A Study on Dielectric Properties of Printed Circuit Board(PCB) Materials in the Frequency Range of 100MHz to 1GHz

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Abstract

This paper presents the results of studies made for measuring the relative complex permittivity of PCB sheet material in the frequency range of 100 MHz~1 GHz using vector network analyzer. A measurement cell was developed for this purpose using broad-band impedance method and the dielectric constant and loss tangent of two PCB sheet materials, glass-epoxy and teflon, were measured. The effect of copper cladding was studied.

I. Introduction

The performance of dielectric materials at RF is becoming more and more important with an increase in the use of electronic circuits operating at high frequencies. The relative complex permittivity of printed circuit board materials is an important parameter that affects circuit performance. The printed circuit board (PCB) is a low loss dielectric substrate made from glass epoxy, teflon or PE with copper cladding. Since the clock frequencies of computers are ever increasing to higher levels for high speed signal transmission, it is necessary to evaluate the dielectric properties of PCB-materials at RF. Besides the low frequencies, the range between 1 MHz to 1 GHz is of special interest. Several measurement techniques such as parallel plate method, coaxial line method and resonator method are reported for the determination of dielectric properties. A review of the various techniques for the determination of material parameters is given in reference[1].

For frequencies below 30 MHz, the parallel plate method is generally used. In this method, the admittance of a parallel plate capacitor with the material under study as dielectric is measured and the relative complex permittivity is calculated. The resonant methods using a network analyzer and a microstrip line on the PCB sheet, are suitable for frequencies above 1 GHz.

Recently a technique that enables the determination of complex impedances from a few Hz to a few GHz with one measuring set up has been reported[2]. This technique can be used to determine dielectric constant as well as loss factor using broad-band impedance measurement. Fig. 1 shows the frequency coverage of permittivity measurement methods[3].

In measurements in the RF range, phase variations and multiple reflections must be taken into account. Network analyzers are widely employed to make combined reflection and transmission measurements, which are then used to calculate the dielectric properties[4]. Broad-band impedance method used with a network analyzer generally involves the use of a matched measurement cell with the unknown impedance of samples inserted into a transmission line.

In an industrial environment, often, one needs to measure the deviation of the dielectric constant and loss factor from sample to sample in a large number of substrates of approximately the same dielectric constant and loss factor. Therefore, there is always a need for methods, which require simple sample preparation procedures and are applicable to broad-band determination of dielectric constant as well as loss factor, possibly at different temperatures.

In this paper, we present the results of our studies utilizing broad-band impedance method for the measurement of the complex permittivity of PCB materials. No data on the dielectric properties of PCB materials studied were available in the frequency range of 100 MHz to 1 GHz. We therefore used, for comparison purposes,

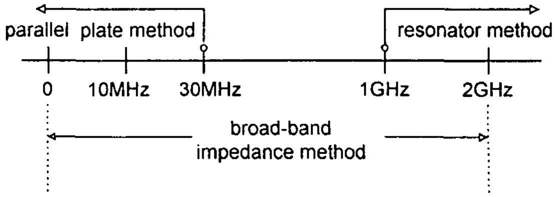

Fig. 1. Frequency coverage of permittivity measurement methods.

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a method involving microstrip lines in which the major sources of error are eliminated[5] for the determination of the dielectric constant of the PCB materials.

During this study a measurement cell for broad-band impedance method was developed and the complex permittivity of PCB materials, teflon and glass-epoxy, were measured using this cell.

Ⅱ. Broad-band Impedance Method

In this method, a measurement cell is inserted into a transmission line which is connected to a signal source and the detector of a network analyzer that automatically measures the amplitude and phase of the transmission coefficient.

A block diagram of the experimental setup to measure the transmission coefficient of RF signal through the PCB sheet samples in measurement cell is shown in Fig. 2. A measurement cell is connected to two ports of the network analyzer via coaxial transmission line.

