As an example, a folded cylinder for use at L band should have a spacing between cylinders of 0.030 in. At a pressure of 1 mm Hg of argon, the recovery time will be about 60 μsec. This spacing is still about twice the skin depth in a fully ionized plasma.

CONCLUSIONS

There is no reason why gas tube duplexers cannot be designed so as to handle extremely high powers and still meet other system requirements. The power-handling ability of a duplexer may be increased by using pure inert gases, by using tube materials with high heat conductivity, such as beryllium oxide, by narrowing the height of the window, or by putting the TR tube at the center of a high-Q cavity. An ATR duplexer may be used to spread the heat dissipation over a larger area. The actual tube spacing and fill are usually determined by considerations of easy firing, recovery time and tube life.

ACKNOWLEDGMENT

The author wishes to thank C. W. Jones and Dr. R. J. Carbone for many helpful discussions during the preparation of this paper.

Quasi-Optical Surface Waveguide and Other Components for the 100- to 300-Gc Region*

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Summary—**Components and techniques for the generation, transmission, and detection of energy in the 100- to 300-Gc frequency region were investigated theoretically and experimentally. The design and construction of fundamental components, such as harmonic generators and detectors, were necessary since many items are not available commercially. A detailed theoretical analysis was performed for the propagation characteristics of single-conductor transmission lines, and attenuation calculations were made for several dielectric image lines. Experimental measurements were made at 105 and 140 Gc on these two types of surface waveguides. Attenuation of these lines is compared with that of dominant-mode rectangular waveguide. An analysis of phase-correcting Fresnel zone plates was carried out, and several zone plates were designed, constructed and successfully tested at frequencies of 140, 210, and 280 Gc. Zone plates were used at several frequencies to make relatively long path transmission measurements and were also used in a specially designed Michelson interferometer. The frequency stability of the source klystron and the dielectric properties of a number of plastic materials were determined by measurements made with the interferometer. A method of frequency filtering by focal isolation was demonstrated with this equipment.**

I. INTRODUCTION

An investigation is being conducted to develop new components and techniques for use at wavelengths shorter than 3 mm. Much of the work completed to date has dealt with special rectangular waveguide devices, surface waveguides (dielectric image lines and coated or uncoated single-conductor transmission lines), and devices of an optical nature.[1] The basic instrumentation consisted of adaptations of conventional rectangular waveguide components. Signal power was provided by crystal harmonic generators driven with a few tens of milliwatts of power at a fundamental frequency of either 35 or 70 Gc. Experimental measurements were made at 105, 140, 210, and 280 Gc. Video detection with silicon crystals resulted in output signal levels with a dynamic range of about 45 db above noise, except at 280 Gc, where the range was somewhat less. For some sets of measurements at 140 Gc, a range of 55 db was available.

At the time the program was started there was a scarcity of commercial components for frequencies above 100 Gc, and it was therefore necessary to design and construct various waveguide items such as detectors, harmonic generators, horn antennas, and filter sections.[2] Coin-silver waveguide with a cross section of 0.0325- by 0.065-in ID (RG-136/U) was chosen because the guide has a TE_{10}-mode cutoff frequency of 90.8 Gc and propagates only the dominant mode at frequencies below about 180 Gc.[3] (The slightly larger size RG-138/U

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[1] M. J. King, *et al.*, "Quasi-Optical Components and Surface Waveguides for the 100 to 300 kMc Frequency Range," Electronic Communcations, Inc., Timonium, Md., Rept. No. 2 on AFCRL Contract No. AF 19(604)-5475; November, 1960.

[2] *Ibid.*; design details are given in this report.

[3] The harmonic generators use RG-96/U or RG-98/U waveguide inputs.

guide was not chosen, even though some commercial components were available in this size, because this guide has a TE_{10}-mode cutoff frequency of 73.8 Gc and this is too close to the operating region of typical klystron sources in the 4-mm wavelength region.) Waveguide "squeeze" section filters were built to provide suppression of 105- or 140-Gc harmonic signals when operating at higher frequencies. Suppression of 140-Gc and 210-Gc harmonic frequencies was also accomplished by the focal isolation technique described below.

