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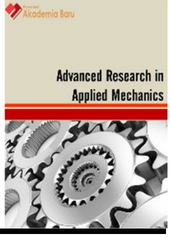

Sea-Water Based Reconfigurable Reflectarray Antenna

S. H. Zainud-Deen[1,*], H. A. Malhat[1], M. M. Abdelbary[1]

[1] Department of Electronics and Electrical Engineering Faculty of Electronic Engineering, Menoufia University, Egypt

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ABSTRACT

A high efficiency sea-water based reflectarray antenna for maritime wireless communications at 740 MHz is introduced in this paper. The proposed reflectarray consists of 169 unit-cell elements covering an area of 330.2×330.2 cm^2. Each unit-cell element consists of a cylindrical dielectric container filled with sea-water mounted on conducting plate and introduces phase variation from 0 to 313 degrees. The reflectarray is designed and analyzed using the finite integral technique and compared to that calculated using the finite element method. The radiation characteristics of 13×13 sea-water based reflectarray are investigated and presented. The main beam direction of the sea-water based reflectarray is controlled by the water level in each unit-cell element through an electronic valves. The reflectarray introduces maximum gain of 26.2 dB at 740 MHz with 1-dB gain bandwidth of 50 MHz The effect of temperature variation on the electrical properties of sea-water and the radiation characteristics of the water-based reflectarray are depicted.

1. Introduction

Recently, water-based liquid antennas have attracted increasing interest for maritime wireless communications [1]. Water-based antenna is a type of antenna which utilizes water to transmit and receive electromagnetic signals. They are typically fabricated by injecting water into a dielectric substrate (e.g., polydimethylsiloxane, PDMS) and are therefore flexible and mechanically durable [2]. They can be considered as either dielectric resonator antennas (DRAs) or conducting antennas. In the literature, water-based liquid antennas, pure water and salty water, are most commonly used where their characteristics are well documented in the open literature [3]. These antennas introduce many advantages such as: 1) low cost, 2) compact size, c) conformability, it is easy to make the antenna to the desired shape, d) configurability (physical, electrically and chemically). The conductivity of the water-based antenna can be altered by modifying the salinity percentage of the water which make it reconfigurable [4]. The water-based liquid antennas have been used in a variety of applications as Digital Video Broadcasting to Handheld (DVB-H), HF under water communications, and wearable or implantable bio-monitoring. Different water-based antenna

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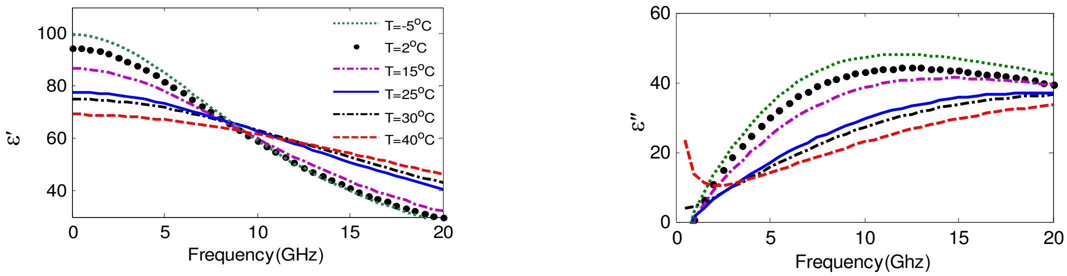
[*] *Corresponding author.*
E-mail address: anssaber@yahoo.com (S. H. Zainud-Deen)

designs have been investigated such as wideband saline water antenna monopole [5], cylindrical DRA [6], leaky-wave antenna using periodic water grating [7], and water patch antenna [8]. Modern communication systems employ sophisticated forms of antennas to transmit and receive signals over great distances such as phased antenna arrays and parabolic reflector [9]. Antenna array having hundred elements can be constructed for increasing antenna gain. However, it usually suffers from power loss in the feeding network. High efficiency parabolic reflectors avoid the usage of complex feeding network but it is bulky and have complex supporting structure. Recently, reflectarray antennas made from a flat reflecting surface of isolated elements and illuminated by feed antenna are investigated [10]. Reflectarray antennas combine the same features of parabolic reflectors and phased arrays providing a directive beam in a desired scanned angle. Several methods are reported for reflectarray elements design to achieve a planar phase front such as, variable size patches, dipoles, perforated, or rings so that elements can have different scattering impedances and, thus, different phases are compensated [11].

