Loss Measurements of the Beam Waveguide*

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Summary—**The diffraction loss of a new low-loss waveguide for millimeter and shorter wavelength, called the beam waveguide, was measured. The loss measurements were made using a resonator technique. The beam waveguide resonator derived from the beam waveguide consists of confocal paraboloids and is itself a very useful millimeter and sub-millimeter wave circuit component having already found application in some optical masers. Measurements made to determine the reflection loss of the resonator end plates also resulted in information on the loss of 90° bends in the beam waveguide. The results of the loss measurements made on the beam waveguide, in the frequency range near 9 Gc, are in good agreement with theoretical values given by Goubau.**

I. Introduction

When the term waveguide is mentioned one usually thinks of a hollow metal tube used for the transmission of microwave energy. However, an ordinary open two-wire transmission line or a solid dielectric rod are also guides for electromagnetic waves and are included in the more general definition of a waveguide. One might ask the question, is it possible to guide electromagnetic waves through space with small loss without the use of metal conductors or dielectric rods? The answer to this question is yes. A practical method for accomplishing this at millimeter and shorter wavelengths has been developed by Goubau[1,2] and is known as the beam waveguide.

Fig. 1 shows a schematic diagram of a section of the beam waveguide. Electromagnetic waves are propagating from left to right through a series of dielectric lens-shaped plates labeled A, B and C. These plates merely serve to alter the cross-sectional phase distribution of the propagating waves. The dotted lines in Fig. 1 indicate the cross-sectional diameter of the electromagnetic wave beam. Fundamental to the understanding of the beam waveguide is the fact that the field at all points in the section between planes aa' and bb' is identical to the field at corresponding points in the section between the planes bb' and cc'. The field in the plane aa' may be considered the source radiating energy toward the plane bb'. If the field at bb' can be made identical to that at aa', then it can serve as the source for cc' and so on, thus establishing a reiterative wave beam. The conditions under which the field at bb' will be identical to that at aa' have been given by Goubau. He showed that when finite diameter phase plates have a paraboloidal surface and are spaced at their focal length, a reiterative field having linear polarization, a uniform phase front, and a Gaussian radial amplitude distribution will appear in the center plane of each phase plate. Furthermore, there will be a maximum energy concentration in a given aperture size and hence, a minimum of energy will be diffracted out of the beam. Under these conditions the beam waveguide is said to be operating in the lowest loss mode.[3] In order to determine the actual diffraction loss of the guided electromagnetic wave beam, Goubau has developed an integral equation whose eigenfunction expresses the field intensity variation in the radial direction at the center plane of a phase plate. The eigenvalue of this equation then gives the ratio of the electric field intensity amplitude at one phase plate to that at the succeeding plate; that is, it is a direct measure of the diffraction loss. Fig. 2 shows a plot of this eigenvalue as a function of a, where

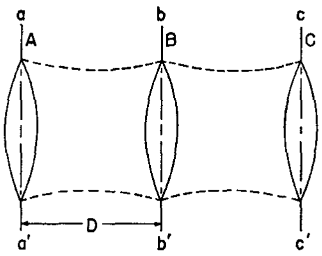

Fig. 1—Beam waveguide.

$$a = \sqrt{\frac{k}{D}}\, R \tag{1}$$

and

$k = 2\pi/\lambda$
$D =$ plate spacing
$R =$ plate radius.

The purpose of this paper is to provide an experimental verification of the losses predicted by the theoretical curve of Fig. 2.

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† Department of Electrical Engineering, University of Wisconsin, Madison, Wis.

[1] G. Goubau and J. R. Christian, "A New Waveguide for Millimeter Waves," presented at URSI-IRE Fall Meeting, San Diego, Calif.; October, 1959.

[2] 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.

[3] J. B. Beyer and E. H. Scheibe, "Higher modes in guided electromagnetic-wave beams," IRE Trans. on Antennas and Propagation, vol. AP-10, pp. 349–350; May, 1962.

