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UWB Antenna as a Sensor for the Analysis of Dissolved Particles and Water Quality

Jeyagobi Logeswaran* and Rajasekar Boopathi Rani

Abstract—This paper aims to test the concentration of dissolved particles such as salt and sugar in a water sample and also test the quality of water. Ultra-Wide Band (UWB) antenna has been designed and used to test the water sample. The proposed UWB antenna has been resonated from 3.2 GHz to 10.6 GHz. The fractional bandwidth of the UWB antenna is 1.15. The measured antenna's characteristics were in good agreement with the simulated results. Then, the designed UWB antenna was used as a sensor on the water samples such as distilled water, rainwater, pond water, seawater, and Reverse Osmosis (RO) water. Hence, this paper explains the concentration of dissolved particles and testing of the quality of the water sample by using the return loss characteristics of the antenna when it is immersed in the water sample. This technique can be further extended for testing the quality of any other liquids.

1. INTRODUCTION

Water is the basic need for all living beings. Surface water and groundwater are important sources of drinking water. Drinking water is polluted due to fast urbanization and industrial development [1]. Water quality cannot be justified simply by looking into the water sample. It might be contaminated even when it appears clear and good. Consumption of impure water leads to various diseases such as cholera, typhoid fever, diarrhea, etc. Hence, it is essential to test the quality of the water [2]. In general, the quality of the water is tested in the laboratory under technical supervision, and also it requires high-cost testing equipment. Total Dissolved Solids (TDS) is the parameter to characterize the amount of inorganic salts and micro-organic particles present in the water sample. There are two conventional methods to calculate the TDS level in the water sample [3]. The first method is the gravimetric analysis technique. In this method, TDS is calculated by evaporating the liquid sample and then measuring the mass of the residual particles. This method is accurate but complex [4]. The second method is the use of a conventional conductivity meter. In this method, the TDS level is calculated by dipping the meter into the water sample. The TDS value is related to the conductivity of the water sample. This approach is easier to test, but the accuracy is low [5]. Both these methods are laboratory-based and need technical expertise. Hence, this paper aims to provide a viable solution for the problem by using an antenna as a water quality sensor. Antenna is a transceiver that can transmit and receive an electromagnetic signal in the dielectric medium. Like the conventional conductivity meter, the antenna can be dipped into the water sample. It is reported that the water sample was analyzed at 2.4 GHz [6]. However, the water quality cannot be concluded from a single frequency band. It is inevitable to analyze the quality at several frequency bands. Hence, wideband antennas have been preferred for the quality test. The wideband response can be obtained using Ultra-Wide Band (UWB) antenna. Federal Communications Commission (FCC) approved the UWB frequency range from 3.1 to 10.6 GHz for commercial purposes. The fractional bandwidth of the UWB antenna is 1.1 [7]. UWB antenna can be fabricated using a planar

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* Corresponding author: Jeyagobi Logeswaran (logeswaranjg@gmail.com).
The authors are with the Department of ECE, National Institute of Technology Puducherry Karaikal, Puducherry UT, India.

microstrip structure, which has several advantages like low-profile, lightweight, compact, and robust [8]. The dissolved salt and sugar concentrations were analyzed using an antenna as a sensor, but there were no analyses and remarks about water quality [9, 10]. Hence, it is essential to design a UWB antenna and explore a mechanism for testing the water quality. Considering this objective, the rest of the paper is organized as follows. Section 2 and Section 3 deal with the design and fabrication of the UWB antenna. In Section 4, test setup and measurement are discussed. Water quality and concentration of dissolved particles are analyzed in Section 5.

2. ANTENNA DESIGN

This section presents the design of the UWB antenna. The proposed antenna was simulated using Ansys High-frequency Structural Simulator (HFSS) 2019. The antenna patch was excited through a 50 Ω edge feed line. The overall antenna dimension is 33.7 mm × 27.5 mm × 0.8 mm. Fig. 1 shows the geometry of the proposed antenna. The patch dimensions are calculated using standard design equations [11] for FR4 substrate. The calculated dimensions were optimized to obtain a wider bandwidth response. Further, the bandwidth can be improved by introducing the two-stepped structure near the feed line. Multiple resonances were obtained by this approach. The resonance fine-tuning can be done by engraving the Defective Ground Structures (DGS) at the bottom ground plane and blending the two top corner edges of the patch. Half of the guide wavelength (0.4 mm) is taken as the radius of the blend, which provides better matching. By this optimization, the fractional bandwidth response of the antenna has been increased to 1.15. The dimensions of the antenna are given in Table 1.

