COMPLEX PERMITTIVITY MEASUREMENT OF SUBSTRATES USING RING RESONATOR

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Abstract

This paper deals with a complex permittivity measurement of dielectric substrates for planar circuits using ring resonator. This method is based on measurement of transmission and reflection coefficients of a transmission-type ring resonator with capacity coupling. Dielectric constant and the dissipation factor can be measured at wide frequency band by adjusting base resonant frequency of a ring resonator. Required parameters could be simply calculated according to information in this paper.

1 Introduction

Complex permittivity measurements are important in microwave engineering, material processing, as well as biomedical applications [1]. Recently, planar circuits, such as microstrip lines, coplanar waveguides, and strip lines have found their applications in complex permittivity measurements. Planar structures, which are lightweight, compact and low cost, have been successfully applied to the determination of substrate permittivity, material moisture etc. Planar circuit measurements are classified into resonant methods (with high accuracy and sensitivity) and non-resonant methods (broadband measurements). When high loss materials contact a planar circuit resonator directly, the resonance condition will not be hold. Therefore, the resonant measurement methods based on planar circuits are usually limited to low loss materials.

The term complex permittivity measurement means the measurement of relative permittivity ε_r and loss factor $tg\ \delta$.

Among the possible methods that are used for the measurement of dielectric parameters, we can place a measurements on the RLC Bridge, waveguide measurement, measurement in cavity resonators, measurement in free space and measurements on planar resonant structure.

When measuring method of the RLC Bridge is used, the dielectric substrate is metal coated on both sides form a plate capacitor. Knowing the elements of the equivalent circuit of the capacitor, which are the resistance *R* and the capacity *C*, complex permittivity of the material can be computed. This method can only be measured at low frequencies and it is necessary to dimensionally adjust the measured material.

Measurements in the waveguide also have its difficulties. The great disadvantage of this measuring method is the need for precise machining of the sample. When inserted into the waveguide there must not be air in the surroundings, otherwise we create an error in the measurement.

Measurement in the cavity resonator is also one of the very frequently used methods, but it belongs to the destructive ones, so this can be a problem in most cases.

Also, measurement is not possible in free space. This method has a non destructive nature, but the results are very approximate and also difficult to calculate. There is not an empirical formula from which the material parameters were calculated.

When choosing the measurement method, we have to take into account the non-destructive form of measurement. Therefore the most appropriate method is a modified resonance method. Out of all the possible structures of resonant circuits, resonant ring with the capacitive coupling has been chosen. Ring resonator has well-defined fields, and its structure can be easily computed. The measurement is based on the insertion of material between the measured ground plate and resonant ring. This ensures that the material may not be modified in any way and there is no threat of its destruction.

On the basis of the above mentioned methods, we concluded that the most appropriate method is the ring resonant circuit with a capacitive coupling.

2 Solution of the problem

Calculating electromagnetic field means solving Maxwell's Equations the fundamental equations of electrodynamics. Their notation in a differential form is given by the following equations, which we introduce in the form of general time dependence. From the group of equations (1-4), the first two are so-called main Maxwell equations and express the link between electric and magnetic field.

$$rot\mathrm{H} = \frac{\partial \mathrm{D}}{\partial t} + J_v . \tag{1}$$

$$rot\mathrm{E} = -\frac{\partial \mathrm{B}}{\partial t} . \tag{2}$$

$$div\mathrm{D} = \rho . \tag{3}$$

$$div\mathrm{B} = 0 . \tag{4}$$

Following three equations (5-7) are called the material equations in non homogenous environment.

$$\mathrm{D} = \varepsilon \mathrm{E} . \tag{5}$$

$$\mathrm{B} = \mu \mathrm{H} . \tag{6}$$

$$\mathrm{J_v} = \mathrm{J} + \sigma \mathrm{E} . \tag{7}$$

2.1 Derivation of complex permittivity

For harmonic excitation we can write Maxwell's equations in following form (8-11).

