

RADC-TR-88-32, Vol I (of two)
Final Technical Report
March 1988



AD-A196 844

DTIC FILE COPY

DIELECTRIC MILLIMETER WAVEGUIDES

University of California

Cavour Yeh

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

This effort was funded totally by the Laboratory Director's fund.

**ROME AIR DEVELOPMENT CENTER
Air Force Systems Command
Griffiss Air Force Base, NY 13441-5700**

**DTIC
ELECTE
MAY 25 1988
S E D**

88 5 20 069

This report has been reviewed by the RADC Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be releasable to the general public, including foreign nations.

RADC-TR-88-32, Vol I (of two) has been reviewed and is approved for publication.

APPROVED:



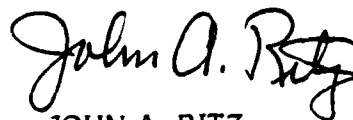
JAMES C. SETHARES
Project Engineer

APPROVED:



JOHN K. SCHINDLER
Acting Director of Electromagnetics

FOR THE COMMANDER:



JOHN A. RITZ
Directorate of Plans and Programs


If your address has changed or if you wish to be removed from the RADC mailing list, or if the addressee is no longer employed by your organization, please notify RADC (EEAC) Hanscom AFB MA 01731-5000. This will assist us in maintaining a current mailing list.

Do not return copies of this report unless contractual obligations or notices on a specific document requires that it be returned.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED			1b. RESTRICTIVE MARKINGS N/A		
2a. SECURITY CLASSIFICATION AUTHORITY N/A			3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.		
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE N/A					
4. PERFORMING ORGANIZATION REPORT NUMBER(S) N/A			5. MONITORING ORGANIZATION REPORT NUMBER(S) RADC-TR-88-32. Vol I (of two)		
6a. NAME OF PERFORMING ORGANIZATION University of California Dept of E. E.		6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION Rome Air Development Center (EEAC)		
6c. ADDRESS (City, State, and ZIP Code) 7732 Boelter Hall Los Angeles CA 90024			7b. ADDRESS (City, State, and ZIP Code) Hanscom AFB MA 01731-5000		
8a. NAME OF FUNDING/SPONSORING ORGANIZATION Rome Air Development Center		8b. OFFICE SYMBOL (If applicable) EEAC	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER F30602-81-C-0206		
8c. ADDRESS (City, State and ZIP Code) Hanscom AFB MA 01731-5000			10. SOURCE OF FUNDING NUMBERS		
			PROGRAM ELEMENT NO. 61101F	PROJECT NO. LDFP	TASK NO. 03
					WORK UNIT ACCESSION NO. P6
11. TITLE (Include Security Classification) DIELECTRIC MILLIMETER WAVEGUIDES					
12. PERSONAL AUTHOR(S) Cavour Yeh					
13a. TYPE OF REPORT Final		13b. TIME COVERED FROM Mar 86 to Feb 87		14. DATE OF REPORT (Year, Month, Day) March 1988	
15. PAGE COUNT 24					
16. SUPPLEMENTARY NOTES Proj I.D.: Dielectric Mill Waveguide - I, UCLA; Dielectric Mill Waveguide - II, Univ of Texas This effort was funded totally by the Laboratory Director's funds.					
17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)		
FIELD	GROUP	SUB-GROUP			
17			Dielectric Waveguides Millimeter Waves		
19. ABSTRACT (Continue on reverse if necessary and identify by block number) 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.					
20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS			21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED		
22a. NAME OF RESPONSIBLE INDIVIDUAL JAMES C. SETHARES			22b. TELEPHONE (Include Area Code) (617) 377-4663		22c. OFFICE SYMBOL RADC (EEAC)

DD Form 1473, JUN 86

Previous editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED

Table of Contents

Acknowledgment

I. Introduction.....	1
II. Summary of Accomplishments.....	1
III. Future Research Areas.....	9
IV. Personnel.....	12
References.....	13

Accession For	
NTIS GRA&I	☒
DTIC TAB	☐
Unannounced	☐
Justification	
By _____	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A-1	



Acknowledgment

The author wishes to thank Jim Sethares for his careful monitoring of and his interest in this project. His encouragement is also gratefully acknowledged.