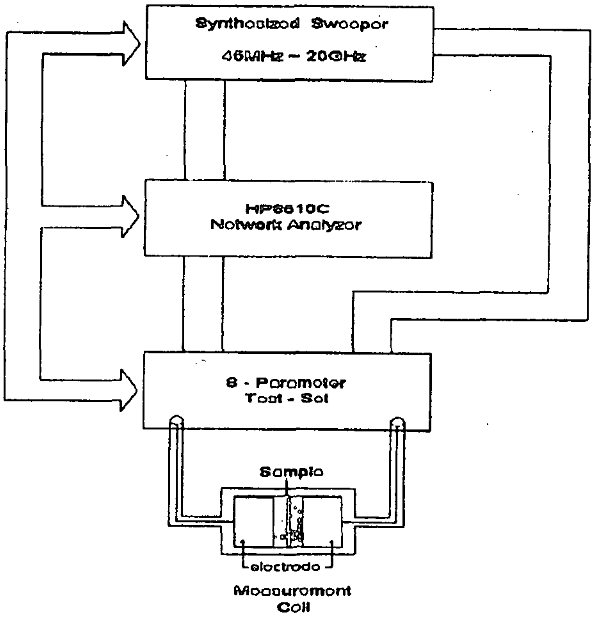


Fig. 2. Block diagram of the experimental setup for broad-band impedance method.

This measurement cell is a coaxial transmission line made up of a pair of inner electrodes at a constant distance from an outer conductor, which operates as a shielding cover. The configuration of the measurement cell is shown in Fig. 3. The characteristic impedance of a coaxial line is given by

$$Z_0 = \frac{377}{\sqrt{\varepsilon_r}} \ln(D/d) \tag{1}$$

where ε_r is permittivity of the dielectric material between the conductors, D is the inside diameter of the outer conductor and d is the outer diameter of the inner conductor.

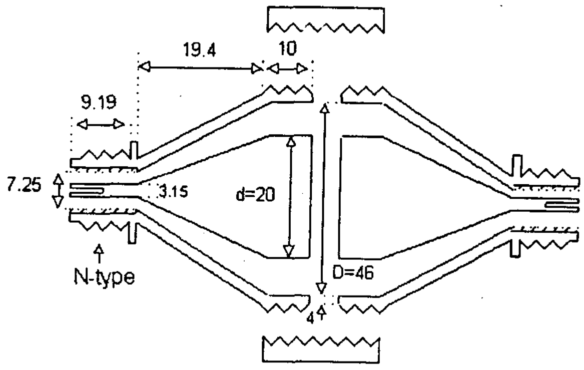


Fig. 3. Configuration of the developed measurement cell.

The characteristic impedance of the coaxial line is governed by the ratio of the diameters. We have designed a conical shaped coaxial line for obtaining same characteristic impedance throughout the length. For suitable connection of the measurement cell, the ports of the measurement cell are made of N-type connector. The cylindrical sample is held between the circular electrodes. For the configuration of the cell used (Fig. 3) the characteristic impedance is the same at any cross section, so that reflections are minimized.

The maximum measurement frequency (f_{max}) is limited by the geometry of the measuring cell. Considering capacitor plates, sample and cylindrical shielding cover as a part of a coaxial air line, the following condition must be satisfied in order to ensure that the altered electromagnetic field distributions due to higher order modes do not affect the measurement[6].

$$f_{\max} \leq \frac{C}{\pi(r_c + r_{sh})} \tag{2}$$

where r_c is the radius of circular capacitor plates, r_{sh} is the inner radius of the shield and c is the speed of light.

