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Stacked Stepped-Fed Super Wideband Antenna Performance in Free Space and Liquid Medium for Biomedical Applications

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Abstract. A new design of compact Super Wideband (SWB) antenna for performance comparison between in free space and in plain water is presented in this paper. The proposed antenna consists of basic circular patch as radiating element associated with partial ground and a zinc reflector to realize high gain and wide bandwidth. Dimension of 20 mm × 30 mm made the proposed antenna as a compact antenna. The significant feature of this design is the cautious manufacturing of the feed line with additional of two microstrip lines between the patch and the feed line known as stepped transmission line that altering the capacitance between the radiating element and the ground plane. The patch is directly connected with SMA connector using 50 Ohm microstrip feed line through side feeding and deploy the air gap stacked. The antenna exhibit high performance in free space indicated by operated frequency ranged from 4.3 GHz until more than 15 GHz (<-10dB) with maximum gain of 9.79 dB. On the other hand, plain water medium degraded the antenna performance yet still within acceptance limit associated with resonant frequency ranged from 4.7 GHz until more than 15 GHz (<-6dB) and 2.2 dB for the maximum gain. The results reflect the reliability of the SWB antenna operated within liquid medium for various related applications especially for biomedical related applications such as microwave imaging for cancer detection.

1. Introduction

Current wireless communication technology of super wide band antenna (SWB) functioned to cover both the short and long range transmission for ubiquitous applications. Significant advantages offer by SWB technology especially larger channel capacity and higher time precision has made the technology more attractive and more essential toward many potential applications related with wireless communication technology. SWB technology demonstrated impedance bandwidth ratio larger than 10:1 with <-10 dB reflection coefficient [1]. SWB technology provided large bandwidth, high and fast transmission data rate as well as low power cost for many wireless communication applications [2]. Underwater sensor connection could be established through electromagnetic signals radiated in distances of few meters. Therefore, the antenna becomes an essential component in term of propagation aspects of the electromagnetic waves in liquid for such condition. Underwater sensors that deployed SWB technology have advantages of transmitting high amounts of data using extremely little power over relative short distances [3]. The main reason triggering inspiration to investigate underwater SWB antenna is the inadequate work done towards this kind of antennas. In fact, currently there are a lot of designs for SWB antennas yet all of them are function for air communication applications. Until now, all SWB devices are utilized to perfectly function for air environments. Hence, this paper introduced SWB antenna to work in plain water environments. It is compulsory for SWB technology to operate well with a high performance underwater to ensure functionality of particular applications. It is supported by the high demands for inter-medium communication systems since rapid development of trans-medium human activities. Intersect communication between air-water boundaries is gaining interest day by day as underwater communication under on-going process to established itself within the same time [4].



Apart from that, most of the electromagnetic waves studies in water environment emphasize on narrow band antennas such as dipoles or loops isolated with plastics. Loop antennas are directional antennas which have advantages of sensitive reactions towards magnetic fields realized them as the suitable candidate for seawater antenna [6]. Designing SWB antenna for underwater applications is a great challenge due to variety of potential solutions. Moreover, the device has to be compact, not bigger than 5 cm of length and wide in order for the device to be operated at the optimum level. This limitation in term of size causes additional challenge to discover a right antenna with a good performance during underwater measurement take place. Besides that, the constraint on data transmission over distance in water also have to be concentrated on since the propagation of electromagnetic waves in water is very different than in the air. High dielectric constant of water resulted in far higher attenuation compared with attenuation occurred in air.

The omnidirectionality is one of the significant features needs to be demonstrated by underwater antenna in order for the antenna to transmit in entire directions. This requirement ensures that particular antenna covered wide range for data transmission and data receiving to take place resulted in high data rates. Hence, the radiation pattern should be as much omnidirectional as possible to have high performance of underwater antenna. Antenna that contributes in equal radiation towards all directions is known as isotropic antenna. An omnidirectional antenna is one that radiates uniformly in one plane [5]. Presently, the amount of underwater applications engage with completely data exchange occurred underwater is extremely few. Among of those applications are involved with animal tracking, environmental monitoring, mainly in marine environment as well as pipeline monitoring, underwater navigation and wireless communication technologies. Current trend for underwater applications nowadays emphasize more on increasing the transmission data rate. This is due to actual acoustic or optical wireless transmission technologies do not achieve the target regarding both relative low cost and high data rates [7]. Hence, an omni-directional with high gain and high data rates of small SWB antenna operated underwater is required.

