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CIRCULAR MICROFLUIDIC SUBSTRATE INTEGRATED WAVEGUIDE RESONATOR SENSOR FOR MATERIALS CHARACTERIZATION

Amyrul Azuan Mohd Bahar[1], Zahriladha Zakaria[1], Eliyana Ruslan[2], Azmi Awang Md Isa[1] and Rammah A. Alahnomi[1]
[1]Microwave Research Group, Centre for Telecommunication Research and Innovation (CeTRI), Faculty of Electronics and Computer Engineering, Universiti Teknikal Malaysia Melaka (UTeM), Durian Tunggal, Melaka, Malaysia
[2]Faculty of Engineering Technology, Universiti Teknikal Malaysia Melaka (UTeM), Hang Tuah Jaya, Durian Tunggal, Melaka, Malaysia
E-Mail: amyrulazuan@yahoo.com

ABSTRACT

In this paper, a novel planar microfluidic microwave sensor based on a Substrate Integrated Waveguide (SIW) for materials characterization is proposed. The design structure is simulated to analyse the effect of electric flux (electric fields distribution) on the several common liquids. The resonator sensor was integrated with quartz microcapillary which is functioning as sensing tube for characterizing solvents. The SIW resonator sensor is designed at 2 GHz and it demonstrates the changes of resonant frequency as well as the amount of electric flux based on different type of liquid samples. Finally, the operation of the sensor with presence of liquid samples such as water, ethanol, and methanol are performed and reported. This type of microwave sensor is useful for chemical, bio-medical and pharmaceutical applications which are related in materials characterization.

Keywords: microwave applications, materials characterization, resonant sensor.

INTRODUCTION

Microwave sensors are the major pursuit in the chemical, bio-medical and pharmaceutical industries which are linked up in materials characterization [1]. Various types of resonator sensors have been put in over the last decade and has been exploring the strength and performance due to the sensitivity and accuracy of the structure.

The non-planar resonator sensors by using waveguide or coaxial methods are depending on the shifting of position nodes of standing wave forms in a short-circuited which can gain high accuracy measurements [2]. However, some limitations such as high cost, complex designs, and large dimensions are currently possessed with this design method of the sensor. Therefore, waveguide techniques were introduced in the fields of planar resonator sensor which is very useful in the microwave characterization of microfluidic solutions.
Those techniques are often utilized by previous research work in characterization due to the advantages over the traditional sensor which is simple designs, low manufacturing cost, integrability with microstrip and tunable [1]-[3].

One of the method that using waveguide integration is the substrate integrated waveguide (SIW) technique which is became very popular in RF/Microwave sensor application for optimization of resonator sensors in materials characterization. The resonant structures of waveguide are chosen for high accuracy in complex permittivity measurements. The dual port of reflection and transmission line causes a displacement in resonance frequency, insertion loss and quality factor which correlates with the actual and imaginary part of the permittivity and permeability [4]. In this method, high sensitivity to dielectric constant is desired for precise measurements.

Therefore, in this paper, the circular SIW resonator sensor with integrated microcapillary has been introduced as a means of precise characterization of material properties of samples in lowest trace amounts [5]. The technique has improved the sensor's sensitivity, compact in size, as well as can be produced at low cost for industrial applications.

Circular SIW Resonator sensor

A two port measurement using both reflection and transmission methods were constructed, which a sample is identified between the section of two coaxial transmission lines and the cross section of circular waveguide transmission line [2]. This technique can evaluate the s-parameters to obtain the value of permittivity and permeability. Circular substrate integrated waveguide resonator sensor with resonant frequency of 2 GHz is designed by using CST simulation software. The dimension of the structure is calculated based on following relation.

Radius of circular SIW

$$a = \frac{2.405 \times c}{2\pi f_r \sqrt{\varepsilon_r}} \tag{1}$$

Width of the patch

$$w = \frac{c}{2 f_r}\sqrt{\frac{2}{\varepsilon_r + 1}} \tag{2}$$

Effective dielectric constant

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + \frac{12h}{w}\right]^{-1/2} \tag{3}$$

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A design structure parameters of circular substrate integrated waveguide resonator has been considered in order to enhance the sensitivity of the sensor due to several factors such as resonant frequency shifting, quality factor, insertion loss and the presence of electric flux (E-fields). Simulation performed with sample over 1-4 GHz range frequencies, while corresponding resonant frequency for each liquid sample has been recorded.