The broadband impedance measurement involves the following steps:

a) an unknown impedance Z of samples, which has to be determined, is inserted between the two electrodes of the measurement cell, which have a fixed distance during the measurement, and the resulting transmission coefficient S_{21m} of the transmission path is measured

b) two impedances Z_a and Z_b with different known values are realized in succession between the same electrodes as described in (a) having the same distance as described in (a) in the place of the unknown impedance Z, and the two corresponding transmission coefficients of the transmission path, S_{21a} and S_{21b}, are measured in succession.

c) the value of the unknown impedance of samples is calculated from the three measured transmission coefficients and from the values of the two known impedances using the following relationship:

$$Z=\frac{Z_aS_{21a}(S_{21b}-S_{21m})+Z_bS_{21b}(S_{21m}-S_{21a})}{S_{21m}(S_{21b}-S_{21a})} \tag{3}$$

where Z_a is chosen to be a cylindrical metallic short of length d_s *equal to* d *the thickness of sample and radius* r_c. Therefore $Z_a = 0$ holds. Z_b is realized by the impedance of the unloaded plate capacitor(air gap between electrodes) with the same distance d between plates.

If C_b is the capacitance of the unloaded capacitor, $Z_b = 1/j\omega C_b$. The value of C_b is real and independent of frequency[6], provided

$$f < \frac{0.3c}{2\pi r_c} \tag{4}$$

In this study the frequency varies from 100 MHz to 1 GHz and the above condition is satisfied. Therefore, Eq. (3) can be reduced to

$$Z = Z_b\frac{(S_{21a}/S_{21m})-1}{(S_{21a}/S_{21b})-1} \tag{5}$$

The complex permittivity ε_r^* is given by

$$\varepsilon_r^* = \frac{(S_{21a}/S_{21b})-1}{(S_{21a}/S_{21m})-1} \tag{6}$$

III. Experimental Results and Discussion

The dielectric constants of the materials under study were first determined using the microstrip line method. Two 50 ohm microstrip lines were etched on the PCB sheet material under study; one of them was 3cm long and the other 10cm. The connectors were fastened on to the substrate before the substrate was tested. The transfer phase shift Φ through each of the two microstrip lines was measured using HP8510C network analyzer, in the frequency range of 100 MHz to 1 GHz. The electrical lengths were calculated from the phase shifts measured using the network analyzer.

The major sources of error in this method are in the accurate determination of the physical length due to the uncertainty in the position of the probe connections at the connectors and connector mismatch errors. End launcher connectors give more reliable results than surface launcher connectors. The electrical length difference ($\triangle l_e$) and the physical length difference ($\triangle l_p$) between the two lines are used to determine the effective dielectric constant. The major sources of error mentioned above were eliminated by the above procedure because all the four coaxial-to-microstrip transitions are identical.

$$\triangle l_e = \frac{(\Phi_2-\Phi_1)\cdot c}{2\pi f} = \sqrt{\varepsilon_{eff}}\,\triangle l_p \tag{7}$$

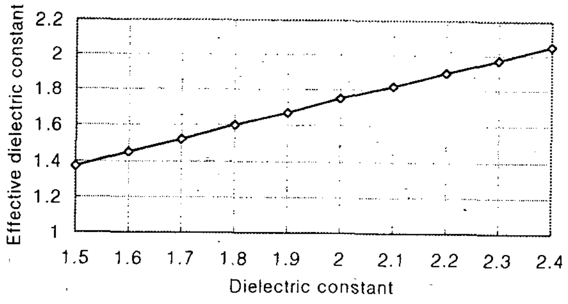
where Φ_2 is the phase shift of the longer microstrip line and Φ_1 is the phase shift of the shorter microstrip line.

From the effective dielectric constant of the microstrip line the dielectric constant of the substrate at any given frequency is calculated using a RF and microwave circuit analysis program TOUCHSTONE marketed by Eesof, Inc.

