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DIELECTRIC MILLIMETER WAVEGUIDES

University of California

Cavour Yeh

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This report summarizes the result of the research carried out for the Postdoctoral Task E-6-7108 administered by the University of Dayton under contract F30602-81-C-0206 with RADC. The primary objectives of this research program were to learn whether there exists a dielectric waveguide configuration which offers lower loss figure than a circular dielectric rod and to establish an experimental technique to measure the guiding characteristics of waves on dielectric structures. These objectives were met. Future research areas are also described in this report.

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Acknowledgment

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I. Introduction

This is a final report on a study sponsored by RADC through the Post Doctoral Program (Task E-6-7108, Contract F30602-81-C-0206) administered through the University of Dayton) from June 24, 1986 through October 30, 1986. The principal objectives of this research were to learn whether there exists a dielectric waveguide configuration which offers lower loss figure than a circular dielectric rod and to establish an experimental technique to measure the guiding characteristics of waves on dielectric structures. This final report gives a summary of our accomplishments during this phase of the research program.

II. Summary of Accomplishments

At millimeter (mm) or sub-millimeter (sub-mm) wavelengths, the usual metallic waveguides become unbearably small and are very difficult to manufacture. Furthermore, insufferably high conduction losses at these frequencies also render these guides less than useful.[1] A new mm or sub-mm waveguiding structure must be found. A viable/practical mm or sub-mm waveguide should possess the following characteristics:[2,3]

- Low loss
- Flexible, may be curved or bent (can turn corners)
- Can be handled easily (this implies reasonable physical size and guided energy must not be affected by outside environment)
- Cost effective (May be manufactured at a reasonable cost)
- Connectors can be made

It appears that the most promising candidate for flexible guide is the dielectric waveguide[4,5] while the most promising candidate for integrated millimeter circuit is the channel or stripline guide.[6] It is envisioned that a new family of mm/sub-mm wave components, such as mixers, couplers, waveguides, attenuators, polarizers, etc. can be made with purely dielectric material. There are two possible ways of realizing a low-loss millimeter/sub-millimeter (mm/sub-mm) waveguide structure: Through the use of low-loss material and/or through the use of specially configured structure. We shall first provide a brief discussion of available low-loss material suitable for guiding mm/sub-mm waves. Then results of a calculation on a specially configured low-loss structure which was the subject for the short-term innovative research, will be presented.

Brief summary of low-loss material

A series of very detailed measurements in the mm/sub-mm wavelength range on the dielectric constant and loss tangent of groups of promising low-loss material have been performed by the MIT 'Mag-Lab' group in recent years.[7] Results of their findings were summarized in a very comprehensive paper by Afsar and Button.[7] Two types of material appear to possess relatively low-loss characteristic in the mm-sub-mm wavelength range: One is a crystalline type material[5] and the other is a polymer type material.[7] A sample list of the commercially available low-loss material is given in the following:

Crystalline material[5]

	Dielectric constant	Loss tangent
Alumina (at 10 GHz)	9.7	2×10^{-4}
Sapphire (at 10 GHz)	9.3-11.7	1×10^{-4}
Quartz (at 10 GHz)	3.8-4.8	10^{-4}
KRS - 5 (at 94.75 GHz)	30.5	1.9×10^{-2}
KRS - 6 (at 94.75 GHz)	28.5	2.3×10^{-2}
$LiNbO_3$ (at 94.75 GHz)	6.7	8×10^{-3}

Polymer material[7]

	Dielectric constant	Loss tangent
Teflon (at 10 GHz) (PTFE)	2.04	2×10^{-4}
Rexolits (at 10 GHz)	2.56	2.6×10^{-3}
RT/duroid 5880 (at 10 GHz)	2.2	9 x 10-4
Polyethylene (at 50 GHz) (LDPE)	2.3	10^{-4}

It can be seen that the polymer material in general has much lower dielectric constant than crystalline material. The best lost-tangent is around 10^{-4}. Using a nominal dielectric constant of 2.0, the attenuation constant for plane wave in this bulk material is 1.3 dB/m at 100 GHz which is already better than the 3 dB/m loss for conventional metallic waveguides at this frequency. The attenuation constant for plane wave is calculated from the following equation:

$$\alpha = 8.686\ (\pi\ \sqrt{\varepsilon}/\lambda_0)\tan\delta\ . \tag{1}$$

Here ε is the relative dielectric constant, λ_0 is the free-space wavelength and $\tan\delta$ is the loss tangent. According to Equation (1), it appears that in addition to requiring as small a loss tangent as possible lower dielectric constant is also helpful in achieving lower loss. Hence, flexible polymers such as LDPE (Polyethylene) and PTFE (Teflon) are the natural choice for the making of low-loss mm/sub-mm waveguides.

