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Analysis and investigation of a novel microwave sensor with high Q-factor for liquid characterization

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Abstract

In this paper, a new design of microwave sensor with high Q-factor for liquid characterization is analyzed and investigated. The new microwave sensor is based on a gap waveguide cavity resonator (GWCR). The GWCR consists of upper plate, lower plate and array of pins on the lower plate. The liquid under test (LUT) is characterized by placing it inside the GWCR where the electric field concentrates using a quartz capillary that is passing through microfluidic channels. The results show that the proposed sensor has a high Q-factor of 4832. Moreover, the proposed sensor has the ability to characterize different types of liquids such as oils, ethanol, methanol and distilled water. The polynomial fitting method is used to extract the equation of the unknown permittivity of the LUT. The results show that the evaluated permittivity using the proposed sensor has a good agreement with the reference permittivity. Therefore, the proposed sensor is a good candidate for food and pharmaceutical applications.

Keywords: *dielectric properties, gap waveguide, liquid characterization, microwave sensor,*

1. Introduction

Dielectric properties are important for industries, which is used in different fields such as agriculture, Geoscience, food processing, bioengineering and pharmaceutical industries. The electric behaviour of the material depends on the dielectric properties of that material. Therefore, material properties measurement plays an important role in increasing the demand number of industrial applications such as quality control in material science, food industries, and bio-sensing [1, 2].

Different techniques have been used for material characterization [3, 4]. Many types of microwave sensors have been used in different applications such as planar microstrip resonators for liquid [5], solid [6-8] and Petroleum oils [9, 10] characterization. Substrate integrated waveguide (SIW) technique has been used for liquid [11] and humidity [12] detection. These sensors have several advantages such as low manufacturing cost and simple to design. However, the disadvantage of these sensors is the low Q-factor, which reflects the low sensitivity. Therefore, some researchers tend to use a metal waveguide to increase the Q-factor and sensitivity [13-15].

The gap waveguide technology has been proposed for the first time in [16]. The gap waveguide is cheaper to manufacture compared to the conventional waveguide and has lower losses compared to the planar microstrip, thus it has been used for antenna design [17] and filter design [18].

In this paper, a new design of a microwave sensor with high Q-factor based on gap waveguide cavity resonator (GWCR) for liquid characterization is proposed. The GWCR consists of upper plate, lower plate and array of pins on the lower plate. The GWCR is suitable for material characterization where it restricts the electric field in the sensing area and this leads to increase the sensitivity and Q-factor. The liquid under test (LUT) is placed where the electric field is maximum using a quartz capillary. The LUT perturbates the electric field and leads to

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changes in the response of the GWCR which known as perturbation theory. The polynomial fitting method is used to extract the equation of the unknown permittivity of the LUT.

2. Sensor Design

The sensitivity of the microwave sensor can be expressed by the Q-factor where it quantifies the concentration of the electric field in the sensor. The loaded Q-factor (Q_L) of the GWCR without LUT can be calculated by using [19]:

$$\frac{1}{Q_L} = \frac{1}{Q_U} + \frac{1}{Q_E} \tag{1}$$

where Q_U is the unloaded Q-factor and Q_E is the external Q-factor. Q_u is occurred due to the loss of the sensor itself, and Q_E is occurred due to the LUT which is calculated by using [20]:

$$Q_E = 10^{-[S21(dB)/20]} Q_L \tag{2}$$

The unloaded Q-factor in term of transmission coefficient can be calculated using [21]:

$$Q_U = \frac{Q_L}{1 - S21} \tag{3}$$

The loaded Q-factor in terms of resonant frequency (f_o) and 3dB bandwidth (*BW*) can be found by [22]:

$$Q_L = \frac{f_o}{BW} \tag{4}$$

The unloaded Q-factor in terms of resonant frequency and 3dB bandwidth can be found by [23]:

$$Q_U = \frac{2f_o}{BW} \tag{5}$$

The GWCR is designed and analyzed at 6.1 GHz in the Computer Simulation Technology (CST) using aluminium metal with electric conductivity of $\sigma = 3.56 \times 10^7$ S/m. Figure 1(a) shows the side view of the proposed GWCR which consists of upper and lower plates fed with two SMA connectors. Figure 1(b) shows the lower plate with array of pins on it. The dimensions of the pin are typically of 1 mm^2 [18]. The distance between the top surface of the pins and the upper plate is equal to 1 mm. The height of the pin (h) is calculated by [16]:

$$h = \frac{\lambda}{4} \tag{6}$$

where λ is the wavelength and can be calculated by:

