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Tunable High Frequency Seawater Antenna

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SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING

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Abstract

This research is on the study and design of a tunable high frequency (HF) seawater antenna for military applications. HF is for the range of radio frequencies between 3 MHz to 30 MHz. This corresponds to a wavelength of 100 m to 10 m. Since the physical size of an antenna is determined by its wavelength, approximately half a wavelength, $\lambda/2$, the size of the HF antenna is large and requires significant amount of space for installation and implementation. In a small island such as Singapore where land space is limited, operation of HF communications becomes a challenge.

The objective of this research is to design and implement a tunable HF antenna that requires minimum amount of land space. It is well known that the electrical conductivity of seawater is around 4 S/m. The idea is to make use of seawater to design an antenna such that the antenna can be "switched on" or "off" at will. By varying the length of the water stream, the frequency of the antenna can be varied. Along the coast or at sea, the implementation of the tunable seawater antenna is simple and practical. On land, such antennas can be implemented in reservoirs or as water features by altering the electrical properties of the water.

Simulation results for the monopole antenna was presented at the HF band. The characteristics of the ferrite coil are being examined and analyzed. By varying the outer radius, core radius and the permeability of the ferrite coil, the performance of the antenna will also be varied. Different stream lengths will cause different resonant frequencies response of the seawater monopole antenna. The proposed seawater monopole antenna meets the benefit of tunability. The performance of the seawater monopole antenna improves when the radius of the water stream increases. The seawater bend monopole antenna has a lower resonant frequency due to the additional length of the bend. The seawater monopole antenna including the falling water droplets that was observed in the experiment does not has any effect on the performance of the seawater antenna.

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Chapter 1

Introduction

This chapter serves to provide an outline of the research work. Information on the motivation of the research, its objectives and scope, as well as the organisation of the report is presented.

1.1 Motivation

In a small island such as Singapore where land space is limited, many forests and lands are being cleared for construction of housing. The size of the High Frequency (HF) antenna is large; HF is for the range of radio frequencies between 3 to 30 MHz. This corresponds to a wavelength of 100 m to 10 m. Since the physical size of an antenna is determined by its wavelength, approximately half a wavelength, $\lambda/2$, it will require significant amount of space for installation and implementation. Hence, the implementation of HF antenna becomes a challenge. Therefore, using fluid as an antenna is more practical as we can make use of the natural resources such as water and seawater.

Along the coast or at sea, there is an abundance of seawater, hence implementation of the tunable seawater antenna is simple and practical. On land, we can implement the water antenna in reservoirs or as water features by altering the electrical properties of the water.

Water antennas open up a new avenue for antenna design, besides that it offers many benefits as follows:

- Conformability: Flexible in design as it is easy to make the antenna conforms to the desired shape.

- Tunability: The operational frequency and bandwidth may be controlled by varying the length and width of the water stream respectively.

- Small Radar Cross Section (RCS): Can be turned off or drained when not in use.

- Easy to transport: Especially for a large antenna.

1.2 Objectives

The objective of this research is to design and implement a tunable HF seawater antenna for military applications. The size of the HF antenna is large and requires significant amount of space for installation and implementation. It is well known that seawater is an electrical conductor. The idea is to make use of seawater to design an antenna such that it can be switched "on" or "off", when necessary. By varying the height of the seawater stream, the operating frequency of the antenna can be tuned. Another potential application is that the antenna can also be used on land or on sea as an emergency antenna system.

After performing a literature review on water antenna, we list the key fields of research to be further investigated:

- Study and design of a tunable HF seawater antenna for military applications.

- Design and analyze the characteristics of ferrite core by performing numerical simulations.

- Study the effect on how falling water droplets affect the performance of the seawater monopole antenna

Moreover, it was found that most of the water antennas were operating in the VHF range and above, which is higher than the HF range. There exists a lack of substantial antenna results for water antennas in the HF range. Hence, this warrants further investigations to fulfil the research gap, which constitutes part of the objectives of this research topic.

It was also observed that the water antennas proposed by the mentioned studies had different feed mechanisms, of which majority of them made use of the electric probe feed. An exception is the electrolytic fluid antenna by D. Tam [1-2], which made use of the current probe as the feed mechanism. However, little is known on the characteristics of the current probe and their effectiveness as an antenna feed mechanism.

Hence, this research also aims to study the physical and electromagnetic properties of the current probe and their effects on the antenna performance. Since the current probe is made of ferrite cores, the characteristics of the ferrite core will also be studied.

Furthermore, it is important to determine the ideal dimension in order for the seawater monopole antenna to function. Thus, further investigations were performed by varying the conductivities and radius of the seawater monopole antenna.

When a stream of water is being pumped up to a certain height, the raising water stream will definitely fall back to the ground due to gravity. In the experiment, it was observed that the water stream formed a U-shape bend at the top followed by disconnected water droplets when flowing back to the ground. A seawater bend monopole antenna was simulated to match the U-shape of the seawater monopole antenna including falling water droplets that was observed in the experiment. The objective is to study the effect on how falling water droplets affect the performance of the seawater monopole antenna. Comparison between the fundamental seawater monopole antenna and the seawater bend antenna are presented as well.

1.3 Major Contributions of the Thesis

The contribution of this thesis is to investigate a tunable HF seawater antenna via numerical simulations. Simulations are performed to analyze the characteristics of the current probe, which is used as the feeding mechanism for the seawater antenna. Besides that, the major contributions includes the design of the seawater antenna, fabrication of the current probe and seawater antenna, performing experiments to measure the permittivity of different water and conducting experiment to collect measurement data of the proposed seawater antenna.

Different types of water antenna have been reviewed and studied in this thesis. Comparison of simulation results of the monopole antenna using different probe feed, such as the electric feed and current probe feed was provided. The characteristics of the current probe was also analyzed in this thesis. In particular, the effect of permeability, inner and outer radius of the ferrite core on the reflection coefficient was studied. A DIY current probe was fabricated to be used as a current probe feed for the proposed antenna.

The permittivity of different water was measured. It shows that the relative permittivity of the seawater and the saltwater is equivalent. Hence, in our experiments saltwater was used as an alternative to seawater.

Measurement results of the proposed seawater antenna obtained from the experiment shows that the proposed seawater antenna is not efficient. Hence, the electric probe feed was further investigated. Additional simulations were performed by varying the conductivities and radius of the seawater monopole antenna. A seawater bend monopole antenna was simulated to match the shape of the seawater antenna carried out in the experiment. Comparison between the fundamental seawater monopole antenna and the seawater bend antenna are presented as well. A conical shape seawater monopole antenna was simulated to achieve broadband performance.

In addition, the efficiency of the seawater antenna can be further improved by implementing an automatic impedance matching network/circuit. As we tune to a particular frequency, the height of the water column will changes accordingly.

1.4 Organization of the Thesis

This thesis is organised into six main chapters, as follows:

Chapter 1 Introduction

The current chapter serves to inform the reader of the motivation, objectives and scope of the research.

Chapter 2 Literature Review

In this chapter, some background information pertaining to the topic of interest is provided. Specifically, important concepts on antenna and its parameters are described. A review of relevant works on water antennas is also presented and discussed.

Chapter 3 Investigation of Monopole Antenna

In this chapter, the commonly employed HF monopole antenna is used in the simulation design. Two types of feeds for the monopole antenna were simulated. The characteristics of the ferrite coil are examined and analyzed. Variations of the outer radius, core radius and the permeability of the ferrite coil changes the performance of the antenna.

Chapter 4 Measurement of the Proposed Seawater Antenna

In this chapter, experiments were carried out to examine the practicality of the proposed HF seawater monopole antenna. The first experiment was performed to analyze the relative permittivity of different water. Next, the construction of DIY current probe to be used for the proposed seawater antenna was finalised. Finally, the proposed seawater antenna was measured and results from the experiments are shown and discussed.

Chapter 5 Further Investigation

In this chapter, additional simulations were performed by varying the conductivities and radius of the seawater monopole antenna. A seawater bend monopole antenna was simulated to match the shape of the seawater antenna carried out in the experiment. Comparison between the fundamental seawater monopole antenna and the seawater bend antenna are presented as well. A conical shape seawater monopole antenna was simulated to achieve broadband performance.

Chapter 6 Conclusion

In this chapter, the overall design work accomplished with respect to its initial stated objectives is discussed. Contributions of the thesis as well as its limitations are presented.

Chapter 7 Future Work

Future work for the seawater antenna such as extensions to broadband seawater antenna and array seawater antenna are provided in this chapter.

Chapter 2

Literature Review

This chapter presents some basic concepts of antennas for HF applications and reviews the recent works on water antennas.

2.1 Antennas for HF Applications

An antenna is a device designed to transmit or receive electromagnetic wave, matching these sources of energy and the free-space. It is also known as radiant systems. The IEEE antenna standards define an antenna as "that part of a transmitting or receiving system that is designed to radiate or to receive electromagnetic wave [3]." In other words, antenna is the transitional structure between free-space and a guiding device [4], as shown in Figure 2.1. Antennas are widely used in the field of wireless communications. Mobile communications involving aircraft, spacecraft, ships, or land vehicles requires antennas.

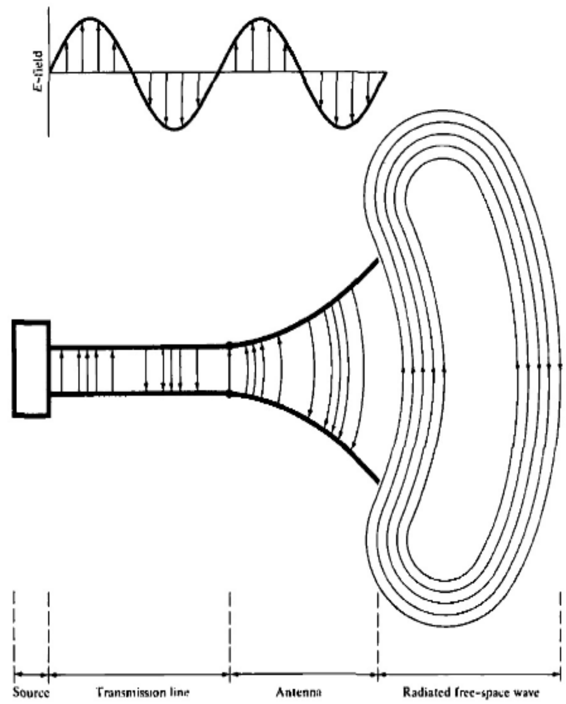


Figure 2.1 Antenna as a transition device [4]

2.1.1 HF Radio Spectrum

Antennas can be designed to transmit or receive electromagnetic waves that belong to different frequency bands. For example, an antenna that is designed to operate in the HF range is termed a HF antenna. Table 2.1 lists the frequency bands and their corresponding wavelengths in the electromagnetic spectrum.

Referring to Table 2.1, HF consists of radio frequency electromagnetic waves between 3 to 30 MHz. It is also known as the decameter wave as the wavelength range from one to ten decameters (ten to one hundred meters). Frequencies below HF are denoted as medium frequency (MF) and the next higher frequencies are known as very high frequency (VHF) [4].

Table 2.1 Radio band chart

Band	Frequency range	Wavelength range
Extremely low frequency (ELF)	<3 kHz	>100 km
Very low frequency (VLF)	3-30 Hz	10-100 km
Low frequency (LF)	30-300 kHz	1-10 km
Medium frequency (MF)	300 kHz-3 MHz	100m - 1 km
High frequency (HF)	3 - 30 MHz	10 - 100 m
Very high frequency (VHF)	30 - 300 MHz	1 - 10 m
Ultra high frequency (UHF)	300 MHz - 3 GHz	10cm - 1 m
Super high frequency (SHF)	3 - 30 GHz	1 - 10 cm
Extremely high frequency (EHF)	30 - 300 GHz	1mm - 1 cm

The radio waves in HF band can be reflected back to earth by the ionosphere layer in the atmosphere, this is known as skywave propagation. The ionosphere is a layer of electrically charged particles at the top of the earth's atmosphere. Multiple reflections between this layer and the earth are possible, hence enabling long distance communications in the HF band.

The disadvantage of this type of propagation is that it depends on the ionosphere, which varies widely during daylight hours. The waves are reflected differently due to this variation and they may take different paths over a period of time. This results in signal strength variations at the receiver, which causes the output to fade in and out.

Another propagation mechanism for HF radio waves is via surface waves (ground waves). Here, the vertically polarized wave propagates over highly conductive surface and it is commonly employed in radars.

The main users of HF spectrum are listed below:

- Military and government communication systems
- Aviation air to ground communications
- Amateur radio
- Maritime sea-to-shore services
- Over the horizon radar systems
- Global Maritime Distress and safety System (GMDSS) Communications
- Shortwave international and regional broadcasting

2.2 Monopole Antenna

A monopole antenna [4] consists of a straight rod-shaped conductor mounted perpendicularly over a conductive ground plane as shown in Figure 2.2.

The monopole antenna is a resonant antenna. The rod functions as a resonator for radio waves, with oscillating standing waves of voltage and current along its length. Hence, the length of the antenna is determined by the wavelength of the radio waves. The most common one is the quarter-wave monopole antenna, where the antenna is approximately 1/4 of a wavelength of the radio waves.

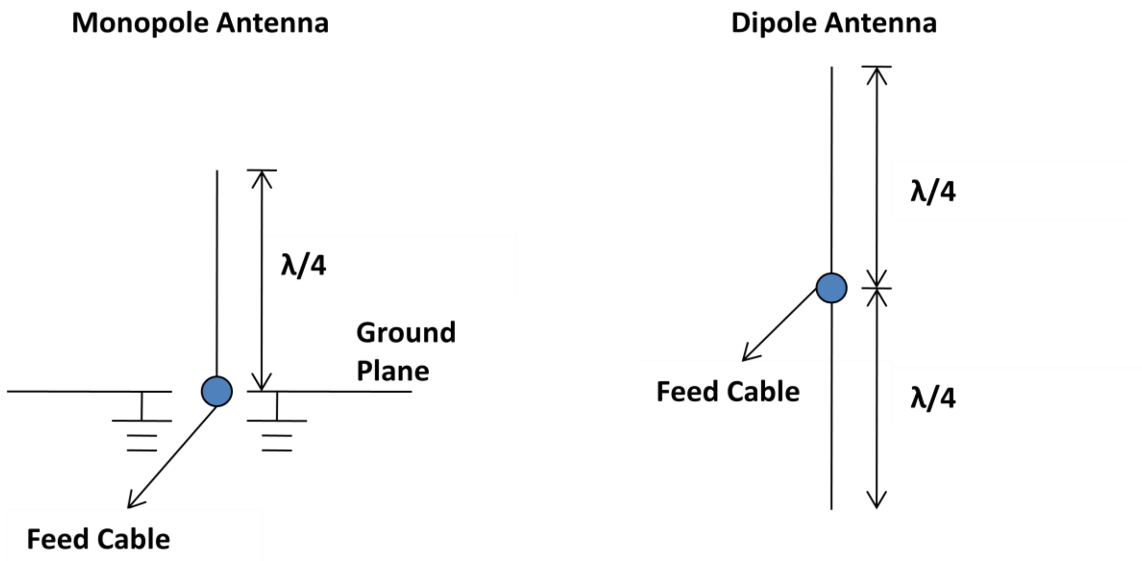


Figure 2.2 Comparisons of monopole and dipole antenna

A monopole antenna is a dipole antenna that has been divided in half at its center feed point and fed against a ground plane. The currents and charges on a monopole antenna are the same as on the upper half of its dipole antenna counterpart, but the terminal voltage is only half the dipole antenna. The voltage is half because the gap width of the input terminals is half that of the dipole antenna and the same electric field over the distance gives half the voltage.

The input impedance for a monopole antenna is therefore half of its dipole antenna counterpart [4]. Because the field only extend over a hemisphere, the power radiated is only half that of a dipole antenna with the same current.

The directivity of a quarter-wave monopole antenna is twice that of a half-wave dipole antenna in free space, D = 2(1.64) = 3.28 = 5.16 dB

The input impedance of an infinitesimally thin quarter-wave monopole antenna is

Z = 1/2*(72 + j42.5) = 36 + j21.3

In chapter 3 of this thesis, besides using a conventional electric probe [5-8, 10, 21, 26-27], a current probe feed can also be considered [1-2]. Although less efficient, the current probe has the advantage of non-contact feed.

2.3 Water Antenna

Water antenna has become a popular and interesting topic in the recent years. There are several kinds of water antennas being reported [1-2, 5-8, 10, 21, 26-27]. In [5], an interesting technique of using electrically conducting liquids such as saltwater and biological fluids (plant-sap) to develop an antenna at microwave frequencies was presented. When an electromagnetic field is applied to seawater, the ions will migrate, thus producing an electric current. Due to the fluidity, the water can be pumped into a plastic tube and thereby “deployed” when the antenna is activated. When deactivated, the water can be pumped out or drained and the tube can also be removed, resulting in very small storage space and radar cross section.

The interest on fluid antenna began in 2005 and 2006 when a major progress was made by H. Fayad and P. Record. Three papers on ionic liquid antenna and saline-water antenna were published in 2005 and 2006 [6-8]. In 2011, Tam *et al* filed two US patents on electrolytic fluid antenna, which gave the components of their seawater antenna [1-2]. These are the works that are more related and worth focusing on for the water antenna which is presented in this report.

2.3.1 Electrolytic Fluid Antenna

Firstly, we will be looking into the water antenna invented by SPAWAR System Center Pacific (SSC Pacific) [1] as shown in Figure 2.3. They make use of seawater to transmit and receive communication signals. The seawater has an electrical conductivity of approximately 4 S/m. The electric currents in seawater are flows of electrically charged atoms (sodium ions). When seawater is used, the movement of the sodium ions in the stream allows electric current conduction for signal reception and transmission. This seawater antenna system works by pumping a stream of seawater through a current probe and depending on the height of the stream, the frequency of the antenna can be determined. The current probe comprises a ferrite core and a metallic housing. Besides that, the diameter of the stream determines the antenna's bandwidth.

