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Microwave/microfluidic sensor fabricated on a flexible kapton substrate for complex permittivity characterization of liquids

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ABSTRACT

A low cost and sensitive microfluidic sensor operating in X-band is proposed and validated. This sensor consists of multiple-stubs coupled to microstrip line and it is dedicated to liquid characterization with perspectives for chemistry and biology. Such device is fabricated using printing technologies on a flexible kapton substrate. The complex permittivity of water–NaCl solutions prepared in different concentrations is estimated by using equations that relate the resonance characteristics and the difference of complex permittivity between the tested sample and the reference one. The calculated values of the real and imaginary parts of the complex permittivity show linear variation as function of the water–NaCl concentrations. For the real part, two linear zones are defined, one for the lower concentrations (<0.5 mol/L) and the second one for the higher concentrations (>0.5 mol/L). However, for the imaginary part, only one linear region is obtained for the concentrations investigated. Good agreement is observed between the results obtained from Cole–Cole model and the estimated values retrieved from measurements. The results obtained demonstrate the sensitivity and the usefulness of the sensor proposed for microwaves microfluidic characterizations. This study has been achieved at 10 GHz but it can be performed for any microwave frequency. Moreover the presented approach with the same calibration can be used to identify other materials that have complex permittivity in the same range. Of course, the sensor presented is not universe and but it can be advantageously used for wide applications in which the solution under test is aqueous.

1. Introduction

RF and microwave microfluidic sensors are of major interest in many applications as they offer numerous advantages compared to traditional techniques [1,2]. Recently, significant attention has been devoted to develop sensing platform based on electromagnetic resonant configurations [3–7]. Compared to traditional methods such as micro-Raman spectroscopy, the microwave sensing technique proposed offers advantages in terms of rapidity of measurement (real time) and cost [8,9]. To get maximum sensitivity of the microwave sensor, the tested sample must be positioned near the maximum of electric field which is usually confined at the resonance peak [4,7]. The benefit of resonant configurations leads to implementations for material sensing in different frequency ranges, from microwaves to optics. A wide choice of substances could be tested by this kind of devices: solid, liquid, or gases.

The fabrication techniques for microfluidic devices which originate from the semiconductor industry are generally based on silicon or glass materials. Most of them are developed on flat substrates which are not the most suitable for liquid analyses. Today with the development of polymer-based fabrication techniques, flexible polymer substrates become more prevalent with the advantages of being economic, easy to fabricate and to integrate in microwave devices with different crumple shapes [8–13]. Line patterning and mask printing methods using lithography process were investigated as a means of selective metal deposition on various flexible substrates. Nevertheless these procedures increase the fabrication cost as they need several production steps to realize basic electronic circuit components. Consequently, the demand for flexible substrates in the electronics industry has highlighted the importance of the development of applicable

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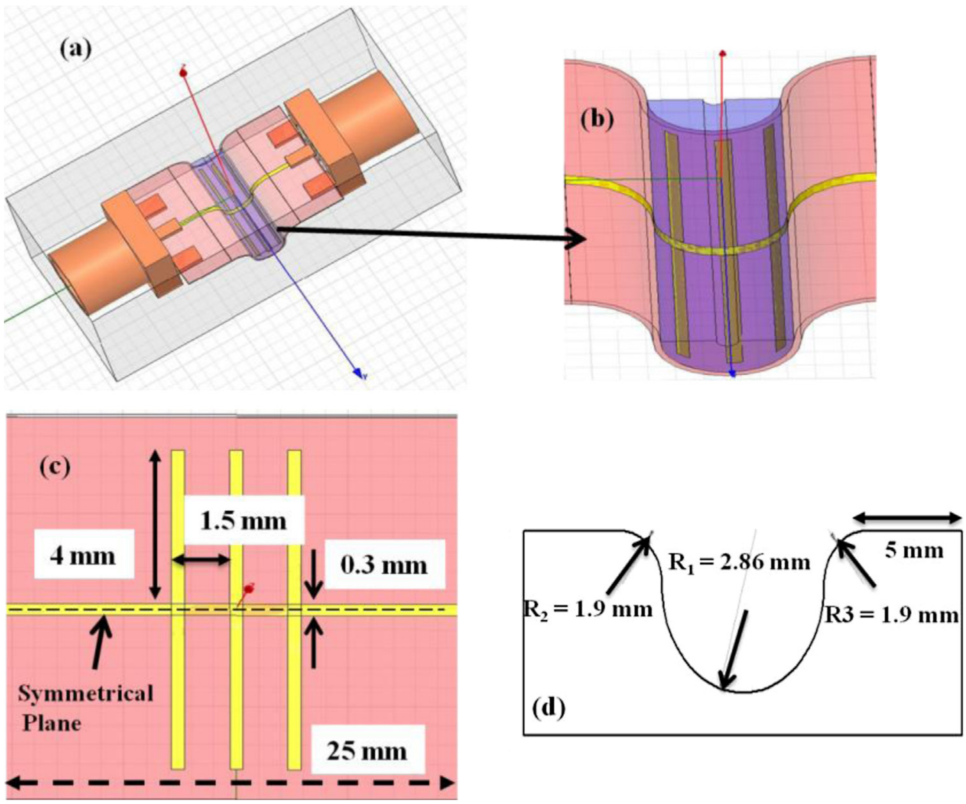