The proposed SWB antenna which demonstrated omni-directional radiation pattern with high gain for underwater (2.2 dB) and very wide bandwidth starting from 4.7 GHz until more than 15 GHz as well as compact size of 30 mm × 20 mm has met the entire requirement needed for an underwater antenna. In this study, the performance of custom-designed SWB antenna will be observed in free-space and in water. The proposed antenna applied stepped transmission lines since impedance matching is essential to obtain wider bandwidth of SWB system. In order to ensure 50 ohms characteristic impedance is received by the radiating element from the source while maintaining the SWB characteristic, the stepped impedance microstrip feeder is chosen. Theoretically, more steps present indicate better characteristic impedance yet feeder with excessive steps will increase the total electrical length and probably exceed the calculated size by resonant frequency. This might leads to additional complicated for antenna production. Two stepped impedance for transmission lines are commonly utilized for designing SWB antenna [17]. The air gap stacked using zinc as the reflector is deployed in this article. reflector plane is introduced at the back side of the antenna to reduce the back lobe. This reflector plane is used at the distance from the ground plane, which creates an air gap between the substrate and reflector [18]. The paper is organized as follows: In Section 2, single SWB antenna side feed with reflector is designed and investigated. The measurements setup for simulation and real measurement are included in Section 3 as well as the simulated and measurement results of S-parameter, gain, and pattern results. Finally, a conclusion will be drawn in Section 4 followed by acknowledgement in section 5. References would be the last section; section 6.

2. Antenna Design and Fabrication

Figure 1 demonstrates the structure of the proposed antenna. The dimension of the proposed antenna represented by $L_s \times W_s$ is considered as very compact in size. The radius of copper circular patch (R_p) with thickness of 0.035 mm is printed on top of the Taconic dielectric substrate. Taconic substrate (TLY-5) with a dielectric constant of $\epsilon_r = 2.2$, a thickness of $t = 1.5748 \pm 0.02$ and tangent loss of $\tan \delta = 0.0009$ has a relative permittivity, thickness and loss tangent of 4.7, 1.6 mm and 0.019 respectively. Meanwhile on the other side of the substrate, the copper partial ground covered the whole length of the microstrip feed line. Two additional of different dimension of microstrip lines known as stepped transmission lines are placed among the radiating patch and the feed line with different impedance characteristic as shown in Figure 1 (a). The capacitance between the ground plane and the patch could be influenced by the present of these lines in determining the impedance bandwidth and reflection coefficient values [7]. Figure 1 (b) shows a reflector consists of zinc with a thickness of 1mm and same dimension of the substrate is placed at the back of the antenna with a certain distance (D) works as the air gap stacked structure. The stacked structure functioned to reflect the back radiation towards the front. The antenna is fed by 50 Ohm SMA connector through side feeding. The feed line dimension is 3 mm in wide to perfectly match the antenna with 50 Ohm source feed. The equations to determine the width of the microstrip feed line in order to have characteristic impedance, Z_o of 50Ω as follows [15]:

$$W_m = \frac{120\pi}{\sqrt{\epsilon_r}} \quad (1)$$

w_m = microstrip feed line width
 h = substrate thickness
 ϵ_r = substrate dielectric constant,
 Z_o = input impedance