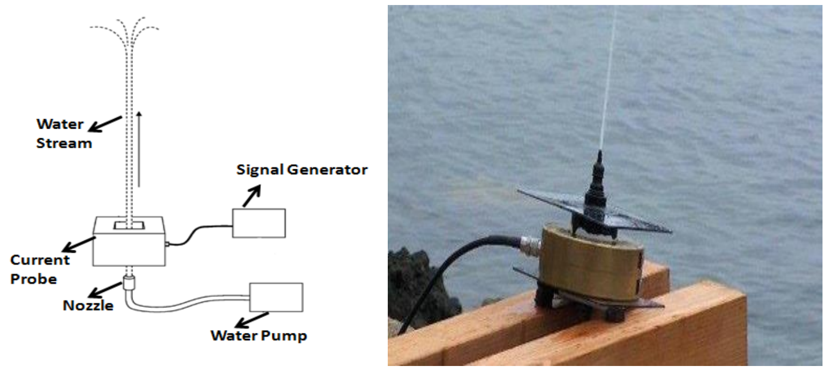


Figure 2.3 Electrolytic fluid antenna [1]

The advantages of the antenna are listed below:

- ✓ Can be turned off when not in use, allowing the antenna to 'disappear' from the environment
- ✓ Tunability
- ✓ Conformability
- ✓ Easy to transport

However, there are also disadvantages for the antenna as follows:

- ✓ Complicated feed structure
- ✓ Lower efficiency

(A) Current Probe Concept

The electrolytic fluid antenna invented by SSC Pacific [1] made use of current probe feed to couple magnetic field into the fluid stream. The current probe comprises a ferrite core and a metallic housing. Figure 2.4 shows a commercial current probe from Fisher Custom Communications.

Figure 2.4 Commercial current probe [9]

The current probe concept can be explained by using Ampere law [9] as stated in (2.1).

$$\oint_c \vec{H} \cdot \overrightarrow{dl} = \oint_S \vec{J} \cdot \overrightarrow{ds} + \frac{d}{dt} \epsilon \oint_S \vec{E} \cdot \overrightarrow{ds} \tag{2.1}$$

Ampere's law shows that a magnetic field can be induced around a contour by either conduction current or displacement current that penetrates the open surface S. A time-changing electric field produces a displacement current. If no time-changing electric field penetrates this surface, the induced magnetic field is directly related to the conduction current passing through the loop.

A current probe is constructed from a core of ferrite material. When a current is passed through a ferrite core with an N number of turns, it will produce a magnetic field circulating around the core, as shown in Figure 2.5. The purpose of a current probe is to measure the amount of current passing through the conductor.

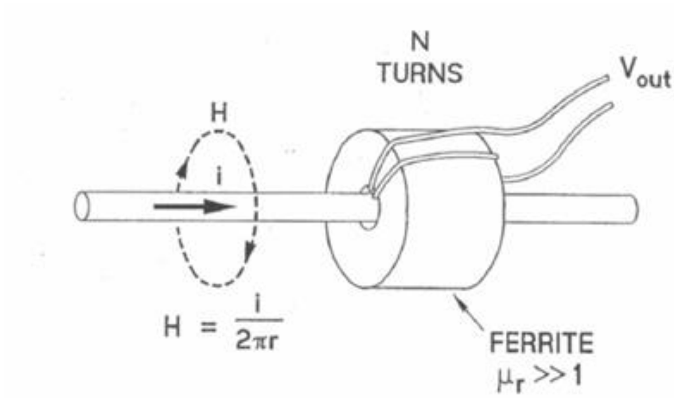


Figure 2.5 Concept of current probe [9]

However, regarding the current probe antenna [9] in general, the antenna voltage is the product of the effective length of the antenna times the incident electric field. An incoming RF signal may be considered as the incident electric field. The antenna current is obtained from the antenna voltage divided by the self-impedance of the antenna. The antenna current in turn generates the magnetic field, which is then picked up by the current probe. The magnetic flux density, or B field, in the current probe depends on the magnetic field in the ferrite core and the permeability μ of the ferrite core as shown in (2.3). The magnetic flux ϕ in the ferrite core is produced by the B field passing through the cross section of the ferrite coil. The changing magnetic flux ϕ produces the output voltage by the one-turn loop on the ferrite core.

$$H = \frac{I}{2\pi r} \tag{2.2}$$

$$B = \mu \cdot H \tag{2.3}$$

$$\phi = \int \mathrm{B} \cdot \mathrm{Ds} \tag{2.4}$$

2.3.2 Wideband Saline-water Antenna

Another team of researchers has come out with a wideband saltwater antenna [6]. In this work, the authors used pure water as the fluid which has good dielectric properties for frequencies up to 2 GHz. This comes about because the molecules increase their thermal energy with increasing frequency and are less able to follow the applied electric field. In addition, salt (Salinity < 6 ppt) was added to modify the dielectric response (real and imaginary) of the pure water at high frequencies (< 2 GHz).

In this paper, PVC tube was used to contain the fluid. The tube was attached to the ground plane via a SMA connection sealed with silicone rubber. The PVC container was positioned so that the container and the feed probe were concentric. The resonant frequency of the proposed antenna is now changed by varying the liquid column height. The structure of the antenna is shown in Figure 2.6.

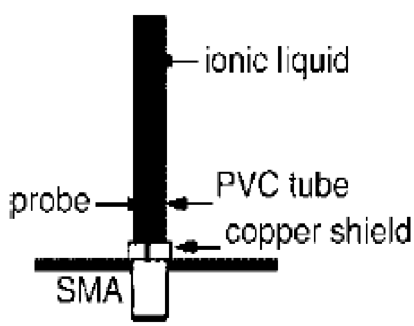


Figure 2.6 Geometry of saline-water antenna [6]

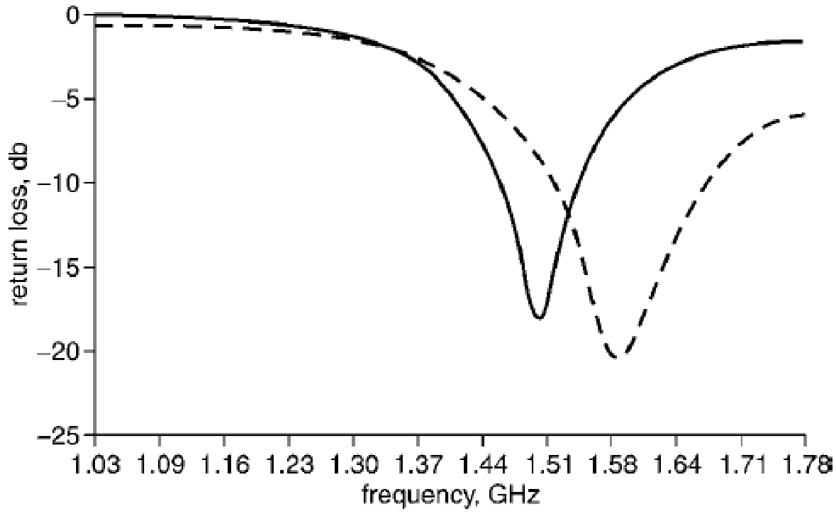


Figure 2.7 Measured and simulated return loss [6]

Here, the authors made use of water and saltwater as the fluids for the antenna. Water is a high permittivity material which has good dielectric properties. The performance of this antenna was carefully studied by dissolving salt into pure water.

The measured and simulated return loss for the 25 mm diameter tube filled with 2.07 cm of pure water is shown in Figure 2.7. The liquid column height was estimated from the known volume of liquid in the PVC tube. The simulated results were in good agreement with the measured results. The resonant frequency for this simulated design was 1.51 GHz with a bandwidth of 8.27%, while the measured results on the prototype revealed a resonant frequency of 1.59 GHz and bandwidth of around 10.06%.

Based on another design for ionic liquid antenna [8] done by the same author, a feeding probe loaded with nut and washer was introduced to improve the performance of the monopole water antenna as shown in Figure 2.8. Two saltwater antennas of diameter 2.5

cm and 5 cm was constructed. For each antenna, the salinity of the salt solution was 35 ppt and 70 ppt. Both saltwater antennas were mounted on a 30 X 30 cm aluminum ground plane.

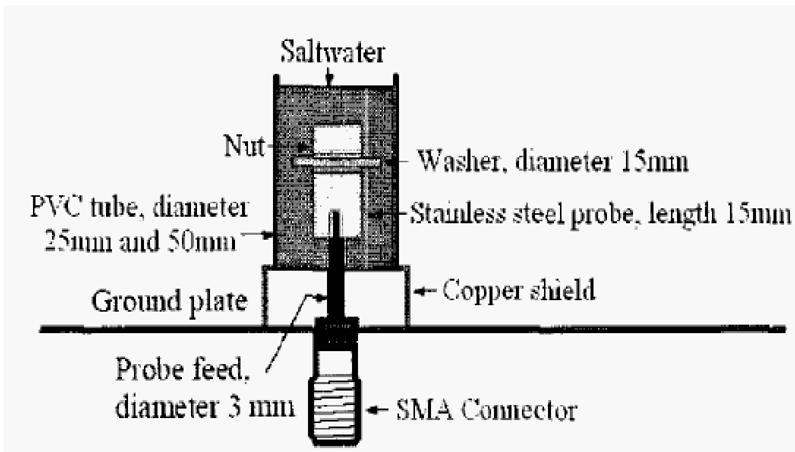


Figure 2.8 Geometry of seawater antenna on the ground plane [8]

Simulation and experimental results shows that the radiation efficiency of the ionic liquid antenna is between 50 to 70% at microwave frequencies. It was also found that the resonant frequency of the antenna is inversely proportional to its radiator height, and a large bandwidth is observed at 1.3 GHz.

(A) Dielectrics materials

In these papers, the authors made use of salt dissolved in water as the radiating element. Conductivity is an important electrical property of saltwater. It is a common parameter used to determine the salinity of saltwater. Salinity is the total amount of dissolved salts in grams in one kilogram of saltwater. It is a dimensionless quantity. In their experiment, measurements are made on water and salt solutions. Saltwater is mostly making up of water. It has both conductive ions in solution and high dielectric constant [8]. Water is a good solvent for substances that are held together by ionic bonds. When we add salt to pure water to make saltwater, the conductivity of the solvent increases. When an electromagnetic field is applied to saltwater, the ions will migrate, thus produce electric current. The conductivity of an aqueous electrolyte solution increases almost linearly with temperature. With an increasing temperature, the mobility of the ions also increases.

2.3.3 A Monopole Water Antenna

A monopole water antenna [10] is another work implemented using a similar concept of varying the liquid column height. The water antenna height is 50 mm. The relative permittivity of the seawater is 81 and the conductivity is 4.7 S/m. A PVC tube with relative permittivity of 4 is used to hold the water. The height and diameter of the tube is 100 mm and 25 mm, respectively. The thickness of the conducting ground plane is 1 mm.

The outer conductor of coaxial feed was connected to the ground plane. In addition, a dielectric foam base is used to maximize its bandwidth. The conductivity of the water is controlled by adding salt. Different conductivity of the saltwater produces different efficiency. With the different conductivities, the antenna can be regarded as a dielectric resonant antenna. The structure of the fluid antenna is shown in Figure 2.9.

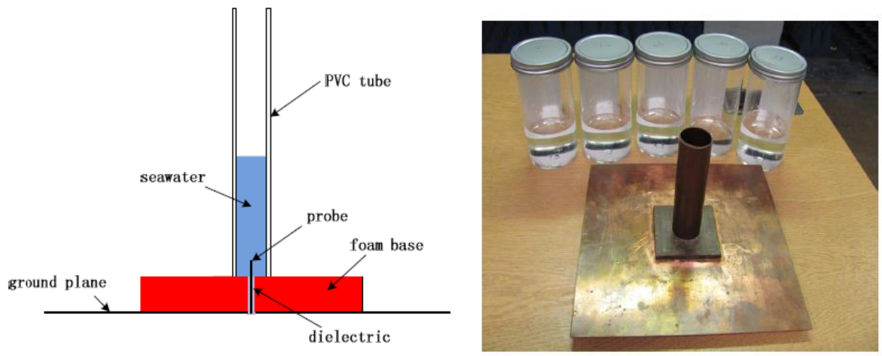


Figure 2.9 Geometry of monopole water antenna [10]

In this section, a monopole water antenna with a relative permittivity of 81 [11] and a variable conductivity has been studied. Two issues are addressed in the paper. Firstly, the relationship between the conductivity and antenna radiation efficiency is investigated. Secondly, a new feed design for the water antenna is proposed and a good return loss, radiation efficiency and radiation pattern are obtained.

The simulation and measurement results are shown in the Figure 2.10. The measured resonant frequency has 0.2 GHz shift.

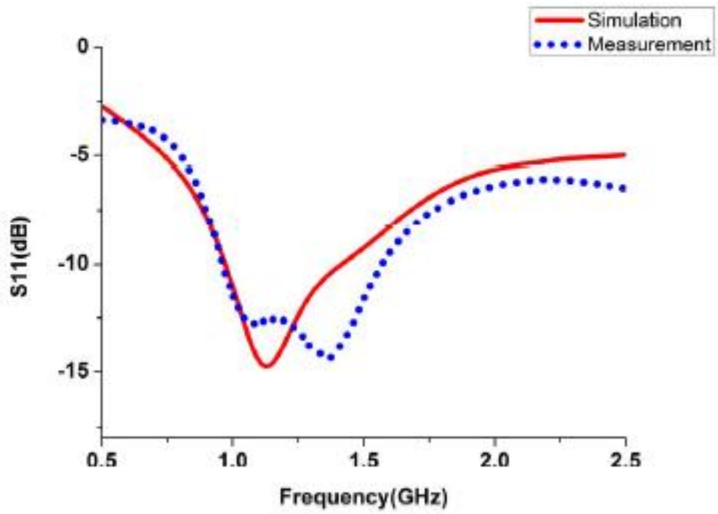


Figure 2.10 Simulation and Measurement S11 Result [10]

The conductivity of the water can be controlled by adding salt into water. When the amount of salt added to water increases, the bandwidth also increases. When the salt concentration reaches to saturation, the bandwidth will be stable. In the measurement, three samples with salt concentration 0.001 g/ml, 0.005 g/ml and 0.01 g/ml are chosen to test the S11 response. It showed that saltwater with concentration 0.005 g/ml has the deepest point.

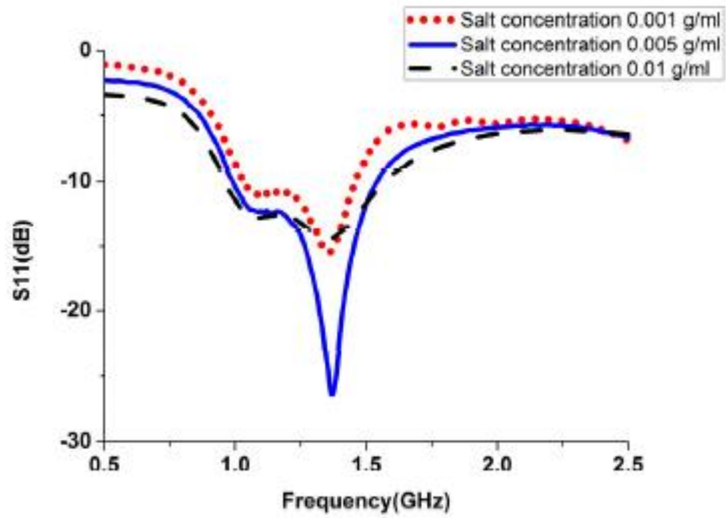


Figure 2.11 S11 results for different salt concentration [10]

(A) Dielectric Resonator Antenna

A dielectric resonator antenna (DRA) can be regarded as a kind of resonator fabricated from low-loss microwave dielectric materials and the resonant frequency is predominantly a function of its size, shape, and material permittivity [12]. Much work has been done in studies of this type of antenna. Different shapes, feed structures as well as antenna arrays have been considered, and also in how to make it compact and wideband [13-15].

From 1980s to the present, a lot of publications have demonstrated DRAs' attractive features in following aspects: a) high efficiency (> 95%) for little/no conductive or surface wave loss; b) flexible in design since many different shapes can be used; c) easy to integrate with various existing technologies as several feeding mechanisms can be applied; d) versatile modes can be excited forming different radiation patterns and serving various applications; and e) materials with a wide range of permittivity can be used to fabricate DRAs, so different sizes can be employed for the same frequency [12]. A significant number of the recent publications involved designing DRAs for special applications, including integration into mobile handset, UWB and radar applications, breast-cancer imaging, RFID etc [16-18].

As a special type of DRAs, fluid (such as water and ionic liquid) antennas open up a new avenue for antenna design and may offer some benefits in the following aspects: a) conformability – it is easy to make the antenna to the desired shape which may be hard to achieve using other dielectric or metal; b) tunability – the operating frequency and bandwidth may be controlled using the length, height and width of the liquid stream; c) small RCS – it can be turned off or drained when not in use; d) easy to transport – especially for a large antenna and e) low-cost, in particular if it is water or seawater; f) improvement in electromagnetic coupling – an air gap between probe and dielectric introducing unwanted changes in resonance and impedance can be improved [19].

(B) Conductivity

In [10], it is proved that the conductivity will affect the antenna radiation efficiency. Hence, conductivity is an important parameter to look into when we are choosing different fluids. By changing the conductivity of water, the antenna will show different performance. Seawater may be considered as a conductor and suitable for making normal conducting antenna.

