Unorthodox technique in sensing with the metamaterial-based resonator sensor at millimetre frequencies

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ABSTRACT

A metamaterial-based resonator is presented in this paper for liquid-sensing applications. The designed sensor operates at millimetre-wave (mm-w) frequencies, and it can characterise the samples that may possess identical characteristics. This paper relies on the extracted permittivity of the structure in the characterisation of the samples, mainly liquids. The sensor requires a very small amount of samples for sensing and it is used in distinguishing oil, ethanol, methanol, glycerol and water. A shift in the resonance frequency of about 200 MHz per unit increase in the epsilon value of samples was achieved. The oil sample showed the lowest value in the extracted permittivity value, while water showed the nearest to zero extracted permittivity. This relationship of variation in extracted permittivity parameter with the change in the sample's epsilon value is found to be linear and reliable regardless of the change in thickness of the sample.

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1. INTRODUCTION

The development in the technology of the sensors in recent times is evident almost everywhere. Biosensors are important in many fields, such as diagnostics of diseases, and monitoring of the atmosphere and food health, and they are often critical instruments for investigating biological phenomena. The widely accepted method of measuring dielectric characteristics of gases and liquids involves quantifying their interaction in the vicinity of the electromagnetic (EM) field [1]. In this approach, the electrical parameters of the materials including conductivity and permittivity can be measured [2]. Microwave frequencies provide means of liquid characterisation due to liquid polarization, which causes the molecules to interact with the electric field at these frequencies [1]. Metamaterial-based sensors can be vital in label-free and non-invasive sensing due to their highly sensitive response to the dielectric constant of material under test (MUT) placed in the surrounding or most sensitive area of the resonator structure [3], [4].

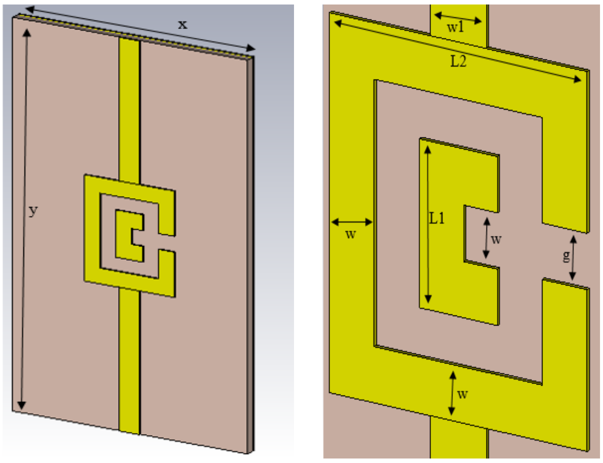
Major developments have been made in sensor technology centred on metamaterials, contributing to the creation of specific metamaterial-based components to detect sample and situation details. Metamaterial resonator-based biosensors have been exploited for various applications such as; distinguishing the branded and unbranded diesel fuel [5], measurements of protein concentration [3], characterisation of dielectric materials [6], detection of common solid materials [7], displacement sensing [8], liquid's dielectric characterisation [9], characterisation of cooking oils [10], and non-invasive glucose detection [11]–[13].

Recent works have focused on measuring the dielectric constant of the sample by a shift in the resonant frequency [7], [14]–[16]. Akhir *et al.* [17], a split ring resonator operating at 1 GHz was presented for sensing of humidity. On other hand, an antenna integrated with polydimethylsiloxane operating at 3.5 GHz was presented in [18] for medical imaging application. The antenna was designed with the t-shaped partial ground and the rectangular patch with notches. Particularly for oil sensing applications, A microwave sensor was presented in [19]. The sensor's technique was based on the gap waveguide cavity resonator and coconut oil, fish oil, caster oil, olive oil, and linseed oil were used as samples.

However, there are still some unresolved problems such as the amount of the sample and accuracy in the sample's obtained dielectric characteristics. Valuable spectroscopy methods are offered by the millimetre-wave (mmWave) for material characterisation. Moreover, the characterisation in this band can be performed in free space as compared to optical frequencies [20]. Therefore, a novel metamaterial resonator is designed as a potential liquid sensing device. The sensor operates in the millimetre-wave band, and it is resonating near 36 GHz. The objectives are to differentiate the liquid materials at high frequencies having different dielectric constants by extracting constitutive parameters of the structure. In addition, the method of distinguishing the sample and finding its characteristics in previously published papers relies on either resonant frequency or its magnitude. This study also shows net changes in the permittivity of metamaterial sensor on impact of external samples.

