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High-Efficiency Sea-Water Monopole Antenna for Maritime Wireless Communications

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Abstract—This paper presents a study of sea-water monopole antenna at very high frequency (VHF) band for maritime wireless communications. The sea-water monopole antenna consists of a feeding probe and a sea-water cylinder held by a clear acrylic tube. The feeding probe is loaded with a disk on the top to improve the excitation of TM mode. A theoretical study of the sea-water monopole antenna based on the three-term theory is presented, which has not appeared in literature. Commercial software packages ANSYS HFSS and FEKO are used to simulate this antenna. Experimental results of a fabricated sea-water monopole antenna with a radius of 50 mm show reasonably good agreement with theoretical predictions. Measurement shows that the proposed sea-water antenna has high radiation efficiency. Meanwhile, due to the transparency and liquidity of sea water, the proposed antenna is almost optically transparent and can be easily reconfigurable. The center frequency of the antenna is tunable by lengthening or shortening the water cylinder, while the bandwidth of the antenna can be adjusted by widening or narrowing the water cylinder.

Index Terms—Monopole antenna, radiation efficiency, reconfigurable, sea-water, transparent antennas, VHF band.

I. INTRODUCTION

IN recent years, liquid antenna [1] was becoming an interesting topic. For a liquid antenna, the fluid that carries charged particles in the form of ions is used as the radiating medium. Due to the fluidity, the fluid can be pumped into a plastic tube and thereby “deployed” when the antenna is activated. When deactivated, the fluid can be pumped out or drained and the tube can also be removed, resulting in very small occupation space and radar cross section (RCS). As a special case of fluid antenna, water antenna is probably the most popular, due to its low cost and easy access. Many kinds of water antennas have been reported so far [2]–[6]. A simple broadband monopole water antenna was presented in [2], [3]. The performance of this antenna was carefully studied by dissolving salt into pure water. Based on this design, a feeding probe loaded with nut and washer was introduced to improve the performance of the monopole water antenna [4]. Another monopole water antenna was presented in [5] by inserting a dielectric base between water and the ground plane to maximize the bandwidth. In [6],

a cubic water dielectric resonator antenna (DRA) with compact size was designed due to high permittivity and low loss of the distilled water at the low frequencies.

Most of the early studies of water antennas were based on fresh water, and carried out only by experimental analysis [2]–[5]. However, in a maritime environment, sea water is more readily available than fresh water. In [7], a sea-water monopole antenna was made by SPAWAR, which mainly consists of a current probe and a sea-water stream supplied by a pump. It has the advantages of dynamic and reconfigurability. However, at upper very high frequency (VHF) and ultra high frequency (UHF) bands, the efficiency of this sea-water monopole antenna is low because the thin sea-water stream is not an efficient radiator. It is also known that the thinner the stream becomes, the larger is the loss resistance and the lower is the radiation efficiency [8].

In this paper, a new transparent and reconfigurable sea-water monopole antenna operating at VHF band is proposed, which is well suited for maritime wireless communications. In comparison to the dynamic-type sea-water monopole antenna in [7], our structure is relatively simple, mainly consists of a transparent plastic tube filled with sea-water and a top-loaded feeding probe. Furthermore, our proposed antenna has a higher efficiency due to an efficient feeding structure and the thick sea-water cylinder used. A theoretical study of the sea-water monopole antenna based on the three-term theory [8] is presented, which has not appeared in the literature. Experimental results are provided to verify the theoretical calculations, and reasonable agreements between them are obtained. Measurements show that our proposed antenna has a higher radiation efficiency compared to the water antennas in [2]–[5] due to the small surface resistance of our sea-water monopole. In addition, due to the transparency and liquidity of the sea water, the proposed antenna is almost optically transparent and can be readily reconfigurable. Details of the antenna design and experimental results are presented and discussed.

