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Microwave Microlitre Lab-on-Substrate Liquid Characterisation based on SIW Slot Antenna

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***Abstract*—A microwave microlitre binary liquid mixture concentration detection sensor with potential biological analysis is presented. The microwave lab-on-substrate sensor is fabricated using a substrate integrated waveguide (SIW) slot antenna. The microfluidic channel encapsulating liquid under investigation is located on top of the antenna slot at a quarter wavelength from the short-circuited end of the SIW. The radiated electric near-field interaction with the liquid mixture exhibits different relationships between the complex permittivity of the liquid mixtures versus the resonant frequency and return loss, discriminating types and percentages of mixed liquid. The sensor was initially demonstrated with three types of samples: deionised water, methanol and air. A resonant frequency shift of 110MHz was measured to discriminate between air and deionised water while we obtained a 20MHz resonant frequency shift between air and methanol. Furthermore, the sensor was used to assess deionised water-methanol mixtures with methanol fractional volumes of 0 to 1 in 0.2 steps. The microwave-microfluidic sensor is contactless, uses readily available materials, cost effective and offers fast and accurate liquid characterisation.**

***Index Terms*—SIW, slot antenna, resonance, permittivity measurements, Biological.**

I. INTRODUCTION

The advent of substrate integrated circuits has opened up various opportunities in circuit and system integration as it offers efficient electromagnetic coupling and interconnections with various types of planar circuits [1]. The transitions to either the microstrip or coplanar waveguide enable uncomplicated measurements of substrate integrated circuits. Furthermore substrate integrated circuits offer reduced size and weight [2] compared to their traditional counterparts, which makes them attractive for applications requiring compact devices. Substrate integrated devices however, suffer from low quality factor (Q-factor), due to the dielectric filling when compared to nonplanar structures, e.g. a metallic air filled waveguide can offer Q-factor between 5000 to 10000 whereas a substrate integrated waveguide can offer between 500 to 1000, which is still higher than that of a microstrip. Where the high Q-factor is not one of the highly desired parameters, they have found wide use especially in the past decades.

Recently, substrate integrated waveguides (SIW) have found application in antennas, filters, couplers, power dividers, transitions, resonators and oscillators. The SIW structure is formed when a conductor-plated substrate is complemented by two rows of vertical metallic posts called vias. In [3] it is demonstrated that when the distance between the posts, so-called pitch, and the post diameter are properly chosen such that the pitch is equal to or less than twice the diameter, the field leakage is tremendously reduced and the SIW performance approaches that of a conventional solid metallic rectangular waveguide. This work presents a novel SIW-based slot antenna microfluidic sensor that characterises and quantifies binary liquid mixtures in microlitre volume without the liquid direct exposure to the antenna element.

Liquid detection and quantification has found huge application in biosensors. In [4], a coplanar waveguide biosensor was designed that was able to perform cell quantification and counting in solution while in [5] a biosensor was made that was able to detect and quantify small molecules, proteins or living cells. In this work, the presented binary liquid quantification and detection sensor uses some of the advantages in [4] and [5] where the sensors are also designed based on planar structures. However, our design drastically enhances measurement accuracy by using a resonant technique. The novel concept also allows characterisation of very small quantities of liquid mixtures in the lower region of microlitres without compromising any performance.

II. DESIGN PROCEDURE

The microwave-microfluidic sensor in this paper is based on an SIW single slot antenna operating in the X-band at 10GHz. The design procedure starts with appropriately selecting the via hole diameter (d) and the pitch (p) of the post structures given by (1) [6]

$$d < \frac{\lambda_g}{5} \; and \; p \leq 2d \tag{1}$$

Fig. 1 shows the top view of a single slot SIW antenna with the design parameters. The design is based on Rogers RT/Duroid 5880, which has a dielectric constant of 2.2, a loss tangent of 0.0009 at 10GHz and substrate thickness of 1.575mm.

