

Design of an axial mode helical antenna with buffer layer for underwater applications

Afiza Nur Jaafar¹, Hajar Ja'afar¹, Yoshihide Yamada², Fatemeh Sadeghikia³, Idnin Pasya Ibrahim⁴, Mohd Khairil Adzhar Mahmood⁴

¹School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA, Terengganu, Malaysia

²Malaysia-Japan International Institute of Technology, Universiti Teknologi Malaysia, Kuala Lumpur, Malaysia

³Wireless Telecommunication Group, ARI, Ministry of Science, Research and Technology, Tehran, Iran

⁴School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA, Selangor, Malaysia

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ABSTRACT

Recently, there is an increasing demand for high-speed wireless communication network for short-range underwater communication. From previous research, most underwater antennas produced omnidirectional radiation pattern which has lower antenna gain. There are a few considerations that need to be taken if the antenna is designed to operate in water environment. This paper discusses the electromagnetic properties which affect the underwater antenna design. Physical properties such as electrical permittivity and conductivity of water contribute significant effect to the size of the antenna as it influences the behavior of electromagnetic signal that propagates in water. In this study, an axial mode helical antenna with waterproof container is presented which operates at 433 MHz. The axial mode helical antenna has circular polarization and is suitable to support wireless application which is surrounded by some obstruction. The proposed antenna produces a bidirectional radiation pattern by placing it into a waterproof casing. Good agreement between the simulation and measurement results validates the concept. However, a little discrepancy between the simulated and measured results may be attributed to the noise originated from the equipment and the environment.

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Corresponding Author:

Hajar Ja'afar

School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA

Cawangan Terengganu, Dungun Campus, Terengganu, Malaysia

Email: hajarj422@uitm.edu.my

1. INTRODUCTION

Nowadays, wireless communication is preferred as the use of copper wires in the connections of the underwater sensor networks with radio signals or acoustic signals may result in higher costs and the difficulty of maintenance or installation [1]. There are three techniques that are commonly used in wireless underwater communication. The oldest technology is acoustic system which occupied sound signal as the medium to transfer the information. It is widely used as it allows the longest range of signal transmission [2]. However, it has some limitations in term of the low transmission rate, and it is also affected with the doppler effects [3]. The propagation of sound underwater is affected by temperature, salinity, hydrostatic pressure and other factors [4]. Apart from that, optical and radio frequency (RF) are also available in water communication. Nevertheless, these optical and RF technologies can provide higher throughput compared to acoustic but both technologies have limitation in term of the transmission distance [5]. For optical signal it normally requires line-of-sight between the transmitter and receiver that is hard to be achieved in water due to the higher

particle inside [6]. Meanwhile, RF technology which relied on the antenna seems more suitable to be considered for short distance transmission with moderate data rate [7]. Performance of conventional RF communication schemes in water is limited by the relatively small RF skin depth [8]. The underwater antenna design is strongly dependent on the physical characteristic of water such as the permittivity and conductivity [9]. Therefore, the wavelength in the medium which depends on the physical characteristics of the environment where it is immersed, eventually influenced the size of antenna.

There are a few studies that focused on the underwater communication which utilized RF signal to transfer the information signal. Karagianni [10] explained about a bowtie microstrip antenna with arc-shaped circular slots that is designed to encounter the high path loss and to fulfil the bandwidth requirements in sea water. Research conducted by Rycroft *et al.* [11] presents a real world results at 433 MHz operating frequency in raw water. This research proposed a bowtie antenna that achieved distances of 7 m at 1.2 Kbps and 5 m at 25 Kbps. Aboderin *et al.* [12] studied about three types of antenna, specifically, loop, dipole and J-pole for application in fresh and sea water environment. The research shows that J-pole antenna has significant advantages over the other antenna. Pasya *et al.* [13] proposed the utilization of a buffer layer with dielectric constant value calculated using geometric average among air and the transmission medium. Sinha *et al.* [14] created a micro-strip patch antenna that operates in the 402 to 405 MHz band and could possibly be implanted in a human body phantom model due to its flexibility and lower radiation properties.

A suitable antenna design is proposed to establish an underwater communication employing RF technology that can transmit higher data rate over a short distance. The axial mode helical structure that can exhibit higher gain is presented for the first time. The operating frequency of the proposed antenna is 433 MHz, and it can be tuned accordingly by changing the axial dimension and diameter. With 6 to 7 dB gain, the proposed antenna is expected to be reliable for underwater communication in a harsh environment.

