Lawrence Berkeley National Laboratory

Recent Work

Title

A BROADBAND, AUTOMATED, STRIPLINE TECHNIQUE FOR THE SIMULTANEOUS MEASUREMENT OF COMPLEX PERMITTIVITY AND PERMEABILITY

Permalink

https://escholarship.org/uc/item/3624k11h

Author

Barry, W.

Publication Date

1985-02-01

eScholarship.org Powered by the California Digital Library
University of California

LBL-19068
Preprint

Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

RECEIVED
LAWRENCE
BERKELEY LABORATORY
MAR 26 1985
LIBRARY AND
DOCUMENTS SECTION

Accelerator & Fusion Research Division

Submitted to IEEE Transactions on Microwave Theory and Techniques

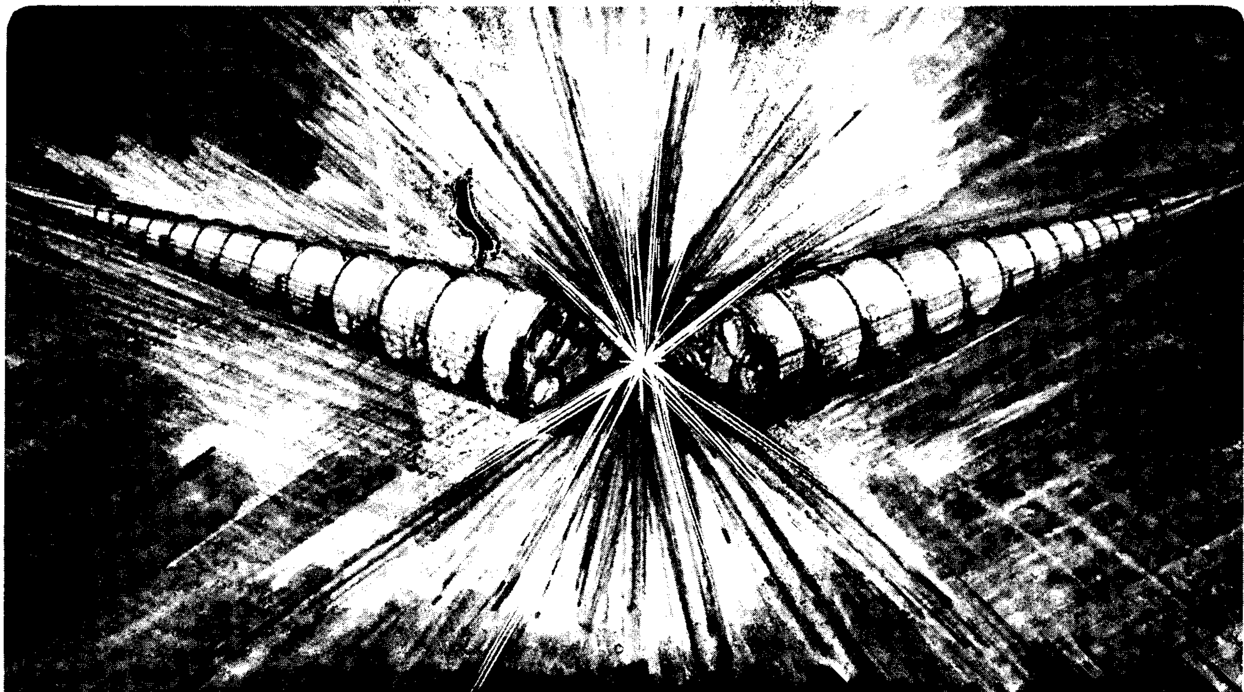
A BROADBAND, AUTOMATED, STRIPLINE TECHNIQUE FOR THE SIMULTANEOUS MEASUREMENT OF COMPLEX PERMITTIVITY AND PERMEABILITY

W. Barry

February 1985

TWO-WEEK LOAN COPY

This is a Library Circulating Copy which may be borrowed for two weeks.



LBL-19068 c.2

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

LBL-19068
BECON-49

A BROADBAND, AUTOMATED, STRIPLINE TECHNIQUE FOR THE SIMULTANEOUS MEASUREMENT OF COMPLEX PERMITTIVITY AND PERMEABILITY*

Walter Barry

Accelerator and Fusion Research Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

February 1985

*This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, High Energy Physics Division, U. S. Dept. of Energy, under Contract No. DE-AC03-76SF00098.

A BROADBAND, AUTOMATED, STRIPLINE TECHNIQUE FOR THE SIMULTANEOUS MEASUREMENT OF COMPLEX PERMITTIVITY AND PERMEABILITY*

Walter Barry

Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

ABSTRACT

A broadband automated technique for making frequency — swept measurements of complex permittivity and permeability simultaneously is described. ε_r and μ_r are computed from S-parameter measurements made on a strip transmission line device loaded with the material under test. The derivation of ε_r and μ_r as functions of S_{11} and S_{21} is included as well as a practical design for a stripline sample holder. Measured ε_r and μ_r data for several dielectrics and ceramic ferrites is also presented. The technique has been found to have an overall accuracy of better than ±5%.

