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Performance analysis of patch antenna for underwater wireless communication in seawater

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ABSTRACT

Underwater wireless communication in seawater is becoming more interesting and challenging in recent years. The development of antenna for underwater wireless communication in seawater at 900 MHz UHF range frequency is implemented by using patch antenna. In this paper, the antennas were designed using FEKO, an electromagnetic simulation software, and a suitable size for rectangular patch antenna for seawater application was developed to study the relevance between λ_0 with W and L in seawater. The major difference between the patches in free space and seawater was the feedpoint distance for antenna. For L size, which was slightly bigger, about 0.9 mm than free space size can consider almost same. But the gain for patch antenna in seawater was found at -2.51 dBi, lower than patch antenna in free space, which was 5.76 dBi due to the path loss in seawater. This shows that attenuation happened, and a better antenna will be design. The one that has better gain, which is around above 2dBi in seawater, in order to get better performance antenna in seawater environment.

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1. INTRODUCTION

Underwater wireless communication in seawater becomes more interesting because of research in aquatic environment is growing day by day. There are acoustic, free space optical and electromagnetic radio frequency applications that are involved in aquatic environment. This paper will concentrate on the use of electromagnetic radio frequency in designing a patch antenna. The proposed antenna is designed at 900 MHz licensed band for device-to-device underwater in seawater application especially for diver use.

The major issue of this study is that underwater communications have been limited in distance due the high attenuation for seawater RF communication frequencies. Although reliable RF communication distance is only a few meters, the main advantage of RF is that it can cross water and air surface borders, and this is significant [1]-[3]. This study is important in multiplying the selection of antenna types that can be applied in seawater, and to choose the best one for a particular application because ocean technology is growing in underwater communications because of its varied applications such as in marine research, oceanography, marine commercial operations, offshore oil industry, defense and leisure [3]. Compared to the initial communication system, sustained research over the years has resulted in better performance and sturdiness in underwater communication, which resulted in many communication products for use in water being available today.

There are several previous works that present similar application as this paper but with different types of antenna and frequency. In [4], they used a loop antenna with a diameter of 16 cm with a performance of S11 39 MHz, while gain was not mentioned. In [5], they used dipole antennas with parasitic elements with sizes ranging from 82 mm to 475 mm, and the performances were 65 MHz for bandwidth, and 25 MHz and 40 MHz for gain. Furthermore, in [6] loop, dipole and J-pole antennas were used with sizes around 74.55 mm, 115.50 mm and 121.80 mm for 40 MHz, which had bandwidth performances of 13.94 MHz, 11.89 MHz and 10.43 MHz. While in [7], they used 3 types of loop antennas with ground plane for 40 to 100 MHz resonance, and the size were around 130 mm to 400 mm that gave directivity from 13 to 19 dB. In [8], a bow-tie antenna was used for dual band at 2.4 and 5.1 GHz with a size of around 11 mm to 12 mm, and the maximum gain achieved was 1.2 dBi at θ =0◦, and a variable received power of -71 to -64 dBm. And in [9], half wave dipole antenna of 33.37 cm long at 30 kHz obtained attenuation in seawater at 6.54dB/m. The novelty of this study is frequency and measured permittivity value was used for antenna performance. Creativity is about the relationship between the antenna gain and antenna loss propagation with the depth of this paper is the full analysis of antenna performance between free space and seawater.

All previous works mentioned above did not provide complete antenna performances and just discussed several performances. A problem that will be solved in this paper is how to design a rectangular patch antenna with good antenna performance as a free space one. The reasons of comparison study between free space and seawater propagation is to study how the differences of the patch antenna size between free space and seawater and other characteristics that involve in developing seawater antenna for RF communication. In this paper, the probability of the development of patch antenna in seawater was studied to determine the suitable size and to get best antenna performance. This paper is organized as the following. Section 2 is the theoretical part, simulation and antenna performance, Section 3 is the discussion, and Section 4 will conclude the paper.

