PERMITTIVITY CHARACTERISTICS OF KEVLAR, CARBON COMPOSITES, E-GLASS, AND RUBBER (33% CARBON) AT X-BAND (8-12 GHZ)

Reza Zoughi and Brian Zonnefeld

Electrical Engineering Department
Colorado State University
Ft. Collins, CO 80523

INTRODUCTION

In many industries such as aerospace, construction, and transportation various types of composite materials have found permanent use. In conjunction with the development and utilization of these materials, nondestructive techniques by which these materials are characterized, and their defective properties detected and evaluated must also expand and improve. Microwaves possess great potential for nondestructive evaluation of the properties of these materials. Some of the advantages of using microwaves for this purpose are

1- ability to penetrate dielectric media
2- use of small sized probes
3- ability to obtain fine resolutions
4- ability to identify various boundaries
5- non-contact, and nondestructive nature of measurements
6- polarization capabilities can determine preferred directions of inhomogeneities and defects
7- evaluation of materials properties.

In order to use microwaves for nondestructive purposes, the dielectric properties of a material under test must be known. Once the permittivity of the material is determined, the depth of penetration of the microwave signal in that material is also determined. One is concerned with the relative to air permittivity of a material which is usually complex and is given by $\varepsilon_r = \varepsilon'_r - j\varepsilon''_r$. The real part is known as the dielectric constant, and the imaginary part as the loss factor. The goal of this paper is to use a microwave transmission technique to evaluate the permittivity characteristics of Kevlar, carbon composites, E-glass, and rubber (33% carbon) at X-band (8-12 GHz). Subsequently the depth of penetration of microwaves at these frequencies in these materials will be determined. The first three materials are made of unidirectional fibers of glass and carbon. Thus, their permittivity characteristics for vertical, and horizontal polarization will be determined. Vertical polarization is when the direction of the microwave signal electric field vector is parallel to the direction of fibers, and horizontal polarization is when electric field vector is orthogonal to the direction of fibers.

Review of Progress in Quantitative Nondestructive Evaluation, Vol. 10B
Edited by D.O. Thompson and D.E. Chimenti, Plenum Press, New York, 1991

THEORETICAL DEVELOPMENT

A plane wave propagating the the z direction can be represented by [3]

$$E_i = E_{io} e^{-j(\beta + j\alpha) z} \tag{1}$$

where α (Np/m) is the attenuation constant and β (rad/m) is the phase constant of the medium in which the signal is traveling. Thus, the propagation constant of the medium is given by

$$\gamma = \alpha + j\beta \tag{2}$$

For a lossy medium (a medium with nonzero ε''_r) once α and β are found the real and imaginary parts of the permittivity can be expressed by [4]

$$\varepsilon''_r = (\alpha\beta)\lambda_o^2/19.7 \tag{3}$$

$$\varepsilon'_r = (\beta^2 - \alpha^2)\lambda_o^2/39.5 \tag{4}$$

where λ_o is the wavelength in free space. The depth of penetration is defined as the distance in the medium where the magnitude of the penetrating microwave signal reaches to 1/e times of its value at the surface of the medium. The penetration depth is given by

$$\delta = \frac{1}{2\alpha} \quad \text{(m)} \tag{5}$$

APPROACH

The microwave transmission technique has proven to be an effective technique for permittivity characteristic measurement of dielectric slabs, and for determination of the slab thickness [1-2]. The experimental apparatus is shown in Figure 1. A microwave sweep oscillator is used to generate a signal in the range of 8-12 GHz. This signal is passed through an isolator which prevents any reflections to return into the oscillator (which may damage it, and also may contaminate the signal). This signal is then spilt into a test signal and a reference signal via a directional coupler. The reference signal is fed into the reference channel of a microwave network analyzer. The test signal illuminates the dielectric material (shaped into a uniform slab) via a transmitting horn antenna. This signal is then picked up by another horn antenna, and is fed into the test channel of the network analyzer. Comparison of the difference in the amplitudes, and phases of these two signals in the absence and in the presence of the dielectric material is related to the real and imaginary parts of the material permittivity.

TEST SAMPLES

Kevlar, E-glass, and carbon composite samples were all constructed of uni-directional fiber bonds in an epoxy matrix (250^{oF} cure). E-glass

