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Low-Loss Modes in Dielectric Lined Waveguide

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Recent studies of the heat loss characteristics of the normal modes in dielectric lined circular waveguide have shown that modes other than those of the circular electric type may have low loss over wide frequency bands. This unexpected behavior of the mode loss characteristics is explained by utilizing the well-known duality relationships between the electric and magnetic fields. Specifically, it is shown that the lowest loss modes are alternately circular electric and circular magnetic as frequency (or lining thickness) increases, with low loss occurring at frequencies and lining thickness where the wall impedance of the dielectric coated guide approximates a short circuit (or electric wall) for circular electric modes, and an open circuit (or magnetic wall) for circular magnetic modes.

These findings will influence and aid in the selection and design of an appropriate waveguide(s) (employing the circular electric TE_{01} mode) for the WTS millimeter wave transmission system which is presently under development; they may also influence the design of future guided wave systems.

I. INTRODUCTION

The possibility of using a circular electric (TE_{01}) mode in circular waveguide has been of considerable interest since the initial discovery of its desirable low-loss characteristics (in the following, we are concerned only with the heat loss in the guide). One type of guide currently under consideration (Fig. 1) consists of a highly conducting outer wall to which a thin dielectric liner is bonded to break the degeneracy in phase velocities for the TE_{01} and TM_{11} modes in metallic circular waveguide.

The circular electric mode loss characteristics of thinly lined circular waveguide have been determined by H. G. Unger.[1–3] This work has

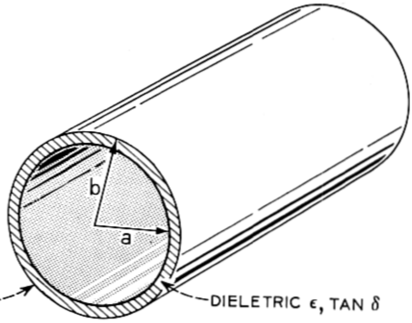

Fig. 1—Dielectric lined circular waveguide.

since been extended[4] and it was found that other modes also have very low heat loss over an appreciable frequency range. A full scale discussion of the analysis is beyond the scope of this paper but will be available in a forthcoming paper.[4] In the following, the analytical approach is indicated and some typical results for the heat loss (copper and dielectric loss) of the TE_{01}, TE_{02}, and TM_{02} modes in lined circular guide are given.

II. DISCUSSION

The problem of obtaining the normal mode loss for a perfectly straight circular waveguide with a uniform lining, as shown in Fig. 1, was approached in two ways. In one approach, the well-known induced current method was used. The field and wall currents in the guide were found for a lossless structure; they were then used to determine the heat losses of the waveguide. In the second approach, the impedance at the dielectric-free-space interface was prescribed as a boundary condition for the solution of the wave equation. This impedance was established by using a transmission line model to transform the surface impedance of the copper conducting wall through the dielectric lining, which was assumed to have a small but finite loss tangent. The complex eigenvalue equation was then solved and the overall losses thus determined.

The results of these two methods are in good agreement. The wall impedance approach aids in understanding the physical phenomena occurring in dielectric lined guide and is used in the following paragraphs to explain the loss characteristics of circular electric and magnetic modes in dielectric lined guide.

In Fig. 2, we have plotted the total heat loss for some circular electric and magnetic modes in lined waveguide with a 1-percent lining ($\rho = 1.01$). Here ρ is defined as the ratio of the waveguide conductor radius to dielectric radius. The losses of the circular electric modes initially decrease with increasing frequency, as in unlined waveguide, and reach minimum values at approximately 140 GHz (at this point, the dielectric loss accounts for 8 percent of the total heat loss). The TE_{0n} losses then increase rapidly with a further increase in frequency. We observe an interesting phenomenon at approximately

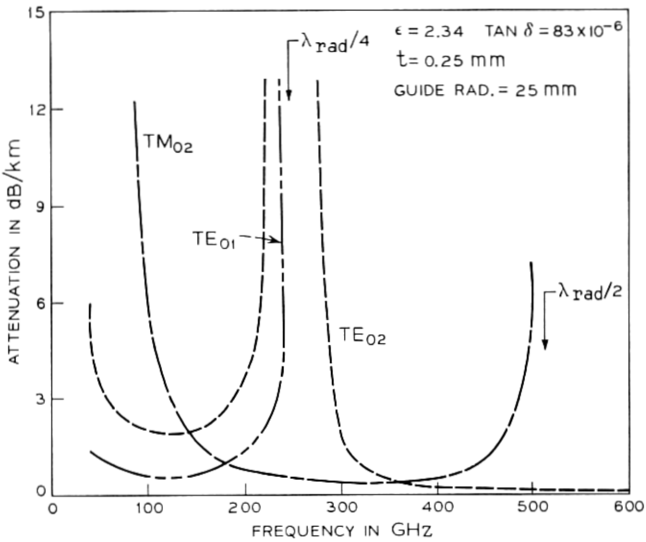

Fig. 2—Loss characteristics of circular symmetric modes in lined waveguide (wall impedance model).

