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Metamaterial-inspired microfluidic-based sensor for chemical discrimination

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***Abstract*—This work proposes a metamaterial-inspired microfluidic-based chemical sensor. The sensor comprises a microwave split-ring resonator (SRR), an important building block of metamaterials, integrated with a disposable flow-channel made of a transparency film. The electromagnetic response of the sensor is observed in the presence of various analytes including glycerol, ethanol, and phosphate buffered saline. It is found that the resonance frequency in the transmission amplitude and the zero crossing in the reflection phase of the sensor are good features for discrimination of these analytes and for determining their concentrations. The developed metamaterial-inspired microfluidic-based chemical sensor has a potential for advanced chemical sensing applications.**

I. INTRODUCTION

Metamaterials are artificial materials with electromagnetic properties not found in nature such as negative permittivity and negative permeability. They usually comprise periodically arranged structures with geometric features much smaller than the wavelength of the interacting electromagnetic wave [1]. A split ring resonator (SRR), a metallic open loop with a dielectric gap, is among the most common structures used in metamaterials. It exhibits a strong electromagnetic resonance with frequency and Q factor depending on the geometry, dimensions, and compositions of the structure. At resonance, the structure strongly couples with free-space electric or magnetic waves, resulting in localized electric field in the gap and a strong current oscillation in the metallic loop. This local resonant field is very sensitive to a change in the dielectric properties of a material in the gap region. This particular feature is thus promising for sensing applications [2-4].

Recently, metamaterial-based sensing platform has been implemented for chemical [5-6] and biological sensing [7-9]. The key advantages of this sensing platform include high sensitivity, real-time, and label-free detection ability. However, the use of this device for liquid-phase sensing applications requires precise control of analyte's shape and volume presented in the gap. The microfluidic platform is thus a potential solution to this issue [10-12]. In addition, integration with the microfluidic system permits low sample consumption. Nevertheless, there have been only a few reports of metamaterial-inspired sensors integrated in microfluidic systems. In this work, the metamaterial-inspired microfluidic-based sensor is developed and assessed for detection of distinct model chemicals, including glycerol, phosphate buffered saline (PBS), and ethanol dissolved in deionized (DI) water. Glycerol is a viscous liquid, widely used in pharmaceutical formulation, PBS is a common buffer solution for biological analytes and ethanol is a versatile solvent with many potential applications.

II. DESIGN AND FABRICATION

The metamaterial-inspired sensor was designed based on a microstrip-coupled SRR structure as illustrated in Fig. 1(a). The dimensions of the structure in the diagram were given as follows: l = 7 mm, w = 7.5 mm, g = 0.15 mm, r = 0.2 mm, c = 0.65 mm and w_s = 1.7 mm. The metallic structure was supported by a dielectric substrate, which had a full ground plane on its bottom side. The designed 50-Ω microstrip line, SRR, and ground plane were fabricated using standard photolithography and chemical etching. The dielectric substrate was RT/duroid 6010.2LM high-frequency laminate (ceramic-PTFE composite) with a thickness of 1.90 mm, a relative permittivity of 10.2, and a loss tangent of 0.0023, as demonstrated in Fig. 1(b).

A fluidic channel was then integrated on to the sensor by the craft-cutting method. The diagram of the disposable flow-channel integrated device is shown in Fig. 2(a). The 60-μm-high, 0.6-mm-wide and 3.0-mm-long channel was made by successive craft-cutting of a transparency film and doubled-sided tape. The fabricated channel was then aligned and attached across the SRR gab as shown in Fig. 2(b). This well-defined channel ensures the consistency of the volume and shape of the analyte over the gap area. The fabricated device