2. ANALYTICAL METHOD

Water is a material which has high permittivity (ϵ) and electrical conductivity (σ). Therefore, in the aqueous environment, electromagnetic signal propagates with different behavior as compared to the normal propagation through air [15]. With a relative permittivity of 78 to 81 [16], water has the highest permittivity among any material and has a significant impact on the angle of refraction from air to water and vice versa [17]. High conductivity leads to strong attenuation of electromagnetic signal in water. Relative permeability, μ_r is approximately equal to 1 as water and air, both are non-magnetic in nature [18]. Therefore, there is only little effect of relative permeability of water to the magnetic field component [10].

Compared to acoustic and optical signals, the RF signal can pass smoothly through the water/air boundary provide with moderate transmission rates up to Mbps [10]. Nevertheless, due to the strong attenuation of electromagnetic signal in water [19], it is restricted for short distance transmission only. The speed of electromagnetic wave is affected by relative permittivity and relative permeability [18] as in (1):

$$v_{(water)} = \frac{1}{\sqrt{(\mu_r)(\epsilon_r)}} \quad (1)$$

where $v_{(water)}$ is the velocity of signal propagation in water, μ_r and ϵ_r are the relative permeability and permittivity of water, respectively. ϵ and μ are calculated as (2) and (3).

$$\mu_r = \mu_0 \mu_1; \mu_1 = 1 \text{ and } \mu_0 = 4\pi \times 10^{-7} \text{ Hm}^{-1} \quad (2)$$

$$\epsilon_r = \epsilon_0 \epsilon_1; \epsilon_1 = 78 \text{ and } \epsilon_0 = 8.85 \times 10^{-12} \text{ Fm}^{-1} \quad (3)$$

The high permittivity of water limits the velocity of signal propagation when it propagates in this medium. Propagation loss inside water is as in (4) [20]:

$$\alpha = \omega \sqrt{\mu \epsilon} \left\{ \frac{1}{2} \left[\sqrt{1 + \left(\frac{\sigma}{\omega \epsilon} \right)^2} - 1 \right] \right\}^{\frac{1}{2}} \quad (4)$$

where σ is the water conductivity, ω is the angular frequency of the RF signal, and μ is the vacuum permeability. Attenuation loss (in dB) can be computed by (5):

$$L_{attenuation} = 10 \log(e^{-2\alpha d}) \quad (5)$$

where d is the distance which the signal is propagated.

Increasing the frequency of the signal will cause the attenuation of the signal increases exponentially [21]. Therefore, selection of frequency is crucial to ensure RF signal can be transmitted successfully to the receiver point. Due to the attenuation issue, special arrangement of devices that are immersed in water should be properly designed to ensure there are no significant losses that will occur during the propagation.

An axial mode helical antenna at 433 MHz is considered in this study for underwater application as it provides circular polarization with higher gain value than normal mode. This characteristic is important to be considered when the antenna is installed in the environment which has many obstacles that leads to greater signal reflection. Furthermore, axial mode helical antennas have many advantages compared to other types such as microstrip patch antennas, especially in terms of the gain value and stability of the antenna performance. This antenna is also ideal to radiate signals in a directional pattern, as compared to the normal-mode helical antenna which radiates an omni-directional pattern.

Generally, in order to get a strong directivity along the axis with circular polarization, the pitch angle α of the helix is designed to be between 12° to 14° and the circumference to be about one wavelength [22]. A helical wire antenna is more suitable to be used in underwater environment, as it can go directly into the medium, without a requirement to protect the antennas from water, unlike printed antennas that require spraying of epoxy resin on either side, which will alter the design frequency [23].

Figure 1 shows the structure of the proposed helical antenna with a front view in Figure 1(a) and a top view in Figure 1(b). It is made of a conductor wound into a helical shape and mounted on a small plate which acts as a ground plane. This structure is simulated using CST Studio Suite software. Performance of the helical antenna is determined by D/λ , and different D/λ values correspond to different radiation patterns of the antenna [24].

