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To cite this article: Khuzairi Masrakin et al 2021 J. Phys.: Conf. Ser. 1755 012017

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Dielectric Properties Characterization of Material Under Test using Microstrip Ring Resonator

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Abstract. The Resonator is one of the techniques widely used to determine the dielectric properties of a material. It is due to the accuracy of the resonator technique as compared to the other methods such as open wave guide sensor, transmission method, and coaxial probe. The accuracy plays an important role in any measurement devices as this is one of the features to show that the device is competent enough to perform a specific task. So, as to cope with accuracy issues, two microstrip ring resonators were designed and prototyped to detect the dielectric properties of Material Under Test (MUT) in this study. Both utilize Rogers Duroid 4003C as the substrate for the dielectric sensor and is meant to resonate at 4 and 5 GHz in which the substrate possesses 3.38 dielectric properties and 0.0027 loss tangent. Several features in designing the resonator such as the coupling gap, d, and radius of the ring, R were taken into consideration. Those parameters were verified and validated through software simulation and measurement using Vector Network Analyzer (VNA) to achieve the expected sensor prototype to operate in the real environment. The measurement was made to test two known dielectric properties of MUT to demonstrate the sensitivity of the sensors. The outcome from the measurement was evaluated in terms of S-21 parameter. The dielectric measurement leads to a change in frequency response against different MUT. The measurement was extended to study the performance of the resonator through the R and d of the resonator in which these parametric studies were made by varying the R and d of the resonator with the presence and the absence of MUT. The outcomes from the measurement suggest the best R and d for the resonator in terms of dielectric permittivity.

1. Introduction
The resonators are frequently being employed in RF/microwave applications. The resonator structures such as ring resonators have been widely utilized in the characterization of dielectric material. It is merely a transmission line formed in a closed loop in which the basic circuit consists of the resonator itself, feed lines, and coupling gap [1]. The coupled feed line port power into and out of the resonator and is separated from the resonator by a distance called the coupling gap, d. The area in the loose coupling gap should be adequate enough to allow the coupling of power [2][3]. Choosing the best coupling is important for a specific application in a circuit as in [4][5][6]. The coupling can be understood by the meaning of the distance between the ring and the feed lines. Large coupling gaps do not affect the resonance frequency of the ring [7]. In contrast, tight coupling gap makes the capacitance negligible. This causes the deviation of the intrinsic resonance frequency of the resonator.
[2]. Thus, the coupling gap should be considered in designing a ring resonator [1][5][6]. Another important feature is the ring radius, \( R \). Substantial amount of studies focuses on the importance of ring radius since the radius can affect the performance of the resonator. Study in [8][9] has mentioned that the primary factors that affect the resonance frequencies are the width, radius and thickness. Study in [10] suggests that apart from the coupling gap and width [11], ring radius [12] also is the parameter that determines the base resonant frequency in which all these parameters influence the electric field distribution at resonance. Hence, the importance of considering the ring radius was paramount in designing the resonator and was considered. In this study microstrip ring resonator considering the coupling gap and ring radius variation was designed to measure dielectric properties of a material. It can be measured by using the resonator technique due to its’ high sensitivity as compared to the conventional coaxial probe. Although the coaxial probe can also perform dielectric properties measurement, it has a high form factor which makes it difficult to implement on a hard surface or on a chip [13]. Furthermore, its’ coaxial line reflection has a limitation on the accuracy [10][12]. It was aimed to perform as a sensitive dielectric sensor. The sensitivity of the sensors is determined by the dimension and shape of ring resonators by means of its inductance and capacitance. The sensors were used to determine dielectric properties of MUT which are Rogers4003C and FR-4 board with dielectric constant at 3.38 and 4.3 respectively. These two substrate boards with their known dielectric constant were deliberately chosen in order to validate the performance of the simulated design of the presented dielectric sensors with measurement. From the measurement results, it indicates accurate detection values against two different MUTs.