$$rot\mathrm{H} = \left(j\omega\varepsilon + \sigma \right)\mathrm{E} = j\omega\left(\varepsilon - j\frac{\sigma}{\omega} \right)\mathrm{E} . \tag{8}$$

$$\varepsilon * = \varepsilon' - j\varepsilon'' . \tag{9}$$

$$\varepsilon * = \varepsilon'\left(1 - jtg\delta\right) . \tag{10}$$

$$tg\delta = \frac{\omega\varepsilon'' + \sigma}{\omega\varepsilon'} . \tag{11}$$

Interaction between electromagnetic field and dielectric material is affected by the substrate dielectric constant ε, generally in complex form.

Complex permittivity of lossy environment is generally dependent on the frequency *f* and temperature *T* [2]. The dependence on the pressure and intensity of the electric field can be neglected compared to frequency. Fig. 1 shows the waveform of the complex permittivity in wide frequency range.

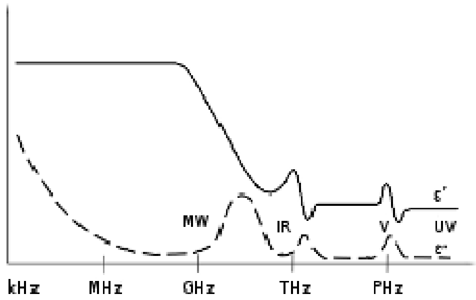

Figure 1: Complex permittivity over the wide frequency range.

3 Design of the resonator

Resonance structure can be seen in Fig. 2; this type is the best ring resonator setup that enables to achieve the best signal to noise ratio using the S_{21} parameter, making it possible to calculate the relative permittivity ε_r and material loss factor *tg δ*.

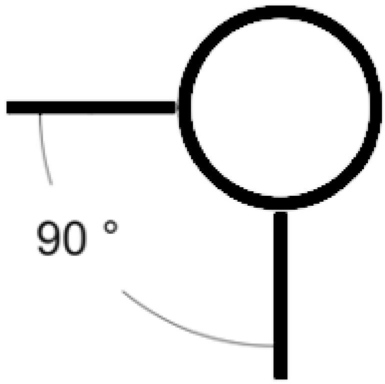

Figure 2: Basic scheme of the resonant ring structure.

Circuit consists of two supply microstrip lines that are turned against each other by 90°. This angle was chosen with respect to subsequent measurement method. In this measurement, we inserted measured material between resonant ring and ground plane.

The microstrip lines are connected to two subminiature version A (SMA) type connectors (see Fig. 3), and between the microstrip lines is placed the ring resonator separated by coupling spaces.

The ring has a resonance that is made by selecting the angle between the main microstrip lines [3], same as when choosing angle, 90° angle corresponds to the odd multiples of the fundamental resonant frequency will suppress, transfer will be minimal and even multiples of the fundamental resonant frequency passes through the circuit with the maximum transmission.

Such a two port circuit is described by the following equation (12-13) which expresses the relationship between resonance frequency and radius resonator.

$$2\pi r = n\lambda_g \,. \qquad (12)$$

$$r = \frac{n\lambda_g}{2\pi}. \quad (13)$$

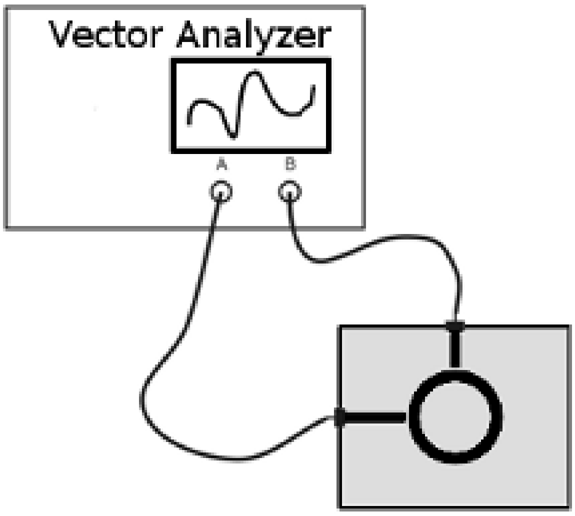

Figure 3: Setup of the measurement using the ring resonator.