II. STRUCTURE OF THE SEA-WATER MONOPOLE ANTENNA

Fig. 1 shows the geometry of the sea-water monopole antenna mounted on a ground plane. As shown, in order to hold the sea-water cylinder, a clear acrylic ($\epsilon_r = 2.7$) tube is chosen to be vertically fixed on a Teflon base and sealed with silicone gasket. Its transmittance is nearly perfect; therefore it can be used to design an optically transparent antenna. The feeding probe is loaded with an aluminum disk on the top before being inserted into the sea water, which improves the excitation of TM mode. To achieve the desired TM mode, the clear acrylic tube and the feed probe are concentric to maintain its structural symmetry. It is clear that the sea-water monopole antenna can be

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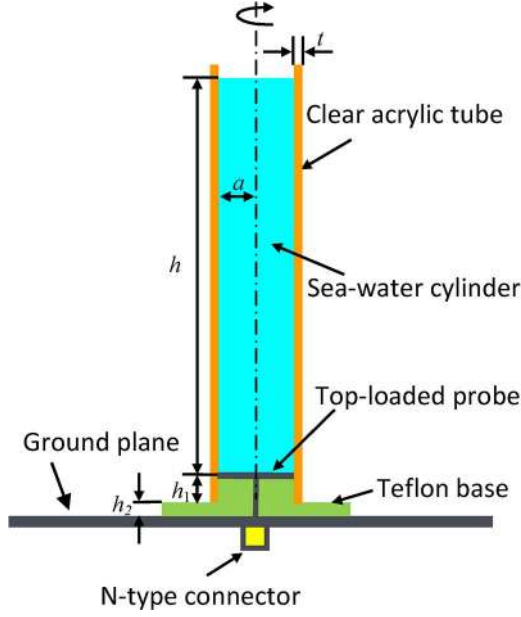


Fig. 1. Geometry of the sea-water monopole antenna.

reconfigurable which means that its center frequency and bandwidth can be adjusted by changing the height and radius of the sea-water cylinder.

Generally speaking, the dielectric constant of sea water is ~ 81 , and the conductivity is ~ 4 S/m. However, it is worth mentioning that the electrical properties of sea water depend on its chemical composition which varies from place to place and from time to time. In addition, electrical properties of sea water vary with the temperature, pressure, and frequency [9], [10]. Therefore the electrical properties of sea water used here are characterized by using a coaxial line reflection method [11] to obtain an accurate design. It is found that the dielectric constant of the available sea water varies between 77.6 and 79.8 over the frequency range of 30–300 MHz, while the conductivity varies between 3.9 and 4.2 S/m.

III. THEORETICAL ANALYSIS

In the frequency range of interest from 40 to 100 MHz, sea water can be treated as a good conductor ($|\sigma/\omega\varepsilon| \gg 1$); but fresh water ($|\sigma/\omega\varepsilon| \ll 1$) can only be treated as imperfect dielectric. As a result, a sea-water cylinder acts as a monopole antenna, while a fresh-water cylinder may serve as a dielectric resonator antenna. In this paper, we only focus on monopole antenna made of sea water. The analysis of the sea-water monopole antenna is conducted by employing the three-term theory introduced by King and Wu for imperfectly conducting cylindrical antenna [8]. It begins with the well-known Pocklington integral equation for the surface current $I(z)$ along a cylindrical half-wavelength dipole antenna made of sea water. For simplicity, the dielectric constant ε_r of sea water is chosen to be 78.7, and the conductivity σ is chosen to be 4 S/m over the operating frequency range. Meanwhile, the thickness of the clear acrylic tube is much smaller than the operating wavelength, therefore its effect is almost negligible. The cylindrical dipole antenna is along the z -axis of a system of cylindrical

coordinates (r, θ, z) with a radius of a and a height of $2h$, where h is the height of the monopole antenna. It is driven at $z = 0$ by a gap delta-function source with electromotive force (EMF) V_0 . The Pocklington integral equation of this cylindrical dipole antenna can be expressed as [8]