2. Methodology

2.1. Microstrip ring resonator design

The Microstrip ring resonator frequently used to determine the microwave substrate properties specifically in the dielectric constant and loss tangent [14]. To use the ring for microstrip measurements, an annular ring is constructed into which microwaves are injected. When the ring is an integer number of wavelengths long, a standing wave pattern is set up, and the ring displays resonant characteristics. The microstrip ring resonator was used extensively in the study of microstrip dispersion due to the ease of measuring the effective dielectric constant. P. Troughton has first presented the ring resonator who describe a new technique and plotted graphs on the effective dielectric constant of various microstrip lines on Alumina in the year 1969 [15]. The resonance frequency of the ring can be calculated from the equation [14]

\[
n \cdot \lambda_{res,n} = \pi \cdot d_m
\]

(1)

where \( n \) is the harmonic number, \( \lambda_{res,n} \) is the resonant wavelength, \( \pi \) is the number Pi, and \( d_m \) is the mean diameter of the ring. The resonant wavelength at the n-th resonance frequency \( f_{res,n} \) is also a function of the speed of light \( C_0 \) and the effective permittivity \( \varepsilon_{eff} \).

\[
\lambda = \frac{C_0}{\sqrt{\varepsilon_{eff}} f_{res,n}}
\]

(2)

Hence \( \varepsilon_{eff} \) at the n-th resonance frequency can be calculated as:

\[
\varepsilon_{eff} = \left( \frac{n C_0}{\pi d_m f_{res,n}} \right)^2
\]

(3)

Thereby, the microwave characteristics of the microstrip ring resonator are in general depending on the geometrical structure, the regarded frequency, and the effective permittivity. The two microstrip feed lines make the electric coupling due to a small coupling gap available and can be connected with a VNA to get the microwave characteristics by measuring the S-parameter
Figure 1. The proposes microstrip ring resonator

The resonant frequency depended on the radius of the ring above and beyond that expected from the total track length alone, and it can be concluded that the curvature of the ring affected the resonance frequencies. The microstrip ring resonators were designed in this study to perform sensors activity to measure the dielectric properties of MUT. The variation in response toward two known MUT’s dielectric properties can be detected by measuring the S-parameter namely transmission coefficient, S-21 parameters. The ring shape is selected instead of a common rectangular shape due to its discontinuity in which the ring shape has a smooth path that allows current to conduct smoothly over the ring and has a larger bandwidth than a regular rectangular shape [10]. Furthermore, the rectangular shape has a poor discontinuity at the edges of the shape and possesses small bandwidth, thus makes it incompetent to perform the accurate measurement. The design of the sensors was first illustrated in Figure 1. The ring resonator was located in the middle of a coupled transmission line. The coupling gap was made small to acquire a better resonance peak. Thus, the activity of the sensor will then enhance with shifted frequency. The design was made by using Computer Simulation Technology (CST) software which allows the design to be simulated and optimized. Both sensors were designed to operate at frequencies ranging from 1GHz to 10GHz in overall. The first sensor takes up 1.86mm ring radius and 50 Ohm characteristic impedance. It also considers the coupling gap ratio which was determined by varying the thickness ranging from 0.10mm, 0.15mm, 0.20mm, and 0.25mm. It was paramount as this was one of the parameters that affect the resonance frequency and the quality factor of the sensor. The smaller the ratio of the coupling gap, the higher the quality factor, thus higher sensor accuracy. In order to design the second sensor structure, mean radius, R of the designed ring was measured to discover the base resonant frequency. It was crucial due to the electrical field distribution that can be affected at its’ resonance, hence affecting the sensitivity of the sensor. The ring radius was also varies ranging from 9.72mm down to 4.84mm. The sensors were then fabricated by using Rogers Duroid 4003C substrate which takes up 0.508mm of thickness as illustrated in Figure 2. It has stable dielectric constant over frequency which is 3.38 and low electrical loss at 0.0027 attenuation coefficient. It is also having low moisture absorption which makes it an ideal candidate for the resonator design. The resonant frequencies $f_r$ of the resonator structure was determined by [10]:

$$f_r = \frac{c}{L_{ch} \sqrt{\varepsilon_{eff}}}$$

(4)

where $L_{ch}$ is the inductance of the ring structure which can be determined by [5]

$$L_{ch} = 2\pi R$$

(5)
\[ \varepsilon_{ett} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left( 1 + \frac{1}{1 + \frac{8}{\pi^2}} \right) \]  

(6)

Where \( \varepsilon_r \) is the dielectric constant of the microstrip substrate, \( h \) is the substrate thickness and \( w_f \) is the width of the transmission lines. In this structure, \( w_f \) is equivalent to \( Z_0 = 50 \Omega \) transmission lines which are determined using the formula in [3]

\[ \frac{W}{d} = \frac{2}{\pi} \left[ \ln(2B - 1) \right] + \frac{\varepsilon_r - 1}{2\varepsilon_r} \left\{ \ln(B - 1) + 0.3q - \frac{0.61}{\varepsilon_r} \right\} \]

