are tapered graphite from a carpenter's marking pencil and they have copper electrodes electrodeposited onto the tip of the taper and the back of the load. These contacts enable dc connections to be made to the load so that dc power dissipated in the load can be used for calibration of the calorimeter. The two waveguide and load units in each calorimeter are identical, so that either one can be used as the active load and the other as the reference load. To measure the temperature of the active load and compare it with the reference load, there is a string of three small bead thermistors connected in series and cemented to each waveguide. The two thermistor strings are incorporated into a 1000 cps bridge in order to measure small temperature changes easily. The remaining bridge components are installed in the small compartment on the back of the outer box. The bridge is operated as a deflection instrument, calibration curves being made of bridge unbalance as a function of time for various dc power inputs to the graphite loads. Then millimeter wave power is measured by graphing the same function with a millimeter wave input. The calorimeters will accurately measure power levels as low as 4 mw for the 4-mm model, and 0.3 mw for the 2-mm model, without taking extreme precautions regarding temperature isolations.

A number of other more conventional waveguide components were designed and constructed for 2-mm operation, and it is of interest to note that despite the short wavelength no particular difficulty was experienced in obtaining reasonable operation. Of course, some mechanical modifications had to be made due to the small size of the waveguide; however, none of these was of major significance.

Conclusion

High-power 2-mm energy has been generated by a ferrite harmonic generator excited by a 4-mm source. However, more 2-mm energy could be generated by further refinements in the experimental system and by the use of better ferrite materials when they become available. The material property of most importance to harmonic generation is the ratio $4\pi M_s/\Delta H$. Millimeter wave isolators, calorimeters, and other components have been designed and constructed without encountering unexpected problems due to the short wavelengths.

Acknowledgment

The author wishes to acknowledge the continuing assistance of Drs. J. L. Melchor and P. H. Vartanian. He also wishes to thank R. Hosking for his excellent laboratory work, including the construction of most of the delicate components.

Some Characteristics of Dielectric Image Lines at Millimeter Wavelengths*

JAMES C. WILTSE†

Summary—**The attenuation characteristics of several dielectric image lines have been calculated for the frequency range extending from 24 to 100 kmc and have been checked experimentally at 35 and 70 kmc. To obtain low attenuation at these high frequencies, dielectric materials with little loss and small size of cross section are required, while low values of the dielectric constant are also desirable. The effects of the size and shape of the dielectric cross section and of low dielectric constant are treated separately. To find proper materials with low dielectric constants several new foam plastics were investigated. Three types were found suitable for image line use, and in fact, these plastics have such good electrical and physical properties that they should be useful in many microwave applications.**

A qualitative measure of field extent is given for several image lines at 35 or 70 kmc, and various image lines and associated components are discussed. A new type of image line, called the tape line, is described.

* Manuscript received by the PGMTT, June 10, 1958.
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Introduction

IN THE frequency region above K band, dominant-mode rectangular waveguide has the important disadvantage of high attenuation. Fig. 1 shows the theoretical attenuation for several standard waveguides. Further disadvantages are small physical size and relatively low power handling ability. These undesirable properties have stimulated the study of other types of waveguides which might have improved characteristics. One type which appears to be satisfactory is circular metal waveguide propagating the TE_{01} mode. This type has low attenuation, but since it is not a dominant-mode waveguide, mode suppressors are required. This feature adds considerable complexity to the design and construction of components and sections of guide.

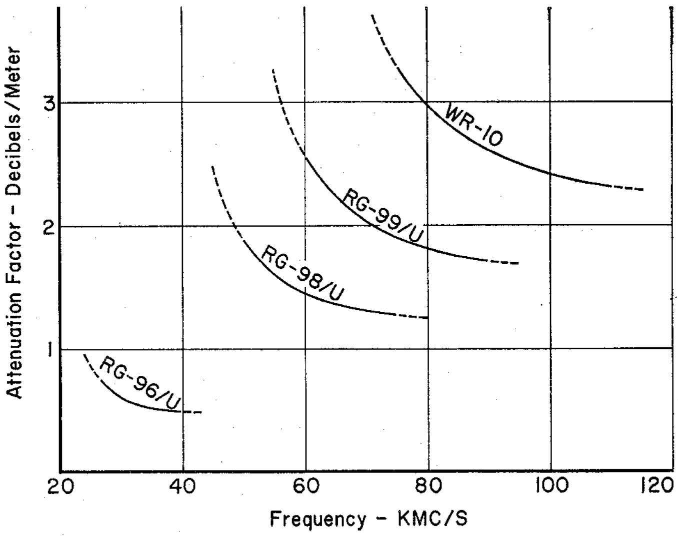

Fig. 1—Attenuation of several types of rectangular waveguide as a function of frequency.