The parameters for the slot antenna after optimisation using finite element method (FEM) software (HFSS) are a_{SIW} =15.4mm, l=11.7mm, x=1.6mm, w=0.5mm, d=0.5mm and p=0.9mm

For liquid characterisation, a single slot antenna is sufficient because the radiation region of interest is in the near field. The

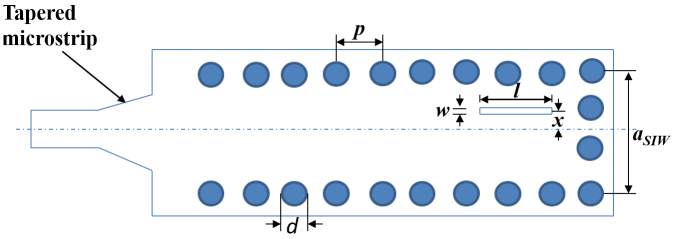

Fig. 1: SIW single slot antenna showing parameters

slot antenna is therefore composed of a single longitudinal shunt slot in the broad face of the SIW. The longitudinal shunt slot is chosen over the series slot for uncomplicated fabrication. The centre of the slot was designed to be a quarter wavelength from the short-circuited wall of the waveguide. The displacement from the centre of the waveguide is calculated from the effective shunt conductance of the longitudinal slot [7], which is given by

$$g(x) = g_0 \sin^2(\frac{\pi x}{a}) \tag{2}$$

where g_0 is dependent on the dimensions of the slot, the ratio of the height to the width, b/a_{SIW} and the guide wavelength [8] is given by

$$g_0 = (2.09a\frac{\lambda_g}{b\lambda_0})\cos^2(\frac{\lambda_0 \pi}{2\lambda_g}) \tag{3}$$

Since the SIW is a dielectric filled waveguide, the slot length [9] is calculated by

$$l = \frac{\lambda_0}{\sqrt{2(\varepsilon_r + 1)}} \tag{4}$$

For the design frequency of 10GHz and relative permittivity of 2.2, the calculated slot length of the antenna is 11.86mm. This was optimized with HFSS to 11.7mm for maximum near-field radiation, resulting in highest sensitivity of the sensor.

A 50-ohm microstrip line is used to feed the SIW structure with a tapered microstrip line to SIW transition to match the guide impedance [10]. The tapered microstrip line converts the TEM mode of the microstrip to the TE10 mode in the SIW. It is desired that the liquid flows on top and across the point of maximum field radiation to achieve highest interaction between the electromagnetic field and the liquid. Since the slot antenna exploits the standing wave phenomena, the maximum field point for a single slot antenna occurs at a quarter wavelength from the end of the SIW, which is also the middle of the slot. The integrated microfluidic channel is fabricated by using a very low loss and thin substrate material. Rogers Duroid 5880 is chosen with thickness of 0.79mm because a reasonable thickness is required so as to be able to hold the liquid. The substrate is first placed on top of the SIW slot antenna, protecting the antenna slot from direct contact with liquids. Then another substrate layer with a microfluidic channel built in at the centre of the slot position is bonded. The optimised microfluidic channel width is 500um for highest sensing accuracy and sensitivity. An encapsulating substrate layer is then placed on top as in Fig. 2. Fig. 3 shows the fabricated prototype of the slot-antenna lab-on-substrate microfluidic sensor. All the substrate layers in the fabricated prototype are epoxy bonded. The liquid filling process into the microfluidic channel is accomplished by a $100-\mu l$ syringe. During measurement, the microfluidic channel ends were sealed to ensure that the liquid mixture was encapsulated within the microfluidic channel without air gaps.

