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Estimation of Dielectric Constant for Various Standard Materials using Microstrip Ring Resonator

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Abstract: Microstrip ring resonator (MRR) is known for dielectric constant determination and many studies used Teflon as a standard sample. However, there are many other materials available which able to perform better or equivalence as the Teflon in calibrating certain dielectric constant measurement. This paper presents simulation of the MRR to investigate frequency shift of materials for dielectric constant estimation using the CST STUDIO SUITE 2016 software. The MRR was designed on RT/Duroid®5880 substrate (ε_r = 2.2, $tan\delta$ = 0.0004) with 50 Ω matching impedance where microstrip width, substrate thickness and ring mean radius were 4.893, 1.575 and 14 mm, respectively to resonate at 2.65340 GHz. Teflon, Polyimide, Isola FR408, Arlon AD250, Arlon AD270 and Gil GML1032 were alternately selected to be placed on top of the MRR as a standard sample to obtain the frequency shift. The frequency shifts for the above materials were 2.56932, 2.46149, 2.44680, 2.53748, 2.52007 and 2.48608 GHz, correspondingly. The differences in frequency shift were used in NetBeans IDE 8.1 algorithm of Java for dielectric constant calculation. The results indicated that Polyimide and Arlon AD250 had the lowest and highest mean percentage error of 0.83536 and 1.76505 %, respectively. Hence, Polyimide might as well be the most suitable candidate as a standard sample in MRR technique for dielectric constant measurement.

Keyword: Microstrip Ring Resonator; Frequency Shift; Dielectric Constant; CST Simulation.

1.0 Introduction

There are many types of measurement and analysis for determining dielectric properties of materials. The most common methods are open ended dielectric probe, closed waveguide system and coaxial cavity due to high sensitivity and accuracy. However, microstrip ring resonator (MRR) also has been widely used in the measurement of the dielectric properties of the low-loss materials due to its simple structure, easy in fabrication, relatively low cost, low profile, and versatility. Information such as relative dielectric constant, ε_r and loss tangent, $tan\delta$ of material under test (MUT) can be obtained using the MRR based on resonant frequency shift mechanism [1-3]. The resonant frequency shift is a measure of frequency deviation between loaded and unloaded MRR. Loaded means when MUT is placed on top of the MRR while unloaded is without MUT. Unknown and unitless parameter, D is required in the calculation of dielectric constant of MUT [4-5]. Thus, it is an essential to investigate the accuracy of the estimation since this frequency shift method requires a material to be as standard sample.

Thus, in this work the MRR was designed to resonate at frequency, f_r of 2.6 GHz on RT/Duroid®5880 dielectric substrate which has uniform ε_r of 2.2 with $tan\delta$ = 0.0004 and simulated using CST STUDIO SUITE 2016 software tested on several different types of dielectric materials that act as standard sample. The characteristic impedance, Z_o of the MRR feed line dimension was set at 50 Ω according to microstrip impedance equation so that transmitted signal lost could be minimised where the substrate thickness was 1.575 mm. Therefore, the effectiveness of measuring the MRR resonant frequency as well as dielectric properties estimation of MUT could be increased [6]. The minimum return loss (S_{11}) of microwave signal of the designed MRR could

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be seen at its resonant frequency due to maximum transmission [7]. In this paper, only ε_r was calculated from the simulation result. The materials used were Teflon, Polyimide, Isola FR408, Arlon AD250, Arlon AD270 and Gil GML1032.

2.0 Methodology

2.1 Designation Parameters of the MRR

First thing needed for the simulation of the MRR is the dimension parameter of the MRR. For this paper, the substrate of RT/Duroid® 5880 was used with the thickness, h of 1.575 mm.

The resonator has to satisfy the resonance condition:

$$2\pi R = n\lambda_g \text{ ; for } n = 1, 2, 3, \ldots, N \quad (1)$$

where λ_g and R are the guided wavelength and the mean radius (in meter) of the ring circuit. Symbol n is the order of harmonic of the resonance. The λ_g can be calculated as:

$$\lambda_g = \frac{c}{f\sqrt{\varepsilon_{eff}}} \quad (2)$$

where c and f are the speed of light in vacuum and the resonant frequency. The effective permittivity, ε_{eff} is expressed as:

$$\varepsilon_{eff} = \begin{cases} \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[\frac{1}{\sqrt{1+12h/W}} + 0.04\left(1-\frac{W}{h}\right)^2\right] & \text{for } \frac{W}{h} \le 1 \\ \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(\frac{1}{\sqrt{1+12h/W}}\right) & \text{for } \frac{W}{h} > 1 \end{cases} \quad (3)$$