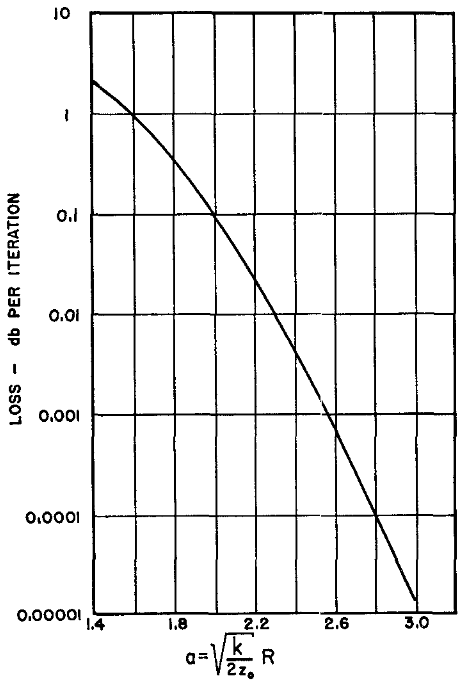

Fig. 2—Diffraction loss for the fundamental mode.

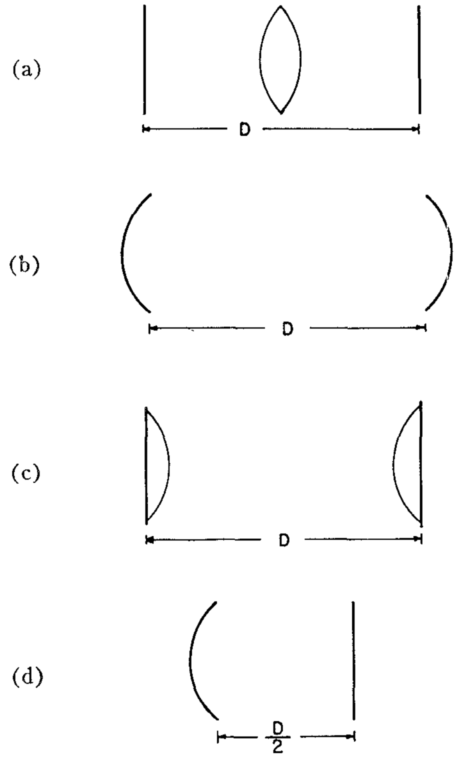

Fig. 3—Beam waveguide resonators.

II. Experimental Method

A beam waveguide system in operation will have other losses in addition to the diffraction loss predicted in Fig. 2. In a practical system there would be launching and receiving losses, reflection losses at the dielectric air interfaces and dissipation losses within the dielectric lenses. Loss measurements on a related system, the surface wave line, were made using a resonator technique.[4,5] The resonator method also lends itself well to the present problem for several reasons. The reflection and dissipation losses due to the presence of the dielectric can be eliminated, the conduction loss in the resonator end plates can be independently measured, and the diffraction loss, which results from the finite size aperture, can be conveniently measured with good accuracy.

A characteristic property of all waveguides including open guides is that resonant lengths can be formed. Thus, forming a beam waveguide resonator is a natural and obvious consequence of the transmission line properties of the beam waveguide except that the resonator length must be arranged to coincide with positions of plane phase fronts along the waveguide. Fig. 3(a) shows one iteration of the beam line of Fig. 1 short circuited by metal plates. A resonator can also be formed by the arrangement shown in Fig. 3(b). As pointed out earlier the fields at all points in transverse planes spaced a distance D apart are identical. If the metal plates in Fig. 3(b) have the same diameter as the lenses, the loss in the resonator due to diffraction will be identical to that encountered in a distance D on the beam waveguide. However, in addition to the diffraction loss, losses of reflection and dissipation caused by the dielectric lenses and a conduction loss due to the metal end plates will be present in this resonator. A resonator in which the losses due to the dielectric are eliminated is shown in Fig. 3(c). Here the necessary phase correction is provided by paraboloids instead of dielectric lenses. A still more desirable form of resonator in which a conducting plane of infinite extent is inserted midway between the paraboloids is shown in Fig. 3(d). For this case a wave front propagating through the resonator has its phase altered twice by the same paraboloid per iteration instead of once by each of two separate paraboloids. In a practical beam waveguide resonator, the flat plate need only be of the order of the radius of the paraboloid since it is located at the focal point of the paraboloid and hence, is in the region of maximum energy concentration of the beam, *i.e.*, minimum beam diameter.

