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Experimental Verification of Low-Loss TM Modes in Dielectric-Lined Waveguide

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Experimental measurements have been carried out to verify the recent theoretical prediction that, in dielectric-lined circular waveguide, modes other than those of the TE_{on} family can exhibit a loss characteristic which decreases with increasing frequency. The TM_{11} waveguide was launched in 51-mm diameter circular waveguide lined with a 200-micron layer of polyethylene, and its loss characteristics were measured. Losses of 23 dB/km at 80 GHz and 3.5 dB/km at 110 GHz were measured, thus confirming the decreasing loss with increasing frequency trend predicted by theory.

I. INTRODUCTION

Recent analytical studies[1–3] of the heat loss characteristics of the normal modes in oversized dielectric-lined circular waveguide indicate that modes other than those of the circular electric type have low loss (<10 dB/km). Specifically, in 51-mm diameter waveguide lined with a 200-μm layer of polyethylene, the TM_{11} mode was predicted to have a theoretical attenuation coefficient which decreases with increasing frequency and achieves values less than 10 dB/km over the 80- to 110-GHz frequency range. This paper reports some recent experimental results which confirm the decreasing heat loss versus frequency trend predicted for the TM_{11} mode in lined waveguide.

The differential phase constant ($\Delta\beta$) for the TE_{01} and TM_{11} modes,

$$\Delta\beta \equiv h_n - h_{01}, \tag{1}$$

was also measured and found to be in good agreement with the theoretical predictions. Here, h_n and h_{01} are the phase constant (propagation constant in lossless guide) for the spurious mode and the TE_{01} mode, respectively.

II. MEASUREMENT METHOD

The loss and $\Delta\beta$ measurements were carried out with a CW reflectometer test set as shown in Fig. 1. Before proceeding to a discussion of the test set, it is helpful to first summarize some recently-arrived-at conclusions[4] concerning the normal-mode scattering properties at the junctions of three common types of circular waveguide.

The normal modes of helix or dielectric-lined guide, as defined herein, are characterized in terms of the equivalent wall impedance of the guide.[3] They are defined as TE_{pn} or TM_{pn} modes, although they are in fact hybrid modes. The so-called TE_{pn} or TM_{pn} modes tend to the TE_{pn} or TM_{pn} modes of metallic waveguide as the *wall impedance* (or equivalently the lining thickness for dielectric-lined guide) tends to zero. Since the modes in dielectric-lined or helix guide may differ from the modes in copper guide, we will add the appropriate superscript (Cu-copper guide, DL-dielectric lined guide, HX-helix) to the usual TE_{pn} or TM_{pn} notation.

For the helix and dielectric-lined guides used in the present study, the scattering properties of interest over the 80- to 110-GHz frequency range may be summarized as follows:

(*i*) The TE_{11}^{Cu} mode scatters $\lesssim 80$ percent of its energy into the TE_{11}^{HX} mode. Almost all of the remaining energy scatters into

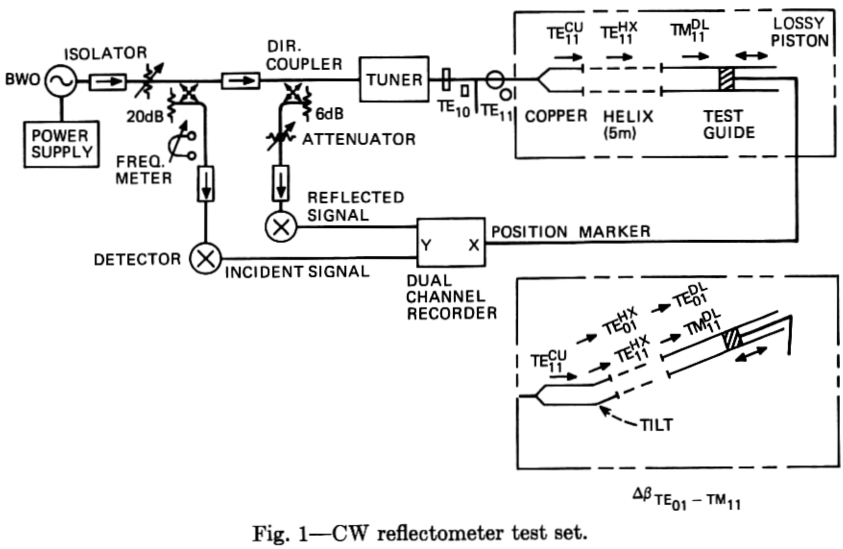

Fig. 1—CW reflectometer test set.

the TM_{1n}^{HX} modes which have much higher losses then the TE_{11}^{HX} model.