2. FUNDAMENTAL KNOWLEDGE (THEORETICAL PART)

2.1. Patch antenna design in free space

The rectangular patch antenna for free space was designed using formula (1), which is the basic formula to find *L* value that suitable for operational frequency and material used. In (2) Estimates the value of width for that patch antenna (3) and (4) are extended formulas for the better size designs of patch antenna [10]. By using all the formula, it is easy to start designing the model in Feko using the calculated size.

$$L = 0.49\lambda_g = 0.49\left(\frac{\lambda}{\sqrt{\varepsilon}}\right) \tag{1}$$

$$Width = \frac{c}{2f_0\sqrt{\frac{\varepsilon_r + 1}{2}}} \tag{2}$$

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[\frac{1}{\sqrt{1 + 12\left(\frac{h}{W}\right)}}\right] \tag{3}$$

$$Length = \frac{c}{2f_0\sqrt{\varepsilon_{eff}}} - 0.824h\left(\frac{(\varepsilon_{eff} + 0.3)(\frac{W}{h} + 0.264)}{(\varepsilon_{eff} - 0.258)(\frac{W}{h} + 0.8)}\right) \tag{4}$$

The patch antenna was fitted to the class of resonant quatiantennas, then its resonant behavior was responsible for the main challenge in patch antenna adequate bandwidth, which is conventional patch designs that produced bandwidths as low as a few percent [10]. To develop a design of a suitable patch antenna, length and width were calculated using the formulas (1), (2), (3) and (4) is shown in Figure 1(i).

The two ends of the patch that were connected to, and opposite from, the feed connection provided the radiation, acting as slot antennas, where each slot is the gap between the ends of the patch and the ground plane beneath the dominant dielectric layer [10]. The arrows on the left and right ends of the patch represent the currents between the patch conductor and ground plane as shown in Figure 1(ii). At the ends, where they were not contained, these currents resulted in the desired radiation of electromagnetic waves from the two end slots. The microstrip feedline excited the centre of the slot formed by the end of patch that to which it was connected. Between the underside of the patch and the substrate ground place, a low impedance transmission line was formed that subsequently fed the slot on the opposite side [10]. There are also have another patch antenna type but not apply yet in seawater. The previous work was dielectric dense patch antenna applied in zamzam water [11], P-shape patch antenna applied for radar, mobile and others wireless communication [12] and monopole patch antenna for ultra-wideband (UWB) application [13]. Future research to use these previous work antennas and apply it in seawater to find the new gain that antenna will obtain.

The parameters used in simulation for free space were tabled as in Table 1. Figure 2(i) shows the value of frequency 901MHz when the input impedance is 50Ω and that also obtained the electric field as Figure 1(ii) as the fundamental resonance was achieved. It means the balance amplitude on *L* side, and the antenna can be considered as a *λ/2* transmission line resonant cavity with two open ends where the fringing fields from the patch to the ground are exposed to the upper half space (z > 0) and are responsible for the radiation [10]. The gain obtained is 5.76 dBi as in 3D view. S11 or return loss is -24.2 dB at 900.26 MHz and the bandwidth is 5.71 MHz. All performances for the free space antenna were obtained as theoretical results.

Table 1. Simulation parameters in a free space

Aspect	Parameter	
Simulator	Altair FEKO 2019	Method of Moment
Frequency	UHF	900 MHz
Antenna	Length (L_0)	101 mm
	Width (W_0)	120 mm
	Height of substrate (h)	1.524 mm
	Feedpin from origin	19.5 mm
Dielectric (Arlon)	Permittivity, ε_r	2.55
	Conductivity, σ	0 S/m
	Tan δ	0.0018
	Mesh size, *Δm*	λ16