*This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, High Energy Physics Division, U. S. Dept. of Energy, under Contract No. DE-AC03-76SF00098.

A BROADBAND, AUTOMATED, STRIPLINE TECHNIQUE FOR THE SIMULTANEOUS MEASUREMENT OF COMPLEX PERMITTIVITY AND PERMEABILITY*

Walter Barry

Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

Introduction

This paper presents a method for simultaneously measuring the real and imaginary components of both permittivity, (ε) and permeability, (μ) of a given material. The general method, previously referred to by Weir,[1] makes use of the complex S parameters measured for a waveguide or transmission line loaded with the material under test to calculate ε and μ. The technique described here employs a strip transmission line fixture into which blocks of the material to be measured may be inserted easily. An automated network analyzer system is used to make frequency-swept S-parameter measurements on the loaded stripline fixture from which complex ε and μ may be calculated. The measurement technique was developed to characterize accurately the electromagnetic properties of certain ceramic ferrites in the .5-5.5 Ghz frequency band. These ferrites are to be used for RF signal attenuation between pickups and kickers in the beam cooling rings of the antiproton source at Fermi National Laboratory.[2] The ability to measure electric and magnetic parameters simultaneously makes the automated stripline technique ideal for this application as well as for measuring the properties of materials for general electromagnetic applications.

*This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, High Energy Physics Division, U. S. Dept. of Energy, under Contract No. DE-AC03-76SF00098.

Theory

The diagram in Fig. 1 represents a strip transmission line of length $2\ell + t$ loaded in the center with a material of length t and unknown complex relative permittivity and permeability:

$$\epsilon_r = \epsilon_r' - j\epsilon_r''$$

$$\mu_r = \mu_r' - j\mu_r''$$

The stripline has a characteristic impedance of Z_o (free space regions I and III) which when loaded with the sample material (region II) becomes Z where:

$$Z = Z_o \sqrt{\frac{\mu_r}{\epsilon_r}} \qquad (1)$$

In the unloaded regions the propagation constant is $k_o = \omega \sqrt{\mu_o \epsilon_o}$, while in the loaded region the propagation constant is generally complex and is designated by k where:

$$k = k_o \sqrt{\mu_r \epsilon_r} \qquad (2)$$

At the plane boundaries between regions I and II, and regions II and III, there are complex reflection coefficients R and $-R$ respectively where:

$$R = \frac{Z - Z_o}{Z + Z_o} \qquad (3)$$

Using (1), Eqs/ (2) and (3) may be solved simultaneously to yield the desired parameters:

$$\varepsilon_r = \frac{k}{k_o}\left(\frac{1-R}{1+R}\right) \tag{4}$$

$$\mu_r = \frac{k}{k_o}\left(\frac{1+R}{1-R}\right) \tag{5}$$

Thus, knowing k and R enables ε_r and μ_r to be calculated. The values for k and R may be found from the values of S_{11} and S_{21} measured at the input (far left of region I) and output (far right of region III) terminals in Fig. 1.

In order to relate k and R to the measured S parameters consider the relationship between the forward and reverse voltages[3] at the input terminal, C_1^+ and C_1^-, and at the output terminal, C_2^+ and C_2^-:

$$\begin{bmatrix} C_1^+ \\ C_1^- \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} C_2^+ \\ C_2^- \end{bmatrix} \tag{6}$$

where the matrix [T] is the total wave amplitude matrix for the "device" in Fig. 1. The elements of [T] may be found by multiplying the wave amplitude matrix for each transmission section and reflection as follows:

$$[T] = \begin{bmatrix} e^{jk_o \ell} & 0 \\ 0 & e^{-jk_o \ell} \end{bmatrix} \begin{bmatrix} (1-R)^{-1} & R(1-R)^{-1} \\ R(1-R)^{-1} & (1-R)^{-1} \end{bmatrix} \begin{bmatrix} e^{jkt} & 0 \\ 0 & e^{-jkt} \end{bmatrix} \begin{bmatrix} (1+R)^{-1} & -R(1+R)^{-1} \\ -R(1+R)^{-1} & (1+R)^{-1} \end{bmatrix} \begin{bmatrix} e^{jk_o \ell} & 0 \\ 0 & e^{-jk_o \ell} \end{bmatrix}$$

