Defence Science Journal, Vol. 71, No. 2, May 2021, pp. 378-382, DOI : 10.14429/dsj.71.16718

Non-Contact Multiple Ring CSRR Based Planar Microwave Sensor for Accurate Quality Estimation of Water Samples with Varying TDS

Smriti Agarwal

Motilal Nehru National Institute of Technology Allahabad, Prayagraj - 211 004, India
E-mail: smritiagarwal@mnnit.ac.in

ABSTRACT

Water pollution and scarcity of pure drinking water is a current challenging problem. In this situation, quality monitoring of water is of vital importance in order to avoid any health issues caused due to intake of contaminated water. Hence, in this paper, a non-destructive technique using multiple ring CSRR based microwave sensor has been proposed for accurate estimation of relative permittivity of unknown water of varying TDS values. Further, a closed form numerical expression using the curve fitting technique has been developed in order to accurately estimate the quality of any unknown water sample. Less than 1% of error has been achieved in the prediction of relative permittivity and hence, TDS of unknown water sample. The proposed planar microwave sensor will be of great importance towards the real-time water quality monitoring systems development.

Keywords: Microwave sensor; CSRR; Water quality; TDS; Curve fitting

1. INTRODUCTION

Water quality anticipated for human use is typically good as produced at the purification plant, but it may generally deteriorate on reaching to consumers due to the occurrence of different chemical substances or pipeline leakage/ breakage. Pollutants of water can be organic, inorganic, biological, physiological and physical pollutants. As a result, water monitoring is of primary concern for most health and security authorities[1]. A review of water quality sensors for monitoring different chemicals in real time was proposed Yaroshenko[2], *et al.*. A SRR based sensor was proposed for ethanol based solution testing[3].

Accurate knowledge of permittivity is of vital importance in order to characterise any unknown sample and to estimate the quality of that sample[4]. Different application areas like; agriculture industry, medical, military, food industry, and healthcare seldom require quality estimation and monitoring of various goods[5-6]. There are various approaches that are used for permittivity assessment such as, near field, transmission line, free-space and resonance based methods[7-9]. Also, these techniques can be classified as resonant and non-resonant methods. However, resonant method for retrieval of unknown permittivity is preferred due to its higher sensitivity, precision and reduced complexity as well as cost. In this method, the shift in the resonant frequency on mounting the sample under test (SUT) over the resonant structure gives the information regarding permittivity of the material sample. The cavity perturbation method is also used for precise narrow band applications but it has the disadvantage of being bulky and costly for characterisation of materials.

Recently, the use of split ring resonator (SRR) based resonant planar microwave sensors are being researched for easy characterisation of different unknown material samples[10-11]. In these types of sensors the planar microstrip line or CPW line are excited by SRR in the same plane or CSRR etched on the ground plane at the opposite side of the substrate. Thus, the sensor design is simple, inexpensive along with precise characterisation. Further, sample preparation is also easy for these types of sensors.

The sensitivity of circular CSRR is better as compared to rectangular one i.e. shift in the resonant frequency for the circular CSRR under the loaded condition is greater than that of the rectangular CSRR[12]. Therefore, in this paper a multiple ring circular SRR (MR-CSRR) has been used to design the microwave planar sensor for the water quality estimation of unknown water samples having different TDS. Also, a mathematical closed form expression has been developed for accurate estimation of relative permittivity of any unknown water sample and hence its quality measurement.

2. MICROWAVE WATER QUALITY SENSOR DEVELOPMENT

2.1 Theoretical Background

In transmission-line approach, the dielectric properties of materials are generally characterised by placing the material sample in the resonant region of the line section. The transmission line based microwave sensor proves to be

