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Non-invasive Measurement of Complex permittivity using a Compact Planar Microwave Sensor

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Abstract

This work describes the development of a compact planar microwave sensor for non-invasive complex permittivity measurement of liquids. The sensing element is a quarter wavelength stepped impedance resonator realized on an asymmetric coplanar stripline. To characterize the material, the sensor detects the resonance frequency and phase of the reflection coefficient. Numerical simulations were conducted for non-invasive and invasive measurements and mathematical relations are formulated for extracting the dielectric constant and loss tangent of the sample. The sensor is intended to operate at 5.6 GHz in free space. A prototype of the designed sensor is fabricated and tested with using a modest volume of test liquids as a proof of concept. The actual dielectric properties of the solution are measured using a commercially available dielectric probe. The extracted dielectric measurement acquired with the sensor are very similar to those obtained with the dielectric probe.

1. Introduction

Material characterization has grown increasingly significant in today's environment since dielectric parameters are used in various applications[1]. In the literature, various strategies for material characterization using RF/microwaves have been proposed. Because of its simplicity, cost effectiveness, and precision, the resonant technique using a planar resonator is gaining popularity. The split-ring resonator (SRR), complementary split-ring resonator (CSRR), stepped impedance resonator (SIR), and open stub are the most common resonating elements in planar sensors [2]. Material characterization involves the determination of real and imaginary parts of permittivity. The resonant frequency is used in various publications to obtain the dielectric constant, whereas the quality factor/magnitude of the transmission/reflection coefficient is used to calculate the loss tangent[3, 4]. Another property used to determine dielectric values is the phase of the reflection coefficient[5].
When electromagnetic waves of a specific frequency interact with materials, anomalous dispersion in the phase response at that frequency is observed when the material's atomic resonance coincides with the wave frequency. The electromagnetic wave is entirely absorbed by the material at this frequency, and the resulting phase change can be used to determine material properties[6].

This paper proposes employing a uniplanar asymmetric coplanar strip (ACS) fed SIR sensor to extract complex permittivity of liquids. Invasive and non-invasive measurements are numerically simulated, and the real and imaginary components of permittivity are mathematically modelled. On the fabricated prototype, experiments with various liquid samples and mixes are carried out. The samples with dielectric constants ranging from 2-78 are tested. The sensor's resonance frequency and phase are measured. The test liquid is kept in a square cuvette at different distances from the sensor for non-invasive measurement.

2. Sensor design, Operation and Methodology

The sensor consists of a quarter-wave SIR connected to an open-ended ACS feed line. This compact uniplanar sensor is designed to operate at 5.6 GHz in free space and has a dimension of 11 x 10 x 1.6 mm^3. The sensor is built on an FR4 substrate with a relative permittivity of 4.4 and a loss tangent of 0.02 using the full-wave electromagnetic simulator CST microwave studio. The schematic of the proposed sensor is shown in Figure 1(a). The SIR's high impedance line is connected to the ACS feed line, while the low impedance line is kept open. Figure 1(b) depicts the sensor's electric field pattern. The sensing zone is chosen to be the open end of the sensor, which provides the maximum electric field. Figure 1(c) shows the sensor's equivalent circuit.

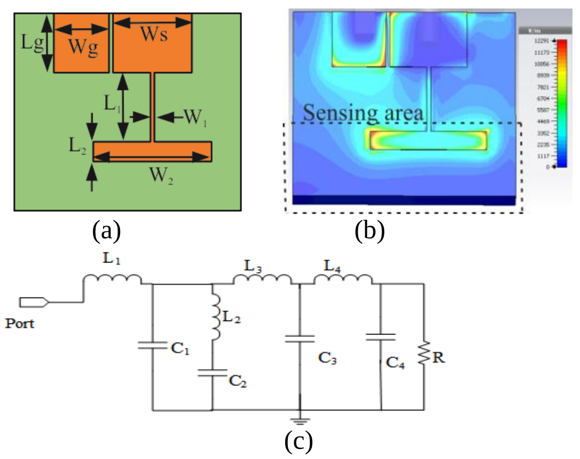


Figure 1. (a) Schematic diagram of the proposed sensor. (Lg= 3 mm, Wg= 3 mm, Ws = 4 mm, L_1 = 4 mm, W_1= 0.2 mm, L_2 =1 mm, W_2 = 6 mm). (b) Electric field distribution, (c) Equivalent circuit.