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, at-

tenuators, 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 material⁵ 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 material⁵

	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 material⁷

	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	9×10^{-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 loss-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:

$$\alpha = 8.686 (\pi \sqrt{\epsilon}/\lambda_0) \tan\delta \quad (1)$$

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}

$$\alpha = 8.686 \pi \tan\delta \left(\frac{\epsilon}{\lambda_0} \right) R \quad (\text{dB}/\pi) \quad (2)$$

with

$$R = \left| \frac{\int_{A_i} (\underline{E} \cdot \underline{E}^*) dA}{\sqrt{\frac{\mu_0}{\epsilon_0}} \int_A \underline{e}_z \cdot (\underline{E} \times \underline{H}^*) dA} \right| \quad (3)$$

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 $1/\sqrt{\epsilon}$ 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 ${}^e\text{HE}_{11}$ 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 ${}^e\text{HE}_{11}$ 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.

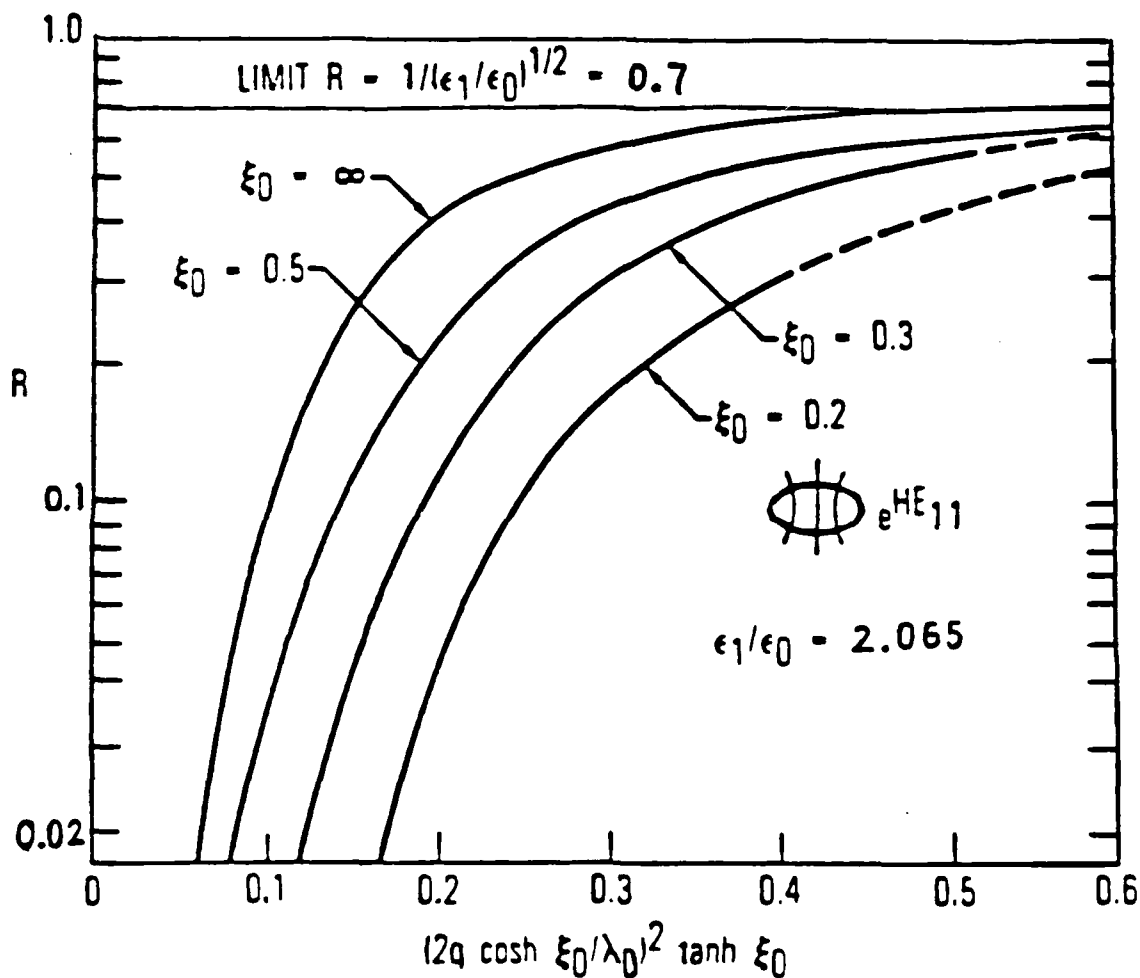


Fig. 1. Attenuation factor R for the eHE_{11} wave as a function of normalized cross-sectional area of an equivalent ellipse; $\tanh \xi_0 = b/a$, where a is the semi-major axis, b is the semi-minor axis and q is the semi-focal distance of the ellipse.

