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Planar Edged UWB Antenna for Water Quality Measurement

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Abstract—A compact planar edge ultra-wideband (UWB) antenna is designed to operate at a frequency range of 3.5 GHz to 10.4 GHz for water quality detection. The design was constructed on an FR4 substrate with an overall dimension of $30 \times 35 \times 1.6\,\text{mm}^3$. The presented design is used to detect the presence of salt in the water in terms of reflection coefficient (S_{11}). The proposed antenna's performance was examined by increasing the salinity of the three water samples: distilled water, reverse osmosis (RO), and raw water. The results showed the decrease of the S_{11} with the increment of salt in the water samples. In addition, the antenna showed good sensitivity as the resonance frequency of the antenna slightly shifted to a lower frequency as the dielectric constant of water increased. Hence, the proposed UWB antenna can be prominently suitable for monitoring water quality and sensors.

1. INTRODUCTION

Freshwater is required for basic human survival, agriculture, industry food, and beverage industries. In addition, every person needs between 80 and 110 gallons of water per day. Water is polluted by various physical, chemical, and biological factors. Water-borne diseases such as cholera and typhoid are caused by contaminated water. Therefore, it is essential to maintain the freshwater quality from being polluted. Some existing systems that measure water parameters like pH, alkalinity, hardness, and total dissolved solids (TDS) have been on the market. Antennas, which have become an important device in communication and telecommunication technologies, improve communication systems' speed and overall performance [1, 2]. Aside from being fast, communication technologies are designed to address the issue of size [3]. A few standardized procedures have been established to determine salt and sugar contents in food and beverage industries. The conventional drying method, electrical conductivity method, and microwave measurement technique sense the dielectric concentration of salt in the soil and salt-starch solutions [4, 5]. Dielectric based sensor technique has been studied and explored based on dielectric characteristics of the materials. The waveguide probes [6], rectangular dielectric waveguide techniques [7] implemented to determine the dielectric properties of biological tissues and oil of palm fruits. However, the performance of the antenna in practical application has been significantly affected by the environment. A microstrip patch antenna using Taconic TLY-5 substrate has been reported [8] for detecting salt and sugar concentration in water at the ISM band 2.45 GHz. In [9], a tuning fork-shaped antenna has been used only for 8 GHz to 11 GHz using RT/Duroid 5880 established to detect

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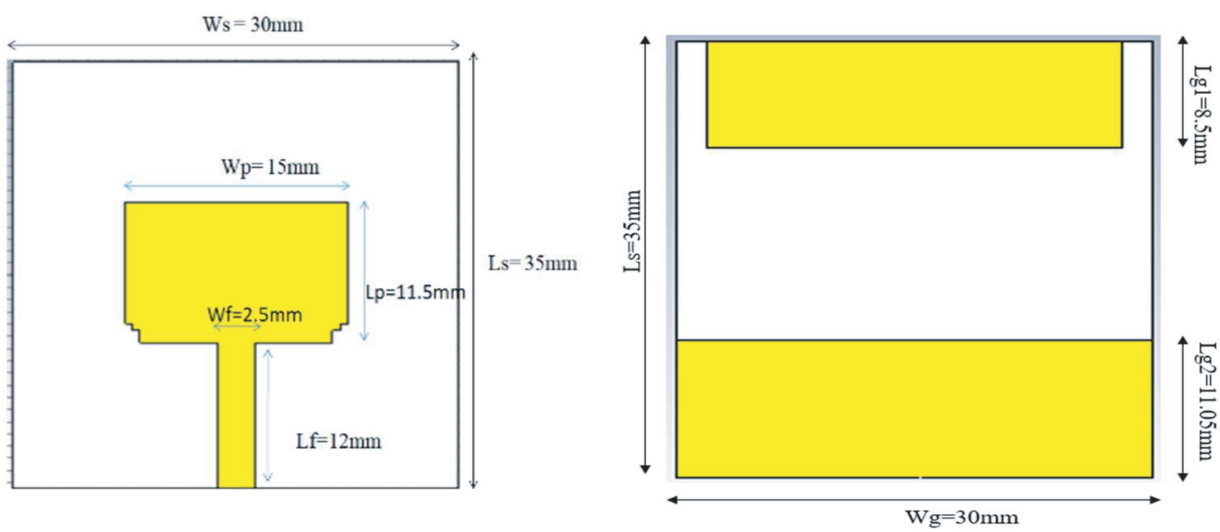
the salinity in terms of reflection coefficients. A bow-tie antenna has been reported for determining the quality of water at 2.4 GHz [10]. The dielectric concentration of salt in the starch solution was determined by using mechanical agitation technique [11].

