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Electromagnetic-based ethanol chemical sensor using metamaterial absorber

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ABSTRACT

We proposed a novel electromagnetic-based chemical sensor that is realized by using a metamaterial absorber. The metamaterial absorber comprises a split-ring-cross resonator (SRCR) and a microfluidic channel. The SRCR can generate LC resonance that is very sensitive to changes in the effective dielectric constant around the capacitive gap. In addition, microfluidic channels can change the effective dielectric constant of the dielectric substrate by using an infinitesimal quantity of a liquid on the order of microliters. The proposed chemical sensor can detect the electrical properties of any unidentified liquids injected into the channels, as well as concentration changes in the liquids. The performance of the proposed sensor is demonstrated using the absorption measurements of a fabricated prototype sample with waveguides. In addition, the relationship between the absorption frequency and chemical concentration is demonstrated.

1. Introduction

In recent years, chemicals in the liquid phase have been used in a variety of industrial applications. Such liquid chemicals are generally categorized and stored according to globally harmonized systems (GHS) of classification and labeling of chemicals, including the material safety data sheet (MSDS). Nevertheless, unidentified or unlabeled chemicals often occur in experiments. Several of these chemicals are harmful to the human body and health. For example, methanol is fatal to the central nervous system and can cause blindness, coma, or death if it is swallowed [1]. Therefore, the accurate detection and quantification of liquid chemicals used in various applications are essential.

Microfluidics has been proposed as a valuable tool for manipulating and analyzing chemicals using tiny amounts of liquid for applications such as blood analysis and bioassays, as well as for controlling manufacturing quality [2–6]. Conventional processes employed for analyzing bioassays and evaluating water quality require large amounts of liquid to fill tubing or valves [7,8]. Most of these liquids are wasted and are never utilized for analysis or measurement purposes. To eliminate the problem of wasted liquid chemicals, microfluidic systems have been introduced. Fluid analysis can be performed on infinitesimal quantities of samples, typically in the microliter range. This is possible because of the monolithic integration of sensing and interface electronics, fluidic manipulation structures, and micrometer-sized fluid channels on a single-packaged chip [6]. Recent research on microfluidics technology led to the development of fluid-tunable radio frequency (RF) systems as well as fluid-sensing microwave systems. Most of the recently reported fluid-integrated RF systems use liquid as a replaceable dielectric material for transmission lines, microwave resonators, or antennas [9–11].

Metamaterial absorbers can be realized using the periodic structures of electric LC (ELC) resonators such as split-ring resonators (SRRs) [12]. The resonance frequencies of metamaterial resonator structures are very sensitive to variations in capacitive and inductive effects because their fundamental resonance response can be modeled by an LC resonant circuit. This characteristic makes metamaterial absorbers suitable for metamaterial sensor applications [13]. For example, metamaterial absorbers implemented with SRR patterns on a silicon substrate have been introduced as strain sensors. The absorber can also be used to sense the mechanical deformation on a surface by measuring shifts in resonance frequency [14].

In this paper, we introduce a metamaterial absorber to realize an electromagnetic-based chemical sensor. The proposed chemical sensor can detect an ethanol concentration from the variations in resonant frequency of the metamaterial absorber. A metamaterial

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absorber is composed of split-ring-cross resonators (SRCRs) and a microfluidic channel carved in cost-effective FR4 substrate. The absorption frequency can be changed by injecting different liquids into the microfluidic channel. This fluid-controllable resonance phenomenon is beneficial for chemical or biosensor applications. The specific design details and experimental results of the proposed chemical sensor are provided in the following sections.

2. Design and structure

In order to design the metamaterial absorber for a chemical sensor application, the SRCR is adopted because of its symmetric and simple structure, as shown in Fig. 1(a). The LC resonance of the SRCR can be generated from the inductance of the crossed wire as well as the capacitance of the gap at the circular ring.

The capacitive components of the SRCR are dependent on the effective dielectric constant (ε_{eff}) around the gap, as shown in the following equation [15]:

$$C \cong \frac{\varepsilon_{\text{eff}} 10^{-3}}{18\pi} \frac{K(k)}{K'(k)} d \quad (\text{pF}), \tag{1}$$

where d is the width of the circular ring, and $K(k)/K'(k)$ is the approximate ratio between the elliptic integrals [16].

It can be noted from (1) that the resonant frequency of the metamaterial resonator is dependent on the geometrical dimensions of the SRCR as well as the effective dielectric constant. Because it is difficult to change the geometrical dimensions after fabrication, a microfluidic channel is introduced to change the effective dielectric constant. The effective dielectric constant can be changed drastically when a liquid is injected into the microfluidic channel of the unit cell. As a result, the resonant frequency will vary depending on the properties of the liquid injected into the microfluidics. Therefore, the proposed chemical sensor can detect the properties and changes in the concentration of liquids by analyzing the shift in resonant frequency.