$$\epsilon = \frac{\epsilon_1}{\epsilon_0} = 2.065$$

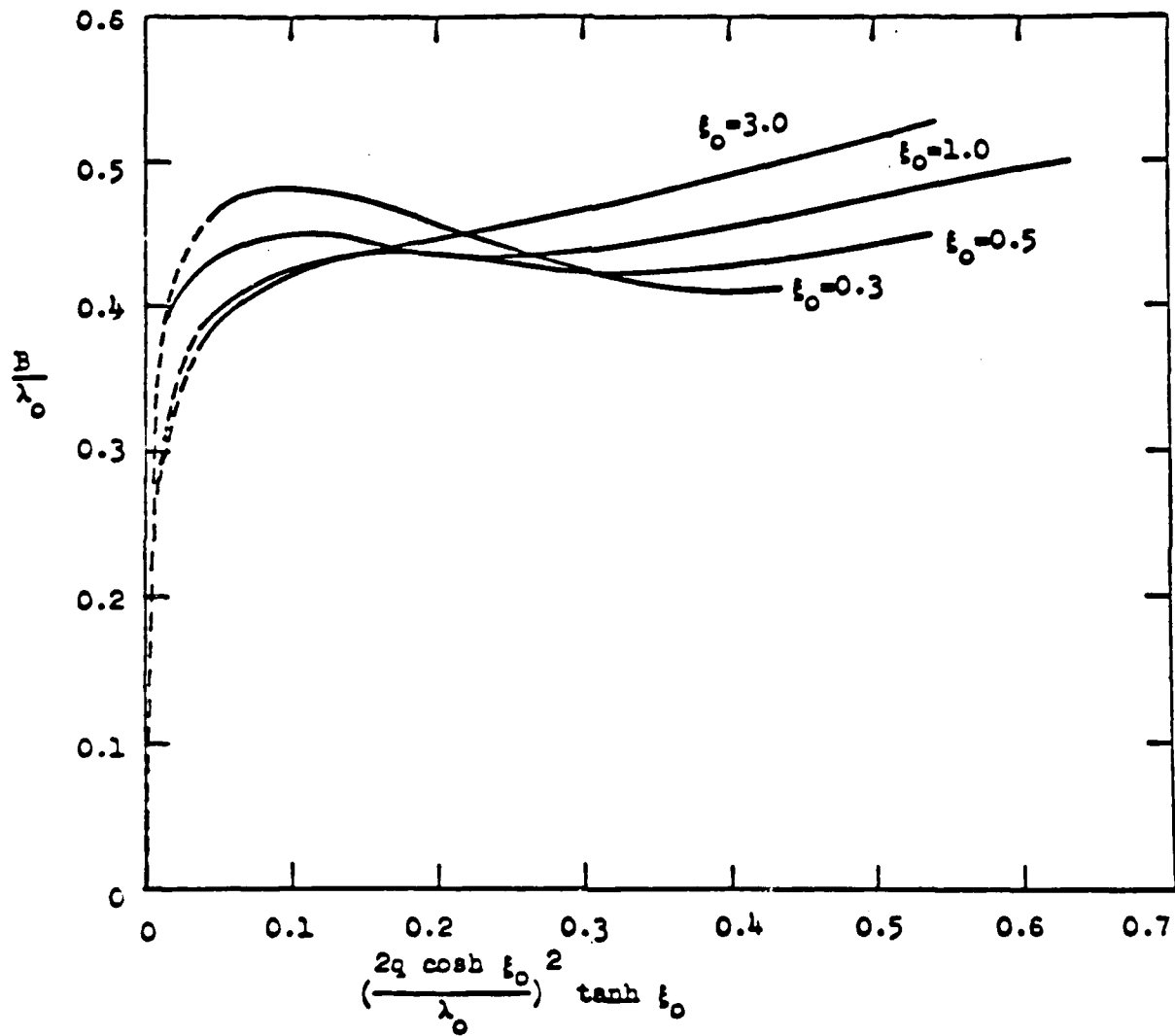


Fig. 2 Normalized axial electric field extent B/λ_0 as a function of normalized cross-sectional area for the HE_{11} mode. B is the distance measured from the origin to the point of observation where $(E_z/E_{z_0})^2 = 0.1$