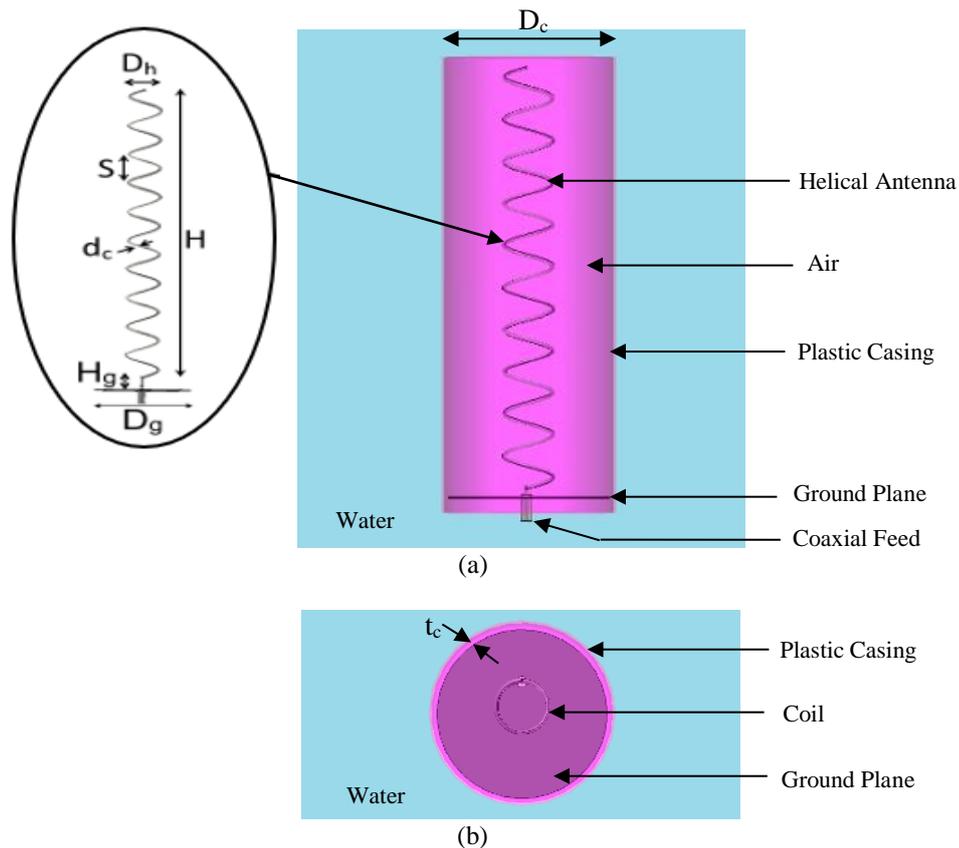


Figure 1. Proposed arrangement of antenna at a different angle with (a) front view and (b) top view

The wavelength, λ for the proposed antenna can be calculated using (6):

$$\lambda = \frac{v}{f} \tag{6}$$

where v is the speed of electromagnetic signal that propagates in water while f is the proposed frequency of 433 MHz. Using (6), the calculated λ is 78.39 mm as the obtained v in water from (1) is $33.9 \times 10^6 \text{ ms}^{-1}$. For the axial mode helical antenna, the helix circumference, C is equal to one wavelength [25]. The axial mode *helical* antenna performs well if the circumference of helix is in the following range [26]:

$$\frac{3}{4}\lambda \leq C \leq \frac{4}{3}\lambda \quad (7)$$

The proposed antenna is excited by a coaxial feed line through a circular ground. Each parameter of the helix such as its diameter, axial height, spacing between turns and wire thickness are shown in Figure 1 and Table 1. These parameters will affect the performance of helical antennas, as discussed in section 4. The proposed antenna was immersed in the water and placed in the polyerhylene terephthalate casing with 3.3 dielectric constant.

Table 1. Specification of the proposed antenna parameter

Quantity	Calculated Value (mm)	Optimized Value (mm)
Diameter of the helix, $D_h=0.32 \lambda$	24.0	20.0
Spacing (center to center) between any two adjacent turns; $S=0.22 \lambda$	17.2	17.2
Circumference, $C=\pi D_h \approx \lambda$	78.0	63.0
Axial Height, $H=NS$	172.0	172.0
Diameter of the helix conductor; $d_c=0.02 \lambda$	1.5	1.4
Diameter of the ground plane, $D_g=0.75 \lambda$	58.0	65
Distance of the helix from the ground plane, $H_g=0.12 \lambda$	9.0	10.0
Diameter of the plastic casing, D_c	N/A	70.0
Thickness of the plastic casing, t_c	N/A	1.0

The proposed antenna comprises of a helical shape as a base structure while the casing is to encapsulate and protect the antenna from water. The velocity of electromagnetic signal will be decreased when it propagates in water environment. Consequently, the wavelength of the signal also decreases. Smaller wavelength value represents smaller size of antenna as the circumference of axial mode helical antenna is approximately equal to the one wavelength, λ as shown in (3). Therefore, the antenna will show a reduction in size when the calculation is considered in water environment. This phenomenon is contributed by the reduction of electromagnetic signal's velocity which decreased when it propagates in water. The antenna was placed in the plastic casing with diameter of D_c with t_c thickness. This design is simulated in water background using CST software for the performance analysis. Radiation pattern, S_{11} and voltage standing wave ratio (VSWR) value have been observed and an optimization process has been carried out to ensure good performance of underwater antenna.

