Observed 5–6 mm Attenuation for the Circular Electric Wave in Small and Medium-Sized Pipes

By A. P. KING

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At frequencies in the 50–60 kmc region the use of circular electric wave transmission can provide lower transmission losses than the dominant mode, even in relatively small pipes.

The performance of two sizes of waveguide was investigated. In the small size (7⁄16″ I.D. × 1⁄16″ wall) the measured TE_{01} *attenuation was approximately 5 db/100 ft and is appreciably less than that of the dominant mode. The measured attenuation for the medium sized (7⁄8″ I.D. × 1⁄8″ wall) waveguide was 0.5 db/100 ft which is about one-fourth that for the dominant mode.*

This paper also considers briefly some of the spurious mode conversion-reconversion effects over the transmission band and their reduction when spurious mode filters are distributed along the line. Allowance has been made for the added losses due to oxygen absorption when air is present.

INTRODUCTION

Since 5.4-mm dominant-mode rectangular waveguide has attenuations of the order of 60 db/100 ft, another transmission technique is required in applications which involve appreciable line lengths. Losses may be reduced by the use of oversize waveguide; some earlier work with dominant mode transmission in slightly oversize round waveguide (two or three propagating modes) has been reported.[1] The possibility of still lower losses exists with circular electric wave transmission in an oversize round waveguide. Miller and Beck[2] have computed the theoretical relative transmission losses of the TE_{01} and TE_{11} modes as functions of

[1] A. P. King, Dominant Wave Transmission Characteristics of a Multimode Round Waveguide, Proc. I.R.E., **40,** pp 966–969, Aug., 1952.

[2] S. E. Miller and A. C. Beck, Low Loss Waveguide Transmission, Proc. I.R.E., **41,** pp 348–358, March, 1953.

guide size and frequency. At 5.4 mm, a $\frac{7}{16}''$ I.D. waveguide has an appreciably lower attenuation with the circular electric mode than with the dominant mode. A $\frac{7}{8}''$ I.D. guide has a circular electric attenuation approximately one-fourth that of the dominant mode in the same pipe.

It is the purpose of this paper to present some experimental results which have been observed with circular electric wave transmission in the 5–6 mm wavelength region. The attenuation for three different lines and the transmission variations due to moding effects are reported. Allowance for the loss due to oxygen absorption has been included.

DESCRIPTION OF THE TEST LINES

The TE_{01} mode attenuation measurements were made on approximately straight runs of line ranging from about 100 to 200 feet in length. The copper pipe comprising these lines is believed to conform to the best tolerances and internal smoothness which are current manufacturing practice for waveguide tubing. The relative tolerances and their effect upon transmission are considered in a later section. Three kinds of copper line were measured: a waveguide of oxygen-free copper, one line of low phosphorous-deoxidized copper and one line of steel with a 20-mil low phosphorous-deoxidized copper inner lining. The oxygen-free high-conductivity-copper with its higher conductivity and somewhat greater ductility was chosen to provide comparative performance data with the low phosphorous-deoxidized copper which is commonly used in waveguide manufacture. A waveguide whose outer wall is constructed of steel to provide the necessary strength and wall thickness to support a very thin copper inner wall has the advantage that such waveguide requires less copper. This composite wall tubing was obtained to ascertain whether the tolerances and the nature of the inner surface would yield transmission data comparable to solid copper waveguide.

The lines were supported on brackets which were accurately aligned and spaced at 6-ft intervals. Although the brackets provided for an accurately straight line, the manufactured pipe was not perfectly straight but, in some samples, varied as much as $\frac{3}{8}''$ in a 12-ft length. Installing the pipe on the brackets tended to straighten the line and reduce these variations to about half this amount. A general view of the lines is shown in the photograph of Fig. 1.