(*ii*) The TE_{11}^{Cu} mode scatters >90 percent of its energy into the TM_{11}^{DL} and TE_{11}^{DL} modes.

(*iii*) The TE_{11}^{HX} mode scatters >95 percent of its energy into the TM_{11}^{DL} mode.

The loss of the waveguide sample is measured using the circuitry in the upper portion of Fig. 1. A dominant $TE_{10}^{\square}$ mode is converted to a $TE_{11}^{\bigcirc}$ mode via a transducer and passed through a smooth copper taper to a 51-mm output diameter. At this point, the copper waveguide is connected to a helix waveguide followed by a dielectric-lined guide (as shown in Fig. 1) or simply to a dielectric-lined guide. The loss of the sample per unit length can then be determined from the slope of the reflected signal level versus piston position. A lossy reflecting piston (<-6 dB reflection coefficient) is used to minimize the effects of trapped resonances in the test set. The slide screw-tuner as shown in Fig. 1 is required to tune out the residual mismatch in the system.

The Cu-HX-DL tandem connection results in the excitation of a relatively pure high-loss TE_{11}^{HX} mode which, in turn, scatters almost all of its energy into the low-loss TM_{11}^{DL} mode as indicated by the reflectometer trace in Fig. 2. The trace in both the HX and DL sections is smooth and free of large oscillations which would be present if other modes were strongly excited. The slope of the trace in Fig. 2 may then be used to determine the loss of the TE_{11}^{HX} or TM_{11}^{DL} mode.

On the other hand, the Cu-DL arrangement results in the excitation of both the TM_{11}^{DL} and TE_{11}^{DL} modes, which leads to the oscillatory trace of Fig. 3. The period of the oscillation in Fig. 3 is one-half of the beat wavelength (λ_B) between the TE_{11}^{DL} and the TM_{11}^{DL} modes, where λ_B is defined as

$$\lambda_B \equiv |2\pi/(h_{TE_{11}^{DL}} - h_{TM_{11}^{DL}})|. \tag{2}$$

h is the phase constant for the modes. For a 51-mm guide with a 200-μm-thick polyethylene lining, the analytic prediction for the $TM_{11}^{DL} - TE_{11}^{DL}$ beat wavelength at 68 GHz is 0.38 m as compared to the experimental value of 0.36 m for the trace in Fig. 3. Note that the relative magnitude of the oscillation is decaying rapidly as the piston travels down the DL section (the TE_{11}^{DL} mode has very high loss) and thus we could use the slope of the average value of the reflected signal in Fig. 3 (the dashed curve) to obtain the TM_{11}^{DL} loss.

The test set in Fig. 1 may be modified in a simple fashion to obtain

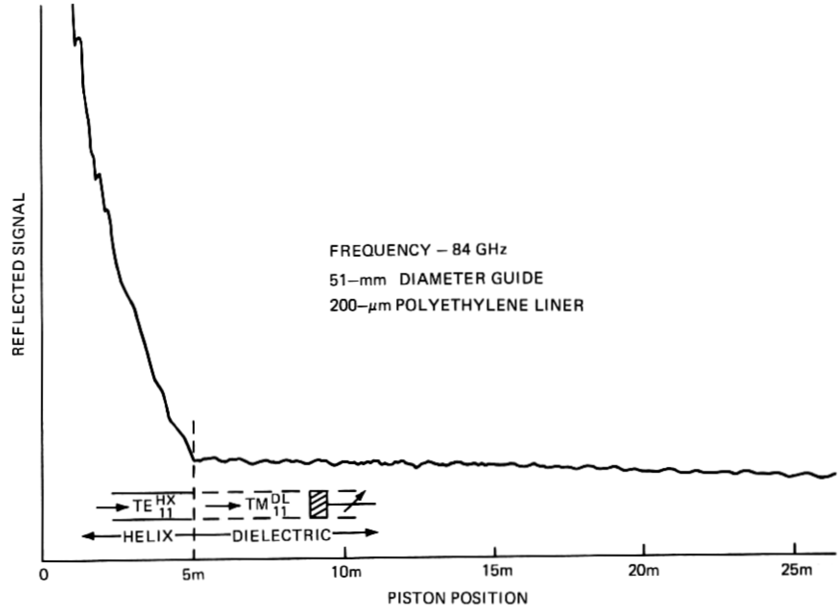

Fig. 2—Returned signal vs piston position for the helix-dielectric guide system, TM_{11}^{DL} loss measurement.