3. RESULTS AND DISCUSSION

During the design optimizing process, physical parameter that was obtained from the initial calculation has been varied to examine the effect on the antenna performance. The number of turns, axial height, axial diameter, wire thickness and distance of wire wound from the ground plane has been varied, then the performance of antenna in terms of S_{11} and gain value has been observed. In response to changes in these variables, S_{11} and gain value both changed, either increasing or decreasing. The following subsection will explain a detail explanation of the result.

3.1. Parametric analysis

For axial mode helical antenna, there are a few parameters that contribute to the antenna performance. Certain parameters will influence the antenna performance significantly while some of them just show a little effect. For instance, generally the beam-width decreases as the number of turns increases [27]. Figure 2 shows the effect of physical parameter of antenna to the operating frequency and S_{11} with the effect of the number of turns, N in Figure 2(a), axial height in Figure 2(b), axial diameter in Figure 2(c), wire thickness in Figure 2(d) and distance of antenna from the ground plane in Figure 2(e). The antenna with smaller number of N resonates at higher frequencies while larger number of N resonates at lower frequencies. The helical antenna with 22 turns, which has larger axial height, resonates at 394 MHz frequency while 18 turns antenna resonates at the higher frequency which is 487 MHz.

The height of the antenna, which is directly related to the size of the antenna, influences the operating frequency. From (7), circumference of axial mode helical antenna depends on the wavelength,

consequently proved that the operating frequency gives a significant effect on the size of antenna. Small changes in diameter values cause the operating frequency to be shifted to higher or lower value. Hence the correct value of the diameter must be properly considered to ensure that the antenna will operate at the desired frequency as a little change has a great effect on the antenna output.

The result shows the diameter of a helical antenna has a significant impact on antenna performance. Figure 2(d) shows the effect of wire thickness, d_c on the antenna performance. This parameter has no significant effect on the performance of the antenna as there are a little difference between the S_{11} values at different thicknesses.

A ground plane is placed at the bottom of the proposed antenna with a certain distance, H_g from the coils. Figure 2(e) shows the effect of this parameter on the antenna performance. From the result, it is observed that the antenna distance causes a small effect as there was a little difference to S_{11} value for each distance. As mentioned previously in Table 1, the distance is calculated up to 0.14λ .