$$\left(\frac{\partial^2}{\partial z^2} + k^2\right) \int_{-h}^h I(z')K(z, z')dz' = j4\pi\omega\varepsilon [Z_s I(z) - V_0\delta(z)] \quad (1)$$

where

$$K(z, z') = \frac{e^{-jk_0 r}}{r}, \quad r = \sqrt{(z - z')^2 + a^2}$$

and Z_s is the surface impedance per unit length of the sea-water cylinder. In the frequency range of interest, sea water can be treated as a good conductor ($|\sigma/\omega\varepsilon| \gg 1$), its surface impedance can well be approximated by [12]

$$Z_s = \frac{k_m}{2\pi a \sigma} \frac{J_0(k_m a)}{J_1(k_m a)} \quad (2)$$

with

$$k_m = \sqrt{\mu_0 \varepsilon \left(1 - \frac{j\sigma}{\omega\varepsilon}\right)}.$$

Then, the surface current $I(z)$ of the cylindrical dipole antenna can be approximately solved from the above integral equation by using the three-term theory. The input impedance of the cylindrical dipole antenna can be obtained as $Z_{dipole} = V_0/I(0)$. For the corresponding cylindrical monopole antenna, as known to all, the distribution of the surface current is the same as the cylindrical dipole antenna, and the input impedance can be expressed as $Z_{in} = Z_{dipole}/2$. Once the input impedance is determined, the reflection coefficient of this cylindrical monopole antenna can be obtained as

$$|S_{11}|(\text{dB}) = 20 \lg(|\Gamma|) \quad (3)$$

where

$$\Gamma = \frac{Z_{in} - Z_0}{Z_{in} + Z_0}$$

and Z_0 is the characteristic impedance of the feeding transmission line.

Figs. 2(a) shows the theoretical surface current $I(z)$ of the cylindrical monopole with different values of radius a . It is found that both components of the current increase continuously in magnitude with an increasing radius a . However, the rate of increase becomes slower as the radius increases. There is only a little change in the magnitude of the imaginary component, when the radius is larger than 60 mm (about one skin depth). Meanwhile, as previously mentioned, the electrical properties of sea water don't always stay the same. It is therefore necessary to provide the current distributions $I(z)$ with different values of conductivity σ . Fig. 2(b) shows the theoretical surface current $I(z)$ with different values of conductivity σ . It can be clearly seen that both components of the current increase in magnitude with the increasing conductivity σ . Similar to Fig. 2(a), the rate of increase becomes slower as the conductivity increases. On the

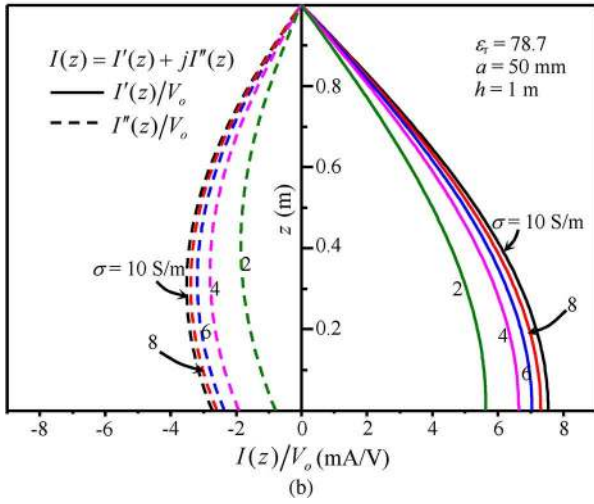
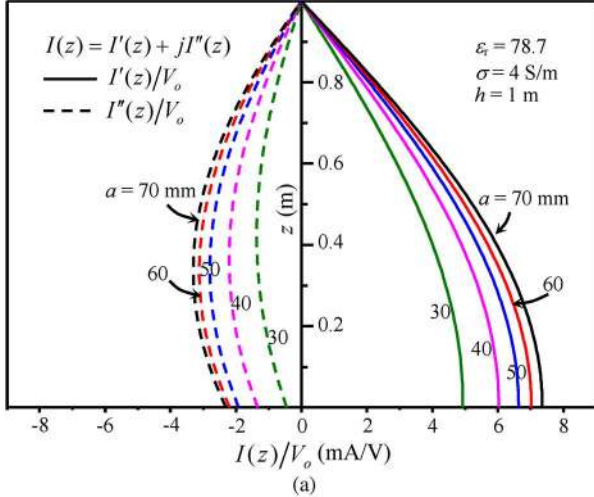