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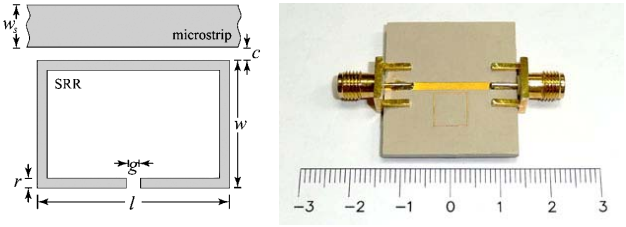
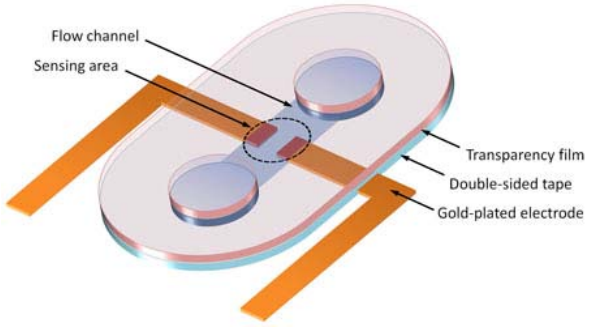
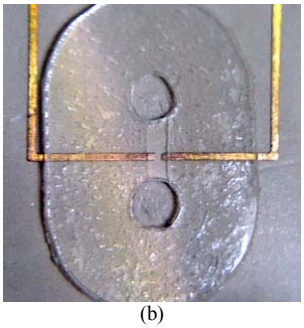


(a) (b)

Figure 1. (a) Diagram and (b) photograph of the fabricated microstrip-coupled SRR based sensor.



(a)



(b)

Figure 2. (a) Diagram and (b) photograph of the integrated disposable flow-channel on top of the SRR.

was then assembled with a sample injection module, which consists of inlet/outlet, rubber seal, clamp and holder as shown in Fig. 3.

III. Experiment and Results

The chemical sensing experiments were then performed using the experimental system as illustrated in Fig. 4. Three model analytes, including glycerol, ethanol and phosphate buffered saline (PBS) were prepared for sensing experiments. Firstly, the initial glycerol sample was prepared by mixing starting glycerol solution ($C_3H_8O_3 \cdot xH_2O$) and Triton® X-100 ($C_8H_{17}C_6H_4(OCH_2CH_2)_nOH$) with 9:1 v/v, while pure ethanol was used as its starting analyte and 0.01 M PBS (pH 7.4) solution was made by mixing an appropriate amount of PBS powder and DI water. It should be noted that Triton® X-100 is required to make the glycerol solution become water soluble. These initial analytes were then mixed with DI water at various concentrations ranging from 0% to 100% v/v with a 20% step increment. All chemicals were purchased from

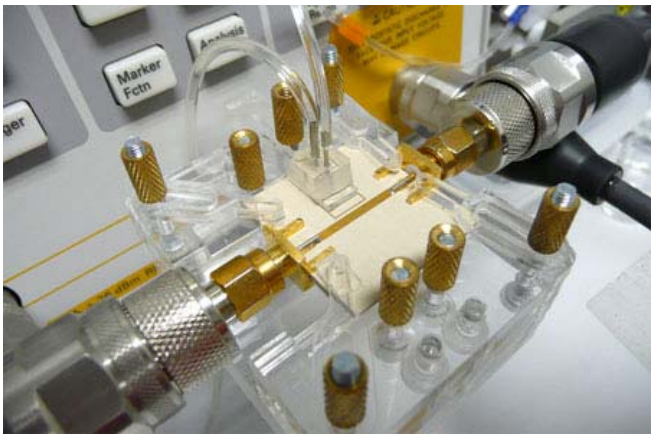


Figure 3. Photograph of the fabricated sensor in sample injection module.