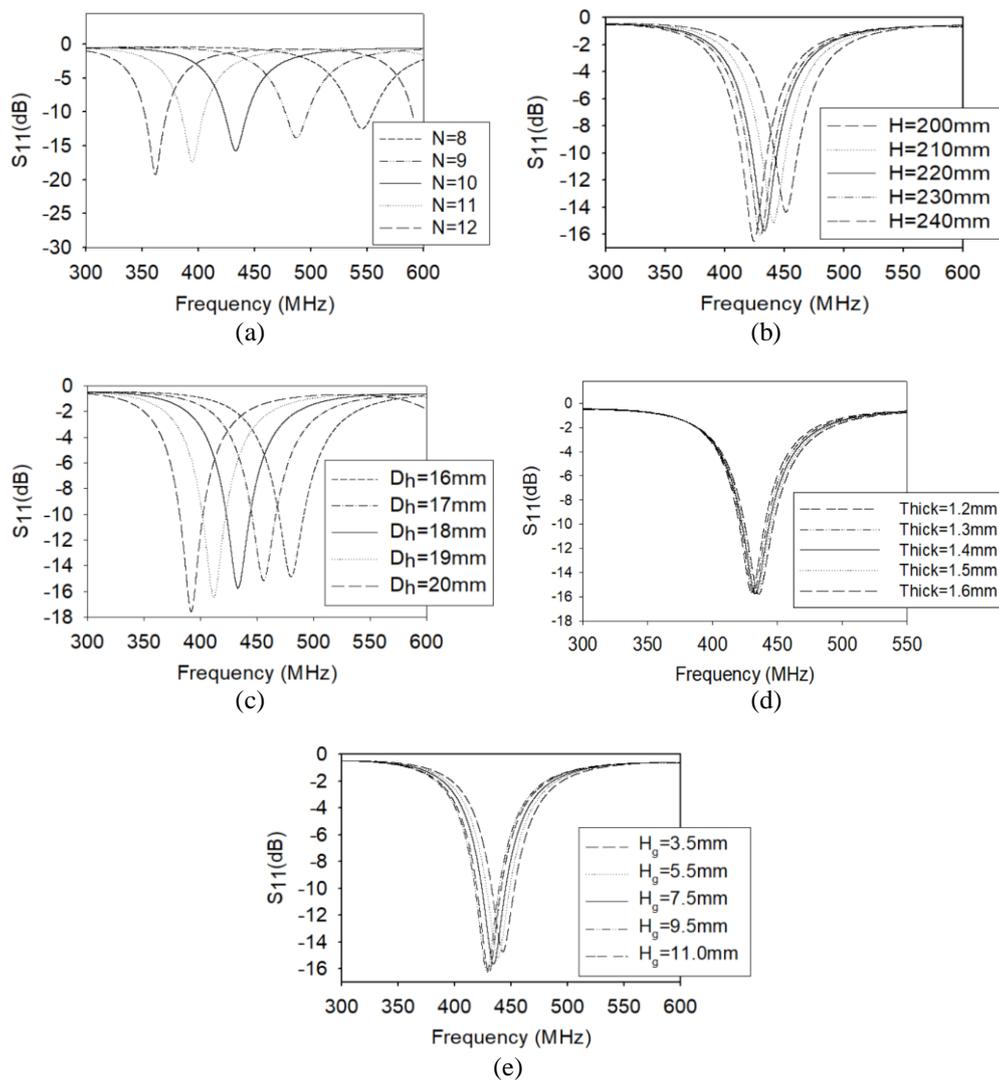


Figure 2. Comparing Simulation Result of S_{11} with the different physical parameter in (a) the number of turn (b) axial height, (c) axial diameter, (d) wire thickness, and (e) the distance of antenna from the ground plane

Figure 3 shows the effect of physical parameter of antenna to the gain value with the effect of the number of turns, N in Figure 3(a), axial height in Figure 3(b), axial diameter in Figure 3(c), wire thickness in Figure 3(d) and distance of antenna from the ground plane in Figure 3(e). From these results, it can be observed that when we increase the number of turns, the gain value will also increase. Similar to the axial length, as it is clear that increasing the height of antenna increases the gain value. The result complies with the concept of the longer the axial length, the greater the forward gain of the helix [28]. Figure 3 also shows

the relationship between antenna diameter and the gain level. The reading indicates that the gain value is reduced when the axial diameter is increased. From these results, it can be observed that there is no specific relationship between the wire thickness and gain value, but obviously variations of the thickness of the wire will affect the gain value. Although there is a small difference, the wire thickness still contributes to the antenna performance. Similar with other parameter, the gain value remains at 6 to 7 dB for each distance of helical from ground plane.