Fig. 2. Theoretical surface currents with different values of (a) radius a and (b) conductivity σ .

other hand, from the theoretical results, it is also found that the dielectric constant has little impact on the current distribution.

Fig. 3 shows the theoretical reflection coefficient $|S_{11}|$ of the cylindrical monopole with different values of radius a and conductivity σ , respectively. As shown in Fig. 3(a), the bandwidth of the cylindrical monopole antenna increases with an increasing radius a . It means that the bandwidth of the sea-water monopole antenna can be adjusted by choosing clear acrylic tubes with different radii. Furthermore, it can be seen from Fig. 3(b) that the resonant frequency of the cylindrical monopole antenna shifts slightly upward with an increase of conductivity σ , while the bandwidth remains nearly unchanged.

The investigation of the radiation efficiency of an antenna is of practical importance, because it is one of the most important indicators to evaluate the performance of an antenna. According to the theoretical current distribution $I(z)$, the ratio of the power dissipated internally in heating the antenna to the total power can be obtained as [13]

$$\frac{P_{diss}}{P_{total}} = \int_{-h}^h \frac{|I(z)|^2 r_s}{|I(0)|^2 R_0} dz \quad (4)$$

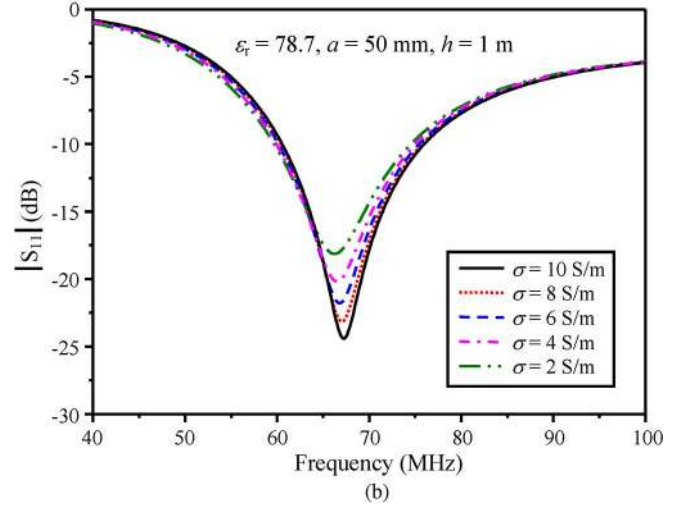
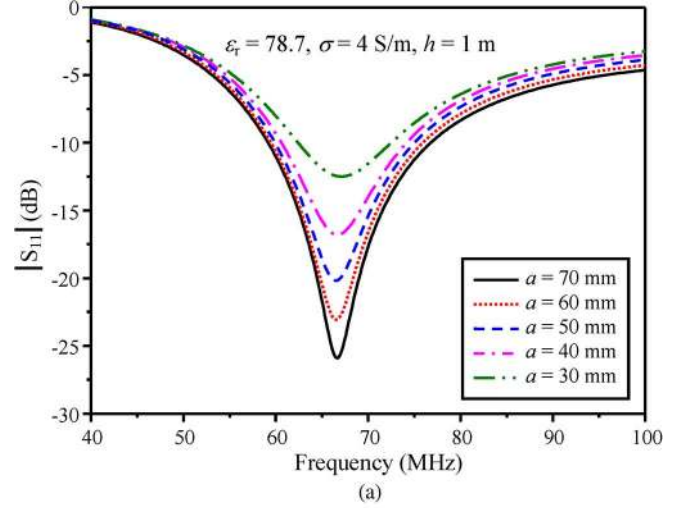