After multiplying, the elements of [T] are found to be:

$$\begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} = \frac{1}{(1-R^2)} \begin{bmatrix} e^{j2k_o\ell}[e^{jkt} - R^2 e^{-jkt}] & -j2R \sin kt \\ j2R \sin kt & e^{-j2k_o\ell}[e^{-jkt} - R^2 e^{jkt}] \end{bmatrix} \tag{8}$$

and are related to the S parameters as follows:

$$\begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} = \begin{bmatrix} 1/S_{12} & -S_{22}/S_{12} \\ S_{11}/S_{12} & (S_{12}^2 - S_{11}S_{22})/S_{12} \end{bmatrix} \tag{9}$$

thus the S parameters are found to be:

$$S_{21} = S_{12} = \frac{(1-R^2)\, e^{-j2k_o\ell}}{e^{jkt} - R^2 e^{-jkt}} \tag{10}$$

$$S_{11} = S_{22} = \frac{j2Re^{-j2k_o\ell} \sin kt}{e^{jkt} - R^2 e^{-jkt}} \tag{11}$$

Equations (10) and (11) may now be solved simultaneously for kt and R in terms of the known and measured quantities:

$$kt = \cos^{-1}\left(\frac{e^{-j4k_o\ell} + S_{12}^2 - S_{11}^2}{2e^{-j2k_o\ell} S_{12}}\right) = \cos^{-1}(\text{arg}) \tag{12}$$

$$R = S_{11} \Big/ \left(e^{-j2k_o \ell} - S_{12} e^{-jkt} \right) \tag{13}$$

and ϵ_r and μ_r may be obtained through Eqs. (4) and (5).

Because of the large number of complex arithmetic operations involved a certain amount of care must be taken when using Eq. (12) in practice. When resolved into its real and imaginary components, Eq. (12) becomes:

$$kt_{real} = \Theta_G \pm 2n\pi \qquad n = 0,1,2,... \tag{14}$$

$$kt_{imag} = - \ln G$$

where Θ_G and G are real numbers defined as follows:

$$\Theta_G = \tan^{-1}\left[\mathrm{Im}\left(arg + \sqrt{arg^2-1}\right) \Big/ \mathrm{Re}\left(arg + \sqrt{arg^2-1}\right) \right] \tag{16}$$

$$G = \left(\left[\mathrm{Re}\left(arg + \sqrt{arg^2-1}\right) \right]^2 + \left[\mathrm{Im}\left(arg + \sqrt{arg^2-1}\right) \right]^2 \right)^{1/2} \tag{17}$$

The integral multiple of 2π appearing in Eq. (14) is a result of the multivalued inverse cosine function. For material lengths in the range $0 \leq t \leq \lambda_m/2$ (λ_m is wavelength inside the material) the principal branch of $\cos^{-1}$ should be used, i.e. $n = 0$. Since material samples of length $t > \lambda_m/2$ introduce dimensional resonances[4] that invalidate the measured values for S_{11} and S_{21}, all samples were kept to $t < \lambda_m/2$, therefore the value of $n = 0$ was always correct.

Stripline Measurement Device

The stripline test "chamber" developed for the ϵ and μ measurements is pictured in Fig. 2. The stripline portion of the device was designed for a characteristic impedance of Z_o = 50 ohms in order to match that of the cables and network analyzer system used to make the S-parameter measurements. The critical dimensions for the stripline chamber are as follows: ground plane separation - 1.000 cm, center conductor width - 1.316 cm, and center conductor thickness - .048 cm. Both the ground planes and center conductor are made of a beryllium copper alloy for rigidity, while the housing is made of aluminum with approximate inside dimensions of 6.0 cm x 4.3 cm x 1 cm. The test samples which fit above and below the center conductor inside the housing must have dimensions t x 4.3 cm x .48 cm in order to fit securely; t must be less than $\lambda_m/2$. It should be noted that although Fig. 2 indicates grooves in the samples for a better fit around the center conductor, it was found that samples without grooves measured equally well, therefore the grooves may be deleted in order to save time when preparing samples.

It was a prime concern in developing the test chamber to obtain the best possible transition from the stripline to the network analyzer. This task mainly involved the development of extremely low-reflection connections from stripline to coax. After considerable experimentation optimum connections were obtained by press fitting standard .250" semirigid cables through the housing walls so that the copper jackets and teflon of the cables were flush with the inside of the walls. The center conductors of the semirigid cables were cut so that they protruded .050" into the chamber and were split with a .018" slitting saw so as to accept the stripline center conductor (see Fig. 3). The stripline center conductor was beveled to a point (20° with respect to the housing wall) to obtain a good match and soldered to the split center conductors of the semirigid cable. Lastly, single-sexed APC-7 connectors were attached to the semirigid cables outside the housing. Capacitive tuning screws which protrude through one of the

ground planes over the stripline/coax joints were then adjusted while monitoring reflection with a time-domain reflectometer in order to optimize each match. Return-loss measurements of the resulting device (without test sample) appear in Fig. 4. The reflected signal for both ports is better than 30 dB down over most of the .5-5.5 GHz band.

Procedure for Material Measurements

In order to compute ϵ_r and μ_r correctly, the S parameters of the empty and loaded test device must be measured to a high degree of accuracy. These measurements were performed with a Hewlett-Packard network analyzer system the main components of which are an 8410C network analyzer, 8746B S parameter test set, and an 8411A harmonic frequency converter. An HP 9816 computer with appropriate interfacing and peripherals was used for automation, data acquisition, computations and printing/plotting.