2. METAMATERIAL DESIGN AND SIMULATION

The introduced metamaterial-based resonator structure that is fed by a couple of microstrip lines is shown in Figure 1. Figure 1(a) shows the perspective view of the design. The structure resembles the C-shape enclosed by a copper loop with a gap of 0.3 mm as shown in Figure 1(b). Rogers RT/duroid 5,880 material was used as the substrate with a thickness of 0.2 mm with a permittivity value and tangent loss of 2.2 and 0.0009, respectively. The thickness of the copper material is 0.035 mm. CST Studio software was used to design and simulate the proposed structure. As shown in Figure 2, two ports were connected to the ends of microstrip lines which behave as the feed transmission line for the structure. The simulation setup is depicted in Figure 2, and it was simulated in a time domain solver.



(a) (b)

Figure 1. Proposed metamaterial-based resonator (a) perspective view of designed resonator and (b) dimensions of the metamaterial structure (x=6mm, y=10mm, w=0.4mm, w1=0.5mm, g=0.4mm, L2=2.06mm, L1=0.7mm)

Figure 2 demonstrates the simulation setup of introduced metamaterial-based resonator in CST studio with an overall dimension of 6×10×0.25 mm^3. The metamaterial resonator behaves as an LC circuit and its resonance is mathematically represented by (1). In order to calculate the resonance frequency, in (1) affirms that effective capacitance and inductance must be known. It is apparent from (2) that effective capacitance is the sum of total capacitances that are caused by the gaps inside the structure, while copper loops contribute to the generation of effective inductance, which is given by (3).

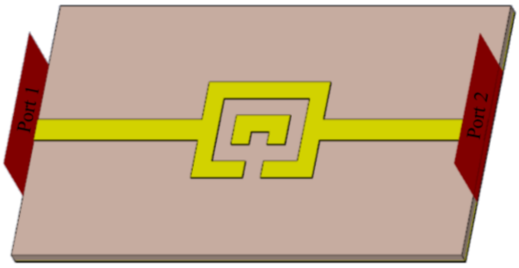


Figure 2. Simulation setup of CST design

$$f_0 = \frac{1}{2\pi\sqrt{CL}} \quad (1)$$

$$C = \frac{C_{eff}tw}{g} + C_{eff(t+g+w)} \quad (2)$$

where,
t=thickness of the gap
w=width of the gap
g=length of the gap

$$L = \frac{\mu l_0(2\pi l_0 - g)}{2\pi} ln\ ln\ \left(\frac{4l}{w} - 2.45\right) \quad (3)$$

where $l\_0 = w/2 + r\_2$

To study the metamaterial characteristics such as the permittivity and permeability of the presented design, a robust method [21] is employed. The numerical calculation process of the effective parameters is given as in (4)-(8), which were coded in Matlab software to extract the values,

$$n = \frac{1}{k_0 d}\left\{\left[[ln(e^{ink_0d})]'' + 2m\pi\right] - i[ln(e^{ink_0d})]'\right\} \quad (4)$$

where;

$$e^{ink_0d} = X \pm i\sqrt{1 - X^2} \quad (5)$$

$$X = \frac{1}{2S_{21}(1 - S_{11}^2 + S_{21}^2)} \quad (6)$$

it should be noted that m is associated with the branch index (n') real part and imaginary part are denoted by (.)' and (.)'', respectively.

$$\varepsilon = n/z \quad (7)$$

$$\mu = nz \quad (8)$$

3. RESULTS AND ANALYSIS

3.1. Transmission coefficient and metamaterial characteristics

The presented MTM structure was optimised to operate at millimetre-wave frequencies. Figure 3 presents the transmission coefficient (S_{21}) and it shows that the final optimised design is resonating at 36 GHz. Using the reflection coefficient (S_{11}) and transmission coefficient (S_{21}), the constitutive parameters of the structure were extracted. Figure 4 shows the extracted permittivity of the structure and the permeability of the structure is depicted in Figure 5. It is illustrated in Figure 5 that the structure has permeability negative at the resonant frequency and it exhibits mue-negative (MNG) characteristics at the desired range of frequencies. Moreover, the permittivity of the structure is found to be near zero at the resonance frequency and it crosses zero point at 31.94 GHz frequency. This phenomenon of achieving permittivity negative and/or permeability negative is the interesting characteristic of metamaterial, causes the bandwidth of resonance narrow, which helps in characterising the materials with small changes in dielectric properties [22].