Low-loss configurations

Other than the material loss factor which we discussed above, the major factor that may influence the attenuation characteristic of guided wave along a dielectric structure is the size and shape of the waveguide. The attenuation constant for a dielectric waveguide with arbitrary cross-sectional shape and surrounded by free-space is given by the following expression:[8,9]

$$\alpha = 8.686\,\pi\,\tan\delta\left(\frac{\varepsilon}{\lambda_0}\right)R \quad (\mathrm{dB/m}) \tag{2}$$

with

$$R = \left|\frac{\int_{A_i} (\underline{E}\cdot\underline{E}^*)\,dA}{\sqrt{\frac{\mu_0}{\varepsilon_0}}\int_{A} \underline{e}_z\cdot(\underline{E}\times\underline{H}^*)\,dA}\right|\ . \tag{3}$$

Here, ε and $\tan\delta$ are, respectively, the relative dielectric constant and loss-tangent of the dielectric waveguide, λ_0 is the free-space wavelength, ε_0 and μ_0 are, respectively, the permittivity and permeability of free-space, $\underline{e}_z$ is the unit vector in the direction of propagation, A_i is the cross-sectional area of the dielectric structure, A is the total cross-sectional area of the guide, and $\underline{E}$ and $\underline{H}$ are the electric and magnetic field vectors of the guided mode under consideration. The loss factor R which is sensitive to the guide configuration and the frequency of operation could vary from a very small value to $1/\sqrt{\varepsilon}$ which is the case for a plane wave propagating in a dielectric medium with dielectric constant ε . Typical behavior of R as a function of k^2A where k is the free-space wave number and A is the cross-sectional area of the dielectric waveguide, for the dominant mode is shown in Figure 1. It is seen that if the propagating mode is somewhat loosely bounded to the guiding structure, i.e., if k^2A is small, the attenuation factor R can be made quite small giving rise to a significantly lower attenuation constant α.

The objective of the short-term innovative research program is to perform calculation for the attenuation factor R for a number of flattened low-loss structures using the finite-element method. Results of our calculation are shown in Fig. 1 in which the attenuation factors R for the dominant ${}_eHE_{11}$ mode along a flattened dielectric waveguide as a function of the normalized cross-sectional area for various values of (major-axis/minor-axis) ratios, are displayed. It can be seen that for the same cross-sectional area the flatter dielectric structure yields significantly lower loss for the dominant ${}_eHE_{11}$ mode. This evidence points to the advantage of using flattened dielectric structure rather than the usual circular dielectric rod, to achieve low loss factor for the dominant mode. Since the guided field extends beyond the core region of the guide it is important to learn the field extent of the guided mode. We have performed such calculation for the flattened guides. Results are shown in Fig. 2.