the differential propagation constant ($\Delta\beta$) defined in (1) for the TE_{01}^{DL} and TM_{11}^{DL} modes. On introduction of a small deliberate tilt at the Cu-HX interface (as shown in Fig. 1), the TE_{11}^{Cu} mode excites the

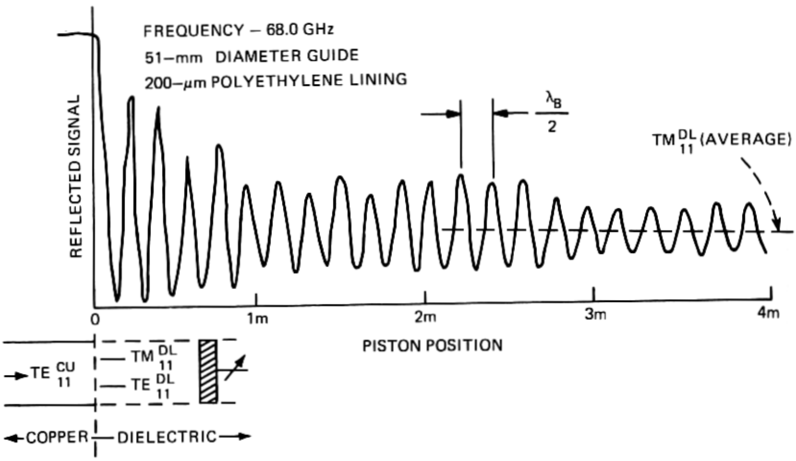

Fig. 3—Returned signal vs piston position for the copper-dielectric system, TM_{11}^{DL} loss measurement.

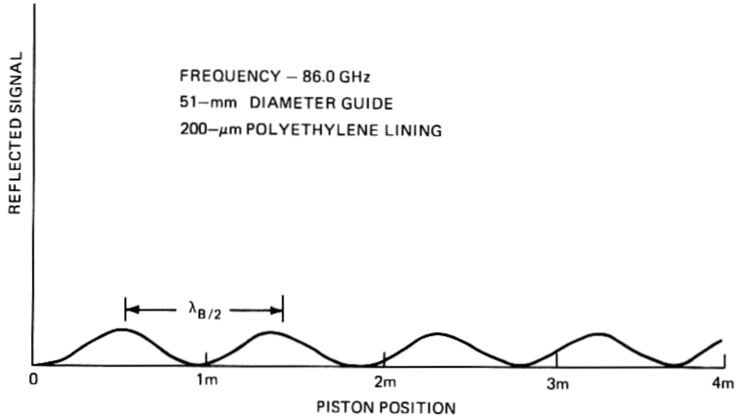

Fig. 4—Returned signal vs piston position for the helix-dielectric guide system with a deliberate tilt, $TM_{11}^{DL} - TE_{01}^{DL}$ differential phase $\Delta\beta$.

TE_{11}^{HX} and TE_{01}^{HX} modes and subsequently the TM_{11}^{DL} and TE_{01}^{DL} modes. The beat wavelength (λ_B) between the TE_{01}^{DL} and TM_{11}^{DL} modes is then twice the period of the oscillations of the moving piston trace shown in Fig. 4. The differential propagation constant $\Delta\beta$ is now related to the beat wavelength λ_B

$$\Delta\beta = 2\pi/\lambda_B. \tag{3}$$

III. RESULTS

By making the moving piston runs described above at different frequencies, it was possible to infer the loss and $\Delta\beta$ vs frequency characteristics of different waveguide samples. Figures 5 and 6 are the loss and phase characteristics obtained for the TE_{11}^{Cu} mode in a 20-m-long sample of copper waveguide. Here, the 51-mm diameter copper output taper can be connected directly to the 20-m sample of 51-mm diameter guide. This arrangement excites both the desired TE_{11}^{Cu} mode and a small amount of TM_{11}^{Cu} (−13 dB down) due to $TE_{11}^{Cu} - TM_{11}^{Cu}$ mode conversion in the taper. It was found that the undesired TM_{11}^{Cu} mode could be lowered to approximately 15 dB under the TE_{11}^{Cu} level by placing a 5-m length of helix waveguide between the taper and the 20-m sample of copper guide, and thus this configuration was used.

