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Dielectric Property Measurements in the Electromagnetic Properties Measurement Laboratory

Robin L. Cravey
Langley Research Center, Hampton, Virginia

Pacita I. Tiemsin
Joint Research Programs Office
Command/Control and Systems Integration Directorate
U.S. Army Communications Electronics Command
Langley Research Center, Hampton, Virginia

Kerri Bussell
Old Dominion University, Norfolk, Virginia

Kenneth L. Dudley
Langley Research Center, Hampton, Virginia

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National Aeronautics and
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Langley Research Center
Hampton, Virginia 23681-0001

Introduction

The capability to measure the dielectric properties of various materials has been developed in the Electromagnetic Properties Measurement Laboratory (EPML) of the Electromagnetics Research Branch (ERB). Two measurement techniques which have been implemented in the EPML to characterize materials are the dielectric probe and waveguide techniques. Several materials, including some for which the dielectric properties are well known, have been measured in an attempt to establish the capabilities of the EPML in determining dielectric properties. Brief descriptions of the two techniques are presented in this report, along with representative results obtained during these measurements.

Description of Measurement Techniques

Measurement of complex permittivity, a property of dielectric or absorptive materials, has gained increasing importance with the expanding use of the radio frequency (RF) and microwave spectrum. There are numerous methods for making these measurements, including the coaxial dielectric probe technique and the transmission line technique (of which the rectangular waveguide technique is an example). These techniques are briefly described below.

Coaxial Probe Technique

The open-ended coaxial probe is essentially a cut-off section of transmission line. The material is measured by touching the flat face of the probe to the material under test (MUT) or immersing it if the MUT is a liquid (Figure 1). The fields at the end of the probe "fringe" into the material and change as they come in contact with the material (Figure 2). Permittivity can be computed from the measured reflected signal.

The coaxial probe is a convenient and broadband technique for lossy liquids and solids. It is nondestructive and little or no sample preparation is required for liquids or semi-solids. In the case of a solid MUT, the material face must be machined at least as flat as the probe face, as any air gap can be a significant source of error. It operates at frequencies between 45 MHz and 26.5 GHz. The technique assumes the MUT to be non-magnetic and uniform throughout. It should be noted that the accuracy in the coaxial probe measurements is dependent on both frequency and dielectric constant, with the best attainable accuracy being 5% in the real part of the permittivity and $\pm$ 0.05 in loss tangent (Reference 1). Therefore, this technique is not suitable for obtaining the loss tangents of low loss materials.

Rectangular Waveguide Technique

The rectangular waveguide technique is an example of a class of two-port measurement techniques, called transmission line techniques, for obtaining the complex permittivity and permeability of a sample. In these techniques, a sample of the material is machined to fill the cross-section of the transmission line, and the reflection from and transmission through the sample is measured. Transmission line techniques are generally more accurate than one port techniques such as the dielectric probe technique provided the samples are machined with precision and fit inside the transmission line with a minimum of air gap surrounding them. Since the transmission line techniques are two-port, more information is available for material property determination and error correction.

The higher accuracy of the rectangular waveguide transmission line technique as compared to the dielectric probe is somewhat offset by the requirement of machining an accurate sample. The band limits imposed by the waveguide may also cause inconvenience, since several different samples and fixtures may need to be used if the properties are desired over a large frequency range.

Measurement Facilities in EPML

The measurement facilities described are located in an RF shielded room to eliminate external RF interference. The measurement system is based on a Hewlett Packard (HP) 8510C Network Analyzer with an HP 8515A S-parameter test set. The main controller is an IBM compatible personal computer with an IEEE-488 (HP-IB) interface card which allows communication with the network analyzer.

The HP 8510C Network Analyzer measures the magnitude and phase response of linear components by comparing the incident signal with the transmitted signal from the device or reflected from the input. The results are measured by S-parameters which consist of a linear magnitude ratio and relative phase angle.

Some materials readily absorb moisture and this may affect the measurement of the properties considerably. The EPML also contains a high temperature drying oven which may be used to reduce the moisture content of a MUT prior to measurement.