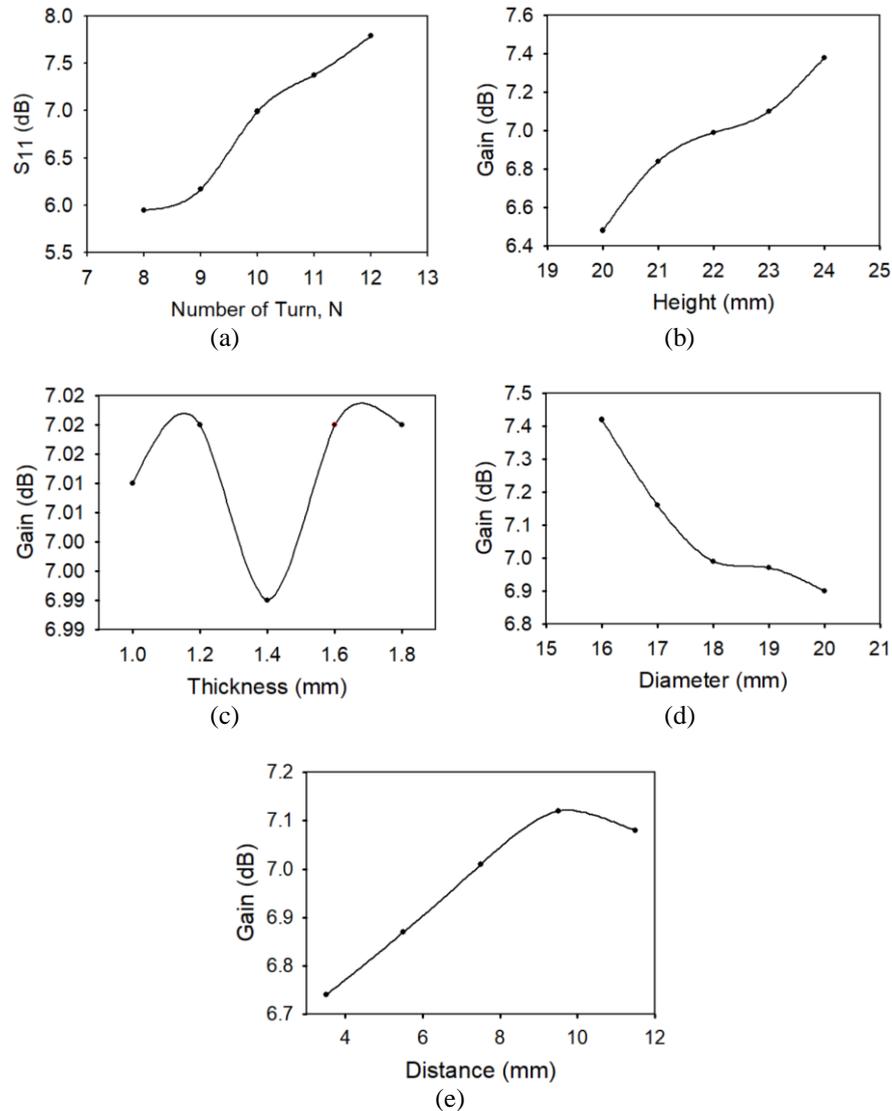


Figure 3. Comparing simulation result of gain value with the different physical parameter in (a) the number of turn (b) axial height, (c) axial diameter (d) wire thickness and (e) the distance of antenna from the ground plane

3.2. Simulation and measurement result

The main purpose of this research is to design a high gain of underwater antenna with directional radiation pattern. Simulation of the proposed antenna has been carried out using CST software. The proposed design successfully obtained the directional pattern when it was simulated in water without a casing as shown in Figure 4(a). Further optimization process has been made by changing the number of coils to $N=5$ and a few other parameters as shown in Figure 4(b). Figure 5 shows the radiation pattern when the antenna was placed in a plastic casing. The pattern was remained in a unidirectional pattern, but there was little improvement in term of back lobe as it shown that the back lobes has been reduced. Further analysis on the buffer layer characteristic will be presented in the upcoming report.

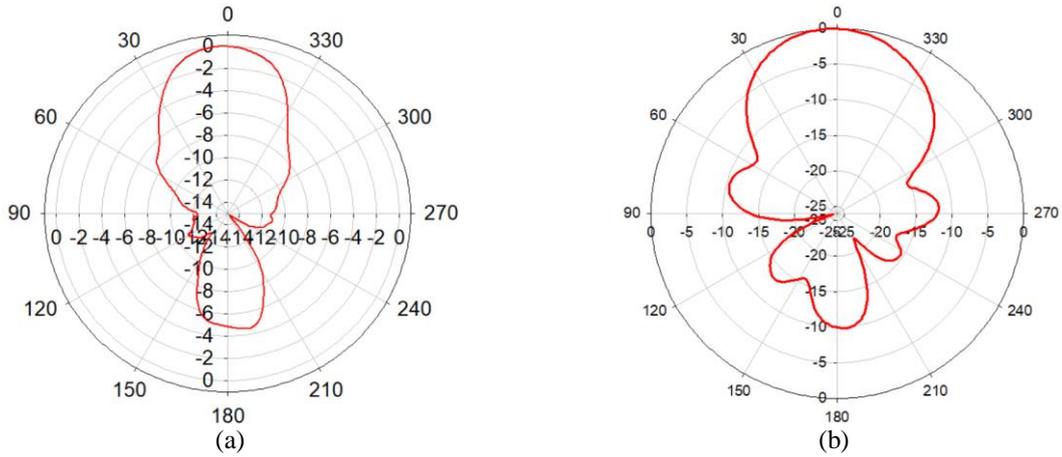


Figure 4. Radiation pattern from antenna outside the casing with (a) original radiation pattern and (b) radiation pattern after optimization process

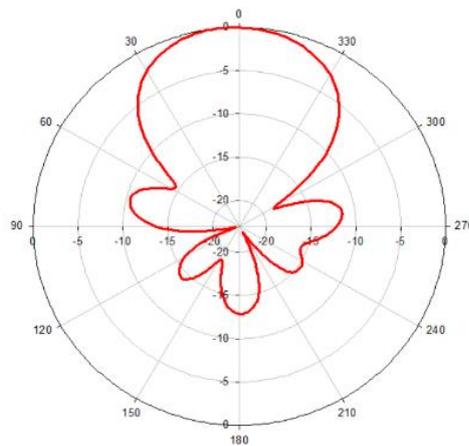


Figure 5. Radiation pattern from antenna that placed in the casing

3.2.1. Simulation analysis

The proposed antenna has a VSWR value approximately 1.5:1 at 433 MHz while S_{11} value is -15.73 dB as revealed in Figure 6. The antenna yielded S_{11} below -10 dB at 433 MHz resonant frequency. At this point, the gain obtained was 6.99 dB. This indicates that the proposed antenna has good radiation characteristics within the targeted frequency. From the simulation result, the proposed antenna has been fabricated according to the dimension that was previously obtained from the simulation process.