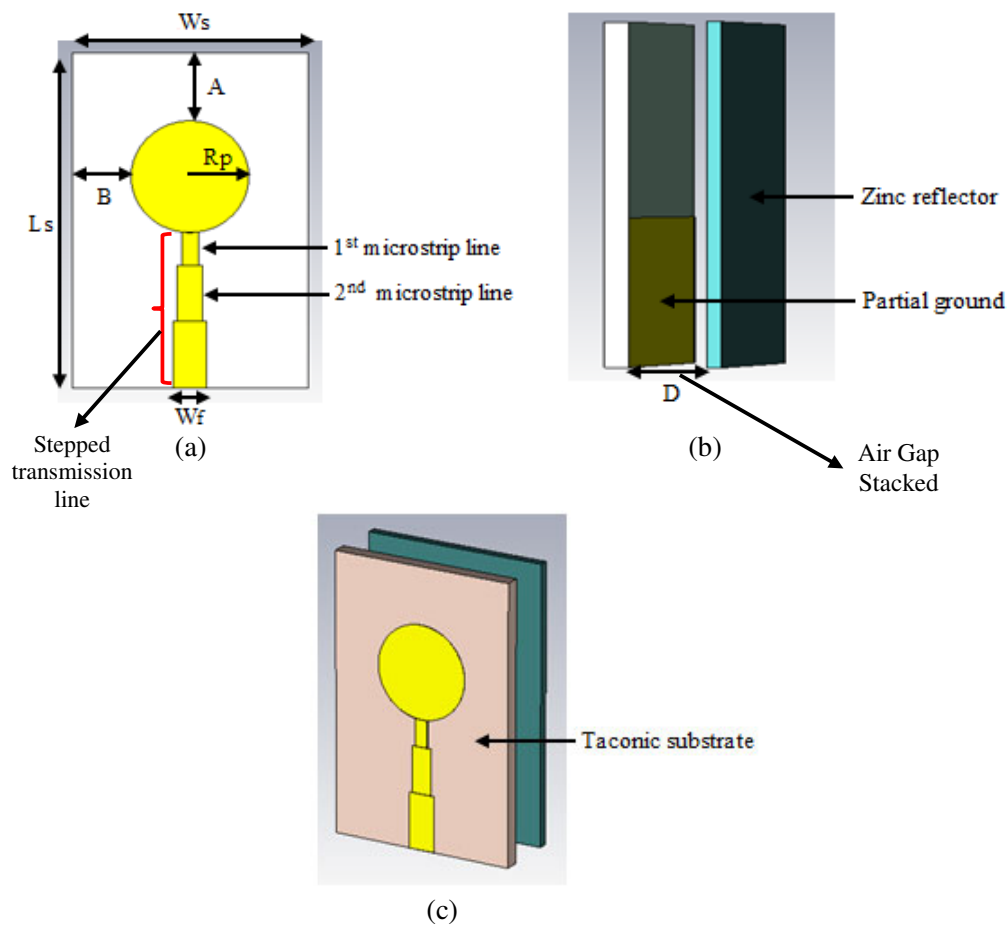


Figure 1. The simulated geometry of the proposed SWB array antenna, a) front view b) angled back view c) angled side view

The patch has characteristic of 7.5 mm in radius and 0.035 mm of thickness. Dimension of the circular patch is derived from the following equation [16]:

$$R = \frac{F}{\sqrt{1 + \frac{2h}{\pi \epsilon_{eff} F [\ln(\frac{F\pi}{2h}) + 1.7726]}}}$$

$$F = \frac{8.791 \times 10^9}{fr \sqrt{\epsilon_{eff}}} \quad (2)$$

The antenna is then fabricated on the Taconic TLY-5 with substrate thickness of 1.5748 mm, dielectric permittivity, ϵ_r of 2.2 and tangent loss, $\tan \delta$ of 0.0009 as shown in Figure 2. Some important parameters of the designed antenna are optimized to obtain the best result in term of compact size, high gain and wide bandwidth. The optimized dimensions for the antenna are tabulated in Table 1. Measurements have been performed using the setup consisting of Agilent E83628 PNA Network Analyzer and Anechoic Chamber. The horn antenna is used as the transmitting antenna, whereas antenna under test (AUT), SWB array as the receiver. Both antennas are placed at DAUT about 0.84 m apart.

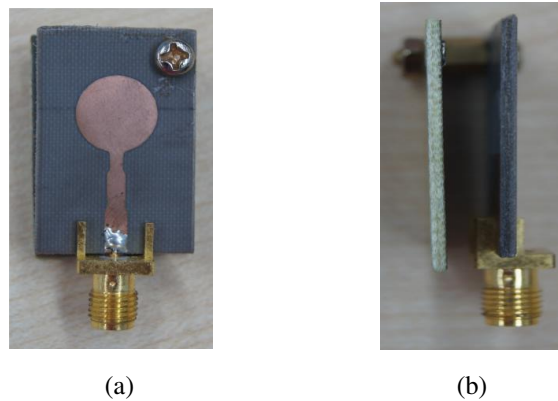


Figure 2. The fabricated SWB array antenna. a) Front view, b) Side View

Table 1: Antenna Parameter

Parameter	Dimension
Substrate Length, L_s	20.0 mm
Substrate Width, W_s	30.0 mm
Patch Radius, R_p	5.0 mm
Stacked Air Gap, D	5.0 mm
Ground Length, L_g	20.0 mm
Ground Width, W_g	13.0 mm
Feedline Width, W_f	3.0 mm
Patch gap with top side, A	6.0 mm
Patch gap with left side, B	5.0 mm