Received : 25 January 2021, Revised : 28 January 2021
Accepted : 04 February 2021, Online published : 17 May 2021

cost efficient as compared to the typically used free-space method. The relative permittivity of SUT is estimated by measuring the transmission (S11, S22) and the reflection (S21, S12) parameters w.r.t. resonant frequency. The change in the resonant frequency gives the information about the dielectric properties of materials. A simple resonator can be modelled by an RLC circuit whose resonant frequency can be expressed as[13]

$$f_r = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

where C and L are the equivalent capacitance and inductance of the resonator. Figure 1(a) shows the unit cell structure of the deigned multiple split ring based CSRR (MR-CSRR) which will be etched on the opposite side of the microstrip line. The equivalent circuit diagram of the micostrip coupled CSRR has been shown in Fig. 1 (b). Here, L_r and C_r are the inductance and capacitance of CSRR and resistance R represents the losses. The transmission line inductance is designated by L and coupling between the microstrip line and CSRR is shown by the capacitance C_c. As per perturbation theory, when a small sample of the SUT is exposed to E and H fields of a resonator, the sample perturbs the field distribution that causes a change in the resonant frequency of the resonator. The relationship between the shift in resonance frequency and the material properties of the SUT can be found by loading a sample in the volume of the resonator in which the electric field is localised with high intensity, but the magnetic field is very weak. By this, permittivity of the sample can be determined by the change in the resonance frequency.

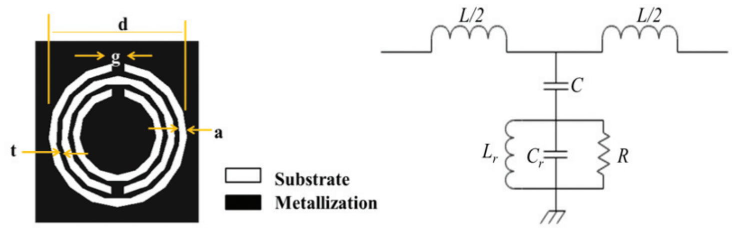
Basically, the shift in resonance (f_r) depends on volume (dv), the change in permittivity ($\Delta\varepsilon$) of SUT. The relationship between electric (E_0) and magnetic (H_0) fields without perturbation and electric (E_1) and magnetic (H_1) fields with perturbation can be expressed by the following equation[14]

$$\frac{\Delta f_r}{f_r} = \frac{\int_v (\Delta\varepsilon\, E_1 . E_0)\, dv}{\int_v (\varepsilon_0 . |E_0|^2)\, dv} \tag{2}$$

Hence, SUT should be placed in the ground plane of the MR-CSRR sensor where the electric field is maximum in order to accurately sense the frequency shift due to change in the E-field and hence to correctly characterise the unknown SUT.

2.2 TDS vs Dielectric Constant of Different Water Samples

Water with different types of contamination present has the varying conductivity[15]. Basically, Total Dissolved Solid i.e. TDS of the water is a measure of the dissolved solids present. Due to the presence of different impurities (like; chlorides, sulphur, phosphate, etc.) and their different concentrations, the TDS of polluted water changes in comparison to pure water. TDS is directly related to the conductivity of the water as shown in Table 1[16]. Further, the different conductivity of water has been associated with different dielectric constant as shown in the last column of Table 1. Hence, by finding the dielectric constant of any unknown water sample, one can have an idea of TDS of the water or in other words, quality of the unknown water sample can be estimated.



(a) (b)

Figure 1. Schematic diagram of (a) Proposed multiple ring-CSRR unit cell, (b) Equivalent circuit of microstrip coupled MR-CSRR.

Table 1. Typical values of water of different TDS w.r.t. their conductivity and dielectric constant[16]

