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A Novel Machine Learning Supported Compact, High Sensitivity EBG Based Microwave Sensor for Dielectric Characterization of Liquids

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ABSTRACT: In this paper, machine learning supports a compact electromagnetic band gap structure (EBG) based dual band microwave sensor which is proposed for dielectric characterization of liquids with high sensitivity. Two edges, located via metalized holes, are electrically coupled with a suspended microstrip line. Two channels are placed in the electric field region of each EBG patch. Therefore, the change in frequency shift and quality factor are observed, which will help to describe the dielectric characterization of Liquid Under Test (LUT). A matrix-based mathematical model and a machine learning based prediction model are developed for the calibration and validation of the sensor. The results are experimentally verified through fabricated prototype for the binary mixture of water and ethanol. The proposed sensor achieved a compactness with size of $0.164\lambda_{2.47\,\mathrm{GHz}} \times 0.164\lambda_{2.47\,\mathrm{GHz}}$, an average sensitivity of 0.931, 0.243, and a quality factor of 170, 230 for band-1 and band-2, respectively. The calculated dielectric constant of different samples shows good agreement with the values reported in the literature. The machine learning based model is developed using the Support Vector Regression algorithm and achieves the high value of coefficient determination (R^2) which is 99.01, and the less root mean square error (RMSE) value is 0.009.

1. INTRODUCTION

The dielectric characterization of liquids is found by their permeability and complex permittivity, which define their electromagnetic response. In last few years, several techniques have been reported for the dielectric characterization of liquids like optical based microwave sensor [1], microfluidic based sensor [2], and microwave based sensor [3]. Microwave sensors are more popular due to compact size, reusability of liquids, etc. In literature survey, various microwave sensors have been reported based on different types of resonators like EBG, Split Ring Resonator (SRR), Complementary Spilt Ring Resonator (CSRR), etc. Also, a few sensors are reported based on sensing parameters like frequency, quality factor, phase [4–9], and optimization paper microfluidic viscometer, etc. [10].

A Cesaro fractal EBG based sensor is reported in [11], for the dielectric characterization of liquids with resonator size of $0.67\lambda_0 \times 0.67\lambda_0$ and achieves a sensitivity of 0.875. In [7], a microwave contactless sensor is reported for the dielectric characterization of liquids using a multiple complementary split ring resonator, and it achieves a quality factor of 400. An SRR based dual band microwave sensor is reported in [12] for the detection of permittivity of various samples. Frequency shift is used as a sensing parameter for it, and achieved quality factor for band-1 and band-2 are 280 and 110 with sensitivities of 0.28 and 0.3 for band-1 and band-2, respectively. In [14], a stack EBG based dual-band microwave sensor is proposed with maximum sensitivity for band-1 and band-2 of 0.65 and 4.62 and resonator size of $0.24\lambda_0 \times 0.24\lambda_0$. Sensitivity is introduced as a simultaneous dielectric detection (SDD) capability parameter to evaluate sensor performance. SV-EBG [15] is reported for the liquid characterization with resonator size of $0.198\lambda_0 \times 0.198\lambda_0$, which achieves a relative sensitivity of 0.588. In [16], a square EBG is reported for the dielectric characterization of liquid with a sensitivity of 0.858 and resonator size of $0.91\lambda_0 \times 0.91\lambda_0$. A novel machine learning based microwave sensor is designed for the dielectric characterization of liquids with different ethanol-water ingredient concentrations. In [17], the overall physical size of the sensor is $0.09\lambda_{1.8\,\mathrm{GHz}} \times 0.12\lambda_{1.8\,\mathrm{GHz}}$. In [18], a novel microwave fluid sensor for the complex dielectric parameter measurement of ethanol and water solution is proposed. It consists of two symmetrically positioned SRRs with circular ring shaped detection area. The overall size of the sensor is $0.098\lambda_{2.45\,\mathrm{GHz}} \times 0.245\lambda_{2.45\,\mathrm{GHz}}$. For its characteristics, the complex permittivities of various ethanol-water mixtures by changing the volume of the ethanol concentration are measured. In [19], dielectric characterization was performed using a resonator of size $0.26\lambda_0 \times 0.26\lambda_0$, achieving a sensitivity of 0.430.

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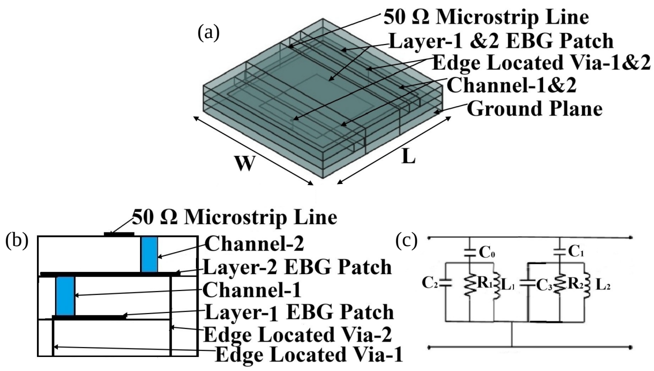

FIGURE 1. Schematic of the proposed sensor. (a) 3-D geometry. (b) Side view. (c) Equivalent circuit diagram. $(W, L, C_0, C_1, C_2, C_3, L_1, L_2, R_1, R_2) = (25, 25, 1.58\,\text{pF}, 4.28\,\text{pF}, 2.2\,\text{pF}, 0.7\,\text{pF}, 3.2\,\text{nH}, 2.23\,\text{nH}, 15\,\text{k}\Omega, 10\,\text{k}\Omega)$.

An ultrahigh sensitivity microwave microfluidic sensor [20], is reported to check the dielectric properties of samples, in which a dual-mode measurement is used to improve the sensitivity of sensor and achieves the sensitivity of 0.43.

