A Novel Cesaro Fractal EBG-based Sensing Platform for Dielectric Characterization of Liquids

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Abstract—This paper presents a compact, cost-effective, and contactless fractal modified EBG-based microwave sensing platform for dielectric characterization of liquids by analyzing the variation in the reflection coefficient of an antenna. The reported design is composed of a triangular-shaped antenna ($0.323\lambda_0 \times 0.323\lambda_0$) placed over a 3×3 array of Cesaro fractal based EBG plane ($0.7\lambda_0 \times 0.7\lambda_0$) operating at 2.45 GHz. A significant enhancement of the E-field in the sensing region has been achieved with the incorporation of Cesaro fractals in the EBG plane which results in increased sensitivity and compactness. To validate its performance, absolute solutions of butan-1-ol, methanol, and water are loaded, and a maximum measured sensitivity of 0.875% and a maximum quality factor of 90.05 is achieved. Moreover, a maximum RMS error in retrieved values of dielectric constant and loss tangent of liquid under test is found to be 1.092% and 0.813%, respectively. Our demonstrated EBG-based sensor has a compact footprint with good precision, affordability, and ease of operation in detecting liquids for microwave sensing applications.

Index Terms— Dielectric Characterization, Electromagnetic Bandgap Structure (EBG), Fractals, Microstrip Antenna, Microwave Sensor, Q-factor, Sensitivity.

I. INTRODUCTION

AMATERIAL is characterized by its complex permittivity and permeability, which defines their electromagnetic response. Therefore, the measurement of dielectric properties of samples has been widely used in industry for various applications such as bio-sensing [1], [2], quality control [3], microwave circuit development [4] and many more. Over the past few decades, optical-based systems and sensors/devices were in high demand mainly for bio-sensing and adulterants detections in material under test due to their remarkable sensitivity and detection efficiency. But such devices are complex, costly, and usually the samples under test are not reusable once it is being processed in them due to

its perturbation [5]. Therefore, there is an extreme need to design some inexpensive, simple, and non-obtrusive device which could complete its process without perturbation.

Microwave sensors emerged as an attractive and promising solution to this problem and have gained a lot of attention of researchers owing to their simplicity, ease of measurement and low-cost fabrication. Moreover, such devices can be integrated with microfluidic channels for sensing applications. A variety of techniques have been found in the literature for measurement of complex permittivity including non-resonant [6]–[9] and resonant methods, among which the latter is more stable and accurate for single-frequency operation [10]–[12]. Cavity resonators [13], [14] are among the conventional resonant techniques which use the perturbational method for dielectric characterization, but they are costly, complex design structures and bulky devices. Therefore, researches are now heading towards exploring planar microwave sensors because of their high accuracy and compactness. Planar resonators work on the principle of measuring the complex permittivity by analyzing the shift in the fundamental resonant frequency, phase/amplitude of reflection/transmission coefficient and Q-factor of liquid under test (LUT). Various planar resonators integrated with fluidic channels have been studied in the literature for an accurate identification of complex permittivities of liquids using different resonating structures such as [15]–[21].

The earliest concept of metamaterial inspired device using liquid substrate was proposed by Lima et al. [22], in which they proposed that the presence of liquid in the close vicinity of FSS will alter its transmission characteristics. Based on this concept, various metamaterial inspired sensors with polydimethylsiloxane (PDMS) microfluidic channels for the passage of fluids were proposed for liquid characterization [22]–[26]. They have an advantage over simple planar resonators because of their compactness as they are subwavelength elements and ensure high Q-factor. But suffer from the problems of high cost and fabrication complexity of PDMS based fluidic channels.

Recently, in 2019, a multilayer reconfigurable EBG based device has been proposed as potential candidate for a liquid detector applications [27]. According to them, a planar array of EBG surfaces can be modified to be used as a detector by edging out trenches between the square unit cell elements. The

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deposition of liquids having different dielectric properties in these trenches will produce a change in the reflection phase of EBG plane, which could be detected by using an antenna as a radiating source above EBG surface. This change in the phase of the surface waves characteristics of EBG plane produces a variation in the reflection coefficient of an antenna, which could be utilized for the detection of different liquids under test. Low-quality factor due to the usage of broadband CPW antenna, large footprint, the low detection range of dielectric properties for the LUT (1 to 21) and lack of sensitivity analysis are the major drawbacks of their proposed design and make it less feasible to be used as a practical liquid sensor.