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 ${}_{\text{e}}\text{HE}_{11}$ 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

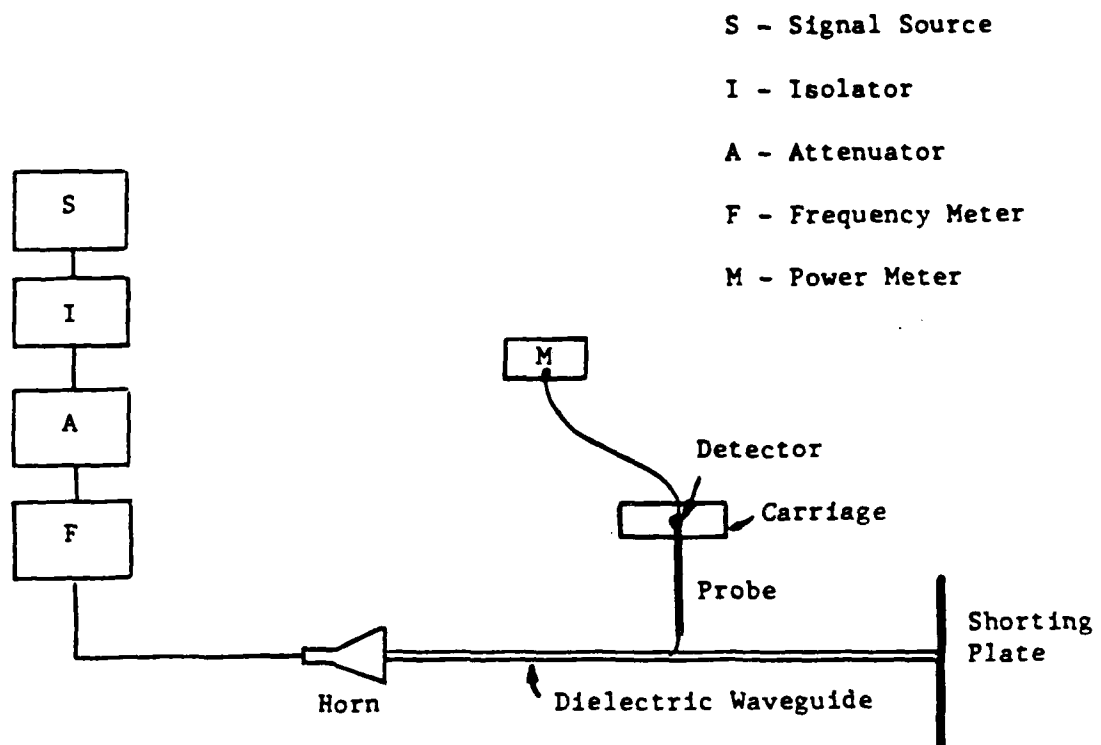


Figure 3(a). Schematic Diagram for the Experimental Setup.

