Non-destructive characterization of dielectric materials by microwave spectroscopy in LS band

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The paper describes the characterization of dielectric materials, by using a resonance based ring-resonator method. A microstrip ring resonator (MRR) method is presented to measure effective dielectric constant (ε_{reff}) of composite laminate materials. Multilayer structure of MRR is designed and simulated using Ansoft's High Frequency Structure Simulation. Comparative study of polytetrafluoroethylene (PTFE), ceramic and ceramic-PTFE composites have been carried out to analyze the ε_{reff} along with its dependence on sheet thickness. From results, it is clearly observed that as the thickness of overlay is increased there is significant change in effective permittivity, which is more noticeable for high-permittivity ceramic material than low-permittivity PTFE material. Measured data is found in good agreement with the reported data.

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1. Introduction

Electric properties of materials are now widely used in various industrial applications. By utilizing these properties, new advancements and trends are introduced in agriculture, material characterization, chemical, geo-sciences, bio-engineering and pharmaceuticals for development of quality products. For the dielectric properties the main parameter is the complex permittivity (ε*) which describes the behavior when it is subjected to an electromagnetic field which is defined by [1]

$$\varepsilon * = \varepsilon' - j\,\varepsilon'' \qquad (1)$$

where, j = −1, ε′ is the real part called dielectric constant or dielectric permittivity which represents the ability of material to store energy when an external electric field is applied and the ε″ is an imaginary part, called loss factor which shows the energy dissipation of a material to an external electric field [2]. The ratio between dielectric constant (real part) and loss factor (imaginary part) of permittivity describes the parameter called, tangent-loss or dissipation factor. The tangent loss ($tan\delta$) represent the energy lost per cycle divided by energy stored per cycle [3]

$$tan\delta = \frac{\varepsilon''}{\varepsilon'} \qquad (2)$$

The loss mechanism is based on another important parameter that is conductivity (σ). Conductivity is the ability of a material to conduct an electric current and it is measured by conducting a known amount of current at constant voltage [4].

Knowledge of these parameters is essential to understand the behavior of dielectric material in the presence of high electromagnetic fields. This information can be used to design high performance RF and microwave circuit and components. The substrate materials are the vital part of high frequency circuits. The main driving force behind, the characterization of substrate material is to improve high-speed digital signal propagation. In addition to substrate materials, fabrication of other microwave circuits often requires a low to moderate permittivity multilayer materials. The multilayer microwave laminate composite materials provide effective and low loss signal propagation throughout the circuit. Ultimately, to design a good quality and high-speed microwave circuit requires a rapid and high accuracy method for the electrical characterization of printed circuit substrates. In literature different methods are used for the characterization of printed circuit substrate, ceramics, laminate, thin-films and foam materials.

In order to determine the dielectric properties of any material, no single technique can characterize all materials over entire frequency band. A measurement with accuracy for both types (lossy and low-loss) of materials is challenging so for each band and their subsequent losses require separate methods. Among various techniques using microwaves; one of the most important technique is resonance method. It is simple, cost-effective and fast (in terms of time) even having higher Q-factor (about 250) than conventional one. Application of ring resonators in characterizing the dielectric properties of materials is not a new idea, they have been used to investigate the moisture content in soil [5] and meat [6], for characterization of materials a higher-order mode ring resonator demonstrated in [7]. Using ring-resonator dielectric measurements of FR-4 substrate, plastic and clay are found very close (2.27%) to published literature [8]. Measurements for printed circuit board material using microstrip ring resonator shown very accurate results over wide frequency band [9]. Sensing for the small amount of liquid solvents presented in [10] and found very useful to identify the impurities in the solution. Results from this technique are validated with other approaches and it shows that noticeable shift in the resonant frequency and the changes in the quality factor are the good indicators.

Therefore, in this study the aim is to utilize the microstrip ring resonator technique for the evaluation of thick-sheet composite materials. The effective dielectric constant (ε_{reff}) is determined for different composite materials and the obtained data is validated with the reported literature.

