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Metamaterial Inspired RF Planar Sensor for Dielectric Characterization and Identification of Adulteration in Vegetable Oils

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Abstract

A low cost RF planar sensor for dielectric characterization and detection of adulteration in vegetable oils is proposed in this paper. The resonance characteristics of the metamaterial inspired sensor vary with the change in electrical properties of the liquid sample in contact. The sensor is designed to operate in 2.4 GHz ISM band and fabricated on a FR4 substrate of thickness 1.6 mm. A numerical model based on finite element method is developed to extract the relative permittivity of test samples. The sensor is experimentally validated by testing different vegetable oils and comparing the measurement results with values available in literature. As a proof of concept, the prototype is tested for adulteration in vegetable oils with different concentration of adulterant oil and their presence has successfully identified. The compactness, ease of fabrication and low manufacturing cost allow the planar sensor to be considered as promising alternative for dielectric characterization and detection of adulteration in vegetable oils. Moreover, the single port topology of the sensor allows direct submersion in the liquid samples and it also distinguishes materials of close permittivity.

1 Introduction

Compact low cost microwave sensors have increased demand in industrial and biomedical applications such as identification of different oils, chemical solvents, biological fluids etc. Since, biological fluid sensing requires a small amount of test samples, expensive and complex microfluidic sensors are prefered in biomedical applications. In industrial applications where the amount of sample is large enough, submersible sensors can be employed in quality assessment and dielectric characterization of liquids. A wide range of materials are used in various microwave applications and their accurate characterization is critical in the optimization of different microwave devices [1]. Among the different material characterization techniques for liquid samples, resonance techniques are the most preferred methods due to the accurate determination of material properties in the desired frequency band. Traditional cavity perturbation techniques require bulky and expensive metallic cavities [2]. Therefore in recent years, various planar microwave sensors based on split ring resonators (SRRs) [3], inter digital capacitor (IDC) [4] and complementary split ring resonators (CSRRs) [5] are reported in literature for the characterization of liquid samples. These planar sensors incorporate the attractive features such as low cost, lightweight, ease of fabrication and compatibility for lab-on-chip applications. But most of the planar resonators employ two port topology which makes them unsuitable for submersible applications [4], [6]. Moreover, the use of microfludic technology in these sensors increase its complexity and manufacturing cost [6]. The proposed submersible planar sensor is an excellent candidate for the accurate determination of dielectric properties of liquid samples and identification of adulteration in vegetable oils with adulterant oils of close permittivity values.

In this paper, a metamaterial inspired sensor is proposed for the retrieval of relative permittivity of different vegetable oils and detection of adulteration in edible oils. The proposed planar sensor consists of a half wavelength quasi-static SRR resonator and is used as a near-field probe for the precise characterization of liquid samples. The sensor has a single port topology and hence it can be easily immersed in vegetable oils to measure its dielectric properties. In addition, the sensor is fabricated using microstrip line technology which is easier and less expensive. The introduction of copper via in the resonator design makes the sensor more compact compared to all of the reported submersible sensors [5] and [7]. In comparison with all of the submersible planar resonant sensors reported till the date, the proposed sensor is simple, low cost and most compact to the best of author's knowledge. This submersible planar RF sensor combines the advantages of resonant perturbation techniques such as high sensitivity and accuracy together with the compactness, low cost and ease of fabrication of microstrip line technology.

2 Theory and Design

The geometry of the proposed metamaterial inspired sensor is shown in Fig. 1. A circular split ring resonator (SRR) is printed on a grounded FR4 epoxy ($\varepsilon_r = 4.4$, tan $\delta = 0.02$) substrate of 30x20x1.6 mm^3. The SRR is fed by a microstrip line of 50 Ω impedance and a copper via of 1 mm diameter is introduced at the point of feed location to the SRR element between the top feed line and the ground. The

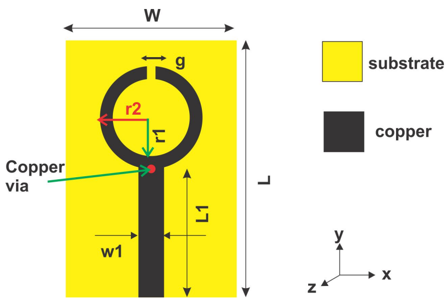

Figure 1. Schematic of the proposed sensor (L = 30 mm, W = 20 mm, $L1$ = 15 mm, $w1$ = 3 mm, $r1$ = 4.5 mm, $r2$ = 6 mm and g = 1 mm)

design parameters are optimized to resonate at 2.409 GHz of the ISM band and the corresponding values are given in Fig. 1.