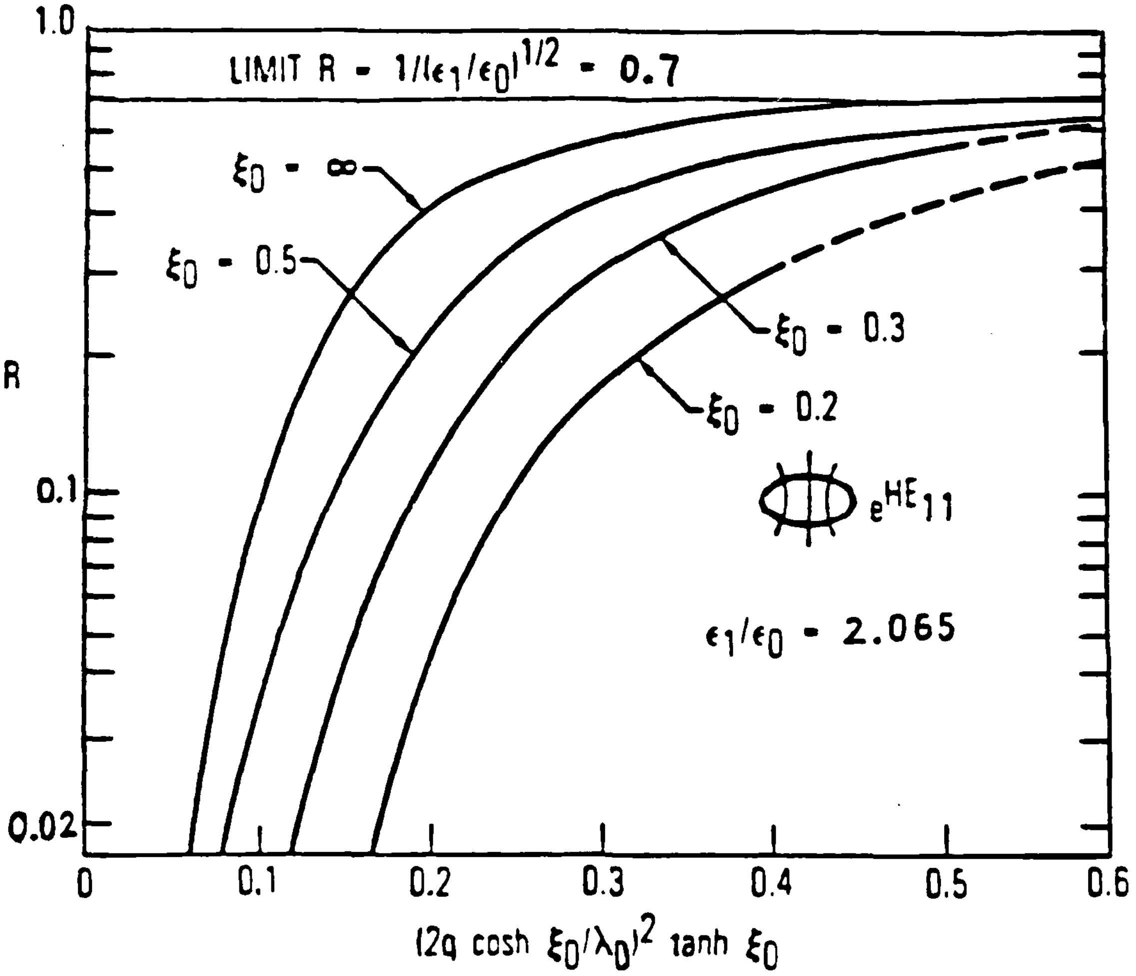

Fig. 1. Attenuation factor R for the $_e\mathrm{HE}_{11}$ wave as a function of normalized cross-sectional area of an equivalent ellipse; $\tanh \xi_o = b/a$, where a is the semi-major axis, b is the semi-minor axis and q is the semi-focal distance of the ellipse.