Fig. 3. Theoretical reflection coefficients with different values of (a) radius a and (b) conductivity σ .

where r_s and R_0 are the real part of the surface impedance Z_s and input impedance Z_{in} , respectively. Thus, the radiation efficiency of the cylindrical monopole can then be written as

$$\eta = 1 - \left(\frac{P_{diss}}{P_{total}} \right). \quad (5)$$

If designed properly, this sea-water monopole antenna may also be used for wide-band applications. Therefore, it may be interesting to look at its radiation characteristics over a wide frequency range (from 40 to 200 MHz), though the slightly large values of $k_0 a$ and relatively small values of $|\sigma/\omega\epsilon|$ in the high frequency band from 100 to 200 MHz may lead to a large approximation error. Fig. 4 shows the theoretical radiation efficiency with different values of radius a and conductivity σ , respectively. It can be observed from both Fig. 4(a) and Fig. 4(b) that the radiation efficiency increases gradually, and tends to oscillate along with an increasing frequency after attaining a maximum. The peak of the curves shifts towards lower frequencies as the radius a or conductivity σ increases. It is also found

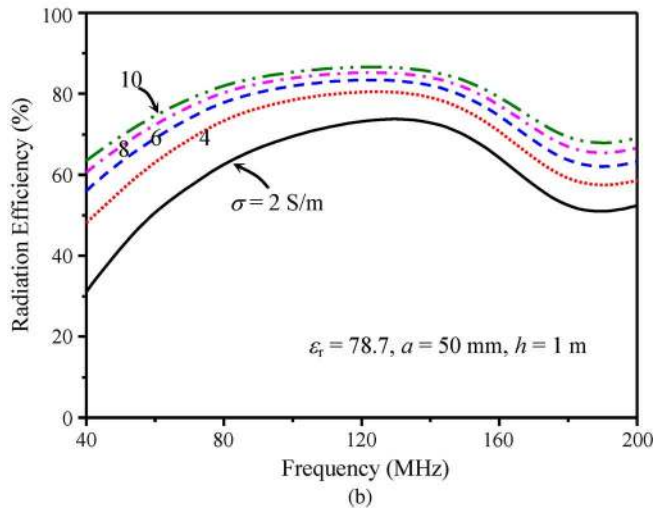
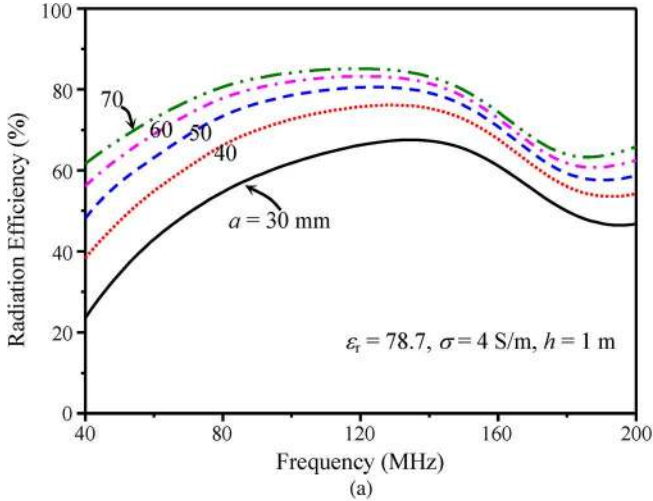


Fig. 4. Theoretical radiation efficiencies with different values of (a) radius a and (b) conductivity σ .

that the radiation efficiency increases continuously with an increasing radius a or conductivity σ . However, the rate of increase becomes slower as the radius or conductivity increases further.