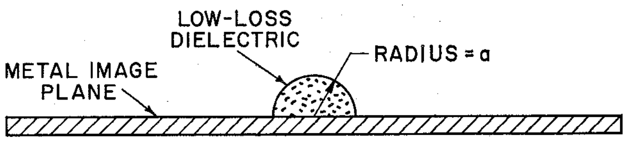

Fig. 2—Cross-sectional view of a dielectric image line.

Another waveguide which has such advantages as low attenuation, dominant-mode operation, and moderate physical size is the dielectric image line. This structure has the further advantages of being simple in design and easy to construct. Fig. 2 shows a sectional view of the dielectric image line. The cross section of the dielectric material need not be semicircular, but this is the only shape which has been mathematically analyzed and for which the field equations and propagation characteristics are fully known.

Prior to the present investigation many properties of image lines had been studied at K band[1] and at X band.[2] These studies included the construction of a variety of image line components and the measurement of losses in straight sections and bends. The present paper deals with the properties of image lines in the frequency region from 24 to 100 kmc.

Losses in a straight uniform section of image line are of two types: conduction loss on the image plane and dielectric loss. Explicit relations have been developed for the contributions to attenuation due to the dielectric and conduction losses when the dielectric has a semicircular cross section (see Appendix). From the information contained in these relationships it is possible to determine which parameters of an image line system should be changed in order to reduce the attenuation. For example, by the use of metals of high conductivity, such as copper or aluminum, the conduction loss may be made relatively small in most cases. Dielectric loss is a function of dielectric constant, loss tangent, and size and shape of the dielectric cross section. Customarily, low-loss plastics such as polystyrene or polyethylene have been used in image lines, and the sizes of the dielectrics have been adjusted to give either a desired attenuatuon or a specified binding of the wave (loose binding results in low loss and vice-versa). In the present study the effects of reduced size, low dielectric constant, and a shape of the cross section other than semicircular were considered separately and in that order.

Small Diameter Polystyrene Image Lines

As a first step in the design of low-loss image lines for use at millimeter wavelengths, values of attenuation were calculated for the case of a copper image plane and a semicircular polystyrene dielectric with a diameter of $\frac{1}{8}$ inch. This diameter was chosen because it appeared to be the smallest size polystyrene rod which could be obtained commercially at that time. The attenuation characteristics of the image line as a function of frequency are given in Fig. 3 where the contributions due to conduction loss (α_c) and dielectric loss (α_d) are shown separately. (In making these and other calculations, a conductivity of 5.8×10^7 mhos per meter was used for copper, while a dielectric constant of 2.56 and a loss tangent of 10^{-3} were assumed for polystyrene.) It is immediately obvious that this particular design is unsatisfactory, because of high attenuation, above 30 kmc.

The next step was to reduce the diameter of the polystyrene rod by turning it down in a lathe to $\frac{3}{64}$ inch, which is about as small as a size as is practicable. Calculated attenuation values for this size semicircular dielectric on a copper image plane are plotted as a function of frequency in Fig. 4. This image line has better attenuation characteristics than RG-98/U rectangular waveguide over most of the latter's normal operating range (50 to 75 kmc). Since this image line showed promise for use at millimeter wavelengths, a section of the line and some associated components (see Fig. 5) were built, tested, and found to give satisfactory performance at frequencies in the vicinity of 70 kmc. The semiparaboloid shown at the right in Fig. 5 is used to focus the guided wave onto a detector mounted in a small gap in the image line dielectric. A micrometer screw drive is provided to permit fine movement of the paraboloid in a direction parallel to the dielectric rod. This makes possible the adjustment of the focus position to give maximum signal from the detector. Further details of the detector are shown in Fig. 6. Much of the diagram is occupied by a drive screw mechanism which has the

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

[2] D. D. King and S. P. Schlesinger, "Losses in dielectric image lines," IRE Trans. on Microwave Theory and Techniques, vol. MTT-5, pp. 31–35; January, 1957.

