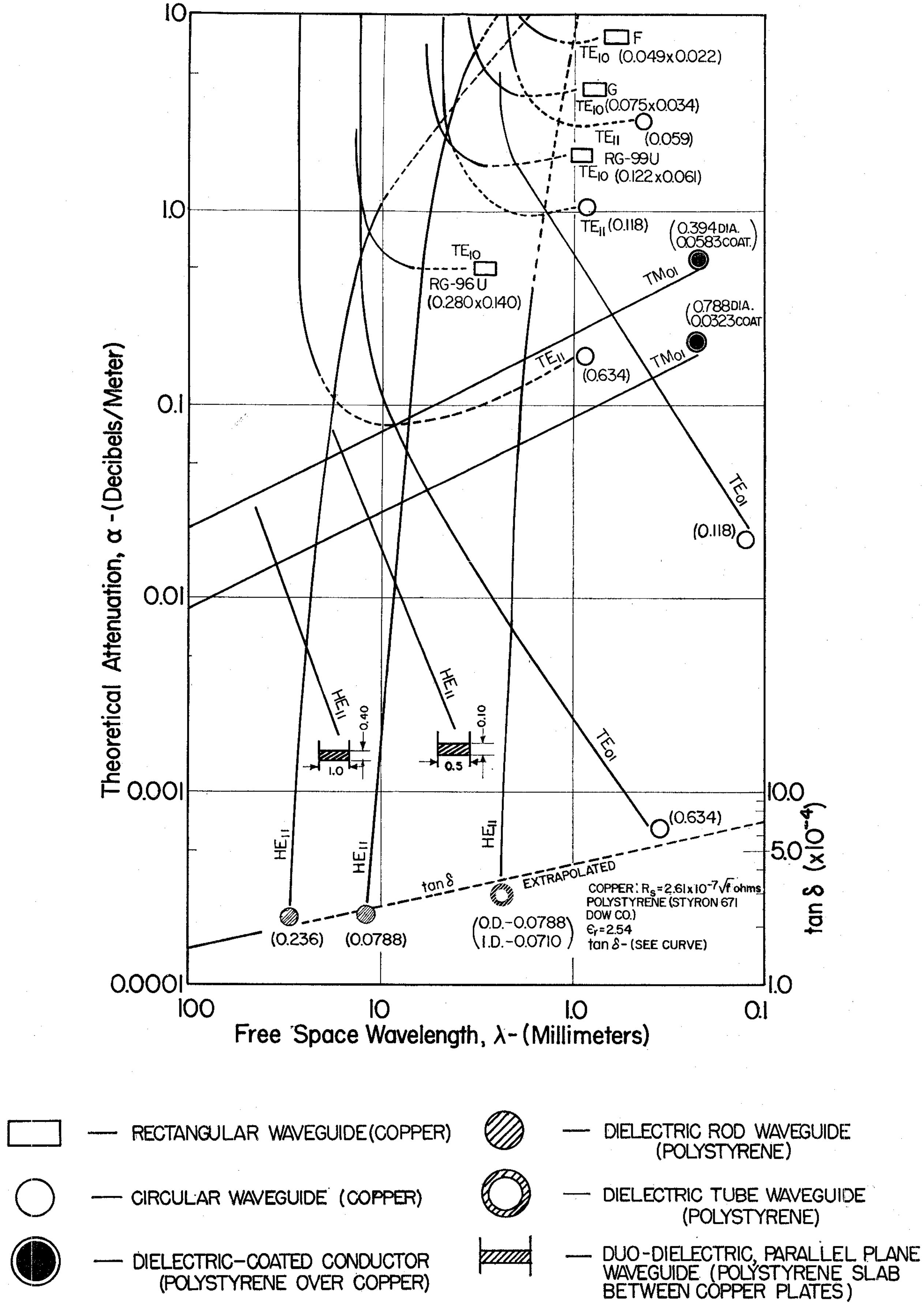


Fig. 7—Comparison of the theoretical attenuation characteristics of waveguides suitable for millimeter wavelength applications.

metal waveguides, have found applications in connection with antennas.

The H guide[27] and duo-dielectric parallel-plane waveguide,[28] consisting of two parallel conducting planes with one or two dielectric slabs between them, have valuable properties for millimeter wave propagation. Tischer reports that one of the hybrid modes, the HEM_{11} which is plotted in Fig. 7, has an attenuation which decreases with increasing frequency similar to the TE_{01} in cylindrical metal guides. The special features claimed for this guide are 1) the nonexistence of longitudinal currents which permits two sections of the guide to be readily joined without special connectors, 2) cross-sectional dimensions greater than those of rectangular guide, and 3) easily fabricated circuits can be made using the guide. However, as far as the authors are aware, there have been no experimental data presented to verify the decreasing attenuation of this mode in the H guide with increasing frequency.

The Armed Services Index does not list any connectors for guides beyond RG-99/U but it is assumed that they might be similar to the UG-387/U cover flanges used with RG-99/U guide. A design of the connector used with the G, F, and E guides by the Ultramicrowave Group at Illinois is shown in Fig. 8. This connector consists essentially of two basic parts, a knurled screw ring and a punched disk. Alignment does not depend on dowel pins but on waveguide tolerances both on the outside and inside dimensions. The connectors are readily joined together and provide a very sturdy joint which is not easily bent out of shape.

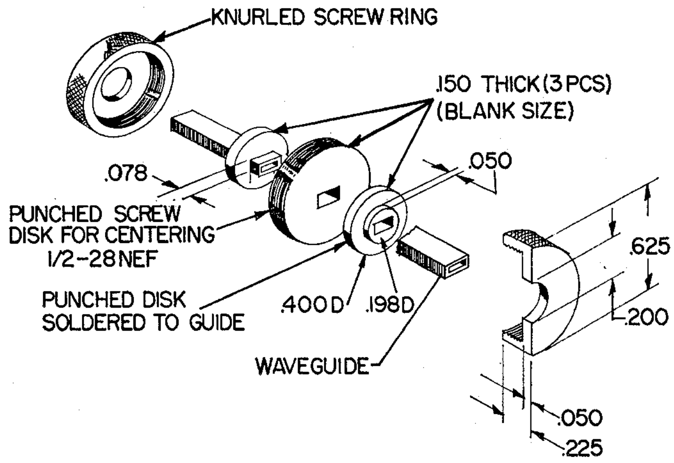


Fig. 8—*G*- and *F*-band waveguide connector (butt type).

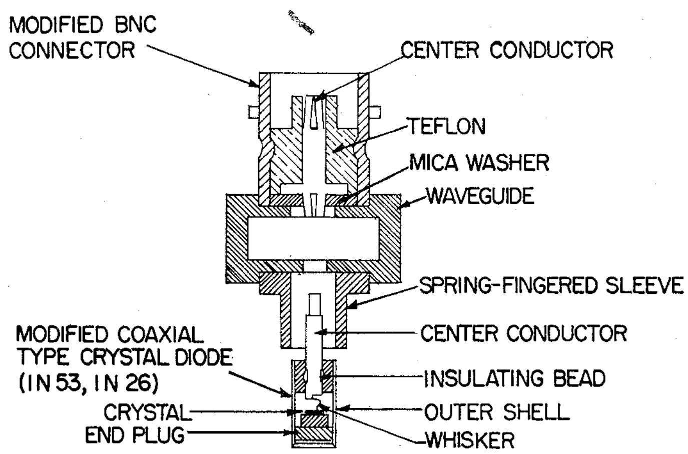


Fig. 9—Crystal cartridge type detector.

Detectors

The three types of detectors most commonly used in the low millimeter range are: 1) the silicon crystal, 2) the Wollaston wire bolometer, and 3) the Golay cell.[29]

A variety of crystal mounts have been designed by workers in the field, but they are essentially only of two basic types: the type where the crystal dicing is mounted directly in the guide, and the type that employs a cartridge crystal such as the 1N26 and 1N53.

Fig. 9 illustrates a typical design[30] using a cut-down 1N26 or 1N53 cartridge. Here, the outer conductor of the cartridge has been machined down to the dielectric bead so as to expose the center conductor. This cut-down cartridge plugs into a fingered sleeve soldered onto one wall of the waveguide. The center conductor of the crystal mates with the center conductor of a BNC connector which has been modified to include either a choke or bypass condenser. A movable short is included in the waveguide for tuning. Also the crystal can be moved up and down or rotated in the fingered sleeve for maximum output signal.

Fig. 10 shows a typical design of the in-guide crystal dicing mount.[31,32] In this unit the pressure of the tungsten cat-whisker against the crystal can be adjusted by advancing or retracting the crystal chip which is mounted on a differential screw. Sharpness of the whisker point is critical in this device. The radius of curvature of the tip is usually made to be of the order 10^{-4} inches or less.

Fig. 11 illustrates an in-guide mount with fixed tuning.[33] Here a tapered ridge from the rectangular guide is used to broadband the device and achieve an RF impedance match. The crystal chip is mounted on a flat spring built into the ridge to provide the contact whisker pressure.

[27] F. J. Tischer, "H-guide—A new microwave concept," *Electronic Ind. Tele-Tech*, vol. 16, pp. 50–51, 130, 134, 136; November, 1956. Also, "The H-guide, a waveguide for microwaves," 1956 IRE Convention Record, pt. 5, pp. 44–47.

[28] R. A. Moore and R. E. Beam, "A duo-dielectric parallel-plane waveguide," *Proc. NEC*, vol. 12, pp. 689–705; 1956.

[29] M. J. E. Golay, "A Pneumatic Infra-Red Detector," *Rev. Sci. Instr.*, vol. 18, pp. 357–362; May, 1947.

[30] H. C. Torrey and C. A. Whitmer, "Crystal Rectifiers," M.I.T. Rad. Lab. Ser., McGraw-Hill Book Co., Inc., New York, N. Y., vol. 15; 1948.

[31] W. C. King, "Millimeter wave spectroscopic components," IRE Trans. on Microwave Theory and Techniques, vol. MTT-2, pp. 13–16; September, 1954.

[32] C. H. Townes and A. L. Schawlow, "Microwave Spectroscopy," McGraw-Hill Book Co., Inc., New York, N. Y., ch. 16; 1955.

[33] Microwave Associates, Burlington, Mass., Catalog 58 S; 1958.