When an electric field is applied to a conductor, the electrons move in random directions but drift slowly (with a velocity $\boldsymbol{v_e}$) in the negative direction of the applied electric field, thus creating conduction current in the conductor [20].

The applied electric field **E** and velocity $\boldsymbol{v_e}$ of the electrons are related by

$$\boldsymbol{v_e} = -\mu_e \mathbf{E} \tag{2.5}$$

where μ_e is defined to be the electron mobility [positive quantity with units of $m^2/(V\text{-}s)$].

The conduction current density is defined as

$$J = nq\boldsymbol{v_e} \quad (A/m^2) \tag{2.6}$$

where q is the electron charge and n is the number of electrons per volume.

Substituting (2.5) into (2.6), we can write that

$$J = nq\boldsymbol{v_e} = nq(-\mu_e \mathbf{E}) = -nq\mu_e \mathbf{E} \tag{2.7}$$

Finally, the conduction current density

$$J = \sigma_s \mathbf{E} \tag{2.8}$$

we define the static conductivity of a conductor as

$$\sigma_s = -nq\mu_e \ (S/m) \tag{2.9}$$

The conductivity σ of a conductor is a parameter that characterizes the free electron conductive properties of a conductor. As the temperature increases, the thermal energy of the conductor increases the free electron's mobility.

In aqueous solutions, such as the saltwater, the electrical current is carried by charged ions. The conductivity is determined by the number of charge carriers, how fast they move, and how much charge each one carries. Hence, for most aqueous solutions, the higher the concentration of dissolved salts (which will lead to more ions), the higher the conductivity. This effect continues until the salinity reaches a maximum value, after which, the conductivity may actually decrease with increasing concentration. This can result in two different concentrations of dissolved salt having the same conductivity. In addition, raising the temperature provides more energy to the ions making them move faster, and hence increases the conductivity.

The conductivity σ_s is referred to as the static or d.c conductivity; the value for typical drinking water is 10^{-2} S/m and the conductivity of the seawater is 4 S/m. The conductivity varies as a function of frequency [20].

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

In 2014, the seawater monopole antenna [21] implemented consists of a transparent plastic tube filled with seawater and a top-loaded feeding probe. The feeding probe is loaded with a disk on the top to improve the excitation mode of TM mode. The dimension of their fabricated seawater monopole antenna is as follows: h = 1 m, h_1 = 30 mm, h_2 = 20 mm, a = 50 mm and t = 3 mm. In order to facilitate the measurement, a small metallic box with an open bottom is used to support the antenna. The geometry of the seawater antenna is shown in Figure 2.12.

The antenna has high efficiency due to efficient feeding structure and the thick seawater cylinder used. The seawater monopole antenna is tunable. Its center frequency and bandwidth can be tuned by changing the height and radius of the water cylinder, respectively.

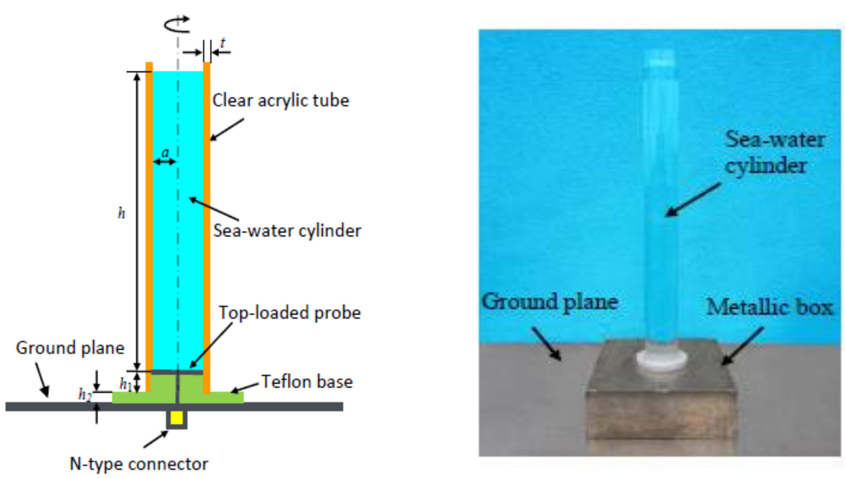


Figure 2.12 Geometry of seawater monopole antenna [21]

Seawater has a relative permittivity of 81 and conductivity 4 S/m [10]. However, the electrical properties of the seawater depends on its chemical composition which varies from time to time and at different locations. Furthermore, the electrical properties of seawater also varies with the temperature, pressure and frequency [22-24].

In the frequency range from 40 to 100 MHz, seawater 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 an imperfect dielectric. Hence, in this case, a seawater cylinder acts as a monopole antenna, while a fresh-water cylinder serves as a dielectric resonator antenna.

The advantages of the antenna are being listed below:

- ✓ Simple feeding structure
- ✓ High radiation efficiency
- ✓ Tunability
- ✓ High Transparency
- ✓ Low cost

However, there is a disadvantage of the antenna

- ✓ Need a tube to hold the water

A comparison of the measured, simulated, and theoretically predicted reflection coefficients is presented in Figure 2.13. 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.

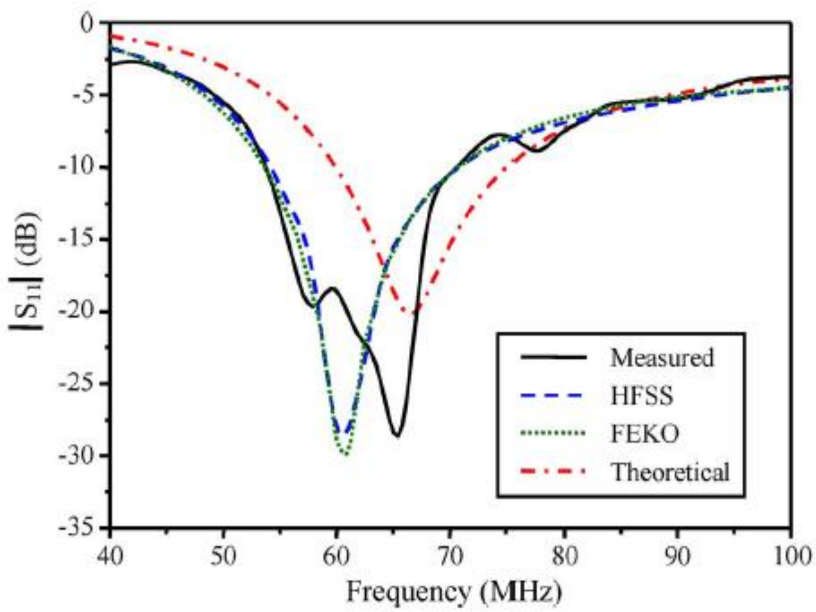


Figure 2.13 Reflection coefficients of seawater monopole antenna [21]

(A) Determination of Radiation Efficiency

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. The radiation efficiency is defined as the ratio of the total power radiated by the antenna to the total power accepted by the antenna at its input terminals during radiation.

System factors, such as impedance and/or polarization mismatches, do not contribute to the radiation efficiency because it is an inherent property of the antenna.

The radiation efficiency [25] can be computed using the equation listed below,

$$\text{Radiation efficiency} = \frac{gain}{directivity} \tag{2.13}$$

where directivity and gain, imply that they are measured or computed in the direction of maximum radiation.

In [20], the radiation efficiency is being obtained as follows. Once the current distribution *I*(z) is obtained, the ratio of the power dissipated internally in heating the antenna to the total power can be calculated as

$$\frac{P^i}{P_{total}} = \int_{-h}^{h} \frac{|I(z)|^2 r^i}{|I(0)|^2 R_0} dz \tag{2.14}$$

where r^i and R_0 are the real part of the surface and input impedance, respectively. Thus, the radiation efficiency for the half-wavelength dipole in free space can be written as

$$\eta = 1 - \left(P^i / P_{total} \right) \tag{2.15}$$

If designed properly, this seawater 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.

2.3.5 Sea-Water Half-Loop Antenna for Maritime Wireless Communications

In 2015, a seawater half-loop antenna [26] was implemented, in contrast to the metal-wire counterpart, it can be tunable and turned off in real time; therefore it is a more convenient small space antenna available to ships for maritime wireless communications. Figure 2.14 shows the geometry of the proposed sea-water half-loop antenna. As shown, the antenna mainly consists of a capacitive coupling feeding structure and a stream of sea water supplied by a water pump. The feeding structure is formed by a metallic tube with a tilt angle θ, a feeding post and a dielectric-filled parallel-plate capacitor. When the antenna is activated, the seawater is first pumped into the metallic tube, and then the water stream shoots out from the tube to form a half-loop. The signal couples to the antenna from the feeding post through the parallel-plate capacitor.

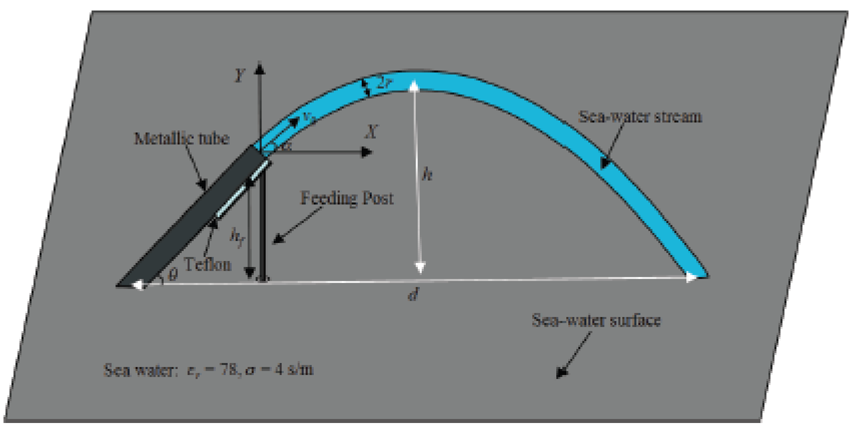


Figure 2.14 Geometry of the sea-water half-loop antenna [26]

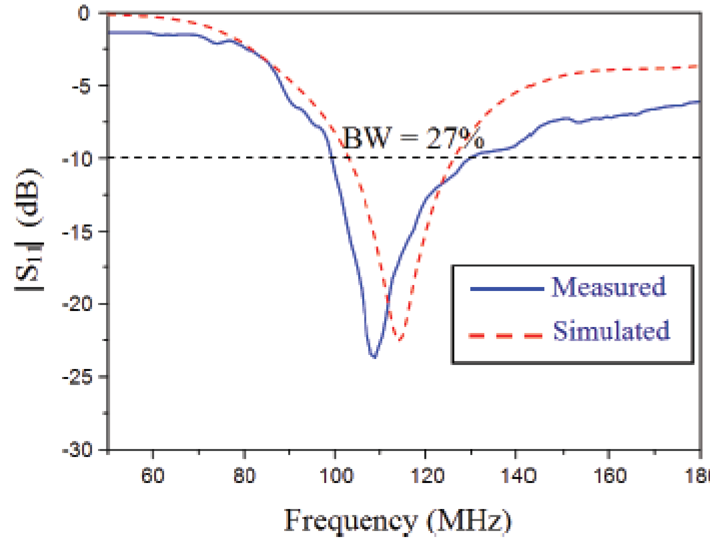


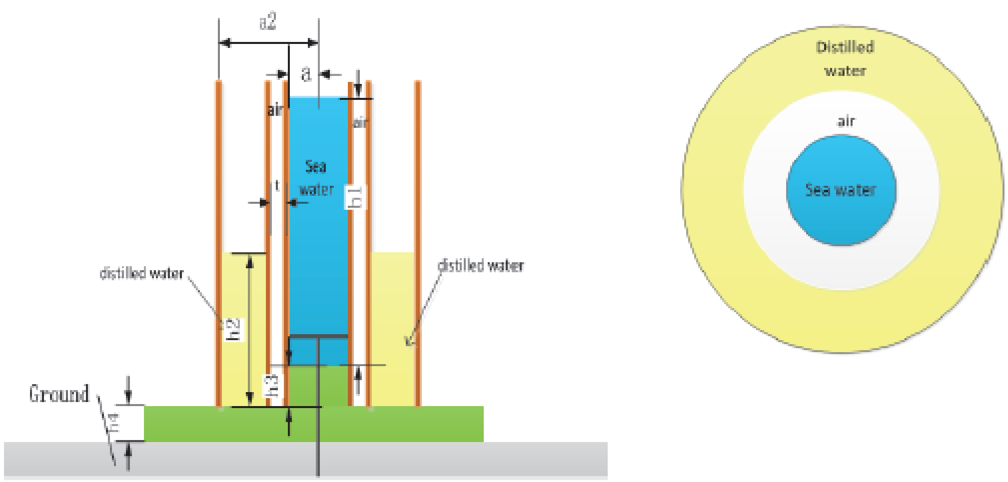
Figure 2.15 Measured and simulated reflection coefficients of the sea-water half-loop antenna [26]

The measurements are conducted in a seaside environment. Figure 2.15 shows the simulated and measured reflection coefficient of the antenna. It can be observed that the impedance bandwidth of this antenna is around 27%. The measured gain is -0.2 dB at 110 MHz, corresponding to a radiation efficiency of about 35%.

2.3.6 Broadband Hybrid Water Antennas

In [27], two novel broadband hybrid water antennas are presented. The hybrid antenna is composed of a seawater monopole and a distilled-water ring antenna.

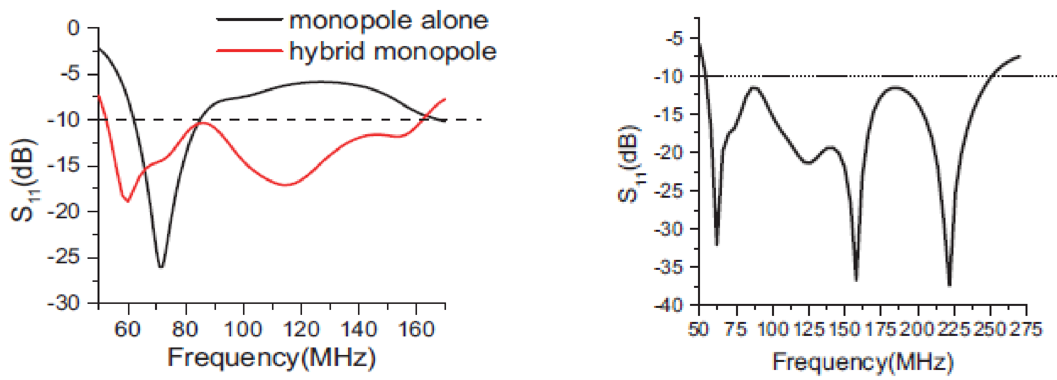
The structure of the proposed hybrid water antenna is shown in Figure 2.16. The seawater monopole is placed on a dielectric base of Teflon with relative permittivity 2.1 and on the ground. A clear acrylic tube is chosen to hold the seawater. It is vertically fitted with the Teflon base and sealed with silicone gasket. The length and radius of the seawater monopole are 1 m and 50 mm respectively. The relative permittivity of seawater is 81 and conductivity 4 S/m. The feeding probe loaded with an aluminium disk is inserted in the seawater tube. A ring tube with distilled-water is placed on the Teflon base surrounding the seawater monopole which plays as a ring dielectric resonator antenna. The final dimension of this antenna are as follows: t = 65 mm, h3 = 30 mm, h4 = 20 mm.



(a) Cross-sectional view (b) Top view

Figure 2.16 Geometry of the hybrid water monopole-ring antenna [27]

The spacing between seawater and distilled-water antennas not only provides a space placing acrylic tubes, but also plays a significant role in coupling the electromagnetic fields between the seawater and distilled-water antennas. The outer radius and height of the ring antenna are 160 mm and 600 mm, respectively. The relative permittivity of distilled water is 81 and conductivity 0.0002 S/m. By changing the space between the monopole and ring antennas, the hybrid antenna can have a good impedance performance, the final simulated S11 result is shown in Figure 2.17(a). A wide impedance bandwidth from 52.5 to 162.5 MHz (102%) is achieved.



(a) single monopole and hybrid water monopole-ring antenna

(b) hybrid water monopole-conical antenna

Figure 2.17 Simulated reflection coefficient of hybrid water monopole antenna [27]

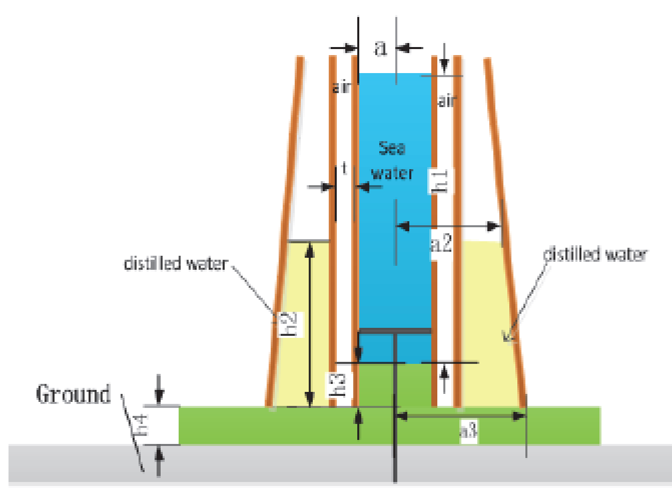


Figure 2.18 Geometry of the hybrid water monopole-conical antenna [27]

If the ring antenna is replaced by conical antenna, the impedance bandwidth can be improved. The cross-section view of the antenna is shown in Figure 2.18. The final dimension of this antenna are as follows: h1 = 1000 mm, h2 = 650 mm, h3 = 15 mm, h4 = 20 mm, a = 50 mm, a2 = 131 mm, a3 = 190 mm, t = 81 mm. The simulated impedance characteristic is shown in Figure 2.17(b). It can be seen that the conical geometry adds an additional resonance. The impedance bandwidth is from 54.5 to 251.4 MHz (129%).