Rogers RT6010 with thickness 1.27 mm is constructed on a dielectric of a relative permittivity 10.2 and loss tangent 0.0023. The thickness of the copper is 0.035 mm to ensure the highest possible Q-factor. The inner radius of the quartz micro capillary is Qi=0.395 mm and outer radius is QO=0.5 mm for extremely small volumes of samples. The sensitivity to the liquid samples is simulated by placing a small volumes of solvent in the micro capillary tube. The reaction of resonant frequency shifting is depending on permittivity of sample under testing. The dimensions of resonator structure is illustrates in Figure-1.

From a practical application, via holes diameter of SIW and its pitch can be determined by applying the design rules as introduced by Deslandes et al [6] which is shown in (4) and (5).

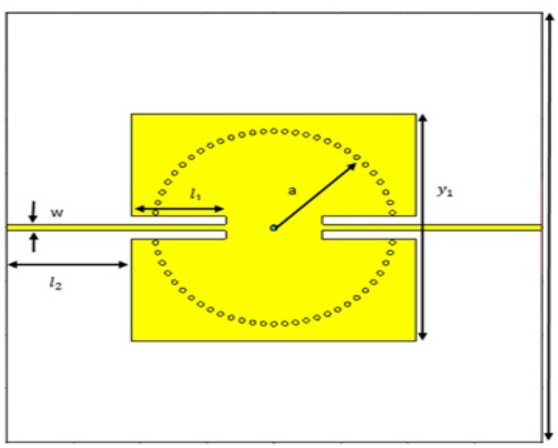

Figure-1. Resonator sensor dimensions structure design.

$$d > 0.2\lambda_o \tag{4}$$

and

$$\frac{d}{p} \leq 0.5 \tag{5}$$

Practically, the computer simulation becomes inefficient and heavy if there is a large number of metallized via holes in the design structure. The loss also tends to diminish as the metallized via holes become smaller for a constant ratio, which is qualified by the manufacturing process [6].

Every single dimension parameter is computed in order to reach optimum performance based on theoretical perception from previous research works. Table-1 shows the complete diameters of the resonator structure of SIW design. The feed line has the advantages over the resonant output since it holds a capability to control the coupling in order to see the best insertion loss and return loss responses by adjusting the dimension slot, i.e. w, l1, and l2.

Table-1. The Dimension parameters of resonator sensor structure.

Parameter	Value (mm)	Parameter	Value (mm)
a	17.98	w	1.20
d	0.85	h	1.27
p	1.60	t	0.035
l1	14.00	y1	42.42
l2	18.75	y2	79.92

SIMULATION RESULT

Analysis on without solvent samples

In this section, since capillary also has permittivity, the comparison of presence capillary was analyze in order to indicate the effect of quartz materials on the sensor before adding the solvent samples. Simulation result of those subjects with/without the presence of capillary is illustrated in Figure-2.

The resonator was designed at 2 GHz without capillary attached at sensing region. The return loss and insertion loss are -26.5 dB and -0.509 dB respectively. Both parameters show good result for precise measurement of sensor. However, when quartz capillary was attached at the center sensing area, the resonant frequency shifted 22 MHz to high frequency and the insertion and return loss became worse than previous. This is imputable to the permittivity of quartz capillary ε_r=3.75 effect on electric flux polarization. The structural position of micro-capillary is placed on z-axis for ease fabrication process and the max amount of e-fields focusing on the center region of substrate resonator through the capillary structure.