Fig. 1. (a) HFSS layout of the proposed microwave/microfluidic sensor filled with liquid solution. (b) Zoom image of the bended section of (a). (c) HFSS layout of straight structure to present the dimensions of the sensor. (d) Dimensions of the 3D-printed ABS plastic support.

printing techniques on these materials. In this context conductive ink formulations and inkjet printing of silver on flexible substrates are proposed as good fabrication techniques [8–13]. Indeed with the improvement of 3D printing technology, objects with special shapes can be fabricated and used as sensing devices [14].

In this paper, a low cost multiple-stubs resonant-microfluidic sensor is presented to quantify the complex permittivity of water–NaCl solutions prepared in different concentrations. The choice of NaCl solutions is motivated by the fact that it is the most abundant ionic fluid in biological samples. Therefore, sensitive detection of NaCl concentration is essential in a large range of applications [8,9]. This sensor is fabricated using ink jet technology on a kapton substrate and a 3D printed plastic support to operate in the X-band frequency. In fact rare work have been achieved in the X-band, most of them are made at lower frequencies [7–9,15]. The X-band has been selected to provide high sensitivity performance compared to the one of the-state-of-art that is in general around 0.3%/εr. By measuring the microwave transmission coefficient of the device, changes in the shape of the resonance peak such as: frequency shift, variation of losses at the resonance frequency and variation of the peak width can be observed. These parameters are used for determining the complex permittivity using empirical models that relate the variation in the resonance characteristics to the differences in the real and the imaginary parts of the complex permittivity with respect to a reference sample. The design and the fabrication process of the proposed sensor are provided in Section 2. In Section 3, theoretical study is presented while the simulation and the experimental investigations are given in Section 4. The analysis from measurements as a function of different concentrations is discussed in Section 5.

2. Design and fabrication of the microwave/microfluidic sensor

2.1. Sensor design

Fig. 1 presents HFSS® layout of the proposed microwave/microfluidic sensor designed on a 0.13-mm-thick kapton substrate. As shown, this sensor is based on multiple-stubs coupled to a microstrip line.

As shown in Fig. 1c, the 25 mm-long microstrip line has a width of 0.3 mm corresponding to the characteristic impedance of 50 Ω. The length of each stub is 4 mm and it is optimized to match 50 Ω impedance. Two stubs have been situated symmetrically on each side of the center stub that is located at the middle of the microstrip line. The spacing between the stubs has been fixed to 1.5 mm. This sensor configuration has been chosen to get a large sensing area with maximum resonance attenuation peak at which the E-field is strongly confined. The system has been designed to get best response in X-band range (8–12 GHz). The dimensions of the curved section are presented in Fig. 1d. As described it consists of two straight sections (5 mm each) and three bended curvatures. For the central curvature, a 9 mm-length of substrate is bent with an angle of 180° while the two other curvatures that matched the two straight sections are bent on 3-mm-length with curvature angles of 90°.

2.2. Sensor fabrication process

The fabrication process of the device has been realized using inkjet technology on a 130 μm-thick kapton substrate. The Kapton® was purchased from Dupont Teijin films. This substrate was chosen for its large thermal stability enabling sintering at higher