2.4 Conclusion

Water antennas have been reviewed in this chapter with published papers and theoretical analysis. The literature review aimed to provide some background information on the topic of antennas, as well as to give an overview of the kind of research that has been done to date on water antennas. A better understanding on the properties of antennas and the various parameters that characterises the design and performance of a water antenna was obtained. The common fluids that are used in all these published works are water, seawater and saltwater.

In addition, the water antennas mentioned in these studies made used of different feed mechanisms. Majorities made use of the conventional electric probe feed except for the Electrolytic Fluid Antenna which made use of the current probe feed. However, the theory for Electrolytic Fluid Antenna that makes use of current probe has not been established. And little is known on the efficiency of the current probe feed as a type of feed mechanism.

Therefore, chapter 3 of this thesis aims to study the physical and electromagnetic properties of the current probe and their effect on antenna performance. Since current probe is made of ferrite core, hence the characteristics of the ferrite core will be studied.

The understanding of physical phenomena involves a balance of theory and experiment. Since theoretical analysis usually provide idealizations of actual situations, theory may only approximate the real world. Hence, theory is essential for our understanding; experimental measurements determine the actual performance.

Chapter 3

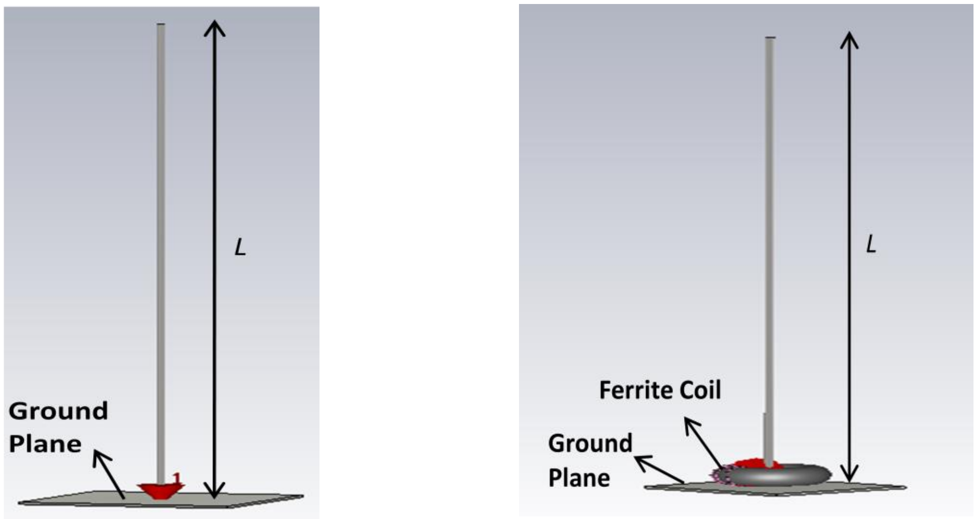
Investigation of Monopole Antenna

In this chapter, the commonly employed monopole antenna will be used for simulations. The monopole antenna or the whip antenna is perhaps the most widely used HF antenna due to its simple structure.

The type of antenna considered here is the quarter-wave monopole antenna. A monopole antenna consists of a straight rod-shaped conductor mounted perpendicularly over a conductive ground plane. In this chapter, the simulation results using commercial software CST Microwave Studio of the S11, radiation pattern and gain of the proposed water antenna will be discussed.

3.1 Comparison of Electric Probe and Current Probe Feeds

In this section, the electric probe and current probe feed will be discussed. The conventional way of feeding the antenna is by using an electric probe where a voltage is fed to the antenna directly via the probe shown in Figure 3.1(a).



(a) Electric Probe Feed (b) Current Probe Feed

Figure 3.1 Geometry of monopole antenna with different feeding mechanism

Figure 3.1(b) shows a monopole antenna fed by a current probe. The current probe uses the source-coupled magnetic field to induce a current onto the monopole antenna.

The radiation boundary was set to infinite boundary as shown in the Figure 3.2. The frequency range was set as 0 to 100 MHz. The computational domain was set to Time-domain as shown in Figure 3.4. The convergence was set to 60 dB as shown in Figure 3.4. Figure 3.5 showed the typical convergence curve. One port was used in the simulation design. The size of the ground plane was set to infinite as shown in Figure 3.2.

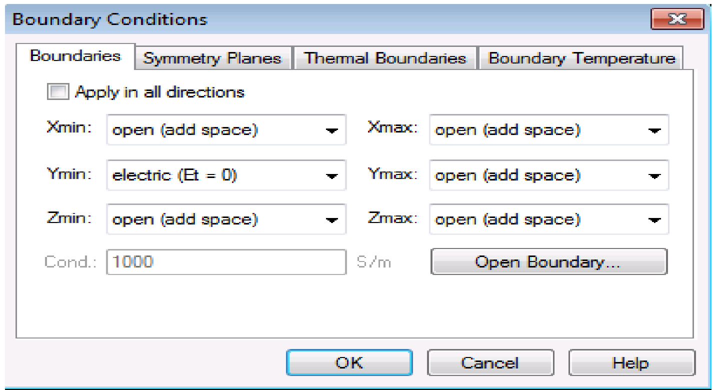


Figure 3.2 Infinite boundary condition

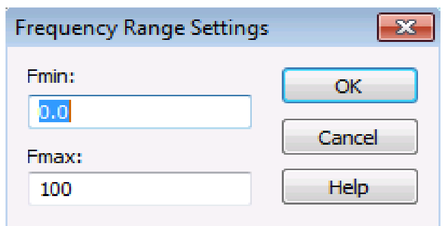


Figure 3.3 Frequency range settings

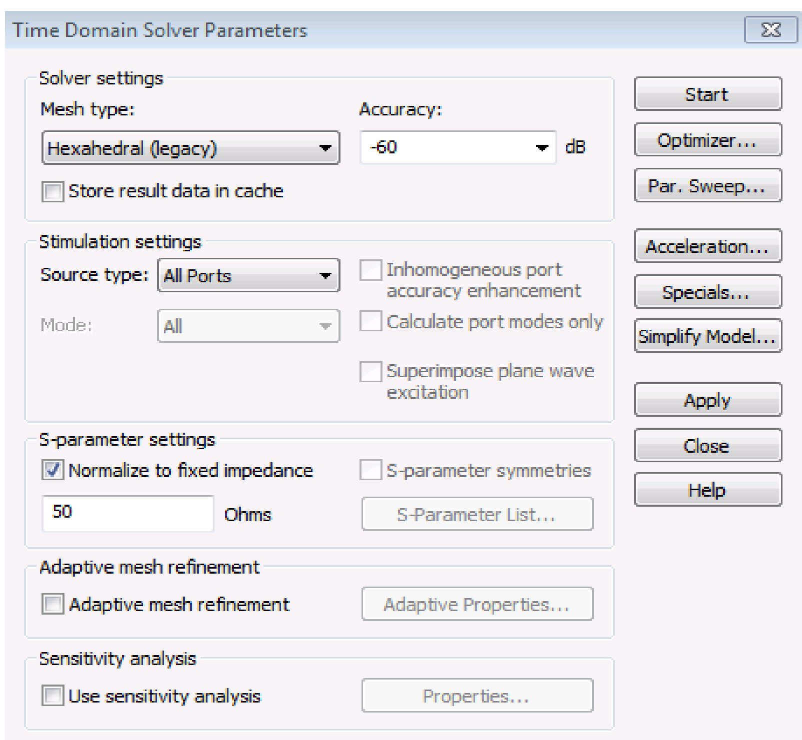


Figure 3.4 Time domain solver parameters

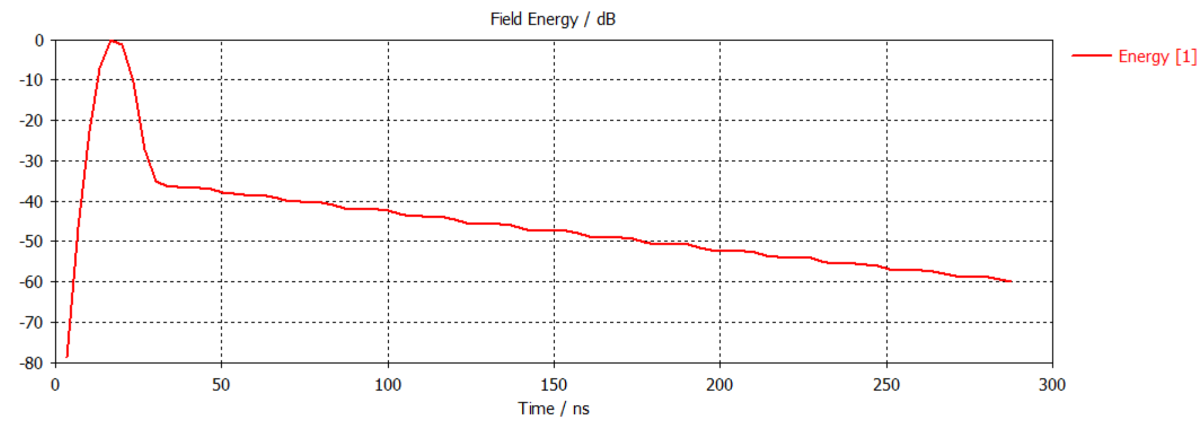


Figure 3.5 Convergence curve

These two feed mechanisms are compared through simulations. For simplicity, a PEC monopole of length L = 2.5m is used for the comparison between the two feeds. The ferrite coil is placed 3 cm above the ground plane and the number of turns N is 2. Simulated results for the monopole fed by both methods are shown in Figure 3.6. As shown in the figure below, the red bold line represents the electric probe fed antenna and the green dash line represents the proposed current probe fed antenna.

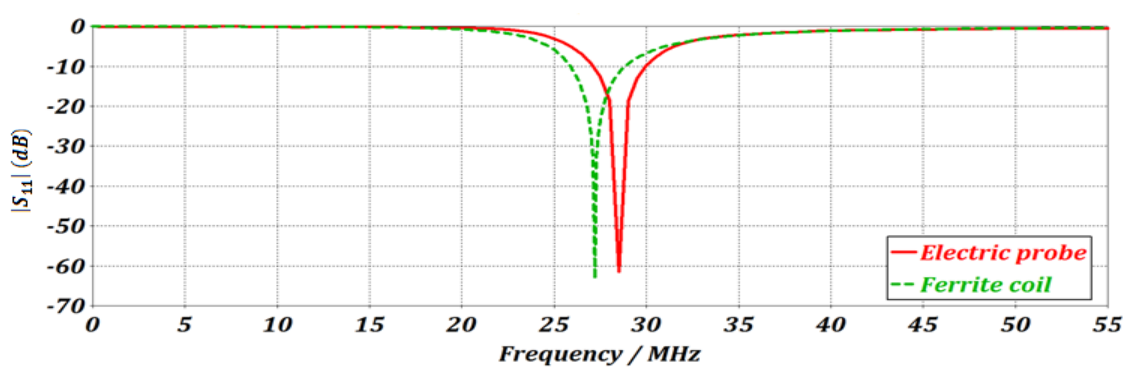


Figure 3.6 Comparison of simulated S11 result

As shown in Figure 3.6, the resonant frequency for the electric probe fed monopole antenna is at 28.5 MHz and the resonant frequency for the proposed monopole antenna is at 27.2 MHz. The resonant frequencies for the antennas of the same length but with different feeds are slightly different. This is due to the position of the current probe which is 3 cm above the ground plane. Hence, the height of the antenna for the current probe feed is reduced by 3 cm. On the other hand, the electric probe feed does not have such an issue of shortening of the height of the monopole because it is fed at the bottom. Both antennas have the S11 magnitude above -60 dB at resonance, which indicates a good impedance match. The two antennas agree well with each other. Furthermore, the resonant frequencies of the two antennas satisfy the theoretical value of λ/4.

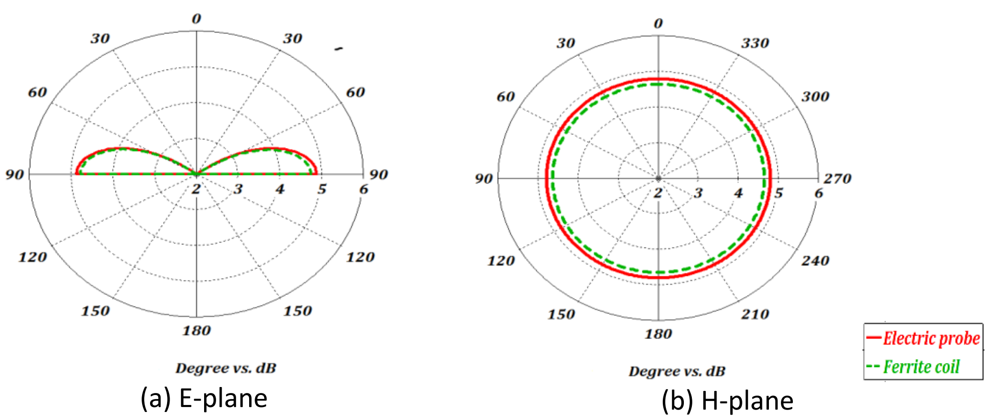


Figure 3.7 Comparison of simulated radiation patterns

Figure 3.7(a) shows the E-plane radiation pattern and Figure 3.7(b) shows the H-plane radiation pattern. Referring to Figure 3.7(a), the proposed antenna has less gain as compared to the electric probe feed antenna. This can be explained by the power lost by the ferrite coil. In Figure 3.7(b), it is clear that both antennas have omnidirectional radiation pattern. The realized gain of the proposed antenna is around 4.6 dB and it is in good agreement with the electric probe fed antenna which has a realized gain of 4.8 dB.

In this section, it can be concluded that the ferrite coil does not change the radiation pattern of the monopole antenna. It has similar characteristics of an omnidirectional antenna as the electric probe fed antenna. Furthermore, the resonant frequencies of both the antennas are well matched at around 28 MHz.

3.2 Effect of Variation in the Length of the Monopole Antenna

The electrical length of the antenna may be varied by adjusting the height of monopole; it is used to determine the operating frequency. Figure 3.8 shows the range of operating frequencies achieved by varying the height of the monopole antenna from 1 m to 3 m. The resonant frequency for the different monopole height agrees with the theoretical value, λ/4. This can be determined by theoretical calculation, using the formulas below.

$$C = f \cdot \lambda \tag{3.1}$$

$$L = \frac{1}{4}\lambda \tag{3.2}$$

$$f = \frac{C}{4L} \tag{3.3}$$

where L is the electrical length of the monopole antenna in meters, f is the frequency in MHz, λ is the wavelength in free space and C is the speed of light, 3 x 10^8 m/s.

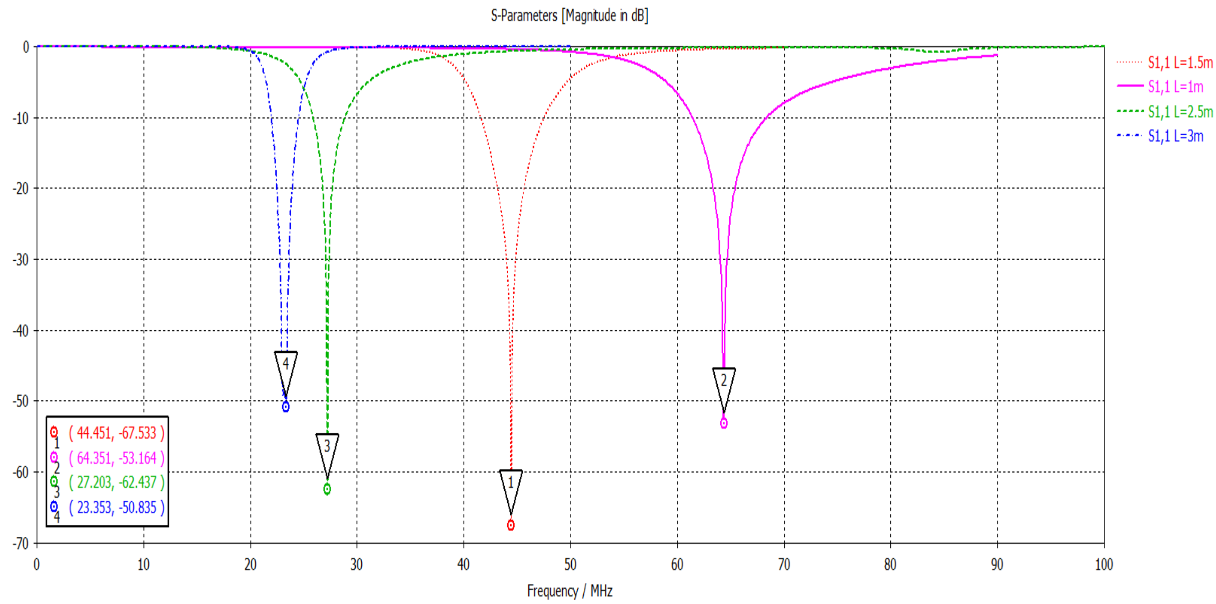


Figure 3.8 Operating frequencies achieved by varying height of monopole antenna

Referring to the simulated S11 results in Figure 3.8, the resonant frequency of 1.5 m monopole antenna is at 44.6 MHz as shown in marker 1. Next, the resonant frequency of 1m monopole antenna is at 66.4 MHz as shown in marker 2. Then, the resonant frequency of 2.5 m monopole antenna is at 27.2 MHz as shown in marker 3. Lastly, the resonant frequency of 3 m monopole antenna is at 23.4 MHz as shown in marker 4. It can be seen that the resonant frequencies obtained for the different monopole height agrees with the computed theoretical values using (3.3). Therefore, it can be concluded that the proposed antenna meets the benefit of tunability.

