Bridge multiple split ring resonator sensor for microwave liquid characterization

Aziean Mohd Azize¹, Amyrul Azuan Mohd Bahar²,³, Wan Haszerila Wan Hassan¹,³, Zahriladha Zakaria⁴, Rammah A. Alahnomi³,⁴ and Mohd Hakim Abdul Hamid⁵

¹Faculty of Electric and Electronics Technology, Universiti Teknikal Malaysia Melaka (UTeM), 76100, Durian Tunggal, Melaka, Malaysia
²Intel Microelectronics, Bayan Lepas Free Zone, 11900 Penang, Malaysia
³Microwave Research Group (MRG), Centre for Telecommunication Research and Innovation (CeTRI), Universiti Teknikal Malaysia Melaka (UTeM), 76100, Durian Tunggal, Melaka, Malaysia
⁴Faculty of Electronics and Computer Engineering, Universiti Teknikal Malaysia Melaka (UTeM), 76100, Durian Tunggal, Melaka, Malaysia
⁵Faculty of Information and Communication Technology, Engineering, Universiti Teknikal Malaysia Melaka (UTeM), 76100, Durian Tunggal, Melaka, Malaysia

Abstract. A planar bridge multiple split-ring resonators (BMSRR) with a microfluidic sensor is a real-time nondestructive sensor designed based on bridge split ring topology. This sensor has the ability to characterize liquid solvents using the extraction of polynomial fitting technique and bridge connector elements were added to enhance the quality factor and sensitivity. The characterization of liquid samples is analysed and numerically expressed based on their dielectric properties and loss tangent with a minimum volume of samples. The unloaded Q-factor improves more than 400 over the bandwidth at an operating frequency of 2.3 GHz.

1. Introduction

Characterization of material properties at microwave frequency has a long history, dating back at the early 1950s [1]. Microwave electronic sensor, especially for material characterization, has gained increasing attention from scientific communities and tremendously developed in these recent years for their wide variety of application and high demand in characterizing platform. This is due to the growth of microwave industries technologies, especially in material characterizing application [2]. Moreover, the ability to non-destructively sense and monitor specific properties of material undergoing chemical or dielectric changes has highly benefited bio-medical, pharmaceuticals and industries [3].

It is important to produce precise information on material characterization science scientific understanding of engineering materials could only be realized from a sensor which can provide such valuable information precisely. However existing conventional sensors are often bulky, expensive, complicated, expensive and even difficult to realise to meet the specific requirement of material characterization. Therefore, many researchers are attracted to microwave planar resonator sensors since they offer simple structure design, compact size, and also cost-effective. Yet, the planar resonator sensor suffers low sensitivity and poor accuracy which restrict its usage and limit its range of applications [4].
This is the reason for design modification which can yield a high Q-factor, compact size, high accuracy high performance and a good measurement result of microwave resonator sensor [5].

The design of bridge microwave multiple split-ring (BMSRR) is the modification of MSRR which has been made to overcome the drawbacks of the planar resonator. The electrical fields’ polarity on the sensing region is improved where the bridge technique is applied between two inner rings of the structure. The bridge is used as a pushing structure to allocate a huge amount of electric flux on the sensing area so that the capability of this sensor can be enhanced.

2. Design

The sensor is designed with RT/Duroid 5880 to meet the specification of 2.3 GHz operating frequency, less than 5 dB insertion loss, first mode order and quality factor more than 300.

The design of MSSR starts with calculating the specification and physical parameters of the split-ring resonator prototype. For the ring resonator, the resonance is produced when the mean circumference of the ring is equal to an integral of the guided wavelength:

$$2\pi r = n\lambda_g$$

where n = 1, 2, 3, 4... and so on

Resonant frequency for n modes given by:

$$\lambda_g = \frac{\lambda}{\sqrt{\varepsilon_{eff}}}$$

Considering Equation (1) and (2) the resonant frequency is given by:

$$f_0 = \frac{nc}{2\pi r\sqrt{\varepsilon_{eff}}}$$

For the 50 Ω characteristic impedance $Z_o$, the w/d ratio and effective dielectric constant can be found using this formula.

$$\frac{w}{d} = \frac{8e^A}{e^{2A}-2}$$

where

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

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r^{-1}}{2} \cdot \frac{1}{\sqrt{1+12\left(\frac{d}{w}\right)^2}}$$

The main radius can be calculated using this formula:

$$r = \frac{n\lambda_g}{2\pi}$$

As moving towards design development, split-ring resonant sensor structure can be described by an equivalent parallel RLC resonant circuit. The value of L depends on the transmission line of the ring and the gap capacitance contribution to C. The resonant frequency can be calculated using:

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$
The numerical expression of dielectric constant and tangent loss are found using the polynomial fitting technique. The derivation of the relationship between dielectric properties and loss tangent is given as follows:

\[ Q_{LUT} = \frac{1}{\tan \delta}, \text{ while } \tan \delta = \frac{\varepsilon''}{\varepsilon'} \quad (9) \]

The simulation of this sensor is executed using EM Simulator software. The ring structure with a coupling gap of 0.2 mm is the key to control the capacitance strength. The bridge connection is the design between the middle and inner ring with 1.5 mm wide and the split structure of 1.0 mm for each ring. This physical structure layout builds an interacting channel with bridge connectivity as a pushing element for flux enhancement at the sensing area [6] so that the bandwidth of the resonator circuit is reduced significantly. Figure 1 (a) and (b) show the BMSRR design structure of perspective view ring structure with close up sensing area and side view with centre hole to place microcapillary [7].