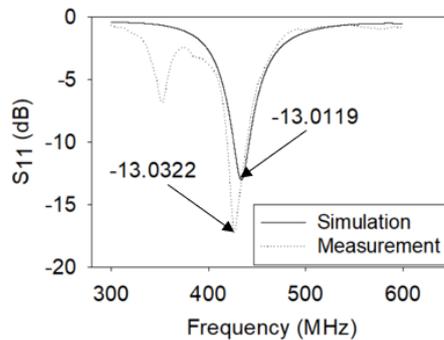


Figure 6. Output result from simulation and measurement

3.2.2. Measurement analysis

The antenna was fabricated according to the values that were obtained from the optimization process. Figure 7 shows the experimental setup of the proposed antenna. The antenna was immersed in the water to measure S_{11} output after it was sealed in a waterproof polyethylene terephthalate casing. There is a small difference due to some measurement error such as noise that originated from equipment or environment. From the simulation result, we observed that the S_{11} is the best at 433 MHz with 13 dB return loss. There was a 25% difference between simulation and the measurement result. The measurement shows that the best return loss is at 426 MHz with S_{11} is equal to -17 dB while 433 MHz at 13 dB for the simulation.

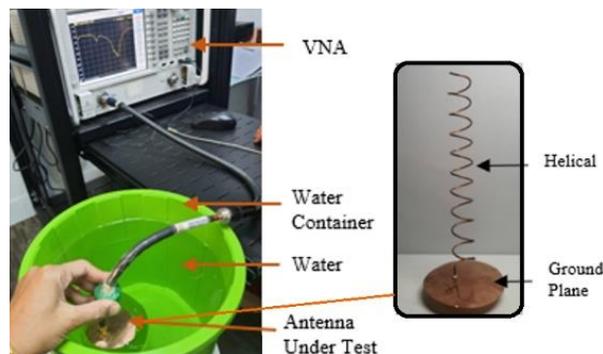


Figure. 7. Experimental setup to measure S_{11} of the fabricated antenna

4. CONCLUSION

This paper studies the effect of physical parameter of water on the helical antenna performance when the antenna operates in water environment. The proposed antenna has been designed and placed into polyethylene terephthalate casing. Result shows that the size of the proposed antenna was reduced if the antenna is designed to operate in water because its size is closely related to the wavelength value. This result agrees with the theory which states that the signal wavelength will be reduced when it propagates in higher density medium. From the simulation result, the proposed antenna is working at 433 MHz with S_{11} and gain equal to -13 dB and 6.99 dB respectively. The radiation pattern is changed from unidirectional to bidirectional behavior after the antenna is placed into polyethylene terephthalate casing. For the future, another similar antenna will be fabricated to ensure the measurement of radiation pattern can be carried out.

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BIOGRAPHIES OF AUTHORS



Afiza Nur binti Jaafar    received the Bachelor’s in Electrical Engineering from Universiti Tun Hussein Onn (UTHM), Malaysia, in 2006 and the Master of Science in Telecommunication and Information Engineering from Universiti Teknologi Mara (UiTM), Malaysia. She is a lecturer at the Faculty of Electrical Engineering, Universiti Teknologi Mara, Terengganu branch. Previously she worked as a Process Engineer at Stats Chip Pac (M) Sdn Bhd from 2006-2009 prior joining UiTM as a lecturer. She is currently pursuing her Ph.D. at Universiti Teknologi Mara (UiTM), Malaysia, working on underwater antenna. Her research interests include radio frequency communication, underwater communication, electromagnetic propagation, buffer and matching layer construction. She can be contacted at email: afizanur.uitm@gmail.com.



Hajar Ja'afar    is Senior Lecturer of Radio-Frequency and Microwave, IoT system at Universiti Teknologi MARA, Malaysia and fellow researcher at Antenna Research Center in Universiti Teknologi MARA, Malaysia since 2016. She was awarded in Ph.D. in Electrical Engineering from Universiti Teknologi MARA in February 2016. She was also a reviewer of IEEE antenna wireless propagation letter, journals and international conference paper. She has been awarded numerous research grant proposal. She has wide experience supervising postgraduate students related to radio-frequency, microwave fields and IoT system. She also as an active member in Graduate Engineer, Board of Engineers Malaysia (No: 97896A), the Institution of Engineers, Malaysia (No: 36254), member of IEEE (No: 92628020), IEEE Antennas and Propagation Society, International Association of Engineers (No: 193643), Malaysia Board of Technologists (No: PT20090126). She can be contacted at email: hajarj422@uitm.edu.my.