Coaxial Probe Measurement System

For coaxial probe measurements, the HP dielectric probe kit is utilized, which consists of the probe, related software, and calibration standards. The calibration consists of measuring three known standards with the probe (usually an open, short, and distilled water at room temperature). The calibration process removes systematic errors from the measurement. The menu driven software is installed on the personal computer, and computes the complex permittivity of the MUT from the S-parameter information which is relayed from the network analyzer.

To reduce cable flexure and probe motion errors during measurements, a fixture was developed which securely clamps the probe and its cable in a vertical position. The fixture is equipped with a small table on which to place the calibration standard or MUT. This table is mounted to a manually operated vertical position translator which allows the operator to raise the MUT up to the probe tip with high positional precision and with the proper contact pressure. Three principal views and an isometric view of the coaxial probe holder are shown in Figure 3, and Figure 4 shows a photograph of the probe fixture in use.

Rectangular Waveguide Measurement System

For rectangular waveguide measurements, the HP 85071A Materials Measurement software is utilized. Before the MUT is measured, a calibration using a standard waveguide calibration kit is done to the measurement plane at the ends of the coaxial-to-waveguide adapters (see Figure 5). The sample and sample holder lengths are input to the software before the measurement takes place. With this information, and the S-parameters relayed from the network analyzer, the software uses one of four algorithms (specified by the user) to compute complex permittivity and permeability. The choice of algorithm used depends on the sample length and other considerations (Reference 1). For this study, the algorithm which uses the Nicholson-Ross technique was used, since the samples were less than 1/2 wavelength in thickness and thus immune to the anomalies which occur in the Nicholson-Ross technique and 1/2 wavelength multiples.

Results

In this section, measurement results for several different materials are presented. Two materials for which the dielectric properties are well known, Teflon and plexiglass, have been measured in the EPML using the dielectric probe and rectangular waveguide techniques described earlier in this report. The rectangular waveguide measurements were done using both X-band (8.2 GHz - 12.4

GHz) and K_u-band (12.4 GHz - 18 GHz) waveguides as sample holders. Since both these materials are low loss, only the real part of the permittivity (e') is presented. In Figure 6, a plot showing e' for plexiglass is given. The reference value for plexiglass is given as 2.59 for a frequency of 10.0 GHz (Reference 2). In Figure 7, a similar plot for Teflon is shown. The reference value for Teflon is given as 2.10 for a frequency of 10.0 GHz (Reference 3). As can be seen from the plots, the waveguide and dielectric probe techniques both give results which agree with the reference data and with each other.

For further validation of the EPML's capabilities to measure dielectric properties, several materials which were measured at near X-band frequencies during a previous effort (Reference 4) were obtained and measured using the dielectric probe and X-band waveguide techniques. Reference 4 details the results of a study investigating high-temperature dielectric properties of candidate space-shuttle thermal protection system and antenna window materials. Of the materials shown in Tables 1 and 2, the following materials were candidate antenna window materials: SLA 220V H/C (silicone ablator), IPBN (isotropic pyrolytic boron nitride), SCFS (Slip-cast fused silica), HD-0092 (hot pressed boron nitride), and AS-3DX (fused quartz reinforced silica composite). These materials are generally quite hard. The Mullite HCF (hardened compacted mullite fibers) and LI-900 (all silica) were possible reusable surface insulation materials having relatively low densities. Dynaquartz was being investigated for use in both of the above capacities. The remaining materials, RL-1973 and S-105, are silicone sponge materials, and were potentially to be used as shock absorbing mounting materials for the surface insulation panels.

Comparison of results for the materials described are presented in Tables 1 and 2. In Table 1, the materials which were given in Reference 4 at frequencies within or very close to the X-band frequency range are compared with the X-band waveguide technique results. Since the measurements were performed over the band with 201 equally spaced frequency points, numerical data is available at a finite number of frequencies. The X-band results are shown at the nearest frequency to those given in Reference 4. Good agreement is noted for the real part of the dielectric constant, with differences in the loss tangents probably due to sample fit errors in the waveguide. For the dielectric probe data, shown in Table 2, loss tangent data was not included due to the inability of this technique to measure small loss tangents.