Various approaches for developing an antenna for communications and determining the moisture, salt, and solid content in various samples are discussed above. However, all conventional antennas were operated in a narrow bandwidth with low gain, and very large size. Also, the determination of water qualities based on dielectric properties was focused only on freshwater with the contamination of salt and sugar samples. Due to the aforementioned reasons, researchers required a wide band to cover more frequency ranges, resulting in the UWB antenna having the appropriate alteration for measuring water quality. Moreover, to the best of our knowledge, there are a few studies on UWB antennas for measuring the water quality, such as in [12–14], thus these works require further investigation.

In this article, a notch-based patch antenna with a dimension of $30 \times 35 \times 1.6\,\text{mm}^3$ is presented. The proposed antenna has a frequency range between 3.5 and 10.4 GHz, and a voltage standing wave ratio (VSWR) of less than 2. The operating principle of water quality measurement depends on the reflection coefficient ($|S_{11}|$) of the proposed UWB antenna within the various concentrations of salt in various water samples. The proposed UWB antenna determines the salt concentration in distilled water, reverse osmosis, and raw water. The reflection coefficient characteristics of an antenna over the resonant frequency are directly related to the impurity concentration in a water sample. The practical investigation of the antenna that has been measured in different concentrations of water is simple and easy to establish.

2. DESIGN OF PROPOSED UWB ANTENNA

The proposed UWB antenna's geometrical structure, depicted in Figure 1, covers a wide bandwidth between 3.5 GHz and 10.4 GHz and was modelled and simulated in CST Microwave Studio using the Finite Integration Technique (FIT). The antenna is based on a defected ground plane and a notch-based patch. The UWB antenna presented here was built on an FR-4 substrate with a dielectric constant of 4.4 and a loss tangent of 0.025. The overall size of the design is $30 \times 35 \times 1.6\,\text{mm}^3$. With an input impedance matching of $50\,\Omega$, a radiating patch with microstrip feed line length, Lf, and width, Wf, is printed on the top of the substrate material, while a defected ground plane is etched on the bottom side of the FR-4 substrate. When the dimensions of the radiating patch structure change due to a difference in the operating frequency of a UWB antenna, the capacitance and inductive reactance of



(a) (b)

Figure 1. Proposed UWB antenna. (a) Front view. (b) Back view.

input impedance change. The proposed UWB antenna's geometrical specifications can be changed to achieve better $|S_{11}|$ across the entire bandwidth.

The evolution of the proposed UWB antenna design is depicted in Figure 2. Adjusting the ground lengths ($Lg1$ & $Lg2$), width Wg, and notches resulted in a UWB resonance across the frequency range, as shown in Figure 3. Because of the electromagnetic (EM) interaction, the notches on the patch and the defected ground increase the impedance bandwidth. The radiating patch's notches improve current distribution and impedance bandwidth. The optimal parameters of the proposed antenna are as follows: $Ws = 30\,\text{mm}$, $Ls = 35\,\text{mm}$, $Wg = 30\,\text{mm}$, $Lg1 = 8.5\,\text{mm}$, $Lg2 = 11.05\,\text{mm}$, $Wp = 15\,\text{mm}$, $Lp = 11.5\,\text{mm}$, $Wf = 2.5\,\text{mm}$, $Lf = 12\,\text{mm}$, $Wn1 = 0.5\,\text{mm}$, $Ln1 = 0.5\,\text{mm}$, $Wn2 = 0.5\,\text{mm}$, and $Ln2 = 1\,\text{mm}$. Figure 4 depicts the fabricated design. The designed UWB antenna was validated using an N9916A 14 GHz Microwave Analyzer. Figure 5 depicts the simulated and measured ($|S_{11}|$) characteristics of the proposed UWB antenna. Over the entire band, the observed and simulated results are consistent even though the measured reflection coefficient ($|S_{11}|$) had a few inconsistencies due to fabrication errors.