Q measurements on the resonator shown in Fig. 3(d) will yield information on the attenuation constant of the equivalent transmission line because the energy storage and loss mechanisms are identical for each. It is relatively easy to show that the required relationship between the loss per iteration and the Q of the beam wave-

[4] E. H. Scheibe, B. G. King and D. L. Van Zeeland, "Loss measurements of surface wave transmission lines," *J. Appl. Phys.*, vol. 25, pp. 790–797; June, 1954.

[5] C. H. Chandler, "An investigation of dielectric rod as wave guide," *J. Appl. Phys.*, vol. 20, pp. 1188–1192; December, 1949.

guide resonator is given by[6]

$$L(\text{db}) = \frac{8.68\pi D}{\lambda Q} \text{ db/iteration.} \tag{2}$$

Inspection of Fig. 2 indicates that diffraction losses of the order of 5×10^{-3} db/iteration may be expected. Thus from (2), Q's of the order of 300,000 will be obtained. If these high Q's are to be determined from the frequency response curves of the resonator, and measurements are to be made in the 9-kMc region, the 3-db bandwidths will be of the order of 30 kc. This means that the driving source must be stable and free of frequency modulation so that its output frequency is known to within 1 kc or better at all times. This restriction places extremely rigid requirements upon any practical oscillator. A high degree of mechanical stability of the resonator is also required since a resonator space at $D/2=1.5$ meters (corresponding to an a value of 2.4 in Fig. 2) will be detuned by 1 kc if its length changes by 0.15 microns.

III. Apparatus

A method for producing optical paraboloidal mirrors has been developed by Archibald,[7] and was used for fabricating the resonator reflectors. The method makes use of the fact that the surface of a rotating liquid will take the form of a paraboloid, and that a liquid resin suitably catalyzed to harden after this form is taken will retain the shape. Particularly useful resins for the purpose are the epoxy resins since they exhibit a very low shrinkage factor.

The finished paraboloids were made reflecting by covering their surfaces with suitably annealed two-mil thick aluminum foil uniformly cemented in place with an aerosol adhesive. The metalized paraboloids were fitted with coaxial coupling loops at their centers. The loops were made adjustable so that both the plane of polarization as well as the coupling coefficient could be varied. The aluminum back plate was fitted with four studs and supported against a cross bracket on coil springs so that independent E and H plane adjustment could be made. Fig. 4 shows a photograph of the beam waveguide resonator. The adjustment screws as well as the coaxial coupling assembly can be seen at the rear of the mirror in the foreground.

Fig. 4 also shows how the mirrors were mounted on an "optical bench" made up of two 4-inch I beams. The massiveness of the entire assembly as well as the rigidity of the I beams was found necessary in order to isolate the system from building vibrations and other mechanical changes. The mirror in the foreground is

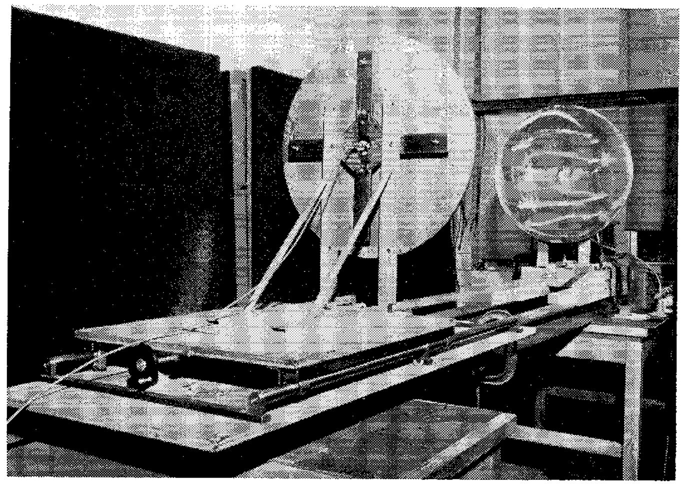

Fig. 4—Beam waveguide resonator.

mounted on an adjustable table. This table can be translated for length adjustments and greatly facilitates tuning of the resonator.

