

Enhancement of microwave ring resonator based on poly-lactic acid thermoplastic substrate

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ABSTRACT

In this paper, the development of a single-port microwave ring resonator (MRR) sensor based on a thermoplastic material, which is poly-lactic acid (PLA), is presented. The open-ended coaxial probe method was applied to identify the dielectric properties of PLA in terms of dielectric constant (2.25) and loss tangent (0.0001). The PLA substrate was fabricated using a hot press machine and with the same thickness (1.6 mm) as FR4. Hence, to consider the PLA as microwave substrate, microwave ring resonator (MRR) operating at 1.1 GHz resonance frequency was designed, simulated, and measured. Based on the observation, the return loss of MRR for the simulation and the measurement of the conventional design are -5.37 dB and -5.02 dB, respectively. The quality factor (Q-factor) for both are 122.22 and 183.33, respectively. Then, the enhanced coupling gap method was applied to improve the performance of MRR sensitivity in terms of return loss and Q-factor. It is observed that the return loss of the enhanced design for the simulation and the measurement are -26.67 dB and -20.23 dB, respectively, and the Q-factor are 122.22 and 200, respectively. Thus, the performance of the MRR based on different designs were compared in order to validate the sensor's sensitivity and PLA can be recognized as a substrate material for RF and microwave applications.

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1. INTRODUCTION

Microwave resonators are integral components in a microwave communication system and are used in a variety of applications including filters, oscillators, amplifiers and other applications that contain series and parallel RLC resonant circuits [1-3]. The two criteria that describe the resonator are (i) the resonant frequency, wherein the energy in the cavity attains maximum value and (ii) Q-factor, which is the capacity of the electromagnetic energy storage. The Q-factor at low frequency is between 50 to 500, and the resonator bandwidth is inversely proportional to the Q-factor. High Q-factor resonators have narrow bandwidths. A high Q-factor is obtained with the highly reactive RLC circuits [4, 5]. Thus, the RLC circuit is integral to the microwave ring resonator (MRR) structure's design, which consists of the substrate, transmission line and patch [6-8].

Normally, the printed circuit board (PCB) is the common material that acts as the substrate in microwave devices. Thus, a newly developed substrate based on thermoplastic is proposed to replace the PCB substrate. Poly-lactic acid (PLA) has been selected in this research because it is a natural material

and that it will help to conserve the environment after the disposal process by not harming the ecosystem [9, 10], as compared with commercial substrates such as the PCB. In addition, a PCB substrate is complicated to be recycled, is a high risk to the environment and requires high cost for its disposal process [11-13]. Therefore, to ensure that PLA is able to act as a commercial substrate, the MRR was designed using the CST software at the resonant frequency of 1.1 GHz.

In order to verify the dielectric properties of the newly developed substrate, the coaxial probe method was proposed to measure the dielectric properties of the material and to verify the properties in terms of dielectric constant and loss tangent in broadband frequency [14]. According to [15], the open-ended coaxial probe method is a non-resonant method which is able to determine the material's characterization and has high accuracy for high loss materials. In [10], PLA was applied as the substrate for an antenna. In this paper, the MRR was designed based on the PLA substrate. To improve the performance of the MRR, the coupling gap method was applied for all designs. The separation between the feed line and the ring, called the coupling gap, is shown in Figure 1.

According to [16, 17] an enhanced coupled MRR was introduced in their research. The larger distance between the feed line and the ring does not affect the resonant frequency. The coupling method could improve the performance of the resonator [7]. In the enhanced coupling method, two coupling gaps on each port are formed between the enhanced feed lines and the ring. The enhanced coupling is implemented by inserting the feed lines into the annular ring element. The technique improves the Q-factor by increasing the gap size. Nevertheless, the coupling method is suitable for all resonator designs to improve the performance of resonator applications [7].