Table 1. Dimensions of the proposed antenna.

Parameter	Values (mm)	Parameter	Values (mm)
W_s	27.5	L_{st2}	0.95
L_s	33.7	W_{st}	0.975
W_p	16.375	W_{st1}	4.185
L_p	11	W_{st2}	2.1
W_f	1.83	W_g	27.5
L_f	11.75	L_{g1}	15.05
L_{st}	8.55	L_{g2}	7.75
L_{st1}	1.5	L_{g3}	10.9

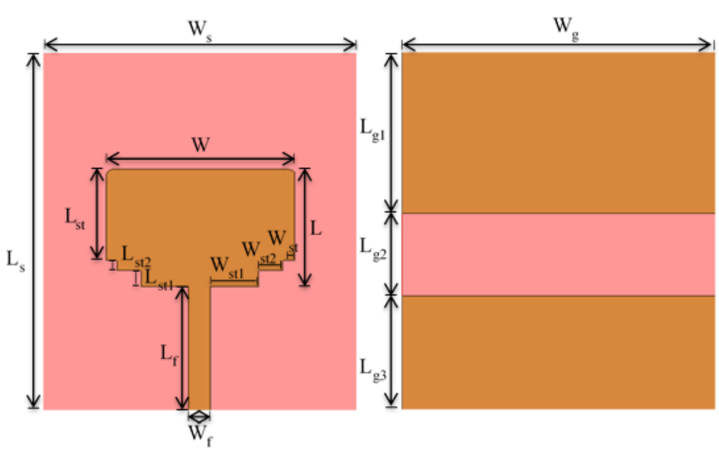

Figure 1. Geometry of the proposed antenna.

3. ANTENNA FABRICATION

The simulated antenna was fabricated using an FR4 substrate. The features of the FR4 are flame retardant and high dielectric strength. The physical characteristics of the FR4 substrates are dielectric constant 4.4 and loss tangent 0.02. The thickness of the substrate (h) is 0.8 mm. The antenna's top and bottom conducting planes were made of tin-coated copper material. The RF signal was fed through the SMA connector. The connector was attached to the microstrip feed line.

4. ANTENNA MEASUREMENT

The fabricated antenna was tested using the N9916A FieldFox Handheld analyzer. The FieldFox analyzer was kept at network analyzer mode for antenna measurement. It can measure the frequency range from 30 kHz to 14 GHz. Initially, the analyzer's port was calibrated using Short-Open-Load-Through (SOLT) method. This calibration eliminates the cable and internal losses over the entire test frequency range. The antenna characteristics were analyzed over the frequency range from 1 to 14 GHz.

4.1. Return Loss Measurement

The return loss characteristics of the UWB antenna has been measured in free space condition using a vector network analyzer and compared to the simulated results, as shown in Fig. 2. The fabricated prototype is also embedded in Fig. 2. The simulated return loss curve shows that −10 dB bandwidth ranges from 2.86 GHz to 10.64 GHz and fractional bandwidth is 1.15. The measured return loss curve shows the −10 dB bandwidth ranges from 3.2 GHz to 12.3 GHz with a fractional bandwidth of 1.17. Hence, the proposed antenna is coveted for quality analysis. A wider bandwidth of 9.1 GHz has been used to test the water sample's quality.

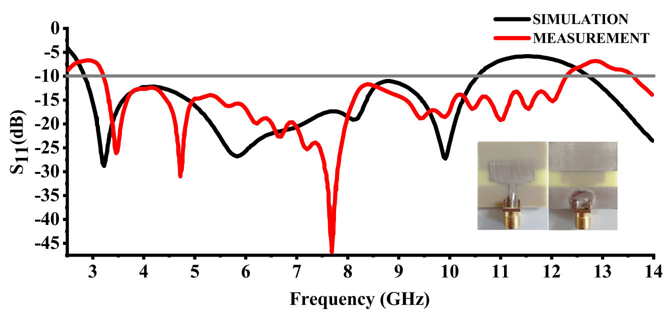

Figure 2. Simulated and measured return loss of the proposed UWB antenna.