A Circular Spiral Resonator (CSR) is loaded with a differential on-chip sensor reported in [21], with the sensitivity of 0.28 and operating at frequencies of 0.44 GHz and 1.45 GHz. In [22], a noninvasive and contactless microwave sensor is proposed based on substrate integrated waveguide (SIW) reentrant cavity. The designed sensor is capable of characterizing its complex permittivity of various liquids with an accuracy higher than 96.76%, operating at 2.18 GHz with the size of $0.4\lambda_0 \times 0.36\lambda_0 \times 0.041\lambda_0$ and sensitivity of 0.366.

The reported microwave sensors are limited in achieving high sensitivity with compact size, and a reported single band sensor does not support simultaneous dielectric detection as it consists of a single sensing region. Therefore, this work aims to propose a microwave sensor with

- High sensitivity, compact size, and peak transmission response.
- Dielectric sensing region which results into simultaneous dielectric detection of two samples.
- Machine learning (ML) and matrix based prediction model which is developed for dielectric characterization of liquids and for the validation of results.
- Liquid Under Test (LUT) can be used further to avoid the wastage of liquid.
- The value of coefficient determination (R^2) is 99.01, and the root mean square error (RMSE) value is 0.009.

This work proposes a novel Two Layer-Edge Located Via-EBG (TL-ELV-EBG) sensor fabricated on a Rogers RT/Duroid 5880 substrate, operating at dual frequency bands (1.05 GHz and 2.47 GHz), and integrated with a Support Vector Regression (SVR)-based machine learning model for dielectric constant prediction. The sensor demonstrates the average sensitivities of 3.40 MHz/% and 1.20 MHz/% in the first and second bands, respectively, with Frequency Detection Resolutions (FDRs) of 19.2 and 4 for the two bands, showing improved performance over existing EBG-based characterization techniques. In this paper, a novel dual-band EBG based microwave sensor is proposed for the measurement of complex permittivity of binary liquids with different concentrations of water-ethanol mixture. Frequency shift is used as a sensing parameter in the proposed sensor. The detailed design and equivalent circuit analysis of the proposed sensor are presented in Section 2. The sensing principle is discussed in Section 3. Calibration and validation of sensor with matrix based and ML based prediction models are presented in Section 4. SDD principle is demonstrated in Section 5, and finally, the paper is concluded in Section 6 by comparing the designed sensor with reported sensors.

2. DESIGN AND ANALYSIS OF PROPOSED SENSOR

2.1. Design of Two Layer-Edge Located Via-EBG (TL-ELV-EBG)

Fig. 1(a) illustrates a schematic 3D geometry of TL-ELV-EBG. The proposed 3D structure is developed using substrate layer-1 and substrate layer-2 with dielectric constant $(\epsilon_r) = 2.2$, loss tangent $(\tan\delta) = 0.009$ with the height of each layer as 1.6 mm, and a 50 Ω microstrip transmission line is developed. A materia with dielectric constant $= 2.2$ is used as a sensing element to detect the resonating frequency of EBG. Two microfluidic channels with the size of $0.205_{\lambda_{2.47\,\text{GHz}}} \times 0.018_{\lambda_{2.47\,\text{GHz}}}$ are placed on the substrate-1 and -2 as shown in Figs. 1(a) and (b). These channels are used to load a liquid under test (LUT). To achieve the dual band and dual sensing region, two EBG patches are used in the design of patch-1 and patch-2 with size of $0.0988_{\lambda_{2.47\,\text{GHz}}} \times 0.0988_{\lambda_{2.47\,\text{GHz}}}$ and $0.164_{\lambda_{2.47\,\text{GHz}}} \times 0.164_{\lambda_{2.47\,\text{GHz}}}$ and are placed on layer-1 and layer-2, respectively. Two edge located vias as shown in Fig. 1(b) are placed to achieve the compactness and sensitivity. The other parameters of the sensor are mentioned in Fig. 1.

The equivalent circuit model of proposed sensor is shown in Fig. 1(c). Capacitances C_0 and C_1 are formed due to the coupling between EBG patch and 50 Ω microstrip line and C_2, C_3 formed due to the coupling between EBG patch-1, -2 and ground. Two edge located via form inductances L_1 and L_2 provide current path between EBG patch-1, ground and patch-2. R_1 and R_2 represent the resistance losses in the substrate. The two channels of sensor loaded with the LUT lead to the change in effective dielectric constant, corresponding to electric field; therefore, there is significant effect on C_0, C_1, C_2, and C_3. The resonance frequencies and quality factors of band-1 and band-2 of the equivalent circuit are given in terms of $L,\ C$, and R [8]. The resonance frequencies and quality factors of band-1 and -2 are defined by $f_{c1} = \frac{1}{2\pi\sqrt{L_1(C_0+C_2)}}$, $f_{c2} = \frac{1}{2\pi\sqrt{L_1(C_1+C_3)}}$, $Q_1 = R_1\frac{\sqrt{C_0+C_2}}{L_1}$, and $Q_2 = R_2\frac{\sqrt{C_1+C_3}}{L_1}$. When LUT is loaded in channel-1, and channel-2, capacitances C_0 and C_1 can be written as $C_0 = C_{01} + \epsilon_{sam}C_{e1}$ and $C_1 = C_{02} + \epsilon_{sam}C_{e2}$, respectively, where C_0, C_1, C_2, and C_3 represent the capacitive effect of the dielectric substrate, channel cavity, etc.; therefore, f_{c1}, f_{c2}, Q_1, Q_2 of the proposed sensor depend on the LUT. Fig. 2 presents the experimental setup along with different fabrication layers of the proposed microwave sensor.