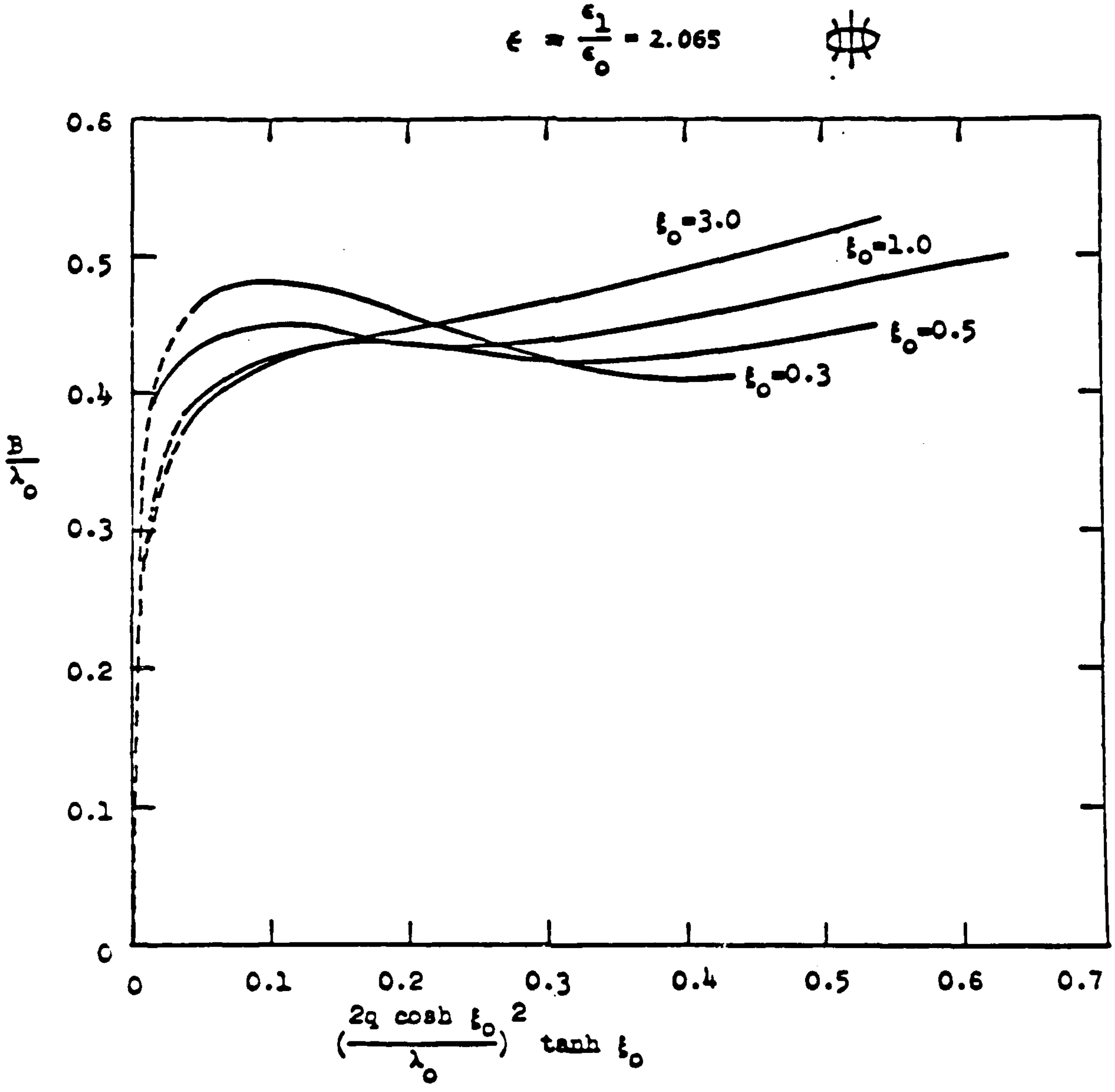

Fig. 2 Normalized axial electric field extent B/λ_o as a function of normalized cross-sectional area for the ${}_eHE_{11}$ mode . B is the distance measured from the origin to the point of observation where $(E_z/E_{z_o})^2 = 0.1$

One notes that the field extent as measured from the center of the guide is relatively insensitive to the flatness of the guide. This means no sacrifice in having larger field extent is necessary in order to achieve lower loss factor by using flatter guides.

Let us now consider a specific numerical example: Using Teflon (with $\epsilon = 2.065$ and $\tan\delta = 2 \times 10^{-4}$) as the dielectric waveguide material, the dimensions of a typical low-loss guiding structure for a 94 GHz signal can be

$$2a = 2.4 \text{ mm}$$

$$2b = 0.8 \text{ mm}.$$

At 94 GHz, the calculated loss factor R for a 3:1 (Major: Minor axis ratio) flattened guide supporting the dominant ${}_{e}HE_{11}$ mode is 0.06, while R for an equivalent circular guide (with the same cross-sectional area) supporting the dominant HE_{11} mode is 0.4. So, the ratio of the attenuation constant for these two structures is

$$\alpha_{\text{flattened guide}} / \alpha_{\text{circular guide}} = 0.15.$$

This numerical example clearly demonstrates the importance in the choice of guiding configuration to obtain low-loss guidance.

The Post Doctoral program provided us with the opportunity to perform analysis to confirm this initial observation.

Experimental Setup

This basic experimental arrangement is shown in Fig. 3. This setup will yield detailed information on the guided wave along a dielectric structure, such as the field decay characteristics, propagation constants, mode configurations, etc. The output of a signal source modulated with 1 KHz square wave is connected to an isolator followed by an attenuator, a frequency meter, a coupling section, the dielectric waveguide, and an appropriate termination. Two ways of terminating the dielectric waveguide may be considered: one consisting of a flat reflecting plate which reflects all of the guided power and sets up a strong standing wave