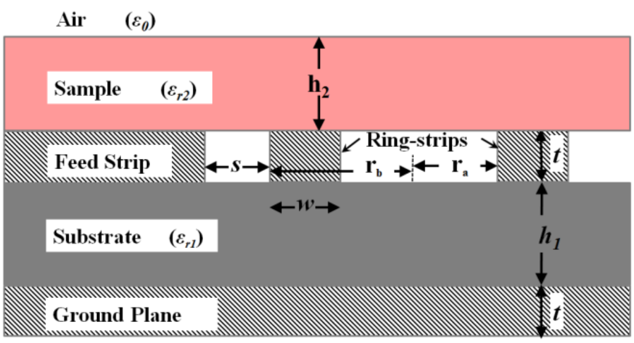


Fig. 1. Side view of proposed multilayer microstrip ring-resonator

2. Theoretical analysis

Dielectric characterization using microstrip ring-resonator is based on a fact that, any change in effective permittivity cause changes in resonator's resonant frequency [11]. In other words, the placement of overlay dielectric layer modifies the air-boundary of a resonator that changes the effective permittivity, thereby shifts the resonant frequency. Theoretically, the resonance is produce when mean circumference of ring is equal to an integral of the guided wavelength [8, 12]

$$2\,\pi\, r = n\,\lambda_g \qquad \text{for } n = 1,2,3\ldots \tag{3}$$

where, n is the mode number, λ_g is the guided wavelength and r is the mean radius of ring. The resonant frequency can be determined for n modes from this equation. Since, λ_g is frequency dependent, thus for microstrip ring-resonator it can be related to frequency by

$$\lambda_g = \frac{\lambda}{\sqrt{\varepsilon_{eff}}} = \frac{1}{\sqrt{\varepsilon_{eff}}}\,\frac{c}{f} \tag{4}$$

where, ε_{eff} is the effective dielectric constant and c is the speed of light. Considering (3) with λ_g will give

$$f = \frac{n\,c}{2\pi\, r\,\sqrt{\varepsilon_{eff}}} \tag{5}$$

By re-arranging the equation (5), the effective permittivity of the ring-resonator can be obtained from

$$\varepsilon_{r\,eff0} = \left(\frac{n\,c}{2\,\pi\, f_0\, r_m}\right)^2 \tag{6}$$

Once the effective permittivity of the unloaded resonator is determined, the effective permittivity of the loaded sample can be evaluated. For this purpose, same test configuration of multilayer resonator is used that shown in Figure 1. It can be seen that, substrate has a thickness is h_1 with its dielectric constant ε_{r1}, the printed circuit of ring and ground plane have thickness t, overlay testing sheet material has dielectric constant of ε_{r2} with the thickness h_2 and on top of structure the air with dielectric constant ε_{r3} of 1. Ultimately, determination of effective permittivity with an overlay test material (that is the, loaded-resonator), can be calculated by [11]

$$\varepsilon_{r\,eff1} = \varepsilon_{r\,eff0}\left(\frac{f_0}{f_1}\right)^2 \tag{7}$$

The evaluation of effective permittivity is widely discussed in literature [13, 14]. A numerical model is presented in [14], to evaluate the effective permittivity in the presence of an overlay dielectric layer on microstrip structure. The method is validated, both experimentally and numerically, for a thick-sheet overlay. The expression for a line capacitance is given by

$$\frac{1}{\mathrm{C}} = \frac{1}{\pi\varepsilon_0 \mathrm{Q}^2}\int_0^\infty \frac{[f(\beta)]\mathrm{e}^2}{\left(\varepsilon_{r1}\dfrac{\varepsilon_{r1}tanh(\beta h_2)+1}{\varepsilon_{r1}+\tanh(\beta h_2)}+\varepsilon_{r2}coth(\beta h_1)\right)(\beta h1)}\,d(\beta h_1) \tag{8}$$

where, ε_{r1} is permittivity of substrate, ε_{r2} is permittivity of superstrate, h_2 is thickness of a superstrate, and h_1 is substrate thickness, β is Fourier variable and $f(\beta)/Q$ is the Fourier transformation of charge distribution function $f(x)$, which is obtained from Yamashita's variational method [13], it is given as

$$\frac{f(\beta)}{\mathrm{Q}} = 1.6\left(\frac{sin\left(\frac{\beta w}{2}\right)}{\frac{\beta w}{2}}\right) + \frac{2.4}{\left(\frac{\beta w}{2}\right)^2}\left(cos\left(\frac{\beta w}{2}\right) - \frac{2\,sin\left(\frac{\beta w}{2}\right)}{\left(\frac{\beta w}{2}\right)} + \frac{sin^2\left(\frac{\beta w}{4}\right)}{\left(\frac{\beta w}{4}\right)^2}\right) \tag{9}$$