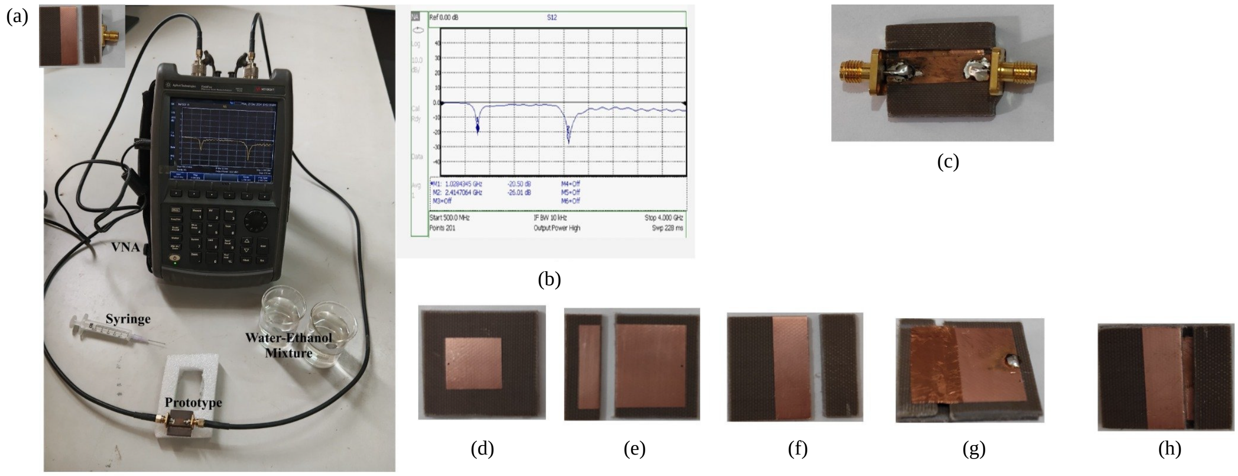

FIGURE 2. Experimental setup with different fabrication layers. (a) Experimental setup of the proposed sensor. (b) Simulation result when channel empty. (c) Prototype of microwave sensor. (d), (e) and (f) Layer-1 and lower EBG patch. (g) Layer-2 and upper EBG patch. (h) Layer-3 with microstrip line.

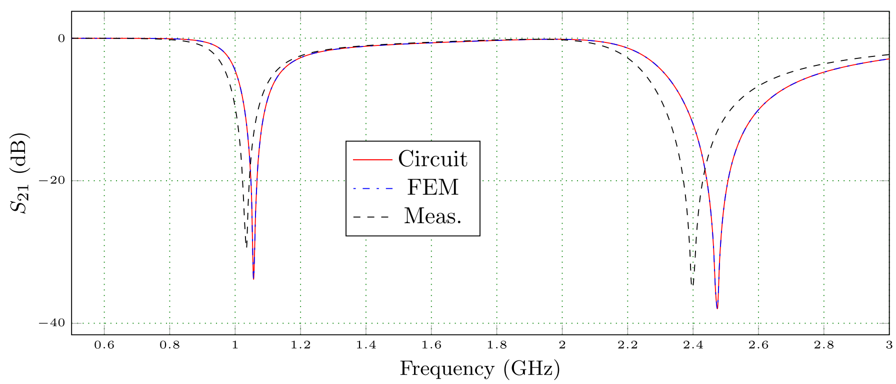

FIGURE 3. Comparison of the S_{21} of FEM, measured and circuit simulation when channels are empty with circuit parameters $(C_0, C_1, C_2, C_3, L_1, L_2, R_1, R_2) = (1.58\,\text{pF}, 4.28\,\text{pF}, 2.2\,\text{pF}, 0.7\,\text{pF}, 3.2\,\text{nH}, 2.23\,\text{nH}, 15\,\text{k}\Omega, 10\,\text{k}\Omega)$.

Fig. 2(a) shows the experimental setup of the proposed microwave sensor. Fig. 2(b) presents the simulated response of the sensor when the microfluidic channels are empty (filled with air). Fig. 2(c) displays the design prototype of the microwave sensor. Figs. 2(d), 2(e), and 2(f) depict the fabricated Layer-1, the lower EBG patch. Fig. 2(g) shows the fabricated Layer-2, upper EBG patch, and Fig. 2(h) shows the final fabricated sensor including Layer-3 and microstrip line. For validating the equivalent circuit model of the proposed sensor, it is simulated using key sight Advanced Design System (ADS). The values used for it are mentioned in Fig. 3, and results are compared with the simulated S_{21} using Ansys HFSS software as shown Fig. 3. The proposed dual-band microwave sensor is fabricated on a Rogger 5880 TM substrate with a dielectric constant of $\epsilon_r = 2.2$ and each layer's height of 1.6 mm. The fabricated prototype and measurement setup are shown in Fig. 4 and Fig. 5, respectively. Fig. 6 shows the electric field generated in the proposed dual-band microwave sensor of water-Ethanol mixture at different frequencies: (a) two channels empty at 1.05 GHz, 2.44 GHz for band-1 and band-2, (b) with 0% water mixture at 0.85 GHz, 2.30 GHz, (c) with 10% water mixture at 0.75 GHz, 2.25 GHz, (d) with 30% water mixture at 0.68 GHz, 2.20 GHz, (e) with 50% water mixture at 0.61 GHz, 2.17 GHz, (f) with 70% water mixture at 0.56 GHz, 2.15 GHz, (g) with 90% water mixture at 0.53 GHz, 2.14 GHz, (h) with 100% water mixture at 0.52 GHz, 2.14 GHz. For the measurement of LUT, it is injected from one side of channel using syringe and collected from the other side of the channel to avoid the interference due to electromagnetic effect, and precautions are taken to maintain a constant room temperature by placing Vector Network Analyzer (VNA) in the middle of the room. It is observed that there is good agreement among circuit simulation, FEM, and measurement results.

