URSI GASS 2021, Rome, Italy, 28 August - 4 September 2021

A Compact Cesaro Fractal EBG-Based Liquid Sensor for Dielectric Characterization

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Abstract

In this work, we propose a compact, contactless fractal-inspired EBG-based microwave sensor for liquid sensing in ISM band (2.40-2.48 GHz). The subjected device contains triangular shaped patch antenna integrated with 2 x 2 periodic array of Cesaro fractal EBG unit cells. The overall dimension of the sensor is 55 mm x 55 mm ($0.45\lambda_o$ x $0.45\lambda_o$). Polypropylene (PP) based fluidic channels are introduced at the horizontal gap between the EBG unit cells for the deposition of liquids. A change in surface wave characteristic of EBG is observed upon loading the device with liquid under test which in result changes the reflection coefficient of the patch antenna. The proposed device is numerically tested for butanol, propanol, and ethanol. The calculated sensitivity and Q-factor indicate that the presented fractal EBG-based design is well suited for liquid sensing.

1 Introduction

Now-a-days planar microwave sensor are being widely used for liquid sensing [1], moisture sensing [2], humidity sensing [3] , biosensing [4] etc. because of their compactness and high accuracy. Different methods have been employed in microwave sensing topology such as cavity resonance method [5] and reflection/transmission coefficient method [6] and numerous prototypes have been developed based on these methods [1–9]. In such topology sensing/ detecting the dielectric permittivity of different liquids can be done by taking the advantage of reconfigurable characteristics i.e. shift in resonance frequency, phase/amplitude of reflection/transmission coefficients of microwave structures.

In last decade, reconfigurable antennas have been widely used as microwave sensors and detectors because of their high sensitivity to surrounding environment [10, 11]. In [10], microstrip patch antenna has been used as a temperature sensor to detect the changes in dielectric constant of substrate with the change in the temperature. Recently, metamaterials (MM's) have been integrated in antenna sensors for improving the sensitivity and Q-factor of the device by concentrating the stored electromagnetic energy in the limited area [12]. These MM inspired resonators when integrated with antenna shows better performance as compared to simple antenna sensors. In [13], authors have developed MM-inspired microfluid microwave sensor consist of a patch antenna and a microfluidic channel. In addition to that, in 2019, another new 3x3 Electromagnetic Band Gap (EBG) array integrated with antenna system has been developed as a promising candidate for liquid sensor and reconfigurable EBG [14] . EBG is an array of dielectric or metallic periodic structure just like metamaterials and can be employed as a high impedance surface for improving antenna matching [15]. Liquid sensing via EBG structures can be possible by observing the variation in surface wave characteristics of EBG surface upon deposition of liquid under test (LUT's). In [16], 3x3 fractal based EBG array is studied to further enhance the performance of the device. Fractal structures are an alternative to MM inspired resonators to concentrate the electromagnetic field distribution and to achieve overall compactness.

In this paper, we present a contactless, 2x2 fractal EBG-based sensing platform to analyse the change in reflection coefficient of a patch antenna with the change in dielectric permittivity of LUT at 2.45 GHz frequency. The proposed sensing platform is compact as compared to previously reported EBG designs [15, 16] and is composed of patch antenna integrated with 2x2 array of Cesaro fractal EBG plane instead of 3x3 array. Polypropylene (PP) fluidic channel has been introduced in the horizontal gap area for the deposition of liquids with different permittivities (butanol, propanol, and ethanol). A substantial change in resonance frequency can be observed when loading the device with LUT's of different material properties. The performance analysis of the proposed device and its compact size suggest that it can serve as a potential candidate for liquid sensing.

2 Proposed Sensing Topology

The proposed design of sensor consists of an antenna integrated with an 2x2 fractal EBG plane beneath it having PP fluidic channels for the passage of LUTs. The optimized geometry of radiating plane used for this purpose is based on the proposed design in [17], as shown in Figure 1. The dimension of the top modified triangular patch and defected ground plane of antenna is 34 mm x 28.58 mm ($0.278\lambda_o$ x $0.241\lambda_o$) and 40.8 mm x 40.8 mm ($0.332\lambda_o$ x $0.332\lambda_o$), respectively.

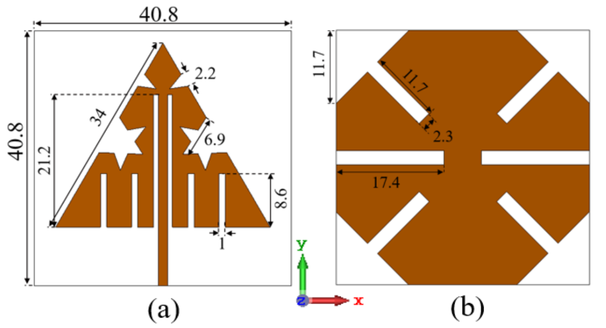

Figure 1. Optimized fractal antenna, dimensions in millimeter. (a) Top view (b) Bottom view.

