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Water Pollution Level Detection using Patch Antenna Measurements at Microwave Frequencies

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Abstract: This work aims at demonstrating a new technique of determining the pollution levels in water by detecting the change in resonant frequency of simple patch antenna while immersed in water (distilled and solutions). The technique is based on the principle that resonance frequency of patch antenna is dependent on the effective dielectric constant of microstrip substrate and the surrounding fluid. An antenna immersed in water has a different resonance frequency than that in air because of the change in effective dielectric constant. Similarly, antenna immersed in salt solutions has a different resonance frequency than that of distilled water. A rectangular patch antenna resonating at 7.65 GHz is designed and operated in air, water and different salt solutions of varying concentration. The resonance frequency shift magnitude is 0.1 to 1 GHz for NaCl solution of 1 to 4 N. However, the resonance frequency shift magnitude for ferric nitrate, potassium chloride, potassium nitrate solutions are 0.5 to 2 GHz for concentration range 0.1 to 1 N. In addition, the frequency shift for acetone mixed with water in proportion of 5 to 25% is determined to in the range 1.3 - 1.5 GHz. Similar studies are performed with antenna immersed in water collected from various sources in Kerala, India. A complimentary theoretical study has been performed to determine the dielectric constant of water with different concentrations of sodium chloride. The calculated values have been used in a simulation software to simulate the shift in resonant frequency when an antenna is immersed in water.

Keywords: microwave; antenna; pollution; dielectric constant; water

Zaznavanje ravni onesnaženosti vode s pomočjo meritev s krpičasto anteno na mikrovalovnih frekvencah

Izvleček: amen tega dela je prikazati novo tehniko določanja stopnje onesnaženosti vode z zaznavanjem spremembe resonančne frekvence preproste krpičaste antene, ko je potopljena v vodo (destilirano in raztopine). Tehnika temelji na načelu, da je resonančna frekvenca krpičaste antene odvisna od efektivne dielektrične konstante mikropasovne podlage in okoliške tekočine. Antena, potopljena v vodo, ima zaradi spremembe efektivne dielektrične konstante drugačno resonančno frekvenco kot antena v zraku. Podobno ima antena, potopljena v raztopino soli, drugačno resonančno frekvenco kot antena v destilirani vodi. Pravokotna krpičasta antena, ki resonira pri frekvenci 7,65 GHz, je zasnovana in deluje v zraku, vodi in različnih raztopinah soli z različno koncentracijo. Premik resonančne frekvence za raztopino NaCl od 1 do 4 N je 0,1 do 1 GHz. Premik resonančne frekvence za raztopine železovega nitrata, kalijevega klorida in kalijevega nitrata je od 0,5 do 2 GHz za koncentracije od 0,1 do 1 N. Poleg tega je frekvenčni premik za aceton, pomešan z vodo v razmerju 5 do 25 %, določen v območju 1,3 do 1,5 GHz. Podobne študije so opravljene z anteno, potopljeno v vodo, zbrano iz različnih virov v Kerali v Indiji. Izvedena je bila dopolnilna teoretična študija za določitev dielektrične konstante vode z različnimi koncentracijami natrijevega klorida. Izračunane vrednosti so bile uporabljene v simulacijski programski opremi za simulacijo premika resonančne frekvence, ko je antena potopljena v vodo.

Ključne besede: mikrovalovi; antena; onesnaženje; dielektrična konstanta; voda

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1 Introduction

Among the various types of environmental pollutions, air pollution and water pollution are the most dangerous types. Pollution of water and air make them a health hazard even though they are imperative for life. Water pollution primarily leads to various diseases like cholera, diarrhoea, dysentery, hepatitis A, typhoid, and polio as per reports by the World Health Organization (WHO) [1]. The main types of water pollutants are inorganic, organic and biological [2]. Organic and inorganic pollutants are usually byproducts (that have been released into the river) from factories. Organic pollutants are alcoholic, ketonic, amino compounds while inorganic pollutants are sulphates, chlorides, carbonates, etc [3]. On the other hand, biological pollutants develop due to the decay of various types of plants, algae, dead animals etc. in water. The guideline concentrations for some chemicals in water are given in Table 1 [4].

Table 1: Sample guideline concentrations as per WHO of chemical substances in water

Substance	Guideline concentration (mg/l)
Acrylamide	0.0005
Alachlor	0.1
Aldicarb	0.01
Aldrin and dieldrin	0.00003
Aluminum	0.9
Antimony	0.02
Arsenic	0.01
Nitrates	50
Benzene	0.01
Sodium	50
Vinyl chloride	0.0003

It can be observed from table 1 that the guideline concentrations of chemicals in water are primarily less than 0.1 mg/l. Thus, even small amounts of contaminants in water are harmful to human beings and should be easily detectable. Thus, it is necessary that the methods of determining contamination levels are cost effective, easily deployable, sensitive and accessible for all.

The established methods of determining pollution levels are UV-Vis measurements, mass spectrometry and electrochemical sensors like ion-sensitive electrodes sensors [5]. UV-Vis spectrometry works on the principle of determining the intensity of light absorbed by the polluted water sample in comparison to the intensity of light absorbed by a reference sample. The process of determining light absorbed by reference sample and calibration are necessary. This technique is prone to difficulties because all pollutants in water may not absorb light of wavelengths in the range of 190-850 nm [5]. Mass spectrometry involves the conversion of molecules to ions and determination of the mass-to-charge ratio (m/z) in a sample. The accurate measurement of the molecular weight of constituents in sample makes this multistep process very complicated [6].

Heavy metals can be detected using multiple electrode techniques. The electrode interacts with the water sample producing an electrical signal which can be detected based on amperometric, voltammetric, and potentiometric method [5][7][8]. However, these electrodes have to be fabricated using very complex process to maintain their sensitivity.