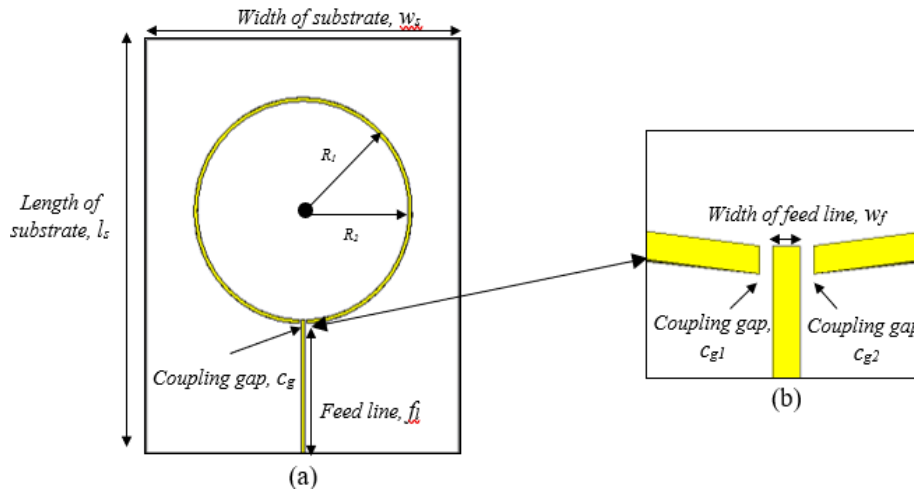


Figure 1. Proposed key-shaped MRR design

2. RESEARCH METHOD

2.1. Part A: Formulation of MRR

Based on Figure 1, the design of the ring resonator consists of a single port and a coupling gap between the feed line and the ring, which is sufficient for the resonance condition as in (1), where R is the mean radius of the ring and n is the harmonic order of resonance [8, 17, 18].

$$2\pi R = n \frac{\lambda_g}{2} \quad \text{for} \quad n = 1, 2, 3, \dots \tag{1}$$

Next is finding the effective permittivity, ϵ_{eff} . The formula is expressed in (2), where ϵ_r is the value of the dielectric constant of the substrate, h is the height of the substrate and d is the thickness of the substrate [8, 17, 18].

$$\epsilon_{eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \frac{1}{\sqrt{1 + 12 \frac{d}{h}}} \tag{2}$$

Thus, the guided wavelength λ_g can be related to frequency by (3), where c is the speed of light 3×10^8 m/s, f is the resonant frequency and ϵ_{eff} is the effective permittivity [8, 17, 18].

$$\lambda_g = \frac{c}{f \sqrt{\epsilon_{eff}}} \quad (3)$$

Commonly, the characteristic impedance Z_0 is 50 Ω , and the dielectric constant of the substrate and the width of the resonator can be calculated as in (4) [8, 17, 18].

$$W = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left[\frac{1}{\sqrt{1 + 12 \frac{h}{w}}} + 0.04 \left(1 - \frac{w}{h}\right)^2 \right] \quad \text{for } \frac{w}{h} \leq 1$$

$$W = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left[\frac{1}{\sqrt{1 + 12 \frac{h}{w}}} \right] \quad \text{for } \frac{w}{h} \geq 1 \quad (4)$$

Then, the transmission line, which is called as the feed line, is calculated using (5), where λ_g is the wavelength of the transmission line divided by a quarter-wavelength, i.e. by four [8, 19]. The feed line and the ring resonator are the printed transmission lines with the width chosen for the 50- Ω characteristic impedance [17, 18]. There is a coupling gap between the feed lines and the ring, where the gap that is introduced as a capacitance gap will affect the performance of resonator in terms of return loss and Q-factor. The single-port design is proposed due to the simple configuration and that it can reduce the number of control parameters. Thus, a single-port resonator produces the dielectric constant only, as well as the single-mode response (T_M or T_E mode) [20].

$$\text{Feed line: } f_l = \frac{\lambda_g}{4} \quad (5)$$

The inner radius and outer radius of the ring are calculated using (6) and (7), where R is the radius of the resonator and W is the width of the resonator [8, 17-19].

$$\text{Inner radius } R_1 = R - \frac{w}{2} \quad (6)$$

$$\text{Outer radius: } R_2 = R + \frac{w}{2} \quad (7)$$

The Q-factor value of a dielectric resonator is the ratio between the energy stored within the resonator, which is related to the capacity of the electromagnetic energy storage [4]. Normally, a high Q-factor is desired for resonator measurements [6]. Therefore, the proposed sensor device performs a high Q-factor with high sensitivity and accurate measurement for characterizing the properties of a material. The Q-factor can be determined by (8), where ω_o is the center of the resonant frequency and $\Delta\omega$ is bandwidth at -3dB [21, 22].