The sections of waveguide were joined together with a more or less conventional threaded coupling, but with one very important difference. The threads, which are cut at the ends of each section, are cut relative to center of the inside diameter and not the outside diameter. This is achieved by employing a precision pilot to provide a center for the cut-

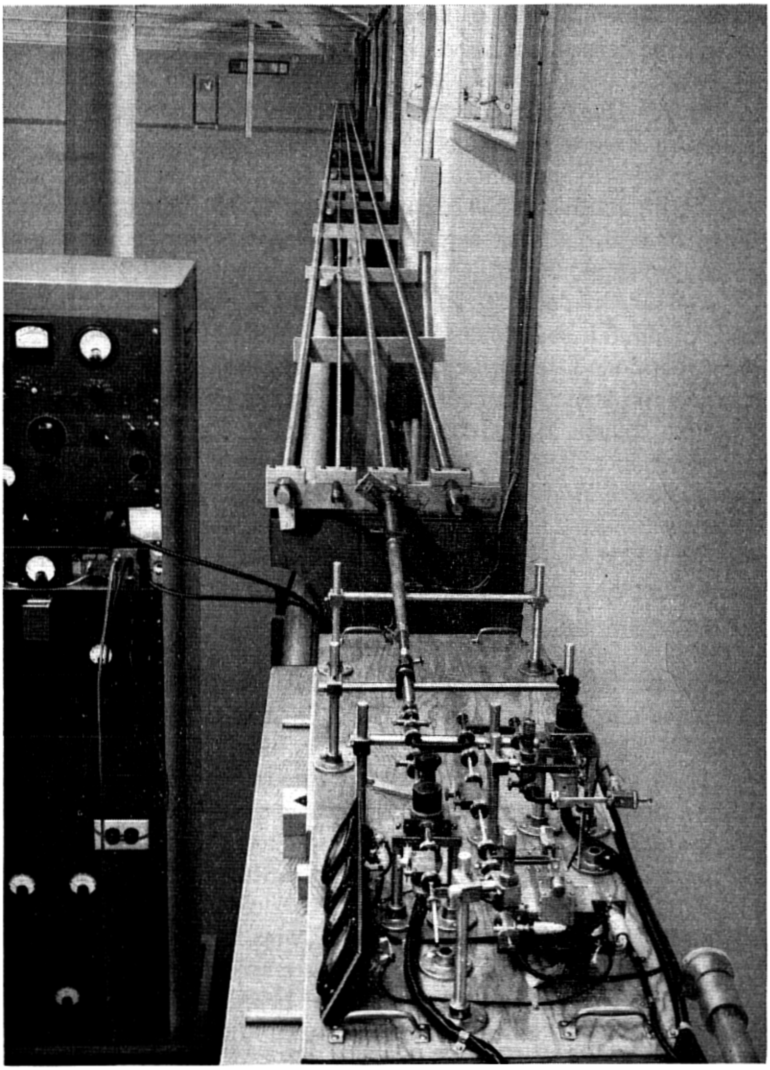

Fig. 1 — General view of the circular waveguide lines and the millimeter wave measuring equipment.

ting die. Since the internal diameter is made as precise as possible, the variations of outside diameter become a function of the tolerances of both the internal diameter and wall thickness and cannot be as precise as the inside of the pipe. Any thread cut relative to the outside diameter as in regular plumbing practice, will not, in general, be concentric to the inside wall. To avoid an offset at the joint it is therefore important that the thread be centered relative to the inside diameter. After a section was threaded the ends were faced off to make the ends square and thus avoid any tilt between sections when the ends are butted together.

Of the two sizes tested the smaller diameter (7⁄16″ I.D. × 1⁄16″ wall) was chosen to provide a moderate line loss, while limiting the number of propagating modes. In the band of interest (5.2–5.7 mm) the theoretical TE_{01} wave attenuation is about 4 db/100 ft. The number of modes which can be supported at $\lambda = 5.2$ mm is limited to 12 modes and to only one of the circular electric modes. The higher order TE_{0n} modes are beyond cut-off. These features limit the number of spurious modes and simplify the mode filtering problem. Furthermore, in this smaller sized waveguide, the associated components which may set up TE_{0n} waves, for example conical tapers, need not be as long proportionately as in larger waveguides. The 7⁄16″ I.D. guide has the advantage of smaller size, lower cost and greater ease of transmitting TE_{01} through specially constructed bends. The attenuation of this smaller diameter guide is large enough that system requirements will usually restrict its usage to lengths of line of a hundred feet or so.