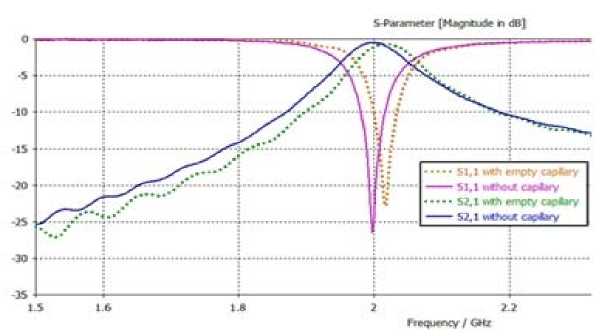

Figure-2. Insertion loss and return loss of resonator with/without empty capillary.

The waveguide of via hole controlled the polarization of electric flux in order to extract the

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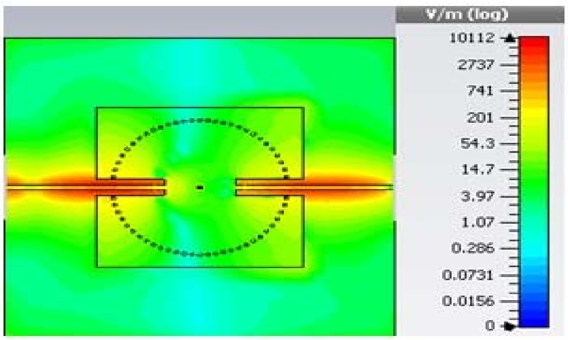
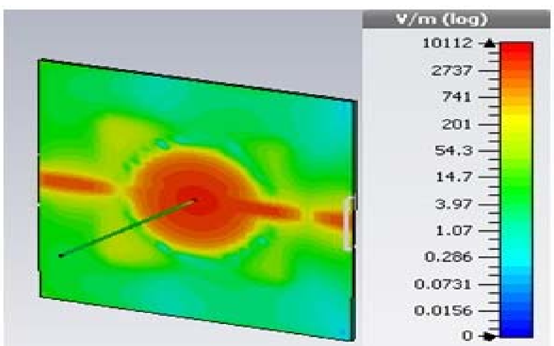
maximum number of e-fields in the center of the sensing area. The e-fields do not resonate on patch of the structure because it acts as a waveguide of e-fields. Therefore, only substrate and feeding line has resonated signal for characterizing purpose. The pattern of electric flux is shown in Figure-3. Theoretically, via hole can avoid electrical leakage among sensing region since it's a waveguide. However, simulation pattern show there is leakage surround circular SIW on the substrate due to the dimension errors of via hole



(a)



(b)

Figure-3. Electric fields distribution of circular SIW sensor for the whole structure. (a) Top view (b) view on substrate.

By placing a capillary, we can see in Figure-3 how the polarization of electric flux radiated on the middle of the system structure and obviously there is no e-fields on the plot. It just radiates on substrate structure as sensing area.

Analysis on presence of solvent samples

The shifting of resonant frequency can be seen in Figure-4 due to the presence of solvent in capillary with minimum volumes. Those solvents results in an increase in reflected power, Pr and Pr is related to the samples properties. Therefore, the properties of samples can be evaluated, recorded and compare as the performance of the resonator can be seen whether the sensitivity is high or vice versa for precise measurement.

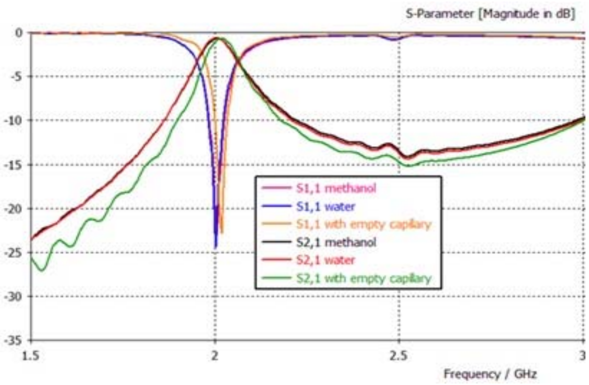


Figure-4. S-parameters of resonator with presence of solvents.

The presence of liquids in a small volume will reflect the electric flux in the sensing area which can interrupt frequency shifting due to the permittivity inserted. The comparison of sensor effectiveness on the presence of solvents is described in Table-2. Every bit we can understand an empty capillary also has a frequency shifting from resonant frequency 2 GHz. Quartz materials (capillary) have permittivity 3.75 and this is contributing to the effects on the amount of e-fields and frequency changing. Higher value of permittivity can have smaller value of shifting, but a higher sum of electric flux in a waveguide.