$$Q = \frac{2\omega_o}{\Delta\omega} \quad (8)$$

2.2. Part B: Fabrication process of PLA

Figure 2 presents the fabrication process of PLA. The fabrication process was started by measuring the volume of the mold (240 mm×240 mm×16 mm). Based on the volume of the mold, the mass of the PLA pellets was defined by density, which is the ratio of the mass over the volume of the material, in g/cm³. Next was the preheating process of the material at 70°C for about 30 minutes using the domestic oven. The purpose of the preheating process is to stabilize the material's condition when the surrounding temperature changes. In addition, it can produce a clear and smooth surface of the developed substrate. After 30 minutes, the PLA pellets were flattened on the mold and covered by aluminum plates at the top

and bottom of the mold. Then, the mold was placed into the hot press machine for the next process. The preheating process continued after the mold was inserted into the hot press machine. The preheating process will take up to 30 minutes at a temperature of 185°C. The next process was the melting process at the appropriate temperature and pressure for 0.5 tonnes of the substrate. The temperature of the hot press machine for the upper and lower platen was set at 185°C and the duration was 18 minutes for the melting process. Next was the cooling process, where water was flowed onto the hydraulic system of the hot press machine for around 30 to 45 minutes until the temperature dropped off to 40°C. The last process was removing the substrate from the mold.

2.3. Part C: Identification of PLA dielectric properties

The PLA properties were identified using the open-ended coaxial probe measurement method. This method was proposed to ensure that the properties of PLA were synchronized with the design of the resonator using the CST software. The open-ended coaxial probe method functioned to measure dielectric constant, loss factor and loss tangent of the material. Figure 3 presents the open-ended coaxial probe for the measurement of the dielectric properties, where the coaxial probe was connected to the vector network analyzers (VNA) and the PLA substrate was placed under the coaxial probe. Before the dielectric properties are measured, a calibration of the dielectric probe was required, which performed with three types of loads; short circuit, free space and load. The calibration's main function was to check the suitability of the calibration before placing the material on the base of the dielectric probe. The main advantage of the open-ended coaxial probe technique is that it is a non-destructive and non-invasive technique due to no changes in the material under test during the measurement [14].

2.4. Part D: Structure of MRR

The MRR was designed and simulated at 1.1 GHz resonant frequency based on the PLA substrate. To produce the best performance of MRR in terms of sensitivity and Q-factor, the enhanced method of the coupling gap was applied. The coupling gap was 0.5 mm for both gaps that were located between the feed line and the ring, where the ring is not in a complete circle and the feed line was located in the middle of the gap. The enhancement of the coupling gap was implemented by inserting the feed line into a cut gap in the annular ring. The proposed design of the MRR, known as the key-shaped resonator, is shown in Figure 1, while Table 1 shows the parameters of the MRR.



Figure 2. Fabrication process of PLA substrate, (a) Hot press machine, (b) PLA substrate



Figure 3. The open-ended coaxial probe for the determination of dielectric properties of PLA substrate

Table 1. Dimension of MRR

Parameters	Unit	Conventional MRR	Enhanced MRR
Width of feed line, w_f	mm	1.00	1.00
Feed line length, l_f	mm	37.40	37.05
Coupling gap, c_g ($c_{g1}=c_{g2}$)	mm	0.50	0.50
Length of substrate, l_s	mm	115.0	115.0
Width of substrate, w_s	mm	90.0	90.0
Inner radius of ring, R_1	mm	28.60	30.45
Outer radius of ring, R_2	mm	29.60	31.45

3. RESULTS AND DISCUSSION

3.1. Part A: Identification of PLA substrate properties

After the fabrication process was completed, the measurements of the dielectric properties of the PLA were done. Figure 4 shows the result of the measurement properties of PLA in terms of dielectric constant and loss tangent. It is observed in Figure 4(a) that the variation of dielectric constant fluctuates starting from 1.05 GHz to 1.2 GHz. At resonant frequency of 1.1 GHz, the intersected dielectric constant is at 2.25. Meanwhile, in Figure 4(b), the loss tangent varies from 1.05 GHz to 1.2 GHz. Again, it is observed the loss tangent's value that intersects at 1.1 GHz is 0.0001. Thus, the result of the PLA substrate properties agrees with the previous works as described by [23, 24].