The larger size (7⁄8″ I.D. × 1⁄8″ wall) is exactly twice the diameter of the small size discussed in the preceding paragraph but has only one-tenth the attenuation, or about 0.4 db/100 ft. The low loss of this larger size becomes more attractive for runs as long as several hundred feet. This diameter guide will, of course, support more modes, 50 at $\lambda = 5.2$ mm; four of which are circular electric modes — TE_{01}, TE_{02}, TE_{03} and TE_{04}. Some of the disadvantages which accompany the increased diameter are: (1) greater care must be taken as to line straightness, (2) longer conical tapers are required when converting from one guide diameter to another, and (3) longer mode filters are required since the desired mode-filtering attenuations vary inversely with the filter diameter at a given frequency. Flexible spaced-disk lines employed as uniform bends for TE_{01} transmission require much greater bending radii than bends in the smaller diameter guide if the bend loss is to be kept proportionately low. This problem is considered in some detail in another paper.[3] With reasonable care the accumulative effect of these foregoing factors can be held to a reasonably low value. Expressed in terms of the ratio of measured to theoretical attenuation the values are, on the average, about 10 per cent higher in the 7⁄8″ I.D. waveguide than in the 7⁄16″ I.D. waveguide.

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[3] A. P. King, forthcoming paper on bends.

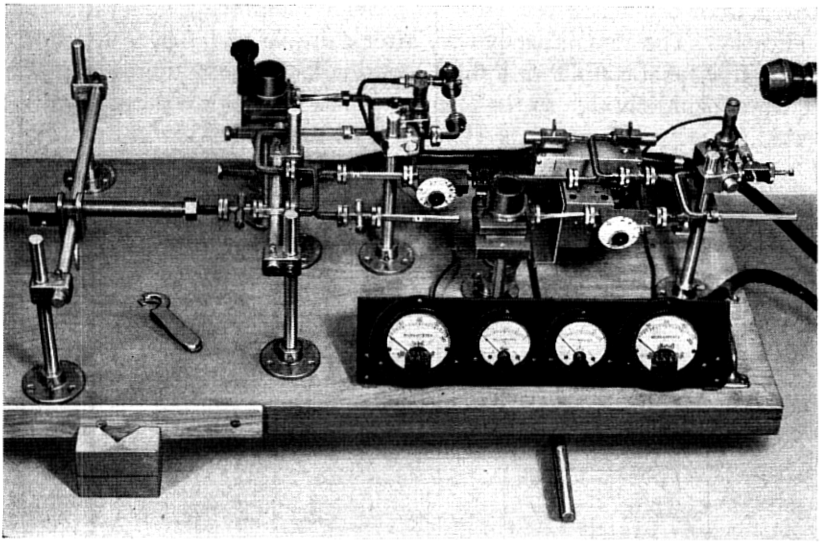

Fig. 2 — Waveguide portion of millimeter wave measuring set.

MEASURING PROCEDURE

With straight runs of round, TE_{01} waveguide lines whose length lies in the 100–200 ft range, it is convenient to make attenuation measurements on a round trip basis. This method has the advantage of convenience in that the attenuation can be measured directly by using a waveguide switch but has the disadvantage of requiring a careful impedance match of the measuring equipment to the line. Fig. 1 shows an overall view of the lines; Fig. 2 shows the arrangement of the 5–6 mm measuring set, and Fig. 3 shows a block diagram of the set-up employed.

This measuring set makes use of two klystrons developed by these laboratories.[4] The double detection receiver features a separate beating oscillator klystron which is frequency modulated and a narrow band (1.7 mc at 60 mc) IF amplifier. The resulting IF pulses are detected with a peak detector and then amplified to provide the usual meter indication. This method with its circuitry has been developed by W. C. Jakes and D. H. Ring,[5] and provides a greater amplitude stability than is possible with a cw beating oscillator.

In the waveguide schematic of Fig. 3 about a tenth of the power is

[4] E. D. Reed, A Tunable, Low Voltage Reflex Klystron for Operation in the 50–60 Kmc Band, B.S.T.J., **34,** p. 563, May 1955.
[5] W. C. Jakes and D. H. Ring, unpublished work.

taken from the signal oscillator to provide monitoring and wavemeter indication. The remaining power, after suitable padding, is fed into a 3-db directional coupler or hybrid junction 2. This junction is employed as a waveguide bridge so that, when arms A and B are properly terminated, no power flows in receiving arm C. Any reflection in line A will,