(7)

Where

\[ B = \frac{377\pi}{2\varepsilon_r \sqrt{\varepsilon_r}} \]

(8)

When MUT is placed on top of the coupling gap, \( d \), it covers the capacitance part of the resonator. The gap covered by MUT results in the change of capacitance value. So that the dielectric material of MUT can be determined. It will also lead to a change of resonant frequency. The optimization of the resonators was obtained using commercial electromagnetic software. The final dimension of the microstrip ring resonator is displayed in Table 1.

| Parameters | Description | Size |
|------------|-------------|------|
| Ls         | Length of Rogers RT/Duroid 4003C substrate | 55   |
| Ws         | Width of Rogers RT/Duroid 4003C substrate | 35   |
| Ht         | Height of copper (pure) conductor | 0.017 |
| H          | Height of Rogers RT/Duroid 4003C substrate | 0.508 |
| Wf         | Length of transmission line | 1.86  |
| P          | Length of feedline | 97    |
| d          | Gap | 0.10 |

2.2. Parametric study of a microstrip ring resonator
The design of the ring resonator was extended to a parametric study by mean of gap and ring radius to study the performance of the resonator sensor in terms of S-parameter which is S-21 parameter. The \( d \) was varied from 0.1mm, 0.15mm, 0.2mm, to 0.25mm. Ring radius was also varied in the design modification ranging from 9.72 mm, 7.28 mm, 5.81 mm down to 4.84 mm. The results of the optimized ring radius were then compared to the one before optimization take place in term of its resonance frequencies. It was also evaluated in S-21 parameters.
3. Result and discussion
The two prototypes of microstrip ring resonator sensors were fabricated in this study as shown Figure 2. with two different resonance frequencies at 4GHz with ring radius, R=7.28, and 5GHz with R=5.81 ring radius. Figure 3. shows the fabricated resonator with MUT (FR4 and Rogers 4003C) on the top of the resonator. The MUT used for the measurements was FR-4 with substrate thickness, h=1.6mm, and dielectric constant at 4.3 while Rogers 4003C substrate thickness at h = 0.508mm and dielectric constant = 3.38 that can be determined by the changes of the frequency shifting.

![Figure 2. The prototype of ring resonator at two frequencies](image1)

![Figure 3. The prototype of ring resonator with MUT](image2)

The graph of the simulated and measured frequency response of the transmission coefficient, S-21 parameter which was obtained from the VNA and CST software is displayed as in Figure 4. without MUT whilst Figure 5 and Figure 6. with the presence of MUT which is FR-4 and Rogers4003C respectively. The simulation and measurements were performed at R=5.81

![Figure 4 Simulation against measurements results of S-21 for R=5.81mm without MUT](image3)
Figure 5. Simulation against measurements results of S-21 for R=5.81mm with FR-4

Figure 6. Simulation against measurements results of S-21 for R=5.81mm with Rogers4003C

Figure 4. displays the plotted graph results without MUT which portrays slight differences of the simulated and measured result of the resonance frequency at 5.35GHz, -19dB and 4.85GHz, -19.5dB respectively. The result in Figure 5. indicates 5.2GHz, -9dB for simulation output whereas measured resonance frequency was at 4.5GHz, -11dB with the presence of F-R4. The plotted graph suggests that the simulated frequency resonates at higher frequency as compared to the measured result. Figure 6. shows the simulated and measured frequency response of S-21 with Rogers4003C as the MUT. The simulated resonance frequency output was at 5.2GHz, -10dB whilst the value of measured output was at 4.7GHz, -12dB.
Figure 7. Simulation against measurements results of S-21 for R=7.28 without MUT

Figure 8. Simulation against measurement results of S-21 for 7.28mm with FR-4

Figure 9. Simulation against measurements results of S-21 for R=7.28mm with Rogers4003C

The evaluated S-parameters were extended to study the performance of ring resonator at R=7.28mm with the presence and the absence of MUT. Figure 7. shows the simulated and measured results without MUT which can be observed that simulated resonance frequency is higher at 4.15GHz, -18dB compared to the measured resonance frequency which resonates at two distinct frequencies at 3.8GHz, -23dB and 7.61GHz, -23dB Figure 8. displays the simulated and measured frequency response results
of S-21 with the presence of FR4. 3.89GHz, -11dB was recorded in the simulation results whereas two measured resonance frequencies were recorded at 3.5GHz, -15dB and 7.05GHz, -16dB. The value of 3.90GHz, -10dB was recorded in the simulation S-21 while measured frequencies resonate at 3.7GHz, -14dB and 7.27GHz, -16dB as shown in Figure 9.