The TE_{11}^{Cu} measured loss appears to be 15 percent larger on the average than the theoretical prediction for the TE_{11}^{Cu} loss in perfectly straight and smooth copper guide. This increase is similar to that observed in dominant-mode rectangular guide[5] and to the measured

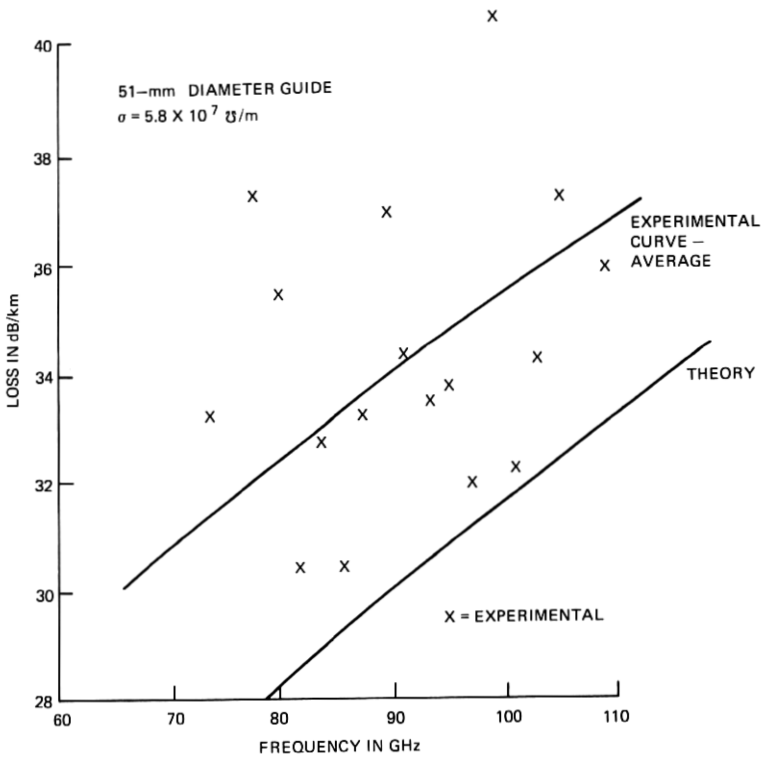

Fig. 5—TE_{11}^{Cu} loss vs frequency.

TE_{01}[6] copper loss in 51-mm copper waveguide and has been attributed to surface imperfections. The individual data points in Fig. 5 are accurate to within ± 10 percent, which accounts for the ± 4-dB spread about the average. The accuracy of the above CW measurement technique could be improved if a better taper were available. $\Delta\beta(TE_{11}^{Cu} - TE_{01}^{Cu})$ also agrees well with the theoretical value as shown in Fig. 6. The experimental points differ by < 3 percent from the theoretical curve. In summary, the method used yields experimental data in good agreement with the theoretical predictions for the attenuation and differential phase characteristics of the TE_{11}^{Cu} mode.

Figures 7 and 8 are comparisons of the experimental results for the TM_{11}^{DL} loss and differential phase constant, $\Delta\beta(TM_{11}^{DL} - TE_{01}^{DL})$, in dielectric-lined guide with the theoretical predictions obtained using the methods outlined in Carlin and D'Agostino.[3] The copper walls were assumed to have an effective 15-percent increase in loss due to the