For designing the microfluidic channels, the electric field distribution of the metamaterial absorber is simulated by a finite-element-method (FEM)-based ANSYS high-frequency structure simulator (HFSS), as shown in Fig. 1(b). The electric field of the incident wave is strongly coupled around the SRCR, especially at the left and right side capacitive gaps. Therefore, the microfluidic channel should be designed considering all capacitive gaps of the SRCR.

Fig. 2(a) shows the first design of the metamaterial absorber with a microfluidic channel. To include all capacitive gaps of the SRCR, the microfluidic channel is designed as a large square cuboid in the dielectric substrate. The microfluidic channel of the first design has a problem of uneven filling because the minimum pressure required to produce flow is inversely proportional to the cross-sectional dimensions of the microfluidic channel according to the Young-Laplace equation [11]. Therefore, the meandering single path is proposed as the second design for ensuring the smooth flow of liquids and filling a larger area of square cuboid, as shown in Fig. 2(b). Fig. 2(c) shows the three-dimensional layout of the final chemical sensor with the microfluidic channel. The proposed chemical sensor consists of three layers: the conductive SRCR pattern layer, the microfluidic channel layer, and the fully metal-covered bottom layer. Because the microfluidic structure is engraved in the dielectric substrate, extra devices for the microfluidic channels are not required. In addition, there is no transmitted wave because an entirely metallic bottom layer is used. Considering practical measurement environments, the final chemical sensor, including the liquid inlet and outlet, is shown in Fig. 2(d). A photograph of the fabricated chemical sensor prototype is shown in Fig. 2(e) and (f). The prototype sample was fabricated by combining three layers of FR4 substrate with a permittivity of 3.7 and dielectric loss of 0.02. The first layer consists of a conductive SRCR pattern etched on 0.1-mm-thick FR4 substrate at the top of the entire structure. The second layer, placed in the middle, is the microfluidic channel with a 0.1-mm thickness carved by using craft-cutting technology. The bottom layer of 0.8-mm-thick FR4 substrate is fully covered with copper on only one side. Each layer is attached to the others by adhesive laminating film. This adhesive lamination film can be simply used as a bonding material. However, this film reacts to acetone, benzene, and propanol. Therefore, the proposed sensor application is limited to ethanol detection. This limitation can be overcome by using other bonding materials such as SU-8. In addition, plastic inlet and outlet devices are used for the easy injection and removal of the liquids.

The electric and magnetic responses of the proposed chemical sensor can be understood by investigating the electric and magnetic field distributions. Fig. 3 shows the electric and magnetic field distributions of the proposed absorber for different microfluidic channel states. When the microfluidic channel is in the empty state, the electric and magnetic fields are strongly distributed around the SRCR at 12.12 GHz; however, they are weakened at 10.42 GHz, as shown in Fig. 3(a). On the other hand, when deionized (DI) water is injected into the microfluidic channel, the SRCR generates strong electric and magnetic responses at 10.42 GHz, but cannot generate the same at 12.12 GHz, as shown

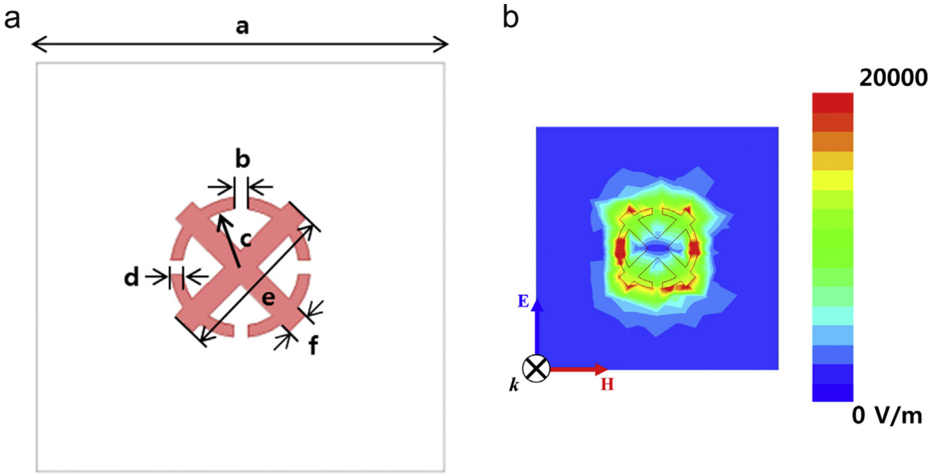

Fig. 1. (a) Layout of the proposed metamaterial absorber without microfluidics (a = 14, b = 0.5, c = 2, d = 0.4, e = 5.5, and f = 0.8; unit: mm); (b) magnitude of electric field distribution of proposed metamaterial absorber without microfluidics.