From equations (8) and (9), the capacitance C can be evaluated, C_0 can be determined by replacing permittivity of both layers to permittivity of air. Thus, the effective permittivity can be evaluated by

$$\varepsilon_{eff} = \frac{C}{C_0} \tag{10}$$

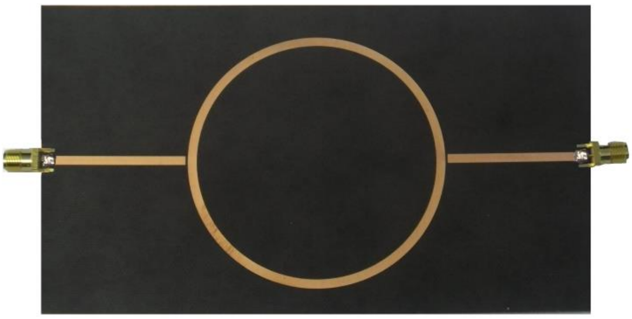


Fig. 2. Fabricated prototype of two port microstrip ring-resonator

Table 1. Microstrip Ring Resonator Design Parameters

Parameter	Design Value
Roger RT/Duriod 5880	ε_{r1} = 2.2
Substrate height	h_1 = 787 mm
Dissipation factor (DF)	$\tan\delta = 9\text{x}10^{-4}$
Copper thickness	t = 17.5 µm
Frequency	f = 1 GHz
Chrac. Impedance	Z_o = 50 Ω
Feed line length	l = 35 mm
PTFE Composites (Sample A)	ε_{rA} = 2.1
Ceramic laminates (Sample B)	ε_{rB} = 3.55
Ceramic-PTFE composites (Sample C)	ε_{rC} = 6.15

3. Experimental

3.1 Design and development of ring resonator

The lower band of microwave frequencies provides some distinct features than millimeters waves. Therefore, in this study for dielectric measurements the L-band frequencies are used. The ring-resonator is designed on fundamental frequency of 1GHz, which yields the radius of r=34.85mm, considering equation (5). The Roger RT/Duriod 5880 material substrate, with dielectric constant of 2.2 and height of 787µm is used to design the ring-resonator. The substrate permittivity, its height, its dissipation factor, copper thickness and line impedance from Agilent ADS LineCalc tool, width of annular ring and effective permittivity are calculated as w=2.40mm and ε_{eff} = 1.875, respectively. A 35mm long feed line with the coupling gap of 200µm connected to the ring with an outer radius of 34.85mm and the conductor thickness taken as 17.5µm. Width of feed line and ring strip calculated as 2.40mm for the characteristic impedance of 50Ω using Agilent ADS software. The total size of the circuit is 141×87.5mm, as sufficient space retained to both sides of ring to strengthen the electric field at ring edges. All design parameters of microstrip ring resonator are listed in Table-1. The fabricated prototype of two-port microstrip ring resonator is shown in Fig. 2.

3.2 Measurement of substrate materials

To study the overlay dielectric materials and their thickness effect on the permittivity, a microstrip ring resonator with multi-layer configuration is used. The structure of ring-resonator is designed in Ansoft's High Frequency Structure Simulation (HFSS) software. After necessary setup procedures, the simulation is carried out up to four periodic resonances. The simulation results are initially analyze in unloaded condition and subsequently, with sample loaded resonator. For loaded resonator three different dielectric materials used; glass microfiber reinforced PTFE composites with a dielectric constant of ε_{rA} = 2.1, hydrocarbon ceramic laminates with a dielectric constant of ε_{rB} = 3.55 and ceramic-PTFE composites with a dielectric constant of ε_{rC} = 6.15 used as a test material, data has taken form open literature [15]. A sheet material is placed on the top of the ring-resonator. Different thicknesses of these samples are then simulated with the range from 500µm to 1400µm with each step-increment of 100µm. The typical experimental setup is illustrated in Figure 3, in which two-port ring-resonator is connected with vector-network analyzer and accessible with personal-computer.