The first step in the measurement procedure is to calibrate out certain errors associated with the S parameter test set and cables leading to the stripline device to be measured. These errors include forward and reverse signal errors in directivity, source match, load match, isolation, reflection path tracking and transmission path tracking. The calibration consists of making all four S-parameter measurements on precision APC-7 terminations, shorts and opens. Correction terms for the errors mentioned above can then be calculated and applied to the actual device measurements.

Once the system is calibrated, S_{12} for the stripline device without a sample is measured so its total length may be determined. The length parameter ℓ may then be computed by subtracting the thickness t of the sample to be tested from the total length and dividing by two. S_{11} and S_{12} measurements of the device with the test sample centered inside are then made and used to compute ϵ_r and μ_r with Eqs. (12), (13), (4) and (5). A provision for calculating the electrical length

of the sample as a function of frequency was included to ensure it did not exceed $\lambda_m/2$ at any point.

ε_r and μ_r Measurements

For the purpose of assessing the validity of the measurement technique the first materials to be measured were three dielectrics with well known properties: polyethylene, teflon and lucite. The results of these measurements for the .5-5.5 GHz band appear in Fig. 5. The real parts of ε_r and μ_r in both Fig. 5 and Fig. 6 are represented by solid lines while the imaginary components are represented by dashed lines. The values of ε_r' in Fig. 5 for the polyethylene, teflon and lucite samples are seen to be in close agreement with the generally accepted values of 2.26, 2.10 and 2.60 respectively. As would be expected $\mu_r' = 1$ was measured in all three cases.

Being low-loss dielectrics one would expect to measure values of $\varepsilon_r'' \sim 10^{-3}$ and $\mu_r'' \sim 0$ for these materials, however Fig. 5 indicates that larger values were obtained for these parameters. The reason for this inconsistency is that for low-loss materials i.e. $\varepsilon_r'' < .05$ and $\mu_r'' < .05$ the mismatch at the stripline-to-coax joint and any impedance differences between the stripline and the network analyzer become the dominant factors in the S-parameter measurements and resulting calculations. The latter of these error sources also explains the slight periodic character of the ε_r' and μ_r' data. For values of ε_r'' and μ_r'' greater than .05 these mismatch errors become insignificant. In general, the measurement technique was found to be accurate to better than ±5% for all cases of ε_r and μ_r excluding ε_r'' and μ_r'' less than .05. It should also be pointed out that when first measured, the ε_r'' and μ_r'' data for these materials had sharp peaks at certain frequencies within the measurement band. In particular there were resonant-like peaks at 2.5, 3.5, 4.3 and 5.0 GHz regardless of

which material was being tested. The cause of these resonances was found to be the excitation of cavity modes inside the stripline chamber. The problem was solved by putting small blocks of RF absorber of the type found in anechoic chambers in each corner of the chamber (not shown in Fig. 2).

Permittivity and permeability for three different ferrite materials under consideration for the application described in reference 2 were measured with this technique. The measurement results appear in Fig. 6. The three ferrites, Ferramic 1928 (Indiana General), NZ-51 (Emerson and Cuming) and Stackpole (unknown type from Stackpole Corp.) are all ceramic compositions used mainly in RF attenuation applications. As can be seen from Fig. 6 all three ferrites exhibit approximately the same properties with the exception of Ferramic 1928 which has a higher dielectric constant and loss tangent.

Summary

A broadband automated technique for simultaneously measuring the real and imaginary components of ϵ_r and μ_r has been developed. The technique utilizes a strip transmission line device loaded with the unknown material on which S-parameter measurements are made with an automated network analyzer. ε_r and μ_r are in turn computed from the measured S parameters and have been found to be accurate to better than ±5%. Some measured data for standard dielectrics and ceramic ferrites in the .5-5.5 GHz band has been presented. The measurement technique should be suitable for other materials with electromagnetic applications.