Another phase of the program has been concerned with improving the efficiency of the point contact diodes mounted in harmonic generators and video detectors. Experimental diodes have been formed with some of the recently developed III-V compounds, such as gallium arsenide, indium arsenide, and indium antimonide. Both tungsten and phosphor-bronze whiskers have been used. To date these diodes have not shown any valuable improvement over the silicon-crystal, tungsten-whisker combination. The only encouraging results noted thus far have been obtained with an indium-arsenide polycrystal and a phosphor-bronze whisker in a detector mount. After considerable searching of the crystal surface with the whisker several points were found which gave approximately 10 db more sensitivity than the silicon-tungsten combination. Further work seems warranted with indium arsenide in single crystal rather than polycrystalline form.

II. Transmission Methods for Short Millimeter Wavelengths

At frequencies above 70-Gc dominant-mode, hollow metal waveguide is unsatisfactory for many applications because of very high attenuation. This is illustrated in Fig. 1, which shows calculated attenuation values for several standard waveguides (see also Table I). Measured values would be even larger because of losses at junctions and surface irregularities. The calculated values are based on the assumption of a perfectly smooth metal surface, but for these frequencies, where the skin depth is from 5 to 10 micro-inches, the surface roughness is usually many times the skin depth for most types of finishes. The attenuation was measured at 210 Gc for two different lengths of rectangular waveguide (having inside dimensions of 0.049 in×0.0245 in) and was found to be greater than twice the calculated value (in decibels per foot).

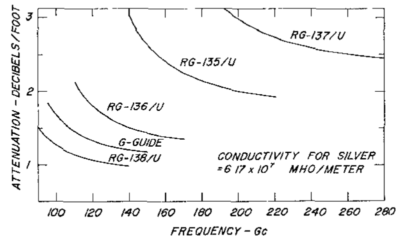

Fig. 1—Theoretical attenuation (TE_{10} mode) in rectangular waveguides of coin silver.

TABLE I

Rectangular Waveguide Data

Designation	Size (ID)	TE_{10}-Mode Cutoff
RG-138/U	0.080×0.040 in	73.8 Gc
G-guide	0.075×0.034 in	78.7 Gc
RG-136/U	0.065×0.0325 in	90.8 Gc
RG-135/U	0.051×0.0255 in	115.8 Gc
RG-137/U	0.043×0.0215 in	137.5 Gc

Certain other types of waveguides may be designed to have low-loss characteristics at these frequencies. Examples are surface-wave structures, hollow circular waveguide propagating the TE_{01} mode, and oversize rectangular or circular waveguide propagating the lowest-order mode. For technical or economic reasons the use of optical transmission techniques also may be useful. (This category includes the beam waveguide recently described by Goubau.[4]) Surface-waveguide and optical transmission methods were used in this study because of their simplicity and low cost.

III. Measured and Calculated Results for Surface Waveguides

A. Dielectric Image Lines

The dielectric image line is simply a strip of low-loss dielectric material centered on a high conductivity metal plane. Because of its ease of construction and support and its low-loss transmission characteristics, this line recently has received much attention. For the image line, both conduction loss in the image plane and dielectric loss contribute to the total attenuation factor. Conduction loss is reduced by the use of higher conductivity metals (such as copper or silver). To obtain low dielectric loss and single-mode operation at millimeter wavelengths, the dielectric material must be small in cross section and must have a low loss tangent and a low dielectric constant.[5] Typical materials which are satisfactory are polystyrene foam (which has been processed to have small cell sizes and uniform density) or Teflon, which can be purchased in thin, narrow tape form with a very thin pressure-sensitive adhesive backing.

The attenuation for the dominant HE_{11} mode on an image line having a semicircular dielectric cross section may be calculated by the use of the following relationship:[6]

$$\alpha = 27.3(\phi\epsilon/\lambda)R + 69.5(R_sR'/\lambda\eta)$$

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[4] G. Goubau and F. Schwering, "On the guided propagation of electromagnetic wave beams," IRE Trans. on Antennas and Propagation, vol. AP-9, pp. 248–256; May, 1961.