3. Measurement Result and Discussion

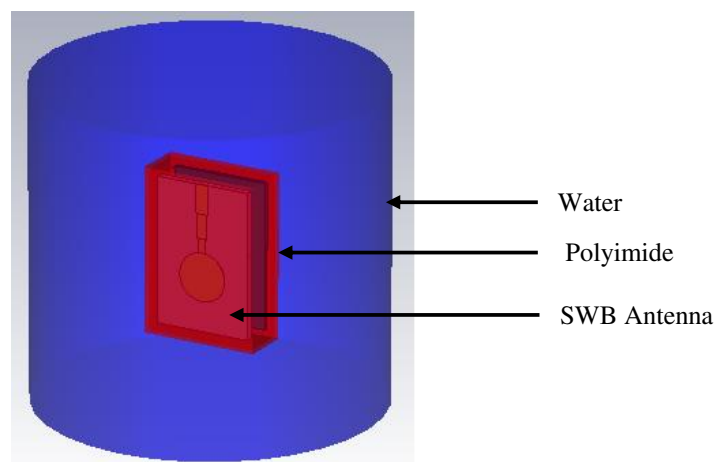
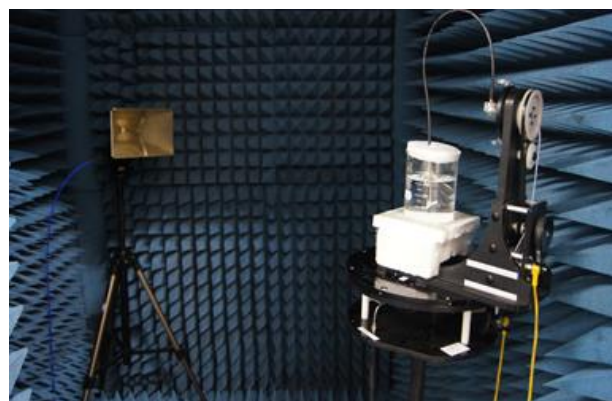


Figure 3. Simulation setup for SWB antenna performance in water

Figure 3 shows the simulation set up for evaluating the SWB antenna performance in water using CST software. The antenna is covered by polyimide as the casing during immersion in water. The casing has size of 30 mm x 45 mm with 15 mm thickness. The casing has hole inside in order to insert the SWB antenna. The level of the water exactly the same with the beaker used for the real measurement.



(a)



(b)

Figure 4. Measurement setup for a) reflection coefficient and b) radiation pattern

Figure 4 shows the measurement process was carried out in anechoic chamber with the help of Agilent Technologies ENA 8051C Network Analyzer to obtain the data for reflection coefficient and radiation pattern. The antenna covered by thin plain plastic is immersed in beaker contain 250 ml of water as shown in Figure 4(a).

In order to observe the performance of SWB antenna in different medium which is in water and in free-space, parameters that are important are reflection coefficient, gain, and radiated power. It is important also to identify the type of antenna's pattern whether directional or Omni-directional. Figure 5 shows the reflection coefficient for simulated and measured in both free space and plain water medium. Both simulated and measured in free space recorded wide bandwidth (< -10 dB) ranged from 3.7 GHz until more than 15 GHz and from 4.3 GHz until more than 15 GHz respectively. However, water medium degrades the bandwidth yet still within acceptable limit (< -6 dB) [9-11]. The antenna recorded bandwidth from 4.5 GHz until more than 15GHz for simulated and from 5 GHz until more than 15 GHz for measured.