Along with the above-mentioned detection techniques various kinds of sensors are also used for detection of pollutants. Primary sensor for detecting pollution are fibretics sensors, lab-on-chip sensors [9], biosensors and EM sensors [7][10]. Among the above-mentioned sensors, electrochemical sensors using solid state devices are better suited for use in wireless network. In addition to that, polymer lab chip-based systems involve the integration of the sample preparation, reaction and measurement on a small chip that reduces the time taken for pollutant detection in a conventional lab. However, various performance parameters related to the minimum quantity that can be detected, reaction and response time depend on the sensor fabrication methods and kind of sensors [11][12].

Microwave sensors have already been used for determination of pollutants presence in water. However, Korostynska et. al., used interdigitated electrodes (IDE) for microwave detection for detection of pollutants [Olga 13]. The IDE sensor was used to measure the change in S_{11} parameter i.e., reflection coefficient to monitor water quality on a real-time basis. It was clearly observed that the S_{11} of the IDE changed when operated in air, deionized water, tap water as well as other pollutants like CuCl, KCl and $MnCl_2$.

In addition to the above-mentioned measurement of changes in chemical and physical properties, dielectric constant variation of water at microwave frequencies is also another property that can be used for detection of presence of pollutants and their quantification. The determination of complex dielectric constant of water with various ionic compounds/solutes has been initially done in 1947 by J. B. Hasted et. al., using waveguide technology at three different microwave frequencies [14]. Lawrence A. Klein et. al., (1977), worked on an advanced permittivity model for sea water that is valid at L and S-band [15]. Further to this research work, Hans J. Liebe et. al. (1991), worked on determining a complex dielectric constant model for water based on Debye's and double Debye's equation [16] that is valid upto 1 THz.

U. Raveendranath et. al. (1995), worked on estimating the contamination level in water at microwave frequencies by measuring complex dielectric constant of polluted water in the microwave frequency band using a waveguide cavity [3]. For this work the water sample is filled in a capillary tube which is then put inside a waveguide cavity. The dielectric constant measurements are performed based on the variation in Q-factor and resonant frequency.

Ahmad H Abdelgwad et. al. (2014), worked on the use of microwave measurements for estimation of pollution levels in water present in underground pipelines [17]. The estimation is based on the comparison of dielectric constant of pure and the polluted water. This technique is based on modelling done by Cole-Cole model [18]. It can be easily observed that microwave measurement techniques have been used for determination of dielectric constant of water, mix of water and salts, mix of water and soil as well as water with various contaminants.

The novelty of this work is to determine the feasibility of using microstrip antennas (either rectangular or of various layouts) for detection of pollutants and their level in polluted water. This is because microstrip antennas are easy to fabricate and are really cheap due to which this method would be a good complementary technique along with the above mentioned sensor based systems. This study involves determining the shift in resonant frequency of a microstrip patch antenna that is immersed in water with different chemicals of varying concentrations. This change in concentration, modify the dielectric constant of water which in turn changes the resonant frequency of patch antenna. The resonant frequency is determined by measuring S_{11} parameter or reflection coefficient of antenna. The resonance frequency shift is different for different salt solutions and also varies with quantity of salt dissolved in water.

In addition, this study involves the theoretical analysis of variation in complex dielectric constant of water with change in frequency as well as concentration of NaCl. This theoretical study has been discussed in Section 2 where the Debye model-based variation of dielectric constant (with change in microwave frequency) of distilled water, water mixed with sodium chloride (NaCl) has been used. Next the design and electrical characteristics of the simple antenna used in this study are also discussed in Section 3. Section 4 presents the relationship between resonant frequency and dielectric constant of water. Section 5 discusses the details of the experimental results involving various salts solutions and shift in the resonant frequency of antenna when dipped in these salt solutions and acetone. The salts used are NaCl, potassium chloride, ferric nitrate and potassium nitrate. The change in the complex permittivity for the artificially prepared contaminated water can be used for determining the impact of the pollutants on permittivity of water which in turn affects the resonant frequency of antennas. This section also gives a detailed analysis of the measurements. The conclusions are given in Section 6.

2 Theory of dielectric constant of distilled water and water mixed with solute

For this analysis it is very important to be able to theoretically determine the dielectric constant behavior of water with change in frequency from 1-10 GHz. Therefore, the initial part of the study involves the theoretical understanding and simulation of the variation of dielectric constant of water and NaCl solution in the microwave frequency range of 1-10 GHz. The Debye relaxation model for dielectric and Debye model for water with NaCl are discussed here along with the results of simulations [12][13].

2.1 Debye relaxation model

Debye relaxation model is used in this study to simulate the dielectric constant of water for a range of frequencies and is called the first order Debye model [19]:

$$\varepsilon = \varepsilon_{high} + \frac{\varepsilon_{st} - \varepsilon_{high}}{1 + j\omega\tau} \tag{1}$$

where, ε_{st} represents the static dielectric constant at static frequency and ε_{high} represents the infinite frequency dielectric constant. The real and imaginary parts of the dielectric constant can be written as equation (2):

$$\varepsilon' + j\varepsilon'' = \left(\varepsilon_{high} + \frac{\varepsilon_{st} - \varepsilon_{high}}{1 + (\omega\tau)^2}\right) + j\left(\frac{\varepsilon_{st} - \varepsilon_{high}}{1 + (\omega\tau)^2}\omega\tau + \frac{\sigma_s}{\varepsilon_0}\right) \tag{2}$$

Where σ_s is the static conductivity, the relaxation time τ is related to the relaxation frequency f_c by equation (3):

$$f_c = \frac{1}{2\pi\tau} \tag{3}$$

The impact of static conductivity i.e., σ_s has to be included in the Debye model because of the movement of group of ions as a result of regular electric field. The above model is the basic model used for simulating the dielectric constant variation at microwave frequencies. The static dielectric constant of water is 80.1. The dielectric constant of distilled water is simulated in the frequency range of 1 to 10 GHz and the results are shown in Figure 1. The permittivity of water decreases from 78.1 at 1 GHz to 60 at 10 GHz. Thus, the dielectric constant of water is seen to follow a non-linear trend of decreasing from 1 to 4 GHz and then a linear trend from 4 to 10 GHz.