By giving value of characteristic impedance, Z_o = 50 Ω and dielectric constant, ε_r = 2.2 of the substrate, the width, W of microstrip ring can be calculated as:

$$W = \begin{cases} \frac{8h\exp(A)}{\exp(2A)-2} & \text{for } \frac{W}{h} < 2 \\ \frac{2h}{\pi}\left\{ B-1-\ln(2B-1) + \frac{\varepsilon_r-1}{2\varepsilon_r}\left[\ln(B-1)+0.39-\frac{0.61}{\varepsilon_r}\right] \right\} & \text{for } \frac{W}{h} > 2 \end{cases} \quad (4)$$

where the A and B in (4) are given as:

$$A = \frac{Z_o}{60}\sqrt{\frac{\varepsilon_r+1}{2}} + \frac{\varepsilon_r-1}{\varepsilon_r+1}\left(0.23+\frac{0.11}{\varepsilon_r}\right)$$

and

$$B = \frac{376.73\pi}{2Z_o\sqrt{\varepsilon_r}}$$

The length of the feed line, L can be calculated:

$$L = \frac{\lambda_g}{8} \quad (5)$$

The inner radius, R_1 and the outer radius, R_2 can be computed as:

$$R_1 = R - \frac{W}{2} \quad (6)$$

$$R_2 = R + \frac{W}{2} \quad (7)$$

All of equations were written using Java algorithm and display calculator was set by NetBeans IDE 8.1. The calculated MRR parameters were as in Table 1.

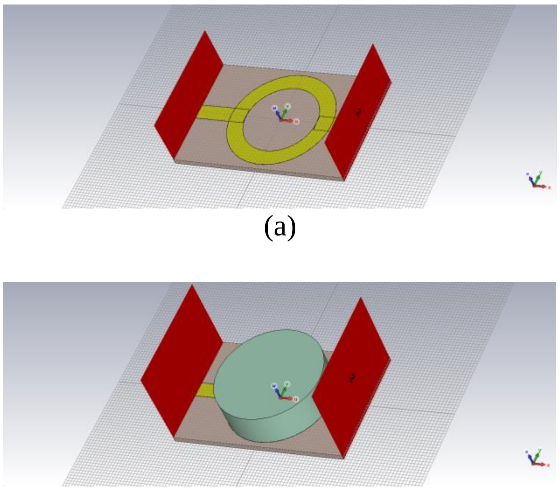
Table 1: The parameters of the designed MRR

Parameters	Value
Z_o	50 Ω
ε_r	2.2
ε_{eff}	1.872
W	4.8933 mm
h	1.575 mm
R	14 mm
R_1	11.55 mm
R_2	16.45 mm
L	11 mm
f_r	2.6 GHz

2.2 CST STUDIO SUITE 2016

CST STUDIO SUITE 2016 software was used for the designation and simulation of the MRR to find the dielectric constant of MUT using the resonant frequency shift method as shown in Fig. 1. The *Planar Device Structure* mode and *Time Domain Solver* were selected as there is a copper strip on the dielectric substrate.

Physical properties of the surrounding space must be defined after designation of the MRR was completed. Materials such as dielectric substrate and MUT were chosen from model library. The radius and thickness of MUT were fixed at 17 and 10 mm, respectively. Port one and two were defined at appropriate orientation direction where the incident signal was fed by port one and received by port two. The simulation frequency was set in the range of 2 – 3 GHz.



(a)

(b)

Fig. 1 The completion model of the (a) unloaded MRR and (b) loaded MRR.

3.0 Result and Discussion

Fig. 2 shows S_{11} with a variation of resonant frequency for unloaded and loaded MRR. It was obvious that the resonant frequency shift mechanism occurred to the loaded MRR gave signatures according to the different properties of MUT. All the loaded MRR shifted to frequencies that were lower than the unloaded MRR. The value of each resonant frequency of the MUT and unloaded MRR were recorded in Table 2. All of the recorded values were logged in five decimal points to achieve as higher accuracy as possible. The difference in frequency change between the unloaded and loaded MRR for each MUT was also defined using $\Delta f = f_{unloaded} - f_{loaded}$.

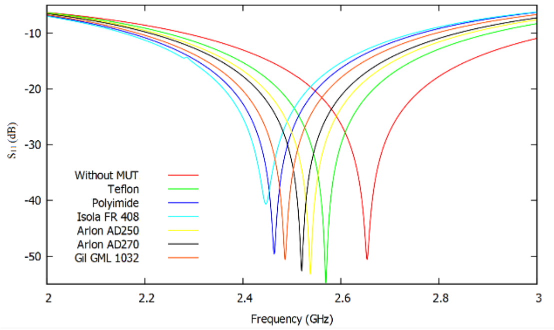


Fig. 2 Variation of resonant frequency for different dielectric materials and unloaded MRR ($f_{unloaded}$ = 2.65340 GHz).