240 GHz. At this frequency the lining is approximately a quarter wavelength thick ($\lambda_{rad}/4$) in the radial direction. The equivalent wavelength (λ_{rad})* in the radial direction for the dielectric region is related to the free-space wavelength (λ) by

$$\lambda_{rad} = \lambda/\sqrt{\epsilon - 1}. \tag{1}$$

As the frequency increases beyond 240 GHz, the TE_{01} loss increases indefinitely. This is attributable to a surface-wave phenomenon (the

* In highly overmoded guide, it can be shown that the radial propagation constant in the dielectric region is $(2\pi/\lambda)\sqrt{\epsilon - 1}$ by considering plane-wave reflection by a grounded slab at grazing incidence.

field is bound to the dielectric region), and the fact that it occurs only when the lining thickness is greater than a quarter wavelength is in agreement with the minimum thickness ($n = 1$) required to propagate a TE surface wave on a grounded slab:[5]

$$t_{min} = \frac{n\lambda}{4\sqrt{\epsilon - 1}} \qquad n = 1, 3, 5, \cdots . \tag{2}$$

The TE_{02} loss (20 percent of which is due to dielectric losses in the lining at this frequency), conversely, decreases as the frequency becomes greater than 240 GHz and reaches a minimum when the lining is a half wavelength thick ($\lambda_{rad}/2$), as shown in Fig. 2. We would find the TE_{02} loss increasing rapidly with a further increase in frequency as it eventually propagates as a surface wave when the lining is three-quarters of a wavelength [corresponding to $n = 3$ in equation (2)] thick.

The most interesting feature of Fig. 2 is the steadily decreasing loss of the TM_{02} mode as the frequency increases. At the upper end of the proposed WTS frequency band (110 GHz), the TM_{02} loss (10 percent is due to dielectric loss) is a surprisingly low 4.7 dB/km for this example. The TM_{02} mode also has lower loss than *any* circular electric mode over the frequency range of 180–350 GHz. At 240 GHz, the TM_{02} loss is 0.54 dB/km and dielectric losses account for 13 percent of this.

From Fig. 2 we observe that the TM_{0n} loss characteristics for a lining of thickness t are similar to those of a TE_{0n} mode in a guide with a lining thickness a quarter wavelength greater. The TM_{0n} modes have loss minima for linings $\lambda_{rad}/4$, $3\ \lambda_{rad}/4$, $\cdots$ thick while the TE_{0n} modes have loss minima for 0, $\lambda_{rad}/2$, $\cdots$ thick linings. The minimum dielectric thickness required for a TM_{0n} mode to propagate as a surface wave is[5]

$$t_{min} = \frac{n\lambda}{4\sqrt{\epsilon - 1}} \qquad n = 0, 2, 4, \cdots , \tag{3}$$

which differs from the minimum thickness for a TE_{0n} surface-wave mode in (2) by a quarter wavelength. From (3) we see that the TM_{01} mode propagates as a surface wave for very thin linings ($n = 0$); the TM_{01} loss curve was not shown in Fig. 2, since the loss steadily increased with increasing frequency from an initial value of 47 dB/km at 40 GHz.

The preceding loss characteristics can be explained by a simple physical argument and the use of duality. Let us consider Fig. 3. Here