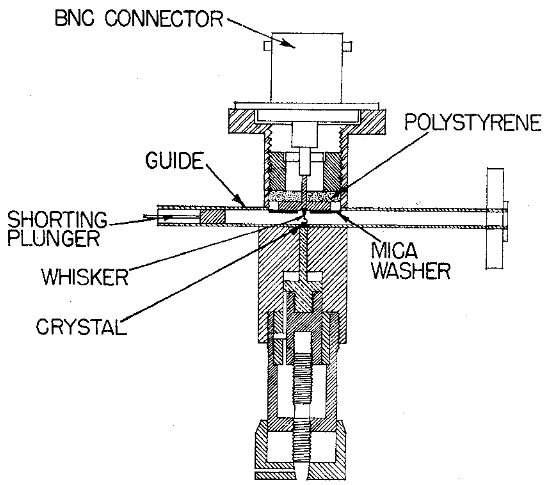


Fig. 10—Crystal-in-guide type detector.

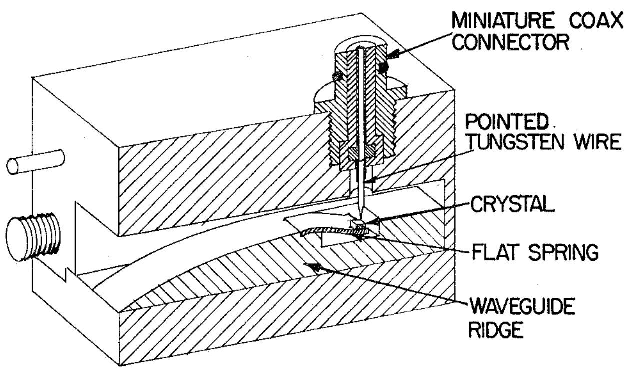


Fig. 11—Ridge waveguide crystal mount.

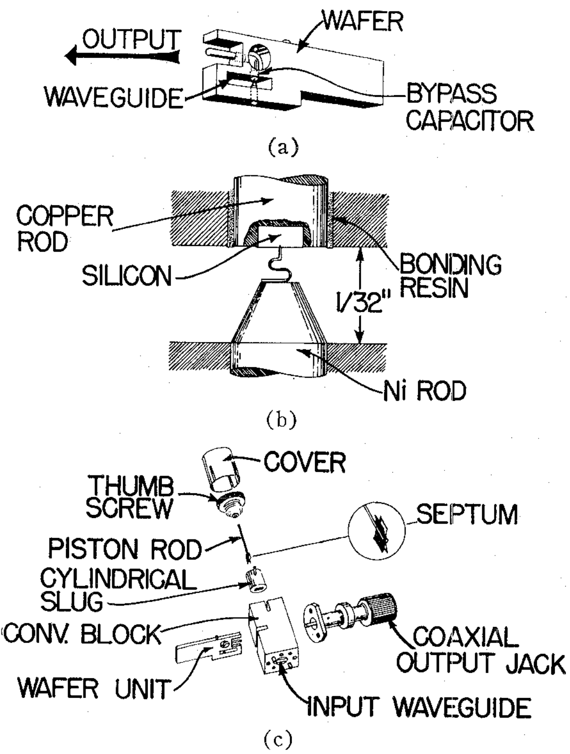


Fig. 12—Wafer type detector.

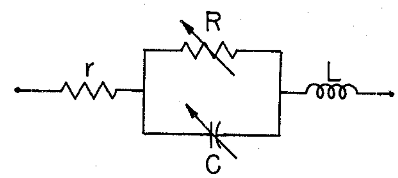


Fig. 13—Equivalent circuit of a crystal rectifier.

A mount which combines the features of an in-guide crystal and those of a cartridge is the Sharpless[34] unit shown in Fig. 12. A wafer contains a short section of waveguide across which the point contact rectifier is mounted. The basic idea is that the wafer containing the rectifier can be inserted and moved in a slot at right angles to the waveguide to obtain a resistive match to the waveguide, while the reactive component of the rectifier impedance is tuned out with an adjustable plunger located in the converter block to the rear of the wafer location.

Using the same crystal material, the in-guide mount is in general the most sensitive unit in the low millimeter range. However, it is time-consuming to construct and adjust and less rugged than the other types. At 4 mm, using a mount constructed in RG-99/U guide, the in-guide devices are from 5 to 10 db better than the 1N53 cartridge type units. A cartridge unit has the advantages of being rugged and cheap to make.

While crystal detectors have been used by Gordy[35] and others to detect signals below 1-mm wavelength, there are still many problems associated with their use in the low millimeter range. The design of good mounts is largely one of art and crystal materials. In the equivalent circuit of the crystal rectifier shown in Fig. 13, the conversion loss is a function of ωCr where C is the barrier capacity and r the ohmic spreading resistance. In terms of the properties of the semiconductor,[30,36,37]

$$\omega Cr = \frac{\pi}{240}\left(\frac{\epsilon}{\epsilon_0}\right)\frac{a}{\sigma D\lambda} \alpha \frac{a}{\lambda}\left[\frac{\epsilon}{b^2 N}\right]^{1/2} \quad (3)$$

where a is whisker radius of contact; D, the barrier thickness; λ, the wavelength; σ, the conductivity; N, the carrier concentration; b, the mobility; and ϵ, the permittivity of the crystal material.

For silicon doped with 0.02 per cent boron, typical values of the parameters are

$$\frac{\epsilon}{\epsilon_0} = 13 \qquad a = 1.25 \times 10^{-6} \text{ meter}$$

$$\sigma = 1.11 \times 10^4 \text{ mho/meter}$$

[34] W. M. Sharpless, "Wafer-Type Millimeter-Wave Converters," Bell Telephone Labs., New York, N. Y., Final Rep. on Contract Nonr-687(00); June, 1951 to May, 1955.

[35] C. A. Burrus and W. Gordy, "Submillimeter wave spectroscopy," *Phys. Rev.*, vol. 93, pp. 897–898; February, 1954.

[36] H. K. Henisch, "Rectifying Semi-Conductor Contacts," Oxford University Press, New York, N. Y.,; 1957.

[37] C. T. McCoy, "Present and future capabilities of microwave crystal receivers," Proc. IRE, vol. 46, pp. 61–66; January, 1958.

so that

$$r = \frac{1}{4\sigma a} = 18 \text{ ohms} \qquad D = 10^{-8} \text{ meter}$$

$$C = 5.7 \times 10^{-14} \text{ farad} \qquad \omega C r = \frac{1.9}{\lambda(\text{mm})} < 1. \tag{4}$$

On the basis of this criterion, a detector using this crystal material would not be suitable for wavelengths below 1.9 mm. An increase in the impurity content or doping increases the value of σ but decreases D. The value of the bracket term in (3) represents fundamental physical constants with a calculable minimum theoretical value[37] for any semiconductor. Germanium has a theoretical value 2.5 times lower than silicon while indium antimonide is much lower than germanium. Thus there is hope in the near future of reducing the value of Cr by an order of magnitude from its best present value.

The surface treatment of the semiconductor also has a marked effect on the rectification characteristics. Bombardment by helium ions[36] is used by some workers to activate the surface, especially for crystals used in crystal multipliers.

While crystal detectors are more sensitive than other detectors at wavelengths longer than those in the millimeter range, at wavelengths below about 3 mm, bolometers show considerable promise. In fact for wavelengths approaching 1 mm, platinum wire bolometers will exceed crystals in sensitivity. Moreover, the response law[38] of a bolometer is accurately known, and the bolometers can probably be made more reproducible.

In commercial bolometers such as the PRD 634,[6] the Wollaston wire is mounted on a mica card. This technique does not appear to be feasible as one goes to smaller wires and guides. Rohrbaugh's[39] group at N.Y.U. has been mounting 10-microinch wire directly in the guide (0.022×0.045 inch) for detection at $K/8$ band. These resistance elements were obtained from Sigmund Cohn Corporation which manufactures Wollaston wires with cores as small as 6 microinches with resistances of the order of 200,000 ohms per inch. Rohrbaugh reports the sensitivity of his bolometers as $\sim 10^{-10}$ watts. A PRD 617 bolometer which contains a 35-microinch wire has a time constant[40,41] of approximately 150 μsec. The N.Y.U. bolometer mounts show a small but definite decrease in rise time and a much greater decrease in the decay time as the wire diameter decreases. Thus there is promise that these small wire bolometers could respond to signal frequencies as high as 10,000 cycles per second or greater.

The Golay detector,[29] a device originally intended as an infrared detector, has been used successfully from the ultraviolet region through the infrared and out to a wavelength of 7.5 mm in the microwave portion of the spectrum. The device consists essentially of a pneumatic chamber which responds to changes in thermal radiation. Typical rise times are about 15 msec in duration, and available sensitivities are of the order of 10^{-8} watts.

Power Measurements

Accurate power measurements in the low millimeter range are difficult to make, especially since the power available for measurement is usually very small. A survey article by Weill[42] gives various methods of measuring the power output of millimeter wave tubes; power ranges from 100 watts to 100 μw are considered. Fig. 14(b) shows one example of a platinum film bolometer described by Weill for the range 100 mw to 100 μw. These enthrakometers avoid the problems of mounting small Wollaston wires but they are still rather delicate.

Commercial bolometer mounts can be obtained from a number of companies. PRD makes a mount, type 632, in RG-98/U guide which uses bolometer wire mounted on a mica card (type 634). F-R Machine Works mounts their Wollaston wires in a cartridge unit identical to the 1N53 crystal so that they can be used interchangeably in the same detector unit.

Sharpless[43] has described a calorimeter for power measurements of the order of 1 mw in the wavelength range 5 to 7 mm. However, there is no reason to believe that this device could not be extended to still shorter wavelengths. Fig. 14(a) illustrates the design of the calorimeter. It consists of a short section of thin-walled round silver waveguide containing a cast conical taper of absorbing material. DC power can be fed through the termination from the outer shell through a small deposited silver band, located at the front end of the termination. The temperature rise is measured by three Western Electric 23A thermistor beads in intimate contact with the exterior of the thin-walled silver tube. Two identical terminations are used in the bridge network shown, where a pulsed signal is used to detect the balance condition.

Frequency Measurements

Most of the frequency meters in the low millimeter range are scaled down versions of TE_{0mn} mode, high-Q cavity wavemeters used at K band which are described, for example, in detail in the M.I.T. Radiation Labo-

[38] G. D. Montgomery, "Techniques of Microwave Measurements," M.I.T. Rad. Lab. Ser., McGraw-Hill Book Co., Inc., New York, N. Y., vol. 11; 1947.

[39] J. H. Rohrbaugh, "A Study of the Generation and Detection of Electromagnetic Waves in the Millimeter Wave Region," New York University, New York, N. Y., Quart. Reps. on AF19(604)-1115; 1956–58.