[5] J. C. Wiltse, "Some characteristics of dielectric image lines at millimeter wavelengths," IRE Trans. on Microwave Theory and Techniques, vol. MTT-7, pp. 65–69; January, 1959.

[6] S. P. Schlesinger and D. D. King, "Dielectric image lines," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 291–299; July, 1958.

where

α = attenuation per unit length
ϕ = loss tangent of the dielectric rod
ϵ = relative dielectric constant of the rod
λ = free-space wavelength (meters)
η = intrinsic impedance of free space
R_s = surface resistivity of the image plane.

The quantities R and R' are complicated functions of the dielectric constant and diameter (in free-space wavelengths) of the dielectric rod.[6]

About the smallest convenient diameter to which a polystyrene foam rod of semicircular cross section may be cut is an eighth of an inch (3.17 mm). The calculated attenuation of such a rod mounted on a copper image plane is shown in Fig. 2, where a relative dielectric constant of 1.05 was assumed for the foam. A second curve is shown for a dielectric constant of 2.0 (Teflon) and a rod diameter of 0.025 in (0.64 mm). (This size was chosen because a semicircular cross section with this diameter has the same area as a tape 0.002 by $\frac{1}{8}$ in.) For each of the curves in Fig. 2 the loss tangent of the dielectric was assumed to be 10^{-3} and the conductivity of copper was taken as 5.8×10^7 mhos/m. Since the dielectrics are already very small, further reduction of attenuation by reduction of dielectric cross section has only limited possibilities. It has been found, however, that lower attenuation may be obtained by using a "flattened" cross section (*i.e.*, rectangular or semi-elliptical) with the longer transverse dimension parallel to the image plane.

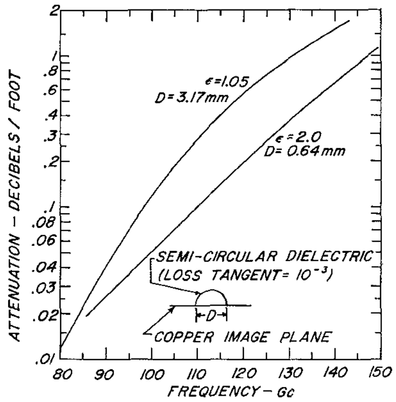

Fig. 2—Calculated attenuation (including dielectric and copper losses) for two dielectric image lines.

A theoretical analysis of wave propagation on dielectric rods of elliptic cross section was carried out during the present investigation.[7] Certain modes were found to exist in the elliptic rod which do not exist in the circular rod. However, of all the modes investigated, only the one corresponding to the dominant circular HE_{11} mode has zero cutoff frequency. Furthermore, as the eccentricity of the rod tends toward unity ("flat" ellipse) the cutoff frequencies of the other modes (for an ellipse of finite width) tend toward higher values. A thin dielectric tape line (Teflon 0.002 in thick) was chosen for the experimental tests since it is a good approximation of the limit for the very flat ellipse and only the HE_{11} mode is present. The use of the metal image plane lying along the major axis further excludes the "even" type modes where the tangential component E_z is represented by functions with even periodicity.

The image planes used for experimental loss measurements were made of copper 4 in wide, in lengths of 5, 12, and 20 feet. The copper was first cleaned and polished to insure a minimum of scratches and other imperfections which could contribute unknown losses to the measurements. The dielectric (pressure-sensitive Teflon tape) was then very carefully laid in a straight line on the center of the plane and pressed to make good contact with the plane. For each tape size the measurements were made on image lines of identical construction except for length; hence, all other losses were constants and the attenuation due to the increase in the length of image line was readily determined. (Further details are given by King, *et al.*[1]) The results of these measurements along with the theoretical loss for a semicircular dielectric cross section of the same area are shown in Table II.

TABLE II

Frequency	Tape Size	Average Measured Line Loss	Theoretical Loss (Semicircle)
105 Gc	$0.002 \times \frac{1}{4}$ in	0.14 db/ft	0.63 db/ft
140 Gc	$0.002 \times \frac{1}{8}$ in	0.43 db/ft	0.7 db/ft
140 Gc	$0.002 \times \frac{1}{4}$ in	0.98 db/ft	3.2 db/ft

The average measured loss is computed from at least five different measurements. The loss calculated for a semicircular dielectric cross section equal in area to that for a given tape is seen to be from 1.5 to 4 times greater than that measured for the tape line. Measurements were made at 105 Gc with a $\frac{1}{8}$-in tape, but the fields extended beyond the edge of the image plane and this caused errors in the loss measurements. An attempt was made to measure the loss for a tape $\frac{3}{8}$ in wide but irregularities in the tape width gave a spread in results which was too large to be useful.