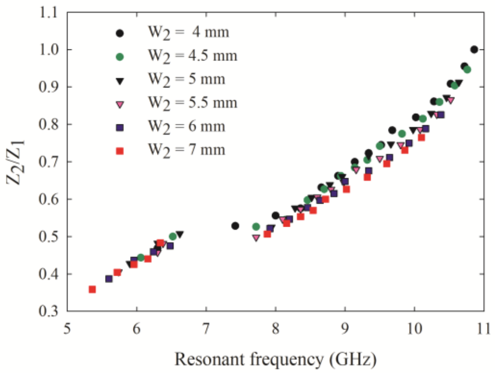
The impedance ratio and length ratio of a SIR are the two characteristics determining its operating frequency[7].

$$K=\frac{Z_2}{Z_1} \quad (1)$$

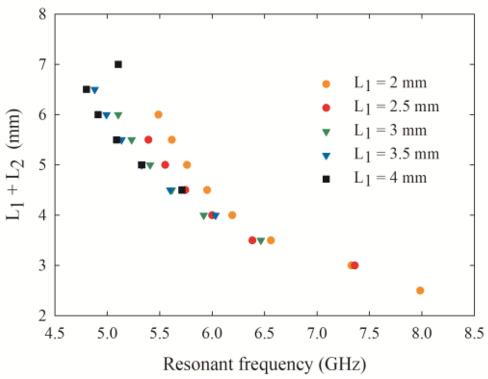
gives the impedance ratio and the length ratio is given by

$$\alpha = \frac{\theta_2}{\theta_1+\theta_2} \quad (2)$$

where Z_1, Z_2 are the impedances corresponding to width W_1 and W_2 and θ_1 and θ_2 are electrical length corresponding to L_1 and L_2. Figure 2(a) and 2(b) shows the relationship between the SIR's impedance ratio and length on the resonant frequency. The resonant frequency lowers as the impedance ratio decreases and the total length of the sensor increases, as seen in the charts. The suggested SIR has a total length of 5 mm and an impedance ratio of 0.38.



(a)



(b)

Figure 2. Change in the resonant frequency of SIR (a) With varying impedance ratio (b) With varying length.

This paper presents two approaches for liquid characterization, Invasive and non-invasive measurement techniques.

2.1 Invasive measurement

The sensor is immersed in a variety of liquid samples, all of which have different dielectric characteristics. In simulations, samples with dielectric constants ranging from 25 to 75 were employed. The reflection coefficient of the sensor when immersed in liquid is plotted in Figure 3. A decrease in resonant frequency can be observed with increase in dielectric constant. Using curve fitting approach, an equation is developed for dielectric constant as a function of resonant frequency, as given by

$$\varepsilon_r = k_0 + \frac{k_1}{f} + \frac{k_2}{f^2} + \frac{k_3}{f^3} \quad (3)$$

where ε_r is the dielectric constant, f is the resonant frequency, k_0, k_1, k_2 and k_3 are constants given by k_0 = 5.1697, k_1 = -88.8451, k_2 = 399.7948, k_3 = -162.8304.

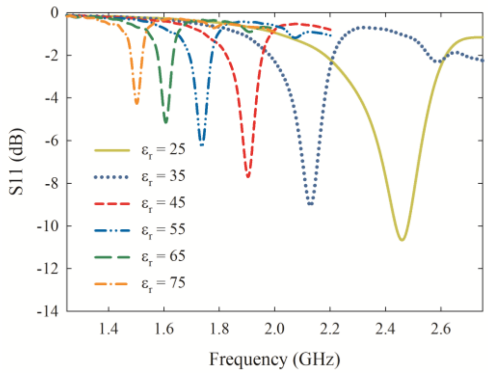


Figure 3. Response of the sensor for varying dielectric constant

The effect of the loss tangent on the sensor's reflection phase is depicted in Figure 4. It is evident from the graph that the slope decreases as the loss tangent increases. A numerical relation for loss tangent is formed from the phase slope as given below.

$$\tan\delta = k_0 + \frac{k_1}{s} + \frac{k_2}{s^2} + \frac{k_3}{s^3} \quad (4)$$

where s is the phase slope, k_0, k_1, k_2 and k_3 are constants given by k_0 = -0.0312, k_1 = 18.19, k_2 = 1492 and k_3 = -141651.

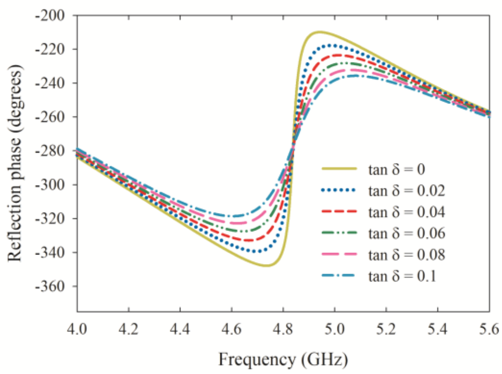


Figure 4. Response of the sensor for varying loss tangent.