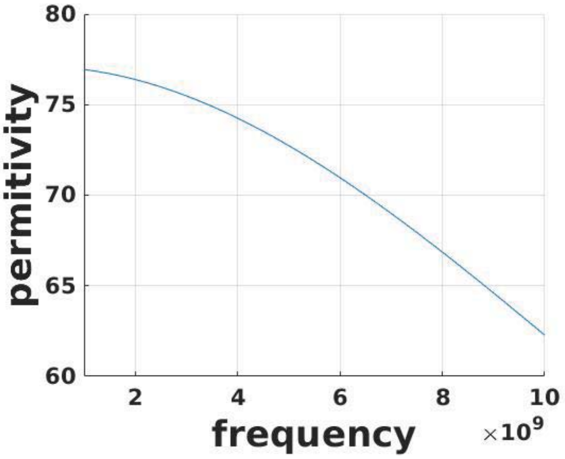

Figure 1: Dielectric constant of distilled water with frequency

2.2 Dielectric constant variation due to change in NaCl concentration and temperature

The analysis in the previous sub-section does not consider variation in the amount of solute and temperature. It has to be noted that dissolving solute in water as well as temperature variation of water result in significant change in the dielectric constant of water. To determine the dielectric constant and dielectric loss of NaCl solution, modified Debye's equation has to be used [19][20]. The variables that depend on change in concentration of solute and temperature are static dielectric constant, ε_{st} and relaxation time τ while the dielectric constant at high frequency ε_{high} is a constant value of 4.9. The equations for ε_s and τ are given by (4) and (5)

$$\varepsilon_{st}(T,N) = \varepsilon_{st}(T,0)\,a(N) \tag{4}$$

$$2\pi\tau(T,N) = 2\pi\tau(T,0)\,b(N,T) \tag{5}$$

where T is water temperature in °C ranging $0 \le T \le 40$ and N is normality of the solution ranging $0 \le N \le 4$. The terms *a(N)* and *b(N, T)* are given by (6) and (7)

$$a(N) = 1.02551N + 5.151\times10^{-2}N^2 - 6.889\times10^{-3}N^3 \tag{6}$$

$$\begin{aligned} b(N,T) &= 0.1463\times10^{-2}NT\times1.000 - 0.04896 - \\ &- 002967N^2 + 5.644\times10^{-3}N^3 \end{aligned} \tag{7}$$

The expression for $\varepsilon_s(T,N)$ is given below in equation (8)

$$\begin{aligned} \varepsilon_{st}(T,0) &= 87.74 - 0.40008T + 9.398\times \\ &\times 10^{-4}T^2 + 1.410\times10^{-6}T^3 \end{aligned} \tag{8}$$

Relaxation time is determined by using equation (9)

$$\begin{aligned} 2\pi\tau(T,0) &= 1.1109\times10^{-1} - 3.824\times10^{-12}T + \\ &+ 6.938\times10^{-14}T^2 - 5.096\times10^{-16}T^3 \end{aligned} \tag{9}$$

The ionic conductivity of NaCl solution is given by equation (10)

$$\begin{aligned} \sigma_{NaCl} &= N\big[10.394 - 2.3776N + 0.68258N^2 - \\ &-0.13538N^3 + 1.0086\times10^{-2}N^4\big] \end{aligned} \tag{10}$$

The temperature T is assumed to be 25°C in all the above equations. The equations (4) to (10) are used along with equations (1-3) to compute dielectric constant and loss of NaCl solution. The parameters such as ε_{high}, ε_{St}, τ and σ_{NaCl} are obtained by varying the normality of the solution from 0 N to 4 N and the calculated parameters ε_s and τ are given in Table 2. The parameters in Table 2, are used for further calculation of dielectric constant and loss variation with frequency as shown in Figure 2 and Figure 3.

The relative permittivity of the NaCl solution is observed to decrease from 77 to 28 for 1 GHz as the NaCl concentration is increased from 0 to 4 N. Similarly, as the concentration of the NaCl in the solution increases from 0 to 4 N the relative permittivity decreases from 67 to 25 at 7 GHz. Thus, there is a significant variation in dielectric constant for small change in concentration of NaCl. The frequency dependency can be observed from Figure 2 where it can be noted that dielectric constant decreases at the rate of 5/5 GHz for concentration 0 N while it reduces at the rate of 5/10 GHz for concentration 4 N.

Table 2: Debye's parameters for NaCl Solution

Normality	ε_S	τ(ps)	σ
0	78.3474	8.0994	0
1	61.8569	7.8045	8.5737
2	50.1994	7.3032	14.8949
3	40.1364	6.8699	19.6984
4	28.4295	6.7788	22.8903