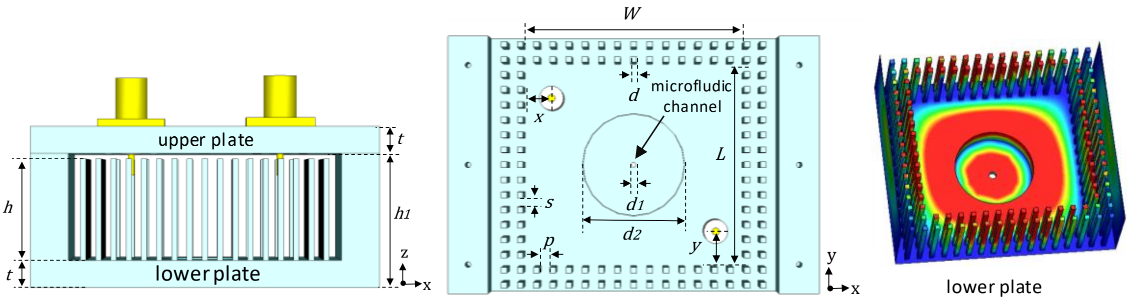
$$\lambda = \frac{c}{f_o} \tag{7}$$

where c is the speed of light which is 3×10^8 m/s. The recommended spacing between the pins is more than 1.5 mm and the thickness of each plate is more than 5 mm according to the CNC machine capabilities. The width of the GWCR is approximately equal to the wavelength at 6.1 GHz. Table 1 shows the optimized values of the proposed GWCR.

Table 1. The Optimum Values of the Design Parameters

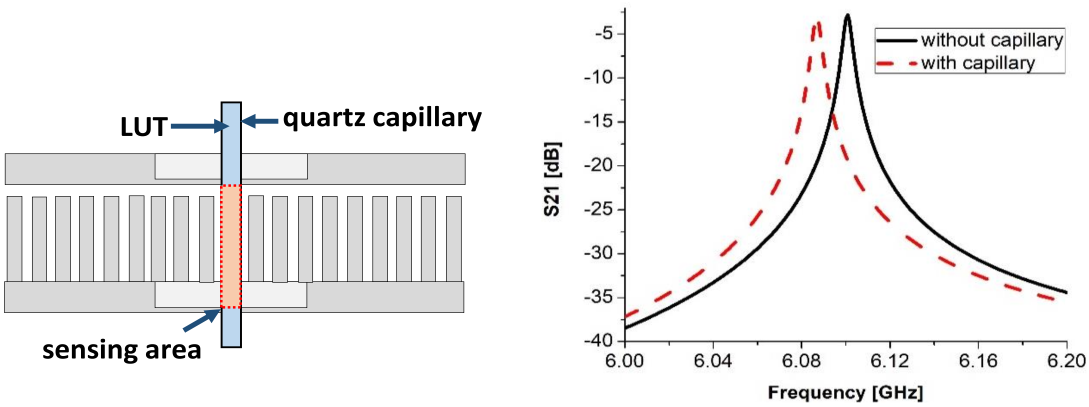
Parameter	Value (mm)	Parameter	Value (mm)
W	38.20	d_2	18.00
L	35.40	x	5.10
d	1.00	s	1.60
d_1	1.70	p	1.80
y	6.35	t	5.00
h	15.75	h_1	21.70

The GWCR sensor operates based on [16], where one plate acts as a perfect magnetic conductor (PMC), and the other plate acts as a perfect electric conductor (PEC). The pins surface on the lower plate acts as an artificial magnetic conductor (AMC). In addition, the array of pins in the lower plate keep the electric field in the middle region as shown in Figure 1(c), which is suitable to interact with the LUT. A quartz capillary with a permittivity of 3.75 is used as a holder to evaluate the LUT as shown in Figure 2(a). The quartz capillary causes a frequency shift due to its dielectric constant as shown in Figure 2(b).



(a) (b) (c)

Figure 1. Simulated (a) structure of the side view for the proposed GWCR, (b) structure of the lower plate, (c) electric field (v/m) at 6.1 GHz



(a) (b)

Figure 2. (a) Geometrical diagram of the GWCR with LUT, (b) transmission coefficient of the proposed sensor without and with capillary

3. Results and Discussions

The proposed sensor shows its ability to sense and detect different types of liquids such as fish oil, coconut oil, olive oil, linseed oil, castor oil, ethanol, methanol and distilled water with relative permittivity of 2.6, 2.9, 3.1, 3.5, 4.7, 24.5, 32.7 and 78.4 respectively as shown in Figure 3. It can be observed that the relationship between the resonant frequency and the permittivity is inversely proportional to each other, where the resonant frequency is decreasing by increasing the permittivity, thus when the permittivity is 2.6 the resonant frequency appears at 6.0624 GHz, while when the permittivity is 78.4 the resonant frequency appears at 4.7968 GHz. The polynomial graph is plotted according to the resonant frequency and permittivity as shown in Figure 4. From the polynomial graph, the permittivity equation is extracted as follow:

$$\varepsilon' = 1.0192 f^2 - 70.914 f + 395.1 \tag{8}$$

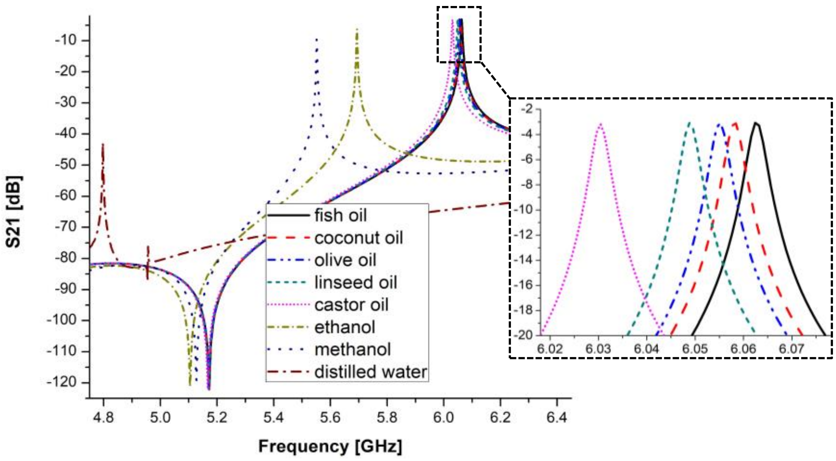


Figure 3. Transmission coefficient of the proposed sensor with LUT

To ensure the accuracy of the proposed sensor, the permittivity for fish oil, coconut oil, olive oil, linseed oil, castor oil, ethanol, methanol and distilled water are evaluated and compared with the reference permittivity, as shown in Table 2.

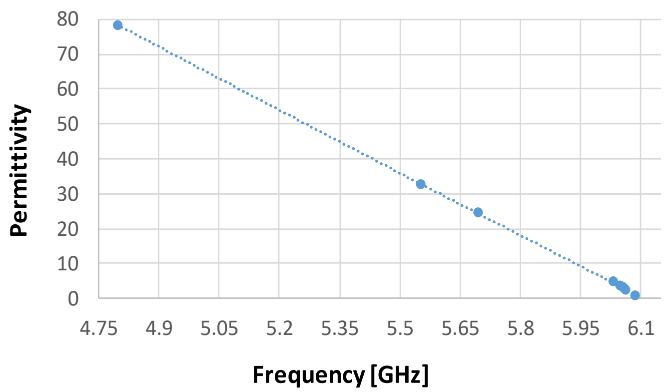


Figure 4. Polynomial graph of the permittivity

From Table 2, it can be said that a good agreement between the evaluated permittivity by the proposed sensor and the reference permittivity with accuracy more than 96%, which means that the proposed sensor has high accuracy and ability to detect different types of liquids. The results show that the proposed sensor has the highest Q-factor compared to the recently proposed sensors in Table 3.

Table 2. Comparison Between the Evaluated Permittivity by the Proposed GWCR and the Reference Permittivity

LUT	Frequency (GHz)	Reference (ε')	Proposed GWCR (ε')	Accuracy (%)
Fish oil	6.0624	2.6	2.649	98.140
Coconut oil	6.0584	2.9	2.884	99.433
Olive oil	6.0552	3.1	3.071	99.064
Linseed oil	6.0488	3.5	3.446	98.453
Castor oil	6.0304	4.7	4.524	96.259
Ethanol	5.6936	24.5	24.384	99.525
Methanol	5.5512	32.7	32.850	99.544
Distilled water	4.7968	78.4	78.391	99.988

Table 3. Comparison Between the Proposed Sensor and Recently Reported Researches

Reference	Technique	Q_u-Factor
[5]	Planar split ring resonator	525
[6]	Complementary split ring resonator	80
[7]	Planar symmetrical split ring resonator	652
[10]	Planar ring resonator	146.67
[11]	Substrate Integrated waveguide	334.6
[12]	Cavity Substrate Integrated Waveguides	≈300
[13]	Re-Entrant cavity waveguide	1190
[14]	Multiresonance rectangular cavity waveguide	2605
[15]	Circular cavity resonator waveguide	47
[24]	Planar split ring resonator	506
[25]	Multiple split ring resonator	430
Proposed sensor	Gap waveguide cavity resonator	4832

4. Conclusion

In this paper, a novel microwave sensor with high Q-factor for liquid characterization is analyzed and investigated. This technique is based on gap waveguide cavity resonator (GWCR). The electric field of the GWCR is investigated, where the results show that the electric field more concentrates in the middle of the GWCR, thus the LUT is placed in the middle of the GWCR using a quartz capillary. The results show that the GWCR has the ability to characterize different types of liquids such as fish oil, coconut oil, olive oil, linseed oil, castor oil, ethanol, methanol and distilled water. Therefore, the proposed sensor is reliable to be used for liquid characterization in food and pharmaceutical industries.

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