Conclusions

The capability of the EPML to measure dielectric properties of materials has been established. For non-magnetic materials for which machining a sample is difficult or impossible, the dielectric probe technique is a convenient, broadband method for measuring the permittivity, and gives reasonably accurate values for both real and imaginary parts of the permittivity provided the materials is somewhat lossy. For materials which can be machined accurately, the rectangular waveguide technique can be used to obtain both complex permittivity and permeability over the specific frequency band. Due to sample and data availability, only permittivity measurements were performed in this study. By using standard materials and previously measured materials data for comparison, the use of these techniques for permittivity determination in the EPML has been validated.

References

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3. Donald R. Askeland, "The Science and Engineering of Materials", PWS-Kent, Boston, 1989.

4. M. C. Gilreath and S. L. Castellow, Jr., "High-Temperature Dielectric Properties of Candidate SPace-Shuttle Thermal-Protection-System and Antenna-Window Materials", NASA TN D-7523, June, 1974.

Table 1: Comparison of X-Band Waveguide and Reference 4 Results

	Reference 4 Results			X-Band Waveguide Results		
Material	Frequency (GHz)	Dielectric Constant	Loss Tangent	Frequency (GHz)	Dielectric Constant	Loss Tangent
Dynaquartz	9.260	1.15	0.00050	9.250	1.15	0.00307
SLA-220V H/C	12.950	1.33	0.00609	12.400	1.34	0.00732
RL-1973	12.960	1.33	0.01280	12.400	1.32	0.00867
Mullite HCF MOD IIIA	8.740	1.29	0.00182	8.200	1.27	0.01022
LI-900	9.300	1.14	0.00057	9.300	1.14	0.00247
S-105	11.400	1.69	0.01282	11.413	1.69	0.01464

Table 2: Comparison of Dielectric Probe and Reference 4 Results

	Reference 4 Results		Dielectric Probe Results	
Material	Frequency (GHz)	Dielectric Constant	Frequency (GHz)	Dielectric Constant
Dynaquartz	9.260	1.15	9.36	1.16
SLA-220V H/C	12.950	1.33	12.96	1.33
RL-1973	12.960	1.33	12.92	1.45
Mullite HCF MOD IIIA	8.740	1.29	8.72	1.33
LI-900	9.300	1.14	9.36	1.23
S-105	11.400	1.69	11.44	1.71
IPBN	5.726	3.00	5.76	3.05
SCFS	5.375	3.40	5.36	3.33
HD-0092	4.915	4.07	4.96	3.88
AS-3DX	5.841	2.88	5.84	2.44

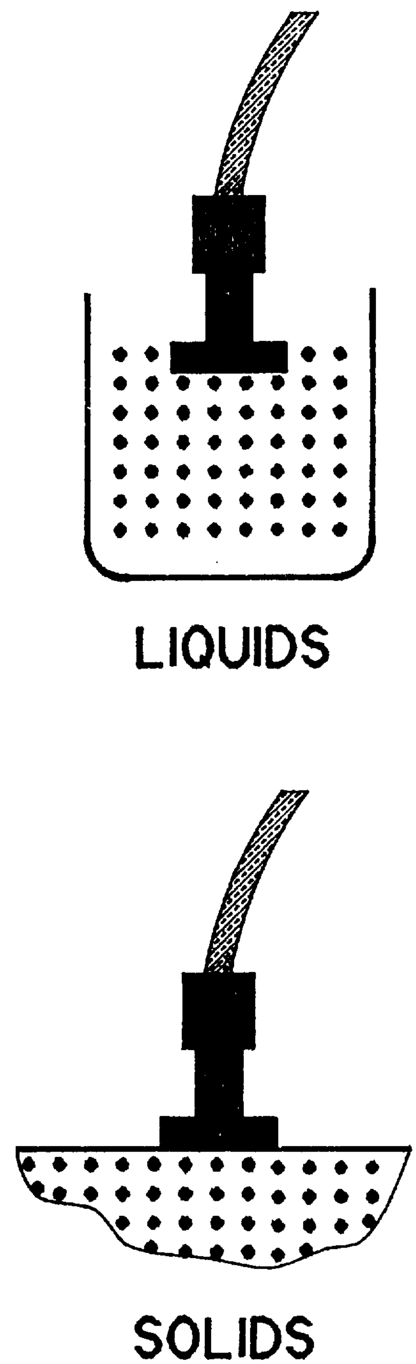


FIGURE I (REFERENCE I)