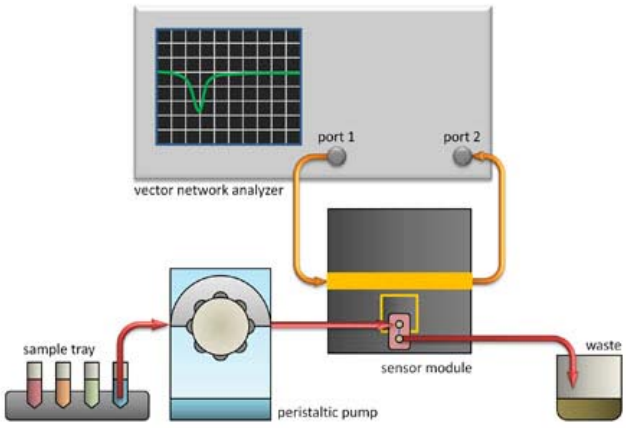
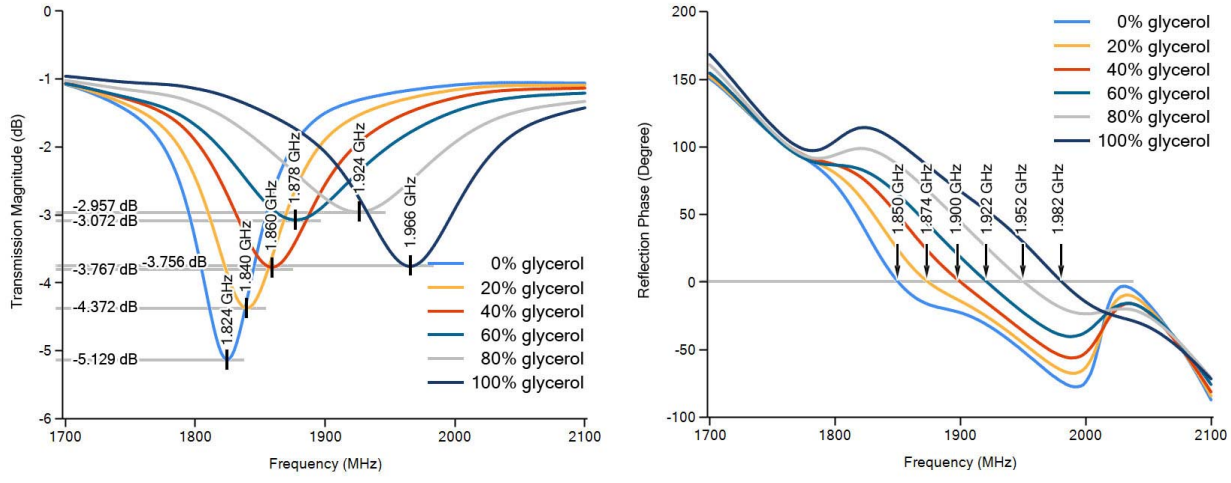


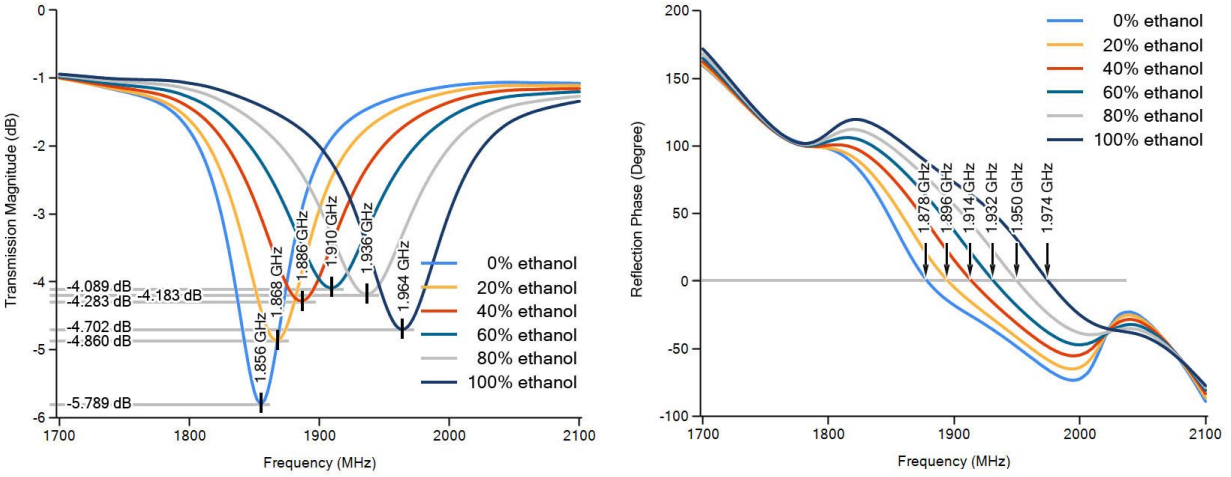
Figure 4. Schematic of the experimental system.

Sigma®. Each analyte were then fed into the flow chamber at a low flow rate of 10 µl/min while the electromagnetic responses were continuously monitored and recorded using the vector network analyzer (Agilent E5071C) as shown in Fig. 4. The electromagnetic response of the sensor was measured in terms of the S-parameters of the two-port network. Port 1 and 2 were connected to the two symmetric ends of the microstrip transmission line via SMA-type connectors. In this work, two parameters, the transmission amplitude ($|S_{21}|$) and reflection phase ($\angle S_{11}$), were used as classification features because their characteristics are directly correlated with the analyte type and concentration.