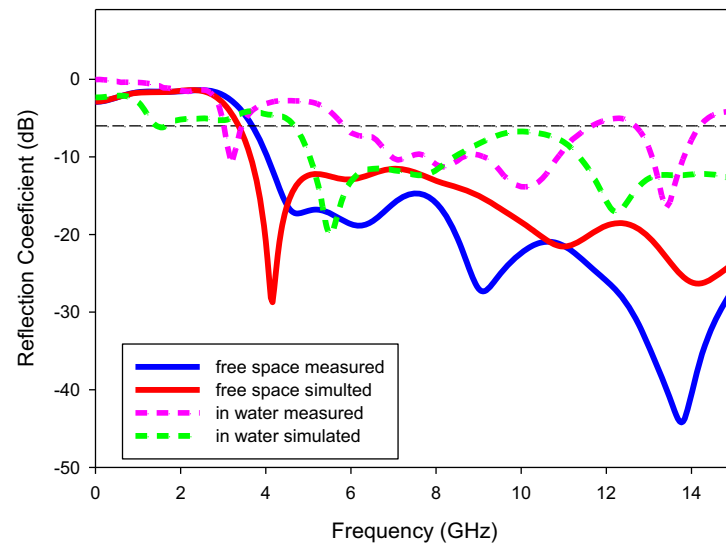


Figure 5. Measured and simulated reflection coefficient in free space and in plain water

For further investigation, the antenna is immersed in water with different level of 25%, 50%, 75% and 100% of immersion as shown in Figure 6. 25% of antenna immersion in water provides widest bandwidth followed by 50 %, 75% and 100% of immersion. However, fully immersion of antenna in water has been emphasize for further analysis in term of gain, reflection coefficient and radiation pattern. Electromagnetic wave propagation in water is totally different compared with propagation air since water has higher dielectric constant value. Rapid attenuation occurrence of the signals leads to degrade the SWB antenna performance as a whole [3]. Roughly, the simulated and measured recorded almost similar result in term of bandwidth wideness as shown in Figure 7.