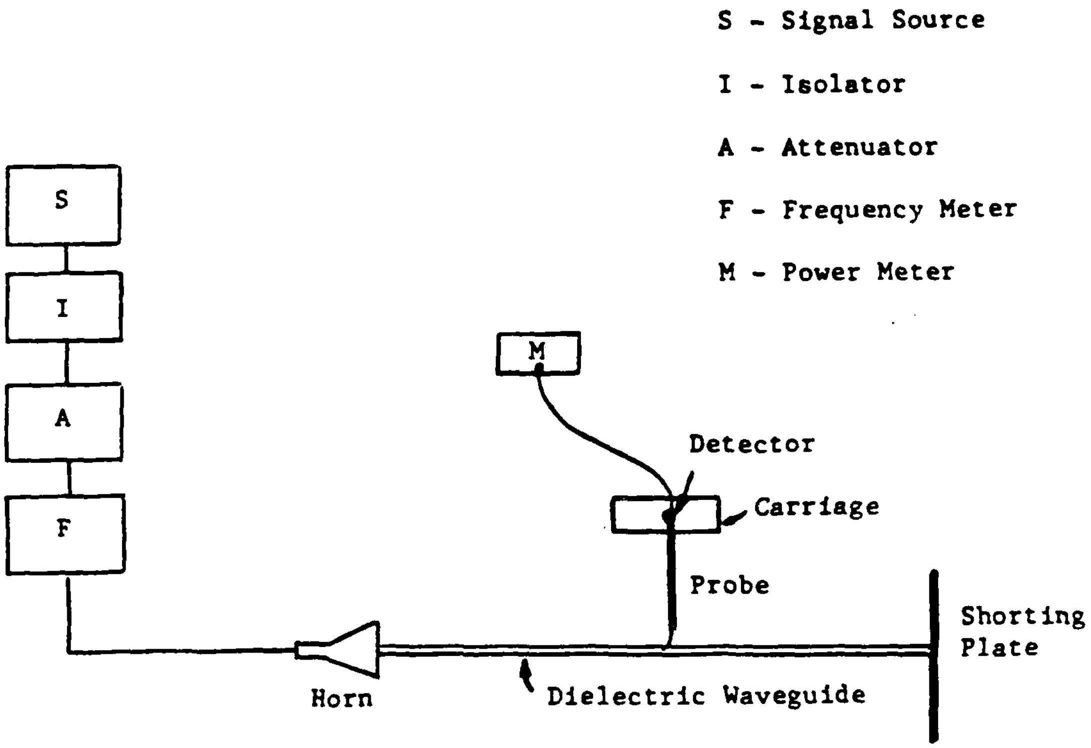

Figure 3(a). Schematic Diagram for the Experimental Setup.

Figure 3(b). Picture of the Experimental Setup.

on the dielectric guide, while the other consisting of a low-reflection coupling section terminated into a matched load with a Schottky detector. The standing wave set up by the reflecting plate can be measured to yield information on guide wavelength and attenuation factor. A picture of the setup is shown in Fig. 3(b).

As a demonstration, this experimental setup was used to measure the guide wavelength of the dominant HE_{11} mode on a circular Teflon guide. Measured date are shown in Fig.4. Also plotted in the figure are the calculated results. Excellent agreement was achieved. One may also measure the attenuation factor R for a dielectric waveguide using this setup. Verification with the calculated results for the circular dielectric guide can provide us with the confidence to perform measurements on non-circular low loss dielectric guiding structures. Performance merits in terms of attenuation, bending loss, propagation constant, field extent, mode stability, polarization preserving characteristics and ease of handling, can now be studied and compared with our theoretical results.

III. Future Research Areas

Having shown that there exists a configuration which may yield lower loss factor than a circular dielectric rod and having established a mm wave experimental setup, we are now in a position to propose additional research tasks as follows:

Verify experimentally the findings of the Post Doctoral research program.

Study the effects of shielding the low-loss structure by a layer of dielectric sheath as shown in Fig. 5.

Study the effects of curvature and explore ways to minimize bending losses.

Explore and study compatible waveguide components such as dielectric waveguide couplers, filters, branches, phase shifters, polarizers, horns, attenuators, mode converters, etc.

Study ways to improve the loss-tangent of guiding materials.

Investigate ways to manufacture these non-circular dielectric waveguides.

