Metamaterial-Inspired Microwave Sensor for Ethanol Detection

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***Abstract*—In this work, a high-sensitive microwave sensor based on an improved split ring resonator (SRR) for detecting ethanol concentration in aqueous ethanol solutions is proposed. This biosensor combines SRR with the inter-digital capacitor (IDC) and adds two pairs of IDCs on the resonator for enhanced electric field concentration over a larger surface area, which provides higher sensitivity for testing dielectric liquids. The coupling between the two resonant elements and the transmission line deepens the amplitude of the biosensor. The material under test (MUT) is properly placed in the IDC region of the SRR, where the highest electric field strength can achieve low-cost, pollution-free, non-contact, high-sensitivity detection. This sensor resonates at 3.44GHz with a resonance amplitude of -17dB. Ethanol in the concentration range of 20%-100% can be measured by the resonant frequency and the S_{21} parameter's change. The sensitivity of this microwave sensor for measuring ethanol is 0.75 MHz/% and 0.03 dB/%, which can be used for quantitative detection of ethanol solution.**

Keywords— Microwave characterization; ethanol sensing; permittivity measurements; split ring resonator (SRR); inter-digital capacitor (IDC).

INTRODUCTION

In recent years, there has been a growing demand for non-contact sensors, and microwave sensors have been widely used in many physical and biomedical fields, such as liquid characterization, cell, gas, temperature, and relative humidity detection [1]. The microwave sensor design is developing toward miniaturization, low cost, easy fabrication, and high sensitivity. The liquid characterization field faces challenges such as tiny variations in the MUT, external influences on the detection environment, and low sample size for detection [2]. Microwave resonators are sensed based on the principle of perturbation and characterize the change in resonant frequency and amplitude caused by the change in the dielectric constant of the MUT [3]. Therefore, performing non-contact sensing sensitively to meet the requirements for liquid characterization is possible.

Metamaterials are artificially engineered materials with negative permittivity and permeability widely used in microwave sensors. Metamaterials can achieve high sensitivity and low sample volume liquid characterization due to their strong local electric and magnetic fields. Such as split ring resonator (SRR), complementary split ring resonator (CSRR), complementary electric LC resonator, etc., are widely used in liquids dielectric characterization due to their high sensitivity and robustness. For example, using metamaterial-excited CSRR to detect ethanol solution [4], the sensor has a size of 20 mm × 25 mm, operates at 2.01 GHz, and can detect ethanol solutions with a concentration of 0-100%, with a sensitivity of 0.35 MHz/%. The sensor with DSRR structure is used to detect alcohol solution with concentration ranging from 0% to 100%, with a sensitivity of 0.2 MHz/% [5]. In this work, the microwave sensor adopts an improved SRR structure reducing the size to 12 mm × 9.2 mm, and increasing the sensitivity to 0.75 MHz/%.

This work combines SRR with IDC to reduce the area of the sensing element and increase the effective high electric field strength area. Two identical resonant elements are symmetrically coupled on both sides of the transmission line, enhancing the resonance amplitude of the microwave circuit and used for high-sensitivity detection of ethanol solution. Section II introduces the design and fabrication of the sensor, including the working principle, equivalent circuit, and simulation results. Section III presents the results and analysis of this microwave sensor for ethanol solution detection.

SENSOR DESIGN AND MANUFACTURING

The conventional metamaterial SRR structure is improved by combining SRR with IDC. Adding the logarithm of the IDC is simulated in the simulation software. Initially, when joining IDCs, the sensitivity increases with the number of IDCs. An excessive number of IDCs will result in the electric field not being coupled to its end, so too many IDCs are not helpful for sensitivity improvement. This sensor uses a symmetrical modified SRR structure and is magnetically coupled to a microstrip transmission line. Higher sensitivity is obtained by using the following: (1) Ensure the width of the transmission line meets the 50 Ω impedance matching standard, enhances the mutual inductance coupling between the coils, and ensures the energy transfer between the transmission line and the SRR structure. (2) Adjust the size of the modified SRR to achieve tighter coupling, increase the effective interaction area, and increase the gap capacitance and the electric field strength at the SRR gap by reducing the gap width. (3) Explored the effect of one set of SRR structures versus two sets of SRR structures coupled with transmission lines, as shown in Fig. 1. When the sensor structure is changed from one group of SRR to two groups of SRR, the resonant frequency is changed from 3.66 GHz to 3.60 GHz, and the resonant amplitude is changed from -17 dB to -24 dB. Therefore the sensor is designed with two sets of improved SRR structures with transmission line coupling to achieve higher sensitivity

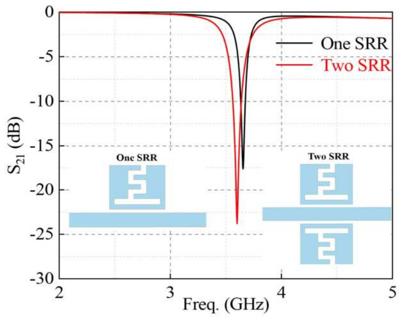


Fig. 1 Simulation results of one SRR and two SRR structures.