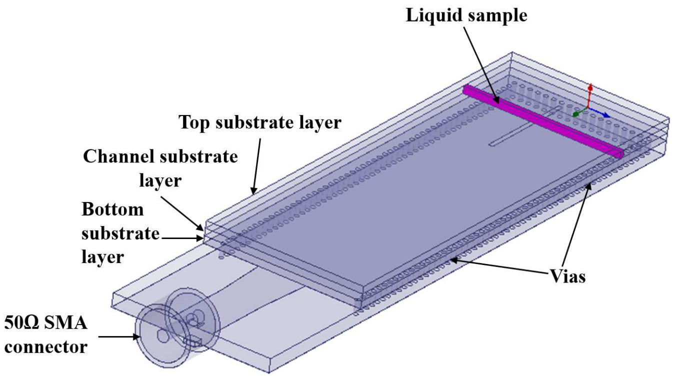

Fig. 2: SIW slot antenna sensor showing sample encapsulated in liquid channel

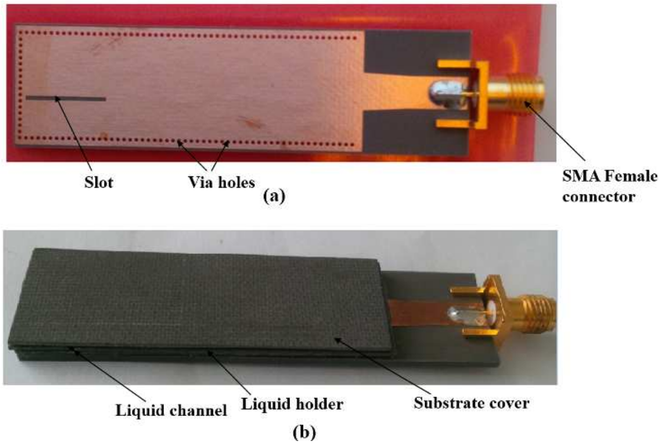

Fig. 3: Realised sensor (a) Showing the fabricated SIW slot antenna (b) Showing the microfluidic channel between substrate layers.

III. RESULTS

A. Simulation Results

The radiated field distribution after various samples interacted with the slot antenna radiation was observed using HFSS. The first simulation is for an empty channel. As shown in Fig. 4, the near-field around the channel does not show much attenuation as expected with air as the sample.

A lot more attenuation however is observed when deionized water (high loss) is the sample in the channel signified by the enhanced field distribution spread around the channel as shown in fig. 5.

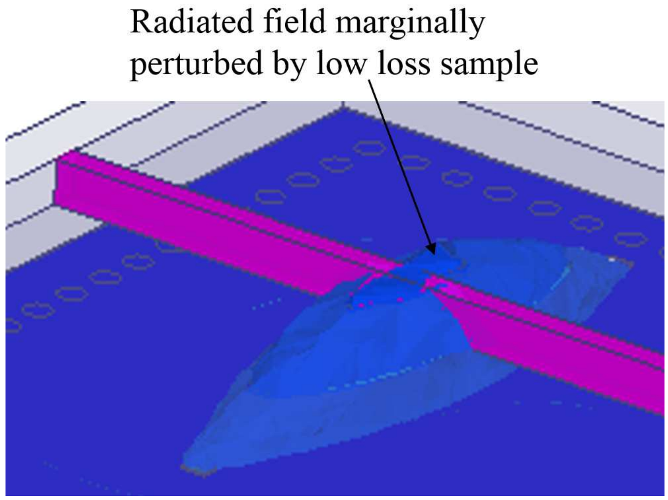

Fig. 4: Electric Field distribution with air as sample in the channel.

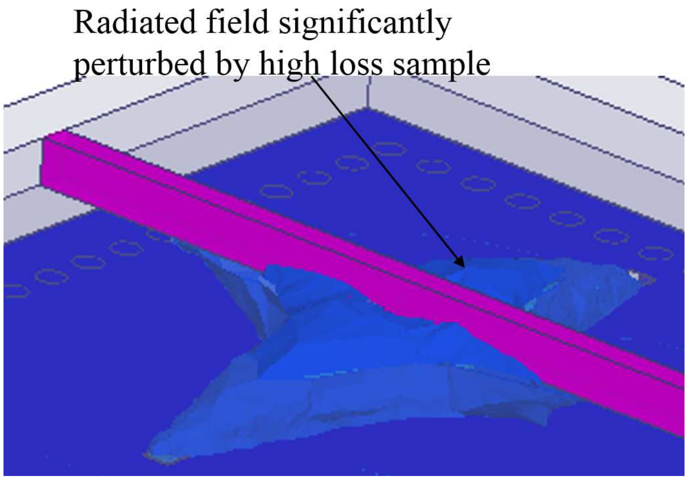

Fig. 5: Electric Field distribution with deionized water as the sample in the channel.

B. Measurement Results

During measurement, with an empty channel (signifying air as the sample), the SIW slot antenna sensor resonated at 8.96GHz with a return loss of 20.02dB. When the channel was filled with deionized water, the resonance shifted to 8.85GHz with a return loss of 28.09dB as shown in fig. 6. When filled with Methanol, the sensor resonated at 8.94GHz with a return loss of 24.51dB. This is as expected as the resonance shift agrees with the theory that states that when a slot antenna is covered by a substrate, the resonance shifts downwards and in keeping with this it shifts more for a material with a higher permittivity.

The observed resonance shift is 110MHz between air and deionised water and 20MHz between air and Methanol, which distinguishes between the samples under investigation and enables relating the resonant change to the sample's complex permittivity.