2.2 Non-invasive measurement

Non-invasive characterization is becoming more popular and highly demanding due to its nondestructive nature. The reflection coefficient and phase of the sensor when it is placed near a cuvette containing a sample are measured. The reflection properties of the system are recorded at various distances from the sensor. Figure 5(a) shows the simulated resonant frequency of the sensor for different dielectric constant with varying distance. Figure 5(b) demonstrates how the slope of the sensor's reflection phase changes as the loss tangent changes with distance.

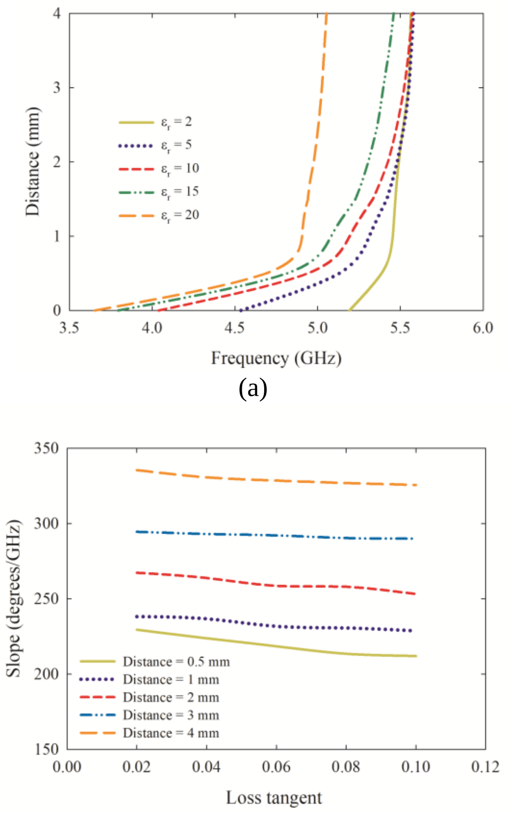


Figure 5. Response of the sensor for varying dielectric properties. (a). Dielectric constant (b). Phase slope.

The resonant frequency reduced as the dielectric constant increased, but the frequency increased with the distance between the sensor and the sample, as in Figure 5(a). For the case of reflection phase, slope decreases with the increase in loss tangent and increases with distance.

3. Experimental results and discussions

The photolithographic technique is used to fabricate the sensor. Keysight PNA N5277A is used for the measurements. Keysight dielectric probe N1501 A is used to measure the sample's actual dielectric properties. Figure 6 shows the sensor's simulated and measured reflection coefficient in free space.

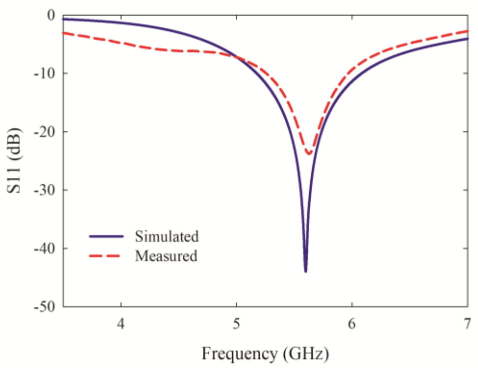


Figure 6. Reflection coefficient of the unloaded sensor.

3.1 Invasive measurement

In order to obtain samples with dielectric constants ranging from 78 to 22 and loss tangents ranging from 0.04 to 0.16, water and acetone were mixed in different proportions. 10 ml of the prepared samples were taken in a container, and the sensor was immersed in the liquid sample until the sensing area of the sensor was wholly immersed in the liquid. Figure 7(a) and (b) shows the sensor's reflection coefficient and phase for different liquid samples.

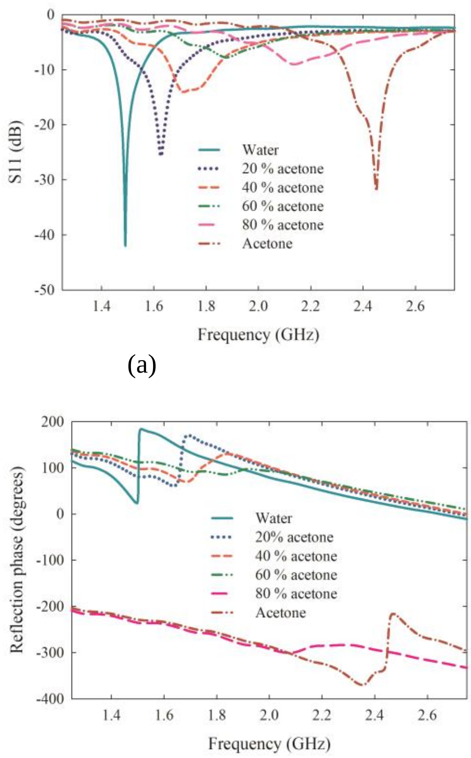


Figure 7. (a) Measured reflection coefficient. (b) Measured reflection phase.