Fig. 5 (a), (b) and (c) show the transmission magnitude and reflection phase at various concentrations of glycerol, ethanol and PBS, respectively. For glycerol in Fig. 5 (a), it can be seen that the resonance frequency for glycerol analyte monotonically increases with an increasing glycerol concentration, while the resonance magnitude initially decreases as the concentration increases from 0 to ~80% but then increases as the concentration increases further. In the case of the reflection phase, it is found that the frequency of the zero-crossing phase linearly increases as a function of the concentration.



(a)



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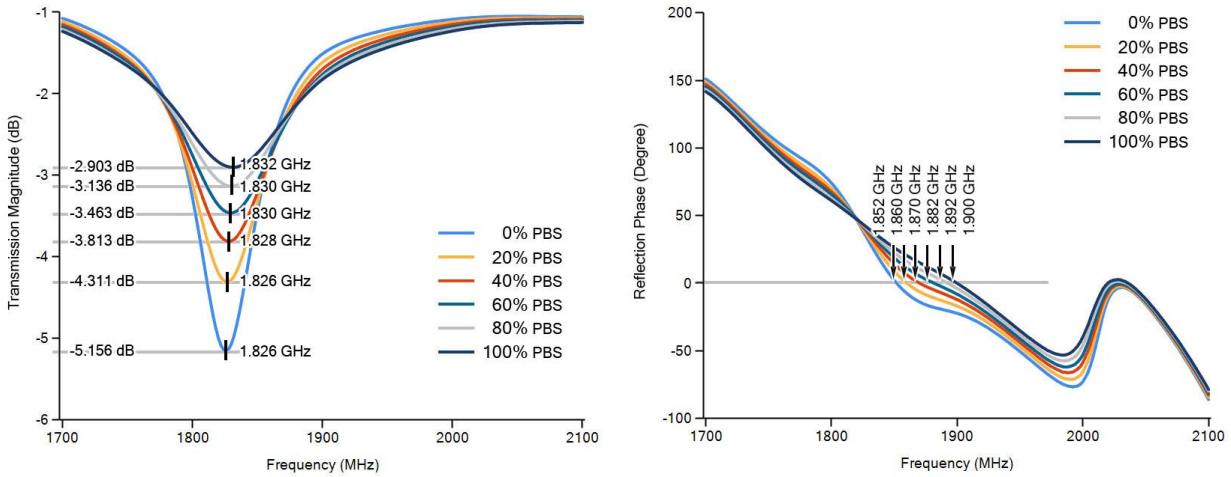

(c)

Figure 5. Measured transmission magnitude (left) and reflection phase (right) of (a) glycerol, (b) ethanol, (c) PBS in DI water at various concentrations.

For the ethanol mixtures, the resonance frequency/magnitude and the frequency at the zero-crossing phase behave similarly to those for the glycerol mixtures. However, it can be noticed that the shifts in the resonance frequency and the zero-phase frequency for the ethanol mixtures are considerably smaller than the shifts observed in the glycerol mixtures. Similarly, the variation in the resonance magnitude for the ethanol mixtures is lower than that of glycerol. In addition, the smallest resonance magnitude for ethanol mixtures occurs around the concentration of 60% which is lower than that of glycerol mixtures.

In contrast, the resonance frequency for the PBS mixtures is almost independent of the analyte concentration, while the resonance amplitude monotonically decreases as a function of the PBS concentration. For the reflection phase, the zero-crossing frequency is seen to increase with the concentration similar as for the other two analytes but the frequency variation is noticeably smaller than the other two cases. Thus, this zero-crossing frequency has a considerably different attribute and could be used together with the resonance frequency to determine the analyte type and concentration.

IV. CONCLUSION

In conclusion, a new metamaterial-inspired chemical sensor based on the SRR structure has successfully been integrated with a disposable flow-channel made of transparency film. The electromagnetic response of the sensor is observed and analyzed in the presence of various analytes including glycerol, ethanol and PBS binary mixtures. The resonance frequency in the transmission amplitude and the zero-crossing frequency in the reflection phase of the sensor are found to be effective for detection of these analytes and for determining their concentrations. In addition, these features provide potentially useful information for analyte discrimination. Therefore, the developed metamaterial-inspired microfluidic-based chemical sensor is a promising candidate for advanced chemical sensing applications. Further work in classification of these mixtures based on the observable features is in progress.

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