![Fr vs \( \varepsilon_r \)](image)

Figure 10. Graph of resonance frequency against relative permittivity for R=5.81mm

| Rogers4003C | FR4 |
|-------------|-----|
| Simulation  | Measured | Simulation | Measured |
| \( \varepsilon_r \) | \( f_r \) | \( \varepsilon' \) | \( f_r' \) |
| 4.1825      | 4.64GHz | 4.95      | 4.6GHz  |
| 5.96        | 4.41GHz | 5.195     | 4.5GHz  |

Table 2. Comparison between simulated and measured permittivity results for R=5.81mm

It can be observed in Figure 10. that the resonant frequency is shifted to the lower frequency when the dielectric properties increased due to the FR-4 substrate has higher permittivity compared to Rogers4003C. The fitting equations for the sensor were formulated with fitting parameters for S-21 coefficient. The fundamental resonant frequency was extracted for multiple permittivities of the test material through simulation. Figure 10. displays the resonance frequencies against relative permittivity of MUT for 5.81mm resonator radius and plotted based on frequency resonance fitting. It was evaluated in both simulation and measured environment where known relative permittivity for Rogers4003C was 3.38. However, the result of the relative permittivity of Rogers4003C under the simulation environment was 4.1825 and it resonates at 4.64GHz while measured relative permittivity of Rogers4003C was 4.45 and resonate at 4.6GHz. Moreover, the dielectric permittivity of FR-4 was simulated and measured at 5.96 and 5.195 respectively and it resonates at 4.41GHz and 4.5GHz accordingly while known dielectric permittivity of FR-4 was at 4.3.

Table 2 summarizes the finding of relative permittivity, \( \varepsilon_r \) against the resonance frequency with two different MUTs between simulation and measured output. Rogers4003C recorded 4.1825 and 4.45 relative permittivities for respective simulated and measured output with its’ resonant frequencies resonate at 4.64GHz and 4.6GHz accordingly.
Figure 11. Resonance frequency against permittivity for R=7.28mm

Table 3. Comparison of simulated and measured results for R=7.28mm

| Rogers4003C | FR4 |
|-------------|-----|
| Simulation  | Measured | Simulation | Measured |
| $\varepsilon_r$ | $f_r$ | $\varepsilon_r$ | $f_r$ | $\varepsilon_r$ | $f_r$ |
| 4.7225       | 3.66 GHz | 4.4525       | 3.7 GHz | 6.095         | 3.5 GHz | 6.095         | 3.5 GHz |

Figure 11. shows the resonance frequency against dielectric permittivity for 7.28mm ring radius. The plotted graph indicates 4.7225 simulated permittivity for Rogers4003C and it resonates at the frequency of 3.66GHz whilst the measured permittivity was at 4.4525, 3.7GHz resonance frequency. The simulated and measured permittivity of FR-4 indicates similar values for its dielectric permittivity at 6.095 and 3.5GHz resonating frequency.

Table 3 summarizes the comparison between simulated and measured relative permittivities against the resonance frequencies for R=7.288mm. From the simulated and measured results, the variation of MUT applied to the sensors will result in the change of dielectric permittivity which differed from the actual datasheet value. The deviation from its default datasheet value might due to the fitting equation which somehow unsuitable enough to be used for the simulation. This was because of the fitting equation was formulated ideally based on simulation.

4. Conclusion

Overall, the design of the microstrip ring resonator sensor has been demonstrated to detect the changes in dielectric properties of the MUT. The resonator sensor has been designed on Rogers 4003C substrates with dielectric constant 3.38 and loss tangent 0.0027. Two designs of microstrip ring resonator have been demonstrated in this paper which have resonant frequencies at $f_r = 4$GHz and $f_r = 5$ GHz and both were investigated in the frequency range of 1 GHz to 8 GHz. To validate the performance of the simulated design of the presented dielectric sensor, two types of known permittivity of MUT were placed on the microstrip resonator sensor, FR-4, and Rogers 4003C substrate board. The dielectric properties values are determined by the frequency response shifting of
the transmission coefficient, S-21. The measured results indicate accurate detection with the known permittivity values of the MUT

Acknowledgements
The authors would like to acknowledge the support from the Fundamental Research Grant Scheme (FRGS) under grant number of FRGS/1/2019/STG02/UNIMAP/02/5 from the ministry of Higher Education Malaysia

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