The dielectric constant decreases as the acetone concentration rise, lowering the resonant frequency. Because of the initial increase in loss tangent, the phase slope is initially reduced and then increased.

In Table 1, the extracted dielectric constant and loss tangent using equations (3) and (4) are compared to the actual dielectric constant (ε_r) and loss tangent (tan δ) measured with dielectric probe.

Table 1. Comparison of the measured results

Concentration of acetone in water (%)	Using proposed sensor		Using dielectric probe	
	ε_r	tan δ	ε_r	tan δ
20	66.05	0.07	67	0.115
40	58.5	0.08	59.48	0.15
60	47	0.139	46.61	0.17
80	34.33	0.161	34.77	0.138

3. 2 Non-invasive measurement

The measurement of standard test liquids at various distances is carried out. In a square cuvette with dimensions of 10 x 10 x 45 mm^3, a 1 ml liquid sample is taken. Figure 8 depicts the measurement setup. The dielectric probe is connected to port 1, and the sensor is connected to port 2. The cuvette with a sample is placed at a distance from the sensor. The fabricated prototype is shown in the inset.

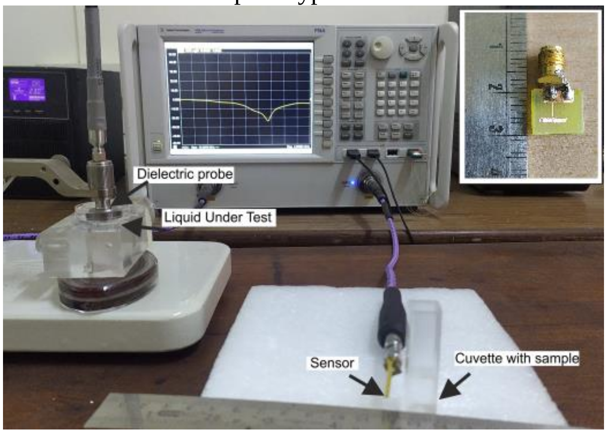


Figure 8. Non-invasive measurement setup.

Figure 9 depicts the reflection coefficient and phase of the sensor for various liquid samples. Figure 9 (a) shows a decrease in resonant frequency as the dielectric constant increases and an increase in frequency as the distance increases. Figure 9 (b) shows a positive slope when the sample is close to the sensor, then a negative slope as the distance increases. With increasing distance and loss tangent, the slope is found to increase.

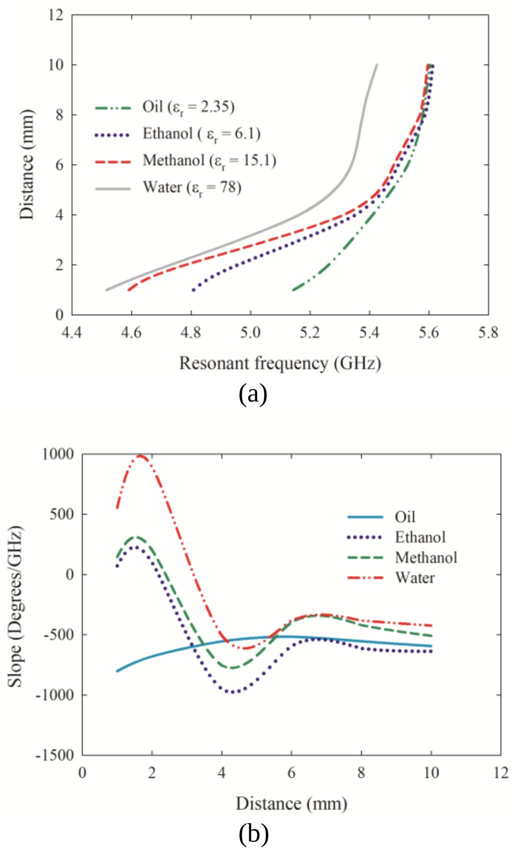


Figure 9. Measured response of the sensor for varying distance. (a) Resonant frequency (b) Phase slope.

The obtained measured values were very close to the simulated outcomes. The sensor is extremely sensitive, small, and inexpensive.

Conclusion

This study presents a method for sensing the dielectric characteristics of liquid samples using a compact, sensitive, low-cost, and non-destructive sensor. From the resonant frequency and reflection phase slope, the sensor measures the complex permittivity across a wide range of 2-78. Invasive and non-invasive measurement techniques are realized using electromagnetic simulations and are validated by measurements. The measured permittivity values are in good agreement with the actual values. Any liquid's complex permittivity can be measured using this sensor.

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