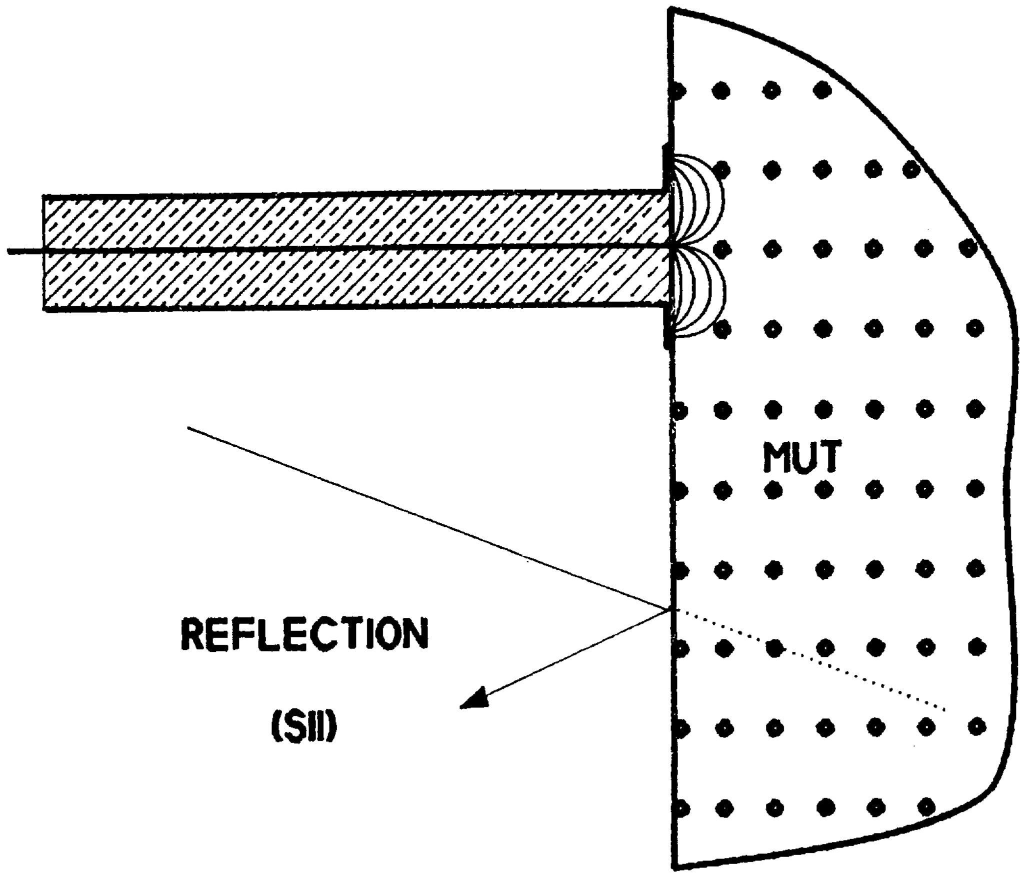


FIGURE 2 (REFERENCE I)