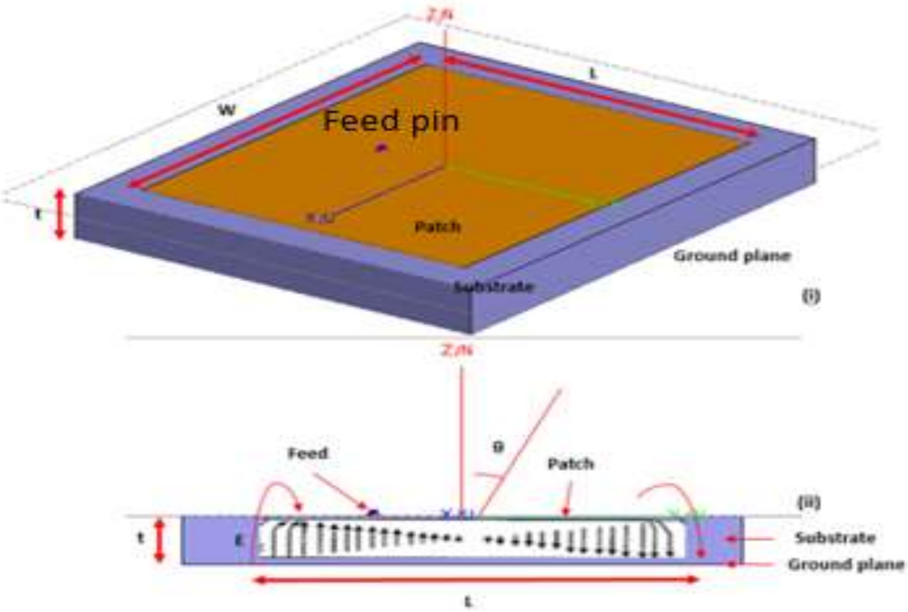

Figure 1. (i) geometry for analyzing the edge-fed microstrip patch antenna, (ii) side view showing the electric fields in free space environment

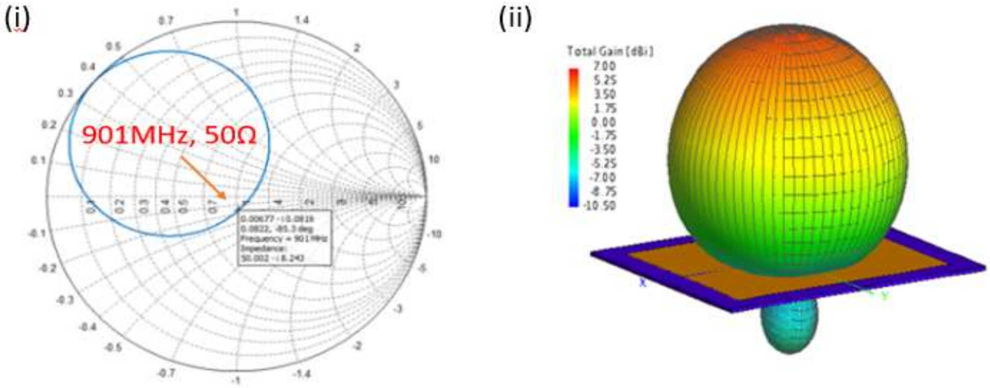

Figure 2. (i) Input impedance for patch antenna in free space; (ii) Radiation pattern for patch antenna in free space for 3D view

2.2. Measurement of electric constants in seawater

Before the simulation in seawater was implemented, the process of measuring permittivity for seawater was performed by using a PNA device (network analyzer), setup with calibration of distilled water permittivity. Then, when the result was accurate (nearly 80), usually around 77 to 79, the measure of seawater permittivity was executed. There were 3 samples of seawater involved, as stated in Table 2. The process of measurement is shown as in Figure 3(i) and 3(ii). The relative permittivity (ε_r) of water depends on several factors like water temperature, salinity and propagation frequency [14], and it can be described by the Debye model [15]-[16] or by the Cole-Cole equation [17]. For this simulation the permittivity and conductivity value used were 58.91 and 0.32 S/m, which were chosen from measured values from Table 2 as the value is the highest. Conductivity was calculated using formula $\sigma = \omega\varepsilon_0\varepsilon' tan\delta$ where $\varepsilon_0 = 8.85x10^{-12} F/m$ [18].

Table 2. Measured permittivity value of seawater

Frequency (MHz) / Name of Beach / Parameter	400			900			1500		
	ε'	ε"	σ	ε'	ε"	σ	ε'	ε"	σ
Batu Feringgi Beach, Penang	54.47	-4.61	0.11	58.91	-7.11	0.32	63.73	-7.18	0.56
Klebang Beach, Melaka	49.26	7.38	0.17	56.87	-1.36	0.06	62.56	-4.12	0.32
Remis Beach, Selangor	39.78	-5.67	0.13	44.30	-9.53	0.43	50.08	-12.03	0.94