As mentioned earlier a high degree of frequency stability is required of the driving oscillator for the measurements. A modified Pound stabilized 2K25 klystron was used for the source. The stabilizing cavity in the Pound system was variable so that the oscillator could be tuned over a narrow range. It was found that with very careful selection of the system components and with very careful adjustment, the frequency modulation and drift in the output could be kept below 100 cycles/sec, for short time periods, which was more than adequate for the intended measurements.

IV. Measurements

The paraboloids used for the resonator were designed for minimum beam diameter in a given iteration length, *i.e.*, confocal paraboloids; this is the case for which the aforementioned value of a (see Section I) characterizes the diffraction loss. The resonator shown in Fig. 4 is of the general type depicted in Fig. 3(d), and has a spacing $D/2=1.5$ meters and a radius of 31.5 cm which corresponds to an a value from (1) of 2.5 at 3.2-cm wavelength. This resonator is typical of the ones used for the measurements, since, in order to vary a, the only change made was the paraboloid focal length and hence, plate spacing. The metalized cast epoxy paraboloid shown at the right in Fig. 4 was fed at its center by a coaxial loop. Driving frequencies in the vicinity of 9360 Mc were supplied by the stabilized 2K25-klystron oscillator. The mirror at the left is the flat reflector also cast of epoxy and metalized by the same method used for the paraboloid. A coupling loop located at the center of this plate fed a microwave superheterodyne receiver through a coaxial line.

Alignment of the resonator plates was critical and time consuming. A reference plane was first established by adjusting the flat plate to be in a vertical plane using a level. The axis of the resonator was then established

[6] J. Beyer, "A Study of the Beam Waveguide," Ph.D. dissertation, University of Wisconsin, Madison, Wis., pp. 23–29; August, 1961.

[7] P. S. Archibald "A Method for Manufacturing Parabolic Mirrors," Lawrence Rad. Lab., University of California, Livermore, Calif., Rept. No. UCAL-5398, Contract No. W-8405-eng-48; April, 1959.

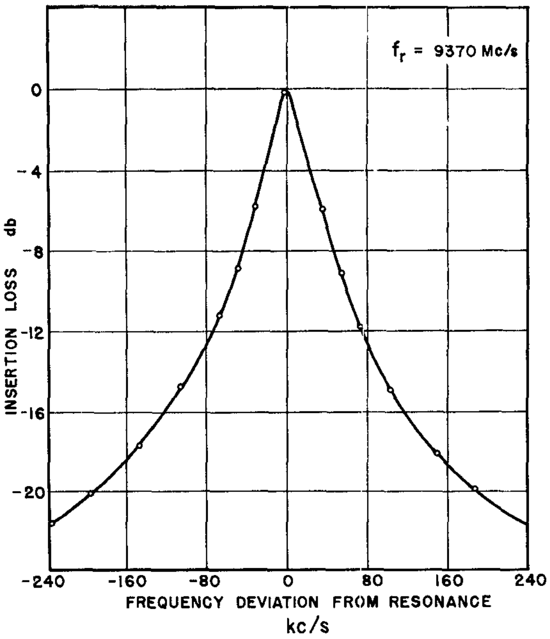

Fig. 5—Resonator response curve.

by sighting with a surveyor's transit through the coupling loop hole along a square held against the plate. The center of the paraboloid was then adjusted to coincide with this axis. Further adjustment was then made measuring the axial as well as diagonal distance between the plates at four equally spaced points along their periphery. In order to assure optimum adjustment the whole procedure was repeated several times before the data was taken.

Several preliminary tests were made before the loss data was obtained. Since a high resonator insertion loss is desirable so that the Q is independent of the circuitry external to the resonator, it was necessary to determine experimentally the effect on the Q of varying the insertion loss. The highest Q resonator was chosen for this test and its insertion loss was varied from 25 to 75 db by means of the adjustable coupling loops. No apparent change in Q was detected over this range of insertion loss, and an insertion loss of 60 db was chosen for use throughout the measurements. The measured response curve of the beam waveguide resonator was analyzed and compared with the theoretical response of an ideal high Q circuit to insure that true Q curves were being obtained.