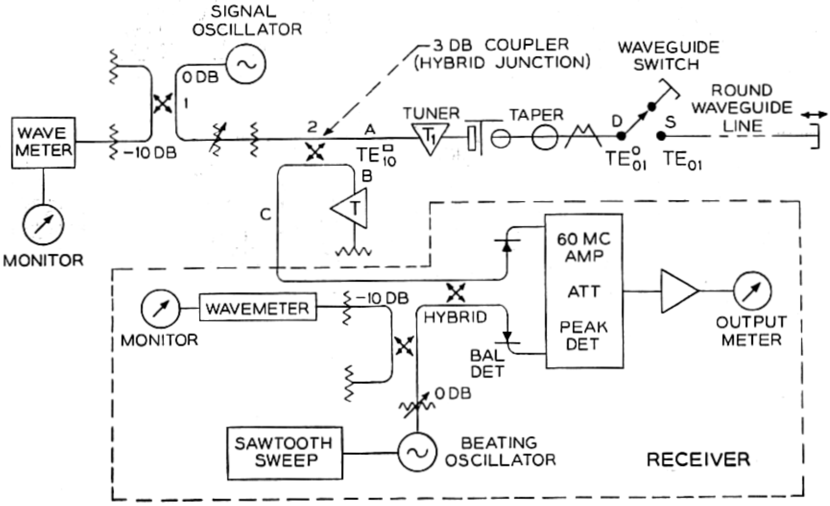

Fig. 3 — Schematic of measuring equipment.

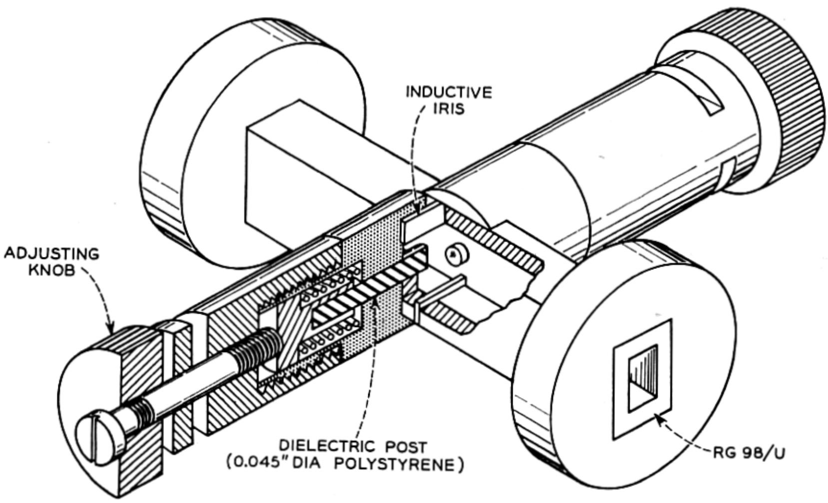

Fig. 4 — Structure of impedance matching tuner.

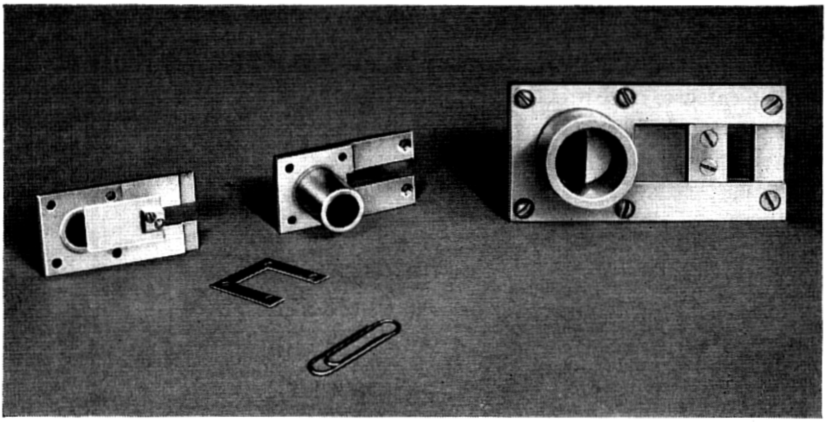

Fig. 5 — Structure of waveguide switch.

however, produce a power flow in the arm C to the balanced converter of the receiver and an indication in the output meter. So far this set is similar to a setup for measuring the round trip loss in a terminated waveguide system. The impedance of the $TE_{10}^{\square} \rightleftarrows TE_{01}^{\bigcirc}$ wave transducer,[6] taper section and mode filter connected as shown in the section A–D of Fig. 3 can be matched to the rectangular waveguide at A by an appropriate adjustment of the dielectric post tuner[7] T_1 whose structure is shown in Fig. 4. Under these conditions a conical taper termination placed in the round waveguide at D will again produce a balance and again no power will flow in arm C. A waveguide switch whose structure is shown in Fig. 5 is connected between the point D and the line under test. A movable short at the far end of the line completes the set-up.