The electric field distribution of the aforementioned resonator is shown in Fig. 2. Based on the electrostatic boundary conditions, the tangential electric field is forced to be minimum at metallic via whereas maximum at the open end of the SRR. Hence, split ring resonator element acts as a half wavelength resonant section. The electric field intensity is maximum between the gaps of the SRR. A rectangular region of 20x7 mm^2 having maximum electric field intensity and minimum magnetic field intensity as shown in Fig. 2 has been chosen as the permittivity sensing zone for the proposed sensor for improved sensitivity. According to resonant perturbation theory, when a test specimen is kept in a region of maximum electric field, the resonant frequency of the resonator varies with the electrical properties of the test sample. This is the working principle of the metamaterial inspired RF planar sensor.

In this work, various vegetable oils were used as test samples and the single port topology of the proposed sensor facilitates the immersion of the sensor probe inside the liquid. The SRR based sensor along with liquid under test (LUT) is modelled using Ansys HFSS software and the shift in resonant frequency is analysed by varying the permittivity of the LUT from 0 to 10. The variation in resonant frequency of the sensor with the change in permittivity of LUT is shown in Fig. 3. Using curve fitting technique the real part of permittivity of LUT (ε_r) can be expressed as

$$\varepsilon_r = k_0 + k_1\left(\frac{\Delta f}{f_0}\right) + k_2\left(\frac{\Delta f}{f_0}\right)^2 \quad (1)$$

$$\Delta f = f_0 - f_{LUT} \quad (2)$$

where f_0 represents the resonant frequency of unloaded sensor and f_{LUT} represents the resonant frequency of the sensor after loading with LUT. The best approximation of the permittivity is obtained for k_0 = 1.0917, k_1 = 23.6525 and k_2 = 18.9592 respectively.

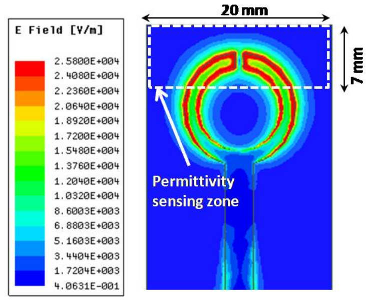

Figure 2. Electric field distribution of the proposed sensor at resonant frequency of 2.4095 GHz.

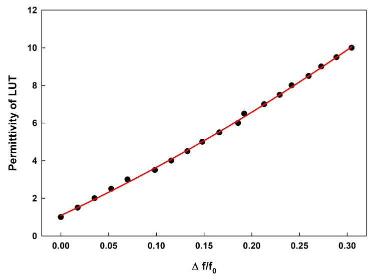

Figure 3. Response of the sensor with variation in permittivity of liquid under test.

3 Fabrication and Measurement Results

The metamaterial inspired RF sensor was fabricated on FR4 epoxy substrate of thickness 1.6 mm and the measurements are done using Anritsu Vector Master MS2038C. The reflection characteristics of the designed sensor is shown in Fig. 4. The fabricated prototype resonates at 2.3986 GHz which shows a good agreement with the simulated resonant frequency of 2.4095 GHz. A slight shift in the resonant frequency is observed due to the tolerances in the standard fabrication process.

3.1 Dielectric Characterization

The experimental set-up for measuring dielectric properties of different vegetable oils and the fabricated prototype are

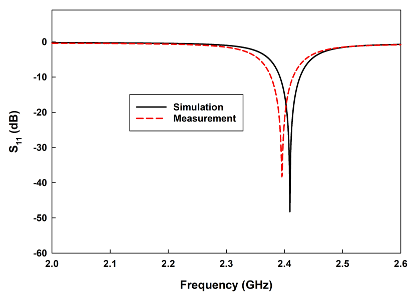

Figure 4. Reflection characteristics of the proposed stand alone sensor.

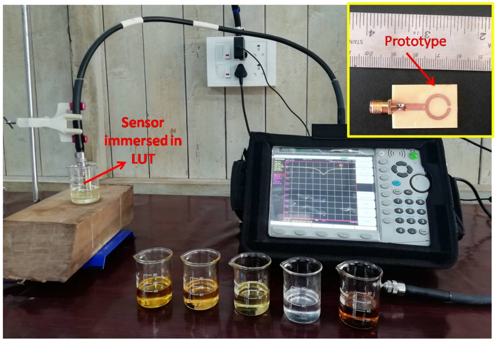

Figure 5. Experimental setup for measurement.