B. Single-Conductor Wire Lines

Surface-wave propagation on a coated or uncoated cylindrical conductor was described some years ago for frequencies as high as 10 Gc,[8] but extrapolation of these

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[7] M. J. King and J. C. Wiltse, "Surface-Wave Propagation on a Dielectric Rod of Elliptic Cross-Section," Electronic Communications, Inc., Timonium, Md., Sci. Rept. No. 1 on AFCRL Contract No. AF 19(604)-5475; August, 1960.

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

results to frequencies above 100 Gc leads to errors[9] with conductor sizes which provide low-loss propagation. A new analysis was made for TM_{01}-wave propagation on coated or uncoated conductors at millimeter wavelengths.[1] (Modes other than the TM_{01} are highly attenuated and are not significant except near the launcher.) The low loss and reasonable field extent of the cylindrical-conductor transmission line offer an advantage over dominant-mode rectangular waveguide, in which the attenuation may be one or two orders of magnitude greater. The power-handling ability is also much greater for the single-conductor line than for rectangular waveguide. Wide ranges of attenuation and field extent are available from various combinations of wire size, material, and/or dielectric coating. These lines do have the disadvantage common to surface-wave lines in that they lack shielding (although shields can be provided). A further disadvantage is the necessity for physical supports which may increase the loss.

Measurements of attenuation were carried out at frequencies of 105 and 140 Gc for uncoated copper wires of circular cross section. Experimental transmission lines of several different diameters were built, and special launching horns were designed and constructed to generate the TM_{01} mode (see Fig. 3). The equipment used to make attenuation measurements consisted of an open wire line 60 feet long with the transmitter and launcher at one end. The pick-up probe (a 28-db horn), a video detector, and an indicator were mounted on a wheeled cart which was moved along the wire in such a manner that the horn was maintained a constant distance from the wire. The smaller wires (0.080- and 0.128-in diameters) were copper-clad steel and were held in place by tension without danger of stretching the wire, as might be the case if solid copper were used. In order to eliminate sag, which is present when the wire is held by tension alone, nylon monofilament (0.008-in diameter) was used to help support the wire. The larger diameter wires (0.375 and 0.500 in) were hard drawn copper tubing and were supported by nylon monofilament placed approximately every 8 feet along the wire.

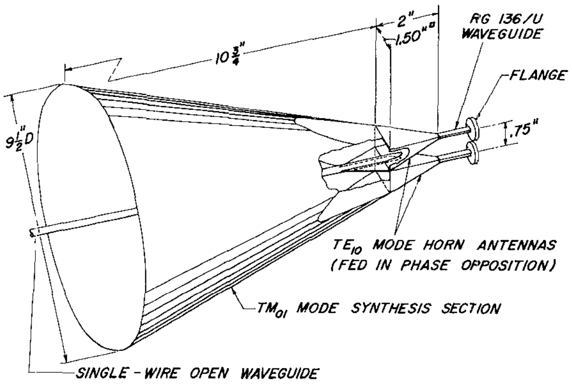

Fig. 3—TM_{01}-mode launcher for single-wire line.

The results of the measurements and the calculated values of attenuation are given in Table III. It may be seen that the measured attenuation is 2 to $2\frac{1}{2}$ times higher than the calculated values for the smaller wires (0.080- and 0.128-in diameter) and is approximately 3 to 6 times higher than the calculated values for the larger wires.

