International Journal of Advanced and Innovative Research (2278-7844) / Volume 7 Issue 6

Non-Destructive Equation Based Method for The Dielectric Characterization of Material Using Resonator

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***Abstract*— Material measurement is a very important step to be conducted before integrating materials in components and devices. The method used here is a mono-frequency method using Microstrip Ring resonator (MRR). The material to be measured is placed on the MRR device in a way, the MRR sandwiched between the substrate and the material to be measured thus forming a Non-destructive measurement. The method uses the MRR as a sensor with specific dimensions and specific equation characterizing the relation between its dimensions, layer thicknesses and permittivity of the layers. The inverse problem to extract the permittivity of the unknown material is an equation based one. The results of measurement are compared to those of finite element method simulation software and the error is non-significant.**

Keywords— **permittivity measurement, dielectric, this films, microstrip ring resonator, transmission line, monofrequency.**

I. INTRODUCTION

Material Characterization is an essential procedure in the domain of materials science, without which no logical comprehension of designing materials can be found out. Several definitions terminate the term's use to techniques which examine the microscopic structure and the characteristics of materials [1-3]. Dielectric properties measurements form the scope of this paper.

Many methods to characterize materials exist such as reflection methods, free space measurement methods, transmission line, Resonators, capacitive, etc. The most familiar are Resonance methods known to be accurate than any other techniques for low loss materials.

There are two main sorts of permittivity measurements strategies: "destructive" and "Non-destructive" methods. A destructive one is performed and the material under test cannot be reused again in applications. While in Non-destructive methods, the material tested can be re-used in applications. The non-destructive techniques are less expensive to execute and simple to manufacture.

Nowadays, most electrical equipment consists of dielectric materials, each one specified by different values of permittivity and conductivity. Material measurement is a very important step to be conducted before integrating these materials in some applications. The method used here to extract the permittivity is Microstrip Ring Resonator. To extract permittivity, the ring resonator is sandwiched between 2 materials (non-destructive strategy), while one of the materials is unknown and need to be found. The measurement will be conducted at the resonant frequency.

In this work S11 and S21 parameters are extracted to find the resonant frequency and an equation based inverse problem is used to extract the permittivity of the material.

II. II. SYSTEM DESIGN

Every material has a special series of electrical characteristics that are dependent on its dielectric properties. So the using of these measurements are precise then it can give researchers and architects commendable data to legitimately use a material into a specific application from high speed circuits to satellite and telemetry application.

There are different methods of dielectric properties measurements like non-resonant and resonant methods [4-6]. Resonant methods do not have a sweep frequency capability for the measured frequency, but they are considered more accurate than any other techniques for low loss material and they have possible Q-factors and results in very high sensitivity. So the resonators can be used as sensors of different physical quantities which depend upon dielectric constant like complex permittivity of MUT. A ring resonator structure on a printed circuit board (PCB) can be utilized to deduce the complex permittivity ∈ of the substrate material. The measurement rely on S21 parameter of a two-port ring resonator to determine the ∈ of the board substrate.

The goal is to extract the unknown permittivity of any material using microstrip ring resonator (MRR) [7-8] after making several simulations with the ring sandwiched between the 2 materials (Non-Destructive).

A. *System Specifications*

A design MRR-Ferro is designed using HFSS 3D EM software, High frequency structural simulator. It gives high performance field wave for EM field.

B. *Hardware Specifications*

Microstrip Ring resonator
Substrate material (low part): sapphire, MgO
Substrate + thin film: MgO + Ferro
Ring and transmission lines: gold
Two parameters are varied under simulator:

- Height of substrate = 'e' different values from (0.5 to 10 um at step unit=0.5um)
- Real permittivity =" ∈ " (different values from 50 to 350 at step unit=50)

III. Theory of Ring Resonator

This section presents a theoretical analysis for a ring resonator-based method for the estimation of complex dielectric permittivity of materials. This structure comprises of transmission lines and a ring printed on a dielectric substrate.

A ring resonator [9-10] is primarily comprised of a transmission line forming a closed loop and can be implemented using Microstrip as shown below in the Fig.1.