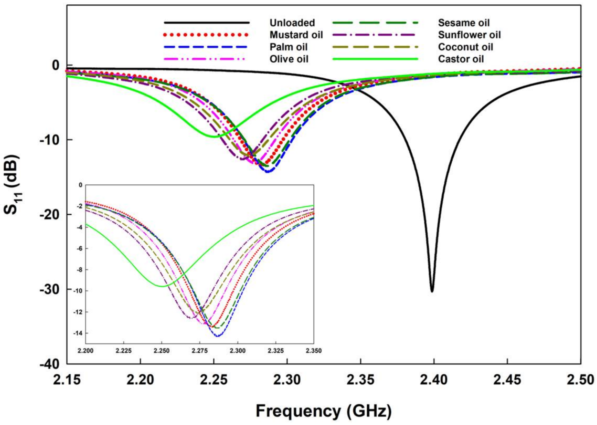

Figure 6. Measured S_{11} of different vegetable oils.

Table 1. Measured dielectric constant of vegetable oils

Sample	Res. freq. (GHz)	ε_r
Palm oil	2.2874	2.2295
Sesame oil	2.2865	2.2387
Mustard oil	2.2825	2.2812
Olive oil	2.2774	2.3357
Coconut oil	2.2740	2.3717
Sunflower oil	2.2695	2.4199
Castor oil	2.2494	2.6368

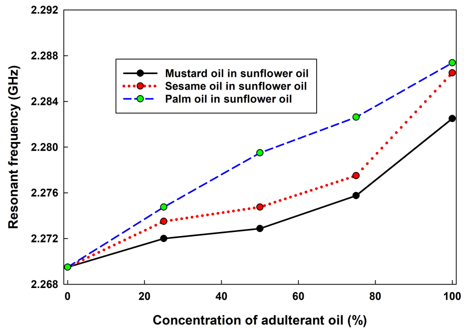

Figure 7. Measured response of the sensor with the variation in concentration level of adulterant in sunflower oil.

shown in Fig. 5. Palm oil, sesame oil, mustard oil, olive oil, coconut oil, sunflower oil and castor oil are used as test samples. The fabricated prototype is immersed inside 40 ml of different vegetable oil samples upto a reference level of 7 mm and the shift in resonant frequency is recorded in each case. Figure 6 illustrates the variation in resonance characteristics of the sensor while loading with different vegetable oils. The permittivity of different oil samples are calculated using Eqn. 1. The measured permittivity of different vegetable oils are tabulated in Table. 1. The measured permittivity values of oils (ε_r = 2-3) are compared with the reference values available in literature [3, 4, 8, 9] and are found to be in good agreement.

3.2 Identification of Adulteration in Vegetable Oils

Cheap, low quality oils are used to adulterate of expensive oils to increase trade profit. The proposed sensor facilitates the distinction of liquid samples of close dielectric constants and shows a sensitivity of 74.875 MHz. Hence, the sensor could be used for the detection of adulteration in vegetable oils. The adulteration of different vegetable oils is measured at room temperature using Anritsu Vector Master MS2038C. As a proof of concept, vegetable oils of close permittivity values are mixed in different concentration levels and the shift in frequency shift is recorded at each concentration levels. The adulteration of sunflower oil by using palm oil, mustard oil and sesame oil is carried out at 25%, 50% and 75% concentration levels. The measured results are shown in Fig. 7. It can be observed that the resonant frequency of the sensor which is loaded with adulterated sunflower oil converges to resonant frequency corresponding to pure sunflower oil as the concentration of adulteration reduces to 0%. The novelty, compactness and the performance of the metamaterial inspired sensor is compared with other sensors available in literature and is tabulated in Table. 2. The proposed sensor is simple, compact, submersible and economical. It could be used for dielectric characterization of liquid samples in industrial applications and quality assessment of vegetable oils compared to conventional complex microfluidic channel based dielectric sensors.