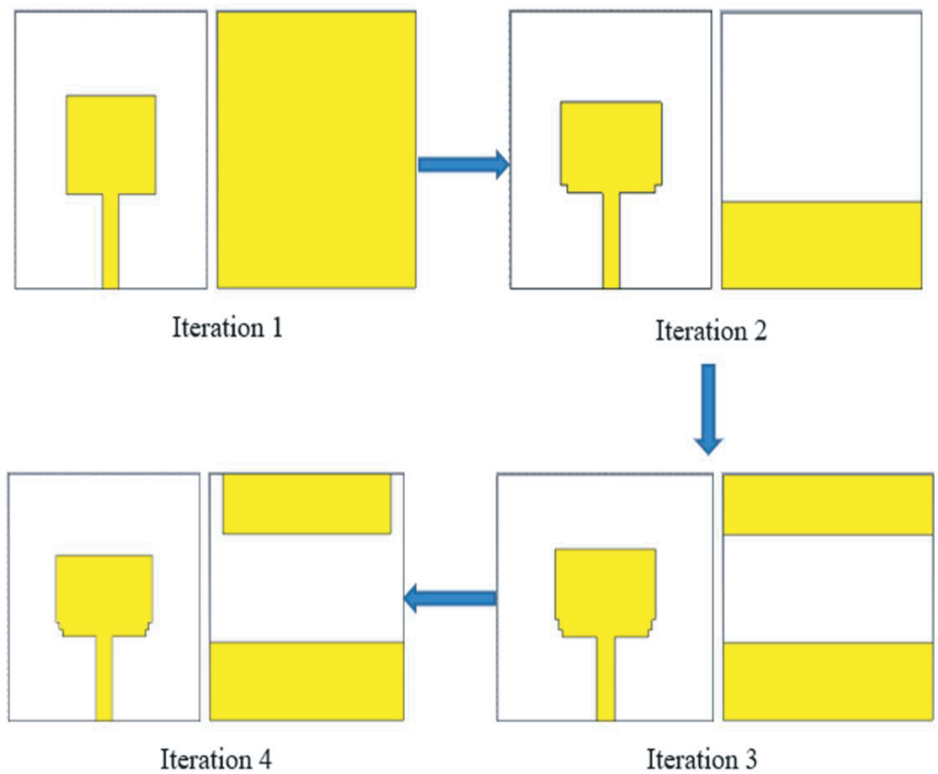


Figure 2. Proposed design process. (i) Conventional Patch and Ground plane. (ii) Single notch and partial ground plane. (iii) Two notches and defected ground plane. (iv) Proposed UWB antenna.

3. VALIDATION OF PROPOSED UWB ANTENNA

Water quality testing is crucial for preventing and detecting the spread of chemicals, pollutants, and diseases. Monitoring water quality ensures that drinking water is safe and that all municipal, state, and federal water regulations are followed. All water intended for human or animal consumption should undergo safety testing. In addition to drinking water, recreational and agricultural water should be tested. Electromagnetic waves are the most important sort of electromagnetic radiation when it comes to monitoring water quality. The water sample will be exposed to EM radiation and its reflection properties, and S_{11} will be assessed to determine the water's quality. Because of the conducting ions in water samples, the antenna is utilised to transmit electromagnetic waves with varying properties. The

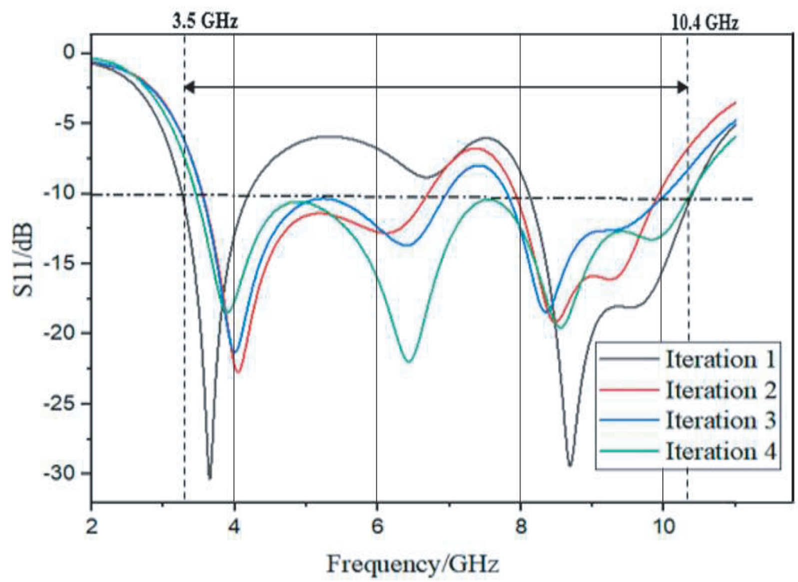
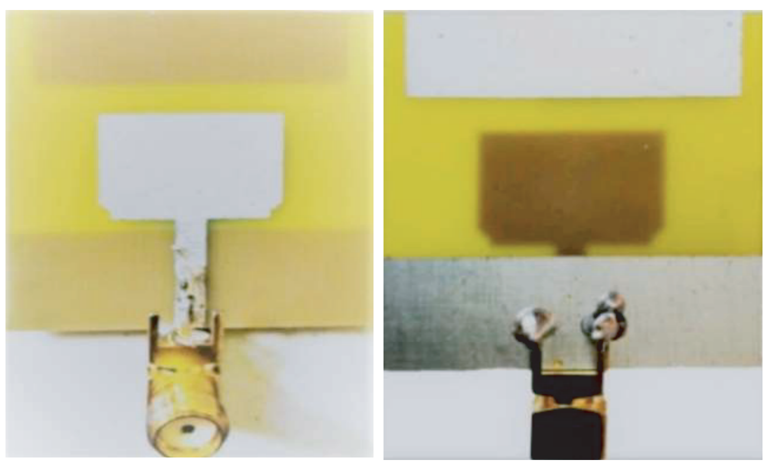


Figure 3. S_{11} based on the evolution process.