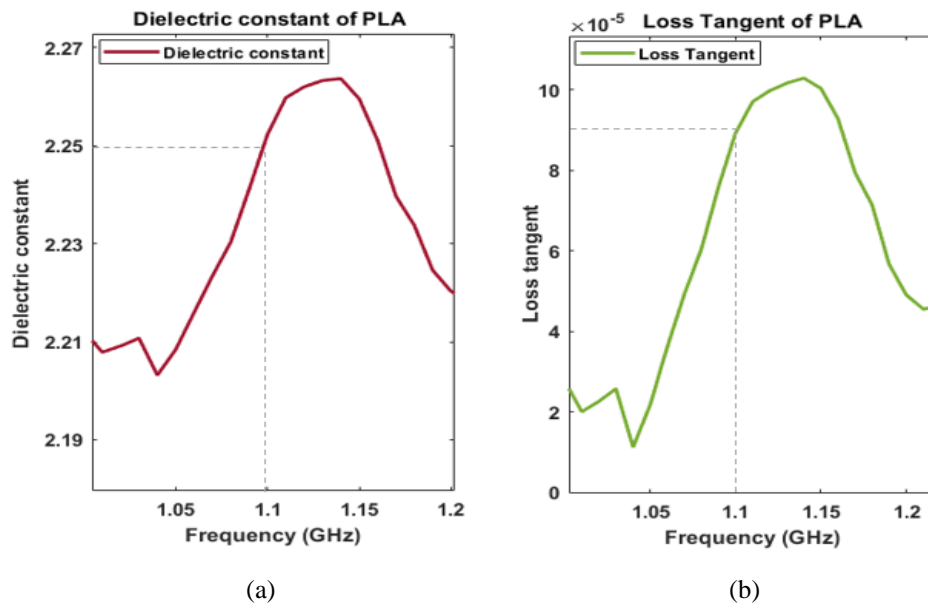


Figure 4. Measurement of the dielectric properties of PLA substrate, (a) Dielectric constant, (b) Loss tangent

3.2. Part B: Simulation and measurement results of microwave ring resonator

This part is mainly about the performances of the MRR for the conventional and enhanced MRR design. The main elements of the analysis are return loss, bandwidth and Q-factor. The return loss is observed based on the simulation and the measurement, where the reflection coefficient is below -3dB. The MRR bandwidth refers to the range between the high and low frequencies when the return loss drops at -3 dB. Thus, the performance of the Q-factor will be determined. Due to the high performance of its Q-factor, the resonator can act as a sensor in microwave applications [25].

Figure 5(a) shows the return loss of the conventional MRR design based on the simulation and the measurement at the resonant frequency of 1.1 GHz. It is clearly shown that the simulation result is good compared with the measurement result, which are -5.37 dB and -5.02 dB, respectively, with an absolute difference of 0.35 dB. Meanwhile, the bandwidth of the measurement is narrow compared with the simulation, which are 0.012 GHz and 0.018 GHz, respectively. Therefore, the Q-factor of the measurement is high with 183.33 compared with the Q-factor of the simulation, which is 122.22.

Essentially, the return loss of both methods fulfills the performance of the return loss, which is lower than -3 dB. But a narrow return loss, narrow bandwidth and high Q-factor will produce a good

performance for the resonator to act as a sensor. Thus, the enhanced design was proposed to overcome the low performance of the resonator and produce a better performance with a high-sensitivity sensor.

Figure 5(b) presents the return loss of the enhanced MRR design based on the simulation and the measurement. It is found that the simulation result is narrow compared with the measurement result, which are -26.67 dB and -20.23 dB, respectively, with an absolute difference of 6.44 dB. The bandwidth and Q-factor of the simulation of the enhanced MRR design are 0.018 GHz and 122.22, respectively, while the bandwidth and Q-factor of the measurement are 0.011 GHz and 200, respectively. The measurement of the enhanced MRR design shows a narrow bandwidth and a high Q-factor with an absolute difference of 0.007 GHz and 77.78, respectively, compared with the simulation. Based on the observation, the enhanced MRR design performs better performance compared with the conventional MRR design due to the performances of the return loss and Q-factor. Thus, the PLA substrate can be an option to replace the PCB substrate. Theoretically, as described in [26], the resonant frequency is inversely proportional to the dielectric constant. Hence, the increased dielectric constant will result in a lower resonant frequency. Moreover, the resonant frequency is directly proportional to the Q-factor, as described in (8).