TABLE III

ATTENUATION OF SINGLE-WIRE TRANSMISSION LINES

Wire Diameter Inches	Frequency Gc	Calculated Attenuation	Measured Attenuation
0.080	105	0.07 db/ft	0.14 db/ft
0.128	105	0.05 db/ft	0.10 db/ft
0.375	105	0.02 db/ft	0.12 db/ft
0.500	105	0.015 db/ft	0.10 db/ft
0.080	140	0.08 db/ft	0.20 db/ft
0 128	140	0.06 db/ft	0.11 db/ft
0.375	140	0.03 db/ft	0.10 db/ft
0.500	140	0.02 db/ft	0.08 db/ft

The excess loss is attributed mainly to copper and radiation losses at surface imperfections, irregularities, and bends and supports along the wires. This is particularly true with the large-diameter wires as the wave is very loosely bound and irregularities along the wire can cause large (percentage) increases in the low-attenuation factors. That is, when the attenuation factor is very low, a small increase in the absolute value of the loss (a few hundredths of a decibel per foot) appears as a large percentage increase. Although the wires were cleaned immediately before making the attenuation measurements, surface oxidation of the copper also contributed a loss term which was not considered in the calculated values. Nonetheless, the measured attenuation for the single-wire line in this frequency range is much lower than that for conventional dominant-mode rectangular waveguide, which has an attenuation greater than 1 db/ft at 105 or 140 Gc.

For the wires possessing lowest losses, the "stability" of the wave (*i.e.*, the degree of "tightness of binding" to the wire) is poor; hence to obtain the lowest losses the wire line must be quite straight and uniform. Because the propagating wave is loosely bound to the wire line, one must use special techniques to go around bends. The wave may be more tightly bound (by the use of a dielectric coating, for example) or plane reflectors may be used (by analogy with optical techniques). Both of these approaches have also been used previously with dielectric image lines.

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[9] P. D. Coleman and R. C. Becker, "Present state of the millimeter wave generation and technique art—1958," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-7, pp. 42–61; January, 1959. The attenuation values given therein (Fig. 7) are in error.

IV. Quasi-Optical Components

A. Fresnel Zone Plates

Quantitative measurements of phenomena involving interference and diffraction are generally much easier to perform in the millimeter wavelength region than at optical frequencies. In fact, some optical devices which have remained essentially laboratory curiosities have analogs in the millimeter wavelength range which can be used as practical system components. One such device is the phase-corrected Fresnel zone plate.

The simplest Fresnel zone plate consists of a set of plane concentric annular rings which are alternately transparent and opaque. The successive radii of these zones are so chosen that the distance from a selected point on the central axis increases by one-half wavelength in going from the inner to the outer radius of any ring. Therefore, if a plane wave is normally incident on the zone plate, the portions of the radiation which pass through various parts of the transparent zones all reach the selected point with phases which differ by less than one half-period. (The integral number of whole-period phase differences may be neglected for this development.) The superposition of these portions of the original plane wave results in an intensity at the selected axial point which may be much greater than that which would result from the unobstructed wave. Thus, the zone plate acts like a lens, producing a focusing action on the radiation it transmits.

The opaque half-period zones may be replaced by zones which transmit the radiation but introduce a 180° phase shift relative to the portions of the plane wave transmitted by the adjacent zones. This may be accomplished in practice by cutting into a dielectric plate circular grooves of the correct dimensions. In this way, all the half-period zones contribute to increasing the intensity at the focus.

Obviously, it is possible to divide each half-period zone into some number of subzones for each of which the phase correction is appropriately determined. If the process is continued, using a dielectric plate for the physical construction, the form of the phase-corrected zone plate approaches more and more closely that of a Fresnel lens, with its annular rings each having a smoothly curved surface. It can be shown that the intensity at the focus of a quarter-period zone plate is only 1 db below the intensity produced by a Fresnel lens of the same diameter and focal length.

For visible light, the limitations of wavelength make it difficult to produce half-period zone plates with large diameters and short focal lengths; a speed of $f/20$ is about as great as can be secured readily with photographic techniques. The fabrication of optical zone plates having subzones with controlled phase corrections requires great skill and effort.[10] On the other hand, phase-reversing plates and quarter-period phase-corrected plates for the millimeter wavelength spectrum are readily produced by common machine shop techniques, and speeds in excess of $f/1$ are quite easy to achieve.