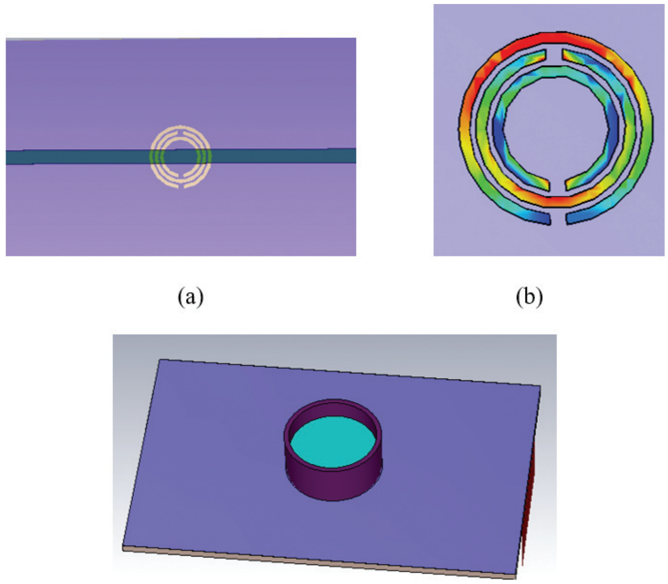
Type of water	TDS (mg/L)	Dielectric constant (ε_r)	Electric conductivity (σ) (s/m)
Pure	0	78.7	0
Tap	1282	78.3	0.2
Saline water	3205	77.5	0.5
	6410	77.3	1
	16026	73.6	2.5
	32051	68.3	5

2.3 Multiple Ring CSRR Microwave Sensor Design

Figure 2(a) shows the top view of the simulated design of the proposed multiple ring CSRR based microwave sensor using 3D EM simulation software HFSS. The substrate FR4 with dielectric constant = 4.4 and loss tangent =0.001 and thickness =0.8 mm has been used. Microstrip line of 50 ohms was formed on the upper side of substrate and the three split rings were etched on the lower ground plane forming the MR-CSRR having dimensions: a=0.39 mm, d=7 mm, g=0.6 mm, t=0.22 mm. Justification for choosing the proposed design is that circular CSRR provides better sensitivity with respect to shift in the resonant frequency as compared to rectangular CSRR. Also, the three split ring CSRR structure was used in contrast to the conventional two rings in order to achieve an enhanced electric field intensity in the sensor region. Fig. 2 (b) shows E- field intensity distribution in MR-CSRR at resonance. Here, the maximum field is concentrated at the three split rings.

The excitation to designed sensor was given through waveport at the two ends of microstrip line. Further, perfect electric, perfect magnetic and open boundary was applied at the appropriate planes for the correct CSRR operation.

Now, since, the performance of this designed sensor is to be analysed for quality monitoring of water samples of different TDS. For this, the setup for SUT has to be modelled in the simulation by placing a beaker filled with liquid at the centre of the MR-CSRR as shown in Fig. 2(c). Here, material of beaker was assigned to be borosil glass (ε_r = 4.6) and to characterise the filled liquid within beaker in accordance to the real water of varying TDS, varying dielectric constant values of water corresponding to different TDS values were used. Since, TDS is directly related to the electric conductivity (σ s/m) of the water. Hence, the water sample with different TDS will disrupt the initial electric field of MR-CSRR, and hence this will change the resonant frequency *(fr) to* f_r'. Now, by analysing this shift in resonance frequency and its accurate



(a) (b)

(c)

Figure 2. Structure of the Proposed multiple ring -CSRR based water quality sensor (a) Top view, (b) Electric Field intensity distribution, and (c) Beaker with sample water under test placed over the resonator.

modelling one can have an idea of permittivity of the unknown water sample and hence TDS. Thereby, the quality of water sample can be tested accurately.

3. RESULTS AND DISCUSSION

3.1 Sensitivity analysis under varying SUT

In order to determine quality of the unknown water sample, varying permittivity water samples were taken analogues to varying TDS in the simulation. Now, for different samples, the results of transmission coefficient were compared as shown in Figure 3. As seen in the fig., the unloaded sensor has the frequency of 6.3 GHz, however, it is shifted on placing the beaker containing the water sample of different permittivity viz. ε_r = 45- 80. This range of ε_r was selected keeping in view of practical values of water of varying TDS values. Here, shift in the f_r with varying ε_r can be clearly observed. From this, it can be inferred that if one can model this shift in f_r w.r.t. to ε_r, then we can easily analyse the quality of any unknown water sample.