4.2. Simulated Gain Response

The gain of the antenna is a vital factor for wireless communication. The water samples are analyzed using return loss characteristics, and also the antenna gain is an additional parameter to characterize the antenna's functionality. Fig. 3 shows the total gain of 4.47 dB at 5.3 GHz, 3.6 dB at 7.41 GHz, and 3.7 dB at 8.68 GHz. From the gain values, it can be observed that the proposed antenna has a positive gain value at the test frequencies.

4.3. Comparison of Proposed Antenna with Existing Sensor Antennas

Table 2 shows the comparison of proposed antenna with existing antennas for water parameter analysis. From Table 2, the antenna in references [12, 13] has narrow bandwidth responses. In wide bandwidth response, the proposed antenna dimension is smaller than other UWB antennas [9, 14]. The proposed antenna thickness is smaller than other existing UWB antennas. A thin antenna improves the patch radiation performance. Existing antennas were used to determine the salt and sugar concentration in the water sample. However, the proposed model can be preferred to measure the salt and sugar concentration and also quality of the water sample.

Table 2. Comparison of proposed antenna with existing antennas for water parameter analysis.

Ref.	Antenna Model	Dimension	Antenna Thickness (mm)	Operating Frequency (GHz)	Sensing Technique	Analyzed Parameters
[12]	Rectangular patch	$0.470\lambda_0 \times 0.388\lambda_0$	1.645	2.5	Reflection coefficient	Salt and sugar content
[13]	Defected Ground Split Ring Resonator	$0.714\lambda_0 \times 0.714\lambda_0$	0.51	9.24	Frequency shift	Salt, sugar and adulterant
[14]	Psi-shaped patch	$1.280\lambda_0 \times 0.960\lambda_0$	1.57	14.6–17.4	Reflection coefficient	Salt and sugar content
[9]	Crescent-shaped patch	$1.130\lambda_0 \times 0.777\lambda_0$	1.6	2.5–18	Return Loss	Salt and sugar content
	Rectangular patch with stepped structure (Proposed)	$0.870\lambda_0 \times 0.710\lambda_0$	0.8	3.2–12.3	Return Loss	Salt and sugar content, Liquid quality