In this paper, a 13×13 water-based reflectarray antenna is designed and analyzed to operate at 740 MHz applications. The electrical properties of water allow the design of compact, small size and reconfigurable antennas compared to the metallic counterpart. The proposed unit-cell is DRA like water-filled container placed above conductor square plate. The reflection coefficient magnitude and phase responses are calculated using the finite integral technique (FIT) and compared to that calculated by the finite element method (FEM) [12, 13]. The paper is organized as follows: Section II introduces the basic electrical properties of water as a function of frequency, temperature and salinity. Section III investigates the design of the proposed unit-cell and the water-based reflectarray radiation characteristics. Section IV presents the effect of temperature variation on the radiation characteristics of the water-based reflectarray. Finally the results are concluded in Section V.

2. Complex Permittivity of Sea-Water



(a) Real part

(b) Imaginary part

Fig. 1. The complex permittivity of sea water variation versus frequency at different temperature

The electrical properties of the liquid are essential for water-based liquid antenna designs. The complex permittivity of sea-water which is a function of operating frequency f, temperature T and substance concentration S [4]. Different models have been developed to estimate the complex permittivity of water have been investigated in [14]. A simple Debye model for the sea-water complex permittivity based on measurement and polynomial fits were derived in [4]. The first order Debye model for complex permittivity is expressed as

$$\varepsilon = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1+j2\pi f\tau} \qquad (1)$$

where $\varepsilon_s$and ε_∞ are the static and high frequency dielectric constants, respectively. τ is the relaxation time constant in seconds and f is the frequency. A general polynomial equation for complex permitivity of sea-water, is

$$\varepsilon(f,\mathrm{T},\mathrm{S}) = \varepsilon_\infty(\mathrm{T},\mathrm{S}) + \frac{\beta_o(T,S)}{\alpha_o(T,S)+j2\pi f} + j\frac{\gamma_o(T,S)}{2\pi f} \quad (2)$$

where the parameter/coefficients ε_∞, α_o, $\beta_o$and $\gamma_o$are dependent on tempreture T and substance concentration S are given by [4]

$$\varepsilon_\infty(\mathrm{T},\mathrm{S}) = \sum_{m+n=0}^{3} C_{\varepsilon mn} S^m T^n$$

$$\alpha_o(T,S) = \sum_{m+n=0}^{3} C_{\alpha mn} S^m T^n$$

$$\beta_o(T,S) = \sum_{m+n=0}^{3} C_{\beta mn} S^m T^n$$

$$\gamma_o(T,S) = \sum_{m+n=0}^{3} C_{\gamma mn} S^m T^n \quad (3)$$

m, n are non-negative integers, m+n=0,1, 2, 3. The coefficients$C_{\varepsilon mn}$, $C_{\alpha mn}$, $C_{\beta mn}$, $and\ C_{\gamma mn}$, are listed[4]. The complex permittivity of sea-water for S =1(ppt) as a function of frequency and temperature are shown in Fig. 1. At constant temperature, by increasing frequency, the real part of the permittivity is decreased and the imaginary part of the permittivity is increased (increased conductivity). At constant frequency below 10 GHz, the real part of permittivity is decreased as the temperature is increased, the real part of permittivity is increased with increasing temperature above 10 GHz. The imaginary part of the permittivity is decreased by increasing temperature, hence the losses is decreased at the same frequency.

3. Design of Water-Based Reflectarray

(a) (b)

Fig. 2. (a) The 3-D construction of 13×13 unit-cell reflectarray, (b) The phase distribution on the 13×13 unit-cell reflectarray for braosighet beam at ϑ_o=ϕ_o=0

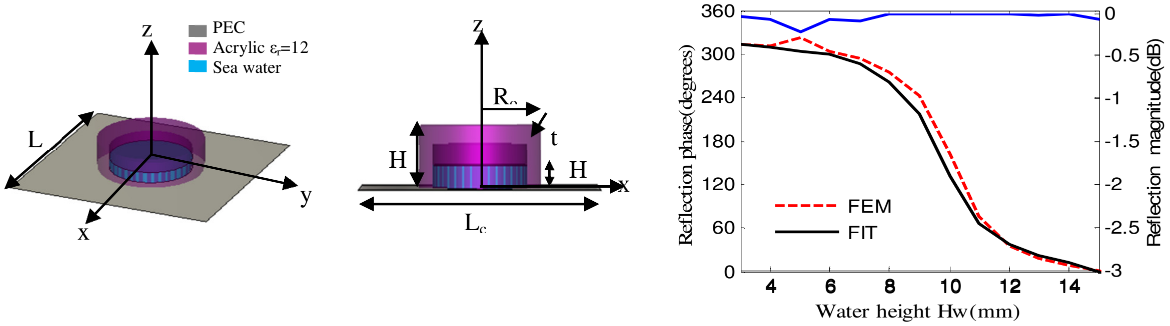
The 13×13 sea water-based reflectarray antenna is arranged on the x-y plane and illuminated by a feed horn as shown in Fig. 2a. The required phase distribution of each unit-cell element in the reflectarray to collimate beam at and (ϑ_o,ϕ_o) is calculated by [10]