3.3 Characteristics of Ferrite Coil

In this section, the characteristics of ferrite coil will be analyzed by varying the parameters such as the outer radius and core radius, keeping all other parameters constant. Besides that, the relative permeability of the ferrite coil is varied in order to find out how it affects the S11 performance. This is to aid the understanding of the effects of these parameters on the performance of the current probe feed. The length of the PEC monopole is fixed at L = 2.5 m, the ferrite coil is placed 3 cm above the ground plane, the inner and outer radii of the ferrite toroid will be varied, the number of turns N is 2 and the *f*o = 28 MHz for the following comparisons. The structure of a ferrite coil is shown below in Figure 3.9.

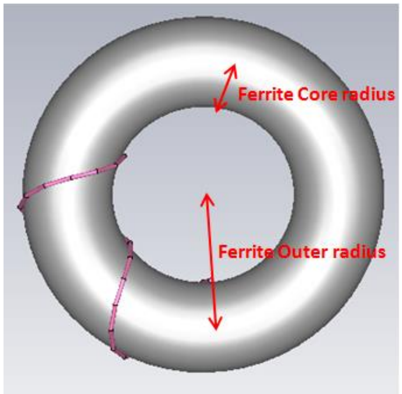


Figure 3.9 Structure of the outer radius and core radius of ferrite coil

3.3.1 Different Outer Radius

When the outer radius of the ferrite coil changes, it will affect the amount of current induced into the monopole antenna respectively.

Comparison of the S11 results for different outer radius values of the ferrite coil when the ferrite coil is being placed 3 cm from the ground of the PEC monopole antenna is shown in Figure 3.10.

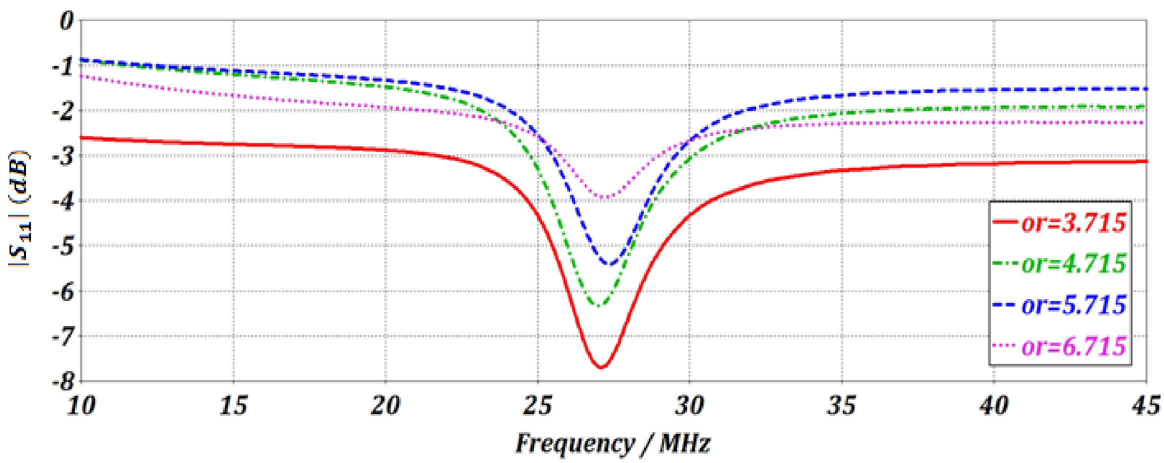


Figure 3.10 Comparison of different outer radius

In this simulation, the outer radius of the ferrite core is varied from 3.7 cm to 6.7 cm with all other parameters kept constant. From the simulated results shown in Figure 3.10, when the outer radius is small, the magnetic field coupled from the source to the monopole is relatively stronger, thus the S11 for the PEC monopole at resonant frequency is relatively better. When the outer radius is large, current probe coupling decreases and the performance of the monopole antenna at resonant frequency is poor.

3.3.2 Different Core Radius

In this section, we will compare the S11 results for different core radius of the ferrite coil, and the ferrite coil is placed 3 cm from the ground of the PEC monopole antenna.

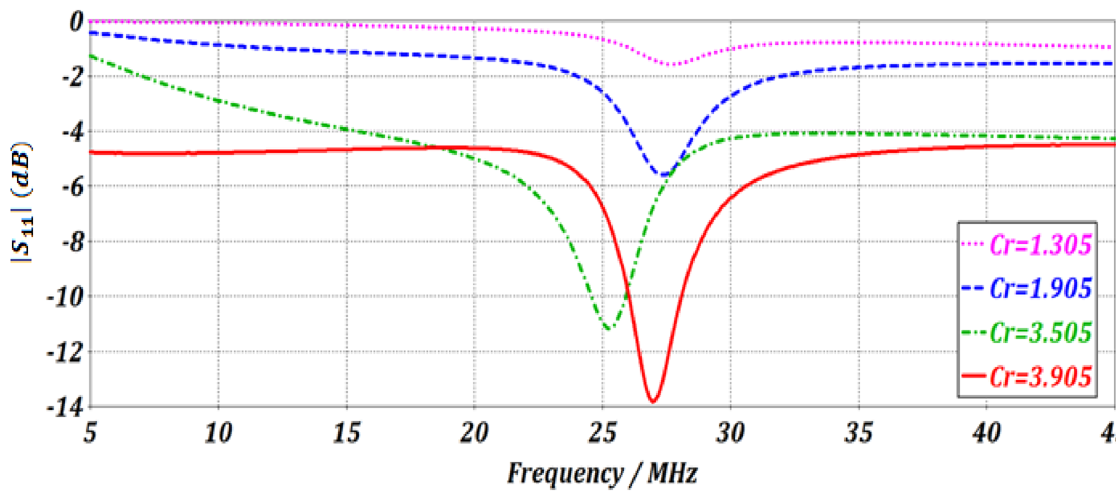


Figure 3.11 Comparison of different core radius

Comparison of the S11 results with different values of core radius of the ferrite coil is shown in Figure 3.11, the red thick bold line represents the core radius which is largest with the 3.9 cm, and the S11 performance for this case is the best. The larger the core radius, the magnetic flux induced in the core by the source is stronger; hence the stronger magnetic flux in the core induces a higher current onto the monopole antenna. This can be seen from the better S11 for a core radius of 3.9 cm compared to 1.3 cm.

3.3.3 Varying Relative Permeability of Ferrite Core

Finally, the relative permeability of the ferrite core is varied from 1 to 3000 while keeping all other parameters constant.

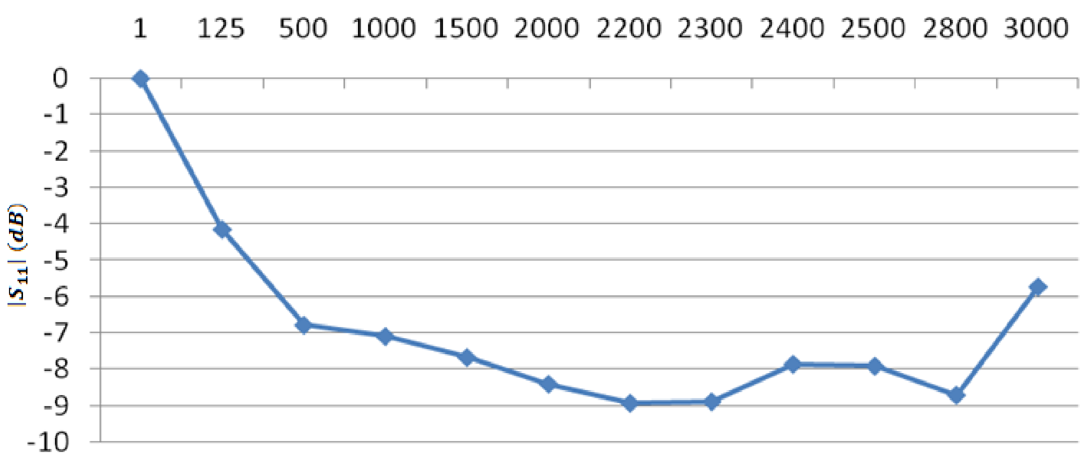


Figure 3.12 Different relative permeability values of the ferrite core

As shown in Figure 3.12, when the relative permeability is air, the performance of the current probe is poor. As relative permeability increases, the current probe becomes more efficient. After about 1000, the performance of the ferrite core is almost constant.

3.4 Conclusion

In this chapter, simulation results for a current probe fed monopole antenna have been presented. The characteristics of the ferrite core are examined and analysed. It is concluded that the outer radius and core radius affect the amount of current coupled onto the PEC monopole. Therefore, the outer core radius should be small and the core radius should be large in order to maximize the current coupling. The S11 gets fairly constant when the relative permeability of the ferrite larger than 1000. Therefore, it can be concluded that as long as permeability is sufficiently high, the current probe feed can function well.

Chapter 4

Measurements of the Proposed Seawater Antenna

In this chapter, information detailing the equipment and methodology used to conduct the experiment of the proposed seawater antenna is presented. Results from the experiment are also provided and discussed.

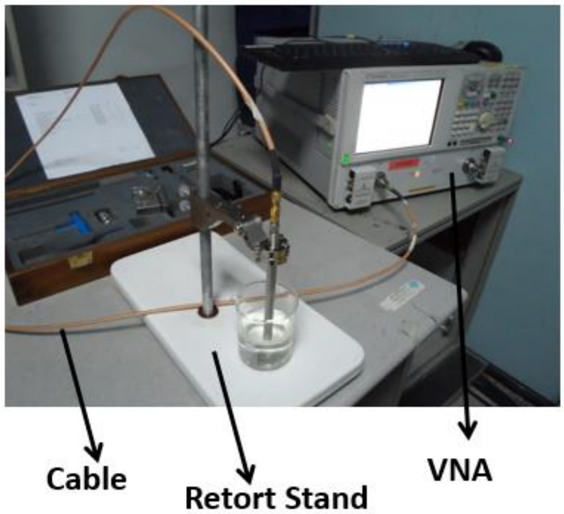
4.1 Overview

The experiment was carried out to examine the practicality of the proposed HF seawater antenna. The first experiment was done to analyze the relative permittivity of different water in a room located at block S2 level B5. Next, the construction of the DIY current probe to be used for the proposed seawater antenna was finalised. The design of the proposed seawater monopole antenna was finalised. The equipment and materials required were assembled. The seawater antenna experiment was carried out on the rooftop of the school building at block S2.1 in Nanyang Technological University.

4.2 Measurements of Relative Permittivity of Water

As water is used as the main radiating element in the design of a water antenna, it is important to first analyse and determine the properties of water that is required for optimal antenna performance. Furthermore, it has been proven that salt solution and seawater is effective antenna radiators from previous literature in chapter 2. It should be mentioned that most of the fluid antennas were designed to operate at frequencies higher than the HF range.

Experimental measurement of relative permittivity of different solvent is measured over frequency range between 10 MHz to 20 MHz, with 100 data points of 0.1 MHz. The experiment was carried out in a room located at Block S2 level B5 of Nanyang Technological University as the Vector Network Analyzer (VNA) and other equipment are readily available. The set-up for measuring the permittivity of the fluids is shown in Figure 4.1. In [17], [21], the relative permittivity of the seawater is 81. In [13], it was found that the dielectric constant of the seawater varies between 77.6 and 79.8 over the frequency range of 30-300 MHz. The relative permittivity value of the seawater agrees with the values from the references [13], [17]. The measured experimental data for the seawater, saltwater, distilled water and rainwater are presented in Figures 4.2 to 4.6.



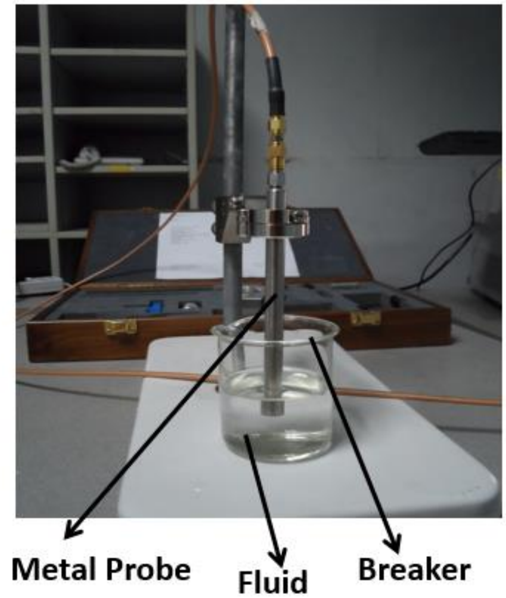


Figure 4.1 Setup for measuring the permittivity of water

The method of measurement for the permittivity of different water is by using dielectric probe kit model 85070E. The methodology are being stated below.

1. Set the frequency range and type of sweep. Click Calibration then enter a Start frequency and a Stop frequency. Click OK. The main window will now show the new start and stop frequencies.

2. Calibrate the system. The calibration consists of measuring three known standards and using the results to characterize the three major sources of measurement error. The default calibration standards are air, a short circuit, and water. To ensure measurement accuracy, do not move the probe cable between calibration and measurements. If you have not already done so, stabilize the cable by locking the

probe in the mounting bracket of the probe stand. Always move the sample to the probe, never move the probe to the sample.

3. Click Calibration, then Perform Cal.

   The following prompts appear to instruct to connect standards.

   a) Leave the probe open in air. This is the open standard. Select OK in the dialog box and a measurement will be made.

   b) Connect the performance probe short block. When it is connected, click OK.

   c) Remove the short circuit and place the probe in 25° C water.

      - Measure the temperature of typical drinking water with a thermometer. It should be 25 ° C.
      - Immerse the probe in the water by moving the water to the probe. Make sure no air bubbles are clinging to the probe tip. Then Click OK.
      - When the calibration is complete, remove the probe from the water and dry it.
      - Now, ready to make measurements. A measurement can be made by selecting Trigger Measurement under the Measure menu.

4. Measure the fluid.

   a. Reinsert the probe into the water you used to calibrate the system, then click OK.

b. Insert the probe into the fluid, then click OK. A measurement will be triggered. The measurement should appear on the display of the computer.

c. Remove the water and dry the probe.

The measured data are being presented in a graph below respectively.

4.2.1 Seawater

Samples of seawater is collected from the seaside at the Tuas area for measurement.

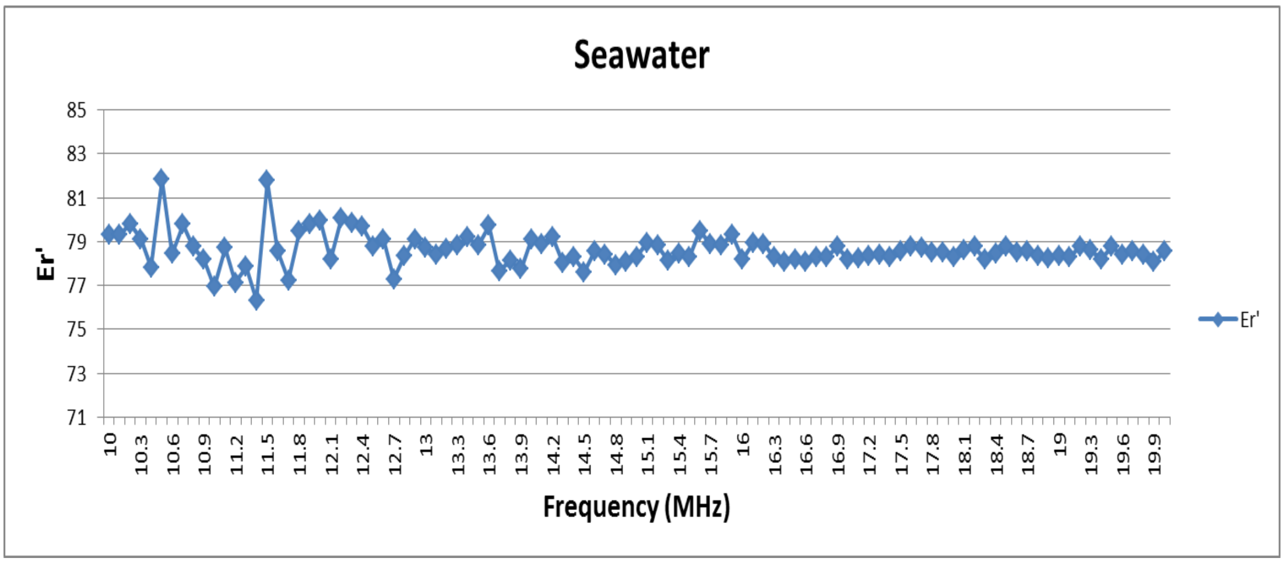


Figure 4.2 Relative permittivity of seawater

Dielectric constant of the seawater varies between 77.6 and 79.8 depending on temperature [21, 23].

4.2.2 Saltwater

The saltwater is made by dissolving 5 kg of aquarium salt with 60 litres of distilled water.