Pairs of $f/1$ phase-reversing zone plates were designed and constructed for use at 140 Gc and at 210 Gc. The plates were machined from polystyrene sheet stock about 0.5 cm thick and 20 cm in diameter. The focusing action of the 140-Gc plates is equivalent to that which would be produced by a plano-convex polystyrene lens (hyperboloidal surface) about 4 cm thick. Fig. 4 shows a section view of one of the plates and the equivalent lens.

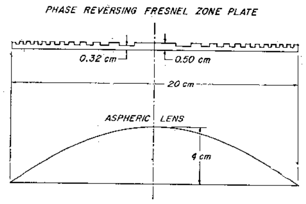

Fig. 4—140-Gc zone plate and equivalent lens.

The measured performance of the zone plates was found to agree very well with the predictions of Kirchhoff's theory. For example, using a small 15-db gain horn as a "point" source of radiation, the measured spread (between 3-db points) of the image, perpendicular to the optical axis, was found to be ±0.3 cm. According to the diffraction theory, the radius of the Airy disk should be $1.22f\lambda/a = 0.26$ cm. In this formula, f is the focal length (20 cm), λ is the wavelength of the radiation (0.214 cm), and a is the aperture diameter (20 cm).

The half-power band-pass of the system composed of a transmitting horn, transmitting half-period zone plate, receiving zone plate, and receiving horn was found to be in approximate agreement with the theoretical value of 7 per cent of the center frequency. Smaller quarter-period plates (see Section IV-C) have a calculated pass band of 20 per cent. The behavior of a phase-correcting Fresnel zone plate as a function of frequency exhibits rather complicated changes over a large frequency interval. The effective gain, the focal length, the diameter (or number of zones), and the depth of the phase-correcting grooves are all interrelated. Adjustment of these parameters permits considerable control over both the frequency bandwidth and the number of secondary maxima and minima in the gain-vs-frequency characteristic. Detailed analysis of this problem is presently underway and will be reported in the near future.

B. Optical Transmission Methods

The feasibility of using phase-reversing zone plates as components for transmission systems has been demonstrated at 140 Gc and at 210 Gc. By using plates with diameters which are large relative to the wavelength, the Fresnel region can be made to extend to rather great

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[10] Phase-reversing zone plates were constructed by R. W. Wood. See R. W. Wood, "Physical Optics," The Macmillan Co., New York, N. Y., 3rd ed., pp. 38–39; 1934.

distances from the aperture. Within this region, radiation from the aperture is not attenuated in accordance with the inverse square law, but at a much smaller rate.[11] The Fresnel diffraction region may be considered as extending from near the aperture plane out to about one-half of the Rayleigh distance R defined by the equation $R=a^2/\lambda$. The Fraunhofer region, in which an inverse square law of attenuation is to be expected, "begins" in the range of 1 to 2 times R and extends to all greater distances. The results of transmission measurements at 210 Gc are shown in Fig. 5. Within the Fresnel region, the relative signal falls off at a rate of about 0.02 db/ft. At distances somewhat greater than R, an inverse square law approximates the measured curve quite well.

H-plane patterns were measured at 140 Gc by using identical horn and zone plate combinations as transmitting and receiving antennas. The receiving combination was placed at distances of 12 feet, 78 feet and 172 feet from the transmitter and rotated about a vertical axis passing through the center of its zone plate. The 12-foot distance corresponds to $0.2R$ and is well within the Fresnel region. The pattern is labeled "Fresnel region" in Fig. 6. Measurements at 78 feet ($1.3R$) and at 172 feet ($2.8R$) gave identical results, shown in the figure by the curve labeled "far field."

Numerous side lobes were found in both the H plane and E plane far-field patterns. For example, in the H plane a total of about 45 lobes was found; of these, 35 are within ±45° of the forward direction and 10 within ±20° of the backward direction. All of these were at least 30 db below the main lobe. No attempt has been made to calculate theoretically this detailed radiation pattern.

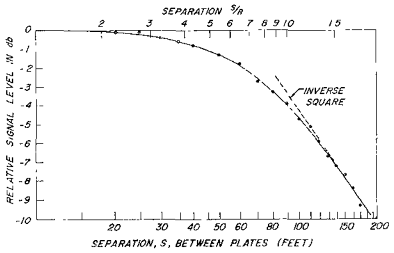

Fig. 5—Optical beam transmission at 210 Gc.