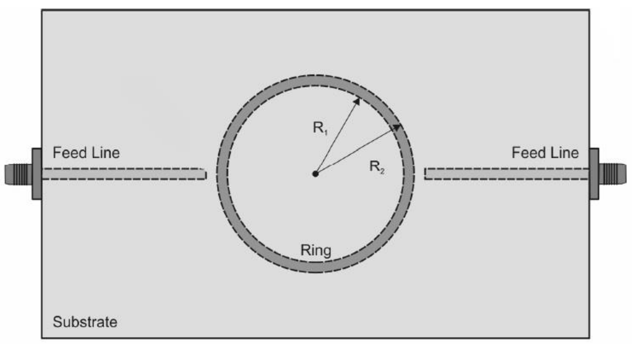

Fig. 1: Planar Ring Resonator structure.

The resonance of this resonator follows the below condition:

$$2\pi rm\,.\beta = 2n\pi \quad (1)$$

With n = 1, 2, 3…. and "β" the phase constant along the microstrip line defined by:

$$\beta = n\pi / l \quad (2)$$

Where "l" is the resonance length related to the wave length

$$\lambda_d = \frac{\lambda}{\sqrt{\varepsilon_{eff}}} \quad (3)$$

rm" is the average radius of the ring and ε_{eff} is the effective permittivity.

To evaluate the effective permittivity using a ring resonator, one can simply measure the resonance frequency of order s: "$f_{r,s}$" and extract "$\varepsilon_{eff,s}$" from the following formula:

$$\varepsilon_{eff,s} = [s.c / (2.\pi r_m f_{r,s})]^2 \quad (4)$$

s.c: radius of the gap

A. *The Quality Factor (Q-factor)*

$$Q = \frac{Fr}{bw} = \frac{Fr}{F1-F2} \quad (5)$$

Where, Fr = resonant frequency
F_1, F_2 = -3db frequency

B. *Parameters*

The width of the microstrip is chosen such that to get a characteristic impedance of 50 Ω.

- The effective permittivity ($\boldsymbol{\varepsilon_{eff}}$), is calculated from:

$$\varepsilon_{eff} = \frac{\varepsilon_{r+1}}{2} + \frac{\varepsilon_{r-1}}{2}\left(\frac{1}{1+\frac{12h}{w}}\right) \quad (6)$$

- The mean radius of resonating ring (Ro):

$$Ro = \frac{\lambda}{2\pi} \quad (7)$$

- And the internal and external radius of ring and R1 and R2 respectively:

$$R_1 = Ro + \frac{w}{2} \quad (8)$$

$$R_2 = Ro - \frac{W}{2} \quad (9)$$

1. Finally, the arm length using:

$$L_s = \frac{C}{2f\sqrt{\varepsilon_{eff}}} \quad (10)$$

C. *Coupling Gap*

So as to have a resonant frequency, a resonator can be fed by microstrip line through coupling gap. These types of coupling are called free coupling. It brings about poor return loss and transmission response, If the gap is reduced, the gap capacitance increases. Under tight coupling gap, capacitance becomes appreciable. This causes the major resonant frequency to deviate from the true value. More tightly the coupling, bigger is the deviation.

IV. IMPLEMENTATION/SIMULATION AND TESTING

Using HFSS program the circuit in Fig. below was implemented, after we sandwiched the substrate with 2 materials (lower material-sapphire, upper material-MgO), then we make a simulation according to different values of permittivity (from 50 to 350 by step unit 50) and a different values of thickness of Substrate-Ferro (from 0.5 to 10 um by step unit 0.5um) as shown in Fig. 2.

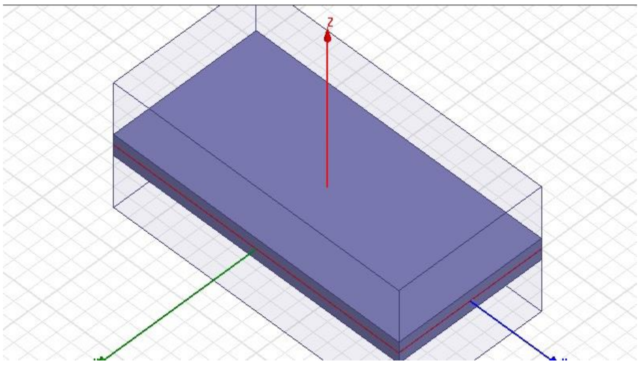

Fig. 2: HFSS Simulation of Boxed Ring Resonator With Cover

The dimension of Ring Resonator we take is shown in table 1:

TABLE 1: DIMENSIONS OF RING RESONATOR

Parameters	Values
Width of feed line	0.01 mm
Feed line length	6.95mm
Coupling gap	1.52mm
Total length of substrate	20mm
Total width of Substrate	10mm
Internal radius of ring	2.5mm
External radius of ring	3.035mm

In this part, results below show the simulation done varying the permittivity and the thickness of the substrate in several steps. The S-parameters are plotted in the below Fig.s (Fig. 3 to Fig. 5).