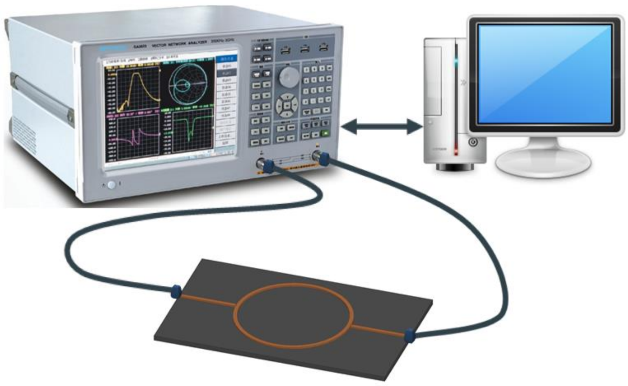
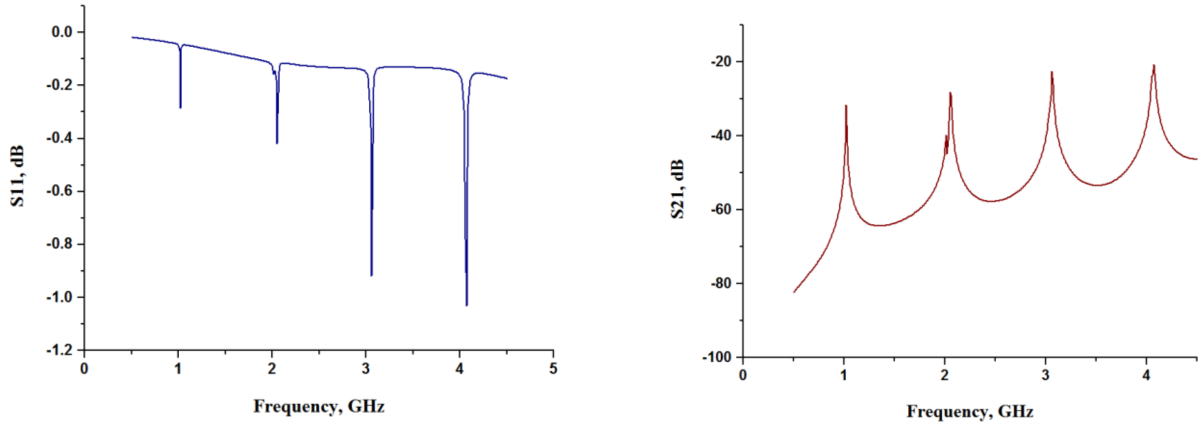


Fig. 3. Illustration of microstrip ring resonator connected with vector-network analyzer

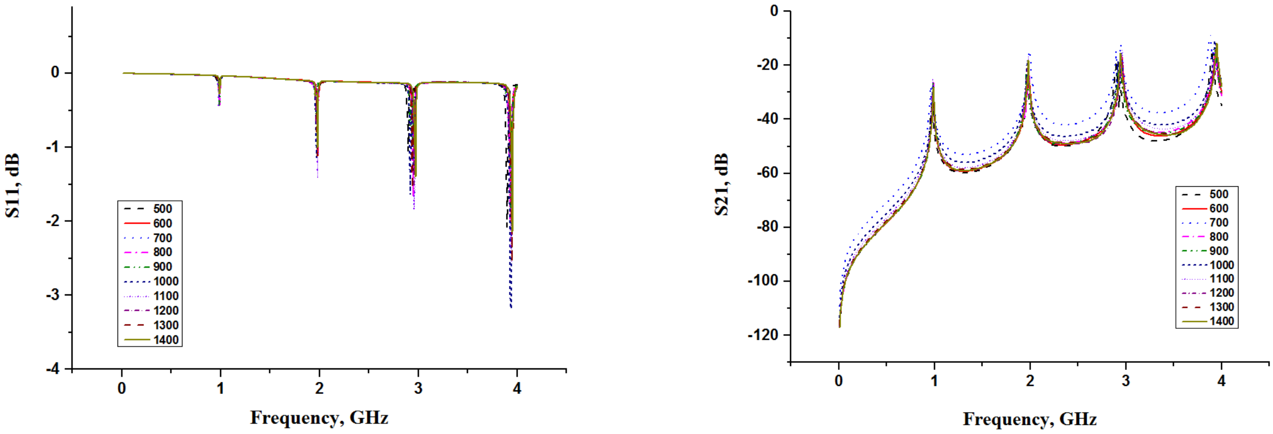
4. Results and discussion

In this section, effective permittivity of microwave laminate materials and the effect of their thicknesses are investigated. Simulated results of S_{11} and S_{12} parameters of microstrip ring-resonator without overlay material are shown in Figure 4. Periodic resonances with 1GHz interval are observed in unloaded condition. For the