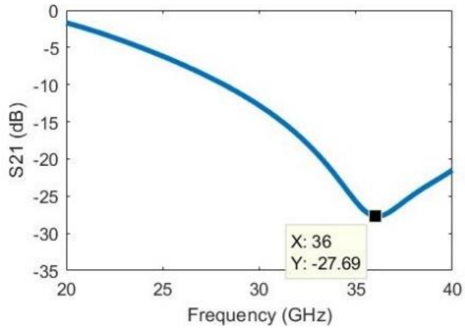


Figure 3. The resonant frequency of the metamaterial sensor

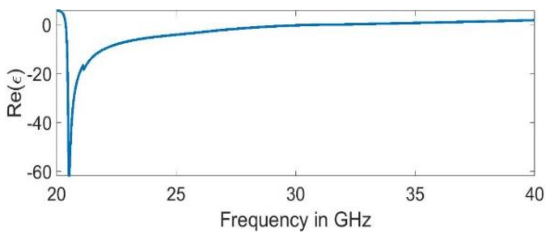


Figure 4. The permittivity of the metamaterial structure

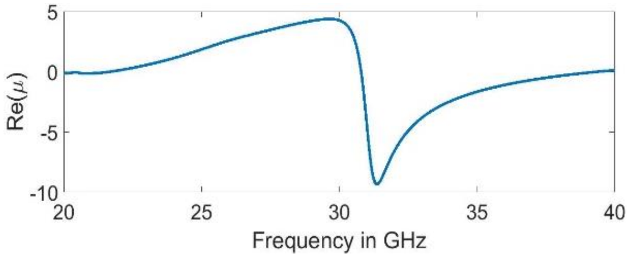


Figure 5. Permeability of the metamaterial structure

3.2. Sensitive area

To sense the smallest liquid sample, it is necessary to place it in the most sensitive area so that high-quality sensing could be achieved. To do so, a sample was considered to be placed on the different positions as shown in Figure 6. The sample was modelled on the bottom (Figure 6(a)), top (Figure 6(b)), centre (Figure 6(c)), and in the gap (Figure 6(d)) of the sensor. It is evident from Figure 7 that the highest shift in resonance frequency is obtained when the sample is placed at the sensor's right position. This phenomenon is further verified by the electric field intensity depicted in Figure 8, where the gap in the resonator has the highest intensity of the electric field.

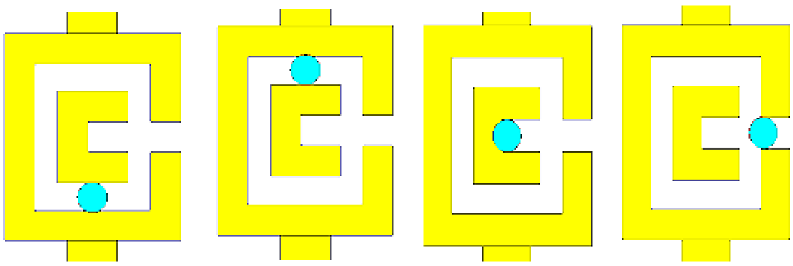


Figure 6. MUT placed at (a) bottom, (b) top, (c) centre, and (d) gap

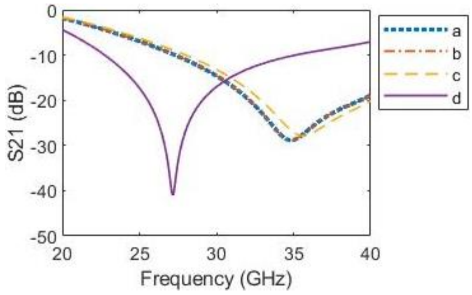


Figure 7. Shift in resonance frequency on the placement of MUT in different positions

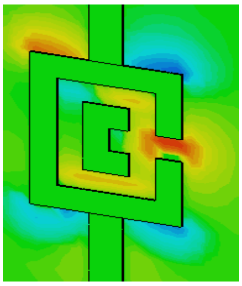


Figure 8. Electric field intensity

3.3. Impact of the thickness of sample

The volume of the samples used was taken into account as it was realised that changing the dimensions of MUT inserted in the surroundings of the metamaterial resonator has also an impact and results in the shift in resonance frequency. The shift in the resonant frequency for a unit size of the sample is called the sensitivity per volume [23]. In this analysis, a sample of the dimensions a little smaller than the gap (0.3 mm) is considered as shown in Figure 9. The unit size of MUT considered in this analysis is 0.035 mm. Figure 10 shows the impact of varying volumes of the sample having a dielectric constant of 30 on the transmission coefficient.