Further, for accurate material characterisation, sensitivity of the used sensor is of prime concern, which is further associated with accurate prediction of the unknown sample. Here, in the designed planar microwave sensor the electric / magnetic field intensity present across the planar resonant architecture and their variation with different SUT (varying ε_r) will determine the sensitivity of the frequency shift of the proposed MR-CSRR water quality sensor. Therefore, a sensitivity analysis has been done in order to see the relative effect on resonance frequencies with varying relative permittivity for different type of water samples.

As shown in Fig. 4, there is a decrease in f_r with the increasing dielectric constant of the water sample. Further, there is an increase in frequency shift with the increase in

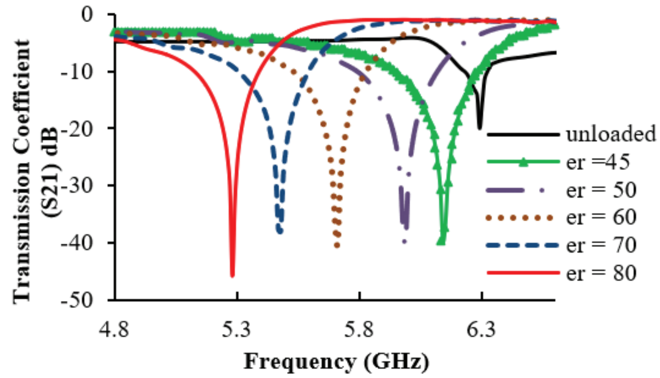


Figure 3. Transmission coefficient *vs* frequency plot for relative permittivity values (ε_r = 45, 50, 60, 70, 80).

permittivity. From this, the proposed water sensor resolution was calculated as defined by frequency detection resolution (FDR),

$$FDR = \frac{(f_1 - f_2)}{\Delta\varepsilon_r} = \frac{(6.33 - 5.28)}{(80 - 40)} = 0.026 \tag{3}$$

where f_1 and f_2 re resonant frequencies for low and high dielectric constant, respectively. FDR comes out to be 0.026 which is appreciably good. Moreover, sensitivity of the sensor is given by stability sensing which determines the accuracy of sensors and is given by

$$S = \frac{(f_1 - f_2)}{f_1} \cdot \frac{1}{\Delta\varepsilon_r} \% \tag{4}$$

$$= \frac{(6.33 - 5.28)}{6.33} \cdot \frac{1}{40} \% = 0.032\%$$

3.2 Numerical Model for Dielectric Constant of Unknown SUT

The accuracy of characterising any unknown SUT depends on how closely the mathematical model is developed. Therefore, in order to establish a numerical relation between the relative permittivity of any water sample and the resonant frequency of the designed MR-CSRR microwave sensor, a curve fitting approach has been used. In Fig. 5, the red dots show the plot of the resonant frequency of the sensor w.r.t. the relative permittivity of water sample having different TDS

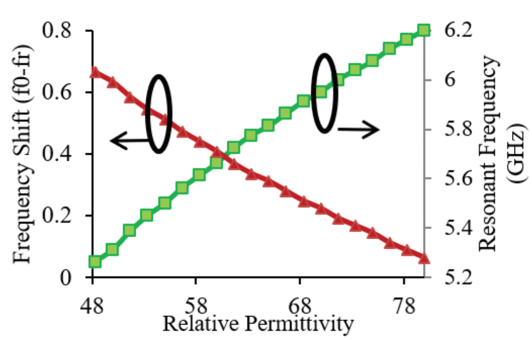


Figure 4. Resonant frequency variation with varying relative permittivity.

values. The blue solid line shows the fitted curve obtained using Matlab based curve fitting tool.

With the help of the curve fitting tool, a 4th order, linear closed form expression between f_r and ε_r was established as given by the Eqn (5)

$$\varepsilon_r(f_r) = P_1 \times f_r^4 + P_2 \times f_r^3 + P_3 \times f_r^2 + P_4 \times f_r + P_5 \quad (5)$$

The value of co-efficients P_1, P_2, P_3, P_4, and P_5 as obtained through curve fitting is -1.859, 39.94, -305.3, 924.5, -724, respectively with 95% confidence bounds. The goodness of fit test was also performed for the developed mathematical model with R^2 value = 0.9999 and RMSE = 0.1543.