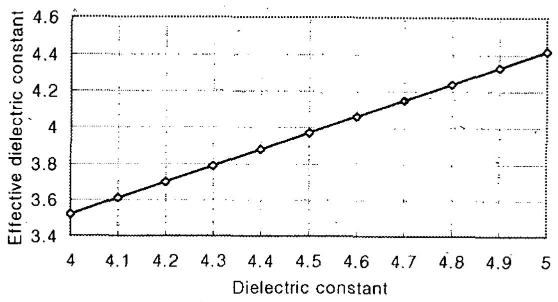
Fig. 4 shows the relationship between the dielectric constant and the effective dielectric constant for teflon and glass-epoxy substrates as obtained from the analysis program.

In Fig. 5 the variation of the dielectric constants of these substrates in the frequency range of 100 MHz~1 GHz are shown. For glass-epoxy sample, the dielectric constant is seen to slightly decrease with increase in frequency. But the dielectric constant of teflon substrate is seen to remain constant in this frequency range.

For the broad-band impedance method of measurement, cylindrical coaxial air line measurement cell[Fig. 3] which has inner conductor providing electrode plates of radius 10 mm and shield cover inner radius of 23 mm was used for the study. HP8510C network analyzer was used for measuring the transmission coefficients. Cylindrical samples of radius 10 mm were made from the PCB sheets under study. The thickness of the samples was 1.2 mm for glass epoxy and 0.8 mm for teflon. The measurements



(a) Teflon



(b) Glass-epoxy

Fig. 4. Relationship between the dielectric constant and the effective dielectric constant for teflon and glass-epoxy substrates.

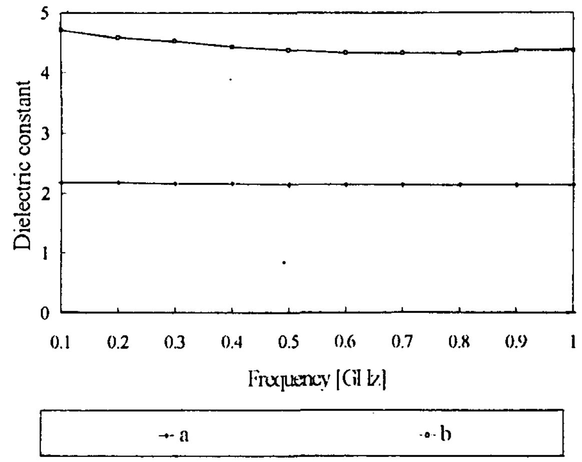


Fig. 5. Variation of the dielectric constants of (a) teflon and (b) glass-epoxy substrates with frequency-microstrip line method.

with teflon and glass-epoxy samples with and without copper cladding normally present on PCB sheets. Fig. 6 shows the variation of the dielectric constant of the teflon and glass-epoxy samples with frequency.

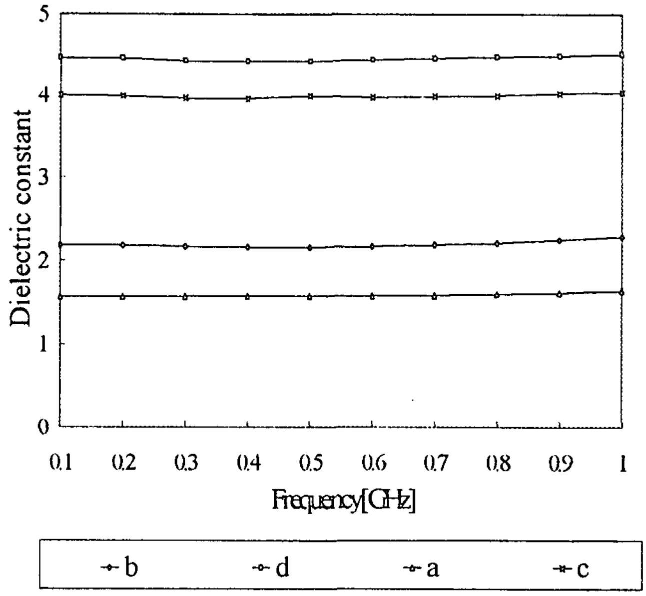


Fig. 6. Variation of the dielectric constants of (a) teflon without copper cladding, (b) teflon with copper cladding, (c) glass-epoxy without copper cladding and (d) glass-epoxy with copper cladding with frequency-broad-band impedance method.