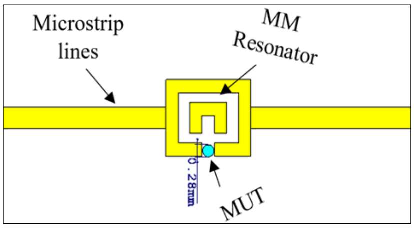


Figure 9. The gap and the placement of MUT

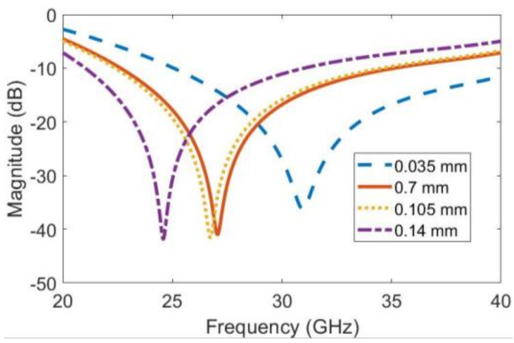


Figure 10. Shift in resonant frequency versus MUT thickness

However, when relying on the permittivity, there is a relatively lower impact of the thickness as compared to the transmission coefficient as depicted in Figure 11 and Figure 12. Therefore, it is highly recommended to consider the thickness of the sample to rule out variation in the dielectric constant of the sample. It should be noted that there is a rise in the permittivity with the increase in the thickness of the sample.

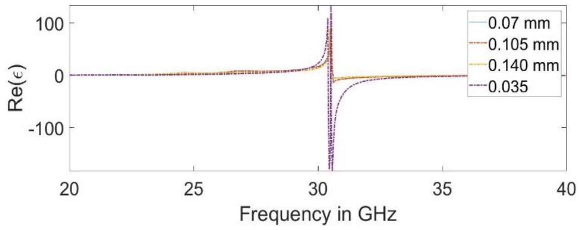


Figure 11. Variation observed in permittivity on the varying thickness of the sample

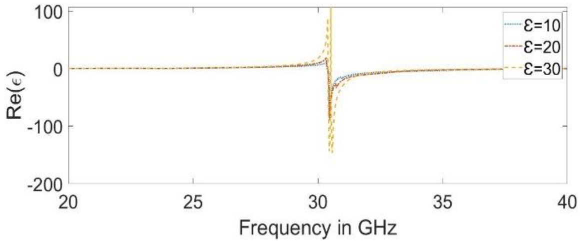


Figure 12. Variation observed in permittivity on varying permittivity values of the sample

4. DETECTION OF LIQUIDS WITH DIFFERENT DIELECTRIC CONSTANTS

The basic method of metamaterial sensing depends on the variation in reflection or transmission coefficient or both when there is a change in the dielectric constant. A shift in the resonance of metamaterial can be observed in presence of an analyte causing alterations in the effective capacitance due to changes in permittivity (ε) and permeability (μ) of the structure [23]. In contrast to the traditional technique of sensing, the permittivity of the samples is used in this paper as the factor of sensing with the extraction of constituent parameters of the metamaterial. The performance of the sensor was tested in simulations with different liquid analytes having distinct values of dielectric constant for sensing, such as oil, ethanol, methanol, glycerol, and water with a dielectric constant of 3.1, 25, 33.1, 57, and 80.3, respectively [24], [25]. The change in the transmission coefficient (S_{21}) is shown in Figure 13 when five different liquid analytes are supposed to be placed in the gap of the sensor.