[40] G. U. Sorgen, "The thermal time constants of a bolometer," IRE Trans. on Instrumentation, no. PGI-4, pp. 165–170; October, 1955.

[41] M. Sucher and H. J. Carlin, "The operation of bolometers under pulsed power conditions," IRE Trans. on Microwave Theory and Techniques, vol. MTT-3, pp. 45–52; October, 1955.

[42] H. Weill, "Mésures de puissance sur tubes millimétriques," *Le Vide*, vol. 12, pp. 122–127; January–February, 1957.

[43] W. M. Sharpless, "A calorimeter for power measurements at millimeter wavelengths," IRE Trans. on Microwave Theory and Techniques, vol. MTT-2, pp. 45–54; September, 1954.

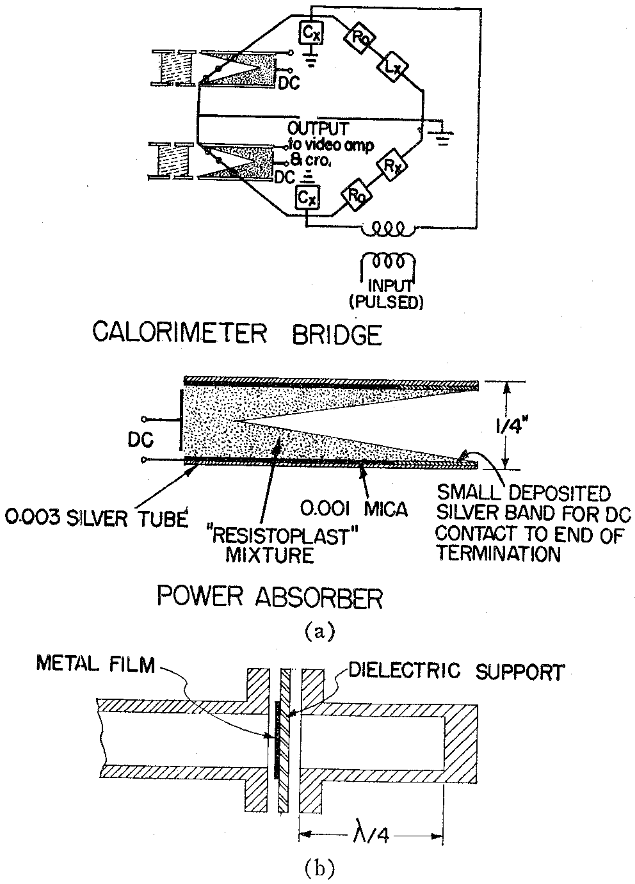


Fig. 14—Power measuring devices. (a) Calorimeter for the 5 to 7-mm range (Sharpless). (b) Platinum film bolometer.

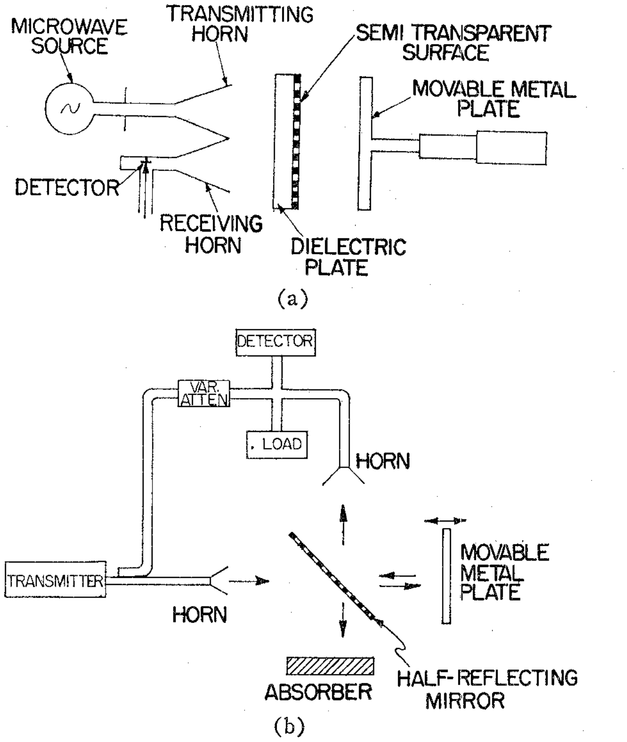


Fig. 15—Frequency measuring devices. (a) Microwave analog of a modified Fabry-Perot interferometer. (b) Microwave analog of Michelson interferometer.

ratory Series.[38] About the only new design change is to replace the micrometer drive with a finer mechanism such as a differential screw which can easily give a travel of 0.001 inch per turn.

As one would expect, microwave analogs of the Michelson and Fabry-Perot interferometers were investigated by a number of workers some years ago.[44,9] Two microwave forms of this device are shown in Fig. 15. The arrangement shown in Fig. 15(b) has obvious disadvantages from the low millimeter viewpoint since it uses a directional coupler and magic tee, both of which are difficult to construct. The Fabry-Perot arrangement, shown in Fig. 15(a), avoids these difficulties by requiring just a horn radiator.

In addition to wavelength measurements, interferometers have uses in the measurement of dielectric constant and attenuation in dielectric materials available in the form of uniform sheets.

Frequency Multiplication with Nonlinear Elements

Circuit Synthesis Problem

Until an idea for a prime, or self-excited, source for the submillimeter wavelength range is discovered, the only

[44] B. A. Lengyel, "A Michelson-type interferometer for microwave measurements," Proc. IRE, vol. 37, pp. 1242–1244; November, 1949.

Problems:
1) Impedance at unwanted harmonics to be zero, infinite, or reactive.
2) Input and output coupling.
3) Circuits components.

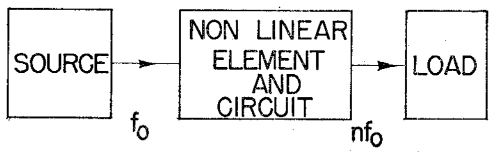


Fig. 16—Frequency multiplication with a nonlinear element.

feasible approach to the problem would appear to be a frequency multiplication by means of some nonlinear effect or element. In principle, this frequency multiplication could be up or down in frequency, since sources exist both above and below the submillimeter range.

Fig. 16 schematically illustrates the frequency multiplication process. A suitable source at frequency f_0 feeds into a circuit containing a nonlinear element. The output coupling is such that only a given harmonic frequency, nf_0, emerges, in turn, to be fed into a load. Ideally, if the nonlinear element used in the circuit were a lossless reactive device and the circuit could be so synthesized that it had dissipation only at a given harmonic frequency nf_0, then it follows that a power gain of one at the desired harmonic could be realized.

The general problems in synthesizing such circuits would be: 1) to find an arrangement where the impedances at the unwanted harmonics are either zero, infinite, or reactive; 2) to find a circuit which could be realized with practical millimeter wave components;

and 3) coupling in and out of the circuit structure.

Nonlinear elements are seldom either purely resistive or reactive. However, two recent papers by Page[45] and Manley and Rowe[46] have appeared which give limits to the power gain for a desired harmonic.

Page considers positive nonlinear resistors through which the current, I, is a real, finite, single-valued, nondecreasing function of the voltage, V, across the terminals. He also assumes the current, I, is zero for V equal to zero.

Let

$$V(t) = \sum_{1}^{\infty} a_n \cos(n\omega t + \theta_n), \qquad (5)$$

then the current will be Stepanoff almost periodic (S^2 ap)[45]

$$I(t) = \lim \sum_{1}^{\infty} b_n \cos(n\omega t + \phi_n). \qquad (6)$$

From the nondecreasing behavior of I, it follows that

$$\theta(x) \equiv \langle\{V(t) - V(t-x)\} \cdot \{I[V(t) - I[V(t-x)]]\}\rangle_t \geq 0 \qquad (7)$$

or

$$\theta(x) = 2\sum_{1}^{\infty} P_n(1 - \cos n\omega x) \geq 0 \qquad (8)$$

where $P_n = a_n b_n/2 \cos(\phi_n - \theta_n)$ is the power absorbed by the resistor at frequency ω^2. Applying (8) to a circuit containing a positive nonlinear resistor wherein there is dissipation only for frequencies ω and $n\omega$, it follows that

$$P_1(1 - \cos \omega x) - |P_n|(1 - \cos n\omega x) \geqq 0 \qquad (9)$$

or

$$\frac{|P_n|}{P_1} = \left\{\frac{\sin(\omega x/2)}{\sin(n\omega x/2)}\right\}^2_{x\to 0} \to \frac{1}{n^2}. \qquad (10)$$

Thus the efficiency of generating an nth harmonic cannot exceed n^{-2}. If a circuit could be synthesized that would approximate the condition given by (8), one solution to the submillimeter wave generation problem would be immediately achieved since appreciable amounts of power are available at K band and higher frequencies.

Manley and Rowe consider nonlinear inductors and capacitors which may contain hysteresis. For conceptual purposes, they suggest the circuit shown in Fig. 17. Let

$$v = \sum_{m=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} V_{m,n} e^{j(m\omega_1 t + n\omega_0 t)} \qquad (11)$$

$$i = \sum_{m=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} I_{m,n} e^{j(m\omega_1 t + n\omega_0 t)}. \qquad (12)$$

[45] C. H. Page, "Frequency conversion with positive nonlinear resistors," *J. Natl. Bur. Standards*, vol. 56, pp. 179–182; April, 1956.
[46] J. M. Manley and H. E. Rowe, "Some general properties of nonlinear elements. Part I. General energy relations," PROC. IRE, vol. 44, pp. 904–913; July, 1956.

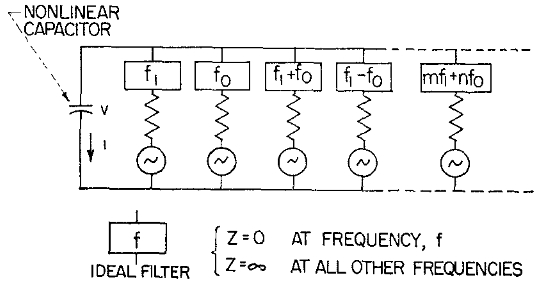


Fig. 17—Circuit with a nonlinear capacitor (Manley-Rowe). Filters—SC to desired frequency, OC to all other frequencies.