(a) (b)

Figure 4. Fabricated design. (a) Front view, and (b) bottom view.

antenna dielectric constant and reflection coefficient, which are used to measure the quality of water samples decrease as the number of contaminants in water increases. The proposed antenna was immersed in three types of water: distilled water, reverse osmosis (RO) water, and raw water. Furthermore, salt was gradually added to the water samples in a range of 1 gm to 3 gm to mimic contaminated water. As shown in Figure 7(a), the proposed UWB antenna was first tested in an empty glass as a reference. The reflection coefficient of the antenna in an empty glass is shifted slightly to the left due to the presence of the glass, as illustrated in Figure 6, compared to the antenna tested in free space.

The measurement technique of evaluating the proposed antenna on an empty glass (reference) and three water samples is depicted in Figure 7. The water sample volume is set to 200 ml and evaluated at 22°C room temperature to obtain accurate findings. The network analyser was used to extract the changes in the water sample's reflection coefficients, S_{11}. Over the frequency range of 3.5 GHz to 10.4 GHz, the proposed antenna was tested in varying salt concentrations in three different water samples. The dielectric constant of the water samples decreases with increasing salt concentration in

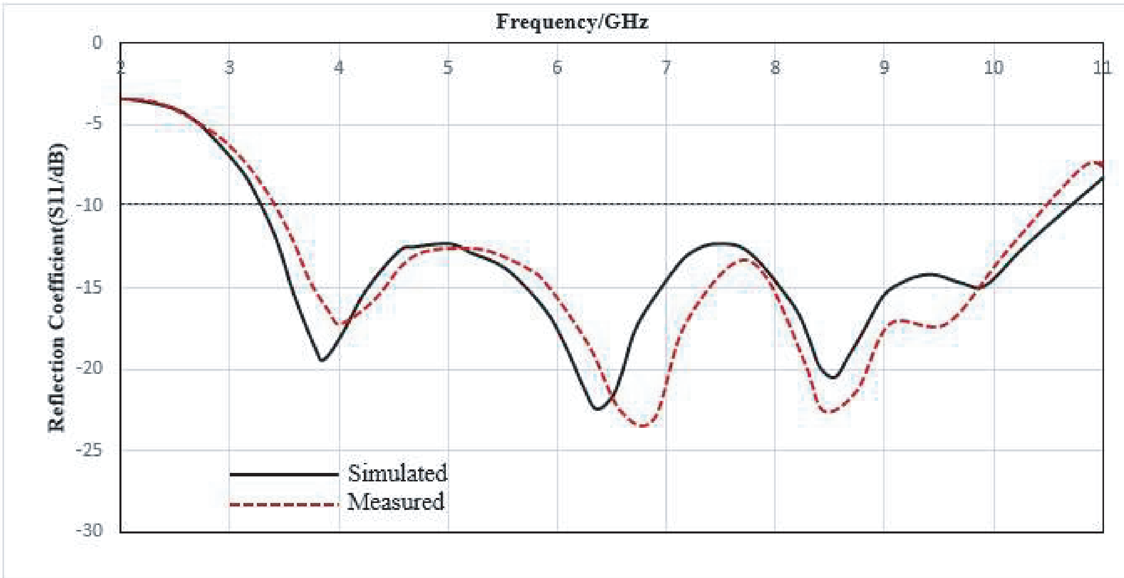


Figure 5. Comparison of $|S_{11}|$ for simulated and measured U.W.B. antenna.