The sensor's design is shown in Fig. 2. Table I lists the geometric parameters of the final design after optimization. The sensor is 12 mm long and 9.2 mm wide and is processed by a wet etching process on a substrate with a dielectric constant of 10.2, a thickness of 1.524 mm, and a loss tangent of 0.003. The resonator, microstrip lines, and ground plane are patterned using copper (35 µm), and the simulated and measured S_{21} parameters are shown in Fig. 3(a). The electric field intensity distribution on the sensor surface is shown in Fig. 3(b). Therefore, placing the liquid channel in the IDC region for high sensitivity detection.

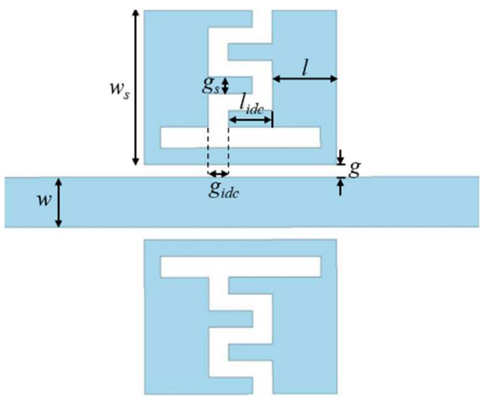


Fig. 2 Sensor design.

TABLE I. DESIGN PARAMETERS OF THE SENSOR

Parameters	w	w_s	g	g_s	g_{idc}	l	l_{idc}
Value(mm)	1.2	3.7	0.3	0.4	0.5	1.6	1.1

The equivalent circuit model of the sensor is Fig. 4. The modified SRR structure can be equated to a parallel circuit of resistance, capacitance, and inductance. As the sensor loads the MUT, the sample interacts with the resonant unit, causing a perturbation of the electromagnetic field and the load cell's total capacitance and electrical impedance. The circuit change caused by this constant dielectric change is expressed as a change in the S_{21} parameter.

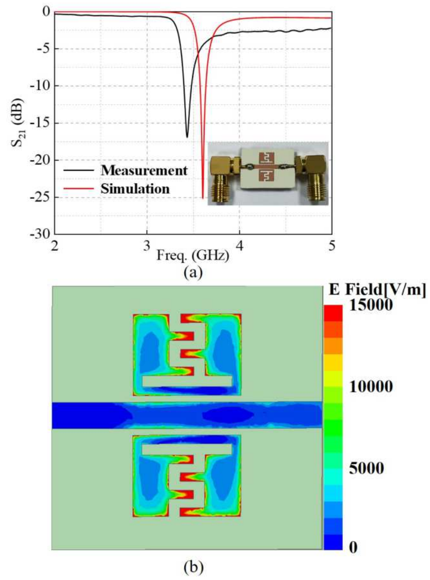


Fig. 3 (a) Simulation and measurement of sensor, (b) electric field simulation of sensor.

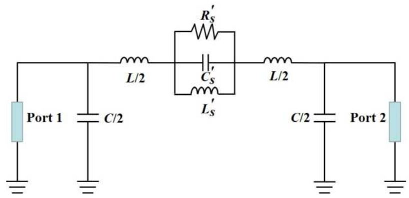


Fig. 4 Sensor equivalent circuit.

RESULTS AND ANALYSIS

This detection uses deionized water and anhydrous ethanol solutions to prepare ethanol solutions with concentrations of 20%, 40%, 60%, 80%, and 100%. A low-cost 0.3 mm × 0.6 mm (Inner diameter × Outer diameter) tube was used as a microchannel for ethanol liquid placed in the sensitive area of the sensor, and the transmission parameters (S_{21} parameters) of the resonator were measured using a vector network analyzer (VNA). VNA for accurate measurements recorded 1001 data points. Different concentrations of ethanol solutions prepared above were passed sequentially during the experiment, and the channels were rinsed with deionized water and dried with air before each measurement. Then recorded the data after the measurement system was stable (Fig. 5).