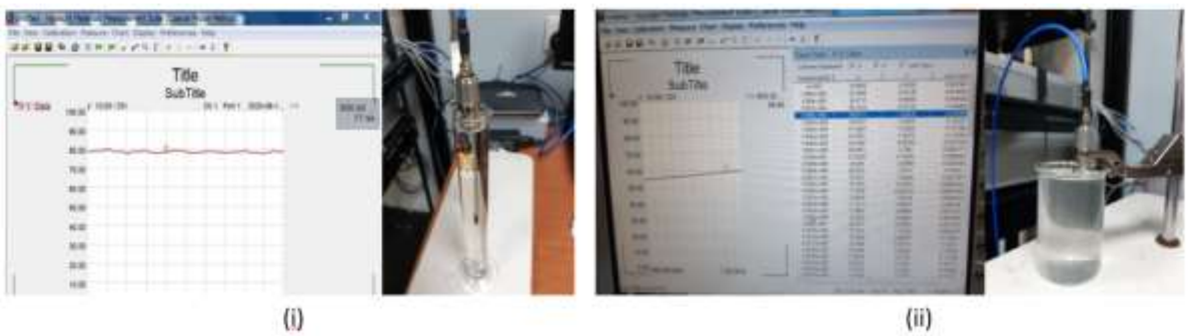

Figure 3. (i) Calibration process; (ii) Process of measuring the value of seawater permittivity

2.3. Simulation of patch antenna in seawater

A challenge in this paper was to find the suitable patch size when placed in seawater because the size of seawater patch antenna cannot be calculated using formulas (1) to (4). So in order to find a solution, a process of trial and error was implemented to get the S11 needed. Firstly, the free patch size was referred to as the starting patch size. Then, the size was changed little by little, by its *L* size and *W* size, to get the actual size of S11 900 MHz. This frequency was selected because it is within the UHF band class that is suitable to extend the distance between antennas when in seawater. In [19], the advantages of electromagnetic radio frequency were many times compared to acoustic and free space optical but the disadvantage is that it has severely limited range in water. The purpose of this paper is to study the importance of developing an antenna in seawater and analyze the performances of the antenna.

This paper is different from others because it concentrates on the theoretical part of development of the rectangular patch antenna in seawater. Others concentrated more on immersed coated loop antenna [20], loop and vibrator antenna [21], dipole antenna [2], loop and dipole antenna [3], loop antenna with ground plane [4], bow-tie antenna [5, 22], half dipole antenna [9] and wideband microstrip circular patch antenna with buffer layer [23]. And [24] is concentrate on underwater antennas and measuring wave propagation in the sea ice and the sea water. The differences of these two antennas were analyzed by their λg. This paper will discuss further two cases of patch antenna in free space and in seawater with the same operating frequency.The parameters of simulation were tabled as in Table 3 and the design of the antenna is shown in Figure 4.

Table 3. Simulation parameters in seawater

Aspect	Parameter	
Simulator	Altair FEKO 2019	Method of Moment
Frequency	UHF	900 MHz
Antenna	Length (L_s)	101.9 mm
	Width (W_s)	120 mm
	Height of substrate (h)	1.524 mm
	Feedpin from origin	49.1 mm
Dielectric (Arlon)	Permittivity, ε_r	2.55
	Conductivity, σ	0 S/m
	Tan δ	0.0018
	Mesh size, Δm	λ16
Dielectric (Seawater)	Length of seawater	181.9 mm
	Width of seawater	200 mm
	Height of seawater	82.524 mm
	Permittivity, ε_r	58.91
	Conductivity, σ	0.32 S/m
	Mesh size, Δm	λ16
	Air gap	10 mm (5 mm + 5 mm)