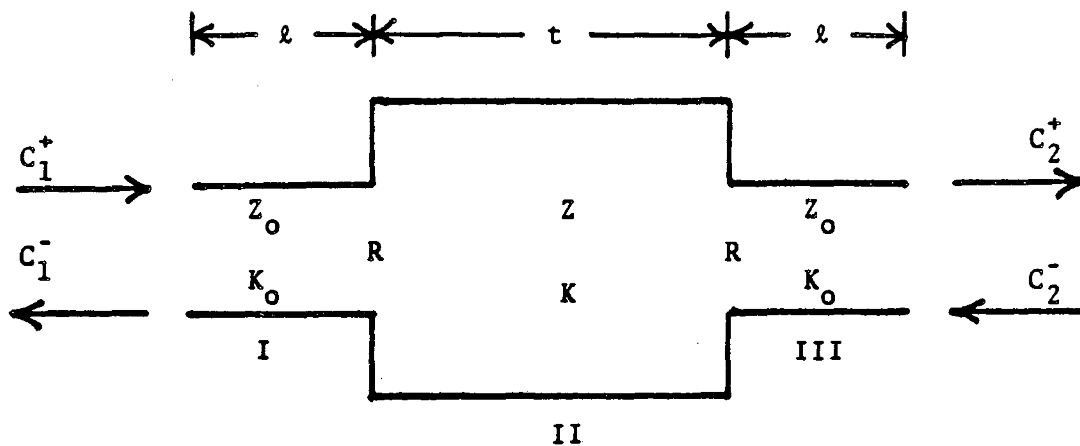


Figure 1. Diagram for determining S parameters