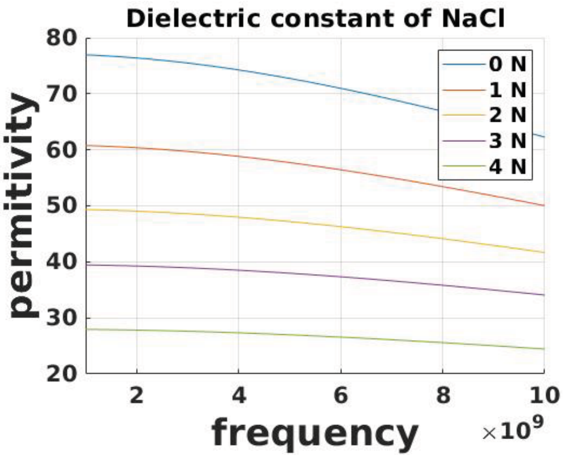

Figure 2: Dielectric constant of NaCl solution for various concentration of NaCl

From Figure 3 it can be observed that the dielectric loss for NaCl solution increases from 80 to 205 at 1 GHz as the concentration of NaCl in the solution increases from 1 N to 4 N. It can also be observed that the dielectric loss is inversely proportional to frequency. However, the rate of decrease reduces as the NaCl concentration is reduced from 4 N to 1 N. For NaCl concentration at 1 N the permittivity decreases from 80 at 1 GHz to 40 at 10 GHz while the dielectric loss reduces from 200 at 1 GHz to 50 at 10 GHz. This is because in the Debye's equation for dielectric loss the first term is dependent on frequency while the second term is independent of frequency.

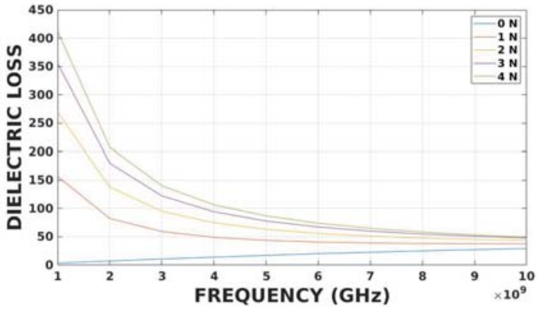

Figure 3: Dielectric loss of NaCl solution

3 Antenna design and measurements

As discussed in Section 1 the sensor for this study is a microstrip patch antenna that operates at 5.3 GHz and 7.5 GHz i.e., it resonated at frequencies of 5.3 and 7.5 GHz. This has been designed using FR4 substrate having permittivity of 4.4 based on theory given in Balanis, 2005 [21] using High Frequency Structure Simulator (HFSS) [22] and is shown in Figure 4. The resonant frequency is determined based on s_{11} parameters shown in Figure 5. The design parameters are given in Table 3. The design layout and the simulation of S_{11} parameter of the antenna are given in Figure 4 and Figure 5, respectively.

Table 3: Design parameters for rectangular patch antenna in air

Frequency (f)	7.5 GHz
Substrate thickness (h)	1.6 cm
Substrate dielectric constant (ε_r)	4.4
Patch width (W)	2.15 cm
Effective dielectric constant of the substrate (ε_{eff})	3.48
Patch length (L)	1.74 cm
Feed inset (y_0)	4.1 cm
Feedline width (w)	2 cm

The reflection coefficient of the antenna (S_{11}) is given by Figure 5 and is approximately -27.5 dB at 7.65 GHz, respectively.

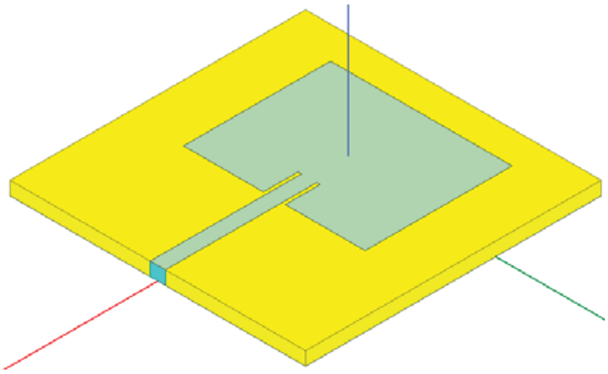

Figure 4: Antenna design

The antenna fabricated using the design is depicted in Figure 6 and shows the top view along with 50 ohm SMA connector. The antenna has been tested using

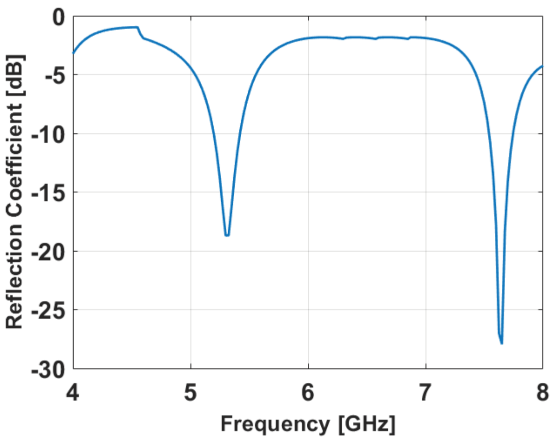

Figure 5: Reflection Coefficient (S11) of designed patch antenna

RHODE & SCHWARZ ZNB8 vector network analyzer (VNA) that can be calibrated and operated from 100 MHz to 8 GHz.

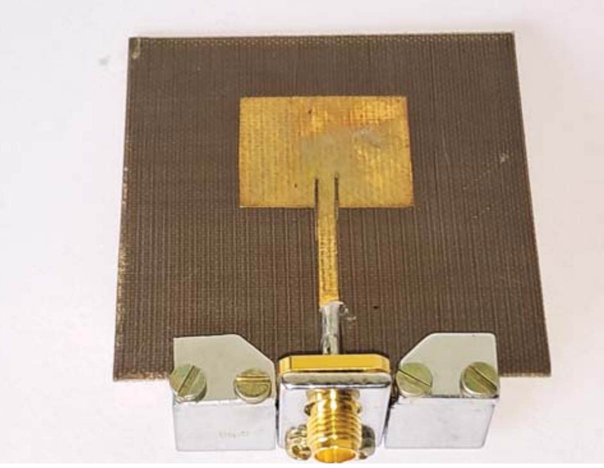

Figure 6: Fabricated antenna

The S_{11} parameter for the antenna is measured using VNA and is shown in Figure 10. It shows that the S_{11} parameter has a dip of -5 dB at 4.8 GHz while there is a dip of -18 dB at 7.65 GHz. The resonant frequency at 7.65 GHz matches well for both the simulation and measurement while the dip at 5.3 GHz has shifted to 4.8 GHz. This is because the simulations were performed without the SMA connector.