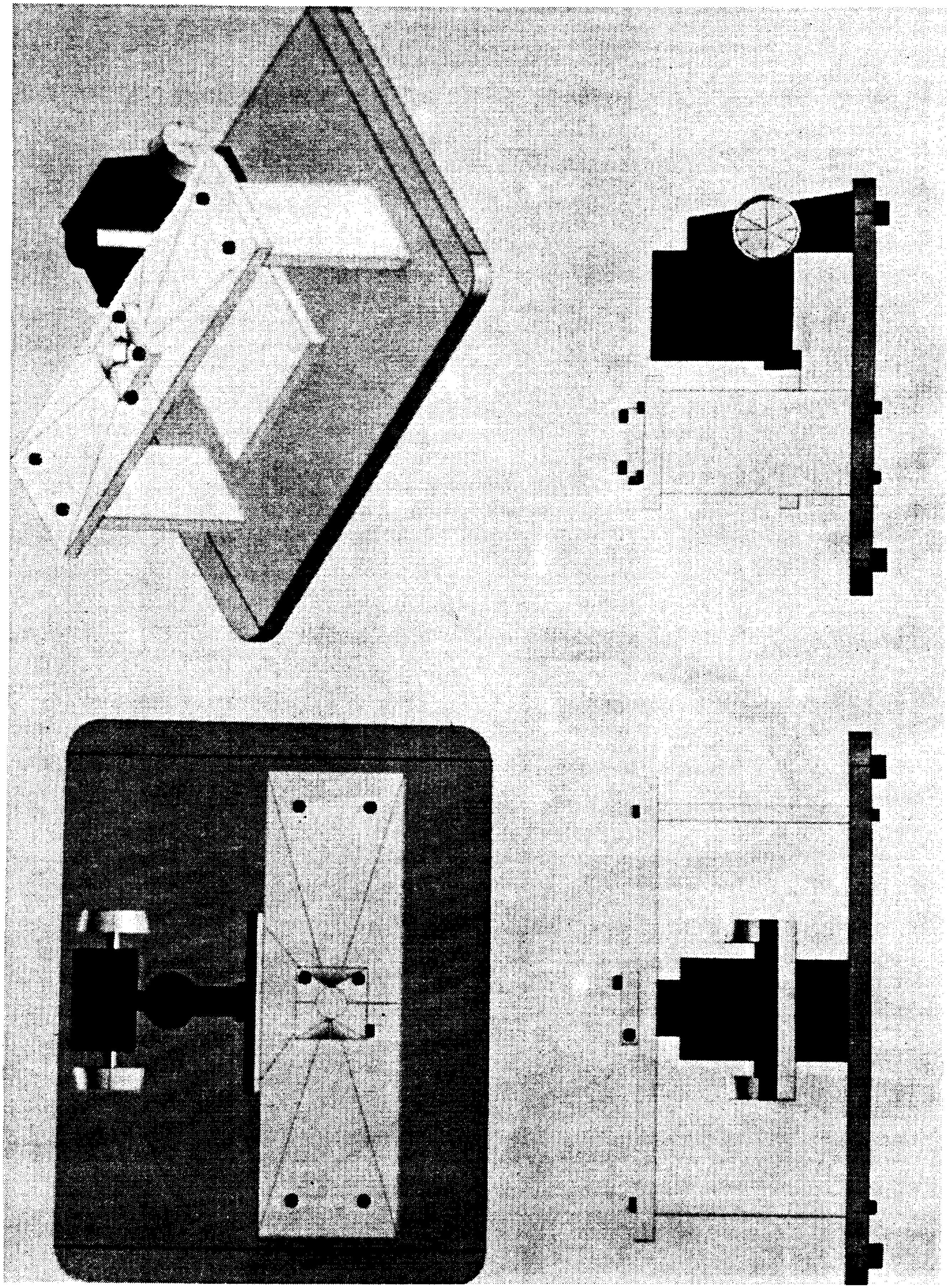


Figure 3

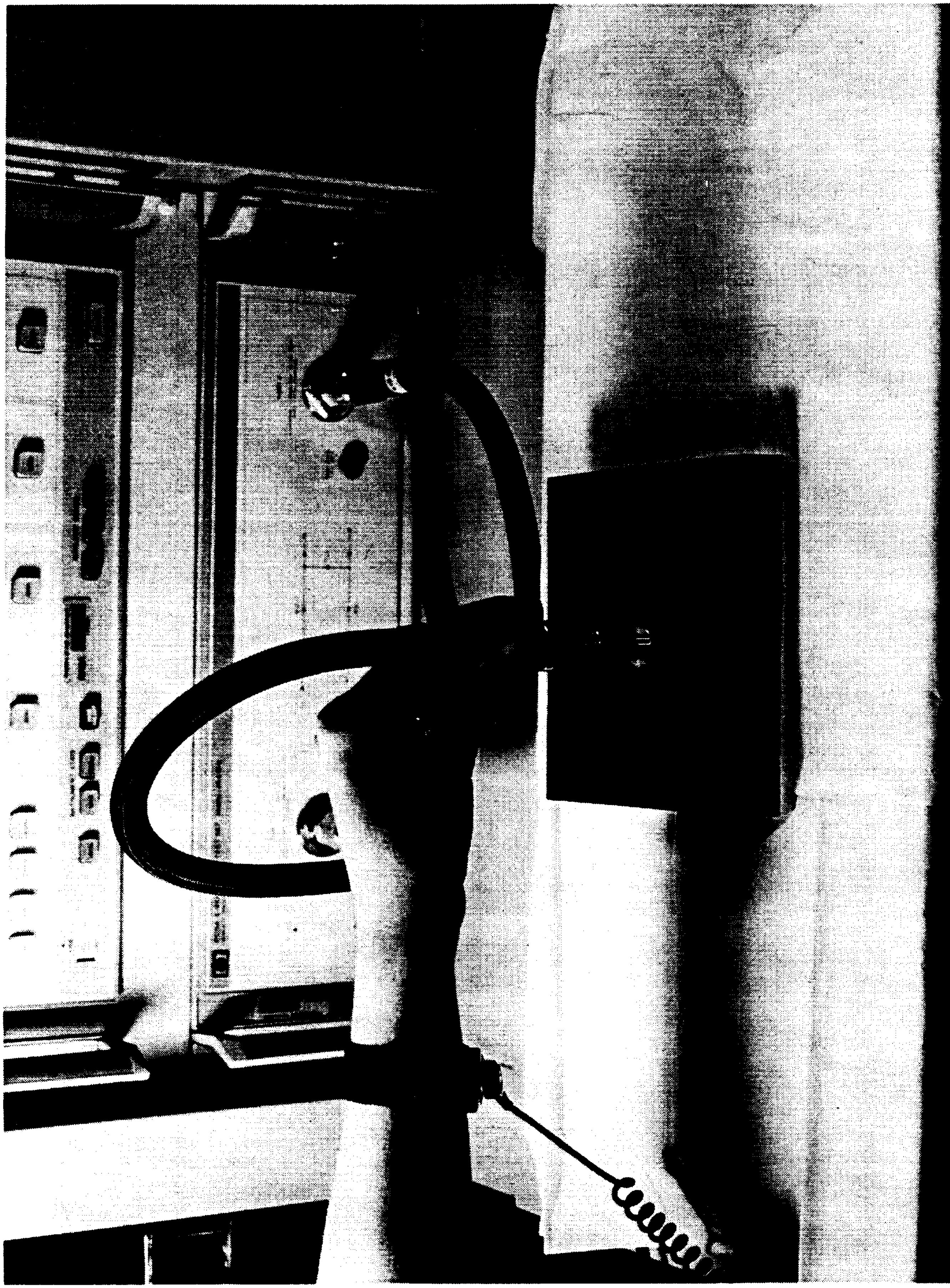


Figure 4

**Waveguide Measurement
Test Set-up**