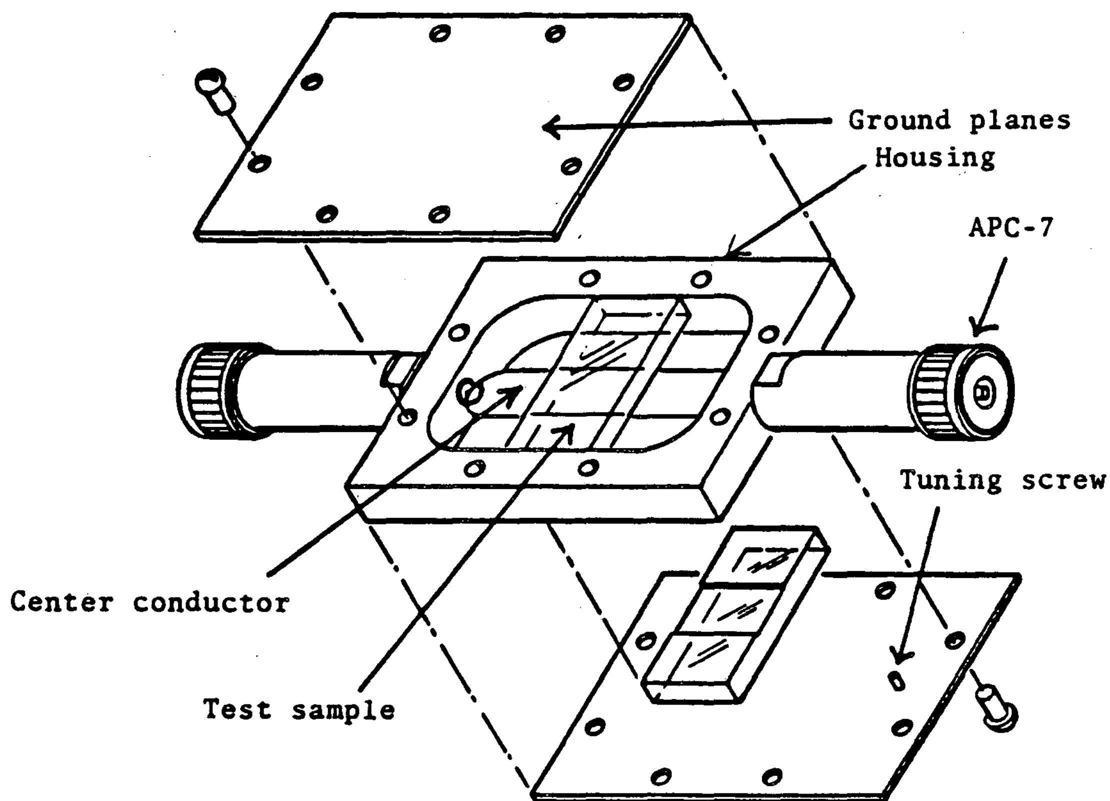
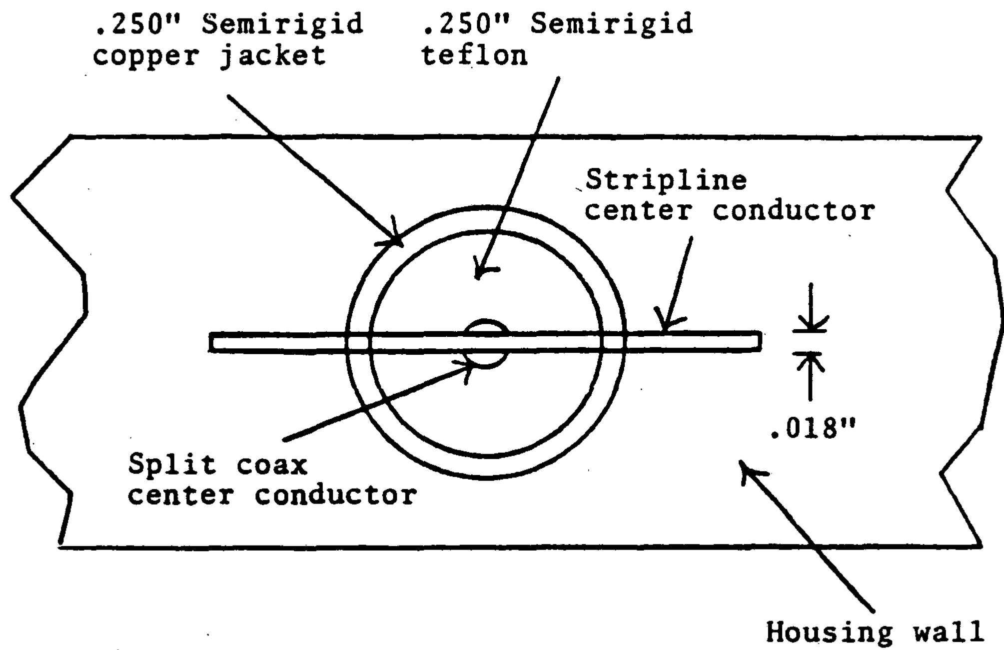
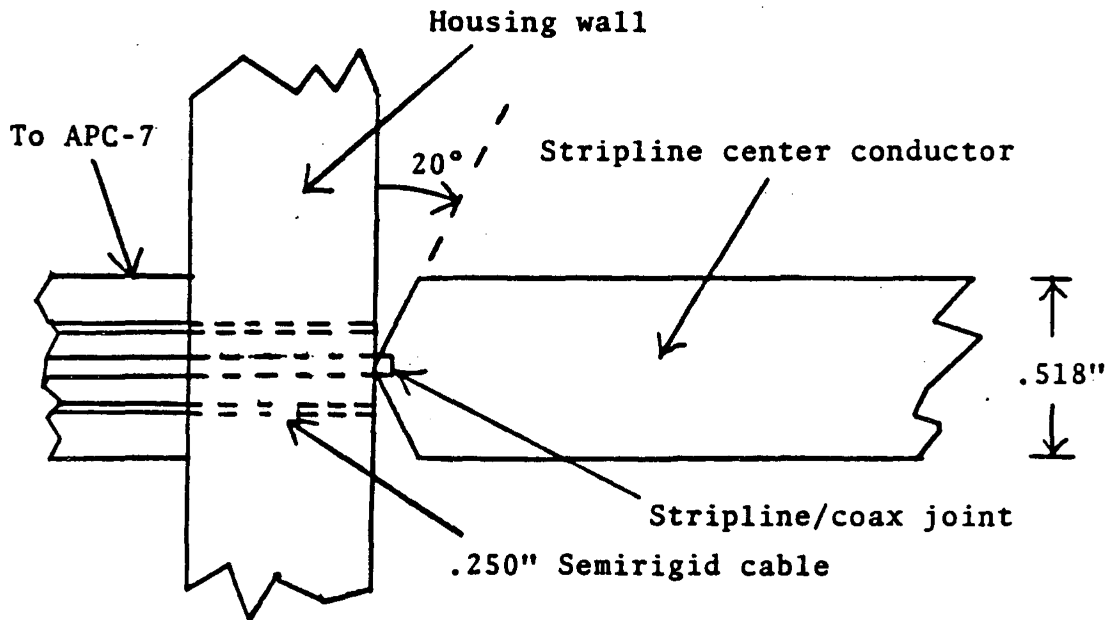