With the impedances matched as described above, the only reflection which reaches the receiver will be from the far end of the line when the switch S is open or, when shorted, from the switch itself. The round-trip attenuation is the difference in attenuation measured for the two positions of the switch. By means of a movable short at the far end of the line, the line length can be varied to produce mode conversion and mode reconversion effects, and the resultant variation in TE_{01} mode transmission can be observed. This phenomena is described in some detail elsewhere.[8]

[6] Reference 2, page 354, Fig. 14.

[7] C. F. Edwards, U.S. Patent 2,563,591, Aug. 7, 1951. The millimeter tuner employs an adjustable dielectric post in place of a metallic tuning screw described in the patent.

[8] Reference 2, pp 356, 357.

LOSSES DUE TO OXYGEN ABSORPTION

In addition to the losses which result from imperfect conductivity, surface effects, and mode conversions, there is a very appreciable loss due to oxygen absorption when the guide is open to the atmosphere. In a waveguide the loss due to O_2 absorption is:

$$\frac{A}{\sqrt{1 - \nu^2}} \tag{1}$$

where

A is the absorption due to oxygen in the atmosphere
$\nu = \lambda/\lambda_c$
λ = free space wavelength
$\lambda_c = \frac{\pi d}{k} = \frac{\pi d}{3.83}$ = cut-off wavelength
d = internal diameter of waveguide
k = Bessel root for TE_{01} mode = 3.832

The loss due to absorption of oxygen which is present in the atmosphere (at approximately sea level) was obtained from the experimental data of D. C. Hogg.[9] The added loss produced by the presence

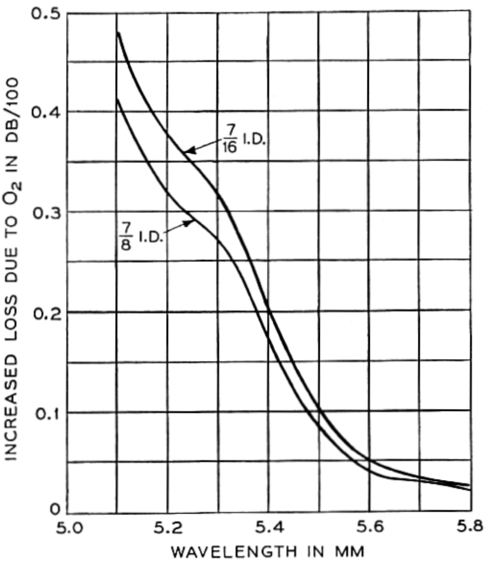

Fig. 6 — TE_{01} transmission loss in waveguides due to oxygen absorption.

[9] A. B. Crawford and D. C. Hogg, Measurement of Atmospheric Attenuation at Millimeter Wavelengths, B.S.T.J., **35**, pp. 907–917, July, 1956.

of oxygen in the waveguide in terms of (1) is plotted in Fig. 6. It will be noted that this loss becomes very appreciable at the short wavelength end of the band. At $\lambda = 5.2$ mm this loss is in the 0.3–0.4 db/100 ft range. For the larger size waveguide line (7/8″ I.D.) the loss due to O_2 is approximately equal to the theoretical wall losses; for the smaller size lines this amounts to about a tenth the wall loss. At the other end of the millimeter band the O_2 losses are very small, being in the 0.02 – 0.03 db/100 ft range at $\lambda = 5.7$ mm.

The relative effects of theoretical wall and expected oxygen absorption losses are shown plotted in Fig. 7. For the two sizes of waveguide the upper dashed curve represents the combined effect of these two factors and the lower solid line curve is the theoretical attenuation of the TE_{01} mode in empty pipe. The shaded area indicates the increase which is the result of oxygen absorption.