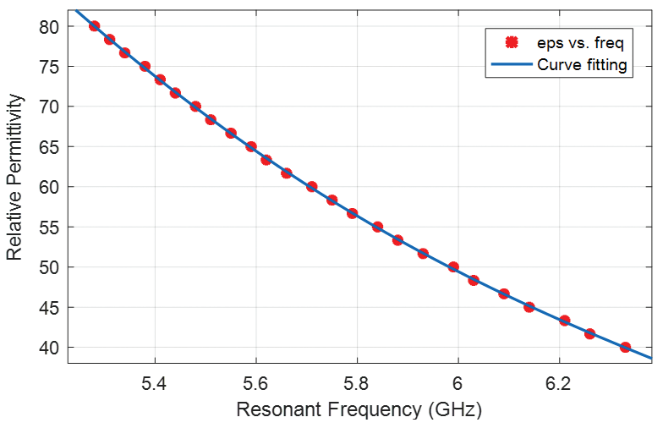


Figure 5. Relative permittivity *vs* resonant frequency curve. The blue solid line showing the fitted curve obtained through curve fitting.

4. VALIDATION OF THE DEVELOPED NUMERICAL MODEL

The numerical model developed using curve fitting was validated using five completely different water samples having different TDS values. For this, the corresponding relative permittivity values were fed in the simulation as SUT. The retrieved resonant frequency obtained from simulation was fed as input in the Eqn (5) and value of the dielectric constant (ε_r') was calculated. This calculated value (ε_r') was compared with the already known value of dielectric constant (ε_r) as shown in Table 2. As seen from the table, the calculated relative permittivity values came in close agreement to the actual values with very less error (<1%), which validates the designed MR-CSRR water quality sensor and the developed mathematical model for estimating the quality of any unknown water sample of varying TDS.

5. CONCLUSIONS

A multiple ring-CSRR based planar RF sensor has been designed and validated with the help of numerical model for characterisation of unknown water samples of varying TDS values. The proposed sensor is very simple and can be easily manufactured using PCB based fabrication technology. Also, the sample preparation does not involve any specific procedure. The developed numerical formulation using curve fitting was verified for different types of water sample. The compared results are very encouraging and accuracy of nearly 99% was achieved in simulation and theoretical models. As a future work, the fabrication of designed microwave sensor will be done and its performance will be tested for practical real water samples. Further, other characteristic parameters will also be studied for specifically classifying the type of contamination present in the polluted water.

Table 2. Estimated relative permittivity of water samples (varying TDS) and their comparison with input permittivity values

ε_r (Input)	f_r (Simulated)	ε_r' (from numerical model)	% Error
68.3	5.51	68.87	0.79
73.6	5.4	74.14	0.74
78.3	5.31	78.75	0.53
77.3	5.33	77.70	0.52
78.7	5.3	79.28	0.74
77.5	5.33	77.71	0.26