It should be pointed out that the temperature of sea water may also affect the operation of the antenna. When the water temperature increases, so does its conductivity [14]. Therefore, according to Fig. 3(b), it is obvious that, when the temperature increases the resonant frequency of the monopole antenna will shift slightly upwards, while the bandwidth remains nearly unchanged. Moreover, it can be noted from Fig. 4(b) that the radiation efficiency will increase continuously with an increasing of temperature.

IV. EXPERIMENTAL CHARACTERIZATION

The dimensions of our fabricated sea-water monopole antenna are as follows: $h = 1$ m, $h_1 = 30$ mm, $h_2 = 20$ mm, $a = 50$ mm, and $t = 3$ mm. Fig. 5 shows the photograph of our fabricated monopole prototype. As shown, in order to facilitate the measurement, a small metallic box with an open bottom is used to support the antenna. When conducting the

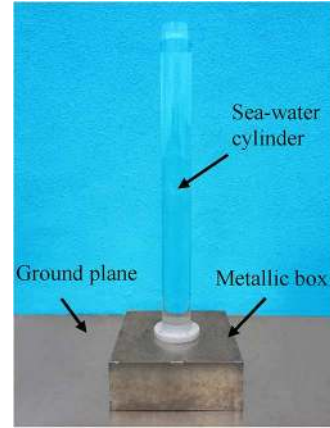


Fig. 5. Photograph of the fabricated monopole sea-water antenna.

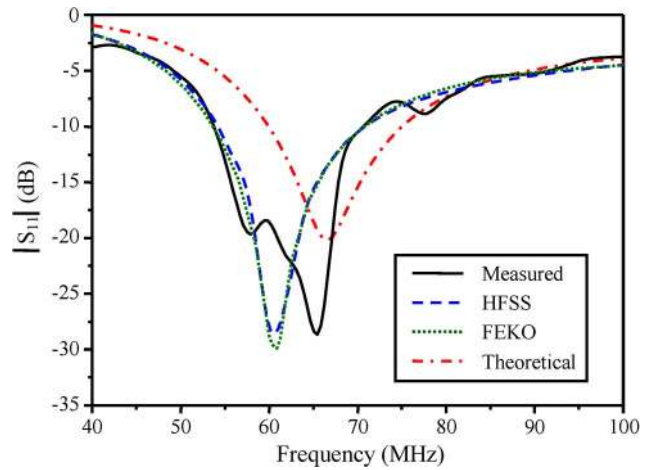


Fig. 6. Measured, simulated, and theoretically predicted reflection coefficients of the sea-water monopole antenna.

measurement, the sea-water monopole with the small metal box is placed on a very large conducting ground whose size is very large compared with the operating wavelength. The metallic box is connected with the ground plane through aluminum tape. The effect of the small box on the antenna's radiation can be neglected, according to the HFSS simulations. It can also be seen in the photograph, due to the transparency of the acrylic tube and the sea water, the whole antenna looks almost transparent. A comparison of the measured, simulated, and theoretically predicted reflection coefficients is made in Fig. 6. It is seen that HFSS and FEKO simulation results are almost the same. It can also be observed that reasonable agreement between measured and simulated results is obtained, with the discrepancy caused by experimental tolerances. The measured and simulated 10-dB impedance bandwidths are 27.8% (53.8–71.2 MHz) and 27.5% (54.3–71.6 MHz), respectively.

In addition to reconfigurable bandwidth mentioned in Section III, it is clear that this sea-water monopole antenna is also frequency-reconfigurable. The measured reflection coefficients with different heights of the sea-water cylinder are plotted in Fig. 7. It is found that, when the height h changes from 300 to 1000 mm, the center frequency of the antenna can be tuned over a wide frequency range of 62.5–180.2 MHz, with