3. SENSING PRINCIPLE

In the proposed sensor, frequency shift is used as a sensing parameter which depends on capacitive area of the sensor where maximum electric field is stored. For the dielectric characterization of LUT, channels are placed close to the high electric field region of the sensor as shown in Fig. 6(a). When LUT is placed in channel-1 and -2, there is change in effective dielectric constant of the substrate; therefore, there is change in C_0, C_1, and these values are approximated as $C_0 = C_{01} +$

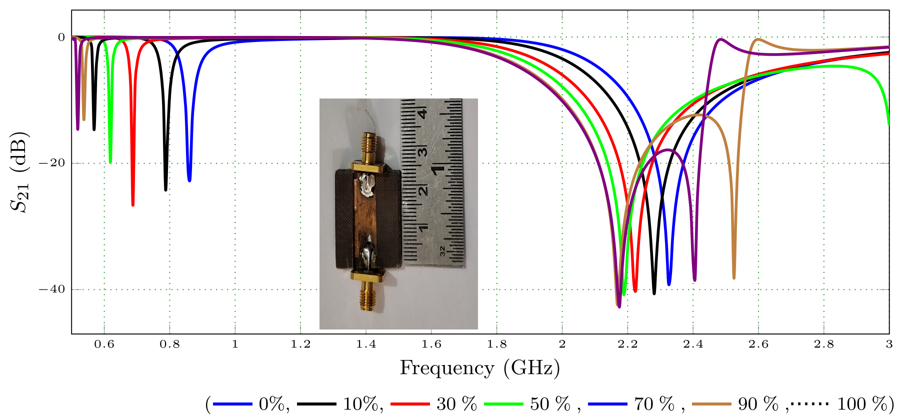

FIGURE 4. Fabricated prototype and measured S_{21} of proposed sensor for water-ethanol mixture sample used for calibration.

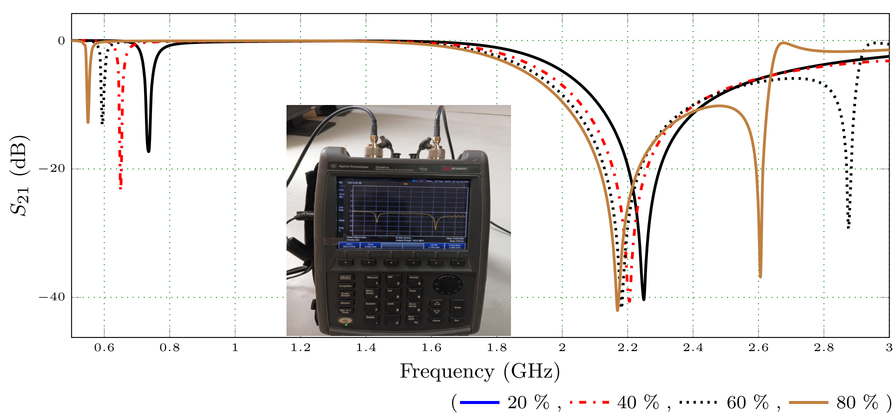

FIGURE 5. Measurement setup and measured S_{21} of proposed sensor water-ethonal mixture sample used for validation.

$\epsilon_{sam}(C_{e1} + C_{e2})$ and $C_1 = C_{02} + \epsilon_{sam}(C_{e2} + C_{e3})$, where C_{01} and C_{02} include the capacitive effect from the channel walls, dielectric substrate, surrounding space, etc. The terms $(C_{e1} + C_{e2})$ and $\epsilon_{sam}(C_{e2} + C_{e3})$ represent the effective capacitances when channels are filled with LUT. ϵ_{sam} is the dielectric constant of sample, and it is approximated for sample as $\epsilon_{sam} = \epsilon'_{sam} - j\epsilon''_{sam}$. Therefore, the capacitive effect due to LUT affects the resonance frequency and quality factor, and formulas for them are mentioned in the earlier section. Due to this dependency on frequency and quality factor, it is possible to calculate the complex permittivity of the LUT.

4. CALIBRATION OF SENSOR, AND VALIDATION OF RESULT

To demonstrate the performance of the sensor towards dielectric characterization of liquids, the binary mixture of water and ethanol is considered. In the measurement, water fractions are considered from 0 to 100% with a step size of 10%. Total eleven samples are considered for calibration and validation of sensor, and 0%, 10%, 30%, 50%, 70%, 90%, and 100% water fractions are considered for the calibration of sensor. Measured transmission response S_{21} for these samples is as shown in Fig. 4. The resonance frequency for band-1 is shifted from 0.86 to 0.52 GHz and for band-2 from 2.28 to 2.16 GHz, and a quality factor is achieved for band-1 which is 170 and for band-2 is 230 obtained for various water fractions. In order to demonstrate the validation of results, matrix based and machine learning based prediction models are developed and explained in the next section.