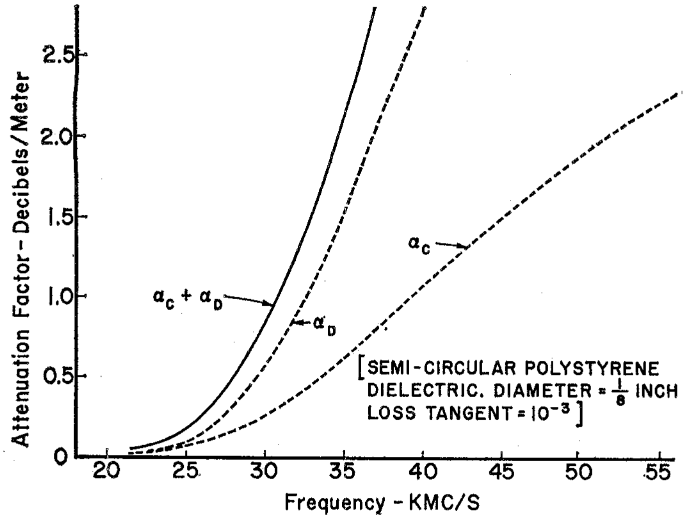

Fig. 3—Image line attenuation due to dielectric loss (α_d) and copper image plane loss (α_c).

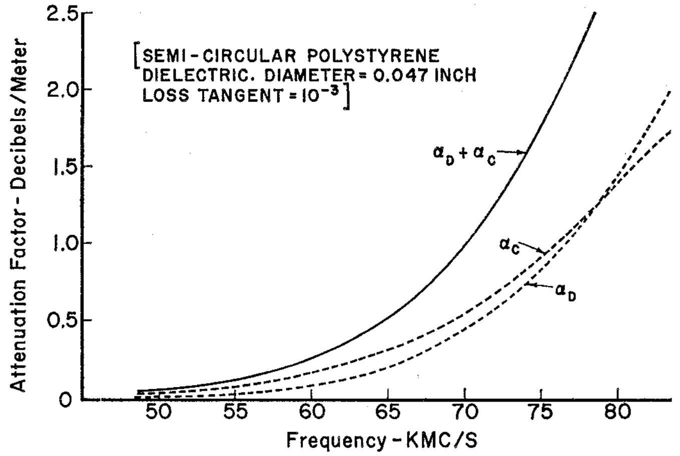

Fig. 4—Image line attenuation due to dielectric loss (α_d) and copper image plane loss (α_c).

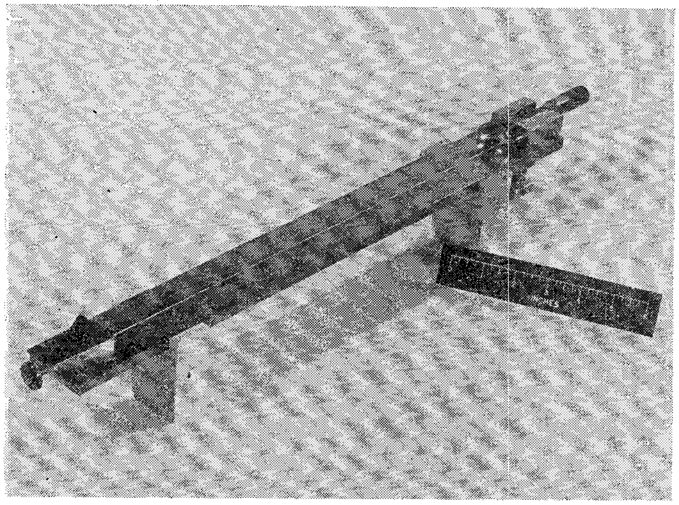

Fig. 5—Dielectric image line with launching horn and detector.