$$\varphi_R\left(x_{cij},y_{cij}\right)=k_o\left[d_{ij}-x_{cij}sin\theta_0cos\emptyset_o-y_{cij}\ sin\theta_0\ sin\emptyset_o\right] \tag{4}$$

and,

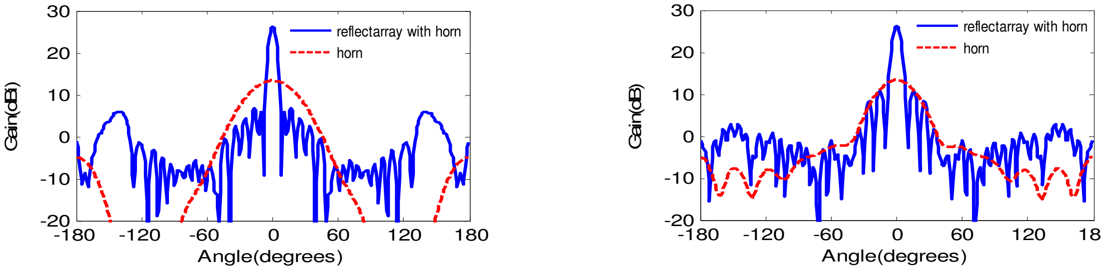
$$d_{ij}=\sqrt{\ (x_{cij}-x_f)^2+\left(y_{cij}\ -y_f\right)^2+z_f{}^2} \tag{5}$$

where $k_o = 2\pi/\lambda_o$, is the propagation constant in free space, $(x_{cij}\ ,\ y_{cij})$ are the coordinates of the unit-cell elements, $(x_f\ ,\ y_f\ ,\ z_f)$ are the coordinates of the phase centre of the feeding horn. The phase distribution of the 13×13 unit-cell reflectarray is shown in Fig. 2b. The phase shift is varied from 0 to 360° according to the position of each unit-cell element. The proposed water-based unit-cell element is shown in Fig. 3a. It consists of acrylic cylindrical container with radius R_o=6.5 cm, thickness t=1.5 cm, height H=5 cm, and relative dielectric constant ε_r=12. The container is placed above perfect conductor (PEC) ground plane of 25.4×25.4 cm^2. The container is filled with sea-water with ε_r=78.7, tan $\delta=1.34\times10^{-11}$ and height H_w. The required phase compensation of each unit-cell element is achieved by changing the water height H_w in the container. The variation of the reflection coefficient magnitude and phase variation versus water height at 740 MHz is shown in Fig. 3b. The reflection coefficient magnitude is approximate 0 dB with phase of 313 degrees. The results are calculated using FIT and compared with that calculated using FEM. Good agreement is obtained between the two techniques. A circular feeding horn with dimensions R_1=31.5 cm, L_h=48 cm, t_h=4.6 cm, and h_g=17.6 cm located at distance 37.9 cm is used to feed the reflectarray. The E- and H-plane radiation patterns for the 13×13 water-based reflectarray antenna and horn are presented in Fig.4. The horn antenna has a maximum gain of 13.4 dB. The HPBW is 6 degrees in E- and H-plane with first SLL of 20.7 dB in E-plane and 15.4 dB in H-plane relative to the main lobe. The gain and radiation efficiency responses of the 13×13 water-based reflectarray antenna are shown in Fig. 5. The reflectarray introduces maximum gain of 26.2dB with 1-dB gain variation of 50 MHz and high radiation efficiency of 99% at 740 MHz.