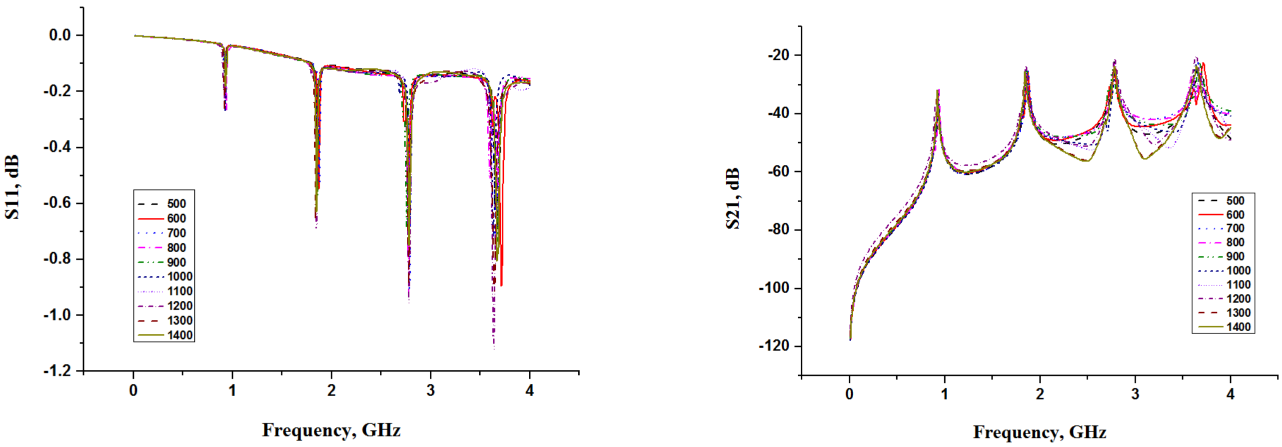
(a) *(b)*

Fig. 4. Resonance frequency response of microstrip ring-resonator without the test material (a) S_{11} parameter (b) S_{12} parameter



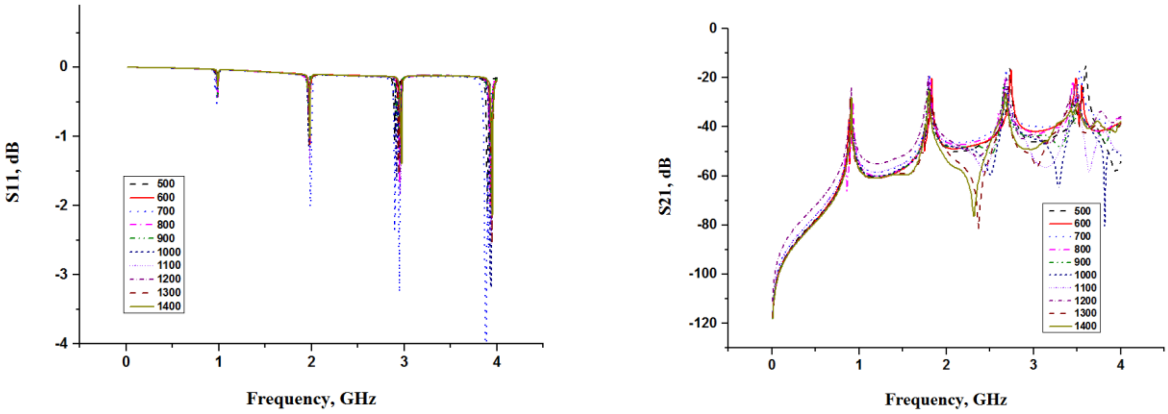
(a) *(b)*

Fig. 5. Resonance frequency response of PTFE as overlay test material (a) S_{11} parameter (b) S_{12} parameter, as function of thickness



(a) *(b)*

Fig. 6. Resonance frequency response of ceramic as overlay test material (a) S_{11} parameter (b) S_{12} parameter, as function of thickness



(a) *(b)*

Fig. 7. Resonance frequency response of ceramic-PTFE as overlay (a) S_{11} parameter (b) S_{12} parameter, as function of thickness

unloaded resonator, it shows the periodic resonances occur at 1GHz intervals. The 1st resonance occurs at 1.02GHz while 2nd resonance is produced at 2.05GHz and then 3rd resonance is at 3.06GHz and the last 4th resonance is at 4.07GHz. In obtained results, the shift in resonance frequency is determined by considering the insertion loss i.e. S_{12} parameter than return loss i.e. S_{11} parameter. This is mainly due to the two port network, in which more emphasize, is on appeared resonances, that are dependent on dielectric overlay material.