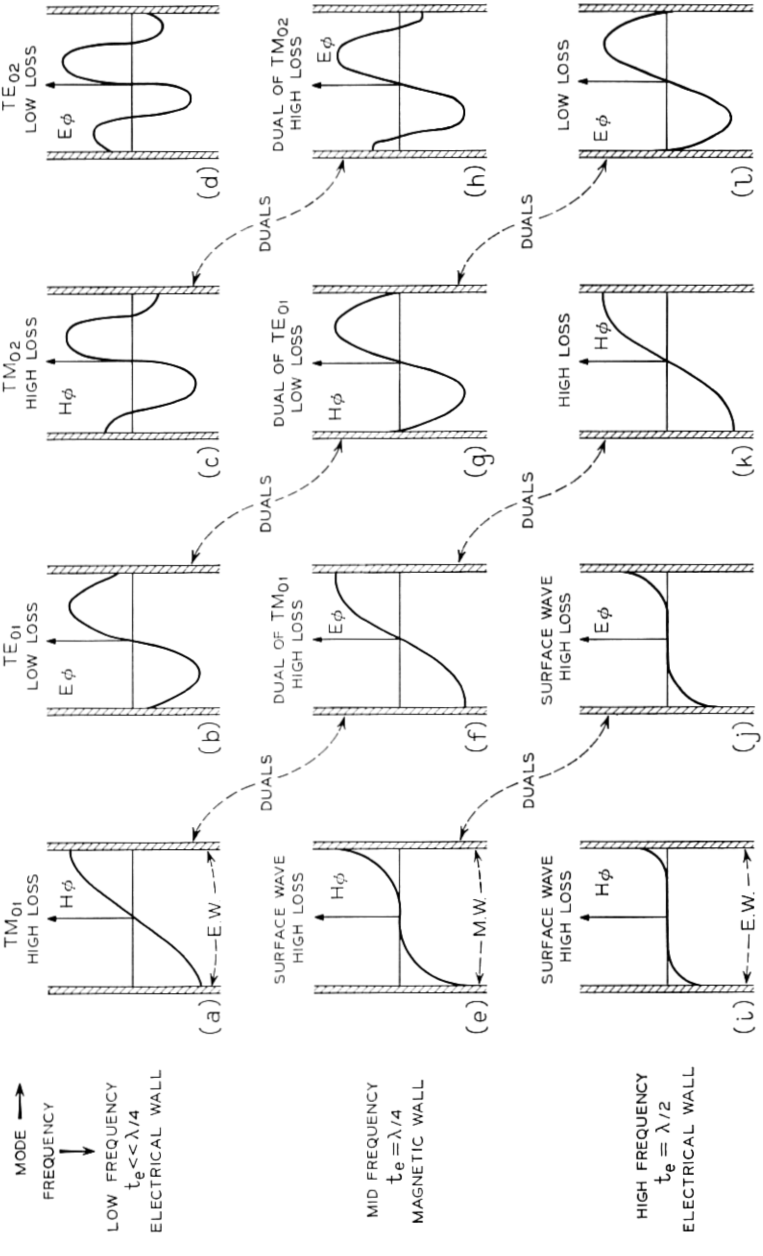

Fig. 3—Field distributions of the circular symmetric modes in unlined and lined waveguide.

we have sketched the field distributions of the circular electric and circular magnetic modes for no lining, a quarter-wave lining, and a half-wave lining. For the TM_{01} and TM_{02} modes with no lining (Fig. 3a and c), we have a strong normal electric field at the wall of the guide with a high induced electric charge density and hence high loss. For the TE_{01} and TE_{02} modes (Fig. 3b and d) the losses are quite low.

For a quarter-wave lining, the impedance at the dielectric inner face is approximately an open circuit or magnetic wall. The TM_{01} mode is trapped in the lining and decays in an exponential fashion towards the center of the guide (Fig. 3e). The field configuration for the TE_{01} in the air region (Fig. 3f) is the dual of that for the TM_{01} mode in Fig. 3a. Hence it will have high losses. The field configuration for the TM_{02} mode (Fig. 3g) is now the dual of the TE_{01} mode in Fig. 3b and hence it is a low-loss mode. On a further increase in the lining thickness to $\lambda_{rad}/2$, we find TE_{01} and TM_{01} both propagate as a surface wave bound to the lining (Fig. 3i and j), while TM_{02} has high loss (Fig. 3k). TE_{02} (Fig. 3l) and TE_{03} (not shown in Fig. 3), conversely, have low losses for this lining thickness.