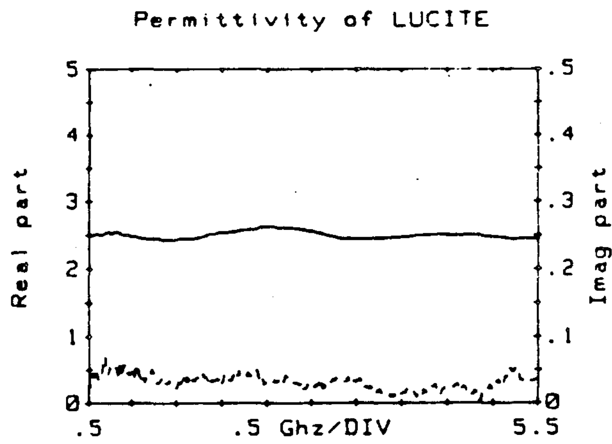
Figure 2. Stripline measurement device

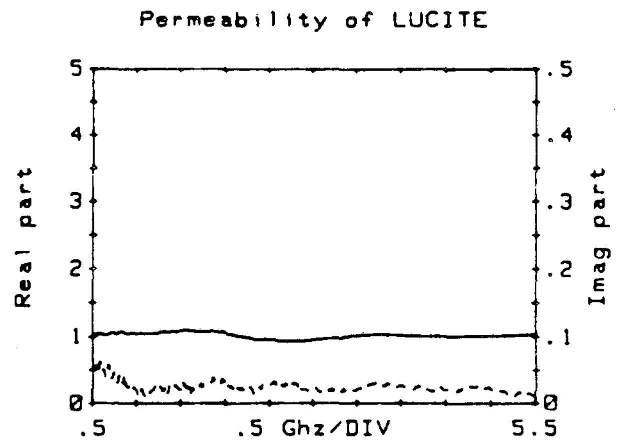


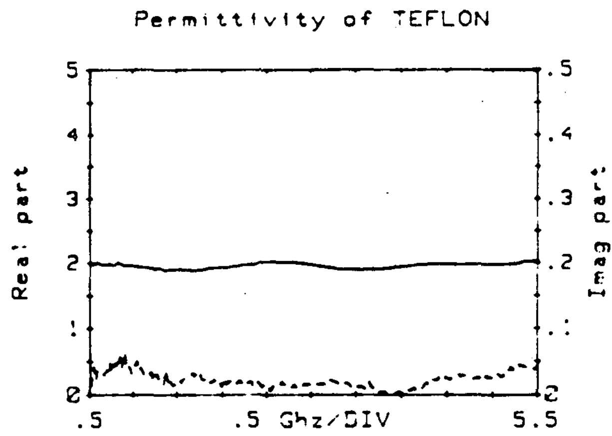


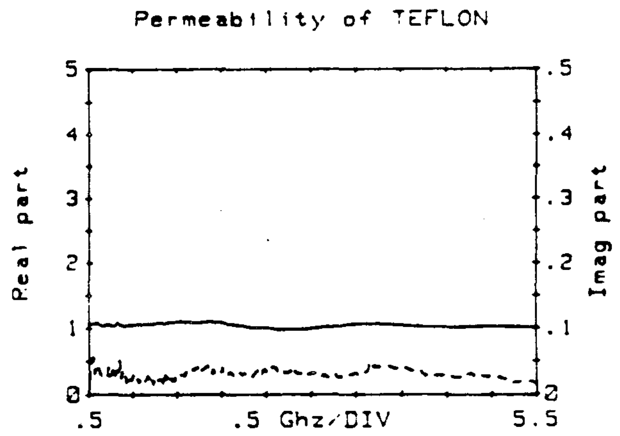
XBL 851-1053

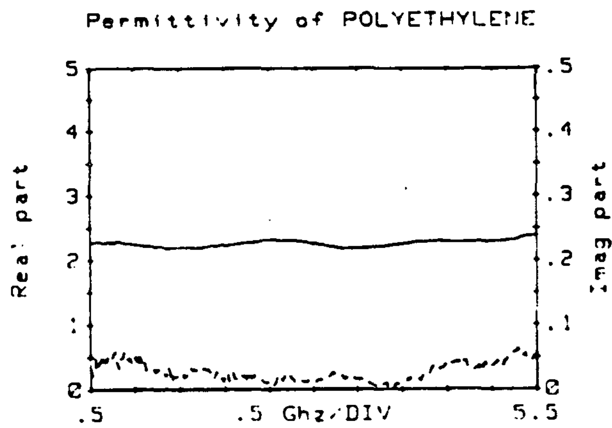
Figure 3. Coax to stripline connection

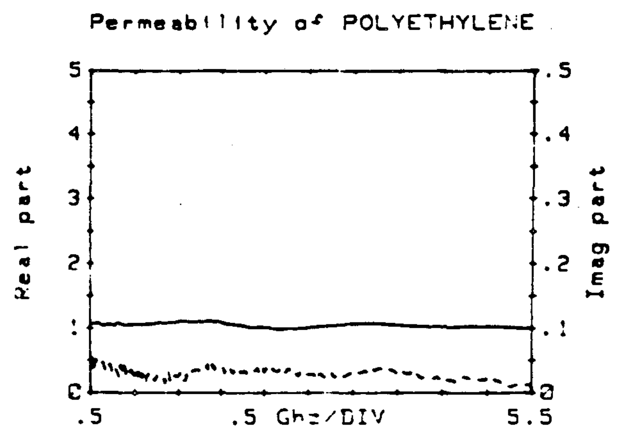






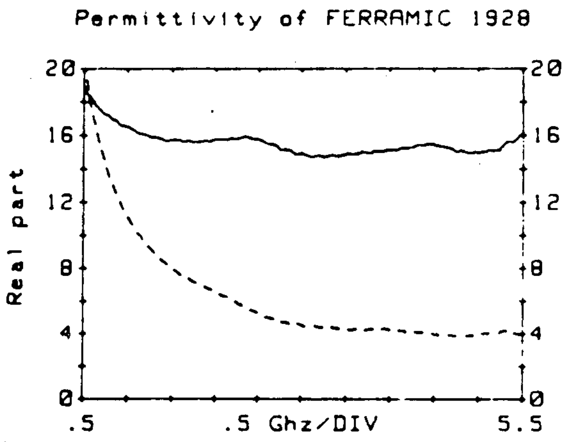


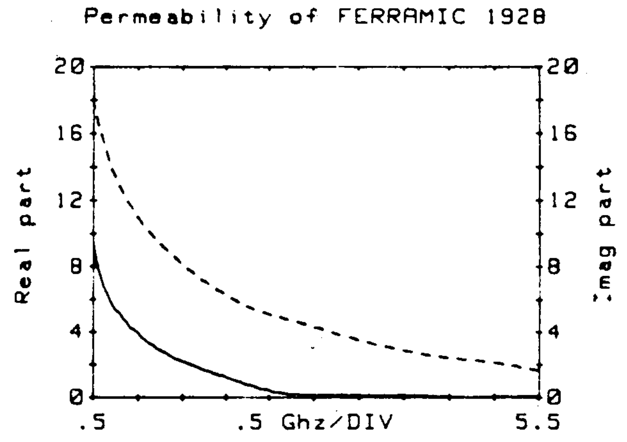


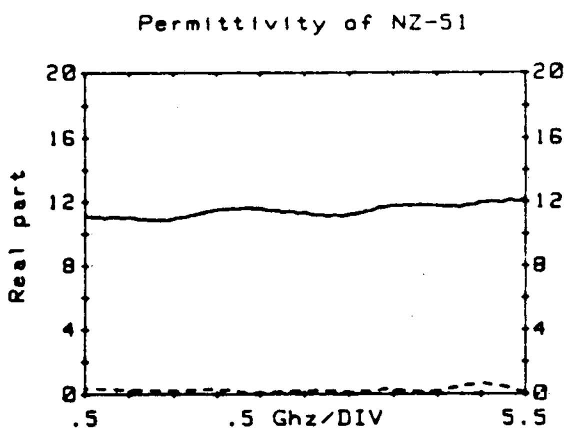


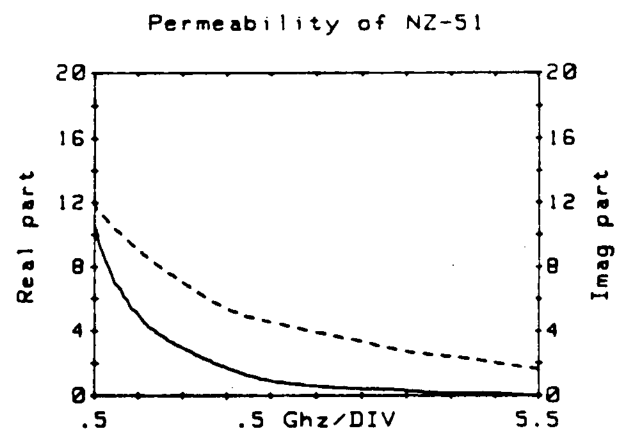
XBL 851-1055

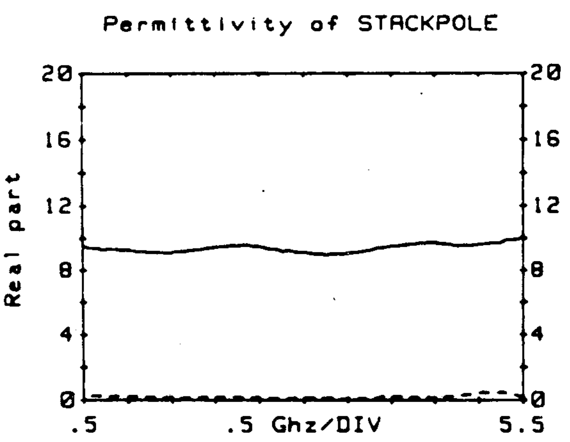
Figure 5. ε_r and μ_r measured for several standard dielectrics