Assume

$$v = f(q) = \sum_{n=0}^{\infty} V_{0,n} \epsilon^{jn\omega_0 t}.$$

Let $W_{0,n}$ be the average power flowing into nonlinear element at frequency nf_0. Then

$$\sum_{n=0}^{\infty} \frac{W_{0,n}}{f_0} = 0.$$

Hence

$$W_{0,1} = -\sum_{n=2}^{\infty} W_{0,n}.$$

Special case: $W_{01} = -W_{0,s}$. ($n = s$, conversion to single harmonic frequency.)

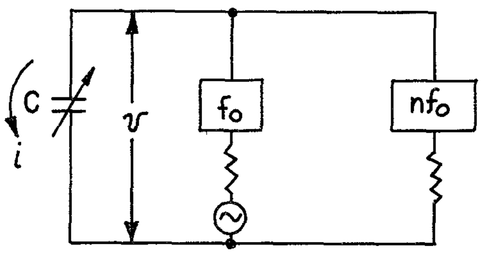


Fig. 18—Frequency conversion with a nonlinear reactive element.

Define

$$2V_{m,n} I_{m,n}^* = W_{m,n} + jX_{m,n} \qquad (13)$$

where $W_{m,n}$ is the real or average power flowing into the nonlinear element at this frequency for either choice of indexes.

Manley and Rowe derive the following relationships

$$\sum_{m=0}^{\infty} \sum_{n=-\infty}^{\infty} \frac{mW_{m,n}}{mf_1 + nf_0} = \frac{H}{f_1} \qquad (14)$$

and

$$\sum_{m=-\infty}^{\infty} \sum_{n=0}^{\infty} \frac{nW_{m,n}}{mf_1 + nf_0} = 0 \qquad (15)$$

where H is the average power dissipated in hysteresis.

In applying this analysis to frequency multiplication the circuit of Fig. 17 reduces to that in Fig. 18 and, when $n = 0$, (14) and (15) become

$$-W_{m,0} = W_{1,0} - H. \qquad (16)$$

As the hysteresis power loss, H, approaches zero, the power gain to the desired harmonic can approach 1 independent of the shape of the nonlinear characteristic of the capacitor C and of the power level. A similar analysis would apply to a nonlinear inductor.

The problem is to find a nonlinear effect in the low millimeter range which can be represented as a high-Q nonlinear capacitor or inductor and then to synthesize a circuit such as that suggested in Fig. 18.

Nonlinear Resistive-Type Elements

Two resistive-type nonlinear elements are currently being used for frequency multiplication in the low millimeter range: the crystal diode and the field emitter diode.

A crystal rectifier is not a positive nonlinear resistor (see the circuit of Fig. 13) so that Page's analysis is not applicable. However, it has been the element used, mainly by spectroscopists, for work in the low millimeter range. The earliest work on crystal multipliers was done by Beringer[47] at M.I.T. in 1944. Most of the recent work has been done by Gordy[35] at Duke University, Johnson *et al.*[48] at Johns Hopkins, Nethercot,[49,50] at Columbia, Ohl[7] at Bell Labs., and Richardson[51] at the National Bureau of Standards. The reports of these groups on crystal multipliers have been mainly on performance characteristics rather than analysis. Hwang[52] has recently attempted an analysis to compute the conversion efficiency of such a device. He obtained values for the second and third harmonics which were fairly close to the experimental results.

Fig. 19 illustrates a typical design of a crossed guide crystal multiplier as given by Johnson *et al.*[48] Energy coming down the larger guide is picked up by the tungsten whisker probe and fed to the silicon crystal. The resulting harmonic currents on the probe are in turn fed into the smaller guide, which is a high-pass filter, filtering out all harmonic frequencies below a certain value.

Hwang gives the equivalent circuit of the multiplier as that shown in Fig. 20 from which he calculates the second and third harmonic powers to be

$$P_2 = 0.011P_{\text{in}} \qquad P_3 = 0.0006P_{\text{in}} \tag{17}$$

or 20 db and 32 db down from the input power, which is in fair agreement with experimental data.

The over-all loss of a good generator and detector for the low harmonics is about 15 db from one harmonic to the next while from the sixth harmonic on, the loss is probably 3 to 4 db per harmonic. No precise data seem to exist because of the difficulty in making low-level power measurements in the low millimeter and submillimeter range.

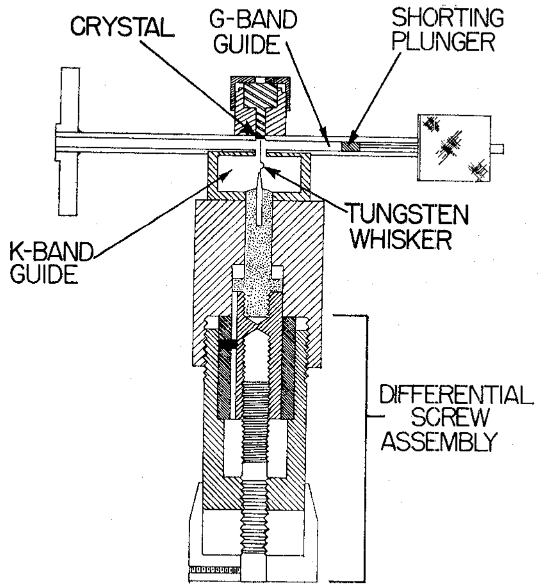


Fig. 19—Cross-guide crystal multiplier.

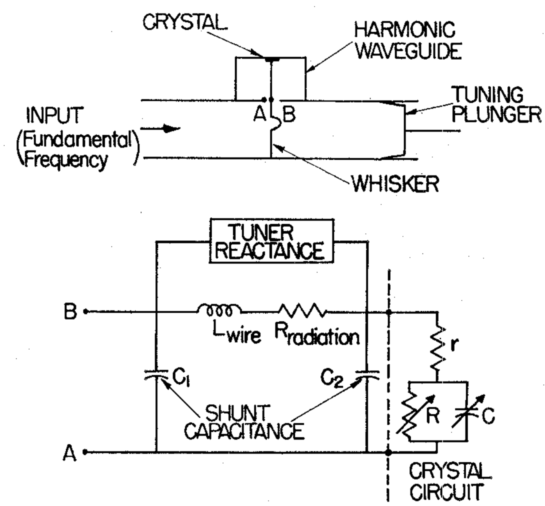


Fig. 20—Equivalent circuit for crystal multiplier (Hwang). The upper diagram shows a crossed-guide crystal multiplier.

Fig. 21 illustrates the data of Richardson and Nethercot on their K-band multipliers. Nethercot does not give actual power output values so that it is difficult to compare their multipliers on this basis. However, it will be noticed that Nethercot's multiplier gives a harmonic power P_n vs fundamental power P_0 relationship, $P_n \propto P_0^n$, which may or may not be significant. Richardson's fourth harmonic power varies as $(P_0)^{1.5}$.

Most of the recent work on crystal multipliers has been done with silicon crystals. Yet North[53] in 1946 showed that welded contact germanium crystal multi-

[47] R. Beringer, *Phys. Rev.*, vol. 70, p. 53; 1946.

[48] C. M. Johnson, D. M. Slager, and D. D. King, "Millimeter waves from harmonic generators," *Rev. Sci. Instr.*, vol. 25, pp. 213–217; March, 1954.

[49] J. A. Klein and A. H. Nethercot, Jr., "Microwave spectrum of DI at 1.5 mm wavelength," *Phys. Rev.*, vol. 91, p. 1018; August 15, 1953.

[50] A. H. Nethercot, Jr., "Harmonics at millimeter wavelengths," IRE Trans. on Microwave Theory and Techniques, vol. MTT-2, pp. 17–20; September, 1954.

[51] J. M. Richardson and R. B. Riley, "Performance of three-millimeter harmonic generators and crystal detectors," IRE Trans. on Microwave Theory and Techniques, vol. MTT-5, pp. 131–135; April, 1957.

[52] Y. C. Hwang, "Harmonic Generation by Crystals at Microwave and Millimeter Wave Frequencies," Elec. Eng. Dept., University of Maryland, College Park, Md., Final Rep. AF18(600)-1246; January, 1956.

[53] H. Q. North, "Properties of welded contact germanium rectifiers," *J. Appl. Phys.*, vol. 17, pp. 912–923; November, 1946.

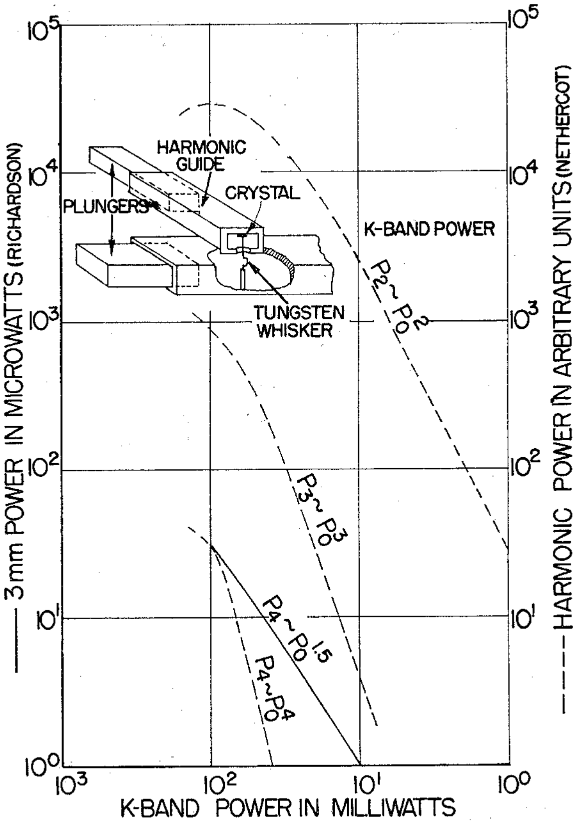


Fig. 21—Power characteristics of the crossed-guide crystal multiplier.

pliers yielded more than twenty times the 4-mm harmonic power output of standard silicon crystals. It would appear that more work on crystal materials and circuit synthesis remains to be done on this type of multiplier.

The crystal multiplier driven by a tube such as a 2K33 klystron is at present the least expensive method of producing low millimeter wave power. In experiments where very low-level signals can be tolerated, the crystal multiplier will probably find use for many years to come, barring the invention of a new self-excited source.

Recent advances in the practical application of field emission[54] have prompted several groups[55–57] to consider field-emission cathodes for harmonic generation. It is well known that electrons are emitted from a cold metal under the action of a strong field, the current-voltage relationship for a given geometry being given by

$$I = Ce^{-D/V} \tag{18}$$

where C and D are constants.