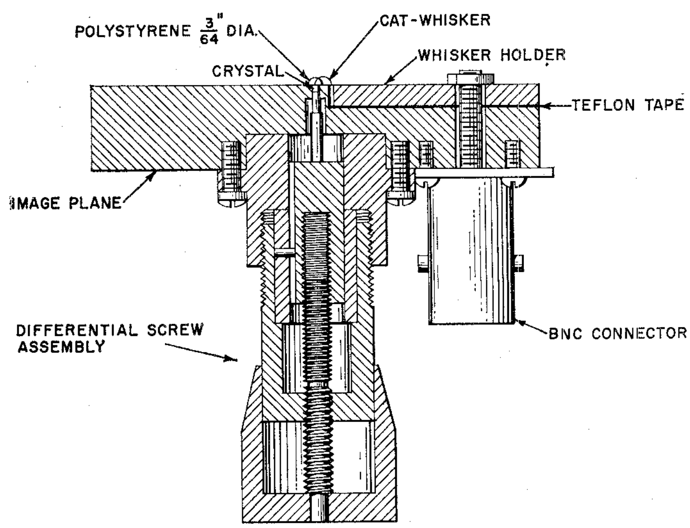

Fig. 6—Crystal detector mount for dielectric image line.

function of raising or lowering the silicon crystal at a very slow rate in order to make a proper contact with the tungsten cat-whisker. The whisker holder is a rectangular piece of metal cut from the image plane and insulated for dc purposes by means of the Teflon tape. The detected signal is taken out through the BNC connector. This detector operated satisfactorily at various frequencies in the range from 40 to 97 kmc.

Foam Polystyrene Image Lines

Above 70 kmc the $\frac{3}{64}$ inch diameter polystyrene image line has undesirably high attenuation. Since it is not practicable to reduce the dielectric size much further in order to obtain lower attenuation, the next step was to obtain low-loss plastics which have dielectric constants considerably lower than polystyrene.

Ordinary polyfoam has the requisite low loss and low dielectric constant, but it has a structure which is extremely nonuniform; cell sizes are appreciable fractions of a wavelength. However, some new foamed polystyrene products now are available which do have very small cell sizes (diameters on the order of 0.1 millimeter for one type), are easily machinable, and still retain the desired low loss, low dielectric constant properties.

Three such materials were selected for image line use. Because their properties had not been studied previously, it was necessary to determine the dielectric constant and loss tangent of each. Samples of the materials were placed in rectangular waveguide and a conventional shorted-line technique previously described by Montgomery[3] was used to measure the values necessary for calculation of the dielectric constant and loss tangent. Table I gives the results obtained for the frequency region from 30 to 40 kmc. In addition, a sample of Dow Q103.21 was measured at 72 kmc and found to have a dielectric constant of 1.09 and a loss tangent slightly less than 10^{-3}.

[3] C. G. Montgomery, "Technique of Microwave Measurements," McGraw-Hill Book Co., Inc., New York, N. Y., p. 621; 1947.

TABLE I

Characteristics of Polystyrene Foam Materials in the Frequency Range from 30 to 40 kmc

Type	Manufacturer	Dielectric Constant	Loss Tangent
Q103.21	Dow Chemical Company	1.1	$\leq 7\times 10^{-4}$
Q865.2	Dow Chemical Company	1.02	$\leq 5\times 10^{-4}$
Extruded Dylite	Koppers Company, Inc.	1.05	$\leq 5\times 10^{-4}$

With the availability of the desired materials established, the attenuation characteristics as a function of frequency were calculated for several image lines. The calculated values were checked experimentally at 35 and/or 70 kmc by means of a transmission-type image line resonator. Since the resonator technique has been described by King and Schlesinger,[2] it will not be discussed in detail here. In the present case the aluminum resonator was 24 inches wide, had semicircular end-plates with a 24-inch diameter and could be varied in length from zero to 36 inches. One end-plate was fixed in position, while the other was movable on the image plane and contained a choke joint along the full 24-inch width of contact with the image plane. (Actually, two different movable end-walls were available, each with a different choke joint, designed for operation at 35 kmc in one case and 70 kmc in the second.) Appropriate input and output waveguide coupling holes were made in the fixed and movable end-walls, respectively, with different adapters available for use with either RG-96/U or RG-98/U rectangular waveguide systems.