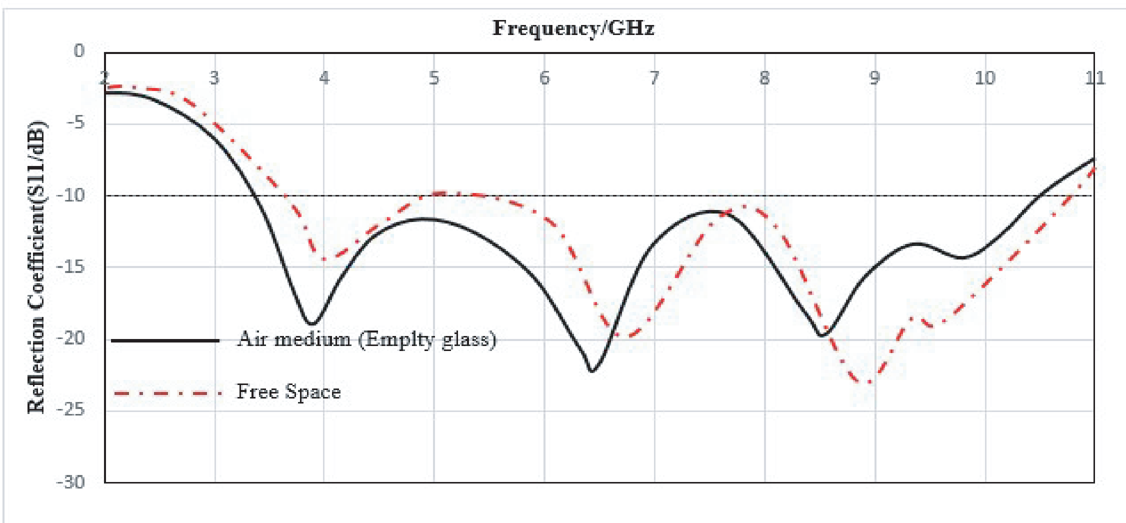


Figure 6. S_{11} for fabricated antenna in free space and in empty glass.

the water samples, because the dielectric properties are changed by dissolved ions and water molecules. Because of this variance, the polarisation of water and the dielectric constant are reduced. Increasing the salt concentration in water samples diminishes polarisation and lowers the dielectric constant of water. As a result, the reflection coefficient (S_{11}) is reduced. The variance in reflection coefficients in different water samples is illustrated in Figures 8, 9, 10 for different resonating frequencies of 3.5 GHz, 6.5 GHz, 8.5 GHz, and 9.7 GHz over the UWB. The equivalent relative permittivity of the fabricated UWB antenna is reduced by testing it in high dielectric materials such as distilled water, RO water, and raw water, which considerably affects the antenna's performance. The frequency shift from higher to lower frequency ranges is due to the high dielectric constant property of the water samples.

(a) (b) (c) (d)

Figure 7. Different water solutions were tested by using a network analyser. (a) Air medium. (b) Distilled water. (c) RO water. (d) Raw water.

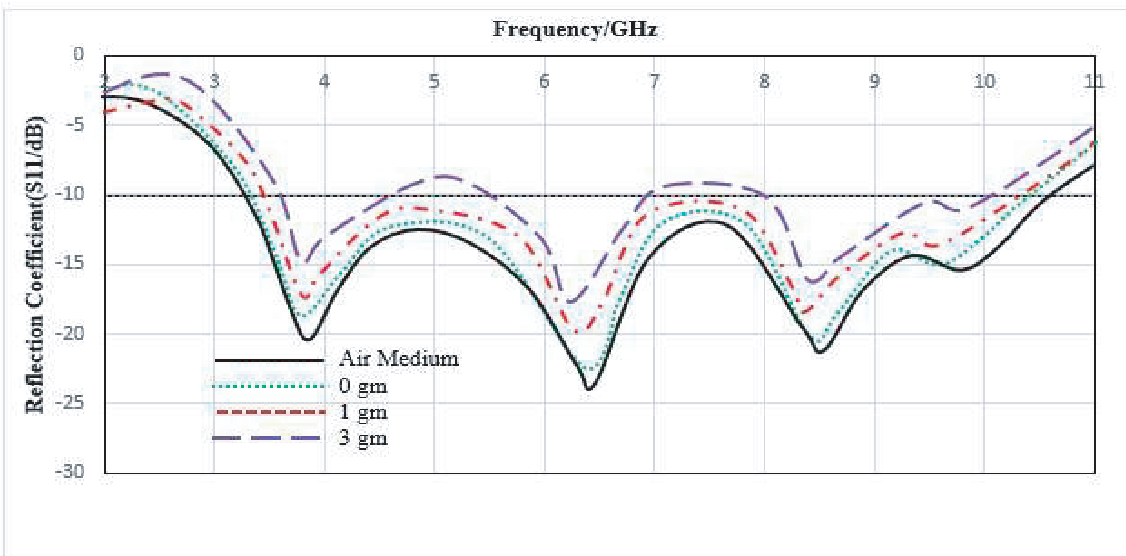


Figure 8. $|S_{11}|$ for the various concentrated salinity in distilled water.

3.1. Salinity Effect on Distilled Water

Distilled water is purified water with both contaminants and minerals removed. It has a conductivity in the range of 0.5 to 3.0 μS/cm [15]. Figure 8 depicts the reflection coefficients, S_{11}, of the air (empty glass) and distilled water added with salt concentration at various frequencies of 3.5 GHz, 6.5 GHz, 8.5 GHz, and 9.7 GHz. It can be seen that the air has the best reflection coefficient, S_{11}, due to its low reflective permittivity ($\varepsilon_r = 1$). In addition, it can be observed that reflection coefficient, S_{11}, was slightly decreased when the antenna was immersed in the distilled water. This is due to the distilled water having high reflective permittivity ($\varepsilon_r = 82$) compared to air. The reflection coefficients for the various salt concentration in distilled water are summarized in Table 1. Table 1 depicts that the reflection coefficient decreases with the increase in the amount of the salt in distilled water.