4.1. Matrix Based-Mathematical Model

In this section, matrix based mathematical model is developed for calibration and validation of results. The dielectric characterization of liquids can be given as ϵ_r. The measured frequency and quality factor are used for the setup as follows:

$$X = \begin{bmatrix} \Delta\varepsilon'_1 & \Delta\varepsilon''_1 \\ \Delta\varepsilon'_2 & \Delta\varepsilon''_2 \\ \vdots & \vdots \\ \Delta\varepsilon'_{11} & \Delta\varepsilon''_{11} \end{bmatrix}, \; Y = \begin{bmatrix} \Delta f_1 \\ \Delta f_2 \\ \vdots \\ \Delta f_{11} \end{bmatrix} \text{ and } Z = \begin{bmatrix} \Delta Q_1 \\ \Delta Q_2 \\ \vdots \\ \Delta Q_{11} \end{bmatrix} \quad (1)$$

from the above Eq. (1), the following unknown coefficients are calculated for the mathematical model [5].

$$\begin{bmatrix} a & b \end{bmatrix}^\top = (X^\top X)^{-1} X^\top Y_1,$$

$$\begin{bmatrix} c & d \end{bmatrix}^\top = (X^\top X)^{-1} X^\top Y_2 \quad (2)$$

$$\begin{bmatrix} \Delta f_0 \\ \Delta Q \end{bmatrix} = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \begin{bmatrix} \Delta\varepsilon' \\ \Delta\varepsilon'' \end{bmatrix} \quad (3)$$

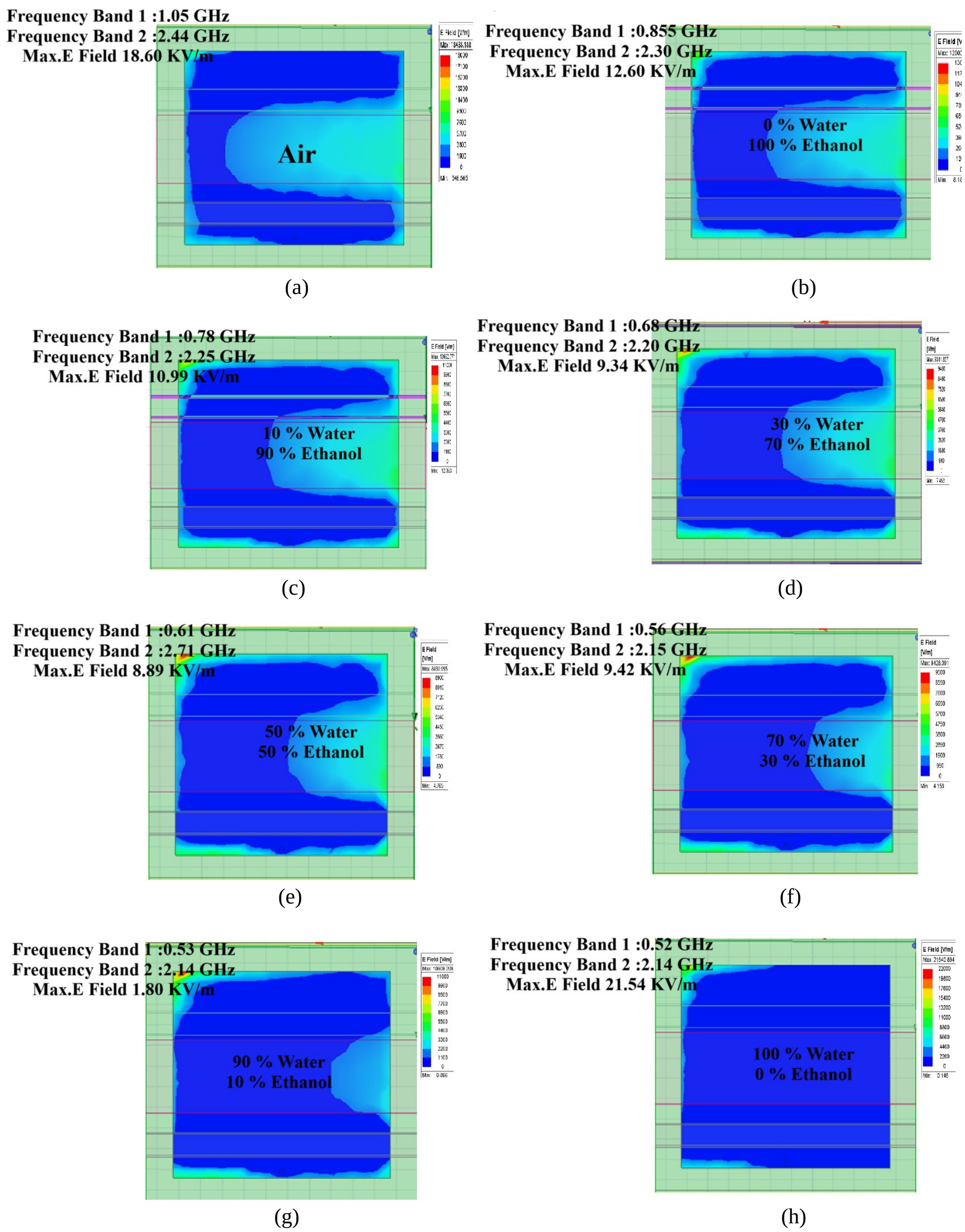

FIGURE 6. The electric field generated in the proposed dual band microwave sensor design (a) two channels empty at 1.05 GHz, 2.44 GHz for band-1, band-2, (b) with 0% water mixture at 0.85 GHz, 2.30 GHz, (c) with 10% water mixture at 0.75 GHz, 2.25 GHz, (d) with 30% water mixture at 0.68 GHz, 2.20 GHz, (e) with 50% water mixture at 0.61 GHz, 2.17 GHz, (f) with 70% water mixture at 0.56 GHz, 2.15 GHz, (g) with 90% water mixture at 0.53 GHz, 2.14 GHz, (h) with 100% water mixture at 0.52 GHz, 2.14 GHz.

As a result, matrix based mathematical model is derived for the proposed sensor.