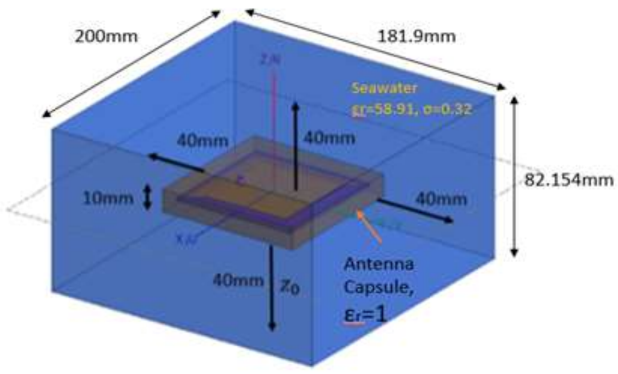

Figure 4. Simulation model of patch antenna in seawater in 3D view

The patch antenna in seawater was designed by changing its *L* size bit by bit to obtain the suitable size that can have a resonance at 900 MHz. Figure 5(i) shows the electric field that was obtained for this case. It shows that the electric field distribution is the same as the fundamental mode resonance as in Figure 1 (ii). Thus, the patch antenna in seawater was judged to be working well in seawater. Meanwhile, Figure 5(ii) shows that 899 MHz obtained at the input impedance 50Ω. Figure 6(ii) show the radiation pattern for this case, where the main lobe is -2.51 dBi. S11 for this case is -26.54 at 900.57 MHz and the bandwidth obtained was 16.53 MHz, which is bigger than the free space bandwidth value.

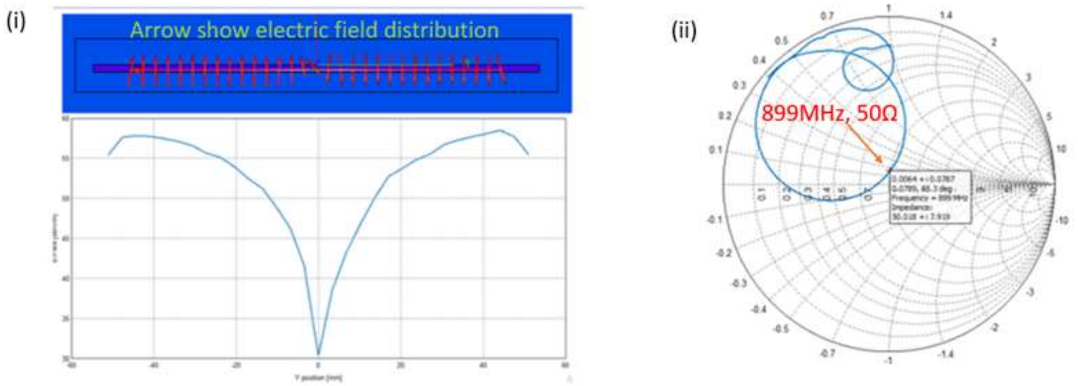

Figure 5. (i) Patch antenna in seawater with electric field result; (ii) input impedance for patch antenna in seawater

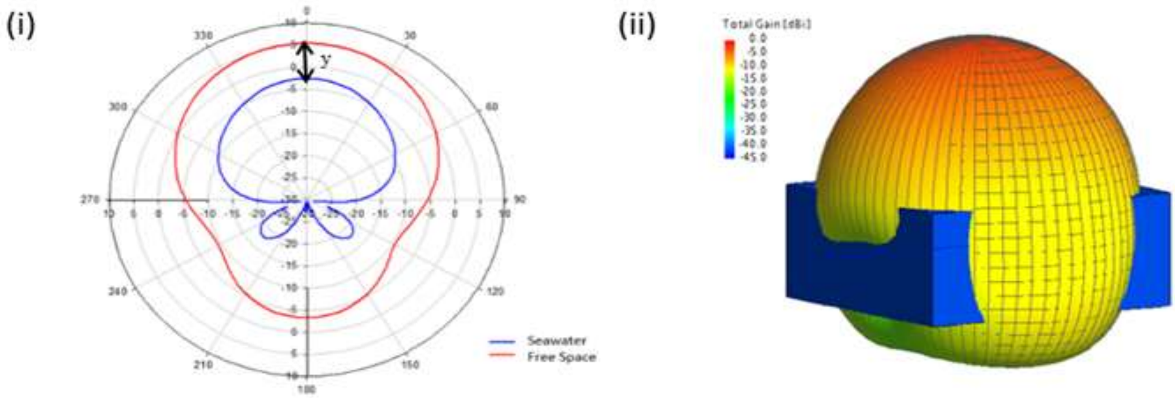

Figure 6. (i) Difference gain between patch antenna in free space and seawater. (ii) 3D view radiation pattern for patch antenna in seawater

3. PERFORMANCE ANALYSIS

3.1. Change of antenna radiation

Table 4 shows, size of patch antenna in seawater was slightly larger than the one in free space but can consider as no change because the difference is only 0.9mm. The position of the feed pin depended on the size of *L* and its proximity to the edge of *L*. Thus the difference of feed pin location between them is about 29.6 mm. Besides that, for seawater the bandwidth was larger than the bandwidth in free space. The gain value in seawater was also found to have attenuated from the gain value in free space. Furthermore, the depth of seawater affected the resonance to get the operational frequency. The deeper the seawater, the bigger the *L* size. Future research will need to design a suitable patch that can obtain the gain or radiation pattern that equals 2 dBi and above to fulfil the best antenna requirement for diver's tool application. There are many RF frequencies that give less attenuation in certain conditions such as in fresh and river water conditions, which is EM out performs acoustics in terms of bandwidth [25].