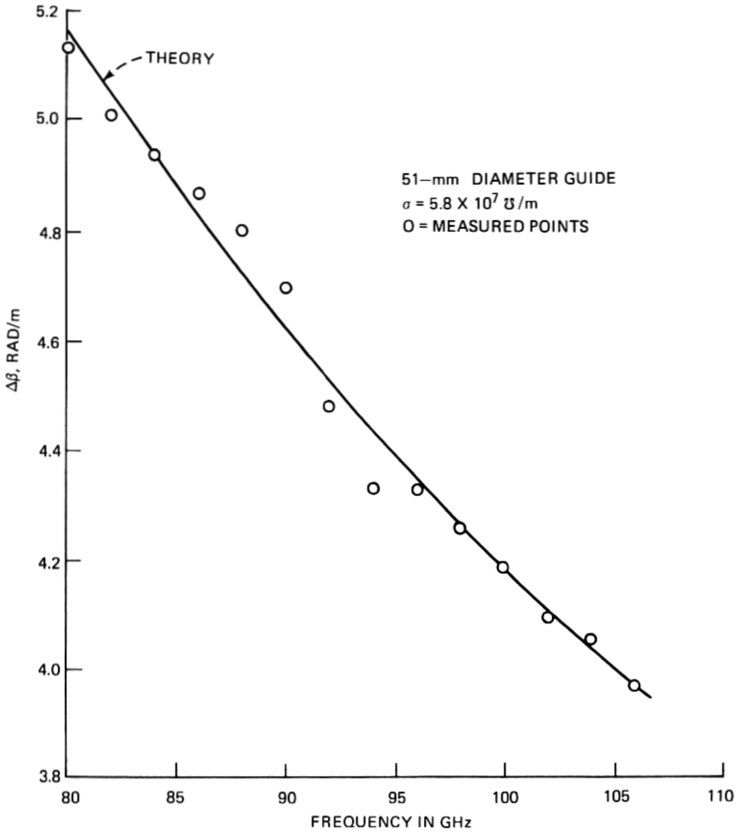

Fig. 6—$TE_{11}^{Cu} - TE_{01}^{Cu}$ differential phase $\Delta\beta$ vs frequency.

effects of surface imperfections. The actual waveguide tested had an adhesive layer of Hydropol* of thickness 12.5 μm to which a 200-μm layer of polyethylene was bonded. The electrical properties (dielectric constant, ϵ_r, and loss tangent, tan δ) of the Hydropol and polyethylene layers were measured[7] at 70 GHz and found to be

	Polyethylene	Hydropol
ϵ_r	2.28	2.5
tan δ	10^{-3}	1.4×10^{-3}

These values were used in obtaining the theoretical heat loss. A sample 30 m in length was used in the measurement of the TM_{11}^{DL} loss and differential propagation constant.

* Partially hydrogenated polybutediene manufactured by Phillips Petroleum Co.

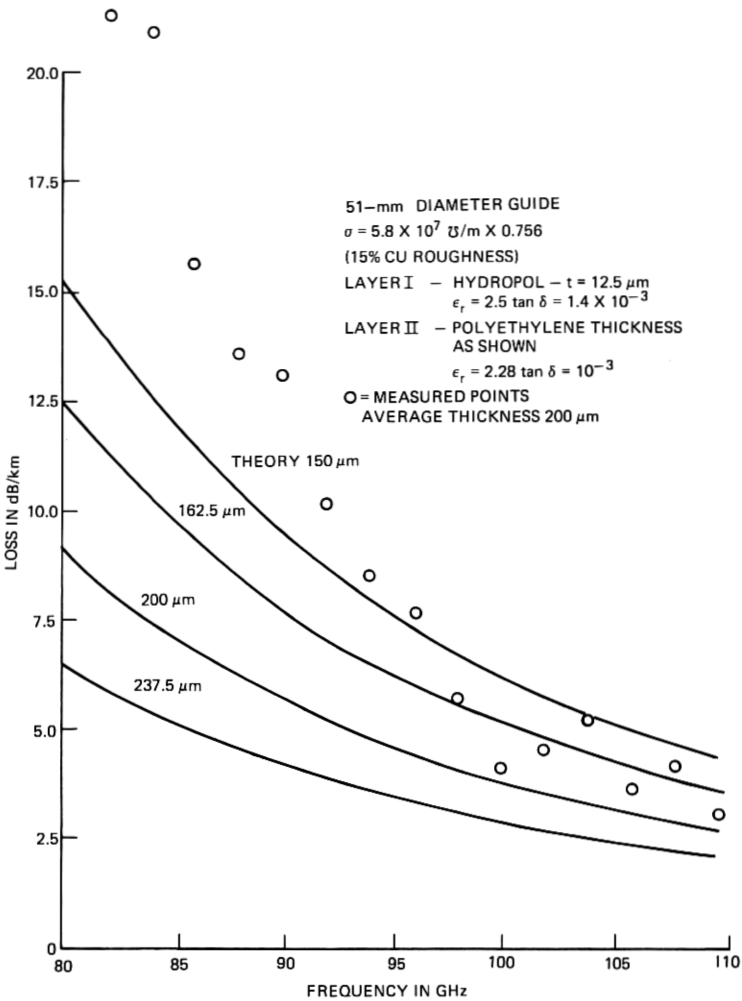

Fig. 7—TM_{11}^{DL} loss vs frequency.