For Band-1

$$\begin{bmatrix} \Delta f_1 \\ \Delta Q_1 \end{bmatrix} = \begin{bmatrix} -0.00331 & -0.0195 \\ 0.0400 & -3.017 \end{bmatrix} \begin{bmatrix} \Delta\epsilon'_{1sam} \\ \Delta\epsilon''_{1sam} \end{bmatrix} \tag{4}$$

Inverse Matrix

$$\begin{bmatrix} \Delta\epsilon'_{1sam} \\ \Delta\epsilon''_{1sam} \end{bmatrix} = \begin{bmatrix} -322.43 & -1.70 \\ -4.282 & -0.354 \end{bmatrix} \begin{bmatrix} \Delta f_{c1} \\ \Delta Q_1 \end{bmatrix} \tag{5}$$

For Band-2

$$\begin{bmatrix} \Delta f_{c2} \\ \Delta Q_2 \end{bmatrix} = \begin{bmatrix} 0.0012 & 0.0063 \\ 0.170 & 1.62 \end{bmatrix} \begin{bmatrix} \Delta\epsilon'_{2sam} \\ \Delta\epsilon''_{2sam} \end{bmatrix} \tag{6}$$

Inverse Matrix

$$\begin{bmatrix} \Delta\epsilon'_{sam} \\ \Delta\epsilon''_{sam} \end{bmatrix} = \begin{bmatrix} -533.36 & 2.090 \\ 55.97 & 0.395 \end{bmatrix} \begin{bmatrix} \Delta f_{c1} \\ \Delta Q_1 \end{bmatrix} \tag{7}$$

where $\Delta f_{c1} = f_{1sam} - f_{1ref}$, $\Delta f_{c2} = f_{2sam} - f_{2ref}$, $\Delta Q_1 = Q_{1sam} - Q_{1ref}$, and $\Delta Q_{2sam} = Q_{2sam} - Q_{2ref}$, $\Delta\epsilon''_{1sam} = \epsilon''_{1sam} -$

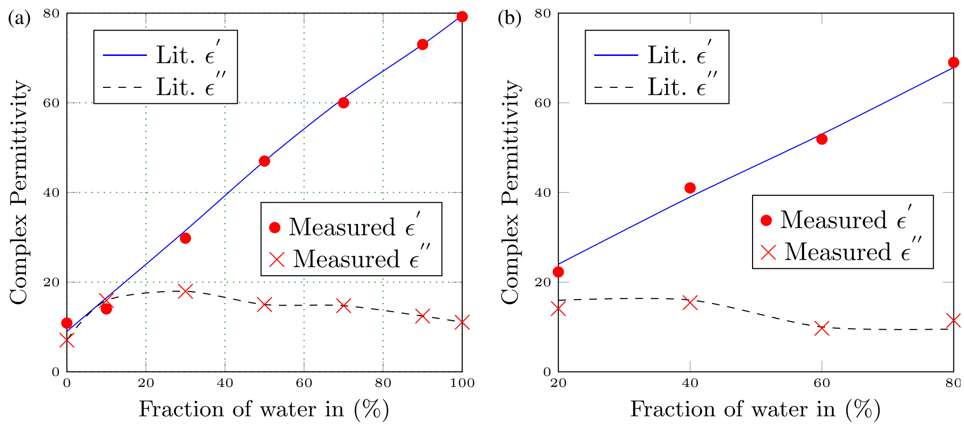

FIGURE 7. Comparison of the different water volume fraction with the literature values and measured values of ϵ_r' and ϵ_r'', (a) for band-1, (b) for band-2.

TABLE 1. Details of resonance frequency and Q factor for band-1 and band-2 associated with different percentages of water and ethanol mixture.

Water (%)	Ethanol (%)	Band I		Band-II	
		F (GHz)	Q-factor	F (GHz)	Q-factor
90%	10%	0.54	177	2.15	270
70%	30%	0.57	140	2.15	217
50%	50%	0.61	204	2.16	210
30%	70%	0.68	229	2.19	203
10%	90%	0.79	195	2.24	285

ϵ''_{1ref}. The above equations are calculated using initial 7 data set values as mentioned in Fig. 7. In order to validate the sensor performance, remaining 4 data sets with water fractions of 20%, 40%, 60%, and 80% are placed in channel and measured with shifting frequency (f_c) and quality factor (Q) for both bands are shown in Table 1. These values are used to calculate the ϵ_r' and ϵ_r'' of the liquids. The measured ϵ_r', ϵ_r'' of band-1 and band-2 are as shown in Fig. 7. It is observed that from the results there is good agreement between the measured and reported values. The sensitivity of the sensor is defined as [13].

$$\%S = \frac{(f_{sam} - f_c)}{f_c(\epsilon_{sam} - 1)} \times 100 \tag{8}$$

where f_{sam} is the resonance frequency for sample under test, when the LUT is present in both channels; f_c is the resonance frequency when channel is empty (air $=$ 1); ϵ_{sam} denotes the permittivity of the sample. Quality factor is defined separately as described in [5].

$$Q = \frac{f_c}{\Delta f_{3db}} \tag{9}$$

The percentage sensitivity of the proposed sensor for band-1 is 0.930, and a sensitivity of 0.243 is achieved using band-2. As shown in Table 2, the proposed sensor is compared with various reported microwave sensors where EBG is used as a resonator. It is observed that the proposed sensor performs well across various parameters such as compact size, sensitivity, and fabrication cost, with characteristics as simultaneous dielectric detection (SDD), reusability of liquids, and easy fabrication process. Therefore, the proposed sensor is useful for the liquid characterization.