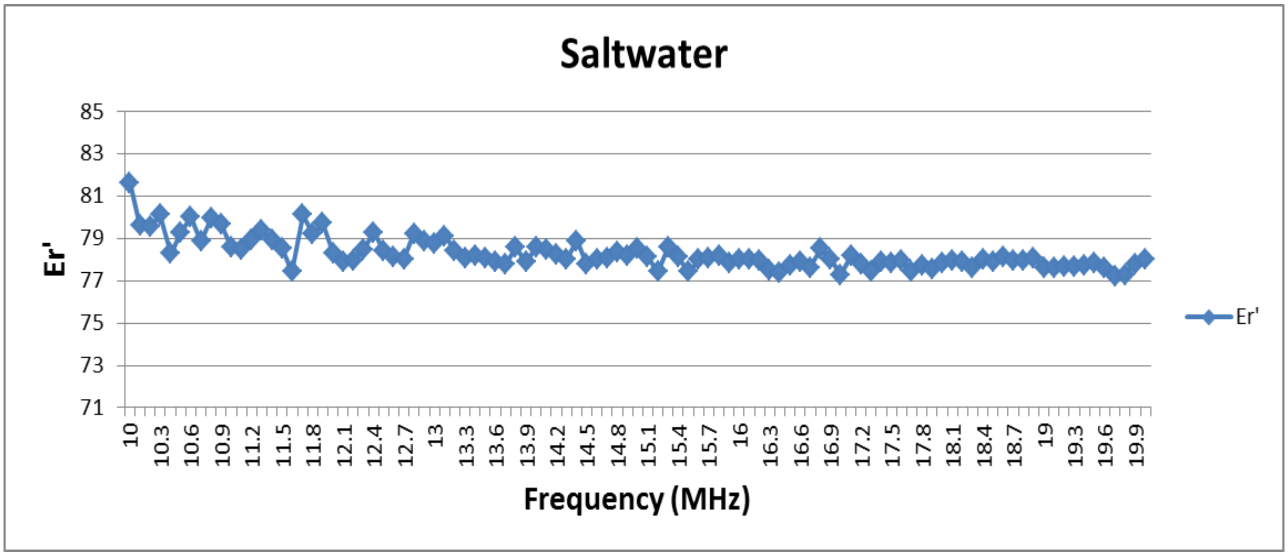


Figure 4.3 Relative permittivity of saltwater

From the measurement of the relative permittivity of both the seawater and aquarium saltwater, it is observed that they actually agrees with each other with the value around 78.

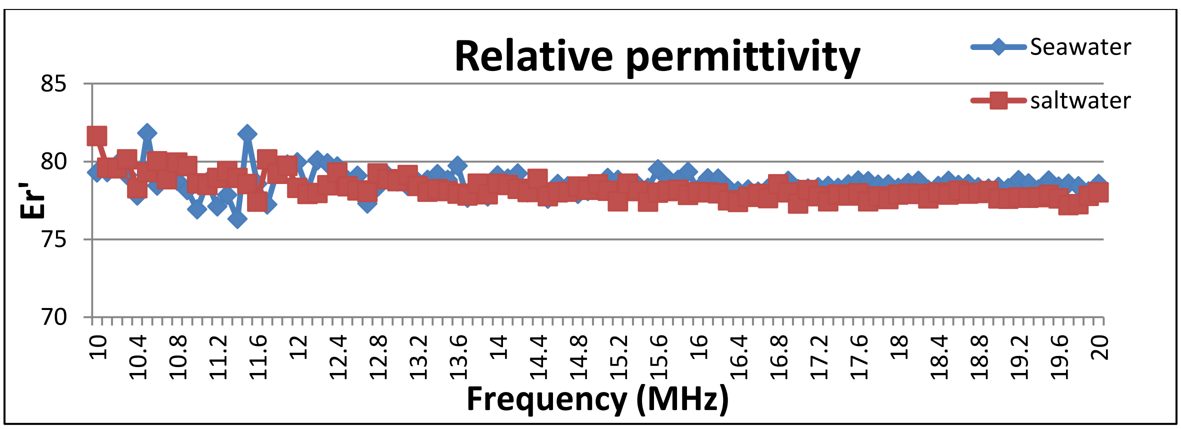


Figure 4.4 Comparison of relative permittivity between seawater and saltwater

4.2.3 Distilled water

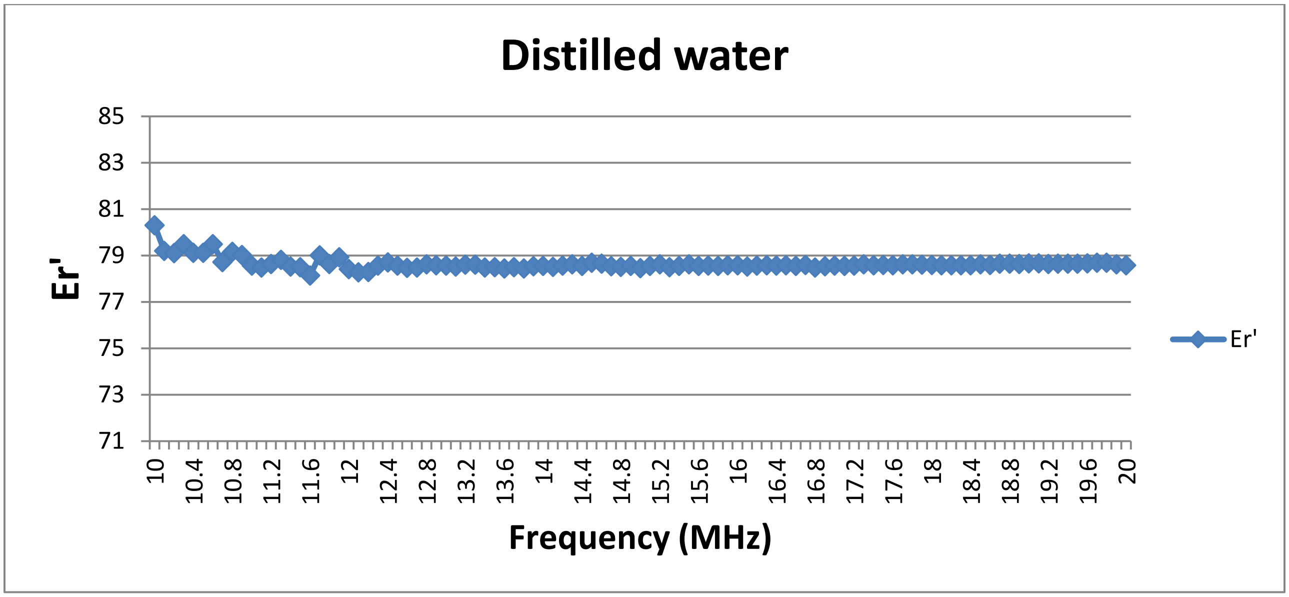


Figure 4.5 Relative permittivity of distilled water

Dielectric constant for the distilled water is 80 [36].

4.2.4 Rainwater

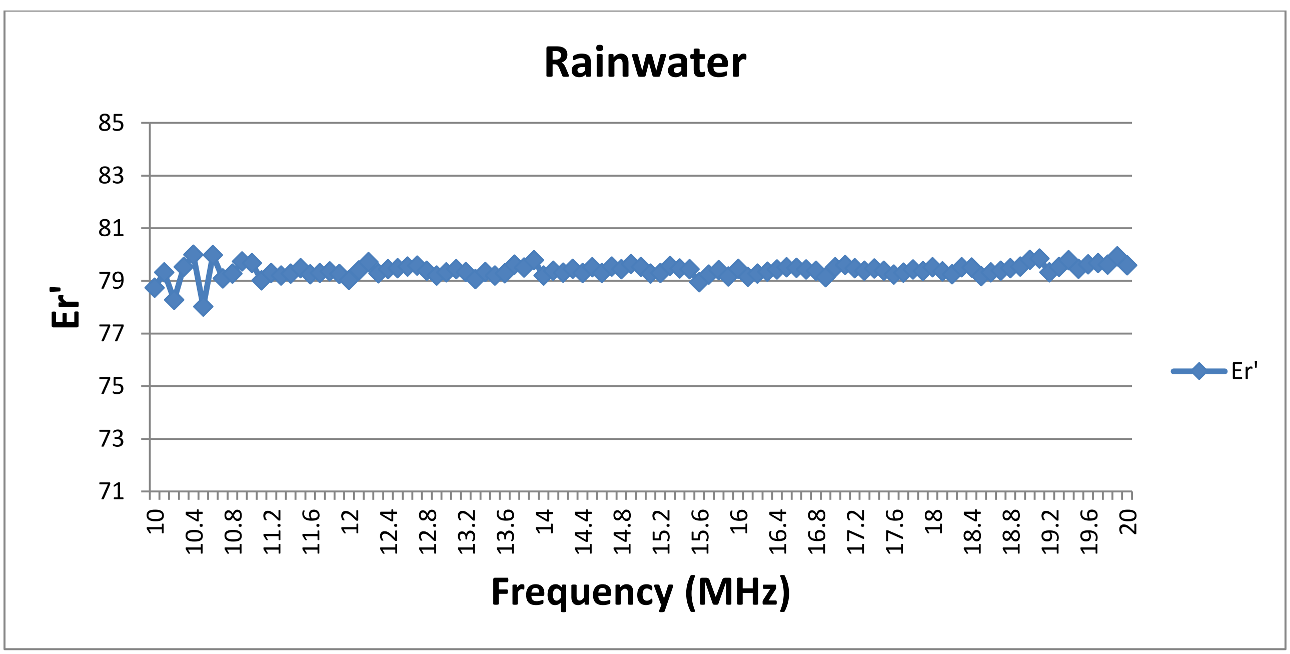


Figure 4.6 Relative permittivity of rainwater

From the measurement of the relative permittivity of both the distilled water and rainwater, it is observed that they actually agrees with each other with the value around 79.

4.3 Fabrication of DIY Current Probe

Most commmercial current probes are pricy, with an estimate price of a few thousand US dollars per piece. Due to budget constraint, an improvised version of the 'Do-it-yourself' (DIY) current probe was fabricated as shown in Figure 4.7(b). It was used in the experiment as the feed for the proposed HF fluid antenna. The DIY current probe consists of a toroid core of outer diameter 5.5 cm and inner diameter of 4 cm, which is housed within an aluminum can. Insulators are used to cushion the ferrite coil and the aluminum can. The input/output signal for the current probe is fed through a female SMA connector, which is connected to coil windings that are wound around the toroid core. The numbers of turns for the DIY current probe is 2. The purpose and theory of the current probe was discussed in the previous literature in chapter 2. Figure 4.7(a) shows the commercial current probes from Fisher Custom Communications while Figure 4.7(b) shows the DIY current probes.

4.7(a): Commercial current probe [9]


4.7(b): DIY current probe

Figure 4.7 Geometry of commercial and DIY current probe

4.4 Measurements of Proposed Seawater Antenna

The proposed seawater antenna experiment was carried out at the S2.1 rooftop of Nanyang Technological University. It is inconvenient to use seawater for the experiment as it is not readily available in the school. Note that the experiment is carried out in the school which is far away from the seashore. As observed, the relative permittivity of seawater is equivalent to the aquarium saltwater. Hence, aquarium saltwater is used to replace seawater for this experiment to establish the seawater antenna. It is more convenient to prepare the saltwater than to keep travelling to the seaside to collect the seawater. As shown in Figure 4.8, 5 kg of aquarium salt was dissolved in a big bucket of 60 litres of water to make saltwater. When saltwater is used in the water antenna, the movement of the sodium ions in the stream allows electric current conduction for signal reception and transmission.

Figure 4.8 Preparation of saltwater

The structure of the proposed seawater antenna shows the benefits of conformability by pumping the saltwater through the nozzle and the water stream forms the shape of a monopole antenna as shown in Figure 4.9. Using seawater as an antenna has the flexibility in design as it is easy to make the antenna conforms to the desired shape. Besides that, the height of the water stream can be varied by pumping a stream of saltwater through a current probe and depending on the height of the stream, the frequency of the antenna can be varied. Different stream height will cause different resonant frequencies of the saltwater monopole antenna. This shows the benefits of tunability of the proposed seawater antenna. In addition, the structure is also easy to transport as presented in Figure 4.10. The setup of the experiment is shown in Figure 4.12 for an overview of the proposed seawater antenna system.

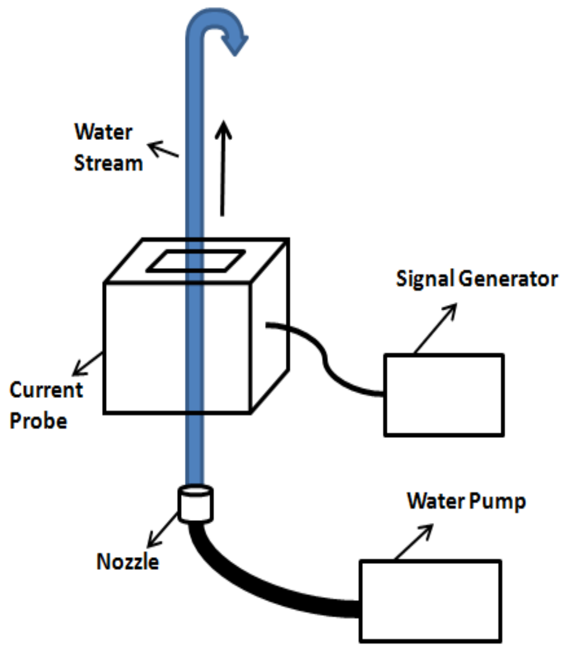


Figure 4.9 Proposed seawater antenna

Figure 4.10 Structure of proposed seawater antenna

When designing the proposed seawater antenna, the vertical height and the shape of the seawater antenna can be altered by proper design of the pump's nozzle. A small nozzle as showed in Figure 4.11 will enable a thinner and taller seawater monopole. In the design, a red color node as showed in Figure 4.11 was used to limit the amount of seawater pumping up the nozzle. This node can change the height and the verticality of the seawater stream of the proposed antenna. Hence, making the proposed antenna tunable.

Figure 4.11 Nozzle and node of the proposed seawater antenna

Figure 4.12 Setup of seawater antenna system

The inverted U shape of the water stream does not affect the performance as the water droplets are not connected when it falls back to the ground. This is further discussed in chapter 5.4.2 of the thesis. The height of the water stream fluctuates only slightly and not randomly. The slight variation in height of the water stream is not noticeable. The serious drawback of the scheme is that it will be affected by the wind conditions. Moreover, it is not feasible to implement the proposed seawater antenna in rainy condition or days with strong wind.

The proposed HF seawater antenna was configured as a receiving antenna, the height of the actual water column of the proposed antenna is shown in Figure 4.13.

Figure 4.13 Actual water column of proposed fluid antenna

A discone antenna as shown in Figure 4.14 was used as the transmitting antenna for measurement of the proposed HF seawater antenna.

Figure 4.14 Discone antenna as transmitting antenna

The transmitting signal provided by the signal generator was configured to transmit sinusoidal waves of frequencies ranging from 4 to 30 MHz. The signal generator from Rohde and Schwarz as shown in Figure 4.15 below is connected to the discone antenna.

Figure 4.15 Signal generator

A spectrum analyzer from Agilent as shown below in Figure 4.16 was connected to the proposed HF seawater antenna for the measurement of the received power.

Figure 4.16 Spectrum analyzer

The procedure of the experiment is listed below:

Step 1:

The signal generator is set to transmit sinusoidal signal of a specified frequency. The RF button is set to ‘ON’. The signal generator is set to start transmission of the RF signal.

Step 2:

The water pump is turned on. The stream of saltwater is pumped through the middle of the current probe which serves as the radiating element of the proposed HF water antenna.

Step 3:

The frequency of the spectrum analyzer is tuned to the frequency specified in Step 1. The measured received power of the frequency specified is recorded from the spectrum analyzer.

Step 4:

The signal generator is set to stop transmission of the RF signal.

The above steps 1-4 were repeated for each specified frequency ranging from 4 MHz to 30 MHz. The measured signal strength of the proposed HF water antenna were recorded and shown in Figure 4.17.

These were the results obtained from the experiment for using the 5.5 cm external diameter DIY current probe.

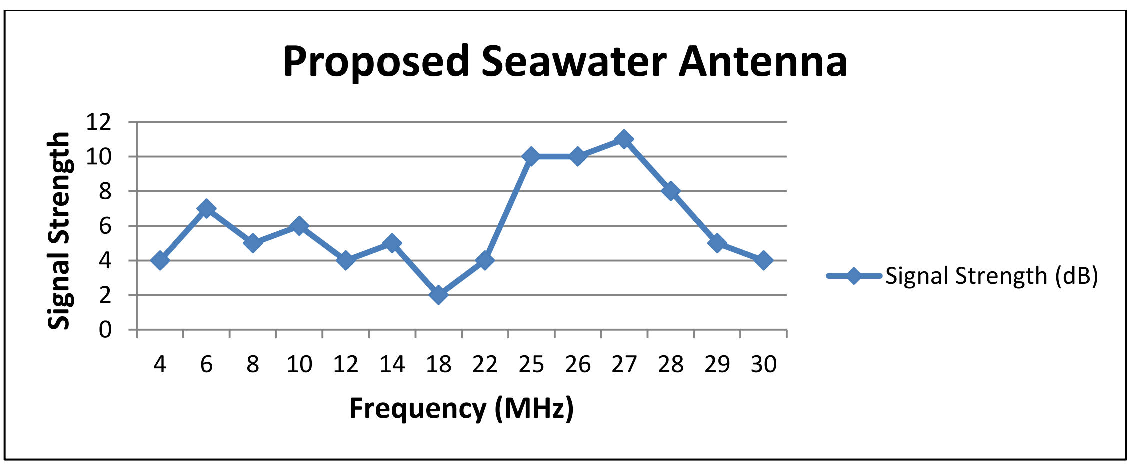


Figure 4.17 Measured signal strength for proposed seawater antenna

From the measurement, the resonant frequency of the proposed HF seawater antenna is around 25 MHz to 27 MHz with the received power difference of around 10 dB. This is the ratio of P_T/P_R and the units should not be dBm as given in [28], P_T is the transmission power and P_R is the receiving power. The resonant frequency of the proposed seawater antenna falls within HF range. The measured result for the proposed seawater antenna and the simulated result for the PEC monopole antenna using current probe feed resonant at around 27 MHz, which is in HF range.