Calculated attenuation data for two foam image lines are given in Fig. 7. The ordinate scale has been expanded by a factor of ten compared with the previous attenuation figures. The measured attenuations at 35 kmc for line number one and at 70 kmc for line number two were approximately twice the calculated values. The larger measured value is attributed partly to the additional loss introduced by the cement used to fasten the dielectric rod to the image plane. Several different cement materials were used in the experiments, but all were known to have considerably more loss than the polystyrenes used for the image lines. A further small loss term may have been caused by radiation from surface irregularities on the image plane or plastic material; in particular, the dielectric rods were cut in relatively short sections, about two feet in length, which meant that butt joints (which never mated exactly) were present in all of the image lines.

A qualitative measurement of significant "field extent" was determined for the image lines of Fig. 7 by moving the end of a $\frac{3}{8}$ inch square aluminum bar toward the dielectric rod (from directly over the rod and also from the side of the rod) and observing the largest radius at which the bar caused an observable effect on the signal detected at the output of the image line resonator. The radius of field extent is three inches for line number

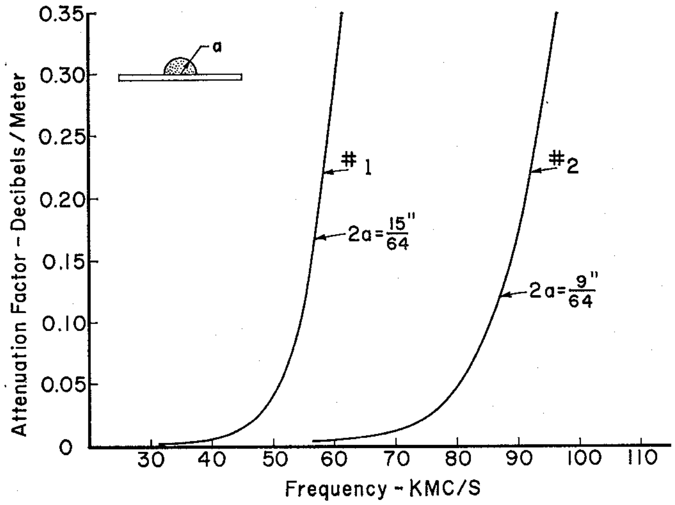

Fig. 7—Characteristics of two different image lines, each with copper image plane and foam polystyrene dielectric ($\epsilon = 1.05$, loss tangent $= 10^{-3}$).

one at 35 kmc and less than $\frac{3}{4}$ of an inch for line number two at 70 kmc.

Tape or Ribbon Lines

It is now possible to obtain polyethylene and Teflon in the form of thin, narrow tapes, some of which even have adhesive backing. The cross section of the tapes is rectangular, but the thickness to width ratio of such a rectangle is so small that the shape may be considered to be a degenerate ellipse (*i.e.*, with an eccentricity of unity). The attenuation for a polyethylene tape $\frac{3}{16}$ inch wide and 0.005 inch thick was measured, using the resonator technique, to be 0.02 decibel per meter at 69.4 kmc. A Teflon tape $\frac{1}{4}$ inch wide and 0.002 inch thick, with an adhesive backing 0.0045 inch thick, had a measured attenuation of 0.09 decibel per meter at 69.5 kmc. The radius of field extent for each tape was approximately one inch. Since thinner and/or narrower tapes than these are available, it should be possible to obtain attenuation factors for the 70 to 100 kmc frequency range which would be considerably lower than those shown in Fig. 7 for a $\frac{9}{64}$ inch diameter foam polystyrene image line.

Discussion

This study has shown that it is possible to construct dielectric image lines which have low attenuation and small field extent in the frequency region from 30 to 100 kmc. Operating bandwidths are comparable to those of dominant-mode rectangular waveguides. The three new foam plastic materials discussed earlier have such good electrical and physical properties that they should be very useful for many purposes at millimeter wavelengths. The ease of construction and basic simplicity of the image lines, especially the tape line, have not been emphasized earlier in the text, but certainly should be noted as an advantage of this type of waveguide.