3.2. Salinity Effect on RO Water

Ions, unwanted molecules, and materials are removed from water through reverse osmosis. With a conductivity value of 0.05–200 μS/cm [16], RO water is acceptable for drinking and cooking, but adding salt to RO water increases water contamination. The reflection coefficients (S_{11}) for varied concentration

Table 1. Variation of ($|S_{11}|$) for the concentrated salinity in distilled water.

f (GHz)/Salt (gm)	Air	0 gm	1 gm	3 gm
3.5 GHz	−20.2 dB	−18.8 dB	−17.0 dB	−15.9 dB
6.5 GHz	−24.1 dB	−23.6 dB	−19.8 dB	−17.3 dB
8.5 GHz	−22.7 dB	−21.3 dB	−18.7 dB	−16.7 dB
9.7 GHz	−15.1 dB	−14.2 dB	−12.7 dB	−11.2 dB

salts in RO water are shown in Figure 9. A smaller number of dissolved ions is shown, indicating an increase in ionic conductivity. Table 2 depicts the fluctuation of reflection coefficients (S_{11}) for different concentration salts in RO water at different frequencies. It can be observed that the decrement of S_{11} occurred when the salt concentration increased in the RO water. At 3.5 GHz, the S_{11} of −17.8 dB is observed for 0 gm salt, and the S_{11} decreases by −16.0 dB and −12.4 dB as salt concentration increases by 1 gm and 3 gm in water, respectively. The reflection coefficient decreases as water contamination increases. As a result, only minor frequency shifting is noticed. Good impedance matching is obtained in RO water.

Table 2. Variation of ($|S_{11}|$) for the concentrated salinity in RO water.

f (GHz)/salt (gm)	Air	0 gm	1 gm	3 gm
3.5 GHz	−20.2 dB	−17.8 dB	−16.0 dB	−12.4 dB
6.5 GHz	−24.1 dB	−18.8 dB	−17.6 dB	−16.9 dB
8.5 GHz	−22.7 dB	−16.3 dB	−14.0 dB	−12.3 dB
9.7 GHz	−15.1 dB	−13.7 dB	−11.9 dB	−9.6 dB

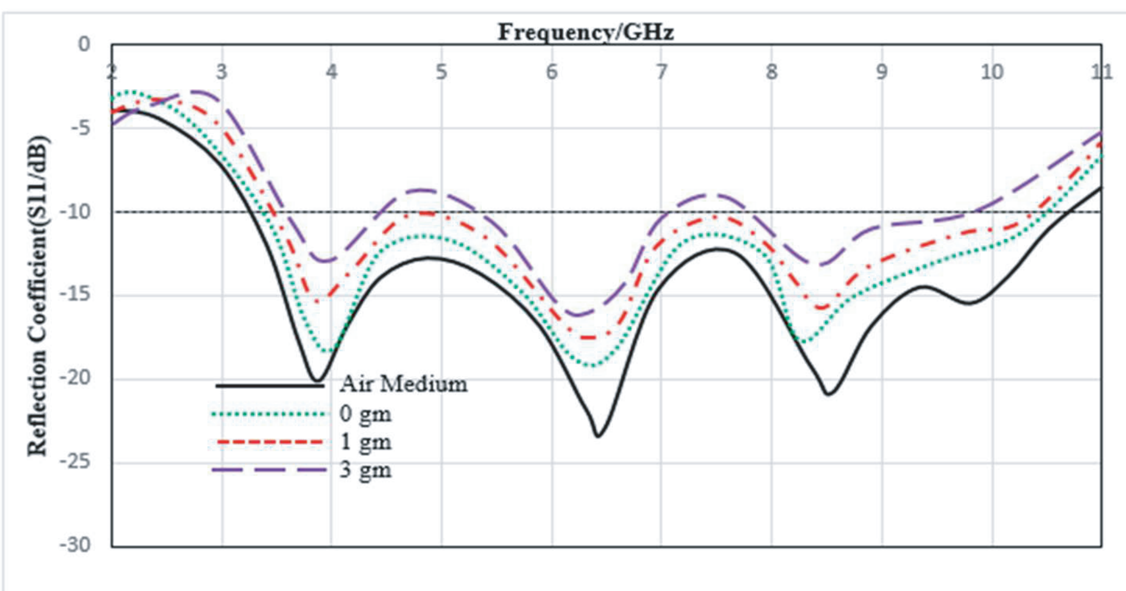


Figure 9. $|S_{11}|$ for the various concentrated salinity in RO water.