However, the received power also suggests that the seawater antenna is not receiving efficiently, given the proximity of the receiving antenna to its signal source. It can be observed that the measured result is not as efficient as compared to the simulated result. This is because the impedance match of the DIY current probe is not as good as the simulated one. An automatic impedance matching network could be introduced to the proposed antenna as the future work. As we tune to a particular frequency, the height of the water column changes accordingly.

The performance of the seawater monopole antenna could also be further improved by designing a better or alternative feed mechanism, such as the electric probe feed.

Chapter 5

Further Investigation

The measured results obtained by using current probe feed in chapter 4 shows that the current probe feed is not efficient. Hence, the electric probe feed will be investigated in this chapter. Additional simulations were performed by varying the conductivities and radius of the seawater monopole antenna. A seawater bend monopole antenna was simulated to match the shape of the seawater antenna carried out in the experiment. Comparison between the fundamental seawater monopole antenna and the seawater bend antenna are presented as well. A conical shape seawater monopole antenna was simulated to achieve broadband performance. In this chapter, the simulated results were obtained using commercial software HFSS. The boundary conditions for all the simulation was set to the radiation boundary and the ground plane was set to PEC infinite ground plane in this chapter.

5.1 PEC Monopole Antenna

The PEC monopole antenna with the following dimensions was simulated in Figure 5.1.

Dimension of antenna:
Radius of PEC Monopole: 0.5 cm
Height of PEC Monopole: 250 cm

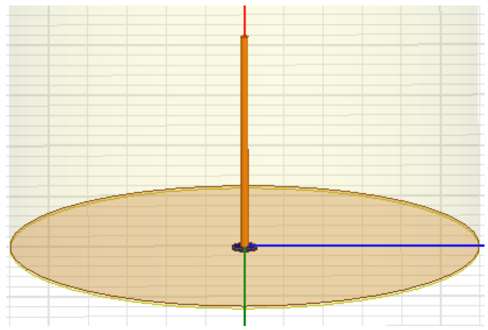


Figure 5.1 PEC monopole antenna

The simulated result is reported in Figure 5.2.

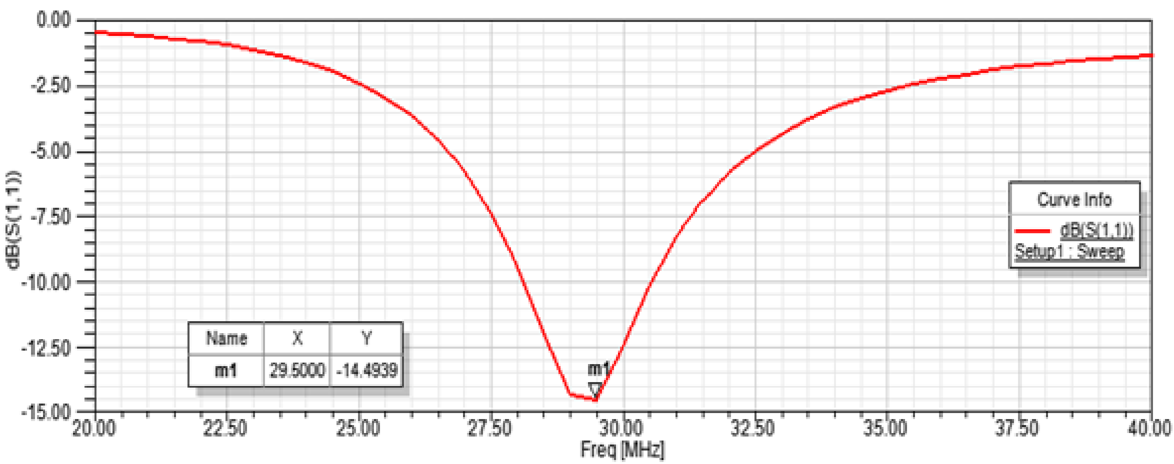


Figure 5.2 S11 result of the PEC monopole antenna

When the radius of the monopole is 0.5 cm, the PEC monopole antenna resonates at around 29.5 MHz as showed in Figure 5.2. However, when PEC is replaced with seawater of the same dimension, the performance of the antenna is poor. A resonant was not observed within the operating band. Hence, it is important to determine the ideal dimension of the seawater monopole antenna in order for it to radiate. These are discussed in the following sections.

5.2 Varying the Conductivities of the Seawater Monopole Antenna

In this section, the conductivities of the seawater monopole antenna was varied to determine how it affects the resonant frequency of the antenna.

Dimension of antenna:
Radius of seawater monopole: 0.5 cm
Height of seawater monopole: 250 cm

Conductivities (S/m)	Resonant Frequency (MHz)
5	-
100	27.5
1000	28.5
100000	29
PEC	30

From the table above, it can be observed that the resonant frequency of the seawater monopole antenna shifts upward with an increase in conductivity. The conductivity of the seawater is set to 5 S/m in the simulation, however due to the thinness of the seawater column, the performance of the seawater monopole is poor. A resonant was not observed within the operating band. Hence, the radius of the seawater column at a conductivity of 5 S/m needs to be thicker. More simulations were performed by varying the radius of the seawater antenna in the next section.

5.3 Varying the Radius of the Seawater Monopole Antenna

By increasing the radius of the seawater antenna, the antenna has better performance. This can be observed in the table below.

Radius (cm)	Height (cm)	S11 (dB)
0.5	**250**	**-0.5**
2.5	**250**	**-4.3**
5	**250**	**-12.3**
7.5	**250**	**-18**
10	**250**	**-19**

From the table above, we can determine that the radius of the seawater monopole antenna should be at least 5 cm. When the radius is big, it implies that the water column is more conductive. Thus, there is a minimum radius for the seawater monopole antenna structure to function. However, there is also a practical limitation for the structure. As the radius of the seawater stream is big, the seawater stream cannot be sprayed high enough and this becomes a challenge in the research work. Furthermore, we will need to take into consideration the effect of the wind as well as it will affect the height of the seawater stream.

The seawater monopole antenna with optimum performance is simulated as follows:

Dimension of antenna:
Radius of ideal seawater monopole: 7.5 cm
Height of ideal seawater monopole: 250 cm

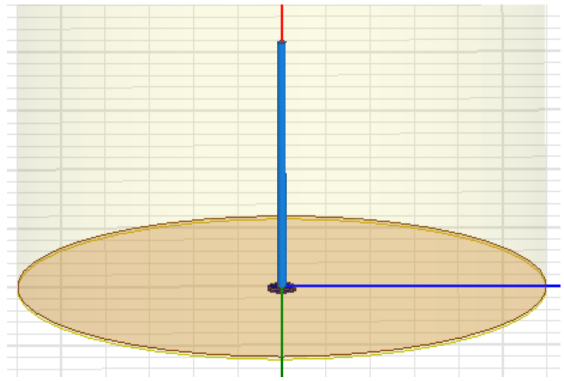


Figure 5.3 Seawater monopole antenna with optimum performance

The simulated result is reported in Figure 5.4.

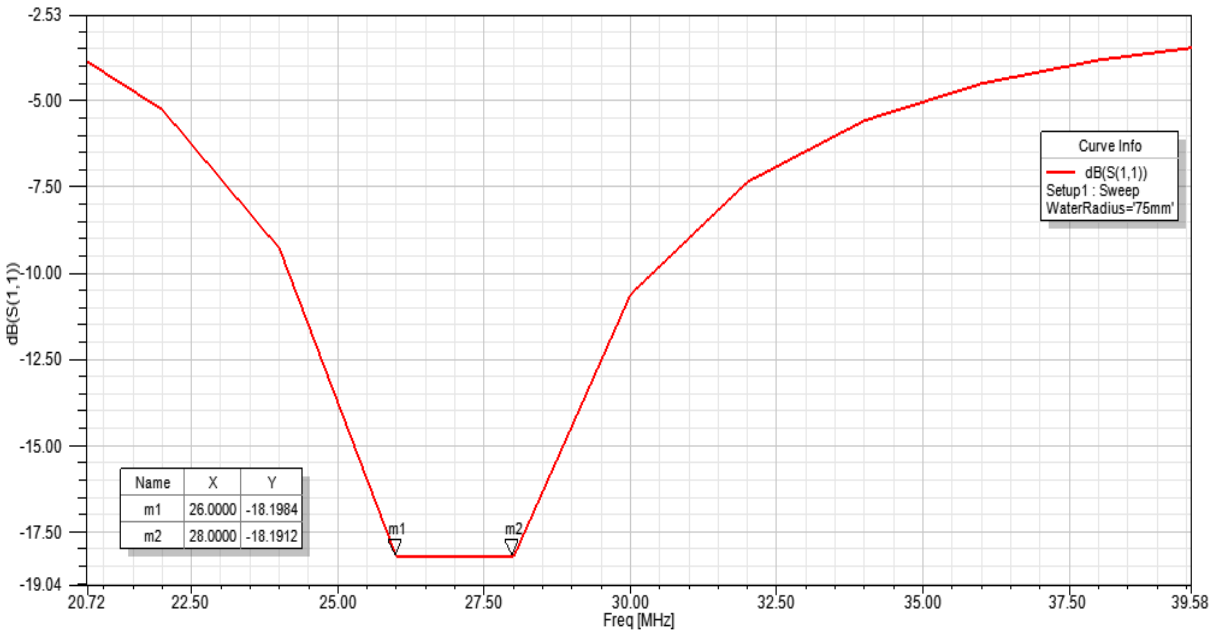


Figure 5.4 S11 result for the seawater monopole antenna

The resonant frequency for the seawater antenna is at around 27 MHz as showed in the Figure 5.4.

5.4 Comparison between Seawater Monopole and Seawater Bend Monopole Antenna

The result of seawater monopole antenna with optimum performance obtained in section 5.3 showed in Figure 5.5(a) was used to compare with the seawater bend monopole antenna showed in Figure 5.5(b). The seawater bend monopole antenna was simulated to approximate the U-shape of the water stream.

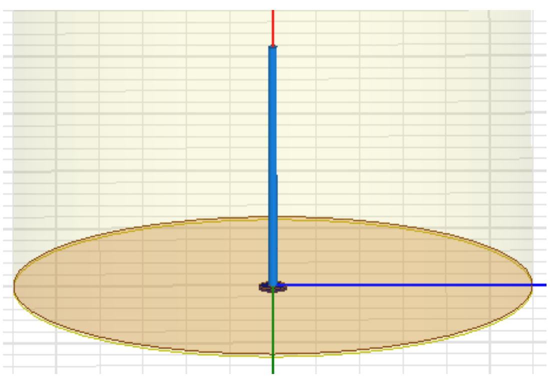
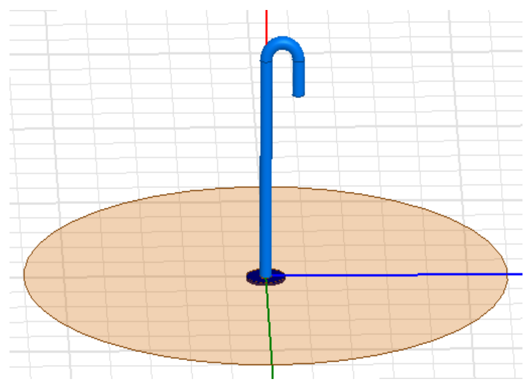
	
5.5(a) Seawater monopole antenna	5.5(b) Seawater bend monopole antenna
Dimensions: Radius of Monopole: 7.5 cm Height of Monopole: 250 cm	Dimensions: Radius of Monopole: 7.5cm Height of Monopole: 250 cm Total Bend length: 102 cm

Figure 5.5 Comparison of the structure of the seawater monopole and the seawater bend monopole antenna

Comparison of S11 result between seawater monopole and seawater bend monopole antenna was showed in the Figure 5.6 below.

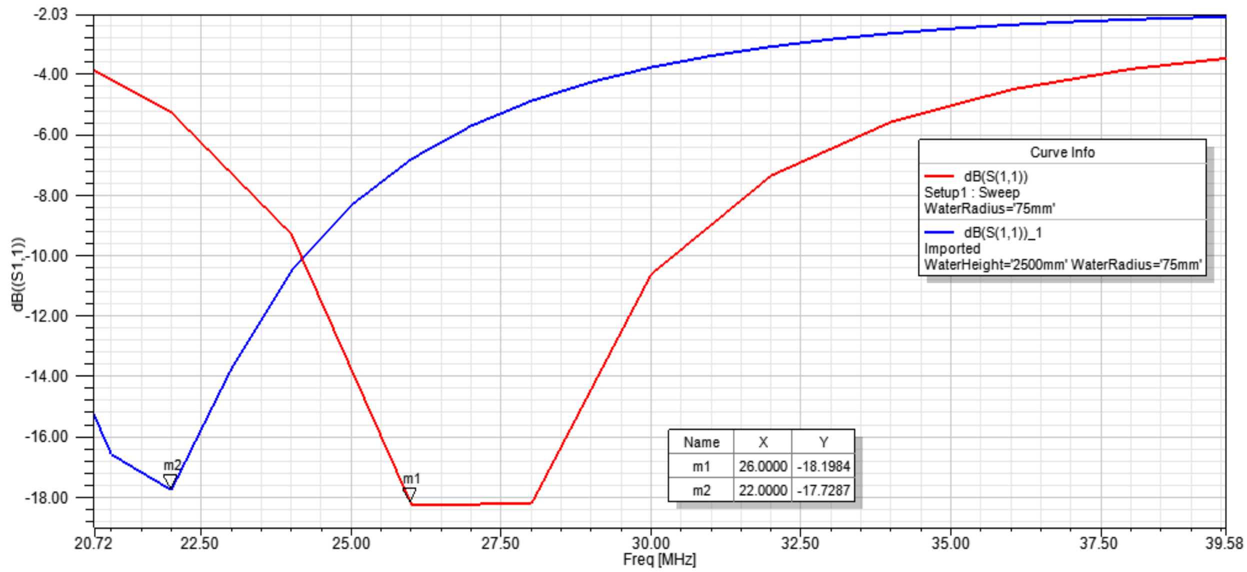


Figure 5.6 S11 result between seawater monopole and seawater bend monopole antenna

The seawater monopole antenna resonant at around 27 MHz, while the seawater bend monopole antenna resonant at around 22 MHz. The bend seawater monopole antenna is longer than the seawater monopole antenna by 102 cm. When the length of the monopole antenna increases, the resonant frequency decreases.

The total length of the seawater bend monopole is 352 cm. A lengthen straight seawater monopole with a total height of 352 cm was simulated to compare with the seawater bend monopole antenna.

5.4.1 Comparison of Lengthen Straight Seawater Monopole with Seawater Bend Monopole Antenna

When the lengthen seawater monopole antenna was straightened to the same total length of the bend antenna, the resonant frequency shifts lower than the bend antenna as showed in Figure 5.7.

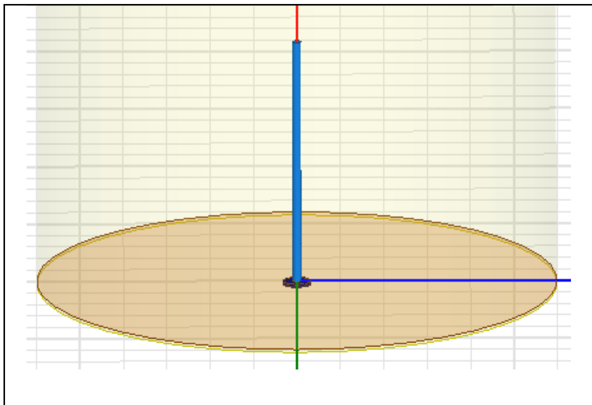
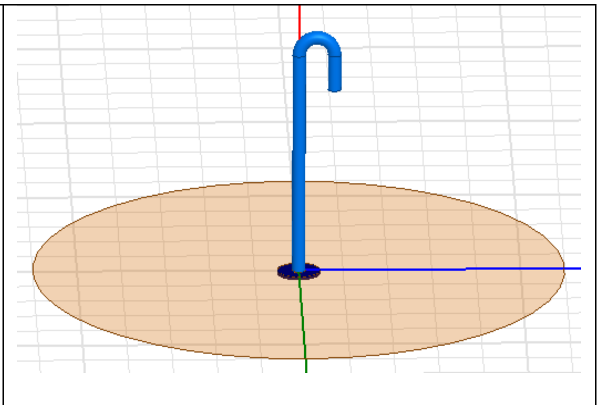
	
5.7(a) Lengthen seawater monopole antenna	5.7(b) Seawater bend monopole antenna
Dimensions: Radius of Monopole: 7.5 cm Height of Monopole: 352 cm	Dimensions: Radius of Monopole: 7.5cm Height of Monopole: 250 cm Total Bend length: 102 cm

Figure 5.7 Comparison of lengthen straight seawater monopole with seawater bend monopole antenna

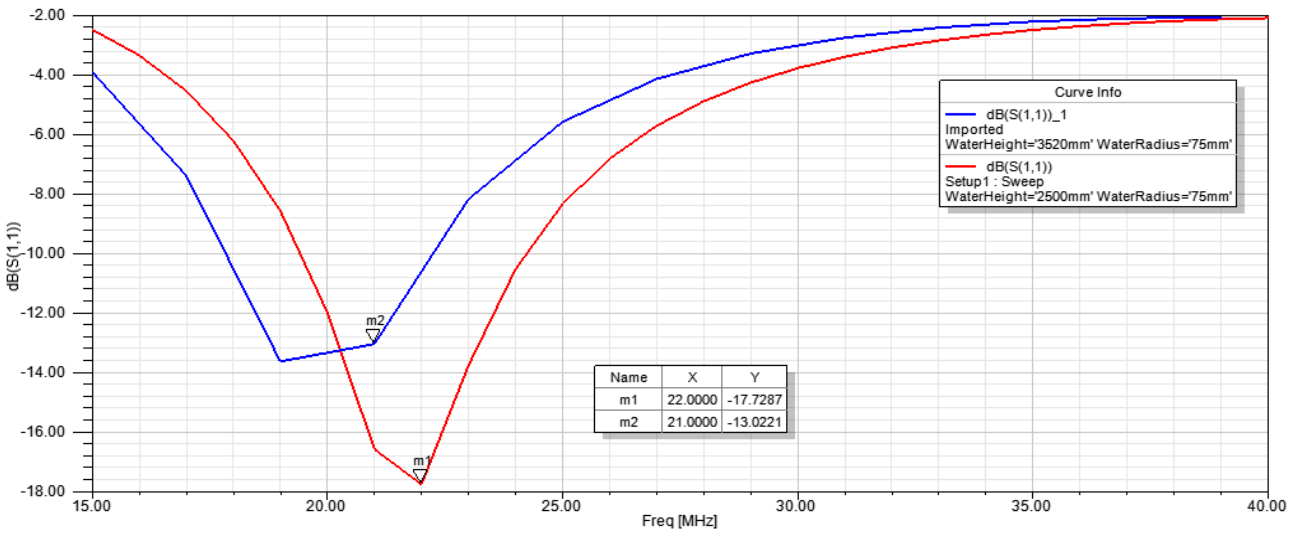


Figure 5.8 S11 result between lengthen seawater monopole and seawater bend monopole antenna

The S11 result showed that the lengthen seawater monopole antenna resonant at around 20 MHz and the seawater bend monopole antenna resonant at around 22 MHz in Figure 5.8. The lengthen monopole shift downwards slightly as compared to the seawater bend monopole antenna. This could be due to the parasitic capacitance between the rising and falling droplets at the bend section. This may have resulted in the shortening of the length of the bend seawater monopole antenna, and caused the resonant frequency to shift upwards slightly.