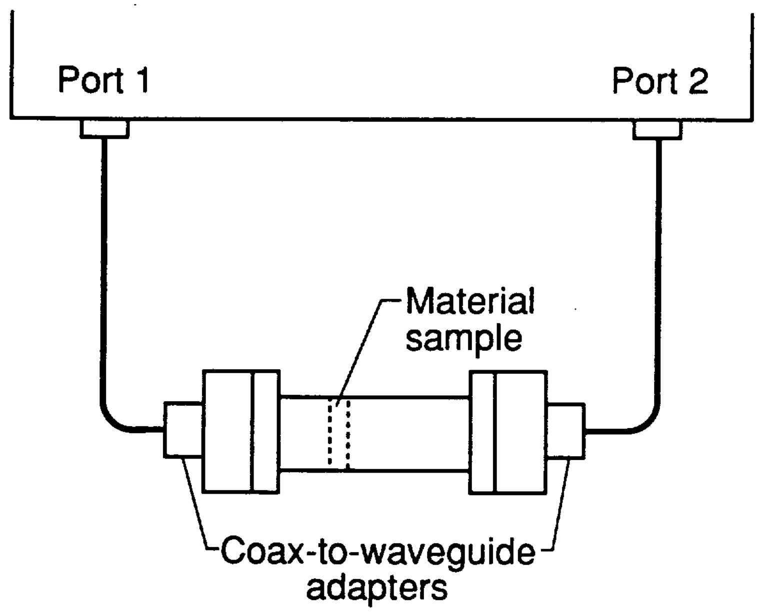
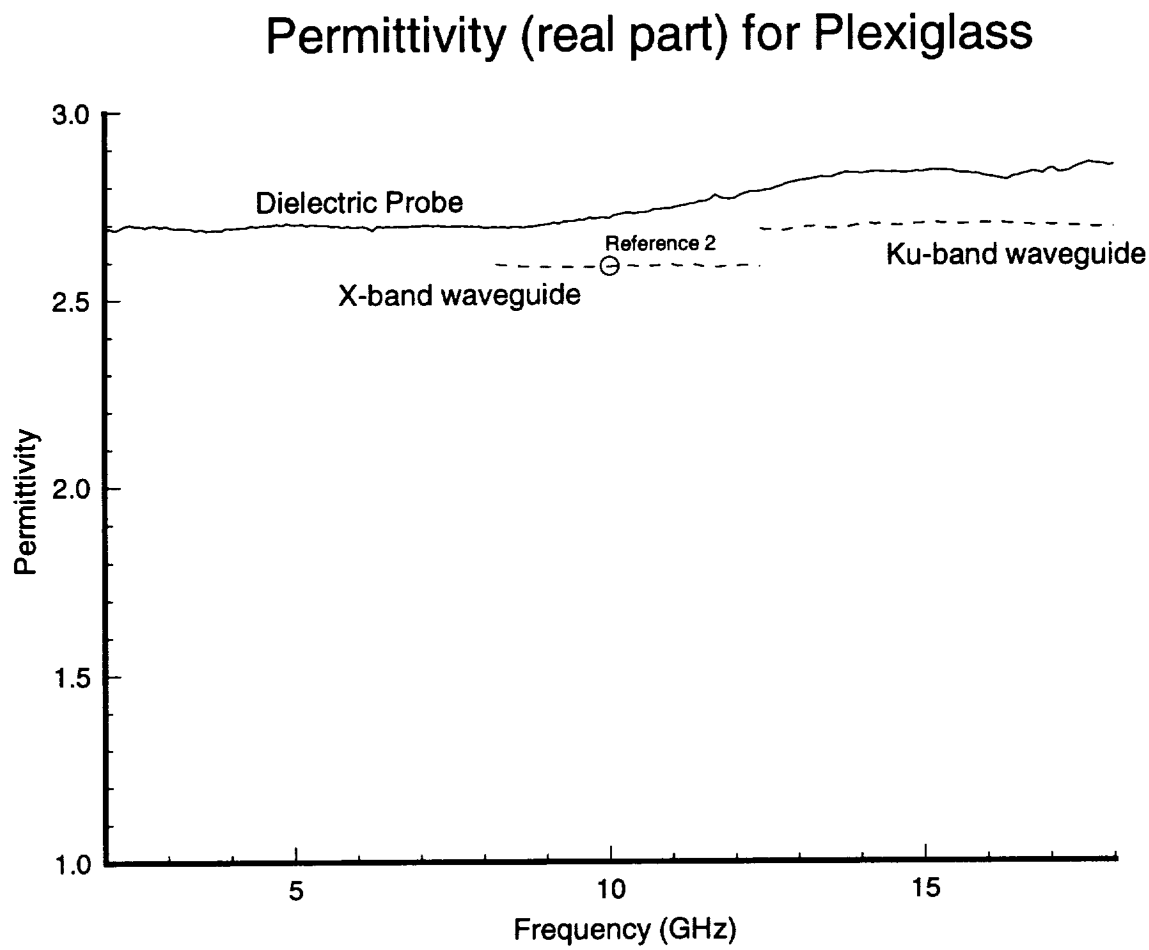


Figure 5



Permittivity (real part) for Plexiglass
3.0
2.5
2.0
1.5
1.0
Permittivity
Dielectric Probe
Reference 2
X-band waveguide
Ku-band waveguide
5
10
15
Frequency (GHz)