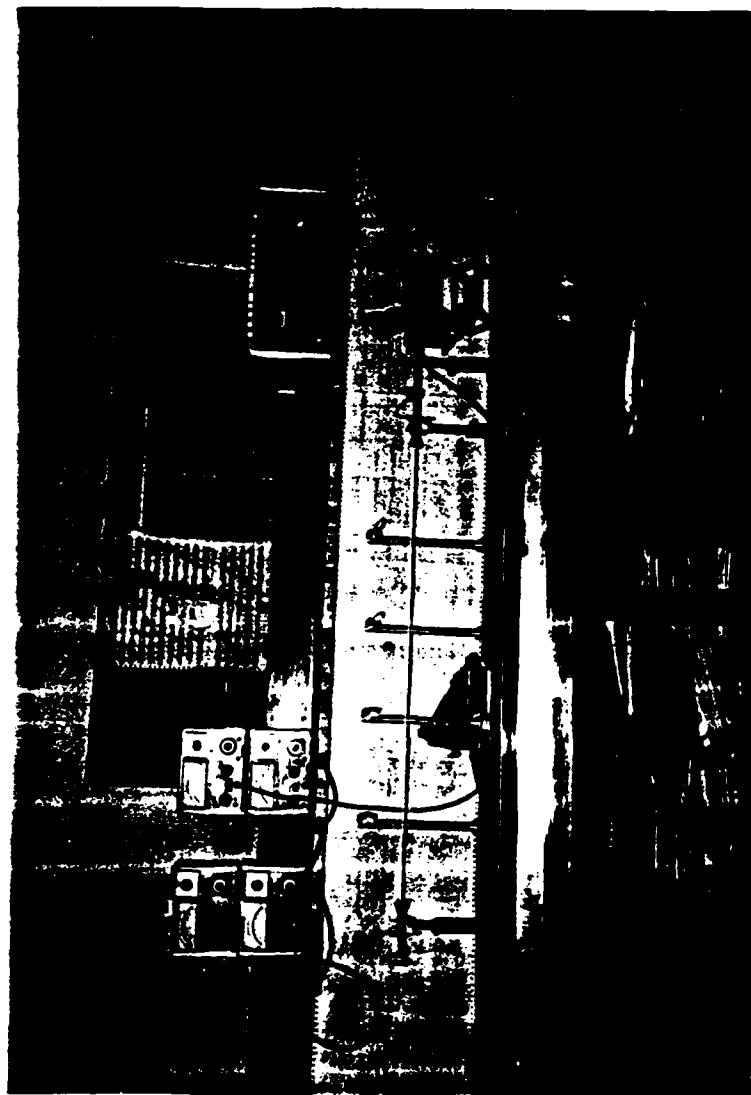


Figure 3(b). Picture of the Experimental Setup.

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 data 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.