The qualitative behavior of the TM_{11}^{DL} loss, decreasing with increasing frequency, is in good agreement with the theoretical prediction. The measurement accuracy is approximately $\pm$ 10 percent at the lower frequencies (80 to 90 GHz) and $\pm$20 percent at the higher frequencies (100 to 110 GHz). The quantitative agreement is also good from 100 to 110 GHz. The discrepancy at the lower frequencies (80 to 100 GHz) is probably due to the fact that the lining thickness is not a uniform 12.5 μm or 200 μm for the dielectric layers as assumed in

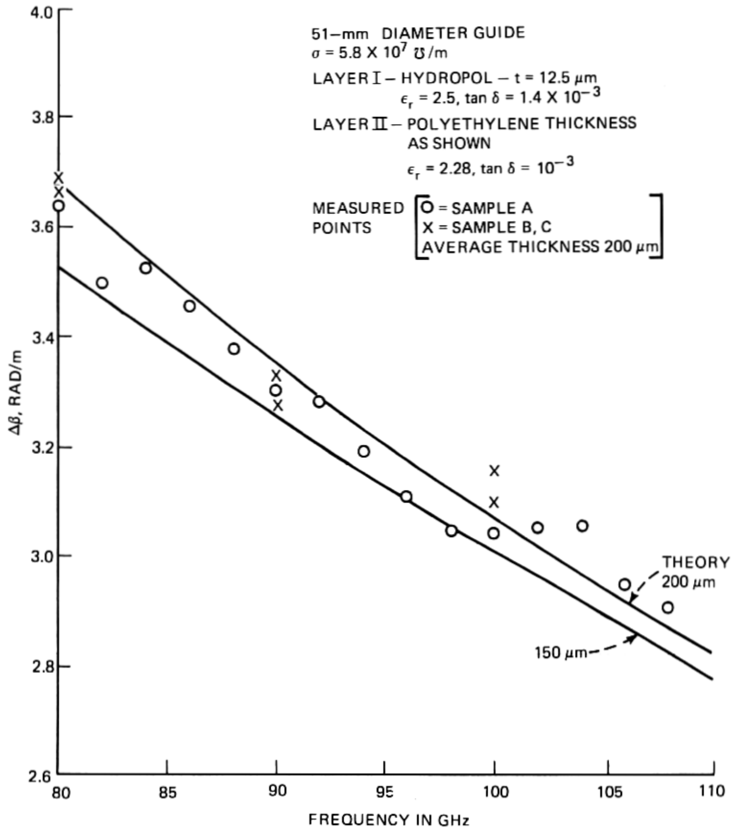

Fig. 8—$TM_{11}^{DL} - TE_{01}^{DL}$ differential phase $\Delta\beta$ vs frequency.

the theoretical models. This has two effects:

(*i*) The total heat loss as shown in Fig. 7 as well as the losses in the various layers and the copper walls is strongly dependent on the thickness of the dielectric layers. A liner with an "average" thickness of 200 μm would have an "average" heat loss higher than that expected for a smooth 200-μm liner, as the loss increased more rapidly for a decrease in lining thickness than vice versa, as seen in Fig. 7.

(*ii*) The field structure of the TM_{11}^{DL} mode fluctuates more rapidly and interacts with fluctuations in lining thickness to a greater degree as the frequency decreases. This is intuitively reasonable from the plots of the TM_{11}^{DL} mode energy density over the guide cross section as given in Carlin and D'Agostino.[3] There the energy density at the air-dielectric interface in dielectric-lined guide decreases as frequency is increased for a fixed lining thickness, or alternatively decreases as lining thickness is increased for a fixed frequency. This suggests that mode conversion losses for the TM_{11}^{DL} mode arising from lining thickness fluctuations increase with decreasing frequency in dielectric-lined guide. A more quantitative investigation of this effect is beyond the scope of this paper.

The measured differential phase constant ($\Delta\beta$) is in excellent agreement with the theoretical prediction as shown in Fig. 8. This is further confirmation of the fact that the launching arrangement in Fig. 1 does indeed excite the TM_{11}^{DL} mode in dielectric-lined guide.

II. CONCLUSION

In summary, it has been confirmed experimentally that the TM_{11}^{DL} dielectric-lined waveguide mode is a mode which has an attenuation constant which decreases with increasing frequency, thus confirming qualitatively the behavior predicted by theory.[1–3] The measured values ($\approx$ 3.75 dB/km) are approximately 30 percent greater than the theoretical predictions from 100 to 110 GHz. At 80 GHz, the measured value (23 dB/km) is approximately 2.5 times larger than the theoretical prediction. The large discrepancy at the lower frequencies is probably due to $TM_{11}^{DL} - TE_{11}^{DL}$ mode conversion losses arising from fluctuations in the lining thickness.

V. ACKNOWLEDGMENT

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