Table-2. Comparison of sensor performance on presence of liquid samples.

Samples	Freq (GHz)	Freq Shifting (MHz)	E-fields (v/m)	ε_r
Empty	2.0175	17.5	10112	3.75
Methanol	2.0050	5.0	10061	32.7
Water	2.0025	2.5	10845	78

Nevertheless, the amount of electric flux of methanol is lower than an empty capillary even through the value of permittivity of methanol bigger than quartz permittivity. This is imputable to the polarization of e-filed on the sensing region was disrupted. The presence of different liquid samples will evaluate e-fields radiation with different variety of patterns.

Analysis on different position of capillary placed

An analysis of position capillary was carried out to verify the cross sectional area of sensing region due to polarization of electric flux. Two different position axis was analyse which is z-axis and y-axis. The performance was illustrated in Figure-5.

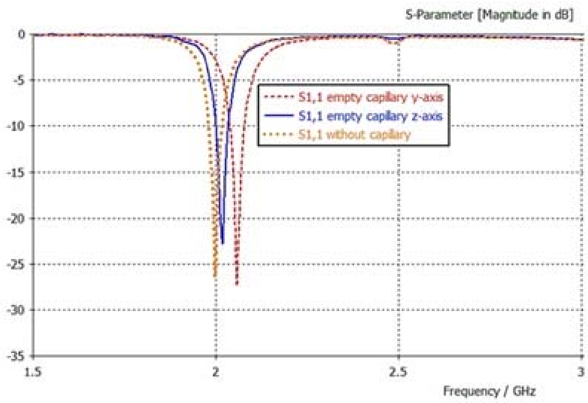


Figure-5. Frequency shifting of different position capillary.

As we compare the changing of frequency on both axis, the y-axis has higher value of shifting towards high frequency. However, the sensing cross sectional area of the y-axis is bigger than the z-axis, which only radiates on small amount of solvents but in terms of the fabrication process, the z-axis are easier and low cost manufacturing materials since the thickness of substrate have been only 1.27 mm. On the other hand, y-axis need thick substrate for capillary to penetrate the substrate. Thus, we choose z-axis position for fabrication step because the advantages of comfortable design, low cost and has better shifting than y-axis. The position of y-axis capillary shown in Figure-6.

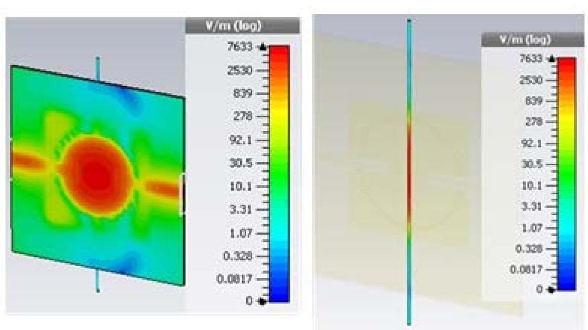


Figure-6. The y-axis position of capillary and the amount of electric flux on sensing area inside capillary

Hopefully, the fabrication and testing process can be done in future works in order to validate the results of simulation. The permittivity and permeability of the samples can be extracted and compare with an ideal theoretical expectation to determine the sensitivity and accuracy of design structure.

CONCLUSIONS

Materials characterizing by using a new SIW resonator method have been introduced in this work. Several solvents were chosen to perform the sensor capability to extract properties of samples. The density and polarization of electric field distribution show significant change with the presence of liquids which high value of permittivity caused more flux in the sensing region. The pros and cons of capillary position are compared and discussed in terms of sensing area and the amount of electric flux. The shifting of resonant frequency is lower in a presence of liquid samples which is 5 MHz towards the lower frequency. Using sensors at higher frequencies can contribute much better measurements of materials. In particular, the precision of the sensors can be enhanced by using different techniques in future research and the sensor may be useful in industries which related on characterizing of solvents.

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