5.4.2 Comparison between Seawater Bend Monopole with and without Water Droplet

A seawater bend monopole antenna was simulated to approximate the U-shape of the seawater monopole antenna including the falling water droplets that was observed in the experiment. The falling water droplets are disconnected with gap in between. And the seawater bend monopole was presented in 3 cases as follows, Figure 5.9(a) Seawater monopole with bend, 5.9(b) Seawater bend monopole with water droplets extended halfway and 5.9(c) Seawater bend monopole with water droplets extended near the ground.

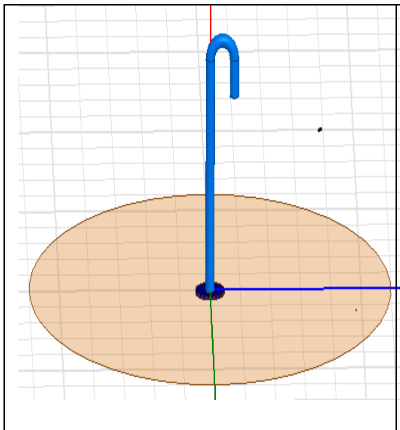
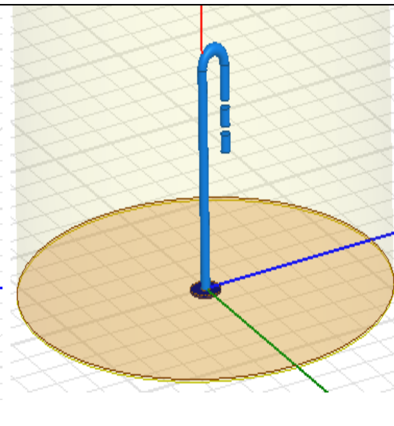
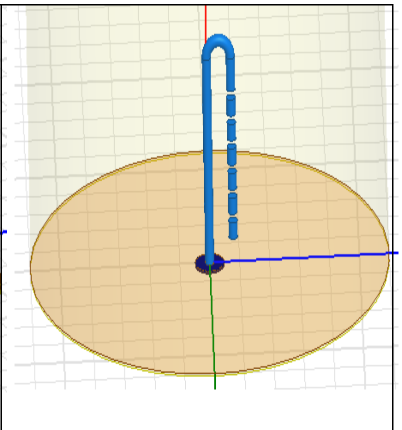
		
5.9(a) Seawater bend monopole antenna	5.9(b) Seawater bend monopole antenna with water droplets halfway	5.9(c) Seawater bend monopole antenna with water droplets near the ground

Figure 5.9 Structure of seawater bend monopole antenna with and without water droplet

The simulated S11 result in Figure 5.10 below showed that the falling water droplets does not have significant effect on the performance of the seawater antenna. The S11 result for these 3 designs agrees with each other.

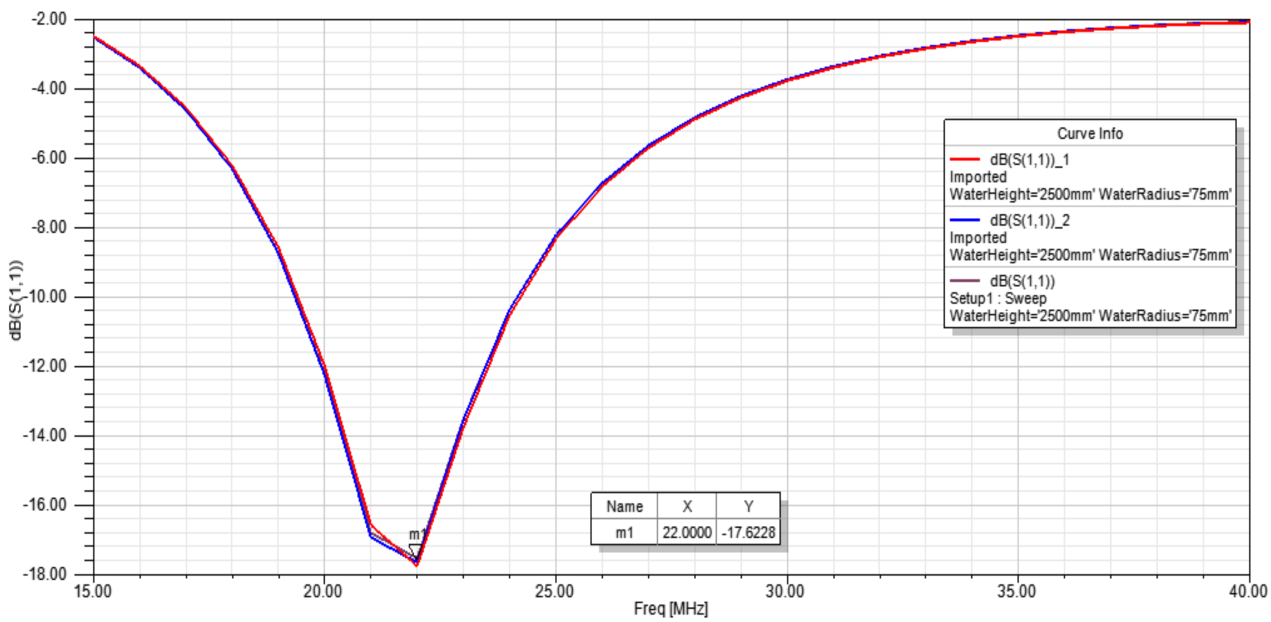


Figure 5.10 S11 result for seawater bend monopole antenna with and without water droplet

5.5 Broadband Seawater Cone Antenna

Using seawater as an antenna has the flexibility in design as it can make the antenna conforms to the desired shape. By changing the nozzle of the pump, it can spray the seawater into a conical shape, such as the seawater cone antenna simulated in Figure 5.11. The conical shape antenna can achieve broadband performance.

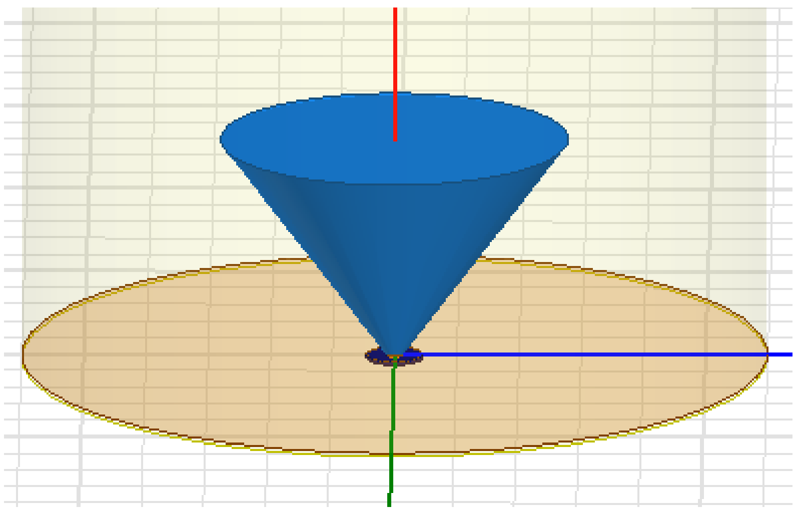


Figure 5.11 Structure of conical shape antenna

Dimensions of structure:

Lower Cone Radius: 7.1 cm
Upper Cone Radius: 140 cm
Height of Cone: 180 cm

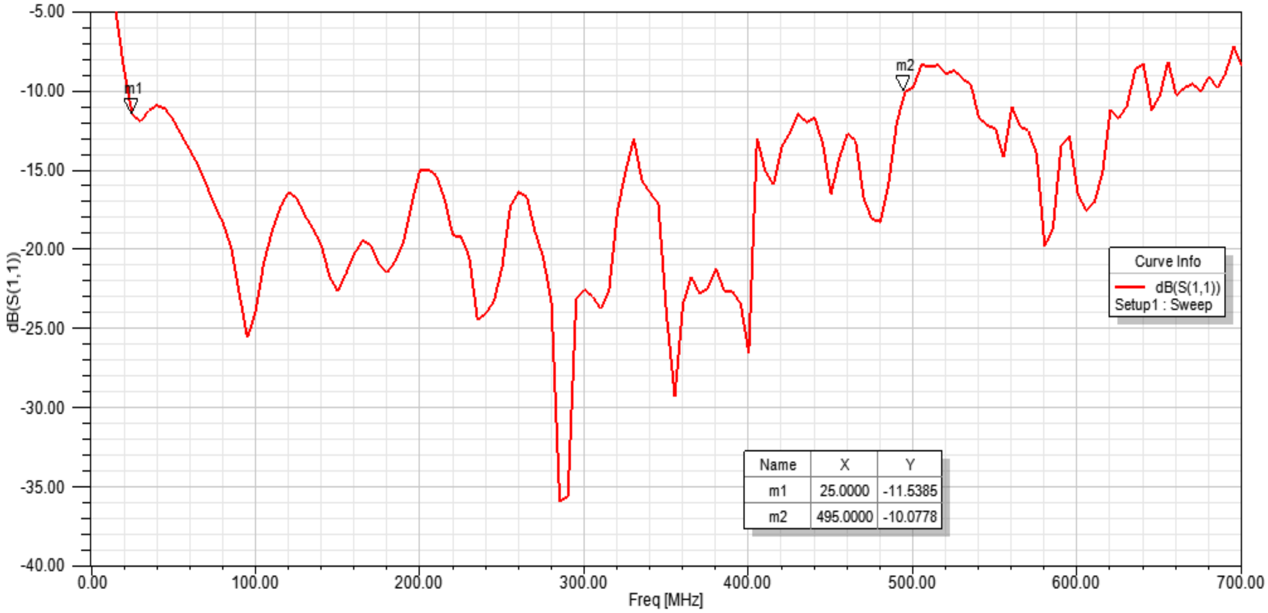


Figure 5.12 S11 result of the conical shape antenna

fc = (495 + 25)/2 = 260

BW = (495-25)/260 = 1.8 (appro. 180%)

From the simulated result in Figure 5.12 above, the conical shape antenna achieves broadband performance with a bandwidth of 180%.

5.6 Conclusion

In this chapter, it can be observed that the resonant frequency of the seawater monopole antenna shifts upward with an increase in conductivity. By increasing the radius of the seawater antenna, the performance of the antenna improves. Hence, it is important to determine the ideal radius of the seawater monopole antenna structure in order for it to function.

A seawater bend monopole antenna was simulated to approximate the U-shape of the seawater monopole antenna including the falling water droplets that was observed in the experiment. The falling water droplets are disconnected with gap in between. And the seawater bend monopole was presented in 3 cases as follows, Figure 5.9(a) Seawater monopole with bend, Figure 5.9(b) Seawater bend monopole with water droplets extended halfway and Figure 5.9(c) Seawater bend monopole with water droplets extended near the ground. In Figure 5.9(a), the seawater bend monopole antenna has a lower resonant frequency due to the additional length of the bend. In Figure 5.9(b) and Figure 5.9(c), water droplets were added to the seawater bend monopole, however, the simulated result agreed with Figure 5.9(a). This shows that water droplets does not has any effect on the performance of the antenna.

Using seawater as an antenna has the flexibility in design as it can make the antenna conforms to the desired shape. A conical shape antenna was simulated to achieve broadband performance.

Chapter 6

Conclusion

In this chapter, the overall work accomplished with respect to its initial stated objectives is discussed. Possible contributions of this research topic, as well as its limitations and recommendations for potential future development of the project are presented.

An antenna is the most important component for wireless communications system. In this report, a tunable seawater monopole antenna at HF band has been investigated.

Measurements of relative permittivity of different water have been carried out. It was analyzed that the relative permittivity of the seawater and saltwater is equivalent. The experimental values of the relative permittivity agreed with theoretical values.

Simulation results for the monopole antenna have been presented at the HF band. The characteristics of the ferrite coil are being examined and analyzed. By varying the outer radius, core radius and the permeability of the ferrite coil, the performance of the antenna will also be varied. Different stream lengths will cause different resonant frequencies response of the seawater monopole antenna. The resonant frequencies of the simulated

S11 results are in good agreement with the computed theoretical values by using (3.3). Therefore, it can be concluded that the proposed seawater monopole antenna meets the benefit of tunability. It was also found out that the ferrite coil does not affect the radiation pattern of the antenna. The proposed monopole antenna has the similar omnidirectional characteristics as compared to the electric probe fed monopole antenna.

As most commercial current probe are very expensive, an economical DIY current probe was designed and fabricated. The fabricated of the proposed seawater antenna shows the benefit of conformability by pumping the saltwater through the nozzle as the water stream forms a monopole structure. Using seawater as an antenna has the flexibility in design as it is easy to make the antenna conforms to the desired shape. A conical shape antenna was simulated to achieve broadband performance.

The performance of the seawater monopole antenna improves when the radius of the water stream increases. Hence, it is important to determine the ideal radius in order for the seawater antenna to function.

A seawater bend monopole antenna was simulated to match the U-shape of the seawater monopole antenna including the falling water droplets that was observed in the experiment. The seawater bend monopole was presented in 3 cases as follows, (a) Seawater monopole with bend, (b) Seawater bend monopole with water droplets extended halfway and (c) Seawater bend monopole with water droplets extended near the ground. In (a), the seawater bend monopole antenna has a lower resonant frequency due to the additional length of the bend. In (b) and (c), water droplets were added to the seawater bend monopole, however, the simulated result agrees with (a). Thus, water droplets does not has any effect on the performance of the seawater antenna.

As we tune to a particular frequency, the height of the water column changes accordingly. An automatic impedance matching network could be introduced to the proposed antenna to tune to the required impedance for that frequency. The performance of the antenna can be further improved by designing a better feed mechanism. This will be explored in the future work.

Chapter 7

Future Work

Based on the studies developed in this thesis, it is found that there is great potential to extend the current research work. The limitation of the proposed seawater monopole antenna is that it is a narrowband antenna. An interesting area for potential development will be the implementation of the broadband water antenna and array water antenna on existing water features in urbanised environments. While the water antenna can be easily implemented at sea or near a shoreline, where water is readily available, water features may be the answer when implementing in urban areas. In addition, future work can also include the investigations of the types of water that are available and suitable for the implementation of the antenna in water features; how the different spray patterns of the water features will affect antenna performance; the types of antenna feed mechanism that can be used to increase the antenna's efficiency.

The advantage of the broadband water antenna is that it allows a range of frequencies to be accessed at the same instant rather than having to tune the frequency. We can investigate broadband water antenna by considering various shape of the water. For implementation of broadband water antennas, water can be spray into different shape such as a conical or spherical shape to produce broadband performance as shown in Figure 7.1 below. Besides implementing it, we can also find out which shape is the optimum.

(a) Spherical Shape (b) Conical Shape (c) Fan Shape

Figure 7.1 Possible shapes to achieve broadband water antenna

Another interesting approach to implement broadband water antenna is by cascading antenna elements in a log-periodic manner.

Next, we can also look into array water antennas. Array antenna can be used as directional antenna where the signal propagates in a specific direction. It can make use of this water feature which is in series alignment or circular alignment as shown in Figure 7.2 below. The benefit of designing a water array antenna is to increase the antenna's directional characteristic.

(a) Circular alignment (b) Series alignment

Figure 7.2 Alignment for array water antenna

Finally, an automatic impedance matching network could be introduced to the proposed fluid antenna in the future work. As we tune to a particular frequency, the height of the water column changes accordingly. Meanwhile, the impedance matching network will automatically match the impedance (at that frequency) of the antenna to the port.

Author's Publication

Portions of the work reported in this thesis have been published previously in the following paper.

Conference Paper

[1] S. L. Ling, Y. H. Lee and Z. X. Shen, "Analysis of Monopole Antenna Excited by a Current Probe," *IEEE Asia-Pacific Conference on Antennas and Propagation*, Jun. 2015.

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