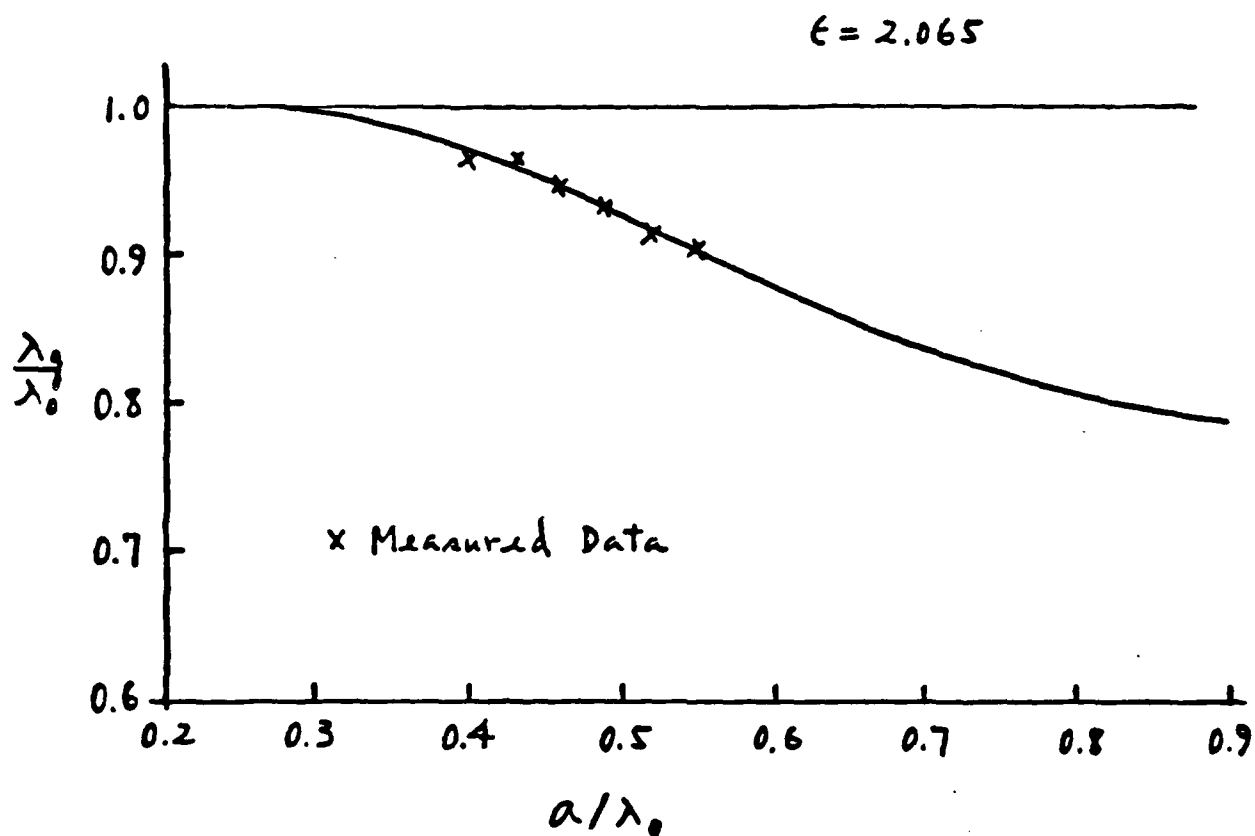


Fig. 4. Comparison of the measured data with theoretical data for a circular Teflon guide supporting the dominant HE_{11} mode. Measurements were made in the 30 GHz range.

↑↑↑ Electric field lines of
the dominant mode.

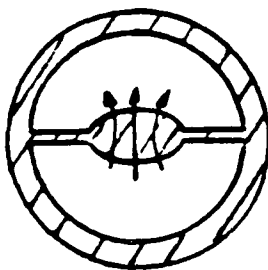


Figure 5. The Proposed Shielded Low-Loss MM Wave Dielectric Waveguide.

IV. Personnel

Principal Investigator:

Cavour Yeh (Senior Engineer)

Other Research Personnel

V. Casey (Engineer)

J. Brown (Engineer)

E. MacDonald (Laboratory Technician)

References

1. T. Yoneyama and S. Nishida, "Nonradiative dielectric waveguide for millimeter-wave integrated circuits," IEEE Trans. on Microwave Theory and Tech., MTT-29, pp. 1182-1192 (1981).
2. J. F. Miao and T. Itoh, "Hollow Image Guides and Overlayed Image Guides Coupler", IEEE Trans. on Microwave Theory and Tech. MTT-30, pp. 1826-1931 (1982).
3. S. T. Peng and A. A. Oliner, "Guidance and leakage properties of a class of open dielectric waveguides: Part I-Mathematical formulations," IEEE Trans. on Microwave Theory and Tech, MTT-29, pp. 834-854 (1981).
4. K. Yamamoto, "A novel low loss dielectric waveguide for millimeter and sub-millimeter wavelength," IEEE Trans. on MTT, MTT-28, pp. 580-584 (1980).
5. William B. Bridges, "Low loss flexible dielectric waveguide for millimeter wave transmission and its application to devices," California Institute of Technology, Report #SRO-005-1 and #SRO-005-2 (1979-1982); William B. Bridges, Marvin B. Kline and Edgard Schweig, IEEE Trans. on MTT, MTT-30, pp. 286-292 (1982).
6. R. Rudokas and T. Itoh, "Passive millimeter-wave IC components made of inverted strip dielectric waveguides", IEEE Trans. on MTT, MTT-29, pp. 978-981 (1976).
7. M. N. Afsar and K. J. Button, "Millimeter-Wave dielectric Measurement of Materials", Proc. IEEE-73, pp. 131-153 (1985); R. Birch, J. D. Dromey and J. Lisurf, "The optical constants of some common low-loss polymers between 4 and 40 cm^{-1} ". Infrared Physics Vol. 21, pp. 225-228 (1981).
8. C. Yeh, "Attenuation in a dielectric elliptical cylinder", IEEE Trans. on Antennas and Propagation, Vol. AP-11, pp. 177-184 (1963).
9. C. Yeh, "Elliptical dielectric waveguides," J. Appl. Phys. Vol. 33, pp. 3235-3243 (1962).