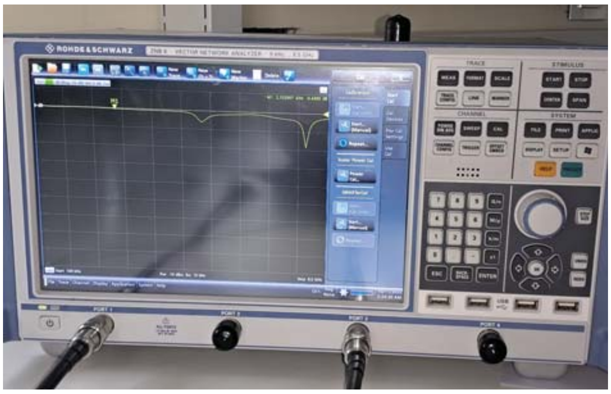

Figure 7: Testing of fabricated patch antenna

4 Resonance frequency and dielectric constant

As already discussed in Section 1 the shift in the resonance frequency of antenna due to immersion in water is used as the technique for pollution level estimation. Therefore, a mathematical method has been used to study the impact of variation of effective dielectric constant of antenna on its resonance frequency when immersed in water. The resonance frequency and effective dielectric constant are related as in equation (11) [15].

$$f_0 = \frac{c}{\sqrt{\varepsilon_{eff}}\, l_{eff}} \tag{11}$$

where f_0 is the resonant frequency, l_{eff} is the effective length and ε_{eff} is the effective dielectric constant. Effective dielectric constant is a function of the dielectric constant of the substrate used for the antenna and the dielectric constant of the environment in which the antenna is supposed to be operating i.e., $\varepsilon_{eff} = f(\varepsilon_r, \varepsilon_{dielectric})$. For the measurement, the microstrip patch antenna is immersed in water sample that in turn results in the interaction of the near field of the antenna with the medium. Thus, the electrical characteristics of the antenna change with respect to the dielectric constant of the material. This results in shifting of the resonant frequency. A polynomial relating shifted resonant frequency and effective dielectric constant was determined. The following process is followed to determine the polynomial:

Based on equation (11), the shifted resonant frequency is used to determine the effective dielectric constant.

From the obtained results, a graph has been plotted using MATLAB curve fit tool to determine a relation between the effective dielectric constant and frequency shift.

The polynomial relation of resonant frequency and the ε_{eff} is given by equation (12)

$$f_0 = p_1\varepsilon_{eff}^3 + p_2\varepsilon_{eff}^2 + p_3\varepsilon_{eff} + p_4 \tag{12}$$

where f_0 is the measured resonant frequency shift when the antenna is immersed in water of varying dielectric constant and the coefficients p_1 = - 3.802 e-5, p_2 = 0.00566, p_3 = - 0.2699 and p_4 = 5.283 which are obtained after the curve fit. The results are shown in Figure 8.

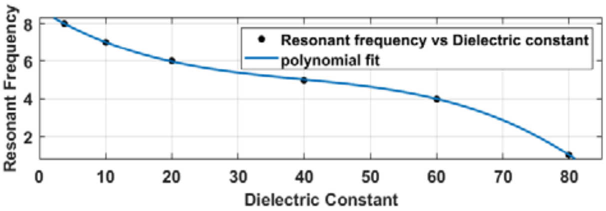

Figure 8: Resonance frequency vs dielectric constant

Thus, if the dielectric constant is in the range of 20-50 the resonant frequency will be in the range of 4-6 GHz.

5 Experiment for resonant frequency measurement and verification

The resonance frequency of antenna in water or solutions of salts is determined for various salts and for acetone. The detailed explanations of the experiment are given in the sub-sections.

5.1 Various salts

The resonance frequency of antenna is determined by dipping the antenna in solutions of sodium chloride, potassium chloride, ferric nitrate and potassium nitrate. Similarly, the measurement of resonant frequency of antenna with change in concentration of salt which in turn results in change of dielectric constant of water is explained here. The experimental setup is shown in Figure 9, which includes the designed patch antenna, water sample to be tested and a vector network analyzer (VNA). The VNA has been used to measure the reflection coefficient for the frequency range of 4 GHz to 8 GHz when the antenna is immersed in the water samples.

5.1.1 Sodium chloride

Solutions of NaCl and water with concentration varying from 1 N to 3 N have been prepared and the antenna has been immersed in water. The S_{11} parameter has been measured for distilled water as well as solution of each normality and the results are shown in Figure 10. For this work the resonant frequency in air at 7.65 GHz has been taken as the reference and its shift with change in dielectric constant is used for the analysis.

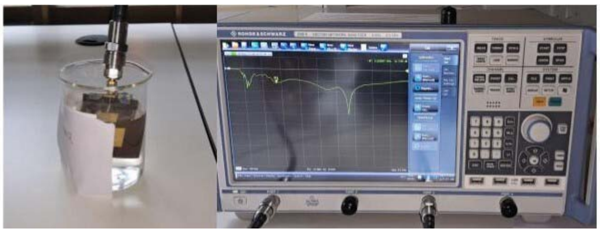

Figure 9: Measurement of dielectric constant using designed patch antenna

It can be observed from Figure 10 that the resonant frequency at 7.65 GHz shifts to the left (reduces) as the dielectric constant changes due to the increase in NaCl concentration. The NaCl solution with 1N concentration has a resonance frequency of approximately 7.2 GHz while the solutions with concentration 2N and 3N have resonance frequency at 7.1 and 6.9 GHz. Thus, there is a clear reduction in the resonant frequency of 7.65 GHz.