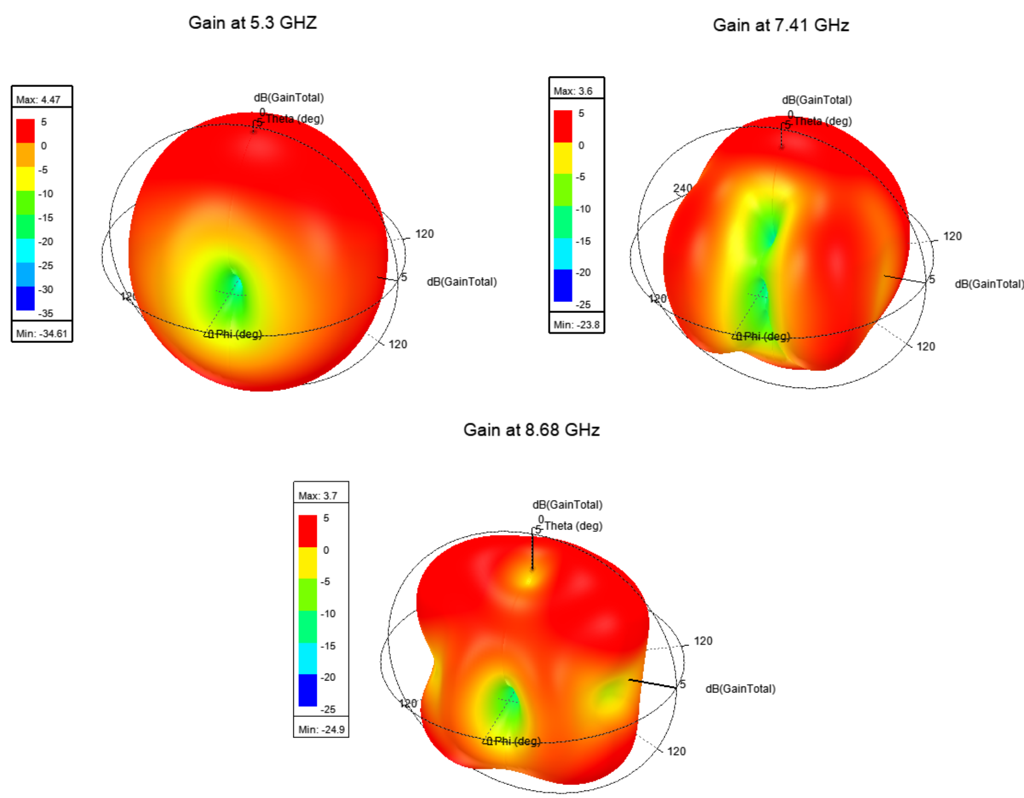

Figure 3. Simulated Gain of the proposed UWB antenna.

5. ANALYSIS OF WATER SAMPLE

The water sample was tested by immersing the antenna into the water. In the test setup, the beaker was filled with 150 ml of water sample as shown in Fig. 4. The analysis was carried out for three different cases of water samples. First, the effect of salt concentration in water was analyzed by adding some

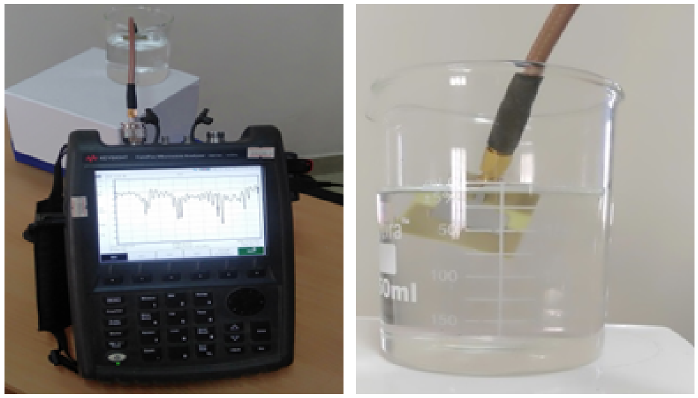

Figure 4. Measurement setup used to test the samples.

amount of salt into the water. This analysis is explained in Section 5.1. Second, the analysis of the effect of sugar concentration in water is explained in Section 5.2. The third set of analyses were carried out for five different natural water samples which are explained in Section 5.3.

5.1. Analysis of the Salt (NaCl) Concentration

The proposed antenna was immersed in the salt mixed water sample. At an interval of 5 minutes, 4 g of salt was mixed into 150 ml of RO water, and then return loss characteristics were measured over the UWB frequency, as shown in Fig. 5. It was observed that the noticeable change in return loss with respect to the addition of salt content has occurred at the frequency range of 5.3 GHz. Further, this helps our interpretation regarding the salt content of water. Generally, the salt concentration and water conductivity are unified with each other. The nature of the water depends on the conductivity parameter and amount of free water molecule [15]. When the sample's conductivity was increased, the return loss value also increased. From this, it can be concluded that if the return loss value is more than −20 dB at 5.3 GHz, then the salt content is more than 8%[#] ([#] with respect to the proportion of water and salt in an equivalent unit of grams).

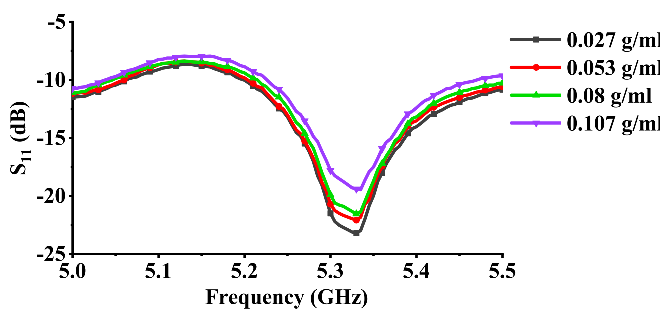

Figure 5. Return loss characteristics of the salt mixed water sample.