4.2. Machine Learning Based Model

In this section, it is demonstrated that machine learning based prediction model is developed for predicting the values of dielectric constant of ethanol-water mixture. The dielectric constant of sample can be defined as $\epsilon_r = \epsilon_r' - j\epsilon_r''$ [5], where ϵ_r' is the real part of dielectric constant, and ϵ_r'' is the imaginary part. Machine learning (ML) based predictive model is developed for the binary mixture of water-ethanol, and it is expressed in terms of resonance frequency f_c as shown in Eq. (10). ϵ_r' and ϵ_r'' predicted values can be calculated using Eqs. (11) and (12). The relationship between the resonant frequency (f_c) and real/imaginary values of dielectric constant of liquid with curve fitting values is shown in Fig. 8 and Fig. 9. With the predictive model based on ML, for band-1 the concentration of ethanol-water ($k_{eth}\%$) is expressed as a function of the resonant frequency f_c in (GHz) as presented in [17].

Therefore, it is observed that ML based prediction model achieves accurate prediction of dielectric constant of liquid. In the ML model, the value of coefficient determination (R^2) is 99.01, and the root mean square error (RMSE) value is 1.732.

For Band-1

$$(K_{eth}\%) = -287.56 * f_c + 237.77 \tag{10}$$

$$\epsilon_r'(Predicted) = -183.4 * f_c + 165.06 \tag{11}$$

$$\epsilon_r''(Predicted) = -287.56*(f_c)^2 + 292.88*(f_c) - 85.44 \tag{12}$$

For Band-2

Similarly for band-2, a predictive model is developed using machine learning techniques to estimate the ethanol concentration from measured resonant frequencies, ϵ_r' (predicted) and ϵ_r'' (predicted) values expressed in terms of f_c as shown in in

TABLE 2. Comparison of state of the art different microwave sensors with the proposed sensor.

Ref.	Type of the Resonator	No. of Resonator	$f_{c(empty)}$ (GHz)	Size ($\lambda_0 \times \lambda_0$)	$S_{avg.}$ (%/%)	S_{21} (dB)	SDD	Reusable Liquids	FDR*/sensitivity* Avg. (MHz/%)
[11]	Fractal EBG	01	2.45	0.67×0.67	0.875	-25.6	No	No	13.33/1.33
[14]	Stack-EBG	02	2.45, 5.8	0.24×0.24	0.65	-17.50	Yes	Yes	10.14
[15]	SV-EBG	01	2.38	0.198×0.198	0.588	-40	No	No	9.38
[16]	Square-EBG	01	2.45	0.91×0.91	0.858	-35.5	No	No	NA
[19]	CLV-EBG	01	1.91	0.26×0.26	0.430	-25.5	No	No	NA
PW	TL-ELV-EBG	02	1.05, 2.47	0.164×0.164	0.930, 0.243	-40	Yes	Yes	19.2, 4/3.40, 1.20

* Frequency Detection Resolution (FDR) calculated with: $\frac{\Delta f_{\min}}{S}$ where $\Delta f_{\min}$ change in minimum Resonant frequency and S is the Average Sensitivity.

* Average Sensitivity (MHz/%) calculated with: $\Delta f_c / k_{eth}$ where Δf_c change in Resonant Frequency, k_{eth} change in the ethanol concentration.

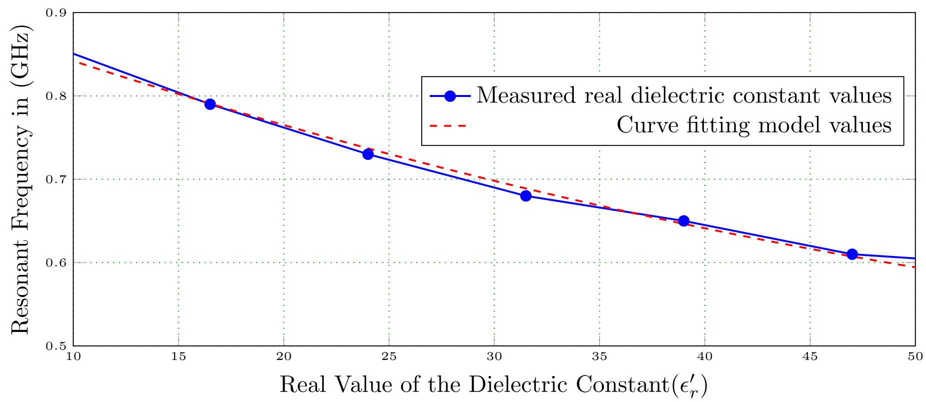

FIGURE 8. With ML predictive model the relation between the resonant frequency and measured real value of the dielectric constant ϵ_r'.

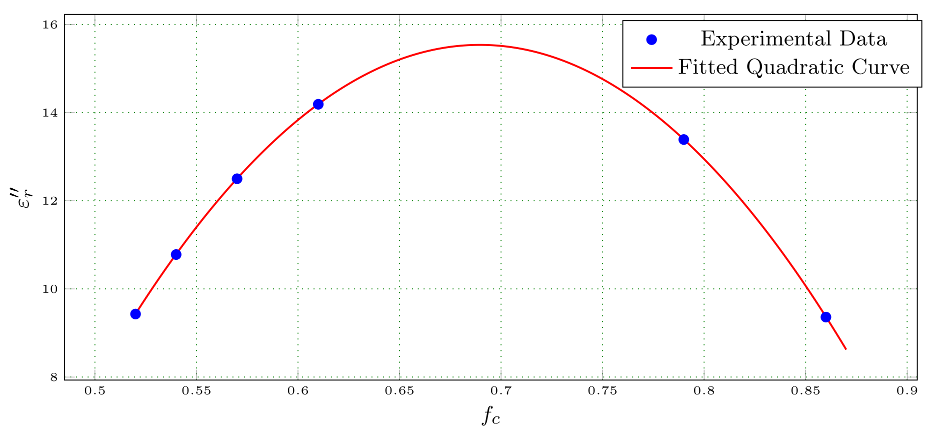

FIGURE 9. With ML predictive model the relation between the resonant frequency and measured imaginary value of the dielectric constant ϵ_r''.