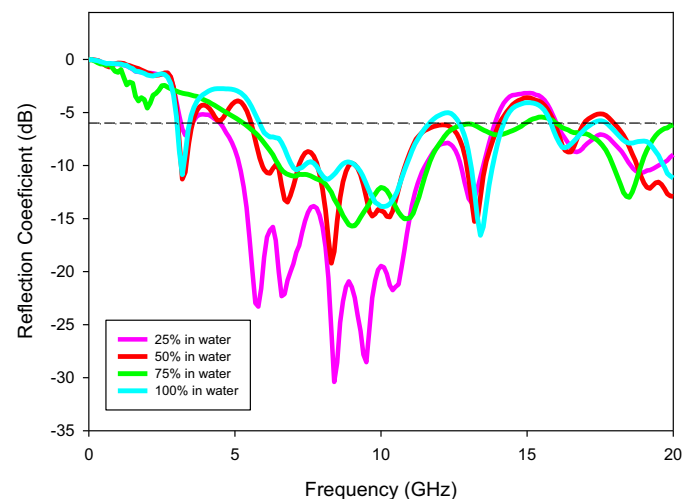


Figure 6. Measured reflection coefficient for immersion level

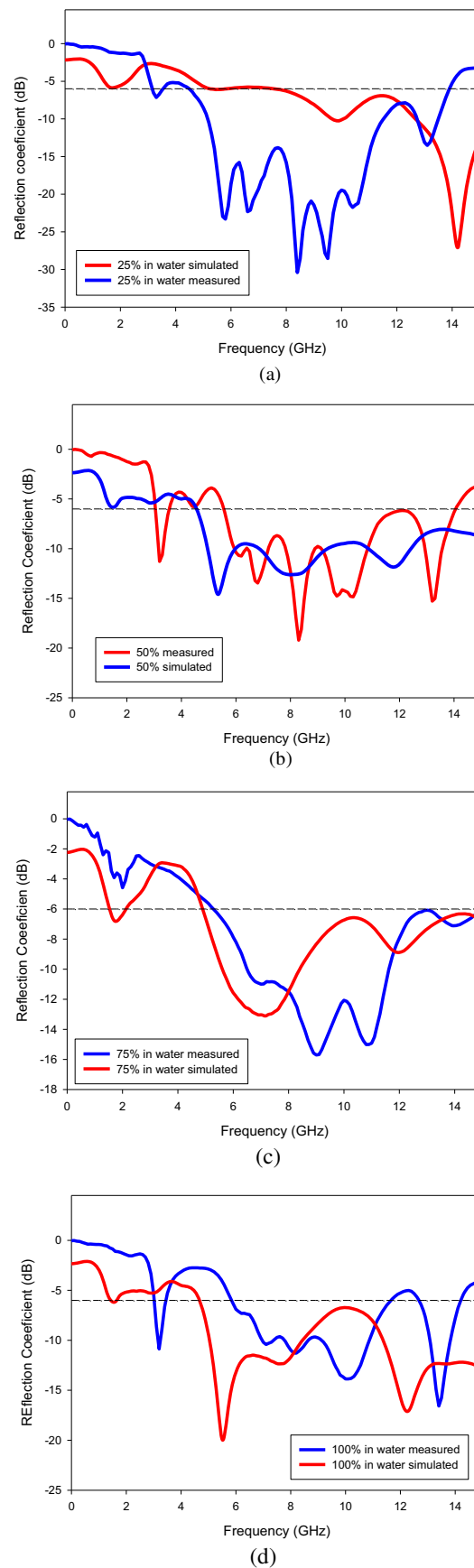


Figure 7. Reflection coefficient of difference immersion level; red (simulated), blue (measured) (a) 25% (b) 50% (c) 75% (d) 100%

The antenna gain in free space and plain water has been plotted in Figure 8. Both mediums show constant increments throughout the frequency with lower gain values recorded for antenna immersed in water rather than antenna in free space. The maximum gain for antenna in free space is 6.2 dB meanwhile for antenna immersed in water, the maximum gain 2.2 dB. Table 2 summarizes the performance of the SWB antenna in term of gain and return loss.

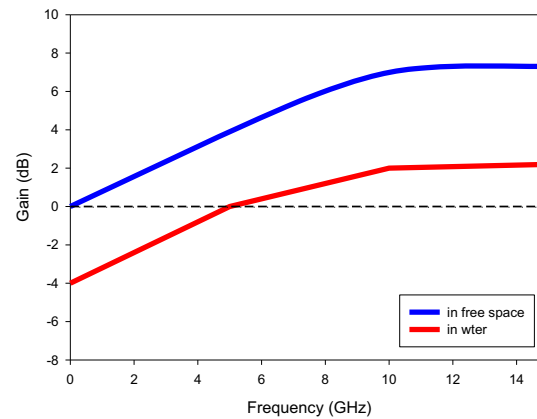
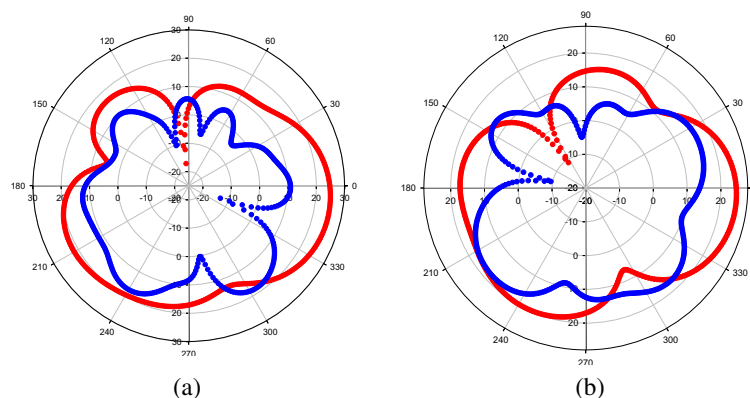


Figure 8. Graph of gain in free space and in water

Table 2: Measurement result of SWB antenna performance in free space and in water

Frequency (GHz)	Gain (dB)		Reflection Coefficient (dB)	
	Free space	Water	Free Space	Water
1	0.5	-3.9	-1.66	-2.96
5	4.5	0.1	-16.94	-9.6
10	7.2	2.0	-22.38	-6.73
15	7.5	2.2	-26.87	-13.06

Figure 9 demonstrate the radiation patterns for the proposed antenna both in free space and in water condition for selective frequencies. The figure clearly shows that the SWB antenna recorded omni-directional pattern for both medium with a little bit degradation for water medium. Omni-directional radiation pattern is very important to ensure underwater antenna radiate in all directions in order to have wider coverage for optimum data transmission.



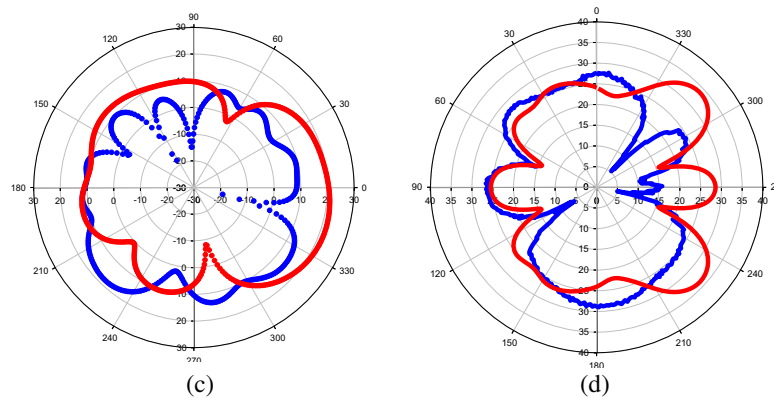


Figure 9. In water (blue) and in free space (red) of SWB antenna radiation pattern of Azimuth-Plane a) 6GHz, b) 8GHz, c) 10GHz, d) 12GHz