In Fig. 5, results shown for glass microfiber reinforced PTFE composites as dielectric overlay material with the thickness vary from 500µm to 1400µm. For PTFE composites with low permittivity and the low loss characteristics ($tan\delta$ = 0.0009) it exhibit 1% frequency shift in S_{12} parameter from its resonance frequency for 500µm thickness at 1st resonance whereas at 4th resonance this frequency shift reached up to 2.5%. For the increased thickness, with 1400µm sample at first resonance a 2% frequency shift is observe while at fourth it becomes 1.3%. For the entire range of thickness, there is small variation in 1st to last, 4th resonance. It is evident from the results shown in Figure 6 for hydrocarbon ceramic laminates material that, due to higher permittivity and lossy nature ($tan\delta$ = 0.0021) of ceramics the frequency shift is higher than PTFE. While using 500µm sample it exhibits 7% shift at first resonance and this shift increases up to fourth resonance with 8% shift. Similarly for thickness of 1400µm with 0.92GHz loaded resonant frequency it shown around 8% drift from unloaded resonant frequency at first resonance while at fourth resonant this shift goes up to 8.8%. Ceramic materials show higher variation with respect to thickness, after 2nd resonance variation is high and at 4th resonance it's become higher. It can be further seen from Figure 7 that microwave laminates that are developed from ceramic-PTFE composites has higher frequency shift. When the combination of ceramic-PTFE is used as a test material, for the 500µm sample thickness, first resonance shows 9% shift from resonant frequency and for the fourth resonance this shift is increased up to 10%.

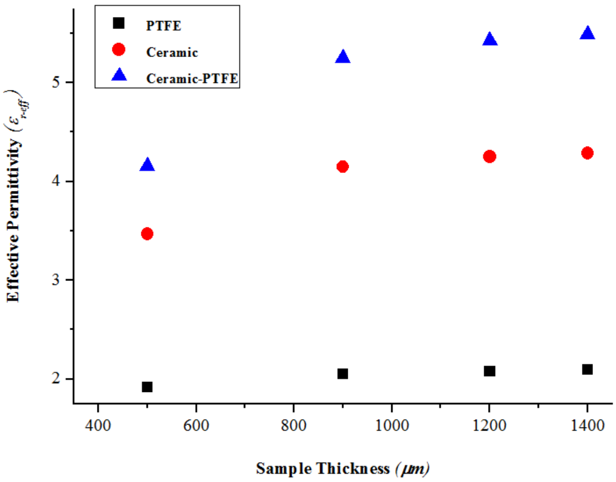


Fig. 8. Measured effective permittivity of the PTFE, ceramic and ceramic-PTFE composites materials.

When the sample thickness is increased up to 1400µm the change in frequency shift has also been observed. At the 1st resonance for the thick sample, frequency shift was 10.3% and similarly for the fourth resonance this shift increased up to 14.5%. Ceramic-PTFE material has shown higher variation than alone PTFE and ceramic materials. In this case, as thickness increases, variation in resonance is also significant in successive resonances. This can be seen in S_{11} and S_{12} responses of all three samples, the response (in dB scale) seems very lossy, the factors other than test material are the, loose coupling between feed and the ring, losses itself in substrate and the air-gap.

In the view of above results it is clearly observed that, for the low-permittivity and low-loss dielectric overlay materials, the obtained shift in frequency is minimal. However, as high-permittivity and high-loss overlay materials are used as overlay, the shift in resonance frequency is further increased. Ultimately, measurements are taken to validate the simulation results. The materials that are commercially available from vendor (Roger corporation), such as PTFE material that is RT5880, ceramic material that is RO4000 and the ceramic-PTFE material that is RT6006, are used for this purpose. The measured effective permittivity is shown in Figure 8 as a function of thickness. The high-permittivity and high-loss material ceramic-PTFE (RT6006) exhibits higher variation in effective dielectric constant ε_{reff} than its low-permittivity and low-loss counterparts. However, variation in effective permittivity is reduced for the thick sheets. The measured data are found in good agreement with the data provided by the Rogers Corporation [16].

6. Conclusion

This paper presents the dielectric characterization of microwave composite laminate materials using the ring-resonator method. During this study it is observed that a material with low-permittivity and low-loss, such as PTFE, exhibits small variation in resonant frequency as a function of sample thickness, even this variation is not so significant in its successive resonances. In contrary, the moderate-permittivity and moderate-loss material such as ceramic exhibited obvious changes in resonant frequency. In addition to these materials, a high-permittivity and high-loss material, such as ceramic-PTFE this variation becomes significant. Even it shows much higher variation in its successive resonances. Thus it can be conclude that the effective dielectric constant of high-permittivity and high-loss material is more sensitive to thickness than low-loss materials and this change is more obvious on higher frequencies.

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