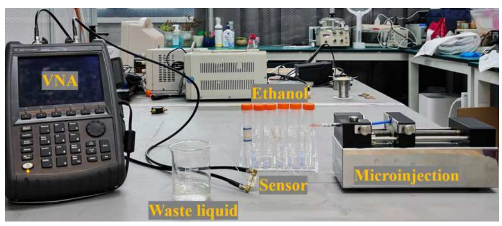
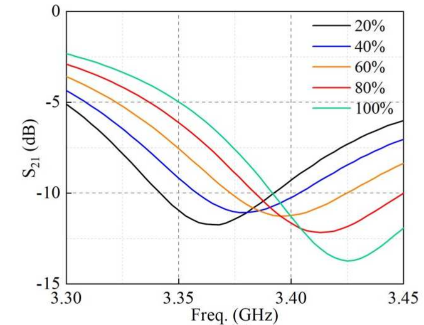


Fig. 5 Measurement platform.



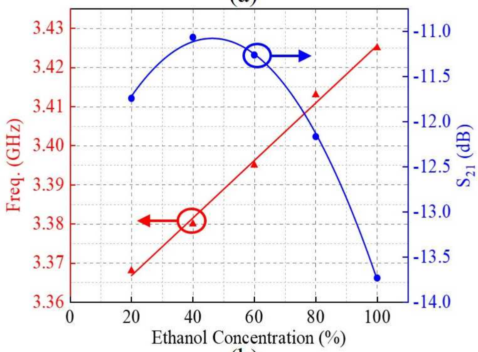


Fig. 6 (a) Measurement parameters of alcohol solutions with different concentrations, (b) changes of S_{21} and resonance frequency with alcohol concentration and fitting curves.

According to Fig. 6(a), it can be observed that as the ethanol concentration increases, the amplitude of S_{21} first increases and then decreases, and the resonant frequency increases. The sensor's sensitivity can be calculated from Eq. (1)(2), which are 0.02 dB/% and 0.71 MHz/%, respectively.

$$S_{ET}=\frac{f_{100\%ET}\text{-}f_{20\%ET}}{100\text{-}20}(MHz/\%) \quad (1)$$

$$S_{ET}=\frac{S_{21\,100\%ET}\text{-}S_{21\,20\%ET}}{100\text{-}20}(dB/\%) \quad (2)$$

The response curve of resonant frequency f with ethanol concentration is shown in the red curve in Fig. 6(b), and the equation after linear fitting is y=3.35+7.35×10^{-4}x, R^2=0.99. The response curve of resonant frequency f with ethanol concentration is shown in the blue curve in Fig. 6(b), and the equation after quadratic polynomial fitting is y=13.65+0.09x-9.26×10$^{-4}x^2$, R^2=0.99. Both curves have R^2 greater than 0.99, possessing a better fitting effect.

The complex dielectric properties of ethanol solutions can be represented by the Debye model [3], as in Eq. (3)(4)(5), where $\omega=2\pi f$;$\tau=1/2\pi f_R$; f_R is the relaxation frequency; ε_∞' is the real part for $f\to\infty$; ε_s' is the real part for $f\to 0$.

$$\varepsilon=\varepsilon'\text{-}j\varepsilon'' \quad (3)$$

$$\varepsilon'(\omega)=\varepsilon_\infty'+\frac{\varepsilon_s'\text{-}\varepsilon_\infty'}{1+\omega^2\tau^2} \quad (4)$$

$$\varepsilon''(\omega)=\frac{(\varepsilon_s'\text{-}\varepsilon_\infty')\omega\tau}{1+\omega^2\tau^2} \quad (5)$$

From the above equation, it can be seen that the dielectric constant of ethanol solution changes with the change in concentration. When the ethanol concentration increases, the relative dielectric constant becomes smaller, and the equivalent capacitance value in the circuit decreases, so the resonant frequency increases. And as the ethanol concentration increases initially, the water in the solution occupies more and gradually develops into more ethanol. The resonant frequency difference between ethanol and water increases and decreases, which is attributed to the dielectric perturbation [5]. So the resonance amplitude value increases and then decreases. In summary, the sensor possesses a high sensitivity for detecting ethanol solutions.

Conclusion

This paper proposes a new low-cost, non-contact, miniaturized and highly sensitive planar microfluidic microwave sensor to detect ethanol solution concentration. The improved SRR structure combines a conventional SRR and an IDC, which improves the sensor's sensitivity. The sensor's performance was verified by resolving ethanol solutions with concentrations ranging from 20% to 100%, with sensitivities of 0.03 dB/% and 0.71 MHz/% when applying the amplitude and resonant frequency, respectively. Due to its low cost and simple fabrication, this device has the potential for liquid sensing research and applications.

Acknowledgment

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