The data for the beam waveguide loss measurements was obtained by determining the Q of six resonators representing a values of from 1.4 to 2.5. The resonator end plate spacings corresponding to these a values ranged from 5.13 to 1.56 meters. The Q values ranged from 4260 to 328,000. Typical response curves for a high Q resonator are shown in Figs. 5 and 6. Fig. 5 is the response to 20 db down and clearly shows the symmetry of the response. Fig. 6 shows the upper portion of the same curve to 7 db down. The distribution of points on this curve attests to the excellent control of the stabilized driving source.

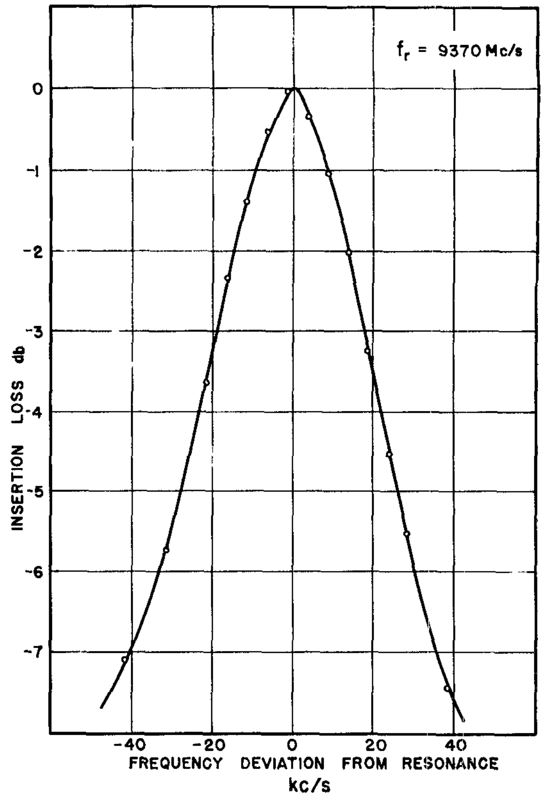

Fig. 6—Resonator response curve.

Before the diffraction loss could be obtained from the above data it was necessary to account for the loss in the metallic reflectors. To a very good approximation, plane wave conditions apply within the resonator, hence, the reflection loss for normal incidence could be calculated from[8]

$$\Gamma^2 = 1 - 2\sqrt{2\omega\epsilon/\sigma} \tag{3}$$

where Γ = reflection coefficient. However, the exact value of the conductivity was not known, and more important, the equation does not take into account the effects of surface conditions of the reflectors. It was deemed desirable to measure this reflection loss.

It is relatively easy to show that for an angle of incidence of 45° the square of the reflection coefficient for plane waves is

$$\Gamma_v^2 = 1 - 2\sqrt{\omega\epsilon/\sigma} \tag{4}$$

when the electric vector is perpendicular to the plane of incidence, here called vertical polarization, and is

$$\Gamma_h^2 = 1 - 4\sqrt{\omega\epsilon/\sigma} \tag{5}$$

when the electric vector is parallel to the plane of incidence, here called horizontal polarization. Inspection of (4) and (5) reveals that the dissipation loss for horizontal polarization is twice that for vertical polariza-

[8] W. K. Panofsky and M. Phillips, "Classical Electricity and Magnetism," Addison-Wesley Publishing Co., Reading, Mass., p. 182; 1955.

tion at this angle of incidence. This fact was made use of in the experimental determination of end plate loss.

An additional flat reflector was introduced into the beam waveguide resonator in such a way that the axis of the resonator contained a 90° bend. As a result, the angle of incidence for waves impinging on the additional reflector was 45°. In this way an additional reflection loss was introduced into the resonator. Furthermore, this additional loss was dependent on the plane of polarization employed. The change in Q, and hence, the change in the loss of the resonator which results when the polarization is rotated from vertical to horizontal permits a determination of an effective value of σ from (4) and (5). This measured value of σ can then be used in (3) to determine the reflection loss at normal incidence of the resonator end plates. The reflection loss so determined was 0.0021 db per reflector compared with a calculated value of 0.0016 db per reflector using the usual value of conductivity for aluminum. The effect of surface irregularities is apparent but not excessive.