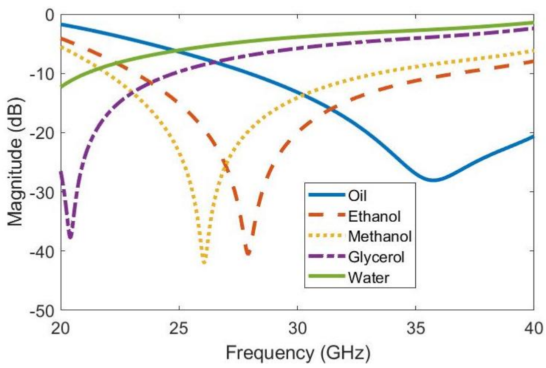


Figure 13. Shift observed in resonance frequency on different samples

As discussed in section 3.3, different liquids may have different thicknesses that may cause a variation in the results when only the transmission coefficient is focused. Figure 13 shows the shift in resonance frequency when samples with a different dielectric constant are investigated. The transmission spectrum shows a shift in the resonant frequency of 0.25 GHz for oil, 8 GHz for ethanol, 10 GHz for methanol, 15.58 GHz for glycerol, and 16.6 GHz for water. The shift in the resonance frequency observed is linear as the dielectric constant increases. The resonance frequency has dropped from 35.75 GHz down to 19.4 GHz for the samples and the average drop in the resonant frequency per unit dielectric constant is about 200 MHz. However, this method is not accurate enough to differentiate between the samples with different thicknesses but different dielectric constants. It is possible high thickness liquid and high dielectric constant liquid could cause an equivalent shift in resonant frequency. In such cases, we examine the change in permittivity value by extracting the constituent parameters as shown in Figure 14. It is evident from Figure 14 that there is a rise in the value of permittivity after the spike around 30 GHz, which was not the case when the thickness of the sample was increased. The value of permittivity is noted at 31.94 GHz where it was near zero without a sample. The increasing value of the permittivity in Figure 15 shows the increasing trend in the value of the dielectric constant.

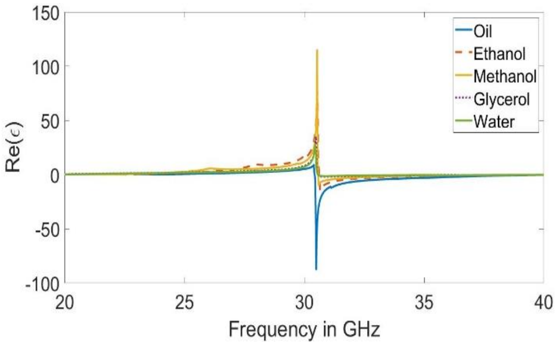


Figure 14. Extracted permittivity values for samples

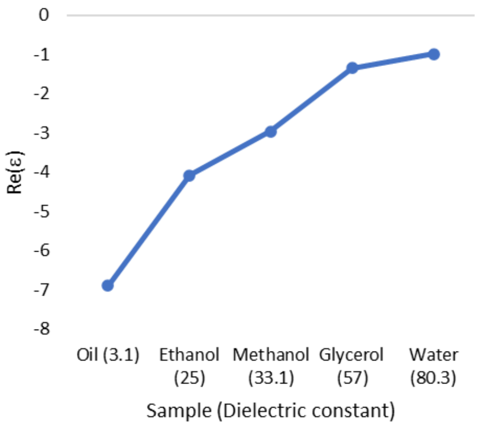


Figure 15. Extracted permittivity values of the samples

The value of permittivity of the structure extracted at 31.94 GHz for the samples is -6.9, -4.07, -2.95, -1.34, and -0.983 for oil, ethanol, methanol, glycerol, and water, respectively. The extracted permittivity values are used in sensing the liquid materials and a distinct difference in the permittivity values is realised for different samples. It should be noted that dielectric values considered in these simulations are not high-frequency dielectric constants of these analytes. Nevertheless, it is expected that the high-frequency values will also give near to the same response as shown in Figure 15 at 31.94 GHz.

5. CONCLUSION

A metamaterial-based resonator is designed in this paper for liquid-sensing applications at mmWave frequency. The metamaterial resonance strongly depended on the permittivity values of the samples. The method used for sensing relied on extracted permittivity values of the structure rather than the shift in resonance frequency. However, a shift in the resonance frequency of about 200 MHz per unit increase in the epsilon values could be achieved. This method is promising for the detection of dielectric constants predominantly when liquid materials are examined. The realisation of this sensor is certainly for the on-site sensing of the liquid materials with high accuracy, especially in medical diagnosis.

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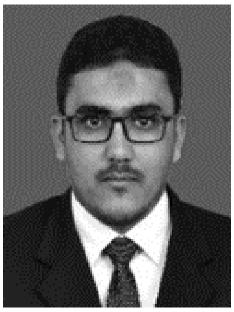

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