REFERENCES

1. Jean, B. R. A microwave sensor for steam quality. *IEEE Trans. Instrum. Meas.*, 2008, **57**(4), 751-754. doi: 10.1109/TIM.2007.913821
2. Yaroshenko, I.; Kirsanov, D.; Marjanovic, M.; Lieberzeit, P. A.; Korostynska, O.; Mason, A.; Frau, I. & Legin, A. Real-Time Water Quality Monitoring with Chemical Sensors. *Sensors,* 2020, **20**(12), 3432. doi: 10.3390/s20123432
3. Kiani, S.; Rezaei, P. & Navaei, M. Dual-sensing and dual-frequency microwave SRR sensor for liquid samples permittivity detection. *Measurement*, 2020, 107805. doi: 10.1016/j.measurement.2020.107805
4. Bao, X.; Ocket, I.; Crupi, G.; Schreurs, D.; Bao, J.; Kil, D.; Puers, B. & Nauwelaers, B. A Planar One-Port Microwave Microfluidic Sensor for Microliter Liquids Characterization. *IEEE J. of Electromagnetics, RF and Microwaves in Medicine and Biology*, 2018, **2**(1), 10-17. doi: 10.1109/JERM.2018.2807984
5. Panda, S.; Tiwari, N. K. & Akhtar, M. J. Computationally intelligent sensor system for microwave characterization of dielectric sheets. *IEEE Sensors J.*, 2016, **16**(20), 7483-7493. doi: 10.1109/JSEN.2016.2599856
6. Agarwal, S., & Singh, D. Optimal Non-Invasive Fault Classification Model for Packaged Ceramic Tile Quality Monitoring Using MMW Imaging. *J. Infrared, Millimeter Terahertz Waves*, 2016, **37**, 394–413. doi: 10.1007/s10762-016-0248-y
7. Nadakuduti, J.; Chen, G. & Zoughi, R. Semiempirical electromagnetic modeling of crack detection and sizing in cement-based materials using near-field microwave methods. *IEEE Trans. Instrum. Meas.*, 2006, **55**(2), 588-597. doi: 10.1109/TIM.2006.870132
8. Ju, Y.; Saka, M. & Abe, H. NDI of delamination in IC packages using millimeter-waves. *IEEE Trans. Instrum. Meas.*, 2001, **50**(4), 1019-1023.

doi: 10.1109/19.948319

9. Nakhkash, M.; Huang, Y. & Fang, M.T.C. A new free-space technique for measuring the complex permittivity and thickness of materials. in Antennas and Propagation. *IEE National Conf. on Ant. Propagation,* 1999. doi: 10.1049/cp:19990007
10. Xu, K.; Liu, Y.; Chen, S.; Zhao, P.; Peng, L.; Dong, L. & Wang, G. Novel Microwave Sensors Based on Split Ring Resonators for Measuring Permittivity. *IEEE Access*, 2018, **6**, 26111-26120. doi: 10.1109/ACCESS.2018.2834726
11. Abdolrazzaghi, M.; Daneshmand, M.; & Iyer, A. K. Strongly enhanced sensitivity in planar microwave sensors based on metamaterial coupling. *IEEE Trans. Microwave Theory Tech.*, 2018, **66**(4), 1843-1855. doi: 10.1109/TMTT.2018.2791942
12. Shafi, K. M.; Jha, A. K. & Akhtar, M. J. Improved planar resonant RF sensor for retrieval of permittivity and permeability of materials. *IEEE Sensors J.*, 2017, **17**(17), 5479-5486. doi: 10.1109/JSEN.2017.2724942
13. Wagner, N.; Emmerich, K.; Bonitz, F. & Kupfer, K. Experimental investigations on the frequency-and temperature-dependent dielectric material properties of soil. *IEEE Trans. Geosci. Remote Sens.*, 2011, **49**(7), 2518-2530. doi: 10.1109/TGRS.2011.2108303
14. Haq, T.; Ruan, C.; Ullah, S. & Fahad, A.K. Dual notch microwave sensors based on complementary metamaterial resonators. *IEEE Access*, 2019, 7,153489-153498. doi: 10.1109/ACCESS.2019.2948868
15. Stogryn, A. Equations for calculating the dielectric constant of saline water (correspondence). *IEEE Trans. Microwave Theory Tech.*, 1971, **19**(8), 733-736. doi: 10.1109/TMTT.1971.1127617
16. Midi, N. S.;, Sasaki, K.; Ohyama, R. I. & Shinyashiki, N. Broadband complex dielectric constants of water and sodium chloride aqueous solutions with different DC conductivities. *IEEJ Trans. Electr. Electron. Eng.*, 2014, **9**(S1), S8-S12. doi:10.1002/tee.22036

CONTRIBUTOR

Dr Smriti Agarwal received PhD from Indian Institute of Technology Roorkee, India in the year 2015. Presently, she is working as an Assistant Professor, Department of Electronics and Communication Engineering at MNNIT Allahabad, Prayagraj, India. Her research interest includes microwave and millimetre wave radar imaging for non-contact target detection and identification, non-invasive material characterisation and planar antenna design. She has published her research work in various reputed international journals and conferences.