TABLE I
COMPARISON OF PROPOSED DESIGN WITH REPORTED EBG-BASED SENSING PLATFORM AT 2.45 GHz

Quantities	Ref [27]	Proposed Design
Size (L x W)	111 mm x 111 mm	82 mm x 82 mm
No. of Fluidic Channels	4	2
Nature of Fluidic Channels	Liquid in Contact with device	Contactless
Detection Range of ϵ_r	1 to 21.3	1 to 78
Max. Measured Q-Factor of LUT	22.71	90.05
Max. Measured Sensitivity of LUT (%)	0.858	0.875
Max. Percentage Error in Retrieval of ϵ_r of LUT	N.A.	1.092
Max. Percentage Error in Retrieval of $\tan\delta$ of LUT	N.A.	0.813

In this work, we proposed a cost-effective, contactless, and novel Cesaro fractal based compact EBG design to be used as a microwave sensing platform for measuring the complex permittivity of various liquids. Owing to the self-similar spatial distribution property of fractal geometries these structures are readily utilized in antenna engineering to design a compact and low-profile surfaces such as EBG plane, metamaterials, small antennas, etc [28], [29]. The proposed design is composed of 3 x 3 array of modified EBG plane using Cesaro fractals and an optimized triangular-shaped patch antenna [30] designed at 2.45 GHz, are presented and analyzed along with their working principle in detail in Section II. All the designing and analysis of the proposed device is carried out using a full-wave electromagnetic simulation solver of CST Microwave Studio software [31]. Section III focuses on the numerical and the experimental performance evaluation of our proposed sensing platform by loading the fluidic channels with LUT (butan-1-ol, methanol, and water). For the deposition of liquid, a simple, cost-effective and contactless solution comprising of Polypropylene (PP) channels is implemented. Upon loading the device with LUT, a substantial frequency shift in the reflection coefficient of patch antenna is detected because of the change in surface wave characteristic of EBG. Based on these shifted parameters, an accurate numerical model is formulated for calculation of complex permittivity along with

sensitivity and Q-factor analysis of LUT. Finally, a conclusion of the presented work is given in Section IV. Table I summarizes the performance analysis of the reported EBG detector and the proposed sensor. It is evident from the results that the incorporation of specialized Cesaro fractals in EBG plane has significantly improved its detection performance with contactless sensing nature and relatively compact footprints as compared to the reported design.

The detailed performance analysis of our proposed sensor suggests that it is a good candidate for an inexpensive, low-profile and contactless sensing applications of liquids without compromising its accuracy and sensitivity. To the best knowledge of authors, this is the first design based on the Cesaro fractal modified EBG structure for dielectric characterization of liquids.

II. DETECTOR DESIGN AND CONFIGURATION

A. Antenna Topology

Fig. 1 shows the top and bottom view of the proposed microstrip antenna as a radiating element. It is composed of a triangular-shaped top conducting plane and a defected ground plane modified using Koch fractal, meandering slits, and chamfering to achieve desired compactness and operational impedance bandwidth [30]. The substrate used for radiating element is 0.508 mm thick polymer-based Roger/RT Duroid 5880 with a dielectric constant of 2.20 and loss tangent of 0.0009. The feeding point and the complete antenna geometries are subsequently optimized to achieve the desired characteristics for the effective detection in its resonating frequency shift. The final optimized dimension of the top triangular patch and defected ground plane is 33 mm x 28.58 mm ($0.269\lambda_0 \times 0.233\lambda_0$) and 39.6 mm x 39.6 mm ($0.323\lambda_0 \times 0.323\lambda_0$), respectively. The overall size of proposed monopole antenna fed using 50 Ω inset feed line is 39.6 mm x 39.6 mm x 0.508 mm (length, width, and thickness), which are $0.323\lambda_0 \times 0.323\lambda_0 \times 0.004\lambda_0$ in terms of wavelength.