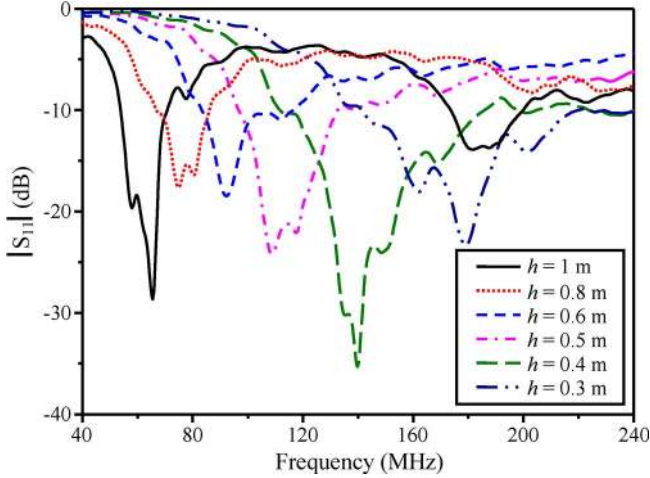


Fig. 7. Measured reflection coefficients with different values of height h .

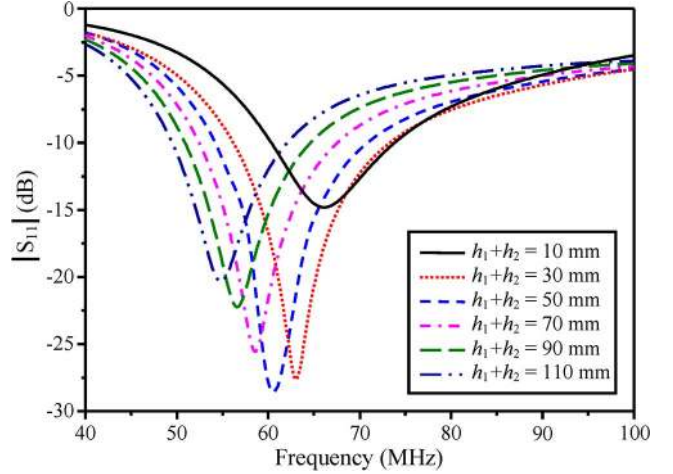


Fig. 9. HFSS simulated reflection coefficients with different values of $(h_1 + h_2)$.

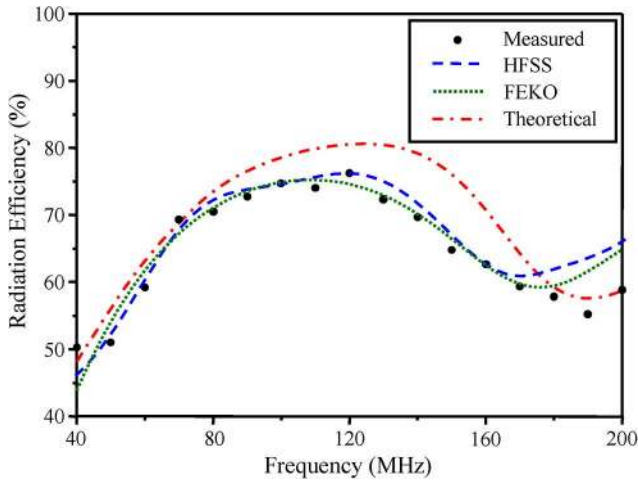


Fig. 8. Measured, simulated, and theoretically predicted radiation efficiencies of the sea-water monopole antenna.

the bandwidth varying between 26.1% and 49.2%. These results are very favorable, as the height of the sea-water cylinder can be easily adjusted by pumping sea water in or out.

The modified Wheeler cap method [15] is applied for measuring the radiation efficiency of the sea-water monopole antenna. Meanwhile, the method reported in [16] is used to change the effective electrical distance between the antenna and the metallic box by varying frequency rather than the box dimensions. Compared with the conventional Wheeler cap method [17], the modified Wheeler cap method allows using a large metallic box since the effect of resonances in the cap can be effectively canceled [15]. The measured, simulated, and theoretical radiation efficiencies of our sea-water monopole antenna are illustrated in Fig. 8. With reference to the figure, good agreement between the simulated and measured results is observed, with the discrepancy mainly caused by experimental tolerances. And reasonable agreement between the theoretical calculation and experimental results is also observed. Meanwhile, the measured radiation efficiency varies between 50.2% and 72.3% over the frequency band of 40–200 MHz.