5.2. Analysis of the Sugar ($C_{12}H_{22}O_{11}$) Concentration

The measurement procedure for the analysis of sugar concentration is also similar to the analysis of salt concentration. If the concentration of sugar dissolved in the water sample increases, then the conductivity of the water decreases due to the absence of ions in the water. When the conductivity of the sample is decreased, the return loss value will also get decrease. These variations are also observed precisely at the frequency range of 5.3 GHz. Hence, this region is alone elaborated in Fig. 6. It can be inferred that the return loss value goes below −10 dB, then the sugar content in the water is more than 8%.

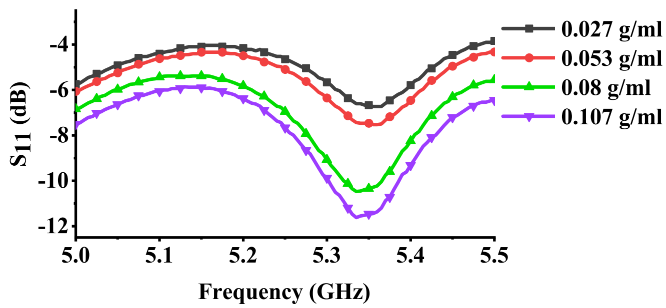

Figure 6. Return loss characteristics of the sugar mixed water sample.

5.3. Quality Observations

The water samples such as distilled water, rainwater, pond water, seawater, and Reverse Osmosis (RO) water are considered for the quality analysis. Three water samples are shown in Fig. 7. In Fig. 7(a) and Fig. 7(b), the samples look similar and clear for eyes, but return loss characteristics are distinct in the network analyzer. The reason for these variations is the testing of distinct water samples. In Fig. 7(a), the water sample is RO water, whereas in Fig. 7(b) water sample is distilled water. This conveys that the nature of the water cannot be predicted and requires testing. The water sample in Fig. 7(c) is unclear and yellow in color. This water sample is taken from the pond, and also return loss characteristics of the antenna are displayed on the network analyzer. Similarly, other samples are tested, the return loss characteristics are observed using the network analyzer, and inferences are drawn.

Figures 8(a), 8(b), and 8(c) depict the return loss characteristics of the antenna that was tested in the several water samples in the UWB range. In this, the noticeable changes were occurred at the frequencies of 5.3 GHz, 7.41 GHz and 8.68 GHz. These were elongated in Fig. 8.

(a) RO Water (b) Distilled Water (c) Pond Water

Figure 7. Measurement setup for different water samples.

As the antenna was immersed in the water medium, the return loss characteristics were influenced by water parameters such as TDS, pH value, dissolved ion concentration, and conductivity. Hence, the examination on return loss characteristics will provide us much water quality related information. The return loss values of the antenna while being kept in the various water samples are listed in Table 3. The following observations are made from Table 3.

(i) The return loss characteristics of the antenna are similar for the rain and distilled at the frequencies of 5.3 GHz, 7.41 GHz, and 8.68 GHz. This is due to the TDS values of the distilled water being 0 mg/l and rainwater being 0–20 mg/l. And also, the conductivity of the rainwater is almost closer to the conductivity of the distilled water. This validates that our approach to testing the quality of water samples is correct.