In Fig. 4, we have plotted the loss for several TE_{0n} and TM_{0n} modes at 100 GHz for lining thickness up to 5 percent. We find the results

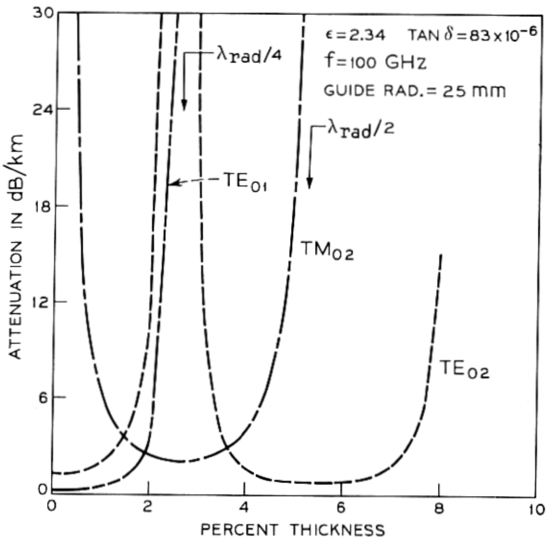

Fig. 4—Loss characteristics of circular symmetric modes at 100 GHz for waveguide lining thicknesses up to 5 percent (wall impedance model of lined waveguide).

for a change in lining thickness are similar to those for a change in frequency. The TE_{0n} and TM_{0n} modes go through relative loss maxima and minima for a $\lambda_{rad}/4$ change in lining thickness. An additional mode also becomes trapped and propagates as a surface wave for every $\lambda_{rad}/4$ change in thickness.

In Fig. 5, some representative solutions of the appropriate eigenvalue equations for TE_{0n} and TM_{0n} modes in dielectric lined guide are given. The eigenvalue (k_n) is defined as

$$k_n = \chi_n a$$

where a is the dielectric radius and χ_n the radial propagation constant in the air region. The eigenvalues for liners which are integral multiples of a quarter wavelength thick in the radial direction are approximately the same as the eigenvalues for circular symmetric modes in empty guide with an electric or magnetic wall. The eigenvalue also tends to zero as the thickness increases and eventually becomes pure imaginary which is indicative of a surface-wave phenomenon with very large heat losses.

III. CONCLUSION

In the preceding sections we have seen that modes other than those of the circular electric type have low loss in dielectric lined guide. In order to transmit a circular electric (not necessarily TE_{01}) mode with low loss, the lining must be significantly less than a quarter wavelength or approximately an integral multiple of a half wavelength thick. On the other hand, it is possible to use a dielectric lined guide with a quarter-wavelength-thick liner (also $3\lambda/4$, $5\lambda/4$, etc.) as a low-loss circular magnetic mode transmission medium. The tolerances on such a system for mode conversion loss would be similar to those on the appropriate dual circular electric guide.

The results also indicate there is a range of thicknesses or frequencies for which both TM_{0n} and TE_{0n} modes have low loss. Since the local character of the fields for any mode near the wall of a metallic waveguide must be similar to that of either a TE_{0n} or TM_{0n} mode, there will be a range of thicknesses and frequencies for which many quasi TM and TE modes have low loss (on the order of 6 dB/km or less) in dielectric lined guide. (This has been confirmed by recent results.[4]) This implies that the ohmic losses in route bends will be reduced. Further, since the dielectric liner not only reduces the heat loss for the spurious quasi TE and TM modes generated by a route bend or other guide deformation but also alters their field distributions relative

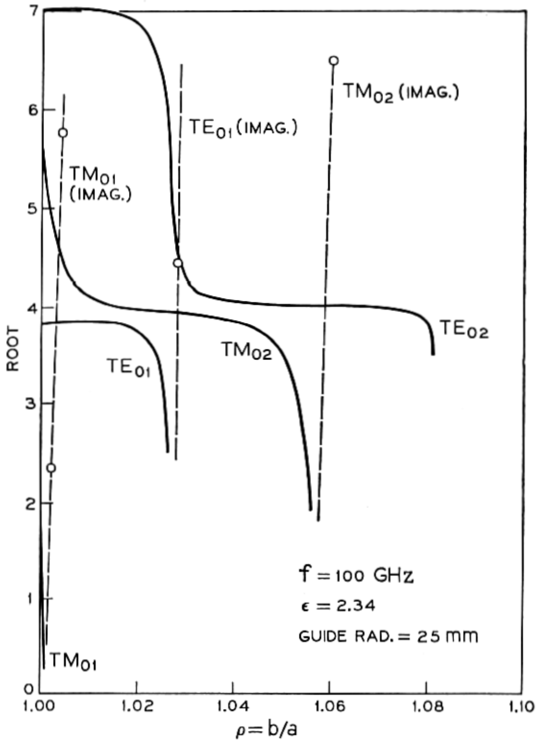

Fig. 5—Eigenvalues for circular symmetric modes in lined waveguide.

to those of unlined waveguide, it will be necessary to design mode filters with this in mind.

IV. ACKNOWLEDGMENT

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