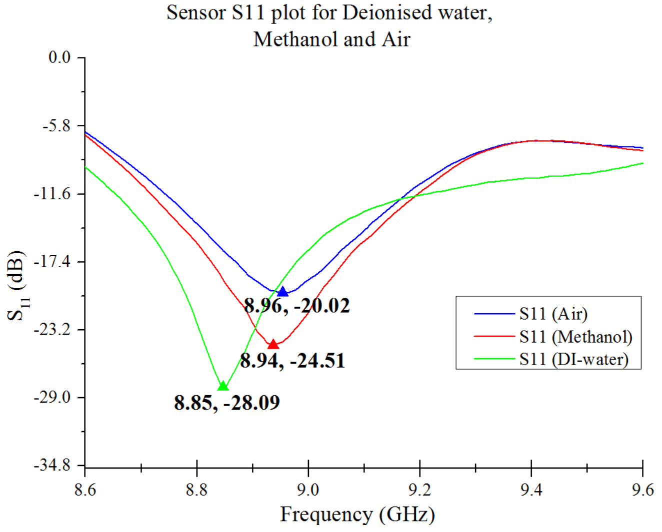

Fig. 6: Measured return loss for empty channel (blue), Methanol (green) and Deionised water (red).

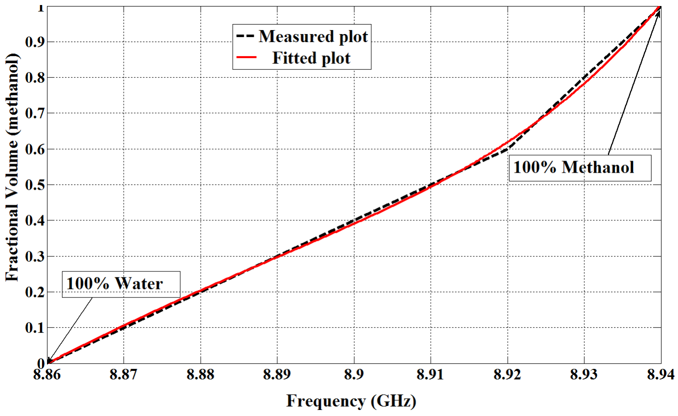

Fig. 7: Water and Methanol mixture measurement plot - water percentage per volume against resonant frequency.

The sensor was further used for liquid quantification by measuring a binary mixture of deionised water and methanol in methanol fractional volume increments of 0.2 from 0 to 1, (0 methanol fractional volume indicating 100% deionised water and vice versa). The response obtained is shown in table I and fig. 7.

The relationship can be better presented by the equation relating methanol fractional volume (vol_f) to resonant frequency

TABLE I: Methanol Fractional volume measurement

Freq. (GHz)	Fract. vol (methanol) -meas	Frac. vol (methanol) - Fit. equa	Error %
8.86	0	0.00067215	0
8.88	0.2	0.20378764	1.89382
8.90	0.4	0.39054383	2.364042
8.92	0.6	0.61892344	3.153907
8.93	0.8	0.78270568	2.16179
8.94	1.0	1.0047337	0.47337

(f_r) as shown in (5).

$$vol_f = 1.47\times10^4 f_r.^4 - 5.22\times10^5 f_r.^3 + 6.94\times10^7 f_r.^2 - 4.1\times10^7 f_r + 9.1\times10^7 \quad (5)$$

The fitted relationship is close to the measured one with the maximum error between the two being 3%. Some of the discrepancy observed in the measurement was attributed to the fact that measurements were being done without the help of an anechoic chamber. As a result the measurements suffered to some degree from the surroundings reflections. An in-depth analysis of this effect is proposed to be undertaken. The measured results shifted more in frequency as well due to the effect of the epoxy used to bond the substrate layers. This effect however had no impact on the results as it was constant through all measurements (mentioned here to clarify the significant downward shift in frequency even for air measurement).

IV. CONCLUSION

This work has shown that with an SIW slot antenna sensor various small volumes of liquids can be characterised to enable their detection and quantification. In this work with only $7-\mu l$ of the liquid, accurate characterisation of the liquid was achieved. The change in resonant frequency and return loss confirms that the sensor is sensitivity enough to differentiate between various small volumes of liquids. The measurement of the mixture of methanol and deionised water showed the potential usage of the sensor in quantification of mixtures. This sensor therefore has potential in the characterization of biological liquids. Ongoing work on this sensor is looking at measurement of various binary mixtures with detailed analysis leading to confirmation of complex permittivity at the resonant frequency for each case.

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