For a reflector plane at first a square unit cell is considered for 2x2 EBG plane [18]. Here in this paper, we have used Cesaro fractal based 2x2 EBG plane . The detailed analysis of reflection coefficient and the evolution from square shaped unit cell to Cesaro fractal unit cell is explained in [16]. The advantage of using Cesaro fractal unit cell is the size reduction of the overall design. The designing and evaluation of EBG unit cell is performed using reflection phase-based characterization method presented in [19] is used. In this proposed Cesaro fractal based EBG unit cell at 2.45 GHz, the reflection phase is 90^o and the obtained operational bandwidth within the $90^o \pm 45^o$ phase values is 180 MHz (2.34-2.52 GHz). The overall size of Cesaro fractal unit cell is 28.3 mm x 28.3 mm, as shown in Figure 2(a).

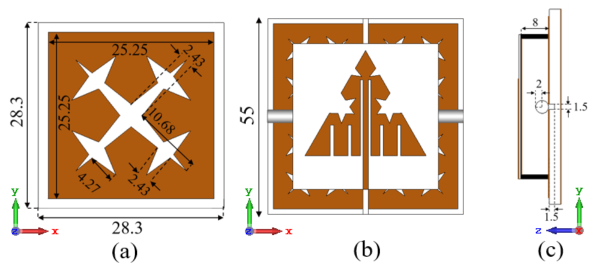

Figure 2. Proposed sensor design, dimensions in millimeter. (a) Unit cell of EBG (b) Top view of proposed sensor (c) Side view.

For an EBG plane, 3.175 mm thick Rogers 5880 having dielectric constant 2.2 and loss tangent 0.0009 is used. The final optimized dimensions of 2x2 periodic EBG plane is 55 mm x 55 mm. For the deposition of LUT's horizontal channel of Polypropylene (PP) material with a 'ε_r' 2.2 and a diameter of 4 mm is introduced where the intensity of electromagnetic field is strongly enhanced. Moreover, trenches of same width and height i.e. 1.5 mm are edged out in EBG array to minimize the surface wave losses and to the improve the antenna matching [20]. A foam (ε_r=1) of 8 mm is used as a separator between antenna and EBG to reduce the impedance mismatch owing to the mutual impedance coupling. Figure 2 shows the final optimized liquid sensing device.

3 Results and Discussion

For performance evaluation, a commercially available full wave simulator CST microwave studio and NI PXIe-5630 two-port RF network analyzer are used for numerical and experimental verification of the fabricated prototype, respectively. Figure 3 shows the comparison of simulated and measured reflection coefficient of fabricated prototype of antenna alone and antenna integrated with Cesaro fractal 2x2 EBG plane. Slight variation in the resonance frequency with respect to simulated results is attributed to the manufacturing and measuring errors along with environmental effects during testing. It is to be noted that the resonance frequency of antenna alone is not 2.45 GHz, that is because when EBG plane is integrated with antenna it undergoes a frequency shift owing to the mutual impedance coupling between antenna and EBG and it is retuned to 2.45 GHz by optimizing the antenna geometry. The measured radiation

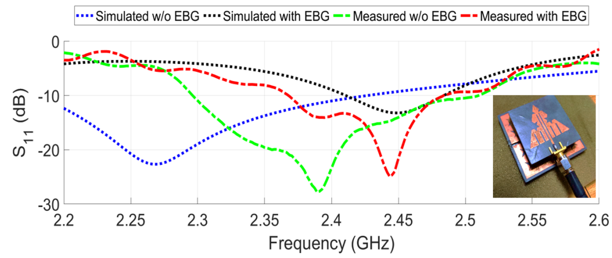

Figure 3. Simulated and measured reflection coefficient of proposed antenna topology with and without Cesaro EBG plane.

pattern of antenna alone and with Cesaro fractal 2x2 reflector plane at 2.45 GHz is shown in Figure 4. The measured radiation patterns demonstrate that the radiated gain of antenna only is 2.41 dBi whereas, when EBG plane is placed beneath it, the gain increases to 7.03 dBi.

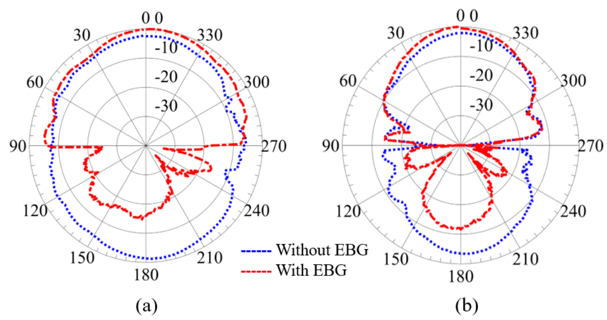

Figure 4. Measured normalized radiation patterns of antenna with and without 2x2 Cesaro EBG plane (a) XZ-plane (b) YZ-plane

To test the proposed device as a potential candidate for liquid sensing, the performance of the structure was simulated by filling the empty PP channels with liquid of different permittivities ranging from 1 to 10 with loss tangent value taken as '0'. It can be seen from Figure 5 that the resonance frequency of the device shifts to lower frequencies with the increase in the value of the dielectric constant. This also demonstrates that larger the change in the value of dielectric constants of LUT's, greater will be the shift in the resonance frequency.