Fig. 1. Final antenna topology for proposed detector, dimensions in millimeter. (a) Top view (b) Bottom view (c) Side view

Fig. 2. Configuration and equivalent circuit model of simple square-shaped unit cell (SSS-UC), dimensions in millimeter.

B. EBG Design

Initially, a square-shaped unit cell is considered as the EBG plane underneath the radiator for the effective detection of a shift in the resonant frequency of an antenna. Here, EBG plane is preferred over a Perfect Electric Conductor (PEC) surface because PEC surfaces exhibit deconstructive interference between the transmitted and reflected signals when placed in the close proximity of an antenna; and they exhibit constructive interference when placed at a distance of $\lambda_0/4$ which is significantly a large dimension for a low-profile device [32], [33].

The detailed analysis of a reflection phase characteristics of a unit cell is done to propose a suitable EBG design for the chosen application. For its design and optimization, the reflection phase characterization method proposed by Yahya Rahmat-Samii *et al.* is used [34]. According to them, the input-match frequency band of an EBG is very close to the range of frequencies having a reflection phase of $90^\circ \pm 45^\circ$. This input-match frequency band is a range of frequencies in which the EBG surfaces neither behave like a PEC plane nor like a PMC plane having a reflection phase of 180° or 0° , respectively, for a normally incident plane wave. Instead, this exhibits a band of frequencies having a good return loss of an antenna.

Fig. 3. Evolution of SSS-UC configuration for optimized EBG plane, dimensions in millimeter. (a) SSS-UC (b) Cesaro UC (Iteration-1) (c) Cesaro UC (Iteration-2)

Fig. 2 shows the equivalent circuit model for the simple square-shaped unit cell (SSS-UC) of EBG [35], designed on the same Rogers 5880 substrate as of proposed antenna in the previous section with a relatively higher thickness of 3.175 mm. The following equations give the total input impedance and the resonant frequency of the SSS-UC:

$$Z_0(\omega) = Z_1(\omega) // Z_2(\omega) = \frac{j(1 - \omega^2 C_1 L_1)}{w(C_1 C_2 L_1 \omega^2 - C_1 - C_2)} \quad (1)$$

$$f_0 = \frac{1}{2\pi} \sqrt{\frac{C_1 + C_2}{C_1 C_2 L_1}} \quad (2)$$

Where L_1 is the inductance of unit cell (UC); C_1 and C_2 are the capacitance between UC patch and ground, and capacitance between two UC patches, respectively. From equation 2, it is quite evident that by increasing the values of either capacitance or inductance, the size of a UC can be made compact in which variation of L_1 has more impact on its size as compared to the variation in the values of C_1 and C_2 . A detailed parametric study of SSS-UC is performed to verify this fact in simulations. From this analysis, it is clarified that the resonant frequency of UC is shifted to lower frequencies by either increasing the height of substrate or a length of UC.

Fig. 4. Simulated reflection phase profiles for final Cesaro modified EBG-UC compared to initial UC geometries.

Fig. 5. Simulated reflection phase of the proposed Cesaro modified EBG-UC tuned at 2.45 GHz center frequency.

Based on this study, SSS-UC is modified using a specialized cross-shaped fractal geometry known as Cesaro fractals [36]. Fig. 3 and 4 show the comparison of proposed Cesaro modified geometry and its reflection phase characteristics of EBG unit cell (EBG-UC) with the initial square-shaped UC, respectively. The achieved simulated bandwidth of reference SSS-UC within $90^\circ \pm 45^\circ$ is 210 MHz (2.31-2.52 GHz), with an overall size of 33 mm x 33 mm. To reduce the size of UC, iterations up to the second degree of Cesaro fractal are introduced in the center of SSS-UC, as shown in Fig. 3. This modification in the UC geometry reduces its resonating frequency by increasing its effective

electrical length and thus results in its compactness [37]. It is clear from Fig. 4 that the 90° reflection phase point of the proposed EBG-UC is scaled down by a factor of 12.3% as compared to the initial square-shaped EBG-UC. Fig. 5 shows the reflection phase of the proposed EBG-UC tuned at 2.45 GHz and its final optimized geometry is shown in the inset of Fig. 5. The achieved bandwidth of final EBG-UC design within $90^\circ \pm 45^\circ$ is 180 MHz (2.34-2.52 GHz), with an overall size of 28.3 mm x 28.3 mm.