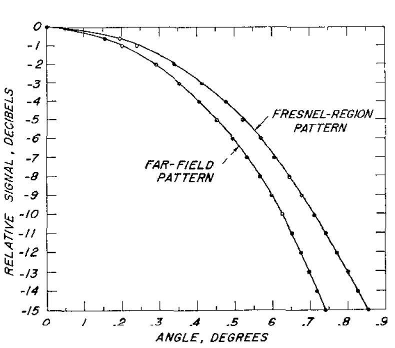

Fig. 6—Main lobe in H-plane pattern of 140-Gc zone plate.

C. Michelson Interferometer

To facilitate the development of quasi-optical components for millimeter waves and to permit the measurement of various properties of materials at frequencies from 100 to 300 Gc, a millimeter-wave Michelson interferometer was designed and constructed. (Culshaw has described a Michelson interferometer[12] and a Fabry-Perot interferometer[13] for millimeter wavelengths.) The most common form of this interferometer employs an extended source of (optical) radiation. However, radiation at millimeter wavelengths is most conveniently emitted from a horn, which behaves essentially like a point source. Also, for visible light, the eye serves as an image-forming device to view the interference fringes, but at millimeter wavelengths the crystal video detector which is used acts like a point receiver. It is thus necessary to use a modification of the Michelson interferometer (first introduced by Twyman and Green) which uses collimated radiation. Phase-corrected Fresnel zone plates were found to be well suited to this application.

Fig. 7 is a photograph of two 7 cm $f/1$ zone plates constructed for the interferometer. The plate at the left in the photograph is phase-reversing, *i.e.*, it is a half-period zone plate. The other is a quarter-period zone plate in which successive rings introduce phase changes of $\pi/2$, π, $3\pi/2$, and $2\pi(=0)$ radians. Two quarter-period plates are used in the interferometer because of their greater collimating efficiency. (Direct measurement confirms the theoretical signal improvement of 6 db over the simpler half-period zone plates.) The other components of the Michelson interferometer, shown in Fig. 8, are exactly like their optical counterparts, with the exception of the beam divider. Rather than a semi-transparent mirror, the instrument utilizes a dielectric sheet (polystyrene) of the proper thickness to yield approximately equal net transmission and reflection for the wavelength at which the measurements are made. The position of the movable mirror can be set repeatedly within 0.0004 cm, and the received signal level at the interference minima is 30 db below that at the maxima.

The frequency stability of the klystron tube (Raytheon QK 369, operating at 70 Gc) was investigated by using the millimeter-wave Michelson interferometer to measure time fluctuations of wavelength. The path lengths of two interfering beams (of equal signal strength) were made to differ by approximately 60 wavelengths, and the respective signals were adjusted to be out of phase (null condition) at the detector. The varia-

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[11] S. Silver, *et al.*, "Microwave Antenna Theory and Design," M.I.T. Rad. Lab. Ser., McGraw-Hill Book Co., Inc., New York, N. Y., p. 349 *et seq.*, vol. 12; 1949.

[12] W. Culshaw, "The Michelson interferometer at millimetre wavelengths," *Proc. Phys. Soc.* (*London*) *B*, vol. 63, pp. 939–954; November, 1950.

[13] W. Culshaw, "The Fabry-Perot interferometer at millimetre wavelengths," *Proc. Phys. Soc.* (*London*) *B*, vol. 66, pp. 597–608; July, 1953.

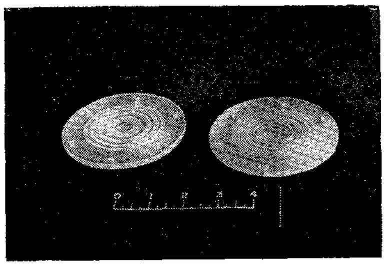

Fig. 7—Half-period and quarter-period zone plates for 140 Gc. (Scale is in inches.)