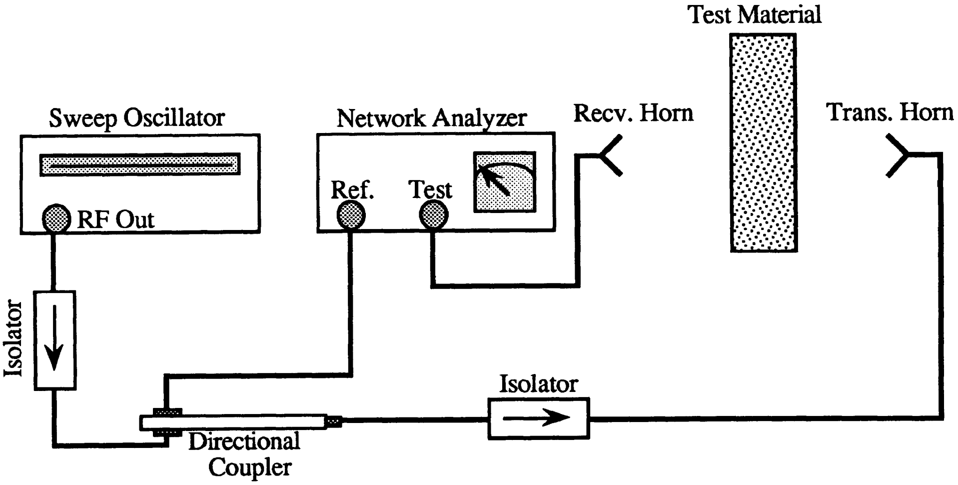

Fig. 1. The experimental apparatus.

fibers were of amorphous material having roughly isotropic construction with the following characteristics: modulus = 10 Msi, strength = 525 Ksi, density = 2.5 g/cc, and ply thickness = 0.008 in. Kevlar 49 (Du Pont) was of synthetic aromatic polymer base, and highly anisotropic where transfer bonds were weak, yielding a tough fiber, but poor transverse mechanical properties. This material had the following characteristics: modulus = 17 Msi, strength = 550 Ksi, density = 1.35 g/cc, and ply thickness = 0.005 in. Carbon composite (T300) was produced by carbonization of a polyacrylonitrile precursor with anisotropic fiber properties, but not as sever as Kevlar. The rubber samples contained very close to 33% carbon black by volume.

RESULTS

Slabs of the said four materials were used to determine their permittivities, and depth of penetration. The results reported here are the average of at least ten independent measurements on each sample. Tables 1 through 8 show the permittivity and depth of penetration results for Kevlar, carbon composite, E-glass, and rubber for vertical and horizontal polarizations respectively.

Table 1. Permittivity, and depth of penetration results for Kevlar (vertical polarization).

Frequency (GHz)	Complex Permittivity	Penetration Depth (cm)
8.0	4.63±.07-j0.52±.17	2.45
8.5	4.30±.06-j0.76±.03	1.55
9.0	4.27±.08-j0.08±.03	1.32
9.5	4.59±.03-j0.28±.03	3.90
10.0	4.63±.03-j0.45±.08	2.30
10.5	4.57±.12-j0.66±.05	1.48
11.0	4.72±.07-j0.75±.16	1.26

Table 2. Permittivity, and depth of penetration results for Kevlar (horizontal polarization).

Frequency (GHz)	Complex Permittivity	Penetration Depth (cm)
8.0	3.40±.05-j0.36±.03	3.32
8.5	3.42±.03-j0.35±.03	2.97
9.0	3.61±.04-j0.48±.03	2.11
9.5	3.53±.03-j0.44±.02	2.14
10.0	3.42±.02-j0.42±.02	2.08
10.5	3.62±.03-j0.46±.03	1.91
11.0	3.50±.03-j0.41±.02	1.99

Table 3. Permittivity, and depth of penetration results for carbon composite (vertical polarization).

Frequency (GHz)	Complex Permittivity	Penetration Depth (cm)
8.0	26.6±.20-j17.2±.13	0.19
8.5	18.2±.22-j14.0±.20	0.18
9.0	20.9±.22-j17.2±.48	0.15
9.5	13.4±.39-j13.6±.15	0.15
10.0	14.2±.19-j13.1±.23	0.15
10.5	10.5±.12-j10.9±.07	0.15
11.0	7.3±.14-j11.6±.16	0.12

Table 4. Permittivity, and depth of penetration results for carbon composite (horizontal polarization).

Frequency (GHz)	Complex Permittivity	Penetration Depth (cm)
8.0	29.4±.16-j13.3±.15	0.25
8.5	22.8±.29-j16.8±.37	0.17
9.0	21.6±.30-j14.7±.16	0.18
9.5	17.6±.01-j12.6±.12	0.18
10.0	15.1±.16-j11.9±.12	0.17
10.5	11.5±.32-j12.9±.15	0.13
11.0	10.5±.14-j11.3±.14	0.14

Table 5. Permittivity, and depth of penetration results for E-glass (vertical polarization).

Frequency (GHz)	Complex Permittivity	Penetration Depth (cm)
8.0	4.71±.09-j0.99±.10	1.31
8.5	4.83±.09-j1.12±.14	1.11
9.0	4.85±.21-j0.30±.12	3.91
9.5	5.12±.10-j0.76±.10	1.49
10.0	4.98±.17-j0.70±.07	1.53
10.5	5.04±.16-j0.80±.06	1.28
11.0	5.24±.18-j0.76±.19	1.30

Table 6. Permittivity, and depth of penetration results for E-glass (horizontal polarization).