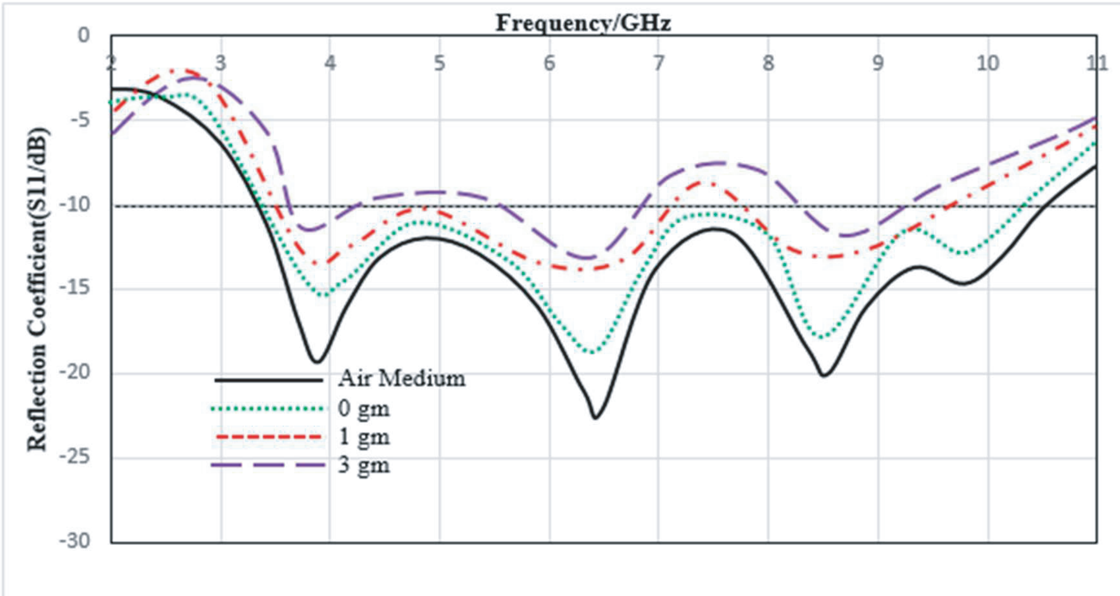


Figure 10. $|S_{11}|$ for the various concentrated salinity in raw water.

3.3. Salinity Effect on Raw Water

Figure 10 depicts the reflection coefficients (S_{11}) for various concentration salts in raw water at various frequencies. Raw water contains the highest concentration of dissolved ions of 50–800 µS/cm [17], which lowers the S_{11} value. Table 3 depicts the variations in reflection coefficients (S_{11}) for various salt concentration in raw water at various frequencies. In raw water, the contamination increases, and the antenna performance decreases. Due to this, the reflection coefficient is decreased, and bandwidth becomes narrowed.

Table 3. Variation of ($|S_{11}|$) for the concentrated salinity in raw water.

f(GHz)/salt (gm)	Air	0 gm	1 gm	3 gm
3.5 GHz	−20.2 dB	−17.8 dB	−16.7 dB	−12.4 dB
6.5 GHz	−24.1 dB	−18.8 dB	−13.8 dB	−12.9 dB
8.5 GHz	−22.7 dB	−17.6 dB	−12.0 dB	−11.4 dB
9.7 GHz	−15.1 dB	−13.6 dB	−8.5 dB	−7.3 dB

3.4. Observations

The finding showed that the degradation of the reflection coefficient, S_{11}, in water samples was caused by an increase in salinity in the water samples. As expected, the conductivity of the water samples increases as the salinity increases which lowers the reflection coefficient of the water samples. Furthermore, the results showed that the frequency responses were slightly shifted to a lower frequency when the dielectric constant of the water samples increased in comparison to the air medium (empty glass). It showed that good impedance matching is obtained through all the water samples.

The antenna's performance in distilled water, RO water, and raw water was evaluated using 6.5 GHz as a reference frequency. Table 4 displays the variation of the reflection coefficient. Figure 11 illustrates that as salinity increases, the coefficient of reflection, S_{11}, decreases. As the salinity of the water sample

Table 4. Comparison of S_{11} for various water samples at 6.5 GHz.

Salinity (gm)/Samples	Distilled water	R.O. water	Raw water
0 gm	−23.6 dB	−18.8 dB	−18.8 dB
1 gm	−19.8 dB	−17.6 dB	−13.8 dB
3 gm	−17.3 dB	−16.9 dB	−12.9 dB

Table 5. Comparison of existing systems with proposed antenna.