It is worth mentioning that the efficiency shown in Fig. 8 is not the antenna's total radiation efficiency but the radiation ef-

iciency excluding the reflection loss. It should be noted that this antenna has a much higher radiation efficiency compared to those water antennas described in [2]–[5]. This is because the radiation efficiency of a quarter-wavelength water monopole antenna is mainly dependent upon its surface resistance. The smaller the surface resistance is; the higher is the radiation efficiency. In the frequency range of interest, the sea-water cylinder can be approximately treated as a good conductor; its surface resistance is relatively small leading to high radiation efficiency.

It is seen in both Fig. 6 and Fig. 8 that there are some discrepancies between experimental and theoretical results. Those disagreements can be attributed to the following three reasons. 1) Only the principal wave is considered in theoretical prediction. 2) The three-term theory involves some approximation when solving the Pocklington integral equation. According to [8], its validity in terms of height h , radius a , and conductivity σ are as follows: $k_0 h \ll 3\pi/2$, $k_0 a \ll 1$, and $|\sigma/\omega\epsilon| \gg 1$. The parameters of our theoretical model are: $\epsilon_r = 78.7$, $\sigma = 4 \text{ S/m}$, $h = 1 \text{ m}$ and $a = 50 \text{ mm}$. Therefore, in the design frequency range of 40–100 MHz, the parameters are within the validity range of the three-term theory. However, in the frequency range of 100–200 MHz, the value of $k_0 a$ becomes slightly large, and $|\sigma/\omega\epsilon|$ is relatively small. As a result, the discrepancies between measured and predicted radiation efficiency increases, as seen in Fig. 8. 3) Our fabricated model and the theoretical model are not completely identical due to the simplification made in the theoretical model. In the theoretical model, the analysis is carried out by only considering the monopole height h , but ignoring the height of the Teflon base ($h_1 + h_2$). It is found that this height ($h_1 + h_2$) will affect the reflection coefficient of the monopole antenna. Fig. 9 shows the simulated reflection coefficients with different values of height ($h_1 + h_2$). It is seen that, when ($h_1 + h_2$) increases, the resonant frequency of the sea-water monopole antenna shifts downwards. In our design, we choose ($h_1 + h_2$) to be 50 mm, due to the optimal return loss.

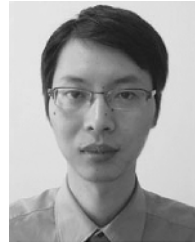
V. CONCLUSION

This paper has presented a detail design of a sea-water monopole antenna at VHF band for maritime wireless commu-

nications. A top-loaded probe has been designed to efficiently excite the dominant TM mode. In order to design an optically transparent antenna, a clear acrylic tube has been chosen to hold the sea water. Theoretical investigation about the monopole sea-water antenna has been carried out, which has not appeared in literature. Experimental results show reasonable agreements with theoretical predictions. The center frequency of this monopole is tunable by controlling the height of the sea-water cylinder, while the bandwidth of the antenna can be adjusted by widening or narrowing the water cylinder. The measured 10-dB impedance bandwidths is 27.8% (53.8–71.2 MHz), and the center frequency of the antenna can be tuned over a wide frequency range of 62.5–180.2 MHz, with the bandwidth varying between 26.1% and 49.2%. Meanwhile, the measured radiation efficiency varies between 50.2% and 72.3% over the frequency band of 40–200 MHz. The main features of the monopole sea-water antenna include its high radiation efficiency, high transparency, reconfigurability, low cost, and simple structure. All these characteristics make this antenna potentially very useful for VHF and HF wireless communications on the sea.

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