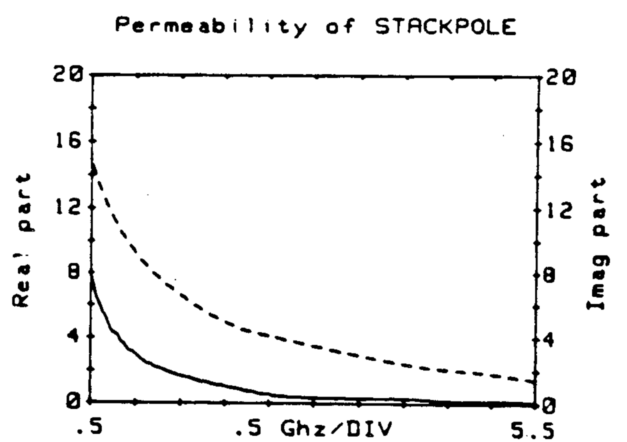












XBL 851-1054

Figure 6. ε_r and μ_r measured for several ceramic ferrites

References

1. W.B. Weir, "Automatic Measurement of Complex Dielectric Constant and Permeability at Microwave Frequencies," Proceedings of the IEEE, Vol. 62, No. 1, January 1974.

2. W.C. Barry, "Mode Analysis of Ferrite Loaded Beam Pipe," Lawrence Berkeley Laboratory, LBID-953, August 1984.

3. R.E. Collin, "Field Theory of Guided Waves," McGraw-Hill, New York, 1960.

4. J. Smit and H.P.J. Wijn, "Ferrites," John Wiley and Sons, New York, 1959.

This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720