Figure 6

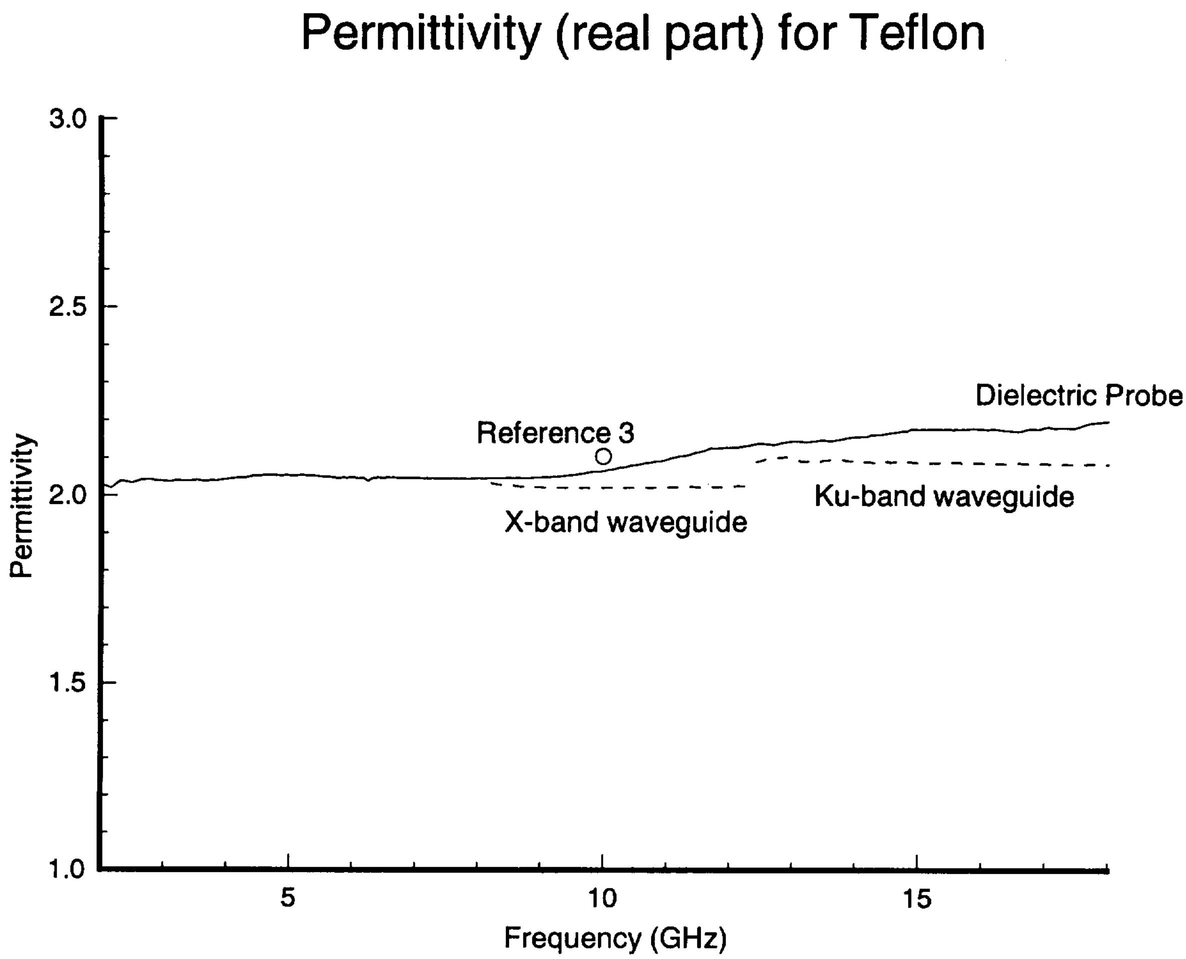

Permittivity (real part) for Teflon
3.0
2.5
2.0
1.5
1.0
Permittivity
Dielectric Probe
Reference 3
X-band waveguide
Ku-band waveguide
5
10
15
Frequency (GHz)

Figure 7

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Robin Cravey, Pacita Tiemsin, Kerri Bussell, and Kenneth Dudley

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