C. Proposed Sensor Design

In this section, the proposed antenna topology is integrated with the 3×3 array of SSS-UC and Cesaro EBG-UC design, as shown in Fig. 6. It can be seen that an overall 14.85% size reduction is achieved by employing Cesaro-type fractal geometry in UC. A separation of 8 mm is maintained between the radiator and the reflector plane to minimize the impedance mismatch due to the mutual impedance coupling caused by their close proximity. The geometry and the feed point of the proposed antenna are also optimized to produce the desired resonant frequency at 2.45 GHz and to match the antenna impedance effectively for $S_{11} < 10$ dB, upon integration with EBG planes.

Fig. 6. Antenna integration on proposed 3×3 array of initial and final EBG-UC, dimensions in millimeter. (a) Upper view of initial topology (b) Lateral view of initial topology (c) Upper view of final topology (d) Lateral view of final topology

Fig. 7. E-field maps of 3×3 initial and Cesaro modified EBG planes. (a) Simple square-shaped EBG plane (b) Cesaro modified EBG plane

After the successful integration of radiating antenna on the proposed reflector plane, a detailed investigation of integrated design is carried out to identify the region of maximum electric fields. This study is done because the regions with maximum electric fields are the best suitable areas for the deposition of liquids to measure their dielectric properties [38]. Fig. 7 shows the electric field of initial and final proposed integrated designs plotted against the same color bar for better comparison. Fig. 7(a) depicts that the electric fields are maximum in the horizontal gap lines between the unit cells. In order to further maximize the electric fields in this region, Cesaro-type fractal geometry is introduced in the center of UC that results in the strongly-enhanced localized electromagnetic fields due to the self-similar spatial distribution of the structure [39]. Fig. 7(b) shows the improved electric field strength in the horizontal gap lines of modified EBG plane which also results in the improvement of device sensitivity and Q-factor, as discussed in the next section.

Fig. 8. Final proposed detector/sensor topology with trenches and two fluidic channels, dimensions in millimeter. (a) Top view of software prototype (b) Side view of software prototype

Fig. 9. Fabricated prototype of proposed sensor topology with empty fluidic channels.

Trenches of 1.5 mm x 1.5 mm are edged out in the horizontal plane of the EBG surface to reduce the effective dielectric constant and surface wave losses which result in improved input impedance matching of an antenna [40]. For the contactless nature of our proposed design, fluidic channels made of commercially available low-cost transparent Polypropylene (PP) material with a dielectric constant of 2.2

and a diameter of 4 mm are introduced on the strongly-enhanced electromagnetic field regions for deposition of LUT, as shown in Fig. 8.

Fig. 9 and 10 show the fabricated prototype and the reflection coefficient evaluation of the final sensor design with empty fluidic channels, respectively. Foam is used to maintain the specified air gap of 8 mm between the antenna and EBG surface. S_{11} evaluation of the sensor shows that antenna with the EBG array has narrow bandwidth due to the mutual impedance coupling caused by the close proximity between them. The simulated bandwidth of antenna with and without EBG plane is 120 MHz and 366 MHz, respectively. Its measured bandwidth with and without EBG is 215 MHz and 283 MHz, respectively. The apparent discrepancies between simulated and experimental results arise due to multiple factors such as changes in temperature, humidity effects, VNA calibration errors, VNA built-in errors, and minor geometrical differences in the fabricated prototype that results in the possible variations in the measurements [41], [42]. Fig. 11 presents the measured radiation patterns of the proposed sensor at 2.45 GHz. The results show that the antenna alone exhibits bi-directional patterns with a 2.1 dBi radiated gain. Whereas, the addition of EBG structure underneath the antenna produces directional patterns with 6.80 dBi radiated gain. The overall size of fabricated prototype fed using 50 Ω inset feed line is 82 mm x 82 mm which is $0.7\lambda_0 \times 0.7\lambda_0$ in terms of wavelength.