While the above data was taken to obtain the reflection loss at a resonator end plate, it is also directly useful for determining the loss at a 90° bend in the beam waveguide. If such a 90° bend is made using a flat aluminum reflector, vertical polarization (electric vector perpendicular to plane of incidence) should be used since horizontal polarization will result in twice the loss. Experimental results using vertical polarization in the resonator indicate that for aluminum the reflection loss of such a bend is 0.0015 db at 9 kMc.

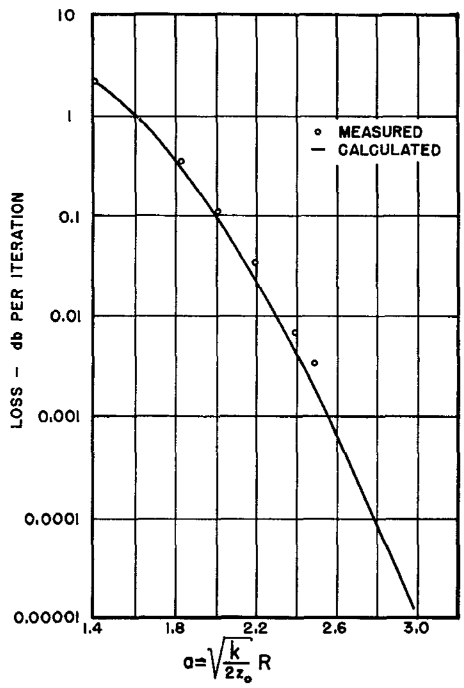

Fig. 7—Measured diffraction loss.

V. Results and Conclusions

Fig. 7 shows the result of the loss measurements plotted along with the calculated data from Fig. 2. The experimental data was obtained from Q measurements and corrected by 0.0042 db to account for end plate losses. Diffraction losses at the larger a values are extremely small and are comparable to the end plate losses. Thus errors in the end plate loss determination greatly affect the value attributed to the diffraction loss. Because of this, the deviation between measured and calculated values in this region may be in part accounted for. In addition, for this very high Q region the limits of the over-all measuring system accuracy are being approached mainly because of mechanical stability problems.

Loss predictions for higher modes have been made[3] and indicate that certain higher modes will always be present at least in the vicinity of launching. The calculated loss curve of Fig. 7 represents the lowest loss mode only. When this curve is used to compare the measured and calculated loss, it is assumed that all the power is being carried in the lowest mode. This assumption is very nearly but not exactly correct because of the presence of higher modes. If the next possible higher mode is considered, the predicted loss of the beam waveguide is increased by only 1 part in 4000. Thus the assumption that the lowest loss mode is the only one of practical significance is borne out by the measurements.

The treatment of the beam waveguide given by Goubau, *et al.*, permits an accurate prediction of its diffraction loss and also applies of course to the resonator. The beam waveguide resonator used in the loss measurements is a useful and practical millimeter and submillimeter circuit element. It is in fact being used at optical wavelengths in many masers and has been extensively treated by Fox and Li,[9] and Boyd and Gordon.[10]

In conclusion, it appears that the beam waveguide is indeed feasible, and in fact, superior in many ways to existing metallic guides for millimeter and shorter wave lengths. This conclusion is based on measurements of the diffraction loss which is the loss inherent in beam waveguides. This loss can be made as small as desired at a given frequency by varying the physical parameters, *i.e.*, lens radius and lens spacing.

Acknowledgment

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[9] A. G. Fox and T. Li, "Resonant modes in a maser interferometer," *Bell Sys. Tech. J.*, vol. XL, pp. 453–488; March, 1961.

[10] G. D. Boyd and J. P. Gordon, "Confocal multimode resonator for millimeter through optical wavelength masers," *Bell Sys. Tech. J.*, vol. XL, pp. 489–508; March, 1961.