The measured and simulated results of radiation pattern in water for 3 GHz, 5 GHz, 7 GHz and 9 GHz are shown in Figure 10. The radiation patterns show good performance across the whole SWB band with high degree of consistency [12]. The ripples in the radiation patterns may be due to the reflections into the field between the proposed (Rx) and horn antenna (Tx). The power loss in the RF cable that is applied in the measurement also contributes to these small scale variations [13, 14].

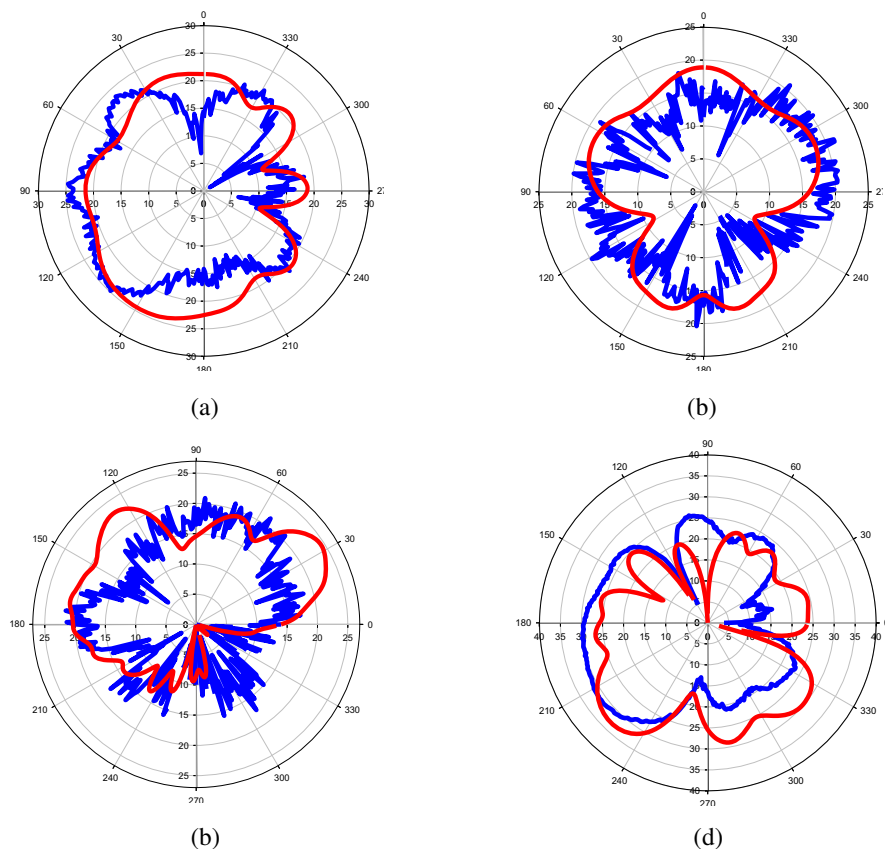


Figure 10: Comparison of Measured (blue) and Simulated (red) of SWB Array Antenna's Radiation Pattern of Azimuth-Plane in water a) 6GHz, b) 8GHz, c) 10GHz, d) 12GHz

4. Conclusion

A new design of compact Super Wideband (SWB) antenna for liquid application has been proposed. Eventhough the liquid medium degrades the proposed SWB antenna performance compared to free space, SWB antenna is still functional in water medium since it recorded good impedance matching ($< -6\text{dB}$) ranged within 4.7 GHz until more than 15 GHz with a maximum gain of 2.2 dB of omni-directional pattern. 25% of antenna immersion in water provides widest bandwidth followed by 50 %, 75% and 100% of immersion. In a nutshell, the antenna has great potential to be deployed in liquid medium for various related applications especially for biomedical related applications such as microwave imaging for cancer detection.

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