Fig. 10. Numerical and experimental reflection coefficient of proposed sensor topology.

Fig. 11. Measured normalized radiation patterns of antenna with and without Cesaro modified EBG plane. (a) xz plane and (b) yz plane at 2.45 GHz

TABLE II
COMPARISON OF SIMULATED PERFORMANCE ANALYSIS OF INITIAL AND PROPOSED SENSOR TOPOLOGY

Design	Medium	Center Freq. (GHz)	Freq. Shift (GHz)	Q Factor	Sensitivity (%)
Simple Square	Air	2.45	-	-	-
	Butan-1-ol	2.387	0.063	65.76	1.027
	Methanol	2.22	0.23	22.02	0.510
	Water	N.D.*	N.D.*	N.D.*	N.D.*
Proposed Sensor	Air	2.443	-	-	-
	Butan-1-ol	2.363	0.08	68.89	1.317
	Methanol	2.2015	0.2415	27.38	0.540
	Water	2.1467	0.2963	62.59	0.179

* Not Detectable (N.D.)

III. PERFORMANCE EVALUATION OF PROPOSED SENSOR

A. Sensitivity and Q-Factor

For the software-based performance evaluation of the proposed design, the integrated fluidic channels on EBG plane are filled with three absolute liquids having different electrical properties. The chosen LUT is absolute solutions of butan-1-ol, methanol, and water. Their electrical properties of dielectric constant and loss tangent are taken at 20°C temperature and 2.5 GHz frequency. According to [43], butan-1-ol has ϵ_r of 3.57 and $\tan\delta$ of 0.47, methanol has ϵ_r of 21.3 and $\tan\delta$ of 0.65, and water has ϵ_r of 78 and $\tan\delta$ of 0.123.

Fig. 12. Simulated reflection coefficient of sensor with LUT.

Fig. 12 shows that our proposed sensor has revealed a good variation in its resonating frequency when the optimized fluidic channels are filled with chosen LUT of different electrical properties. Furthermore, it can be concluded that the resonating frequency will shift to the lower frequencies as the permittivity of LUT increases. Thus, larger the value of dielectric constant of LUT as compared to that of the air, more significant will be the variation in resonating frequency of the proposed design. Table II summarizes the numerical performance evaluation of the proposed design in terms of Q-factor and sensitivity for the chosen LUT based on the criteria proposed in [44]. Mathematically Q-factor is expressed as,

$$Q = \frac{f_c}{\Delta f_{-3dB}} \quad (3)$$

Here, f_c and Δf_{3dB} are the center/resonating frequency and 3 dB frequency bandwidth, respectively. According to the proposed criteria, the sensitivity of the detector is mathematically expressed as,

$$S = \frac{\Delta f / f_s}{\Delta \varepsilon} \quad (4)$$

Where, Δf is defined as ' $(f_o - f_s)$ ' and $\Delta \varepsilon$ is expressed as ' $\varepsilon_s - \varepsilon_o$ '. For sensitivity estimation of the device, empty channels filled with air are considered as a reference, and its permittivity and resonating frequency are expressed as ε_o and f_o , respectively, whereas ε_s and f_s are the dielectric constant and resonating frequency of channels filled with LUT. From this analysis, it is clear that we have achieved improved Q-factor and sensitivity for a proposed design using specialized Cesaro fractal EBG plane as compared to a simple square-shaped EBG surface. For theoretical validation, consider the following expression for Q-factor of a resonating patch [45]:

$$Q = 2\pi f_o \frac{W_m + W_e}{P_{loss}} \quad (5)$$

Here, f_o is the resonating frequency, and P_{loss} is the dissipated power. W_e and W_m are the average stored electric and magnetic energies, respectively and given as:

$$W_e + W_m = \frac{1}{2} \varepsilon |E_o|^2 + \frac{1}{2} \mu |H_o|^2 \quad (6)$$