Frequency (GHz)	Complex Permittivity	Penetration depth (cm)
8.0	5.19±.06-j0.68±.04	2.01
8.5	4.58±.06-j0.60±.05	2.02
9.0	4.50±.15-j0.67±.03	1.69
9.5	4.52±.03-j0.76±.03	1.41
10.0	4.32±.04-j0.55±.04	1.80
10.5	4.57±.03-j0.71±.05	1.36
11.0	4.54±.03-j0.44±.06	2.12

Table 7. Permittivity, and depth of penetration results for 33% carbon rubber (vertical polarization).

Frequency (GHz)	Complex Permittivity	Penetration Depth (cm)
8.0	17.8±.09-j3.4±.06	0.76
8.5	16.3±.03-j3.1±.04	0.73
9.0	13.7±.01-j2.8±.02	0.70
9.5	12.3±.10-j2.6±.01	0.70
10.0	12.0±.02-j2.4±.03	0.70
10.5	12.0±.02-j2.5±.02	0.64
11.0	12.3±.02-j2.3±.01	0.66

Table 8. Permittivity, and depth of penetration results for 33% carbon rubber (horizontal polarization).

Frequency (GHz)	Complex Permittivity	Penetration Depth (cm)
8.0	21.2±.08-j4.5±.04	0.61
8.5	17.5±.06-j4.6±.05	0.51
9.0	15.8±.03-j4.0±.03	0.53
9.5	13.8±.03-j3.4±.02	0.56
10.0	12.0±.03-j3.4±.02	0.62
10.5	10.5±.03-j2.1±.03	0.67
11.0	9.6±.57-j2.5±.10	0.54

CONCLUSIONS

The measured dielectric constant of Kevlar at 10 GHz was compared to those reported by Du Pont Corporation, and very good agreement was obtained [5]. Permittivity values for vertical polarization are slightly higher than those at horizontal polarization due to the fact that the electric field in the former case is parallel to the fiber directions which causes more of the signal to couple into the sample and yield higher permittivity. However, the difference is not large which is due to the electrically nonconductive nature of the material.

For the carbon composite samples the results for both case show similar trends with some polarization sensitivity. The imaginary parts for all frequencies are very high due to the overwhelming presence of carbon which results in very small values for the depth penetration as expected. This clearly indicates that care must be taken in using microwaves (X-band) for defect detection in thick carbon composites.

The results for E-glass at both polarizations are very similar, and the imaginary parts are very small relative to the real parts. This is expected as glass is a very low loss material at these frequencies.

Reported dielectric constant value for glass is between 4, and 10 which agrees well with our measurements.[3].

Permittivity of rubber with 50% carbon black at 10 GHz has been reported to be around 17 - j5 [6]. A simple linear regression from 55% to 33% carbon content results in very close values to those obtained in our experiments. As expected, the depth of penetration is in fractions of centimeters due to the presence of carbon particles.

These results are crucial whenever microwave nondestructive techniques are to be used for defect detection, and evaluation of these materials. For example when an open ended waveguide probe is used to detect an abnormality in thick carbon composites at X-band, either a very sensitive receiver is needed, or an excess power must be transmitted into the sample to reach the abnormality.

ACKNOWLEDGMENT

The authors would like to express their thanks to Professor Donald Radford of the mechanical engineering department at Colorado State University for supplying the Kevlar, E-glass, and carbon composite samples.

REFERENCES

1. Ghodaonkar, D.K., V.V. Varandan, and V.K. Varandan, "A Free-Space Method for Measurement of Dielectric Constants and Loss Tangents at Microwave Frequencies," IEEE Transactions on Instrumentation and Measurements, vol. 37, no. 3, June 1989.
2. Zoughi, R., and M. Lujan, "Nondestructive Microwave Thickness Measurements of Dielectric Slabs Backed by Conducting Plates," Accepted for publication in the Materials Evaluation, 1990.
3. Cheng, D.K., "Field and Wave Electromagnetics," Addison Wesley, Reading, Mass, 1983.
4. Ulaby, F.T., R.K. Moore, and A.K. Fung, "Microwave Remote Sensing, Active and Passive, vol. I," Artech House, pp. 61-67, Dedham, Mass., 1981.
5. "Data Manual for Kevlar Aramid 49," pp. 47, Du Pont de Nemours & Company, Willmington, DE, May 1986.
6. Hashimoto, O., and Y. Shimizu, "Reflecting Characteristics of Anisotropic Rubber Sheets, and Measurement of Complex Permittivity Tensor," IEEE Transactions on Instrumentation and Measurements, vol. IM-34, no. 11, November 1989.