To verify these results, a simulation study has been performed in HFSS where the model of the antenna is simulated and is immersed in water and the S_{11} parameter values have been determined for distilled water and water with NaCl with proportion of 1-4 N as shown in Figure 11.

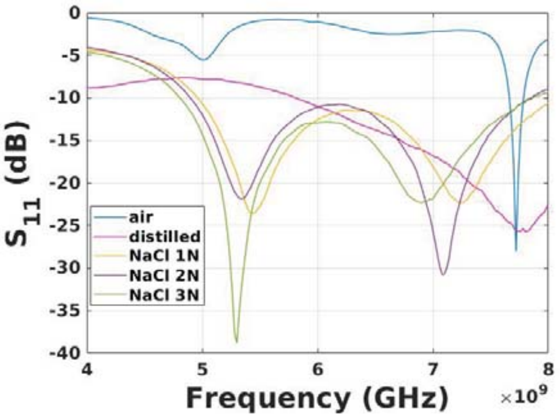

Figure 10: S_{11} parameters for antenna in air and water with various levels of NaCl

However, the simulations showed sensitivity to just the distilled water and NaCl solution with normality 3 N due to which other normality value S_{11} are not presented in this result. By comparing the simulation and measurement results it is very clear that the S_{11} parameters match very well for distilled water and NaCl solution with normality 3 N. It can be observed that the resonance dip is at 7.55 GHz for distilled water for the measurements and the simulation. In addition, it can also be observed that the dip corresponding to 5.2 GHz is not present in the simulations.

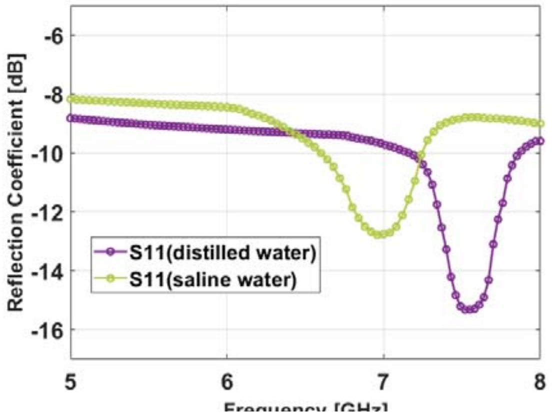

Figure 11: S11 parameters for antenna in air and water with various levels of NaCl

To conduct an in-depth study, the shift in resonance frequency for NaCl solutions is represented as a frequency shift magnitude i.e., the difference between the resonance frequency in air and in water samples. The resonant frequency shift magnitude for various concentrations have been determined and have been presented in Figure 12. The frequency shift magnitude is in the range of 0.4 to 0.9 GHz for the NaCl concentration range of 1-4 N. It can be observed that there is a linear relationship between the NaCl concentration 1-4 N and frequency shift magnitude. The impact of salt concentration on the resonant frequency shift magnitude is studied further where the concentration is varied from 0.1 to 1 N for some of the salts considered in this study. The frequency shift magnitude is from 0.1 to 0.4 GHz for the given concentration range as shown in Figure 13.

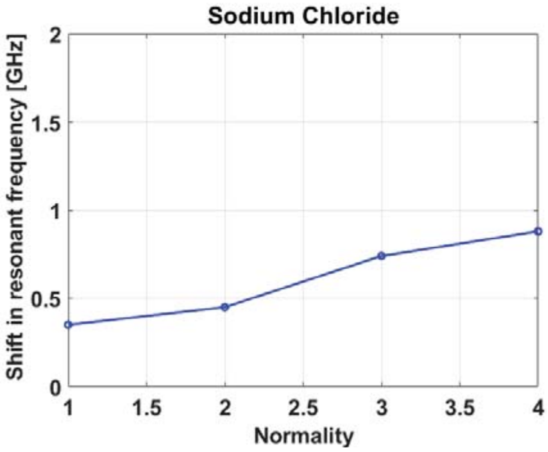

Figure 12: Resonant frequency shift magnitude for NaCl solution of normality 1-4 N

5.1.2 Ferric nitrate, potassium chloride, potassium nitrate

In addition to NaCl solution, the resonance frequency shift magnitude experiments were repeated for various other salt solutions. Solutions used for the testing were made using ferric nitrate, potassium chloride and potassium nitrate with normalities of 0.1, 0.25, 0.6 and 1 N. The resonance frequency was again observed to shift to a lower frequency. The frequency shift magnitude with the change in salt concentration is shown in Figure 13. It can be observed that the values of the frequency shifts are in the range of 1.8 to 1.9 GHz for potassium chloride, 1.4 to 1.7 GHz for potassium nitrate and 0.8 to 1.6 GHz for ferric nitrate.

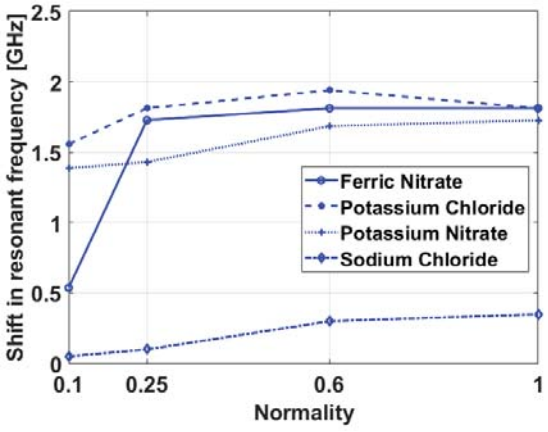

Figure 13: Resonant frequency shift for ferric nitrate, potassium nitrate and potassium chloride for normality 0.1 to 1 N