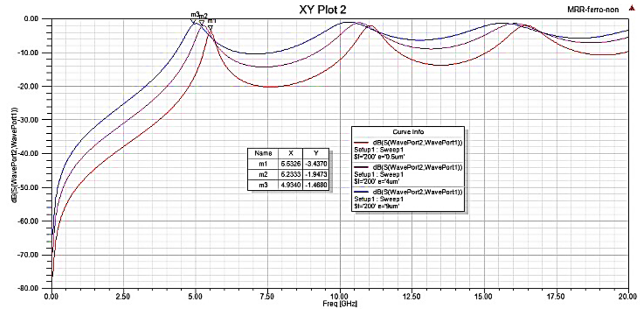

Fig. 3: S21 Parameters at Permittivity 200 at Thickness of (e=0.5, 4, and 9um)

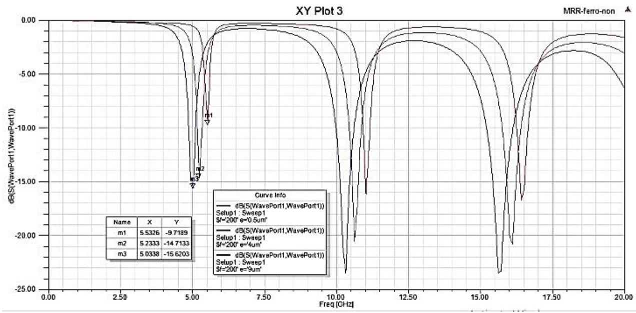

Fig. 4: S11 Parameters at Permittivity 200 at Thickness of (e=0.5, 4, and 9um)

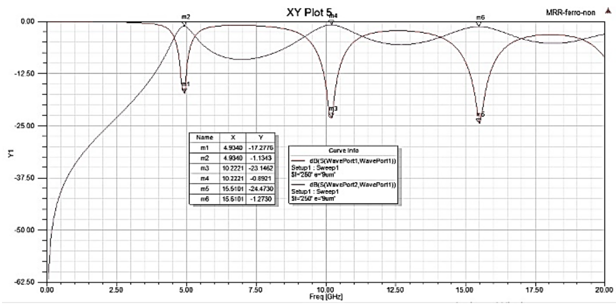

Fig. 5: S21 and S11 Parameters of Permittivity 250 for Thickness e=9um

Notice that, as we increase the value of permittivity and the value thickness the resonance frequency increase and shift to the left.

A. Variation of Permittivity '∈'

The permittivity is varied from 50 to 350 and the resonance frequency is measured at each step. Fig.s 6 to 9 below show us the variation of permittivity as function of Resonance for the 3 resonance frequencies f1, f2 and f3.

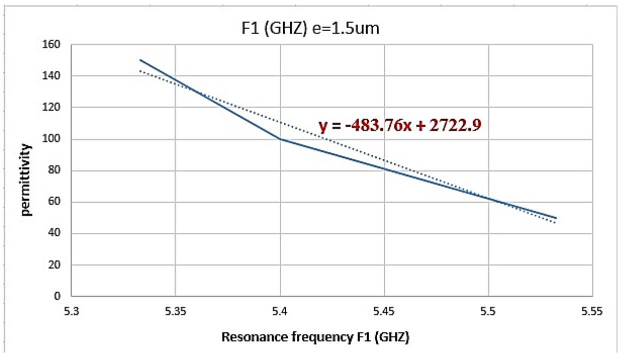

Fig. 6: Result Show us the Variation of Permittivity as Function of Resonance Frequency F1 (GHZ) at Thickness e=1.5um and its Equation

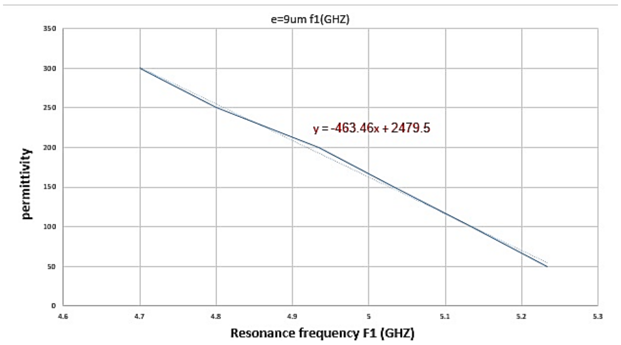

Fig. 7: Result Show us the Variation of Permittivity as Function of Resonance Frequency F1 (GHZ) at Thickness e=9um and its Equation