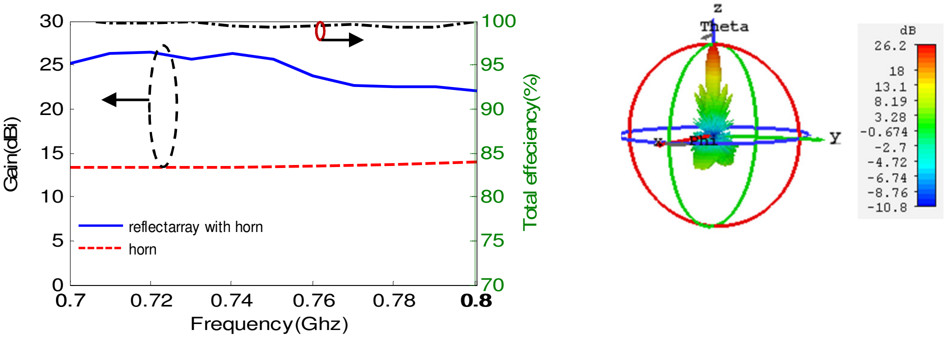
(a) (b) (c)

Fig. 3 (a) The 3-D view, (b) the side-view of the proposed water-based unit-cell, (c) The reflection coefficient magnitude and phase at 740 MHz



(a) (b)

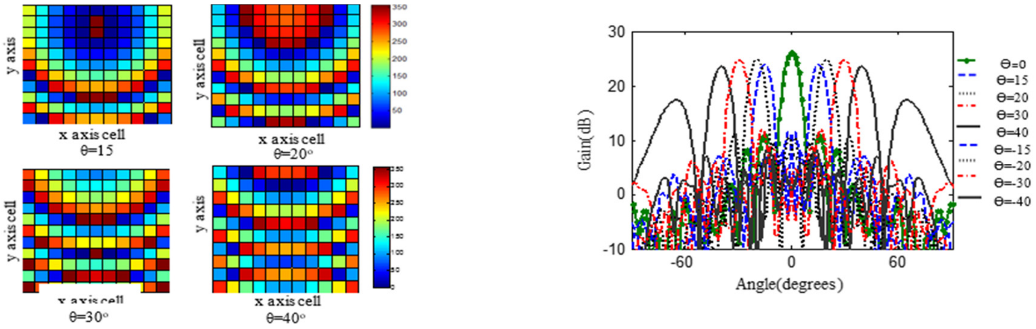
Fig. 4. The E- and H-plane radiation patterns for seawater reflectarray and horn antenna at f=740 MHz



(a) (b)

Fig. 5. (a) The radiation efficiency and gain response, (b) The 3-D gain pattern at 740 MHz

For beam scanning in the plane φ=0, and different θ directions, the water height in the acrylic container is controlled through electronic valves according to the direction of required beam The phase distribution on the 13×13 water-based reflectarray antenna for beam scanning at ± 15°, ±20°, ±30°, and ±40° are shown in Fig.6a. The E-plane radiation patteren for beam scanned from -40° to 40° at 740 MHz is shown in Fig. 6b. The peak of each beam is reduced by increasing the scainning angle due to the deflection from borsiget radiation direction of the unit-cell. The beam-width is increased with increasing the deflection angle from the z-axies.

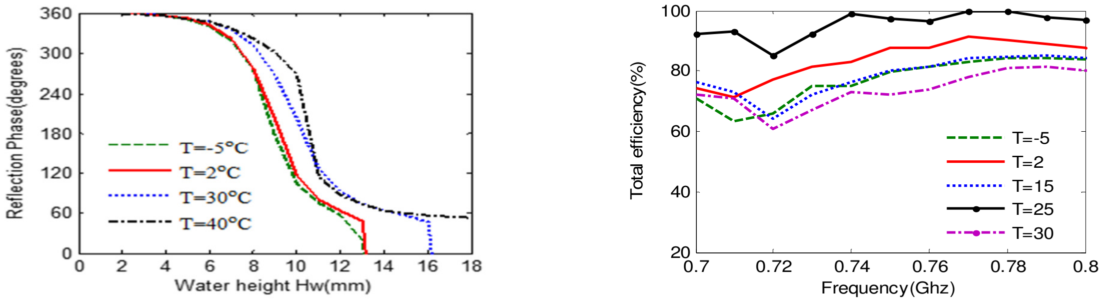


(a) (b)

Fig. 6. (a) The phase distributions of the 13×13 water-based reflectarray antenna for beam scanning at ±15°, ±20°, ±30°, and ±40° , (b) The E-plane radiation patteren for beams scanned from -40° to 40° at 740 MHz