It can also be observed that the frequency shift magnitude increases as the salt concentration increases. However, it has to be noted that the resonant frequency shift magnitude in NaCl, potassium nitrate and potassium chloride solutions are almost linear in the 0.1 to 1 N range but the shift magnitude for ferric nitrate is slightly non-linear. An important analysis is the repeatability of the shifted resonance frequency for multiple measurements using the same antenna for same solutions. For this analysis the mean (shown in red) and standard deviation (shown in blue) of the resonance frequency shift magnitude are shown in Figure 14. It can be observed that the mean values of the frequency shifts magnitude are in the range of 1.8 to 2 GHz for potassium chloride, 1.4 to 1.7 GHz for potassium nitrate and 0.8 to 1.6 GHz for ferric nitrate. The standard deviation of the frequency shift is in the range of 0.1 to 0.4 GHz. The trend followed by the mean value of the frequency shift magnitude are same as that of the measurements shown in Figure 13.

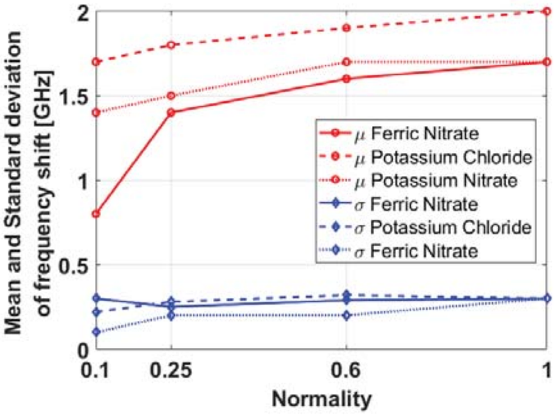

Figure 14: Resonant frequency shift mean (red) and standard deviation (blue) for like ferric nitrate, potassium nitrate and potassium chloride of normality 0.1 to 1 N

There are various observations from these measurements. The frequency shift magnitude increases with increase in salt concentration. The frequency shift magnitude is least for NaCl in this study while it is highest for potassium chloride. Thus, the sensitivity of simple patch antenna resonance frequency is highest for potassium chloride and least for NaCl. All these observations show that this rectangular patch antenna resonance frequency is sensitive to changes in salt concentration as well as to certain type of salts. Some salts have more impact on the antenna resonance frequency shift magnitude than others. Thus, the antenna is very sensitive to small quantities of those salt and can be used for detection of very small amounts of the salt. Therefore, a new design has to be tried to check sensitivity for various salts and chemicals.

5.2 Acetone

The resonant frequency shift analysis was also performed for acetone concentration in terms of volume percentage being varied from 5% to 20% with a step size of 5% to observe the shift in resonant frequency. 5% acetone shows a resonance frequency of 6.3 GHz while 25% acetone shows resonance frequency of 6.1 GHz. From the Figure 15 it can be observed that the frequency shift is not that significant but the magnitude of the reflection coefficient is varying to a great extent. The reflection coefficient is below -10 dB for frequency range from 5.7 to 7 GHz for all concentrations of acetone. The shift in the 10% acetone water mix is not shown over here because the shifted S_{11} response overlaps with the 15% response. The observations in Figure 15 show that the antenna is not very sensitive to changes in concentration of acetone. This is shown from the minimal shift in the resonant frequency with change in concentration from 5 to 25%. Thus, this antenna is not very suitable for detection of very small variation in acetone.

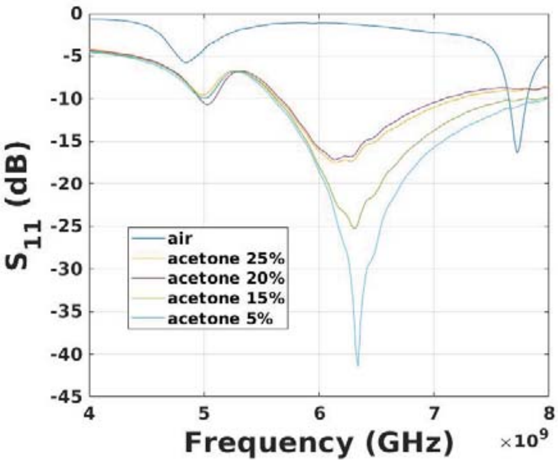

Figure 15: Resonant frequency shift for acetone solution with concentration varying from 5% to 25%

5.3 Resonant frequency shifts due to water from various sources

Implementation and testing of this proposed research technique on actual water samples can provide a lot of practical information on the operational implementation. Therefore, to test the effectiveness of this antenna-based measurement technique, water samples have been collected around IIT Palakkad from various water sources. The water sources i.e., wells and ponds are located as per the map shown in Figure 16. The top figure shows map of the general area from where water samples have been collected. The map also shows the location of IIT Palakkad in the bottom left corner. The location of two of the wells are shown by the blue dots in the bottom two figures of Figure 16. The water samples thus collected have been tested to check the resonant frequency shift magnitude based on S_{11} parameter measurements when antenna was immersed in water. S_{11} parameter measurements in Figure 17 show that the resonant frequency of antenna in water from pond and well4 is approximately 7.3 and 7.4 GHz while the resonant frequency for well3 and well2 is 6.2 and 5.8 GHz, respectively.

A chemical analysis using UV-Vis spectrometer was also performed to determine the level of pollutants in the water sources. The measurements based on the spectrum showed the presence of fluorides. It was observed that level of fluorides was more in well2 and well3 which showed the most shifted resonant frequency at 6.2 and 5.8 GHz.