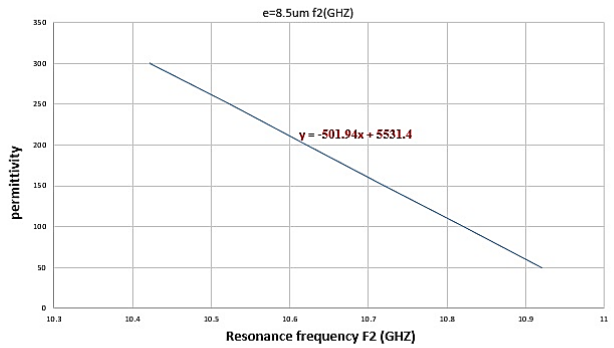

Fig. 8: Result Show us the Variation of Permittivity as Function of Resonance Frequency F2 (GHZ) at Thickness e=8.5um and its Equation

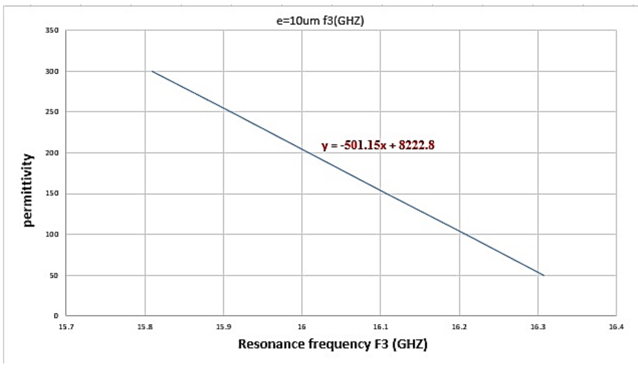

Fig. 9: Result show us the Variation of Permittivity as Function of Resonance Frequency F3 (GHZ) at Thickness e=10um and its Equation

Analyzing the results, it can be clearly seen that curves have comparable straight line equation mainly for each of the frequencies with that of other simulations. For the resonance frequency F1 (GHZ), a plot fitting is done, that include all the line equations found varying the permittivity for 7 measurements. The general graph obtained is presented in Fig. 10. It will be used to calculate the permittivity of the material with known thickness after measuring it resonance frequency.

For the resonance frequency F1 (GHZ), the equation for the curve in Fig. 10 is:

$$y = -439.7x + 2434.1 \qquad (11)$$

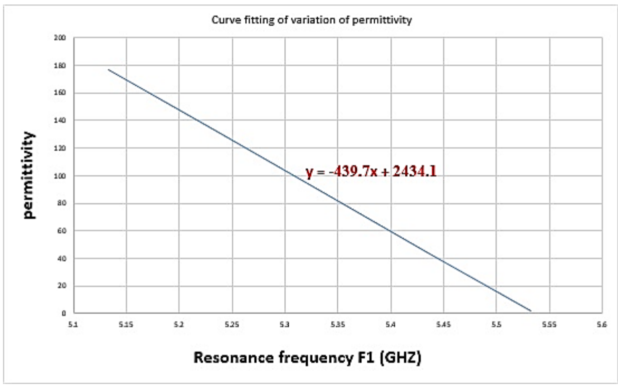

Fig. 10: Curve Fitting of Variation of Permittivity as Function of Resonance Frequency F1 (GHZ)

Example: For material of thickness e=6 um, the resonance frequency is found to be x=f1=5.5331 GHz.

From the curve fitting equation, one gets: y = ϵ =98.85 after calculation, while the real value is 100 for the permittivity.

The induced error is:

Error=$\frac{98.85-100}{100} = \pm 1.16\%$ (12)

There is a small error ($\pm$1.16%) finding the value of permittivity from the graph according to the value of resonance frequency found.

B. Variation of Thickness 'e''

Similarly, varying the thickness from 0.5µm to 10 µm and plotting that variation versus the resonance frequencies. Fig. 11 to Fig. 13 shows this variation.