Reference	Antenna design & size	Operating frequency (GHz)	Solution	Measuring Method	Remarks
[9]	A tuning fork shaped patch, $24 \times 18 \times 1.57\,\text{mm}^3$	2.4	Detect the salinity and sugar	Reflection coefficient	Lower bandwidth
[12]	Crescent-shaped patch, $32 \times 22 \times 1.60\,\text{mm}^3$ size	2.50–18	Salt and sugar solution	Reflection coefficient	Higher frequency
[13]	Elliptical shaped Antenna, $69 \times 90 \times 2.55\,\text{mm}^3$	1.3 and 7.2	Distilled water, sea water, Debye model water.	Reflection coefficient	Invented substrate (Polytetrafluoroethylene (PTFE) layer)
[14]	Microstrip patch antenna, $27.5 \times 33.7 \times 0.8\,\text{m}^3$	3.2–12.3	Salt and sugar content	Reflection coefficient	Existing liquid for measurement
Proposed work	Planar edged UWB antenna, $30 \times 35 \times 1.6\,\text{mm}^3$	3.5–10.4	Salt content in distilled water, R.O. water and raw water	Reflection coefficient	Low-cost substrate, wider bandwidth, easy to fabricate.

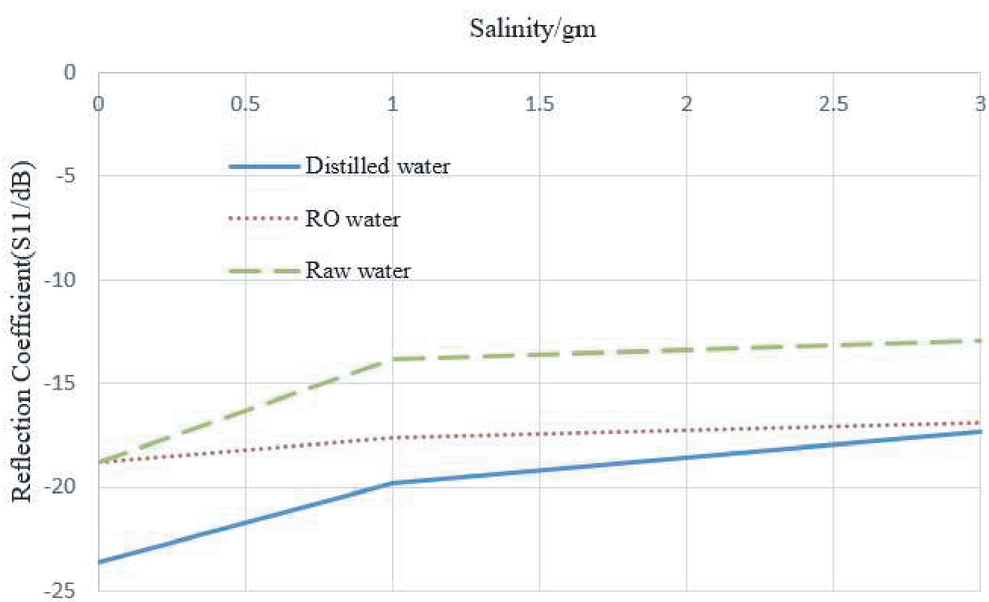


Figure 11. Reflection coefficient (S_{11}) decrement in contaminated samples.

increases, it may be stated that the dielectric constant of the sample decreases. Consequently, the load impedance decreases, resulting in a lower reflection coefficient. It is discovered that distilled water has a greater S_{11} than the other water samples because it is pure water with a lower conductance value than raw water and RO water. After adding a small amount of salt, the conductivity of the distilled water will rise. Table 5 compares the proposed antenna to the existing antenna systems. The Planar Edged UWB antenna proposed offers a broader bandwidth range, uses a low-cost substrate, is small in size, and is simple to fabricate. In addition, the proposed antenna has been tested in distilled water, RO water, and raw water.

4. CONCLUSION

We demonstrate a new UWB antenna for communication and water quality measurement. The UWB antenna measures $30 \times 35 \times 1.6\,\text{mm}^3$ and is mounted on an FR-4 substrate. The proposed UWB antenna resonates between 3.5 and 10.4 GHz to acquire the maximum reflection coefficient over the entire band. The antenna's sensor performance is demonstrated by its ability to detect the changes in salinity increment in several water samples. The decrement of S_{11} illustrates that increasing the salinity in the water samples decreases the dielectric constant of the water and decreases the S_{11}. In addition, the proposed antenna shows good sensitivity as the resonance frequency of the antenna slightly shifted to a lower frequency as the dielectric constant of water increases. These results demonstrate that the proposed antenna can be used to determine the salinity content of a sample in the food and beverage industries. Furthermore, the UWB antenna can be used in water reservoirs to detect floating water contaminants like oil and other liquid monitoring applications like crude leakage.

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