![Figure 1](image-url)
3. Result and discussion

The simulation response of the BMSRR, which is operating in a complete system with a two-port network from the transmission to reflection line is shown in Figure 2. The resonant frequency of this sensor is set to 2.3 GHz with 525 Q-factor and -2.33 dB insertion loss. Figure 2 shows the simulated frequency response and illustrates the improvement of E-fields as the electromagnetic signal propagates through the sensor.

![Figure 2](image)

(a) Simulated frequency response and (b) Electric field of BMSRR

These figures show that the bridge element on the split ring increases the quality factor and minimize the frequency bandwidth, hence boost up the sensitivity of the device. The capability of the sensor will then be verified using several aqueous solvents which have different dielectric properties. Several aqueous solvents with different dielectric constant and relaxation time were chosen to analyse the sensor sensitivity further to differentiate the effect of a bridge element. The comparison of the resonant frequency with and without capillary and its response towards different materials has been carried out. Each sample consist of dielectric properties which perturb the electric fields inside the sensing area is defined subsequently in order to characterize the properties. Figure 3 shows the simulated frequency response with the presence of various liquid samples. It clarifies the resonant frequency, insertion loss, and quality factor clearly changed due to the polar nature of samples.

![Figure 3](image)

Figure 3. Simulated frequency response of BMSRR sensor with the presence of liquid samples.
The value of Q-factor reduce with respect to dielectric properties of presence samples are shown in Table 1. Samples with high permittivity were shifted towards low frequency due to capacitance and inductance strength.

| Solvents         | $S_{21}$ (dB) | Q factor | Frequency (GHz) | Frequency shifted (MHz) |
|------------------|---------------|----------|-----------------|------------------------|
| Without capillary| -2.33         | 525      | 2.30            | -                      |
| Empty capillary  | -10.17        | 151      | 2.26            | 40                     |
| Water            | -6.52         | 440      | 2.20            | 100                    |
| Ethanol          | -14.38        | 147      | 2.23            | 70                     |
| Methanol         | -12.68        | 220      | 2.22            | 80                     |

The fabrication and measurement are shown in Figure 4 with the final dimension width and length of approximate 4.9 cm and 11.3 cm, respectively. The comparison of simulated and measured data are shown in Table 2.

**Figure 4.** (a) Fabricated BMSRR sensor and (b) measurement system

| Test            | $f_r$ (GHz) | $S_{21}$ | Q-Factor |
|-----------------|-------------|----------|----------|
| Simulated       | 2.30        | -2.33    | 525      |
| Measured        | 2.30        | -8.12    | 487      |

The measurement of frequency response shows a good agreement compared with simulated result results, as shown in Figure 5.
Figure 5. Comparison of simulated (s) and measured (m) result (a) without sample and (b) with the presence of aqueous solvents

Shifting of response is the reflection from dimension error uncertainties which may slightly different during the fabrication process, Q-factor and insertion loss may be due to radiation loss at input and output network due to weak connectivity of port coupling. The shifting of response also could be due to the dimension uncertainties, sensing medium characteristic, the properties of the substrate as well as the room temperature during the measurement [8].

The dielectric constant or real part of permittivity was determined using a second-order polynomial fitting technique based on graph pattern of ideal and measured values [9] as shown in Figure 6.

Figure 6. Polynomial fit of dielectric constant

The difference between ideal and measured datasets was analysed based on the cumulative percentage error trend. There are a few sample conditions that have to take into consideration before experimenting such as concentration, temperature, humidity and other environmental circumstances [8].

The determination of the imaginary part of permittivity can be calculated directly from the equation given in [10]. The dielectric constant was fitted against resonant frequency shifting with respect to dielectric properties of LUT, whereas the loss tangent was fitted against the 3dB bandwidth of frequency
response due to the change of quality factor [11]. The relationship of loss tangent and resonant frequency shifting was generated in Figure 7. The relationship between $\tan\delta$ and $\Delta f$ are defined as a second-order polynomial expression to generate an accurate numerical model.

Figure 7. Polynomial fit of loss tangent

Table 3 shows the overall comparison on dielectric properties in term of dielectric constant, dielectric loss factor and loss tangent of the aqueous solvents. These results show BMSRR provide high efficiency and sensitivity of measurement based on the mathematical model.

| Method   | Ideal Values [12] | Commercialized Sensor [13] | BMSSR |
|----------|-------------------|-----------------------------|-------|
|          | $\varepsilon'$   | $\varepsilon''$            | $\varepsilon'$ | $\varepsilon''$ | $\tan\delta$ | er % | $\varepsilon'$ | $\varepsilon''$ | $\tan\delta$ | er % |
| LUT      | 1.00059           | 0                           | 0.0102  | 0.00649        | 0.00649       | 0.06  | 1.001          | 0.0067         | 0.0069        | 0.04 |
| Air      | 24.5              | 23.0545                     | 0.941   | 24.4057        | 22.2657       | 0.9120 | 0.38           | 24.49          | 22.0508       | 0.9036 | 0.04 |
| Ethanol  | 32.7              | 21.5493                     | 0.659   | 32.5538        | 19.4529       | 0.5976 | 0.45           | 32.84          | 20.5230       | 0.6695 | 0.43 |
| Methanol | 80.1              | 9.8523                      | 0.123   | 75.8915        | 19.6661       | 0.2590 | 5.25           | 80.03          | 9.5236        | 0.1205 | 0.10 |

4. Conclusion

The simulation and realisation of microstrip planar technology with multiple split-ring resonator (BMSRR) approach have been achieved and reviewed. The comprehensive analysis and comparative studies have been examined. The analysis shows that the value of dielectric parameters using BMSRR is more accurate compared to the commercial sensor in term of complex permittivity and tangent loss. The design outcomes have reflected the aims of the project, which focuses on high sensitivity liquid planar sensor realization.

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