Where, E_o and H_o are the electric and magnetic field intensities of the unloaded device, respectively. According to [39], [46], the effective incorporation of fractal geometry in the conducting surfaces enhances its EM fields and improves its concentration in the gaps, as shown in Fig. 7, which increases energy being stored in the EBG surface. Moreover, from equation 5, it is clear that the increase in the stored energy will increase the quality factor of the overall device. Thus, the sensor topology with modified Cesaro fractal-based EBG structure has a higher Q-factor as compared to the simple square-shaped EBG, as depicted in Table II. Furthermore, according to the resonant perturbation theory [47], the resonance frequency shift (Δf) due to the LUT and the sensitivity of a device follow the equation as mentioned below:

$$\frac{\Delta f}{f_o} \approx - \frac{\iint_v (\Delta \mu |H_o|^2 + \Delta \varepsilon |E_o|^2) dv}{\iint_v (\mu |H_o|^2 + \varepsilon |E_o|^2) dv} \quad (7)$$

Where, $\Delta \varepsilon$ and $\Delta \mu$ denote the relative change of permittivity and permeability, respectively. For simple and modified UC, keeping all the other parameters constants, the intensity of electromagnetic fields (E_o and H_o) for modified UC is higher as compared to the simple square-shaped UC as mentioned in the previous section. Therefore, from equation 7, it is clear that higher the intensities of EM wave higher will be the shift

in the operating frequency. And from equation 4, it is quite evident that the sensitivity of the device is directly related to this frequency shift, which results in higher sensitivity of modified sensor design compared to its initial design, as reported in Table II. Also, the detection span of the proposed sensor is improved, and it has successfully detected the shift in its resonating frequency when the channels are filled with water as LUT having the highest permittivity of 78 among others.

To experimentally verify the sensing compatibility of the proposed device, the fluidic channels are filled with chosen LUT using a disposable syringe at constant room temperature to ensure the persistent electrical properties of LUT. Fig. 13 shows the experimental reflection coefficient of the proposed device for chosen LUT with different permittivities ranging from 1 to 78, measured using NI PXIe-5630 two-port RF network analyzer. A similar trend has been seen in measured return loss of a device, having a maximum frequency shift of 133 MHz for water with permittivity of 78 and a minimum shift of 54 MHz for butan-1-ol with a dielectric constant of 3.57. Furthermore, it is observed that the experimental results of the device differ from the numerical ones but follow the same trend, i.e., the shift in the resonating frequency of antenna increases as the permittivity of LUT increases. This variation in the measurements can be attributed to the fabrication process, quality of LUT, and possible differences in the values of complex permittivity of LUT from those stated in [43].

Fig. 13. Measured reflection coefficient of sensor with LUT.

B. Dielectric Characterization

For the calculation of complex permittivity of LUT, one of the best ways is to derive a mathematical model using a curve fitting technique, which generates an imperative equations that best fits a given set of data points [48].

In our case, we have used the resonating frequency (f_s) and bandwidth of frequency shifting (Δf) parameters to accurately determine the value of dielectric constant and loss tangent of LUT, respectively. The relationship between the variation in the resonating frequency w.r.t the change in the dielectric values of LUT could be expressed using 3rd order polynomial expression as articulated in the equation below:

TABLE III
SUMMARY OF MEASURED PERFORMANCE ANALYSIS OF SENSOR WITH CALCULATED DIELECTRIC PROPERTIES OF CHOSEN LUT

Mediums	Center Freq. (GHz)	Freq. Shift (MHz)	Q-Factor	Sensitivity (%)	Dielectric Constant (ϵ_r)			Loss Tangent ($\tan\delta$)		
					Ideal	Retrieved	RMS Error* (%)	Ideal	Retrieved	RMS Error* (%)
Air	2.456	-	327.47	-	1	1.041	4.100	0	-	-
Butan-1-ol	2.402	54	75.55	0.875	3.57	3.609	1.092	0.47	0.469	0.213
Methanol	2.359	96.8	90.05	0.202	21.3	21.337	0.174	0.65	0.649	0.154
Water	2.323	133	59.11	0.074	78	78.035	0.045	0.123	0.122	0.813