[54] W. P. Dyke and W. W. Dolan, "Field emission," in "Advances in Electronics and Electron Physics," Academic Press, New York, N. Y., vol. 8; 1956.

[55] Letter Reports on APL/JHU Subcontract No. 77711, "Field Emission Applications to Microwave Amplifier Tubes," Linfield Res. Inst., McMinnville, Ore.; 1956–58.

[56] Consolidated Quart. Status Reps., Basic Electronics Res., Stanford Electronics and Microwave Lab., Stanford, Calif., 1957.

[57] P. D. Coleman, Ultramicrowave Group Tech. Status Reps. on Contract AF18(603)-62, University of Illinois, Urbana, Ill.; 1957–58.

Two characteristics of the field emitter make it attractive for frequency multiplication: its highly nonlinear exponential I vs V relationship, and its high pulsed power capabilities. Characteristics which make its application difficult are 1) high vacuum requirements, 2) stability problems, 3) high impedance, 4) current limitations for a single emitter, 5) multiple emitter fabrication problems, 6) anode heating, and 7) beam focusing.

Fig. 22 illustrates a typical emitter current waveform resulting from the application of a dc bias voltage, V_0, plus an ac voltage, $V_1 \cos \omega_0 t$. Increasing the negative bias causes the current to flow during a shorter phase interval, thereby increasing the harmonic content. The harmonic current amplitudes, under the condition of negative bias, can be computed as follows. From (18)

$$I(t) = Ce^{-D/(V_0+V_1 \cos \omega_0 t)} \simeq Ce^{-D/(V_0+V_1)} e^{-(DV_1/2)[(\omega_0 t)/(V_0+V_1)]^2} \tag{19}$$

where V_0 is the dc bias voltage, and $V_1 \cos \omega_0 t$ is the ac voltage.

Only two terms in the cos $\omega_0 t$ expansion about zero have been retained.

Using the approximation that the current flows for only a small fraction of the total RF phase, the current harmonic amplitude is given by

$$I_n \simeq \left[Ce^{-D/(V_0+V_1)}\right]\left[\frac{\sqrt{\pi}(V_0+V_1)}{\sqrt{DV_1}} e^{-n^2(V_0+V_1)^2/(2DV_1)}\right]. \tag{20}$$

The first term in the bracket gives the peak value of the current pulse which is limited by the maximum tolerable heating of the emitter. The second term in brackets has its maximum value for $DV_1/(V_0+V_1)^2 = n^2$; hence

$$(I_n)_{\max} \simeq \frac{Ce^{-D/(V_0+V_1)}}{n} = \frac{I_p}{n}. \tag{21}$$

Field emitter current begins to flow when

$$V_0 + V_1 \cos (\theta_0/2) \geqq 0 \tag{22}$$

or

$$\theta_0 \simeq \left[\frac{8(V_0+V_1)}{V_1}\right]^{1/2}. \tag{23}$$

Fig. 23 illustrates the results of a calculation made by Houston[58] on the current obtainable from a field emitter under rectangular pulse conditions. Assuming the current waveforms from the emitter under the conditions given by (19) are rectangular to a first approximation, then

$$(I_p)_{\max} = \left[Ce^{-D/(V_0+V_1)}\right]_{\max} \simeq I_{dc}\left[\frac{\pi^2 V_1}{2(V_0+V_1)}\right]^{1/4}_{\max}. \tag{24}$$

[58] J. M. Houston, "Calculation of the Tip Temperature of a Field Emitting Point as a Function of Point Geometry and Material," The Knolls Res. Labs., G.E. Co., Schenectady, N. Y.; 1955.

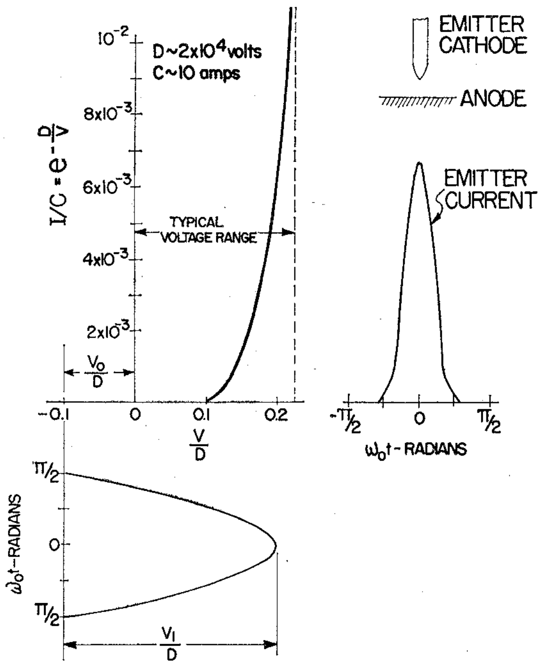


Fig. 22—Field emitter current waveforms.

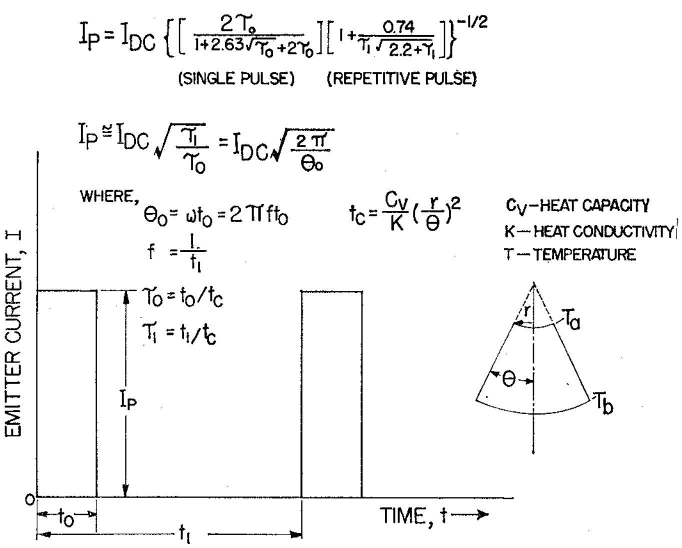


Fig. 23—Pulsed operation of emitter.

The maximum dc current, I_{dc}, is determined by the emitter material and geometry. For a typical tungsten emitter having a tip radius of 0.5×10^{-4} cm and a cone half-angle of 0.1 radian, the maximum dc current is computed to be 0.15 amp. The voltages V_0 and V_1 are chosen in such a manner that short current pulses which are rich in harmonics are produced; however, their values, when combined, must not exceed the breakdown voltage in the reverse direction.

In a two-cavity klystron frequency multiplier, the velocity modulated beam must drift to obtain a bunched, harmonic beam. Using a field emitter, the emitted current immediately has a high harmonic content. This fact, along with the high current densities that can be obtained with a field emitter, are the features that workers in this area are trying to exploit for the production of low millimeter wavelengths. However, the technical problems associated with the field emitter are difficult and the devices in which they are being used are encountering essentially the same fundamental problems that plague the extension of conventional tubes to higher frequencies. Sufficient facts are not yet known to make a final evaluation of the field emitter as a frequency multiplier, but the road ahead looks very rough.

Megavolt Electronics

Frequency-multiplier klystrons[59] such as the one illustrated in Fig. 24 have been used for many years to provide precisely known frequencies in the microwave range. The basic idea being used in these devices is that an electron beam is a highly nonlinear element in the sense that, by velocity modulating a dc beam by a signal at frequency f_0, and then allowing it to drift, a high harmonic content beam is produced. But, this scheme, as used in the klystron multiplier, has the same four fundamental problems that plague all conventional tubes as they are extended into the low millimeter wavelength range. Moreover, space charge limits the bunching action and restricts the harmonic content. Also, since the original velocity modulation of the beam is never removed, the high harmonic content of the beam exists only over a small distance because beyond a certain point the velocity modulation destroys the bunch.

In the klystron multiplier shown in Fig. 24(a) there is no real problem in constructing an output cavity either at S, X, or K band, but in the low millimeter range physical size becomes a problem, especially since the cavities normally used are reentrant to reduce the electron transit time. However, with a drive power of the order of watts, harmonics ranging from the 10th to the 20th, with an efficiency of the order of 0.5 per cent, can be achieved.

From the standpoint of a nonlinear element, a frequency multiplication by a factor of 20 with an efficiency of 0.5 per cent, is generally difficult to accomplish. In this respect, an electron beam represents about as nonlinear an element as one can imagine. Hence, if a method could be found to use an electron beam for multiplication and still circumvent the conventional electron tube problems, one would have an excellent tool for an assault on the submillimeter wave problem. The megavolt electronics system shown in Fig. 24(b) is just such a method.

In principle, the megavolt electronics system is closely related to the klystron multiplier, but with a few critical exceptions. A suitable oscillator at frequency f_0, drives a relativistic electron bunching accelerator[60,61] (called a

[59] H. J. Reich, *et al.*, "Microwave Theory and Techniques," D. Van Nostrand Co., Inc., New York, N. Y., p. 630; 1953.

[60] I. Kaufman and P. D. Coleman, "Design and evaluation of an S-band rebatron," *J. Appl. Phys.*, vol. 28, pp. 936–944; September, 1957.

[61] P. D. Coleman, "Theory of the rebatron—a relativistic electron bunching accelerator for use in megavolt electronics," *J. Appl. Phys.*, vol. 28, pp. 927–935; September, 1957.

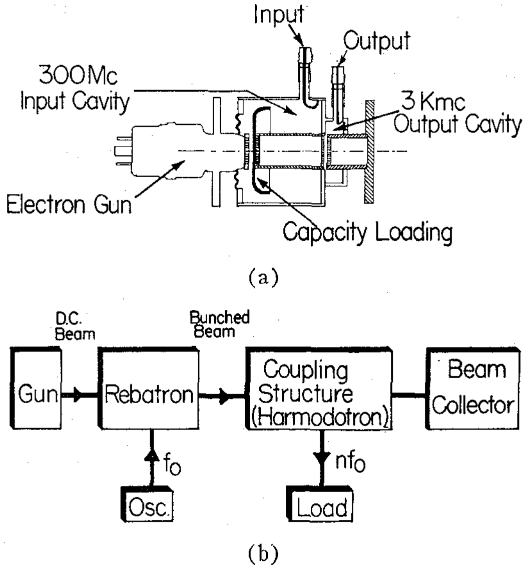


Fig. 24—Frequency multiplication by means of an electron beam. (a) Schematic diagram of a frequency-multiplier klystron. (b) Megavolt electronics system.