4 Calculation

The basic idea used to calculate the relative permittivity is the relationship for calculating ε_{ef}, from which we obtain resonant frequencies of the effective permittivity.

$$\varepsilon_{ef} = \left(\frac{nc}{2\pi rf}\right)^2. \quad (14)$$

Then we determine the relative permittivity according to the following relationships using successive iterations [4].

$$\varepsilon_{ef}\left(f\right) = \varepsilon_r - \frac{\varepsilon_r - \varepsilon_{ef}\left(0\right)}{1 + G\left(\frac{f}{f_m^{TE_{10}}}\right)}. \quad (15)$$

Calculation of loss factor, as a function of frequency is based on the measurement of the loaded resonator's quality factor Q_L planar ring structure of the resonant ring and measuring the resonant frequency. Load loss factor Q_L can be obtained from the decrease of transmission curve S_{21} by 3 dB, (see Fig. 4).

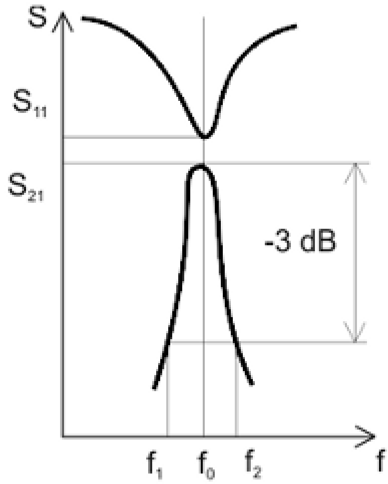

Figure 4: Resonant curve.

The resulting equation for calculating the loss-factor is as follows:

$$tg\delta = \frac{\beta_d \cdot \sqrt{\varepsilon_{ef}}\lambda_0 \cdot (\varepsilon_r - 1)}{\varepsilon_r \left(\varepsilon_{ef} - 1\right) \cdot 27,3}. \tag{16}$$

During the course of development, we have designed MATLAB scripts and graphical user interface for ease of calculation.

5 Conclusions

Complex permittivity was measured on several material samples. The two of them were available to the manufacturer's catalog value, which has been verified that the calculated values correspond to the values introduced by the manufacturer.

Tabulka 1: COMPARISON OF THE MANUFACTURER GIVEN VALUES AND OUR MEASUREMENT.

Manufacturer		*Our measurement*	
ε_r	tg δ	ε_r	tg δ
2.56	0.017	2.52	0,015
2.53	0,027	2,49	0,026

Knowledge of the complex permittivity of substrates is essential for design of microwave circuits.

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0021620806 Studies at the molecular and cellular levels in normal and in selected clinically relevant pathologic states.

References

[1] VORLÍČEK, J. VRBA, J.: *Coaxial Probe for Measuring Complex Permittivity of Biological Tissues*. In 25th Annual Meeting of the European Society for Hyperthermic Oncology - Abstract Book. Verona: Ospedale Borgo Trento, U.O.Radioterapie, 2009, p. 59.

[2] SUZUKI, H.: Microwave Measurement of Complex Permittivity by Placing a Microstripline Resonator on the Material under Test. Proceedings of the 36th European Microwave Conference, Manchester 2006.

[3] HEINOLA, J. M., UTTI, K. P., STROM, J. P., KETTUNEN, M., SILVENTOINEN, P.: A strip line ring resonator method for determination of dielectric properties of printed circuit board material in function of frequency, 2004 Annual Report Conference on Electrical Insulation and Dielectric Phenomena, 2004.

[4] SVAČINA, J.: Řešení mikrovlnných planárních struktur metodou konformního zobrazení.Akademické nakladatelství CERN, 2006.

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