Table 4. Comparison between free space and seawater

Aspect	Free Space	Seawater
Permittivity used (ε)	1	58.91
Conductivity used (σ)	0	0.32
Lambda g, λ_g=c/[(√ε)(900MHz)]	208.74 mm	43.42 mm ~ 40 mm
Feed pin	19.5 mm	49.1 mm
S11	-24.20 dB at 900.26 MHz	-26.54dB at 900.57 MHz
Input impedance (50Ω)	At 901 MHz	At 899 MHz
Bandwidth	5.71 MHz	16.53MHz
Gain	5.76dBi	-2.51dBi

3.2. Propagation loss

Propagation of signal causes losses. These losses can be an estimation by calculating the electric field degradation. The complex propagation constant is (5). Thus, the value of attenuation constant, α is needed and expression (6) shows how to calculate the value. Hence, electric field degradation, L_Z can be calculated by using (7), and z represents the travelled distance of the signal.

Figure 7(ii) above shows that the loss in seawater at z=0.04 m (40 mm), as calculated by using the theory formula, was about -2.73 dB. But as the y in Figure 6(i) shows, the difference between free space antenna gain and seawater antenna gain (attenuation/ loss) was about 8.27 dBi. The difference is 5.54 dB can assume as path loss for 40mm distance. So the gain from the link budget equation, received power (dB) = transmitted power (dB) + Gains (dB) − losses (dB) must be considered to develop the new antenna design that will obtain a high gain, which ultimately will improve the loss of 8.27 dBi as mentioned before.

$$\gamma = \alpha + j\beta \tag{5}$$

$$\alpha = \sqrt{\frac{\omega^2 \varepsilon \mu_0}{2}} \sqrt{\sqrt{1 + \left(\frac{\sigma}{\omega\varepsilon}\right)^2} - 1} \tag{6}$$

$$L_z = 10 \log e^{-2\alpha z} \tag{7}$$

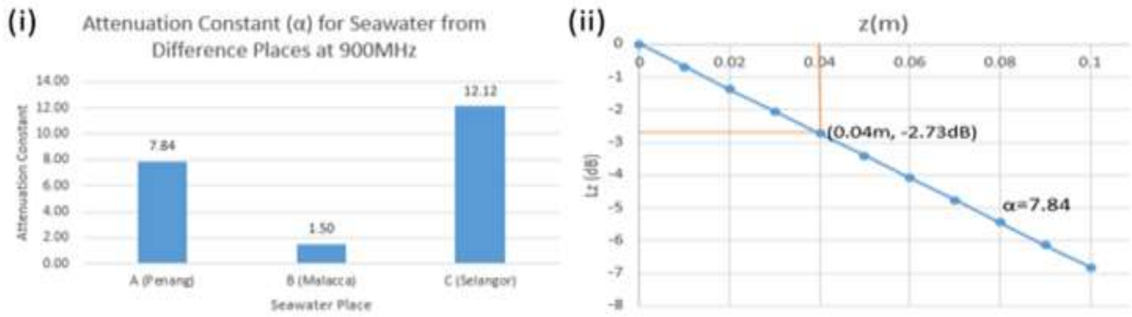

Figure 7. (i) α value of seawater (In (6)); (ii) Propagation loss (L_Z) change of seawater (At (7))

4. CONCLUSION

The performance of patch antenna in seawater obtained was as expected, which is the antenna in seawater can give more bandwidth than the free space one. Also, the size of the patch in seawater was successfully obtained, which in theory, achieved similar radiation pattern as that of in free space with a slight attenuation. The size of antenna is considering same but the major difference is feedpin location of the antenna. For future research, a new antenna design needs to be built to increase the gain in seawater.

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