In order to minimize the transmission losses in any practical system it becomes desirable to exclude the presence of oxygen from the line, for example, by introducing an atmosphere of dry nitrogen. Since the ex-

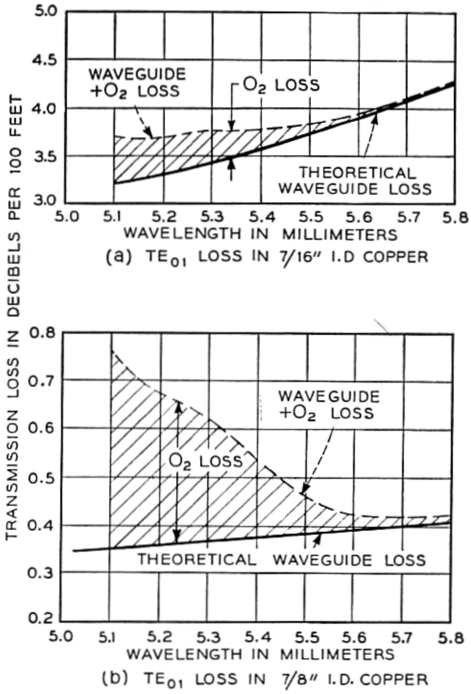

Fig. 7 — TE_{01} transmission losses.

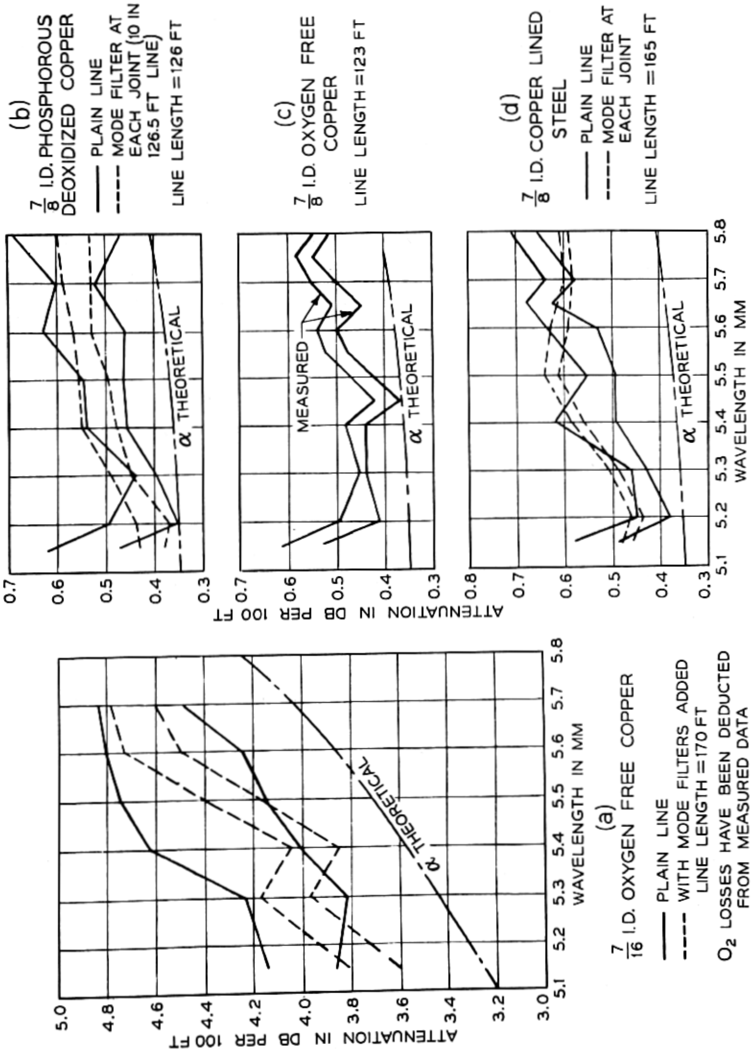

Fig. 8 — Measured and theoretical loss of the four lines studied.

clusion of oxygen was not very feasible in the experimental TE_{01} lines, the effects due to oxygen absorption were included in the measurements. However, in order to simplify the presentation of the attenuation data these absorption losses, as indicated in Figs. 6 and 7, have been subtracted from the measured data.