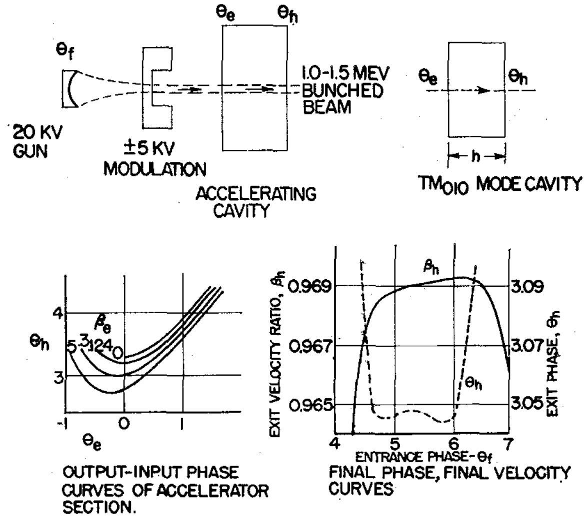


Fig. 25—S-band rebatron.

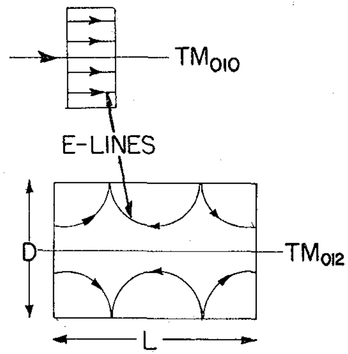


Fig. 26—TM_{0mn} modes for metal cylindrical cavity.

rebatron) as shown in Fig. 25. However, since the electron dynamic equations are nonlinear at relativistic velocities, the velocity-modulation and acceleration process is drastically altered so that it is possible to produce a more tightly bunched beam having very little resultant velocity modulation. This will lead to a traveling current-wave of the form where, ideally

$$i(t, z) = \sum_{n=0}^{\infty} I_n \cos 2\pi f_0 n(t - z/v) \qquad (25)$$

with $I_n \neq I_n(z)$, $v \simeq c$ (the velocity of light), and for perfect bunching

$$i = N\delta(t - t'). \qquad (26)$$

$I_n = 2I_0$ for all n. δ is the Dirac delta function and N, the number of electrons in the bunch.

The output-input phase curves of Fig. 25 give a quantitative indication of the bunching capability of the TM_{010} mode accelerating cavity as a function of the input velocity. These curves are computed for constant entrance velocity ratio, β_e, a condition which is easily realized in practice but which will not yield the desired delta function current and delta function velocity distribution. These characteristics require that β_e be a specified function of the input phase, θ_e, and hence the need for a suitable prebunching system arises. The final phase, final velocity curves which appear in Fig. 25 describe the performance of the over-all rebatron system for a typical set of parametric values.

Megavolt electronics techniques lead to a much higher harmonic content beam than in the klystron multiplier because of better bunching methods and because the bunching forces can be made large compared to the debunching forces. Also, the magnetic force at relativistic velocities "pinches" the beam in the transverse direction to aid in keeping it from spreading.

Assuming that an electron beam of the form given by (25) could be produced, how does this circumvent the problems of conventional electron tubes? First, the cathode and starting current density problem is eliminated since the systems to be considered are not self-excited. Furthermore, by using large gun voltages ($>10^4$ volts), it is not too difficult to produce convergent beams having large current densities.

Second, a beam velocity approaching the velocity of light, c, makes it feasible to couple to higher order modes of a resonant structure,[62,63] thereby greatly increasing the dimensions for the same resonant frequency. For example, take a metal cylindrical cavity operating in the TM_{0mn} modes as shown in Fig. 26. The diameter D, the length L, and the resonant wavelength λ_0 are related by

$$\left(\frac{D}{\lambda_0}\right)^2 = \left(\frac{r_{0m}}{\pi}\right)^2 + \left(\frac{nD}{2L}\right)^2 \qquad (27)$$

[62] P. D. Coleman and M. D. Sirkis, "The Harmodotron—a beam harmonic, higher order mode device for producing millimeter and submillimeter waves," *J. Appl. Phys.*, vol. 26, pp. 1385–1386; November, 1955.

[63] M. D. Sirkis and P. D. Coleman, "The Harmodotron—a megavolt electronics millimeter wave generator," *J. Appl. Phys.*, vol. 28, pp. 944–950; September, 1957.

where r_{0m} is the mth root of the Bessel function of the first kind, and n is an integer. Obviously as r_{0m} and/or n become arbitrarily large, so do D and L. The phase velocity v_p associated with the structure is given by

$$(v_p/c)^2 = 1 + (2Lr_{0m}/n\pi D)^2 \tag{28}$$

and the beam coupling coefficient k_+ by

$$k_+ = \frac{1}{2}\,\frac{\sin\dfrac{\omega L}{2}\left(\dfrac{1}{v}-\dfrac{1}{v_p}\right)}{\dfrac{\omega L}{2}\left(\dfrac{1}{v}-\dfrac{1}{v_p}\right)} = \frac{1}{2}\left[\frac{\sin\dfrac{n\pi}{2}\left(\dfrac{v_p}{v}-1\right)}{\dfrac{n\pi}{2}\left(\dfrac{v_p}{v}-1\right)}\right]. \tag{29}$$

An efficient exchange of energy will be possible when $v \rightarrow c$. For example, consider a silver TM_{018} mode cavity driven by a beam whose velocity v is $0.95c$. It can be shown for $D/L = 0.6$ that the power generated for a harmonic beam current I_n is given by

$$P(\text{watts}) \simeq 3000[I_n(\text{amps})]^2[\lambda_0(\text{mm})]^{1/2}. \tag{30}$$

For $\lambda_0 = 1$ mm and $I_n = 0.1$ amp, then $P \simeq 30$ watts.

Heat dissipation problems are eliminated since the beam passes directly through the higher order mode cavity with little interception of current. Circuit losses have not been eliminated but the Q of the structure has been greatly increased by going to higher order modes.

Megavolt electronics[64,65] provides other approaches to the millimeter wave generation problem based on the use of the Doppler effect[66–68] and Cerenkov effect.[69] In each of these cases, the tightly bunched, relativistic beam can be used to excite coupling structures which are large compared to the wavelength.

It would appear that bunched, megavolt beams represent the most high-power and most nonlinear element yet suggested for frequency multiplication. A frequency multiplication of the order of 50 to 100 should be practical using megavolt electronics techniques. With the development of good, practical X-band (or possibly K-band) bunching accelerators, wavelengths well below 1 mm are feasible. This technique, however, does lead to a pulsed rather than a CW source of radiation.

[64] P. D. Coleman, Quart. Reps. on Contract AT(11-1)-392, Elec. Eng. Res. Lab., University of Illinois, Urbana, Ill.; 1956–58.

[65] K. B. Mallory, Quart. Reps. on Contract DA-36-039 sc-72785, W. W. Hanson Lab. of Physics, Microwave Lab., Stanford, Calif., 1958.

[66] P. D. Coleman, "Generation of millimeter waves," Ph.D. dissertation, Dept. of Physics, M.I.T., Cambridge, Mass.; 1951.

[67] H. Motz, "Application of the radiation from fast electron beams," *J. Appl. Phys.*, vol. 22, pp. 527–535; May, 1951.

[68] H. Motz, W. Thon, and R. N. Whitehurst, "Radiation by fast electron beams," *J. Appl. Phys.*, vol. 24, pp. 826–833; July, 1953.

[69] M. Danos and H. Lashinsky, "Millimeter wave generation by Cerenkov radiation," IRE Trans. on Microwave Theory and Techniques, vol. MTT-3, pp. 21–22; September, 1954.

Ferrites

The application of an RF magnetic field to a magnetized ferrite results in the precession of the magnetic moments of the unbalanced electron spins. For the lossless infinite medium, the equation of motion of a system with angular moment $\bar{J}$ and magnetic moment $\bar{M}$ in a magnetic field $\bar{H}$ is[70]

$$\frac{d\bar{J}}{dt} = \bar{M} \times \bar{H}. \tag{31}$$

But since $\bar{M}$ and $-\bar{J}$ are proportional to each other

$$\bar{M} = \gamma\bar{J} = -\frac{ge}{amc}\bar{J} \tag{32}$$

where γ is the magnetomechanical ratio of the unpaired electrons, (31) can be written as

$$\frac{d\bar{M}}{dt} = \gamma\bar{M} \times \bar{H}. \tag{33}$$

Let

$$\bar{M} = \bar{k}M_s + \bar{m} \quad \text{with} \quad |\bar{M}| = M_s \tag{34}$$

and

$$\bar{H} = \bar{k}H_0 + \bar{h} \tag{35}$$

where M_s is the saturation magnetization, $\bar{m}$ and $\bar{h}$ are the time varying components, and H_0 is the static magnetic field (see Fig. 27). If the expressions for $\bar{M}$ and $\bar{H}$ from (34) and (35) are substituted into (33) the solution, neglecting cross product terms, is

$$m_x = \left[\frac{\gamma^2 H_0 M_s}{\gamma^2 H_0^2 - \omega^2}\right] h_x - \left[\frac{\gamma M_s}{\gamma^2 H_0^2 - \omega^2}\right]\frac{dh_y}{dt} \tag{36}$$

$$m_y = \left[\frac{\gamma^2 H_0^2 M_s}{\gamma^2 H_0^2 - \omega^2}\right] h_y + \left[\frac{\gamma M_s}{\gamma^2 H_0^2 - \omega^2}\right]\frac{dh_x}{dt} \tag{37}$$

or

$$m_x = \alpha h_x - \beta\frac{dh_y}{dt} \tag{38}$$

and

$$m_y = \beta\frac{dh_x}{dt} + \alpha h_y \tag{39}$$

with

$$\frac{dm_z}{dt} = 0. \tag{40}$$

If second-order terms are retained, the solution for m_z gives

$$\frac{dm_z}{dt} = \gamma(m_x h_y - m_y h_x) \tag{41}$$

[70] D. Polder, "On the theory of ferromagnetic resonance," *Phil. Mag.*, vol. 40, p. 99; 1949.