It is interesting to see from Fig. 6 that the values of dielectric constants of both teflon and glass epoxy with copper cladding closely agree with those values measured by the microstrip line method. The measured values obtained without copper cladding are much lower than those obtained with copper cladding. This can be attributed to the better contact between the substrate and the electrodes when copper cladding was present. This makes the preparation of the samples from the PCB sheets all the more simple, as no etching of the copper cladding is required.

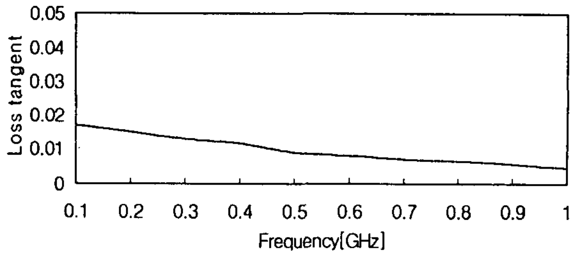


Fig. 7. Variation of loss tangent of glass-epoxy with frequency-broad-band impedance method.

The determination of loss tangent in the microstrip line method is not very practicable as the conductor (magnetic) losses become more predominant than dielectric losses at higher frequencies. To determine the dielectric losses, the magnetic losses must be known. Fig. 7 shows the variation of loss tangents of glass epoxy samples (with copper cladding) as obtained by the broad band impedance method. Considerable scatter was observed in the measured values of loss tangent in the case of teflon. This may be due to the very low dielectric losses in teflon. The loss tangent of glass epoxy was found to decrease with increase in the frequency of 100 MHz to 1 GHz.

IV. Conclusions

A measurement cell was developed for measuring the dielectric properties of PCB substrates using broad band impedance method. The results obtained using the cell and the broad-band impedance method closely agreed with those measured by the microstrip line method.

In the studied frequency range of 100 MHz to 1 GHz the variation of dielectric constants of glass-epoxy and teflon substrates with frequency was found to be small. The loss tangent of glass-epoxy substrate was found to decrease with increase in frequency. The measured values of loss tangent of teflon were found to be very small, the scatter being large.

The copper cladding of PCB substrates need not be etched out while preparing samples for the broad-band impedance method. In fact, removal of copper cladding results in lower measured values of dielectric constant. This makes the sample preparation from the PCB sheets easier.

Acknowledgement

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References

[1] M. N. Afsar, J. R. Birch and R. N. Clarke, The measurement of the properties of materials, Proc. IEEE, Vol. 74, No. 1, pp. 183-199, 1986.

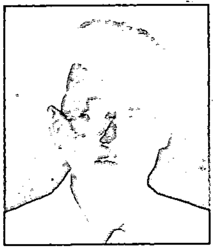
[2] R. Pelster, A novel analytic method for the broad band determination of electromagnetic impedances and material parameters, IEEE Trans. Microwave Theory and Tech., Vol. 43, No. 7, pp. 1494-1501, 1995.

[3] HP Solution Note 4291-4, Permittivity Measurements of PC Board and Substrate Materials using the HP 4291A and HP 16453A.

[4] H. J. Eul and B. Schiek, A generalized theory and new calibration procedures for network analyzer self-calibration, IEEE Trans. Microwave Theory and Tech., Vol. 39, No. 4, pp. 724-731, 1991.

[5] Nirod K. Das, Susanne M. Voda and David M. Pozar, Two methods for the measurement of substrate dielectric constant, IEEE Trans. Microwave Theory and Tech., Vol. 35, No. 7, pp. 636-641, 1987.

[6] S. F. Adam, *Microwave Theory and Applications*, 1st ed., Prentice-Hall, ch. 2.2, p. 42, 1969.



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