The measured attenuation of the four lines are shown in Fig. 8 as a function of wavelength (5.1–5.8 mm). In each case the dash-dot-dash lines represent the theoretical attenuation for copper. Each plot shows two solid lines which indicate the range of values measured over the mm band. The same range was observed either by varying the length of the line by means of a sliding piston at the far end of the line or by imposing a sweep voltage on the repeller of the signal klystron to produce a small frequency modulation. These variations in attenuation correspond to piston movements which are greater than a half wavelength and are due to the mode interference effects produced by spurious modes generated in the line. The resultant signal fluctuations which are due to mode conversion and reconversion effects have been described in considerable detail by Miller.[10]

Referring again to Fig. 8, the measured data shown by the solid lines, which are for a plain line without mode filters, indicates that the oxygen-free high conductivity copper line gave the lowest measured average attenuation as well as the least variation. The low phosphorous deox-

TABLE 1

	7/16″ I.D.	7/8″ I.D.	7/8″ I.D.	7/8″ I.D.
	OFHC Copper	OFHC Copper	Low Phos. Deoxidized Copper	Copper Lined Steel
Wall Thickness	1/16″	1/8″	1/8″	1/8″
α meas. (db/100 ft)	4.33 ± 0.24	0.47 ± 0.02	0.49 ± 0.05	0.52 ± 0.04
$\frac{\alpha \text{ meas}}{\alpha \text{ calc}}$	1.17	1.29	1.34	1.42
Average ovality				
A	1/1100	1/1100	1/1200	1/585
B	0.0004″	0.0008″	0.00075″	0.0015″
Maximum ovality				
A	1/730	1/875	1/875	1/290
B	0.0006″	0.001″	0.001″	0.003″
Maximum tolerance				
A	1/310	1/730	1/430	1/290
B	0.0014″	0.0012″	0.002″	0.003″

[10] S. E. Miller, Waveguide as a Communication Medium, B.S.T.J., **33,** pp. 1229–1247, Nov. 1954.

idized copper was next best while the steel line with a 20-mil inner copper lining was the poorest.

In the 7⁄16″ I.D. oxygen-free high conductivity copper line the measured attenuation was 17 per cent higher than the calculated value (see α meas/α calc in Table I). This higher loss is attributed to spurious mode conversion and to surface conductivity effects. In the ⅞″ line of the same material the α meas/α calc = 1.29 which is an increase of 12 per cent relative to the smaller waveguide. Since the ⅞″ diameter line supports about four times the number of modes of the 7⁄16″ diameter line, this increase in loss is attributed to mode conversion. In the other two ⅞″ diameter guides the added losses are believed to be increased mode conversion which results from the poorer dimensional tolerances. These data are listed in Table I together with dimensional tolerances. In this table α_{meas} is the measured attenuation averaged over the 5.2–5.7 mm band together with the variations shown in Fig. 8; α_{calc} is the average theoretical attenuation for standard (IACS) copper. The I.D. tolerances are listed in two sets of rows A and B; row A gives the fractional variation

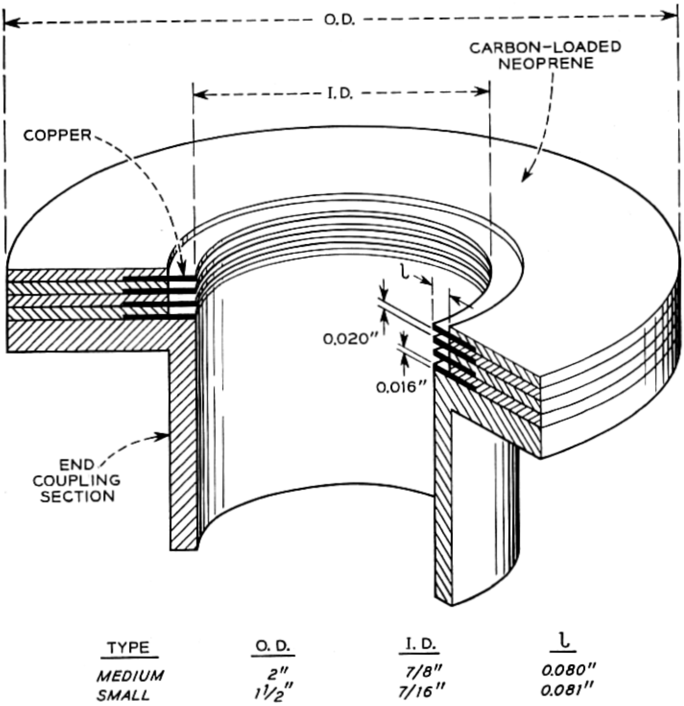

Fig. 9 — Structure of spaced-disk mode filter.