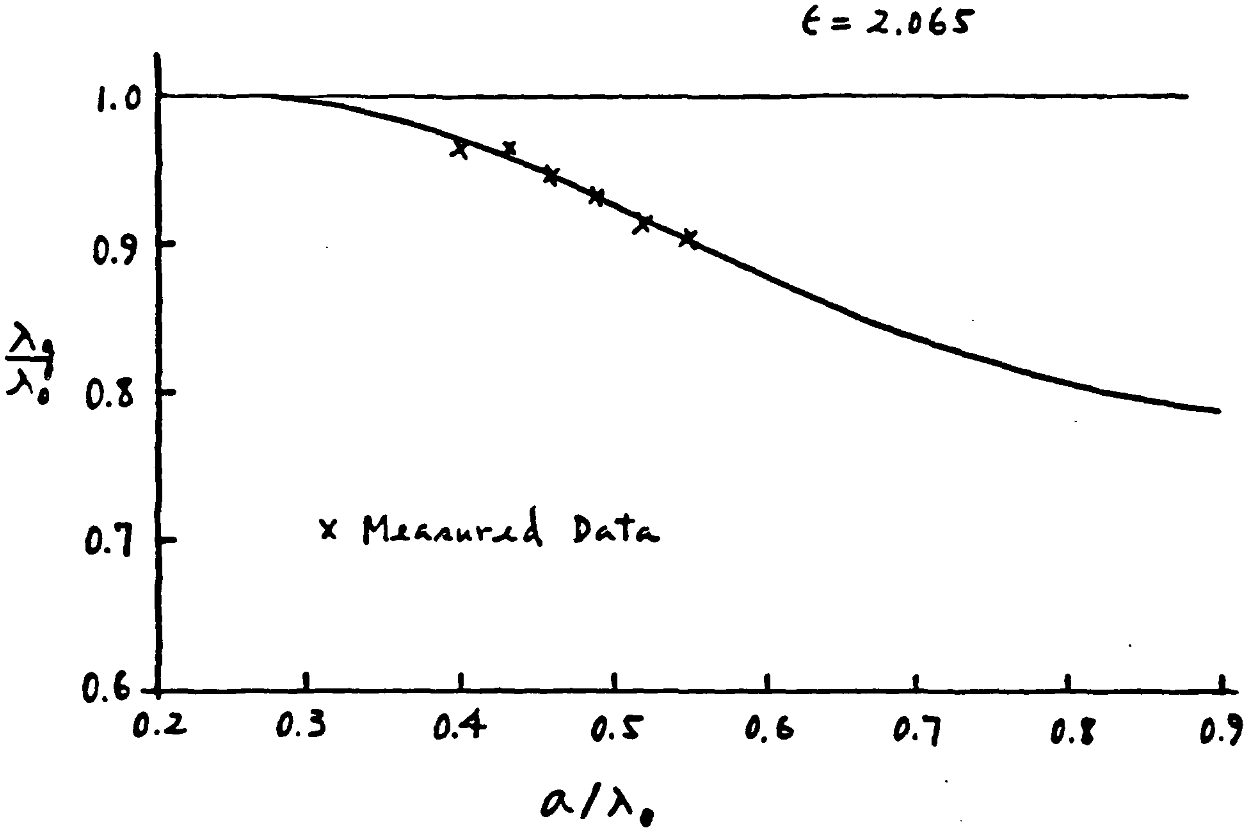

Fig. 4. Comparison of the measured data with theoretical data for a circular Teflon guide supporting the dominant HE_{11} mode. Measurements were made in the 30 GHz range.

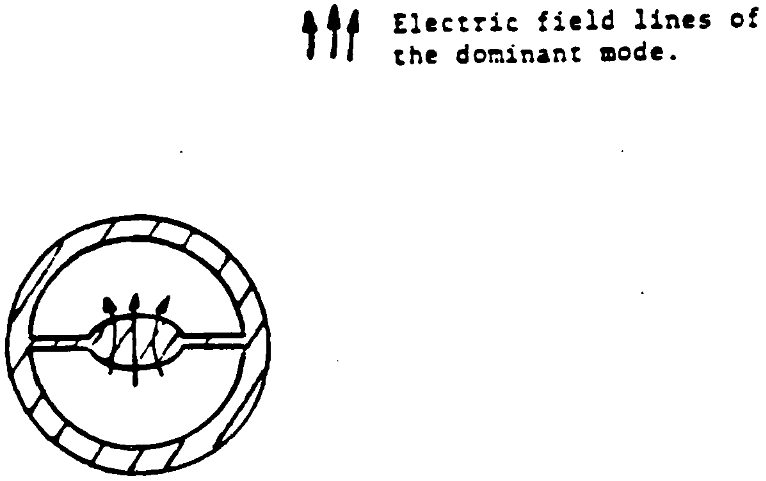

Figure 5. The Proposed Shielded Low-Loss MM Wave Dielectric Waveguide.

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