*Root Mean Square (RMS) Error, calculated with $\frac{\sqrt{(Ideal-Retrieved)^2}}{Ideal}$.

$$\epsilon_r = 10^4 \times (-8.239f_s^3 + 59.83f_s^2 - 144.847f_s + 116.882) \quad (8)$$

Where ϵ_r is the real value of calculated permittivity, and f_s is the resonating frequency of LUT. The relationship between the bandwidth of frequency shifting and loss tangent is mathematically expressed using 3rd degree polynomial equation as the best-fitting graph to produce an accurate numerical model as expressed in

$$\tan\delta = -237.52\Delta f^2 + 40.02\Delta f - 0.9986 \quad (9)$$

Where $\tan\delta$ is the calculated value of loss tangent, and Δf is the bandwidth of resonating frequency for chosen LUT.

Table III summarizes the sensing performance of the proposed device experimentally in terms of its sensitivity, Q factor, and calculated values of both dielectric constant and loss tangent for chosen LUT. The results show that the proposed sensor has a wide span of detection for liquids having real permittivity in the range of 1 to 78, with a maximum measured quality factor of 90 for methanol and the highest sensitivity of 0.875% for butan-1-ol solution. Furthermore, it is observed that the percentage error in the estimation of dielectric properties using the developed numerical model for chosen LUT is less than 5% which validates its performance for accurate measurement of dielectric properties of LUT.

Table IV shows the relative RMS error between the proposed method and the coaxial cell measurement technique for dielectric characterization of liquids at the similar conditions mentioned in the previous section. It is evident from the results that the proposed method is in good agreement with the state-of-the-art measurement technique for the calculation of complex permittivity of LUT. A maximum relative RMS error of 1.635% and 2.495% are observed for the retrieval of dielectric constant and loss tangent, respectively, which further validates its performance for accurate dielectric characterization of liquids.

TABLE IV
COMPARISON OF PROPOSED METHOD WITH COAXIAL CELL MEASUREMENT TECHNIQUE FOR DIELECTRIC CHARACTERIZATION OF LIQUIDS

Dielectric Properties	Methods	LUT		
		Butan-1o-l	Methanol	Water
Dielectric Constant (ϵ_r)	CCMT*	3.55	21.3	78.55
	Proposed (P)	3.609	21.337	78.035
	Relative RMS Error** (%)	1.635	0.173	0.656
Loss Tangent ($\tan\delta$)	CCMT*	0.481	0.652	0.123
	Proposed (P)	0.469	0.649	0.122
	Relative RMS Error** (%)	2.495	0.460	0.813

* Coaxial Cell Measurement Technique (CCMT) [43];

** Relative RMS Error, calculated with $\frac{\sqrt{(CCMT-P)^2}}{\max(CCMT,P)}$.

IV. CONCLUSION

We have demonstrated a low-profile, contactless and single-port fractal based EBG design to be used as a microwave sensing platform for measuring the complex permittivity of different liquids. The proposed device is composed of a radiating antenna and a 3 x 3 array of EBG-based reflector plane operating at a center frequency of 2.45 GHz. A specialized Cesaro fractal is introduced in the EBG structure to improve its sensitivity and detection range by concentrating the E-fields in the region of detection. To validate its performance, it is tested for three absolute liquids (butan-1-ol, methanol, and water) having dielectric constants ranging from 1 to 78. Upon loading the device with LUT, a maximum measured sensitivity of 0.875% and a highest quality factor of 90.05 is achieved for butan-1-ol and methanol, respectively. The retrieved complex permittivities using proposed sensor are in good agreement with the ideal values of LUT with a maximum RMS error of 1.092% and 0.813% for dielectric constant and loss tangent, respectively. This shows that our proposed microwave sensor is suitable for low-profile and low-cost sensing platform for dielectric characterization of liquids with good sensitivity and minimum detection error. The addition of multiband dielectric characterization of liquids for this proposed approach could be a useful extension of this work in the future.

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