Eq. (13), Eq. (14), and Eq. (15) respectively.

$$(K_{eth}\%) = -0.0012 * f_c + 2.2478 \tag{13}$$

$$\epsilon_r'(\mathit{Predicted}) = -479.4872 * f_c + 1095.2912 \tag{14}$$

$$\epsilon_r''(\mathit{Predicted}) = -352.42 * (f_c)^2 + 1236.1 * (f_c) - 1069.8 \tag{15}$$

The machine learning model is developed using 400 samples from simulation results. The data set is divided into three parts. 70% of data is used for training purposes, 15% data used for validation purposes, and remaining 15% used for testing purposes. It also adds 1500 epochs with a batch size 16. Dividing the data set into different parts ensures the reproducibility

TABLE 3. Comparison of different simultaneous dielectric detections using different materials.

Material Name (CH-1, CH-2)	Δ_f (GHz) (Band-1, Band-2)	f_c (GHz) (Band-1, Band-2)	Actual Value (ϵ_r, ϵ_r) (Band-1, Band-2)	Predicted Value (ϵ_r, ϵ_r) (Band-1, Band-2)	Predicted Value $\epsilon_r'', \epsilon_r''$ (Band-1, Band-2)
Ethanol, Butene	0.011, 0.013	1.02, 2,47	24.3, 1.4	31.50, 0.86	0.0019, 0.006
Butene, Methanol	0.003, 0.041	0.70, 2.26	1.4, 32.7	0.86, 28.97	0.0013, 0.0009

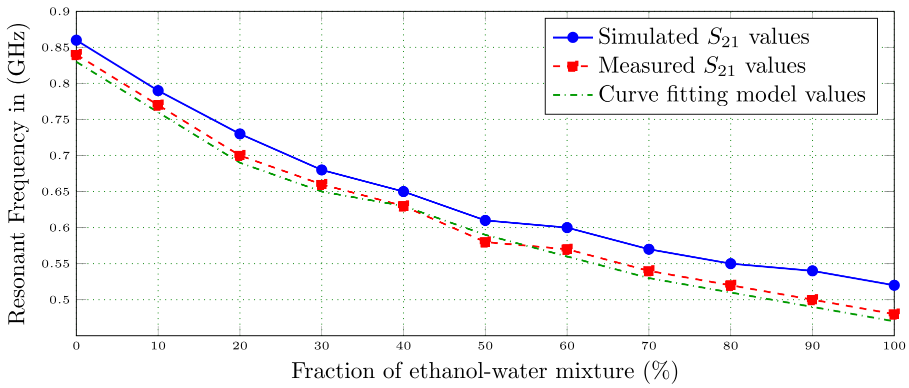

FIGURE 10. The relationship between the resonant frequency and different fractions of ethanol-water mixture.

and credibility of the model performance. In the ML model, the value of ϵ_r' coefficient determination (R^2) is 99.50, and the value of RMSE is 0.009.

The relationship between the different fractions of ethanol-water mixture in percentage and resonant frequency in (GHz) with the simulated, measured, and curve fitting model values is shown in Fig. 10. The advantages of using machine learning over traditional regression methods is that when the results are generated in nonlinear format, the traditional regression methods are not suitable for building the model. So for this study we use a Support Vector regression (SVR). SVR is better than the traditional regression model, and it gives better accuracy and lower the prediction error. The lower the RMSE is, the higher the R^2 is. This result shows that the machine behaviour is not simple or linear, and hence, machine learning is required for accurate modelling

5. SIMULTANEOUS DIELECTRIC DETECTION OF LIQUIDS

In this section, the proposed system to design a microwave sensor having the capability of simultaneous dielectric detection of different fraction of liquids at different resonance frequency is explained.

For Band-1

$$\epsilon_r' = 2855.20\Delta f_1 - 279.18\Delta f_2 + 3.75 \tag{16}$$

$$\epsilon_r'' = 0.02388\Delta f_1 - 0.02294\Delta f_2 + 0.00219 \tag{17}$$

For Band-2

$$\epsilon_r' = -2954.50\Delta f_1 - 126.26\Delta f_2 + 43.02 \tag{18}$$

$$\epsilon_r'' = -0.2540\Delta f_1 - 0.0384\Delta f_2 + 0.00336 \tag{19}$$

For the validation purpose, channel-1 is filled with ethanol and channel-2 filled with butene. The complex permittivity is measured by using the machine learning based prediction model, for band-1 according to Eq. (16) and Eq. (17). The permittivity is calculated using Eq. (18) and Eq. (19), for band-2. When channel-1 is filled with butene and channel-2 filled with ethanol, the predicted and actual permittivity values are mentioned in Table 3. Therefore, it is demonstrated that the proposed sensor is able to measure permittivity values of two different liquids simultaneously.

6. CONCLUSION

In this paper, a novel machine learning supported compact, high sensitivity electromagnetic band gap structure (EBG) based sensor is introduced for the dielectric characterization of liquids, and the results are validated using matrix- and ML-based predictive models. The sensor consists of two patches with various sizes in order to achieve dual sensing region. The proposed sensor is operated at 1.05 GHz and 2.47 GHz frequencies with the attenuation to calculate the dielectric constant of LUT. A prototype of proposed sensor is fabricated, tested, calibrated, validated. It is demonstrated that SDD capability of the proposed sensor achieves maximum sensitivities of 0.931 and 0.243 at the first and second resonances, respectively, and also achieves quality factor 170 and 230 for band-1 and band-2, respectively. It can be concluded that the proposed sensor is a good candidate for the dielectric characterization of liquids with high sensitivity, compact size, and less error.

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