Appendix

The computation of attenuation factors is lengthy and complicated. For image lines which have dielectrics with semicircular cross sections, the contributions to attenuation due to dielectric loss (α_d) and conduction loss (α_c) may be found from the following expressions:

$$\alpha_d = 27.3\left(\frac{\Phi\epsilon}{\lambda}\right) R \text{ decibels/meter} \quad (1)$$

$$\alpha_c = 69.5\left(\frac{R_s R'}{\eta\lambda}\right) \text{ decibels/meter} \quad (2)$$

where

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 factors R and R' are complicated functions of the dielectric constant and diameter (in free-space wavelengths) of the rod. Explicit expressions for R and R' may be found in the paper by King and Schlesinger.[2]

Acknowledgment

The author wishes to acknowledge the advice of Dr. Donald D. King in early phases of the project. Dr. King also collaborated in the design of the detector shown in Fig. 6.

Dr. S. P. Schlesinger supplied certain calculated data, including values of R and R' (identified in the Appendix), which greatly simplified computation of some of the attenuation factors.

Nearly all of the experimental measurements were carried out by James D. Rodgers, whose care and patience are much appreciated.

The Interaction of Microwaves with Gas-Discharge Plasmas*

SANBORN C. BROWN†

Summary—**The interaction of microwaves with gas-discharge plasmas provides a valuable tool for studying the fundamentals of gas-discharge phenomena and methods of controlling and switching microwave power. A summary of our present state of knowledge in this field is presented by using as particular examples the interaction of high density and low density gas-discharge plasmas in *S*-band resonant cavities, both in the presence and absence of dc magnetic fields.**

Introduction

THE effective dielectric coefficient of a plasma[1] in the absence of a magnetic field is given by

$$K = 1 - \left[\frac{\omega_p^2}{\omega^2} \frac{1 + j\dfrac{\nu_c}{\omega}}{1 + \left(\dfrac{\nu_c}{\omega}\right)^2}\right]. \quad (1)$$

Here ω_p is the plasma frequency given by the relation $\omega_p^2 = ne^2/m\epsilon_0$; ω is the applied radian frequency, and ν_c is the collision frequency of electrons in the gas given by ν_c = (constant) p, where p is the pressure. The square root of the dielectric coefficient (1) is related to the attenuation and phase shift of a plane wave, as represented in Fig. 1. This figure is calculated for the specific case of hydrogen gas at a microwave frequency of 4500 mc. In the low density region the attenuation and the phase shift are linear functions of the density, but at higher densities this linearity disappears and the functional relation becomes more complicated. In the usual use of microwave techniques for the diagnostic studies of plasmas, a restriction is placed on the method by the complexities of the solution in high density regions where the linear dependence does not hold. Usually, the microwave technique is restricted to the low density region well below the plasma frequency at which $\omega_p/\omega = 1$.

The solution shown in Fig. 1 is valid in the absence of a magnetic field. If a magnetic field is applied, the dielectric coefficient depends not only upon the density and magnitude of the magnetic field, but also on the geometrical configuration that is under consideration and the direction of propagation of the electromagnetic wave with respect to the magnetic field. Four cases can be distinguished for the purpose of simplifying the discussion; they are given in the following equations.[2]

* Manuscript received by the PGMTT, June 11, 1958; revised manuscript received, July 30, 1958. This work was supported in part by the U. S. Army (Signal Corps), Air Force (Off. of Sci. Res., Air Res. and Dev. Comm.), and Navy (Off. of Naval Res.), and in part by the Atomic Energy Commission.

† Res. Lab. of Electronics, Mass. Inst. Tech., Cambridge, Mass.

[1] H. Margenau, "Conduction and dispersion of ionized gases at high frequencies," *Phys. Rev.*, vol. 69, pp. 508–513; May, 1946.

[2] W. P. Allis, "Motions of Ions and Electrons" in "Handbuch der Physik," Springer Verlag, Berlin, Ger., vol. 21, pp. 383–444; 1956.