4 Conclusion

A metamaterial inspired planar sensor at 2.4 GHz is designed, fabricated and tested. Using resonant perturbation principle, the dielectric properties of vegetable oil samples are evaluated in the operating bandwidth. The planar sensor can be easily immersed in liquid samples and it allows the dielectric characterization of different vegetable oils having too close permittivity values. Using this technique, the adulteration in vegetable oils is measured for different concentration levels of adulterant oils. The resonant frequency of the sensor loaded with adulterated vegetable oil

Table 2. State of the art of liquid characterization techniques

Reference	Submersible	Operating Freq.	Overall dimension (mm^3)	Substrate
Ref. [3]	yes	1.85 GHz	.....	Rogers AD100
Ref. [4]	no	5.85 GHz	34.7x24x1.6	FR4 epoxy
Ref. [5]	yes	11.56 GHz	25x15x0.8	RT/Duroid 5880
Ref. [6]	no	3 GHz	36x36x1.57	RT/Duroid 5880
Ref. [7]	yes	5.85 GHz	75x33x1	F4-B2
Ref. [10]	no	2.45 GHz	53.2x53.2x40	RT/Duroid 5880
This work	yes	2.4 GHz	30x20x1.6	FR4 epoxy

converges to the resonant frequency corresponding to pure vegetable oil as the concentration of adulterant reaches to 0%. Hence, prototype can be successfully deployed to measure the permittivity of vegetable oils and the identification of adulteration in edible oils. The proposed submersible sensor could be considered as a potential candidate for microwave material characterization of liquid samples due to its compactness, low cost and ease of manufacture. It could also be used to check mouldiness of oils. The dielectric properties of solids and other aqueous chemical solvents using the proposed technique will be analysed in future correspondences.

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References

[1] Athira Raveendran, M.T Sebastian and Sujith Raman, "Applications of Microwave Materials: A Review", *Journal of Electronic Materials*, **48**, 5, May 2019, pp. 2601-2634, doi:https://doi.org/10.1007/s11664-019-07049-1

[2] Chen, Lin-Feng, C. K. Ong, C. P. Neo, V. V. Varadan, and Vijay K. Varadan, Microwave electronics: measurement and materials characterization, *John Wiley & Sons*, 2004, pp. 250-265.

[3] G. Galindo-Romera, F. Javier Herraiz-Martínez, M. Gil, J. J. Martínez-Martínez and D. Segovia-Vargas, "Submersible Printed Split-Ring Resonator-Based Sensor for Thin-Film Detection and Permittivity Characterization," *IEEE Sensors Journal*, **16**, 10, May15, 2016, pp. 3587-3596, doi: 10.1109/JSEN.2016.2538086.

[4] M. Shafi K.T., A. K. Jha and M. J. Akhtar, "Non-destructive technique for detection of adulteration in edible oils using planar RF sensor," *2016 IEEE MTT-S International Microwave and RF Conference (IMaRC)*, New Delhi, 2016, pp. 1-4, doi: 10.1109/IMaRC.2016.7939636.

[5] N. K. Tiwari, S. P. Singh and M. J. Akhtar, "Novel Improved Sensitivity Planar Microwave Probe for Adulteration Detection in Edible Oils," *IEEE Microwave and Wireless Components Letters*, **29**, 2, Feb. 2019, pp. 164-166, doi: 10.1109/LMWC.2018.2886062.

[6] A. A. Abduljabar, D. J. Rowe, A. Porch and D. A. Barrow, "Novel Microwave Microfluidic Sensor Using a Microstrip Split-Ring Resonator," *IEEE Transactions on Microwave Theory and Techniques*, **62**, 3, March 2014, pp. 679-688, doi: 10.1109/TMTT.2014.2300066.

[7] C. Liu and F. Tong, "An SIW Resonator Sensor for Liquid Permittivity Measurements at C Band," *IEEE Microwave and Wireless Components Letters*, **25**, 11, Nov. 2015, pp. 751-753, doi: 10.1109/LMWC.2015.2479851 .

[8] Praveen Kumar, A. V., Akshit Goel, Ritish Kumar, Anuj Kumar Ojha, Jose Kurian John, and Jose Joy, "Dielectric characterization of common edible oils in the higher microwave frequencies using cavity perturbation," *Journal of Microwave Power and Electromagnetic Energy*, **53**, 1, 2019, pp. 48-56, https://doi.org/10.1080/08327823.2019.1569899.

[9] Ivanov A, Agliullin T, Laneve D, Portosi V, Vorobev A, Nigmatullin RR, Nasybullin A, Morozov O, Prudenzano F, D'Orazio A, Grande M., "Design and Characterization of a Microwave Planar Sensor for Dielectric Assessment of Vegetable Oils", *Electronics*, **8**, 9, 2019, pp.1030, https://doi.org/10.3390/electronics8091030.

[10] S. Kulkarni and M. S. Joshi, "Design and Analysis of Shielded Vertically Stacked Ring Resonator as Complex Permittivity Sensor for Petroleum Oils," *IEEE Transactions on Microwave Theory and Techniques*, **63**, 8, Aug. 2015, pp. 2411-2417, doi: 10.1109/TMTT.2015.2451110.