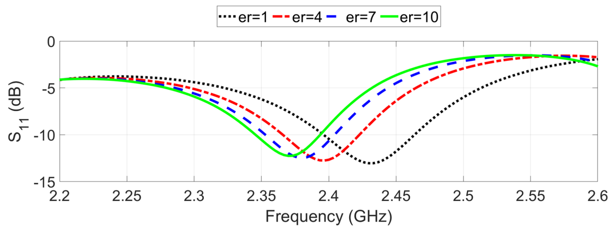

Figure 5. Simulated reflection coefficient of proposed sensor design for variation in permittivity of LUTs.

To further verify the sensing capability of the proposed 2x2 EBG based sensor, it is numerically simulated for three absolute liquids having different material properties. The chosen LUT's are butanol, propanol and ethanol. According to [43], butanol has ε_r of 3.57 and $\tan\delta$ of 0.47, propanol has ε_r of 3.8 and $\tan\delta$ of 0.64, and ethanol has ε_r of 6.57 and $\tan\delta$ of 0.96 at temperature 20^oC and frequency 2.5 GHz. Figure 6 shows the reflection coefficient of loaded device i.e. PP fluidic channels are filled with chosen LUT. A significant variation in resonating frequency for different liquids can be seen in Figure 6. It also indicates that the liquid having highest dielectric constant has the maximum shift in the resonating frequency.

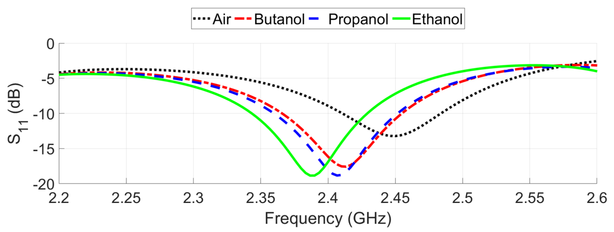

Figure 6. Simulated reflection coefficient of proposed sensor design for chosen LUTs.

A microwave sensor for dielectric characterization is evaluated on the basis of Q-factor and sensitivity values of LUT's. Mathematically, Q-factor is expressed as,

$$Q = \frac{f_c}{\Delta f_{-3dB}} \tag{1}$$

It is the ratio of centre resonance frequency 'f_c' to 3 dB bandwidth 'Δf_{-3dB}'. According to [5] sensitivity is mathematically expressed as,

$$S = \frac{\Delta f}{\Delta \varepsilon} \tag{2}$$

where, $\Delta f = (f_o - f_s)/f_s$ and $\Delta\varepsilon = (\varepsilon_s - \varepsilon_s)$. The evaluation of sensitivity of LUT is done by taking air as a reference medium . Hence f_o and ε_o are the resonance frequency and permittivity of empty fluidic channels (air filled). Table 1 summarized the performance characteristics (Q-factor and sensitivity) of the proposed design upon loading the device. This study manifests that the maximum attained sensitivity of the proposed sensor is 0.645% for propanol and the maximum obtained Q-factor is 74.35 for ethanol. The proposed design has an advantage of overall size reduction as compared to previously reported EBG sensors [15, 16, 18] without compromising the performance of the device.

Table 1. Summary of simulated performance analysis of proposed sensor topology

Medium	Center Freq. (GHz)	Freq. Shift (GHz)	Q Factor	Sensitivity (%)
Air	2.45	-	35.35	-
Butanol	2.413	0.037	59.72	0.596
Propanol	2.40	0.0435	70	0.645
Ethanol	2.38	0.0634	74.35	0.477

4 Conclusion

In summary, this work presents a compact, contactless fractal inspired EBG based microwave detector for sensing different liquids at 2.45 GHz. The proposed design is composed of 2x2 periodic array of fractal EBG beneath a triangular patch antenna and polypropylene based fluidic channels for the deposition of LUTs. The performance of the device is analyzed numerically by loading it with three different liquids (butanol, propanol, and ethanol) with dielectric constant ranging from 1 to 10. A substantial shift in the resonance frequency has been observed with maximum obtained quality factor of 74.35 for ethanol and highest sensitivity of 0.645% for propanol. The proposed design has an advantage of overall size reduction as compared to previously reported EBG sensors without compromising the performance of the device.

5 Acknowledgements

This work was supported in part by the Higher Education Commission (HEC), Pakistan under Grant TDF-03-160. (Corresponding author: Muhammad Zubair.)

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