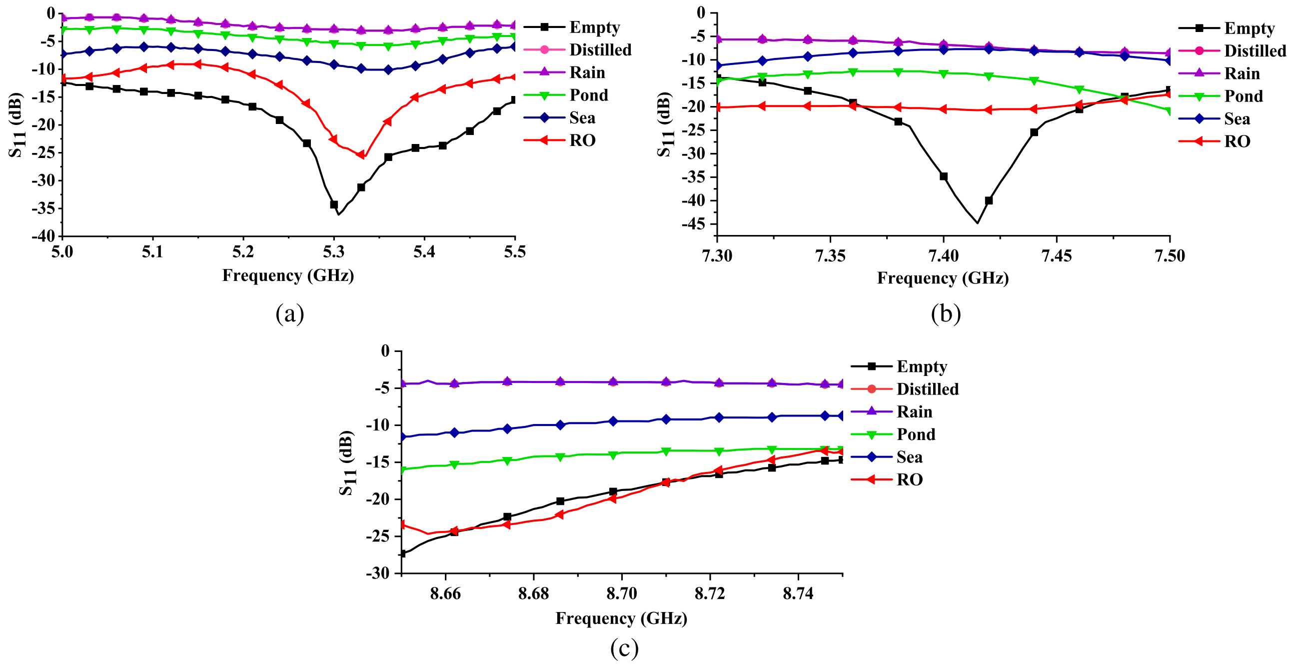

Figure 8. Water sample quality analysis at (a) 5.3 GHz, (b) 7.41 GHz, (c) 8.68 GHz.

(ii) By looking into return loss values of pond water and RO water, it can be observed that the quality of the drinking water decreases when the return loss values increases.

(iii) Drinking water (RO Water sample) has a lower return loss value when compared with other water samples. The return loss value for the RO water was lower than −20 dB.

(iv) It can be concluded that if the return loss value is lesser than −20 dB, then the water is good and may suit drinking purposes.

Table 3. Return loss values of the various samples.

S. No	Measurement Analysis		S_{11} (dB)					
			Empty Beaker	Distilled Water	Rain Water	Pond Water	Sea Water	RO Water
1.	Frequency (GHz)	5.3	−34.28	−2.83	−2.85	−5.33	−9.15	**−22.59**
2.		7.41	−42.12	−7.02	−7.12	−12.89	−7.72	**−20.67**
3.		8.68	−21.3	−4.16	−4.15	−14.23	−9.96	**−22.89**

6. CONCLUSION

The proposed UWB antenna was used to test various water samples. The return loss values for the antenna under different water samples have been measured using a network analyzer. The concentration of salt and sugar in RO water was analyzed and interpreted at the frequency of 5.3 GHz. It can be observed that if the return loss value is more than −20 dB at 5.3 GHz, then the salt content is more than 8%, and if the return loss value goes below −10 dB, then the sugar content in the water is more than 8%. The measured results for the concentration of sugar and salt in the water sample hold a match to the theoretical concept. The quality of the water sample was analyzed at three different resonance frequencies, i.e., 5.3 GHz, 7.41 GHz, and 8.68 GHz. The increase in return loss value can be attributed to the decrease in the quality of drinking water. Hence, it is concluded that the water may be suitable for drinking purposes if the return loss value is below −20 dB. This research article has attempted to explore water quality based on measurements by using an antenna as a sensor. This technique can also be applied for testing other liquids.

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