Table 2 Summary of the f_{loaded} and Δf of various dielectric materials

Material	f_{loaded} (GHz)	Δf (GHz)
Teflon	2.56932	0.08408
Polyimide	2.46149	0.19191
Isola FR408	2.44680	0.20660
Arlon AD250	2.53748	0.11592
Arlon AD270	2.52007	0.13333
Gil GML1032	2.48608	0.16732

3.1 Estimation of Dielectric Constant

According to the Eq. 8, calculation of ε_r for MUT requires frequency of the unloaded and loaded MRR to solve for the value of the parameter, D. The dielectric materials were used as standard sample for dielectric constant estimation procedure. Teflon was first used as the standard sample and the shift in frequency was observed (Fig. 2) and recorded (Table 2). The D_{Teflon} parameter was then calculated using Eq. 8 given that the ε_r of Teflon was 2.1. Then, this D_{Teflon} parameter was used to estimate the ε_r of Polyimide, Isola FR408, Arlon AD250, Arlon AD270 and Gil GML1032 with the respective resonant frequency as listed in Table 3. All these mentioned procedures were repeated for different standard sample as shown in Table 4 to Table 8.

$$\varepsilon_r = 1 + D\left(\frac{f_{unloaded} - f_{loaded}}{f_{unloaded}}\right) \qquad (8)$$

Table 3 Calculated ε_r and % of error for various MUT, D_{Teflon} = 34.71384

Material	ε_r	**Calculated** ε_r	**% of error**
Polyimide	3.5	3.51072	0.30629
Isola FR408	3.75	3.70290	1.25600
Arlon AD250	2.5	2.51656	0.66240
Arlon AD270	2.7	2.74393	1.62704
Gil GML1032	3.2	3.18901	0.34344

Table 4 Calculated ε_r and % of error for various MUT, $D_{Polyimide}$ = 34.56568

Material	ε_r	**Calculated** ε_r	**% of error**
Teflon	2.1	2.09531	0.22333
Isola FR408	3.75	3.69137	1.56347
Arlon AD250	2.5	2.51008	0.40320
Arlon AD270	2.7	2.73649	1.35148
Gil GML1032	3.2	3.17967	0.63531

Table 5 Calculated ε_r and % of error for various MUT, $D_{Isola\ FR408}$ = 35.31873

Material	ε_r	**Calculated** ε_r	**% of error**
Teflon	2.1	2.11917	0.91286
Polyimide	3.5	3.55447	1.55629
Arlon AD250	2.5	2.54298	1.71920
Arlon AD270	2.7	2.77432	2.75259
Gil GML1032	3.2	3.22715	0.84844

Table 6 Calculated ε_r and % of error for various MUT, $D_{Arlon\ AD250}$ = 34.33489

Material	ε_r	**Calculated** ε_r	**% of error**
Teflon	2.1	2.08799	0.57190
Polyimide	3.5	3.48331	0.47686
Isola FR408	3.75	3.67340	2.04267
Arlon AD270	2.7	2.72490	0.92222
Gil GML1032	3.2	3.16511	1.09031

Table 7 Calculated ε_r and % of error for various MUT, $D_{Arlon\ AD270}$ = 33.83931

Material	ε_r	**Calculated** ε_r	**% of error**
Teflon	2.1	2.07229	1.31952
Polyimide	3.5	3.44746	1.50114
Isola FR408	3.75	3.63481	3.07173
Arlon AD250	2.5	2.47835	0.86600
Gil GML1032	3.2	3.13386	2.06688

Table 8 Calculated ε_r and % of error for various MUT, $D_{Gil\ GML1032}$ = 34.88812

Material	ε_r	**Calculated** ε_r	**% of error**
Teflon	2.1	2.10552	0.26286
Polyimide	3.5	3.52332	0.66629
Isola FR408	3.75	3.71647	0.89413
Arlon AD250	2.5	2.52417	0.96680
Arlon AD270	2.7	2.75269	1.95148

Table 9 shows the total percentage of error, mean percentage of error and standard deviation for each tested standard sample. It was found that when using Polyimide as the standard sample in the simulation, the total percentage of error and mean percentage of error were the lowest. However its standard deviation was the second smallest among all materials after Teflon with a difference of 0.00904. This verified that Polyimide could performed better as the standard sample among the tested samples as shown in the simulation.

Table 9 Total percentage of error, mean percentage of error and standard deviation for tested standard samples.

Standard Sample	**Total % of error**	**Mean % of error**	**Standard deviation**
Teflon	4.19517	0.83903	0.58212
Polyimide	4.17879	0.83536	0.59116
Isola FR408	7.78938	1.55788	0.77018
Arlon AD250	5.10396	1.02079	0.62373
Arlon AD270	8.82527	1.76505	0.84778
Gil GML1032	4.74156	0.94831	0.62430

4.0 Conclusion

Among all materials used as standard sample, Polyimide could be considered as the best standard sample due to the lowest total percentage of error and mean percentage of error as well as has the most consistent error. Based on this simulation, accuracy of the estimation of dielectric constant is reliable with the given physical settings and boundaries condition. However, the accuracy of the dielectric constant in actual experimental may slightly vary due to the imperfection of fabricating of the MRR.

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