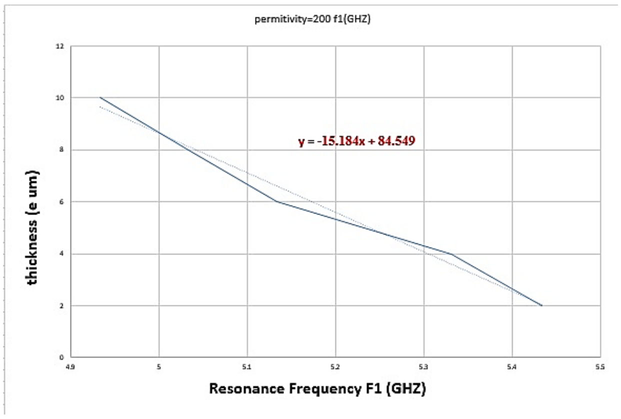

Fig. 11: Variation of Thickness as Function of Resonance Frequency F1 (GHZ)

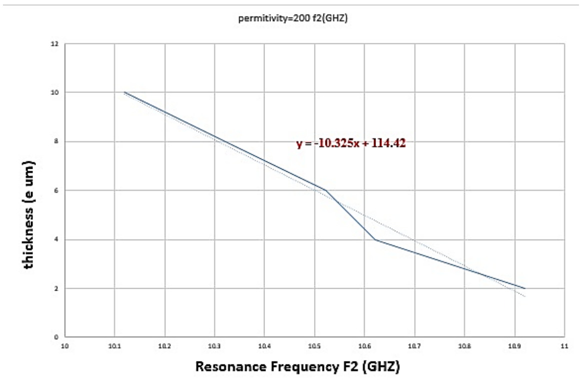

Fig. 12: Variation of Thickness as Function of Resonance Frequency F2 (GHZ)

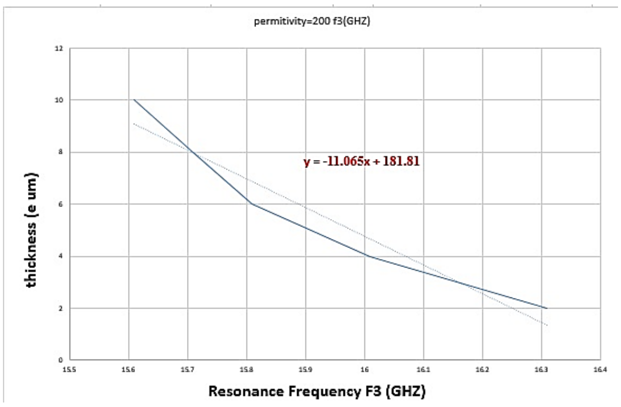

Fig. 13: Variation of Thickness as Function of Resonance Frequency F3 (GHZ)

For frequency F1 (GHZ):

After doing a general plot fitting as above, for the resonance frequency F1 (GHZ), the equation is found:

$y = -18.35x + 102.393$ (13)

Which is the straight line equation describing the plot in Fig. 14.

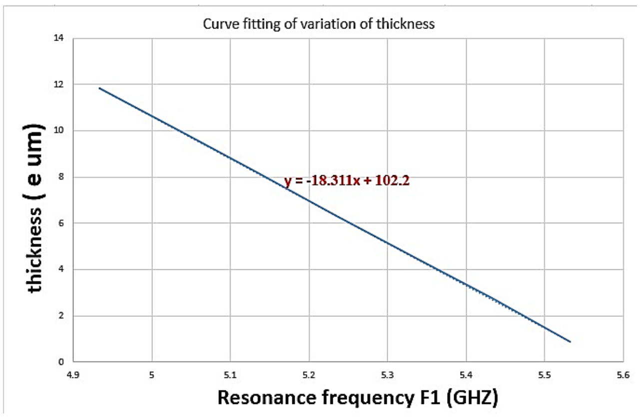

Fig. 14: variation of thickness as function of Resonance frequency F1 (GHZ)

Using this equation, one can predict the resonance for a structure with known permittivity and thickness, with an error that doesn't exceed 2% as before.

The advantage of using non-destructive methods, is that one can re-use the material measured in implementing microwave applications with a low percentage of error. The disadvantages of this system design, it lacks the real measurements due to the absence of the prototype, and the needed technology. The simulations results are promising, but with real life measurements more accurate results can be achieved.

V. Conclusion

Simple planar ring resonator is outlined and applied. Simulation results on HFSS are obtained. Results found are promising, at permittivity measurement level. Other measurements should be done for the loss tangent.

Although promising, yet, Simulations only are not enough; real measurements must be conducted so more accurate results are implemented.

In order to increase the accuracy of measurement, more simulation is needed to obtain a fitting equation that is more precise and on a larger range (polynomial and exponential expressions). But the problem faced here is that the simulation takes very long time (12 hours or more for one step of simulation).

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