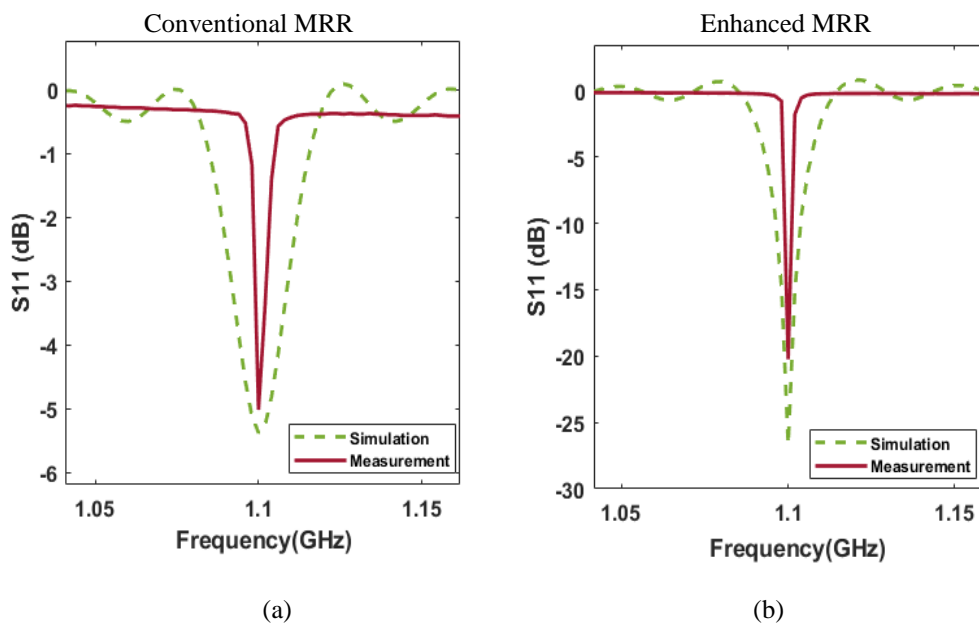


Figure 5. Return loss of, (a) Conventional design, (b) Enhanced MRR design

Table 2 shows the state art based on previous studies. It is found that the two-port MRRs were based on the PCB substrate and operated at 1 GHz, while the proposed MRR was designed with a single port and operated at 1.1 GHz resonant frequency based on a thermoplastic substrate. The frequency operates at 1.1 GHz due to the stability of the performance of the resonator. The proposed MRR produces a better performance in terms of a narrow return loss of -20.23 dB and a high Q-factor of 200 compared with the previous works. Furthermore, the proposed MRR design is simple and small-sized, costs less and is a green technology due to PLA substrate being a recyclable material [9]. Thus, the proposed MRR can be applied in microwave applications due to the good performance of the Q-factor [6].

Table 2. State of art

Previous work	[8]	[21]	[27]	Proposed MRR
Properties				
MRR	Two-port	Two-port	One port	One port
Frequency	1 GHz	1 GHz	1 GHz	1.1 GHz
Q-factor	-	83.92	-	115.80
S11/S21	S21, -8.22 dB	S21, -20 dB	S11, -15 dB	S11, -20.17
Substrate	FR4	FR4	Rogers 5880	PLA
Area×thickness (mm ² ×mm)	16295.5×1.6	-	12337.5×0.787	10350×1.6

4. CONCLUSION

The conventional and enhanced MRRs were designed, simulated and measured successfully based on a thermoplastic substrate (PLA) at the resonant frequency of 1.1 GHz. Based on the observation, the enhanced MRR design's performance is better than the performance of the conventional MRR design. The enhanced MRR design is proposed to overcome the low performance of the conventional MRR design. Hence, the novelty of the proposed MRR design is that a substrate based on PLA can be applied in RF and microwave applications due to the high Q-factor of the MRR and that it is a green technology. Further investigations will be held to improve the performance of the MRR.

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