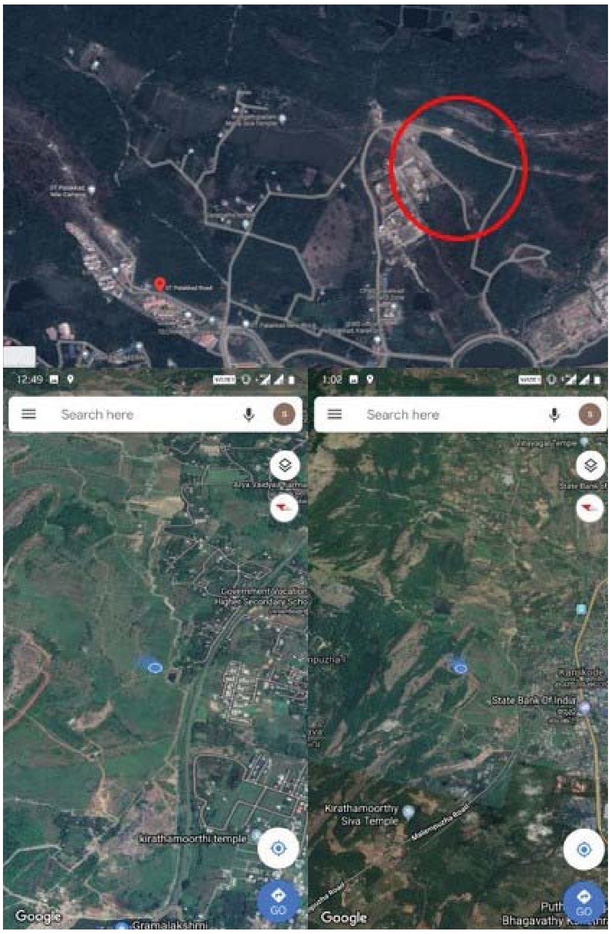

Figure 16: The top figure shows the area near IIT Palakkad where the wells and ponds are located. The bottom two figures show the location of two of the wells under study

The exact amount of fluorides was not determined accurately. From this analysis it is established that the antenna measurement system is able to detect the pollutant levels.

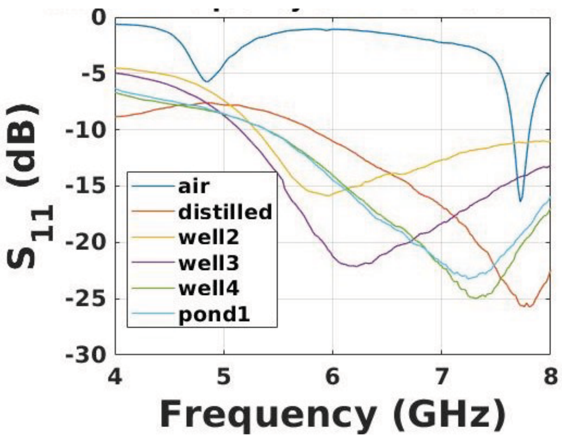

Figure 17: The resonant frequencies for various pollutants present in multiple water sources

Qualitatively low concentration of pollutants shift the resonant frequency of antenna by a fraction of a gigahertz while high concentration reduces the resonant frequency by one to two gigahertz.

6 Summary and conclusion

This study focuses on determining the feasibility of using microstrip antennas (either rectangular or of various layouts) for detection of pollutants and their level in polluted water. The technique is based on the principle that resonance frequency of patch antenna is dependent on the dielectric constant of the microstrip substrate as well as the surrounding fluid. Antenna immersed in water has a different resonance frequency than that of antenna in air because of the change in effective dielectric constant. Thus, there is a shift in the resonance frequency and this shift is related to the dielectric constant of the antenna material as well as the surrounding mixture/solution of salt. To determine the change in dielectric constant of water with frequency and salinity, a simulation-based study has been performed for frequency range 1 to 10 GHz. It has been observed that the dielectric constant of distilled water reduces from 81 to 61 as the frequency is increased from 1 to 10 GHz. Similarly, as the NaCl concentration is increased from 1N to 4N, the dielectric constant reduces to the range of 63 to 31.

For this study an antenna has been designed to operate at 7.65 GHz in air. This antenna is immersed in distilled water as well as in solutions of NaCl, ferric nitrate, potassium nitrate and potassium chloride. A clear shift in resonance frequency dip is observed for antenna immersed in water and various solutions in comparison to the resonance dip in air. For NaCl, the frequency shift magnitude is in the range of 0.4 to 0.9 GHz for concentration range of 1-4 N and 0.1 to 0.4 GHz for frequency range of 0.1 to 1 N. It can also be observed that there is a linear relationship between NaCl concentration and frequency shift magnitude. The frequency shift magnitude is higher at 0.8 to 2 GHz for other salt solutions with concentration 0.1 to 1 N. Similarly, a measurement analysis is performed to determine the shift in resonant frequency when the antenna is immersed in acetone of various level concentrations. It has been observed that resonance frequency shift magnitude is approximately 1.3 to 1.5 GHz. In addition to the above-mentioned tests, the shift in resonant frequency is also determined for water collected from various sources near IIT Palakkad. It has been observed that water from various sources containing various levels of fluorides result in varied frequency shift magnitude.

This whole analysis has clearly shown that a simple patch antenna with a rectangular layout is sensitive to changes in dielectric constant of water which in turn is sensitive to changes in the proportion of salt in water. This antenna is sensitive to small changes in salt concentration of certain types i.e., ferric nitrate, potassium nitrate and potassium chloride. Thus, the sensitivity of the antenna is very high for some of the salts. Antennas can be designed and fabricated for detecting a particular number of polluting agents. Thus, in a multi sensor system for water quality monitoring system a number of antennas can be used for various kinds of pollutants. Thus, antenna resonant frequency measurement systems can complement the present sensor-based techniques to develop an integrated system that is easy to deploy, accurate and cost effective to maintain.

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8 Conflict of interest

The authors of this document do not have any Conflict of Interest (COI) in this paper

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