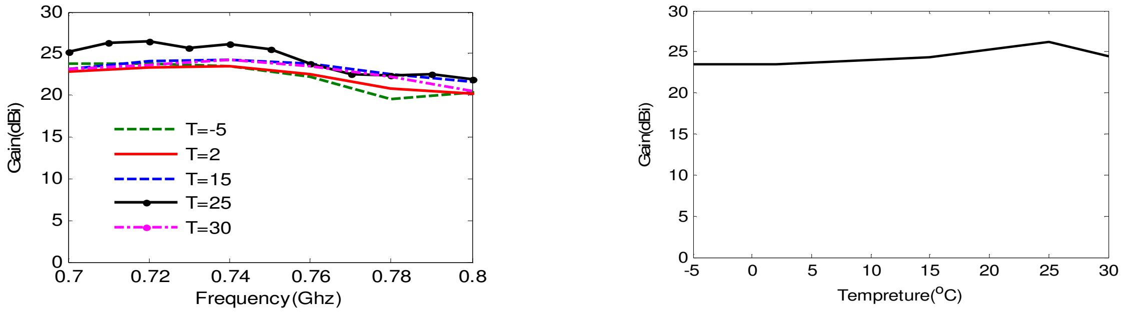
4. Effect of Temperature on the Performance Water-Based Reflectarray Antenna

Due to the variation of the electrical properties of the sea-water with temperature, the effect of temperature variation on the radiation characteristics of the reflectarray is investigated. Figure 7a shows the reflection coefficient phase response with sea-water level in the container at different operating temperature at 740 MHz. By increasing temperature the water level inside the acrylic container of the unit-cell is increased slightly to cover the 300^{o} phase range variation and the curve slope is increased then the overall bandwidth of the reflectarray is reduced. The radiation efficiency response of the 13×13 sea-water based reflectarray antenna at different temperatures are presented in Fig. 7b. The radiation efficiency is varied from 70 % to 99.5% at 740 MHz is achieved over the temperature range variation from -5 ^{o}C to 30 ^{o}C. The gain variation versus frequency at different temperatures are shown in Fig. 8a. The gain variation versus temperature at 740 MHz is shown in Fig.8b. The gain is nearly constant with increasing temperature up to 30 ^{o}C, with maximum gain of 26.2 dB and varied within 2 dB over the temperature range due to the losses in the sea water. The E- and H-plane gain patterns at 740 MHz for different temperatures are shown in Fig.9. Nearly the same radiation patterns with HPBW of 6 degrees and SLL of 17 dB are obtained.



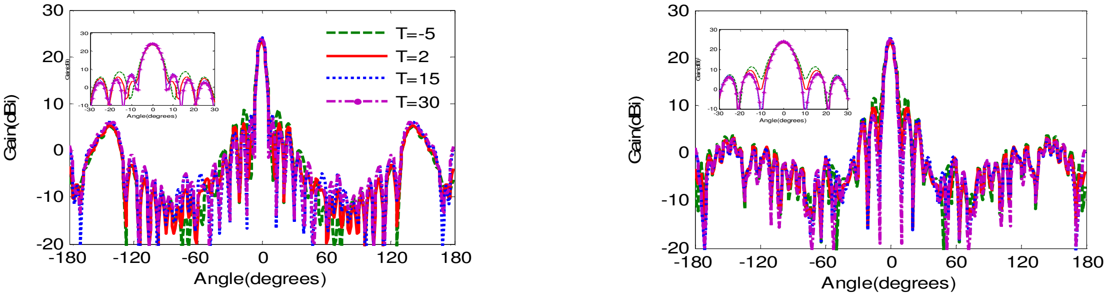
(a) (b)

Fig. 7. (a) The reflection coefficient phase response with water level in the container at different operating temperature at 740 MHz, (b) The radiation efficiency responses at different temperatures.



(a) (b)

Fig. 8. (a) The gain responses at different temperatures, (b) The gain variation versus temperature at 740 MHz



(a) (b)

Fig. 9. The E- and H-plane radiation patterns for seawater reflectarray at740 MHz for different temperatures

4. Conclusion

This paper presents the design of compact, planar, and temperature independent sea-water based reflectarray for wireless communications applications. The electrical properties of sea-water are investigated in terms of frequency and temperature. The unit-cell element introduces reflection coefficient magnitude of approximate 0 dB and phase of 313 degrees at 740 MHz for sea-water level variation from 3mm to 15mm. A 13×13 sea-water based reflectarray antenna with sea-water level in each unit-cell element controlled by an electronic valve is designed and analyzed. The reflectarray introduces maximum gain of 26.2 dB with 1-dB gain variation of 50 MHz and high radiation efficiency of 98% at 720 MHz An electronic beam scanning from -40o to +40o using electronic valves to change the sea-water level in each unit-cell according to the beam direction. The radiation efficiency is varied from 70 % to 99.5% at 740 MHz is achieved over from -5 oC to 30 oC. The gain is nearly constant with maximum gain of 26.2 dB and varied within 2 dB over the temperature range.

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