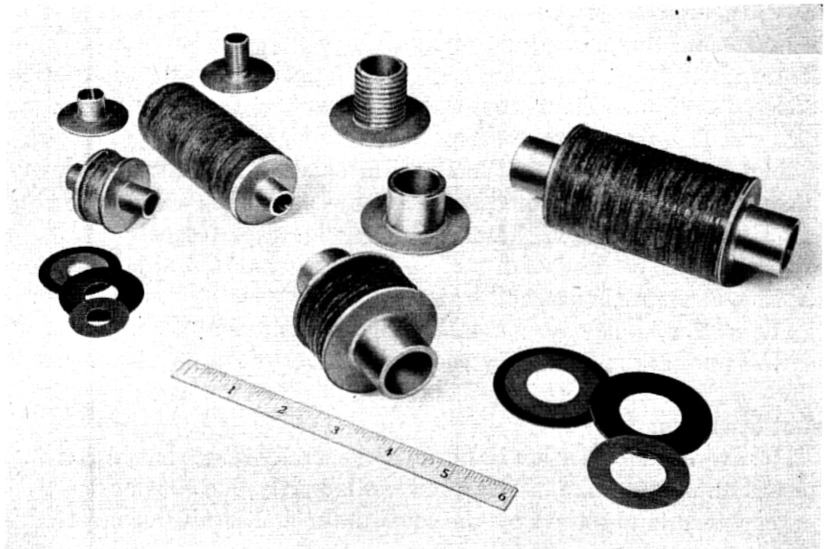

Fig. 10 — Mode filters.

relative to the average diameter and the rows marked B indicate the corresponding variations in inches. The average ovality gives the average difference between maximum and minimum diameters, maximum ovality the maximum difference in diameter and the maximum tolerance gives the maximum difference between diameter and ovality. These measurements have been limited to measuring at the two ends of each section of pipe. In spite of this small sampling the TE_{01} loss measurement appears to follow the I.D. tolerances quite well; the OFHC line shows both the lowest attenuation and the best tolerances.

Mode interference effects can be reduced considerably by increasing the loss to the undesired modes. This effect can be accomplished by modifying the structure so that the spurious modes are highly attenuated while the TE_{01} losses are increased only slightly. One way is to construct

Table II — Average Performance of TE_{01} Waveguides with Mode Filters

	7/16″ I.D. OFHC copper	7/8″ I.D. low phos. deoxidized copper	7/8″ I.D. copper lined steel
α measured (average db/100 ft.)	4.24 ± 0.1	0.51 ± 0.025	0.56 ± 0.012
$\frac{\alpha \text{ measured}}{\alpha \text{ calculated}}$	1.16	1.39	1.52

the waveguide wall with a series of disks which are closely spaced as shown in Fig. 9 and the photograph of Fig. 10. The spacers serve a dual purpose; to hold the disks in alignment and to provide loss for the spurious modes. The circular disks provide the necessary continuity to support the TE_{01} and TE_{02} modes and the gaps introduce high resistivity to the longitudinal currents of the other modes. The spaced-disk filters, which were arbitrarily designed to provide a 10 db loss to the TM_{11} wave, were 1 ⅝″ and 3 ¼″ long for the 7⁄16″ and ⅞″ waveguide sizes, respectively. In the experiments to be described, a mode filter was inserted at each joint of the line, at approximately 12-ft. intervals.

The measured attenuation data with mode filters at each joint of the various lines are indicated by the dashed lines of Fig. 8. As shown the effect of the mode filters is to reduce the TE_{01} loss variation by a factor of at least two.

The average attenuation is, however, generally somewhat higher than for the unfiltered lines. This higher loss is partly due to spurious mode power which is absorbed by the mode filter and is not reconverted to TE_{01} power and to a slight degree to the increased TE_{01} loss introduced by the mode filters. These results are shown in tabular form in Table II, where the nomenclature is the same as in Table I. Because of the excellent performance of the ⅞″ I.D. line (OFHC copper) by itself no measurements with mode filters were performed on this line.

CONCLUSIONS

The measured data presented above indicate the feasibility of realizing transmission losses as low as 0.5 db/100 ft. with the TE_{01} mode over distances up to several hundred feet. The transmission variations which occur over the frequency band are a function of the circularity or tolerances of the waveguide. In a particular line the variations can be reduced considerably by adding mode filters along the line. It is reasonable to expect that these variations can be reduced further by adding longer mode filters at the joints or adding more mode filters at shorter intervals along the line. Oxygen must be excluded from the line if the losses are to be a minimum.

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