Yoshihide Yamada     received the B.E. and M.E. degrees in electronics from the Nagoya Institute of Technology, Nagoya, Japan, in 1971 and 1973, respectively, and the D.E. degree in electrical engineering from the Tokyo Institute of Technology, Tokyo, Japan, in 1989. In 1973, he joined the Electrical Communication Laboratory, Nippon Telegraph and Telephone Corporation (NTT). Until 1984, he was involved in research and development of reflector antennas for terrestrial and satellite communications. From 1985 to 1993, he was involved on research and development of base station antennas for mobile radio systems. In 1993, he moved to NTT Mobile Communications Network Inc. (NTT DoCoMo). In 1995, he was temporarily transferred to YRP Mobile Telecommunications Key Technology Research Laboratories Company Ltd. He was a Guest Professor with the Cooperative Research Center, Niigata University, and a Lecturer with the Tokyo University of Science, from 1996 to 1997. In 1998, he became a Professor at the National Defense Academy, Japan. Since 2014, he has been a Professor with the Malaysia-Japan International Institute of Technology, Universiti Teknologi Malaysia, Kuala Lumpur, Malaysia. His current research interests include very small antennas, array antennas, aperture antennas, and electromagnetic simulation of RCS. He is also a Fellow Member of IEICE and a Senior Member of the IEEE AP Society. He is also a member of ACES. He received the Best Paper Award and the Best Tutorial Paper Award from the IEICE in 2013 and 2014, respectively. He can be contacted at: ndayamada@yahoo.co.jp.



Fatemeh Sadeghikia     was born in Tehran, Iran. She received her B.Eng. and M.Eng. degrees in electrical and electronics engineering from Iran University of Science and Technology (IUST) and K.N. Toosi University of Technology, Iran, in 2000 and 2003, respectively. She also received her Ph.D. degree in telecommunication engineering, in the area of plasma antennas, from Iran University of Science and Technology in 2012. Since 2009, she has been with the Aerospace Research Institute (ARI), where she is currently an Assistant Professor. Her research interests include reconfigurable antennas, microwave and millimeter-wave devices, and applications of plasma technology in wireless communication. She is currently directing research and development of plasma antennas and microwave components at ARI Wireless Communication Engineering Group. Dr. Sadeghikia was the recipient of the 2020 IEEE Transactions on Antennas and Propagation Best Paper Award from the IEEE Malaysia Section. She acts as a reviewer for various international journals including the IEEE Transactions on Plasma Science. She can be contacted at email: sadeghi_kia@ari.ac.ir.



Idnin Pasya Ibrahim     is a Senior Lecturer in the Faculty of Electrical Engineering, Universiti Teknologi MARA. He received the B. E. and M. E. degrees in Information and Communication Engineering from Tokyo Denki University in 2004 and 2006, respectively, and his Ph.D. in Communication Engineering from the same university in 2015. Previously, he worked as an Engineer in Toshiba PC and Network, Tokyo, Japan, from 2006 to 2009, and Pradonet Technology Sdn. Bhd. as Senior Product Engineer in 2009, before joining UiTM in the same year. He contributed to many research publications in the area of antennas and propagation, ultra-wideband communication systems and devices, and MIMO radar and its applications. He received the IEEE MTT Best Paper Award in 2014 IEEE Radio and Wireless Symposium, held in California, USA. He served as the Deputy Director of Microwave Research Institute (MRI), UiTM from 2016-2019. He contributed to IEEE as an executive committee for IEEE AP/MTT/EMC Joint Chapter for the year 2017-2020. He is also an active member of SIRIM Technical Committee on "Electromagnetic Field" (TC/E/6) for the year 2016-2020. Dr. Idnin is currently an executive committee for Malaysia Radar and Navigation (MyRAN) group, where he served as the Head of Radar division for the year 2018-2019. He served as the Deputy Director of Microwave Research Institute (MRI), UiTM from 2016-2019. He is also an active member of SIRIM Technical Committee on "Electromagnetic Field" (TC/E/6) for the year 2016-2020. Dr. Idnin is currently an executive committee for Malaysia Radar and Navigation (MyRAN) group, where he served as the Head of Radar division for the year 2018-2019. He can be contacted at email: idnin@uitm.edu.my.



Mohd Khairil Adzhar Mahmood     is the Deputy Research Officer at Microwave Research Institute (MRI), UiTM Shah Alam. Prior to his current position at MRI, he used to serve as R&D Electrical Engineer in Motorola. His research interest is in the Microwave Engineering field where he works extensively in the process of circuit design, fabrication process and the measurement process involved in any particular project. He is also doing research in the nanotechnology-based materials for microwave applications. He can be contacted at email: khairil833@uitm.edu.my.