TABLE IV

Dielectric Properties of Several Materials

Material	Dielectric Constant 140 Gc	Dielectric Constant 210 Gc	Loss Tangent 140 Gc
Polystyrene	2.52±0.01	2.53±0.01	0.002
Rexolite	2.47±0.01	2.50±0.06	0.002
Teflon	2.05±0.01	2.08±0.03	0.003
Lucite	2.56±0.10	2.58±0.10	—
Mylar	3.35	—	0.01
Ethylcellulose	3.71	—	0.1

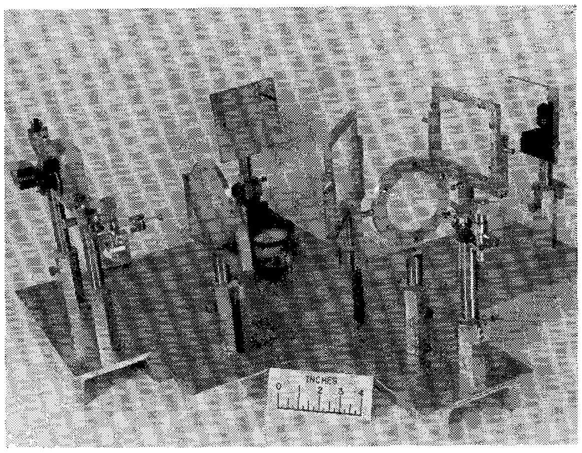

Fig. 8—Millimeter-wave Michelson interferometer.

tions of the detected signal level, representing changes in the amount of cancellation caused by changes in frequency, were recorded for an extended period of time, and corresponding frequency changes were then computed from them. The measured random frequency fluctuation was found to be less than ±10 parts per million over periods of a few minutes and about ±30 parts per million over a period of an hour. Frequency stability is apparently limited primarily by temperature fluctuations of the klystron.

The dielectric constants of a number of plastics have been measured with the interferometer. Actually, the product of magnetic permeability and dielectric constant $\mu\epsilon$ was measured, but for these materials it is known that $\mu=1$. Approximate values for the loss tangents of the materials at 140 Gc were determined by inserting sheet samples in a properly polarized collimated beam with the angle of incidence set at the Brewster angle, $\phi=\tan^{-1}\sqrt{\epsilon}$, at which the reflection coefficient is zero. In practice, this measurement is difficult to perform with good precision, and the values of loss tangents presented in Table IV are probably reliable only within a factor of two.

Experimental tests have been made on an optical technique of frequency filtering at millimeter wavelengths. Suppression of the second harmonic (140 Gc) can be accomplished by using the 210-Gc Fresnel zone plates instead of the conventional "squeeze-section" waveguide filter. If a waveguide filter is not inserted between the crystal multiplier and the transmitting horn, both the second and third harmonics are present in the radiation from the horn, the lower frequency having a greater intensity. However, if the Fresnel zone plates designed for the higher frequency are inserted at the proper distances from the transmitting and receiving horns, the amount of 140-Gc radiation reaching the receiver is greatly reduced by what may be regarded as a defocusing action. Measurements with the Michelson interferometer show that the distance between the regularly spaced interference minima corresponds to half the wavelength of the 210-Gc radiation ($\lambda=0.141$ cm). The presence of a small amount of the lower frequency results in a standing wave pattern having three different null depths which recur repetitively over a distance containing three of the shorter half-wavelengths and two of the longer half-wavelengths. Quarter-period zone plates designed for 280 Gc were used in the interferometer and the presence of this signal frequency was detected. A waveguide squeeze section removed the 140-Gc harmonic and the zone plates themselves defocused the 210-Gc radiation.

The Fresnel zone plates, whose action is wavelength-dependent, thus constitute a frequency filter and produce results quite analogous to those obtained by the method of focal isolation which was devised by Ruebens and Wood[14] for work in the far infrared spectrum. The filtering action of the quartz lenses used by Ruebens and Wood arose from the dispersion of the quartz. In the case of the zone plates described here, the action is similar to that of a focusing diffraction grating. This method of frequency filtering by optical techniques should prove to be of considerable utility in the millimeter and submillimeter wavelength regions where construction of waveguide filters is very difficult or impracticable.

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[14] R. W. Wood, "Physical Optics," The Macmillan Co., Inc., New York, N. Y., 3rd ed., p. 523; 1934.