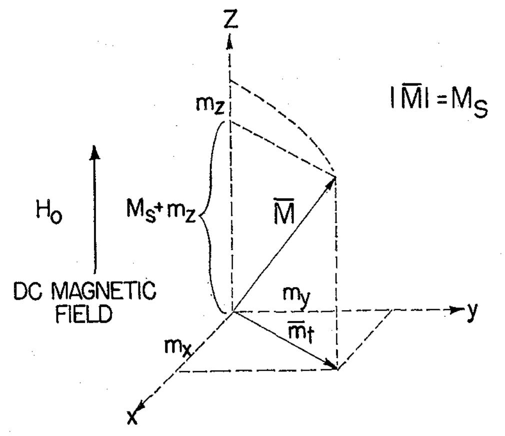


Fig. 27—Frequency doubling in ferrites.

or, using (38) and (39) and then integrating, the value of m_z is given by

$$m_z = -\frac{\gamma\beta}{2}(h_x^2 + h_y^2) + C. \tag{42}$$

The constant of integration C can be obtained from the condition $|\bar{M}| = M_s$, which for the case $m_x^2 + m_y^2 \ll m_s^2$ gives

$$m_z \simeq -\frac{m_x^2 + m_y^2}{2M_s}. \tag{43}$$

If

$$h_x = A_1 \sin \omega t \tag{44}$$

$$h_y = A_2 \sin(\omega t + \Delta), \tag{45}$$

then the time varying part of m_z becomes,

$$m_z(\text{RF}) = -\frac{\gamma^2 M_s}{4(\gamma^2 H_0^2 - \omega^2)} D \sin(2\omega t - \delta) \tag{46}$$

where

$$D \sin \delta = A_1^2 + A_2^2 \cos 2\Delta \tag{47}$$

$$D \cos \delta = A_2^2 \sin \Delta 2. \tag{48}$$

Eq. (46) shows that the z component of magnetization has a component oscillating at frequency $2w$ hence the ferrite will radiate an electromagnetic wave of frequency $2w$. Actually the magnetization has still higher-order terms since only the second-order terms have been retained to obtain (46).

Ayres, Melchor, and Vartanian[71,72] have investigated frequency doubling[73] in ferrites from X to K band using the experimental arrangement shown in Fig. 28(a). The peak power output vs. the peak power input is given in Fig. 28(b) which indicates the ferrite is operating according to a 1.8 power law. From (42) one would expect a square-law device. The deviation from square law suggests some of the energy is being converted to a higher-order harmonic.

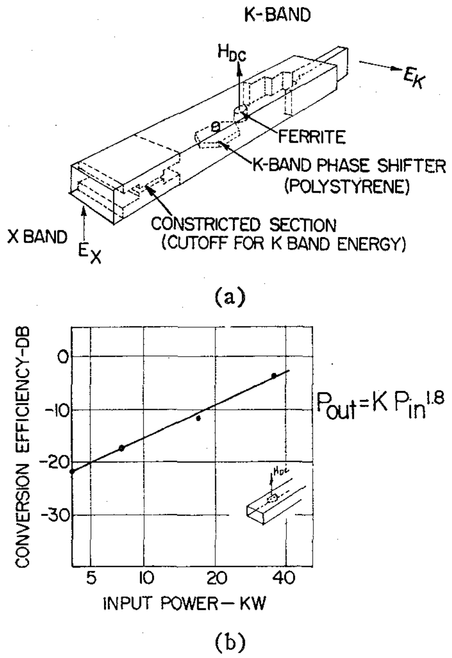


Fig. 28—Frequency doubling in ferrites. (a) Ferrite frequency doubler from X to K band (Melchor, Ayres, and Vartanian). (b) Conversion efficiency (half disk of ferrite against side wall).

An important feature of the ferrite doubler is its high peak power handling capacity and conversion efficiency (the order of -7 db) at these high pulsed power levels.

Parametric Amplifiers

It is well known that one can obtain gain with a modulator as illustrated in Fig. 29(a). Here the signals from the pumping oscillator at frequency f_p and the signal source at frequency f_s are mixed in a variable reactance to generate sidebands at frequencies $f_p \pm f_s$. It is possible for the sidebands to have more power than the signal source. Hence, if a demodulator is used, one could get out an amplified signal at f_s.

In the parametric amplifier,[74,75] the power supplied by the local oscillator is directly converted to signal power at the signal frequency as illustrated in Fig. 29(b). The energy required for amplification in both amplifiers is derived from the pumping oscillator.

The principle of operation of the ferrite parametric amplifier is as follows. First the pump frequency, f_p, and the signal frequency, f_s, are mixed in the ferrite to produce a magnetization varying at the idling frequency $f_i = f_p - f_s$. This magnetization excites the idler circuit into oscillation. Next the idler frequency, f_i, and the pump frequency, f_p, mix in the ferrite to produce a second magnetization varying at the signal frequency. If the signal derived from this magnetization is in phase with the initial signal, amplification can result.

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

[72] J. L. Melchor, W. P. Ayres, and P. H. Vartanian, "Microwave frequency doubling from 9 to 18 kmc in ferrites," Proc. IRE, vol. 45, pp. 643–646; May, 1957.

[73] J. E. Pippin, "Frequency doubling and mixing in ferrites," Proc. IRE, vol. 44, pp. 1054–1055; August, 1956.

[74] H. Suhl, "Theory of the ferromagnetic microwave amplifier," *J. Appl. Phys.*, vol. 28, p. 1225; November, 1957.

[75] M. T. Weiss, "A solid-state microwave amplifier and oscillator using ferrites," *Phys. Rev.*, vol. 107, p. 317; July, 1957.

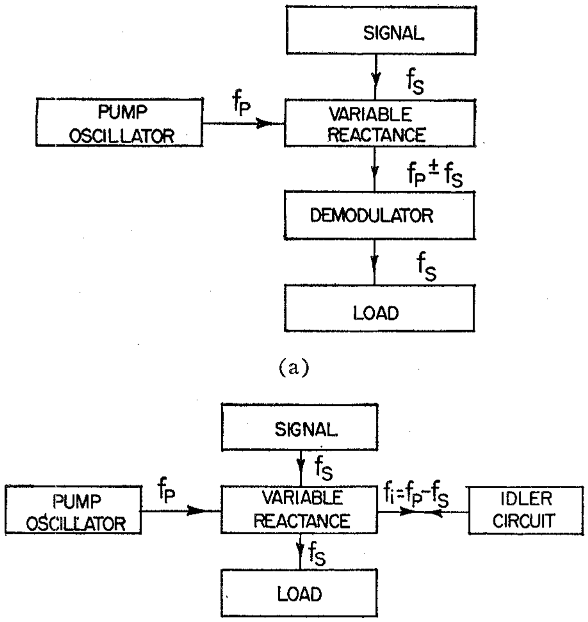


Fig. 29—Block diagrams of amplifiers. (a) Magnetic or dielectric amplifier. (b) Parametric amplifier.

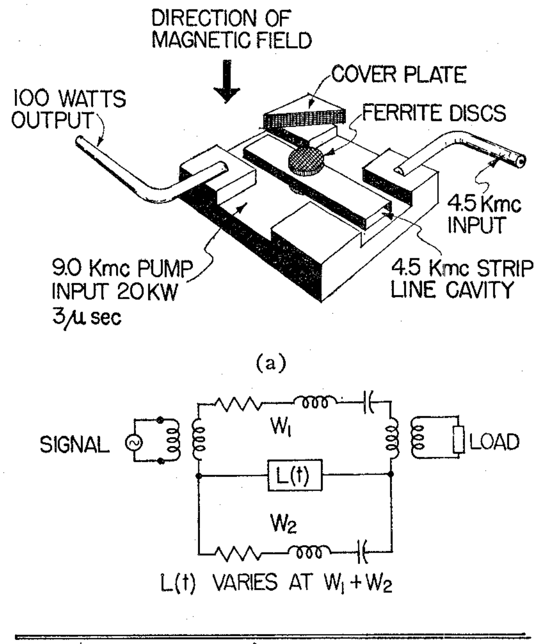


Fig. 30—Solid-state oscillator. (a) M. T. Weiss, "Solid-state microwave amplifier and oscillator using ferrites," *Phys. Rev.*, vol. 107, p. 317; July, 1957. (b) H. Suhl, "Proposal for a ferromagnetic amplifier in the microwave range," *Phys. Rev.*, vol. 107, p. 384; April, 1957.

Three types of operation of the parametric ferrite amplifier may be considered: the magnetostatic, the semistatic, and the electromagnetic. To describe these ways to use a ferrite, one must consider the magnetostatic modes.[76] When the ferrite sample is small compared to an electromagnetic wavelength in the material, propagation effects may be neglected, so that Maxwell's equations become

$$\nabla \times \bar{h} = \nabla \cdot (\bar{h} + 4\pi\bar{m}) = 0. \tag{49}$$

Using

$$\overline{M} = \bar{k}M_0 + \bar{m}\epsilon^{j\omega t} \qquad \overline{H} = \bar{k}H_i + \bar{h}\epsilon^{j\omega t} \tag{50}$$

in the torque equation

$$\frac{d\overline{M}}{dt} = \gamma\overline{M} \times \overline{H} \tag{51}$$

the linear approximation becomes

$$j\omega\bar{m} = \gamma[\bar{k} \times (M_0\bar{h} + H_i\bar{m})]. \tag{52}$$

The solution of (49) and (52), together with boundary conditions, determine the modes of $\bar{m}$ and $\bar{h}$ along with their characteristic frequencies. These modes are called magnetostatic modes. Moreover, their frequencies occupy a limited range on a frequency scale. For a spheroid, for example,

$$\gamma(H_0 - N_z M_0) \leq \omega \leq \gamma(H_0 + 2\pi M_0). \tag{53}$$

In the magnetostatic mode of operation, the pump frequency ω_p is chosen equal to the uniform precession mode γH_0. Since there is coupling between the uniform precession mode and the other magnetostatic modes, any two pairs whose frequencies add up to ω_p will be excited. However, a load can only couple to a small number of these modes so that the power supplied at the pumping frequency would be dissipated as heat in the many unloaded modes, making this type of operation impractical.

In the semistatic type of operation, H_0 is adjusted so that no two magnetostatic mode frequencies add up to the precession frequency. Here the ferrite could be placed in a resonant cavity tuned to resonate at either ω_s or $\omega_p - \omega_s$. One magnetostatic mode is used to supply the other needed circuit at frequency $\omega_p - \omega_s$ or ω_s.

In the electromagnetic type of operation, a doubly resonant cavity is made to supply both low-frequency circuits. The pump frequency is at the uniform precession frequency.

Fig. 30 shows a parametric amplifier made by Weiss.[75] A strip line resonator was used, with coupling by means of coaxial line probes. Both the idler and signal frequencies were made equal at 4.5 kmc. With a peak pumping power of 20 kw, the device oscillated at a peak output of 100 watts, *i.e.*, 23 db down.

A recent investigation[77] has shown that microwave amplification using ferromagnetic materials does not necessarily require the local oscillator or pump frequency to be greater than the signal frequency. New devices requiring four frequencies for signal mixing rather than the usual three, make it possible to obtain

[76] L. R. Walker, "Magnetostatic modes in ferromagnetic resonance," *Phys. Rev.*, vol. 105, pp. 390–399; January, 1957.

[77] C. L. Hogan, R. L. Jepsen, and P. H. Vartanian, "New type of ferromagnetic amplifier," *J. Appl. Phys.*, vol. 29, pp. 422–423; March, 1958.

amplification at a frequency higher than the pump frequency. In addition, such a device can be made to act as a microwave oscillator capable of generating a frequency up to twice the frequency of the local oscillator.

It is seen that the parametric amplifier or oscillator is also a high pulsed power device. However, the structure shown in Fig. 30(a) is not easily made, especially in the low millimeter range. Hence, it may be desirable to try the semistatic type of operation if much higher frequencies are desired.

Other Types of Nonlinear Elements

Nonlinear Capacity—Reverse Biased Semiconductor Junction: A semiconductor *p-n* junction[78] is known to have a nonlinear capacity C shunting the barrier resistance. Its value is given by

$$C = \epsilon A\left[-(V_0 + V)\frac{2\epsilon\mu_n}{\sigma_n}\right]^{-1/2} f. \qquad (54)$$

where

ϵ = permittivity of semiconductor,
A = area,
V_0 = contact voltage,
V = applied bias voltage,
μ_n = mobility of electrons in semiconductor,
σ_n = conductivity of semiconductor.

All units are in the rationalized MKS system.

It is seen from (54) that a semiconductor junction, when biased in the reverse (nonconducting) direction, is a capacitance which can be varied by the bias voltage. The Q of this condenser is given by $1/\omega Cr$ where r is the series resistance of the junction.

Giacoletto and O'Connell[78] have recently described a diode having a nominal Q of 17 at 500 mc. In one of their better units a Q of 36 was obtained. Over the bias range 0 to -16 volts, the capacity varied from about 140 to 25 μfd.

It would appear that biased diodes may have applications in parametric amplifiers and possibly frequency multipliers.

Ferroelectrics: If low-loss ferroelectric materials could be found, one has reason to believe that electric analogs of the ferrite multipliers and parametric amplifiers could be made. Higa[79] has suggested the circuit shown in Fig. 31 as a ferroelectric frequency multiplier using barium titanate. He assumes a relation between $\overline{E}$ and $\overline{D}$ of the form

$$E_x = [a + b(D_x^2 + D_y^2)]D_x \qquad (55)$$

$$E_y = [a + b(D_x^2 + D_y^2)]D_y. \qquad (56)$$

Using these relations in the circuit equation, he derives the following nonlinear Mathieu equation for D_y

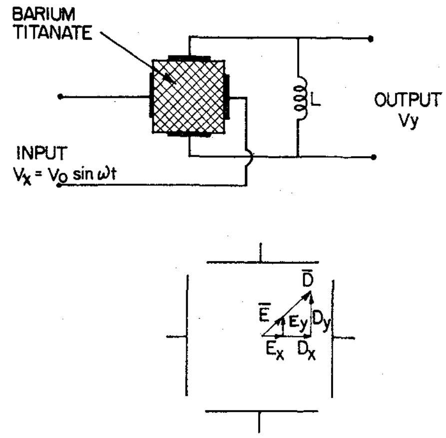


Fig. 31—Ferroelectric frequency multiplier circuit.

$$\frac{d^2D_y}{dt^2} + (\alpha + \beta\cos 2\omega t)D_y = 0 \qquad (57)$$

where, if the constants α and β satisfy certain conditions, the solution for D_y is given by

$$D_y = C_1 \cos \omega t + C_3 \cos 3\omega t + \cdots. \qquad (58)$$

Under other conditions, Higa further shows that by tuning the inductor L to resonate with the capacity at a harmonic of the driving frequency, both odd and even harmonics can be produced. In its present form, the device is limited by the "mild" nonlinearities of available ferroelectrics.

Harmonic Generation in Microwave Tubes

In attempting to overcome the physical size limitations on resonators, one possible solution for conventional tubes is to try to generate harmonics of the highest fundamental frequency for which a tube can be constructed. Bernier and Leboutet[80] have reported on harmonics from klystrons and Gourary[81] and others at Columbia University have been working on harmonic generation in magnetrons.

Bernier and Laboutet indicated that it was possible to construct a reentrant klystron cavity wherein one or more of the higher-order mode frequencies, f_n, could be made an exact multiple of the fundamental frequency f_1. Using a 4.08-cm klystron, they reported that they obtained harmonics as large as the 24th at 1.7 mm with the power output the order of a few microwatts.

The group at Columbia[9] has been working on harmonic generation in magnetrons since 1949. Their original idea was as follows. In a magnetron operating in its fundamental π mode, the space charge rotating on the interaction space resembles a rimless wheel with spokes.

[78] L. J. Giacoletto and J. H. O'Connell, "A variable-capacitance germanium junction diode for UHF," *RCA Rev.*, vol. 17, pp. 68–85; March, 1956.

[79] W. H. Higa, "Theory of nonlinear coupling in a novel ferroelectric device," *J. Appl. Phys.*, vol. 27, pp. 775–777; July, 1956.

[80] J. Bernier and H. Leboutet, "Sur la possibilité d'obtenir des ondes entretenues très courtes en utilisant un klystron reflex donnant de l'energie sur des fréquences harmoniques d'ordre elève de l'oscillation fondamentale," *Comp. Rend.*, no. 4, pp. 797–798; October, 1954.

[81] B. S. Gourary, "The Theory of Harmonic Generation in Magnetrons," Rad. Lab., Columbia University, New York, N. Y., Quart. Reps.; June 30, 1949 to December, 1957.

A spacial Fourier analysis of such a charge cloud shows that it contains components of various angular symmetries, all traveling at the same angular velocity. If one of the modes of the cavity contains a similar Fourier component, it will be driven by the space charge. Specifically, if a π mode of a higher frequency is made to have a Fourier component of the proper symmetry traveling at the same angular velocity as the space charge, then that harmonic π mode will be excited.

Bernstein and Kroll at Columbia Radiation Laboratory have been studying harmonic generation in magnetrons using their *X*-band XHI anodes. In their recent 1957 quarterly reports, these tubes have given a second harmonic power output ranging from 9 to 46 kw with efficiencies of the order of 4 to 12 per cent. Some work has also been carried out on third harmonic generation.

The Ultramicrowave Group at the University of Illinois has tried feeding klystron tubes into waveguides tapered down so that only harmonics of the fundamental can propagate. In particular, it was found that the Amperex DX151 tube gave sufficient 2-mm signals for most low-level test purposes.

Conclusion

The representative, but limited number, of specific examples of conventional microwave tubes, briefly discussed in this paper, has indicated that the present frequency frontier is in the neighborhood of wavelengths of 2 to 3 mm. The fact that all of the tube types are plagued with essentially the same fundamental problems and limitations strongly suggests that one has indeed reached a practical limit in the low millimeter range.

Elliott[82] has indicated that for tubes employing resonant cavities, the frequency limit depends chiefly on the ac beam current density and the noise level in the resonant structure. To put pessimistic numbers in Elliott's current inequality criterion also suggests that experimenters have just about reached the frequency limit with present techniques.

However, with the fabulous tube art and techniques that have been built up, one can expect conventional tubes to make a last-ditch stand by such methods as harmonic generation and subminiature, watchmaker approaches. Whether these techniques can extend the frequency by more than a factor of two to three remains to be seen. It is certain that the present difficulties are taxing the enormous resourcefulness of the people in the electron tube field.

The present status of low millimeter and submillimeter wave generation would appear to be that no ideas for a prime, self-excited, coherent source exist. While it has not been proven that coherent sources in this frequency range are theoretically possible, workers in the field have an optimistic, intuitive feeling that such sources can be made. However, until a "brilliant hunch" bears fruit, most efforts at the present time are directed toward frequency multiplication and conversion using conventional microwave tube sources as driver elements. It may be that the final sources for the submillimeter range will be based on some frequency conversion principle, rather than the dc input rf output energy conversion method used in conventional tubes. It is the author's opinion that for microwave engineers to make progress on this problem they will have to have a good understanding of solid-state electronics.

Megavolt electronics, while not classified here as a conventional electron tube technique, appears to offer the most proven promise of any electronic frequency multiplying method for invading the submillimeter range with a pulsed, coherent source of radiation. Multiplication of the fundamental frequency by a factor of 50 or more is a practical possibility. Hence the development of practical *X*-band or *K*-band bunching accelerators would place megavolt electronics techniques in a very competitive position with regard to frequency multiplying devices. This is particularly true with respect to theoretical peak power capabilities at high harmonic frequencies. The words megavolt electronics and bunching accelerators might, off-hand, cause one to imagine large machines and bulky devices limited only to laboratory experimental uses. In rebatrons, fed by a magnetron-ferrite isolator system, the apparatus is only two to three times the size of the magnetron being used, the bulk of the equipment being simply that of the magnetron power supply.

The solid-state electronics approaches, such as ferrite multipliers and oscillators, have not as yet produced frequencies which are unobtainable by electron tubes. Also, at the present time, the ferrite is usually placed in a more or less complicated microwave circuit which is fed by a high pulsed power tube. Hence, from a practical point of view, one might say that one has neither escaped nor circumvented present difficulties facing microwave tubes and/or techniques. This present aspect of the problem may not be important in the long run since the work in this area is relatively new. Triode tubes existed for a long time before klystrons, backward-wave oscillators, etc., were discovered. One is very optimistic, however, that as more is learned about masers, ferrites, ferroelectrics, parametric oscillators, spin resonances, etc., an idea for a self-excited source will eventually emerge.

Work on low millimeter wave components, detectors, etc., is handicapped at the moment by the lack of suitable signal sources to make tests. Therefore, most of the techniques being used are largely scaled-down versions of the tried and proven microwave methods. However, while it is believed that microwave methods may be extended to higher frequencies than microwave tubes, new techniques must also be forthcoming to handle these new ranges of frequencies.

[82] R. S. Elliott, "Some limitations on the maximum frequency of coherent oscillations," *J. Appl. Phys.*, vol. 23, pp. 812–818; August, 1952.