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Function-Reconfigurable Water Short Backfire Antenna

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ABSTRACT A novel short backfire antenna realized by replacing the metallic wall with water wall is described in this paper. Through controlling the water flow in different layers, the proposed short backfire antenna based on a cylindrical waveguide made of water can switch between two different functions. When the proposed antenna works in Function I, it is a short backfire antenna with pencil beam. When it operates in the other function, conical beam is achieved, and its beam angle can be changed by controlling the height of water cylinder and water wall. Measured results show that when working in Function I, the proposed water short backfire antenna has an impedance bandwidth ($|S11| < -10$ dB) of 11.3% (3.6 GHz to 4.05 GHz). A maximum gain of 10.8 dBi is observed. While working in Function II, the beam angle of a conical radiation beam can be switched between 25° and 60°. The operating frequency of the antenna working in Function II covers a range of 5% (3.9 GHz to 4.1 GHz). Maximum gain of 6.8 dBi for 25° and 2.7 dBi for 60° is obtained. Due to its low cost, good radiation performances, transparent characteristic, and reconfigurability, this novel water antenna may be potentially useful in future communication applications.

INDEX TERMS Reconfigurable antenna, water antenna, short backfire antenna.

I. INTRODUCTION

Liquid antennas have received a growing attention due to several attractive features as conformability, reconfigurability and transparency [1]. Among them, water is a good choice because it is of low cost and readily available. Pure water, sea-water and saline water with different salinities can be used to construct antenna. Many different kinds of water antennas have been reported [2]–[31].

Due to the existence of salt, electrical properties of sea-water and saline water are similar to a good conductor. Hence, they are usually used as a conductive medium to design antennas. In [2], a wideband saline water antenna was proposed and effects of different salinities were studied. A monopole antenna made of sea-water was designed in [3]. The relationship between conductivity and radiation efficiency has been discussed. A shunt-excited sea-water monopole antenna of high efficiency was reported in [5]. A conducting tube and Gamma-shaped feeding arm were employed to feed the structure and high radiation efficiency was achieved. Sea-water half-loop antenna was proposed in [6]. In [7], a sea-water array was designed. The concept of log-periodic monopole array was proposed to achieve wideband operation. In [8], a helical antenna made of saline water was reported.

Pure water can be considered as dielectric due to its high dielectric constant. It has been used to design many different kinds of antennas as well. In [11], a water dielectric resonator antenna (DRA) with a compact size was proposed. A monopole antenna made of pure water was reported in [14]. In [20], a wideband optically transparent water patch antenna was designed. By using water to replace both the metallic patch and ground plane, high transparency feature was achieved. Water leaky-wave antennas were proposed in [21], [22]. By controlling the period of water grating, radiation pattern of the antenna can be tuned. In [23], a beam steering water antenna was proposed. By controlling the water flow to fill different water cylinders surrounding the water monopole, they can act as reflectors and the beam direction can be changed. In [25], a polarization-reconfigurable Archimedean spiral antenna with two water arms fed by a parallel strip line was designed. By tuning the water height to excite different water arm, polarization of the antenna can be changed. In [26], [27], pure water helical antenna with high efficiency was designed. By controlling the water flow to fill water arm with different rotation directions, the helical antenna achieves polarization reconfigurability over a wide band while maintaining a high gain.

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The short backfire antenna has been widely used in maritime, space and many other communication systems since its first report in 1965 [32]. Compared to end-fire antennas like Yagi-Uda antenna, it can achieve a similar gain while requiring only about one tenth of the height. The short backfire antenna is composed of a cylindrical cavity containing a feed system placed between a ground plane and a smaller sub-reflector. The short backfire antenna design has been improved over the past years [33]–[39]. Arc reflector, cone sub-reflector, and a second small reflector were used to obtain higher gain in [34]. In [35], a short backfire antenna fed with a waveguide and bowtie exciter was reported. In [36], corrugated reflector was employed. In [39], metamaterial was used to increase the antenna's directivity and radiation efficiency. However, there is still no design of a short backfire antenna that can exhibit reconfigurability.

In this paper, a new short backfire antenna realized by pure water enclosed with transparent resin is proposed. Due to the usage of pure water, the proposed antenna becomes optically transparent and of low cost. A function-reconfigurable water short backfire antenna is also designed. By controlling the water to fill different layers, the proposed antenna can switch between Function I: a water short backfire antenna with pencil beam, and Function II: a water conical beam antenna with beam angle reconfigurable. The mode excited in the antenna can be changed by controlling the water flow in its feed system, resulting in the radiation pattern being switched between pencil beam and conical beam. When working as a water conical beam antenna, the beam angle can be tuned by controlling the height of water wall and water driven pole. Measured results show that when working in Function I, the proposed water short backfire antenna has an impedance bandwidth ($|S11| < -10$ dB) of 11.3% (3.6 GHz to 4.05 GHz). A maximum gain of 10.8 dBi is obtained. When working in Function II, a conical beam is achieved and the beam angle can be switched between 25° and 60°. The impedance bandwidth ($|S11| < -10$ dB) for Function II is 5% (3.9 GHz to 4.1 GHz). Maximum gain of 6.8 dBi for 25° and 2.7 dBi for 60° is obtained. The proposed water antenna can be potentially very useful in global positioning system, radar, and satellite communication systems due to its radiation performance, transparency feature and good reconfigurability.

The rest of this paper is organized as follows. Section II describes a water cylindrical waveguide, a reconfigurable water feed system and the configuration of the proposed antenna. Function I, a water short backfire antenna with a pencil beam is explained in Section III. Section IV shows its Function II, a water conical antenna with beam angle reconfigurable. Finally, a conclusion is drawn in Section V.

II. ANTENNA DESIGN AND CONFIGURATION

A. CYLINDRICAL WATER WAVEGUIDE

It is known that dielectric media play a very important role in many electromagnetic designs. To some extent, a dielectric layer of high dielectric constant can bound electromagnetic waves. Since the dielectric constant of pure water is extremely high, a water layer of suitable thickness may act as a reflector. The cross-sectional configuration of a water cylindrical waveguide is shown in Fig. 1. It is basically realized by replacing the metallic wall of a conventional metallic cylindrical waveguide with thin pure water layer. The dielectric constant of pure water is measured to be 78 at the center frequency of 4 GHz [40].

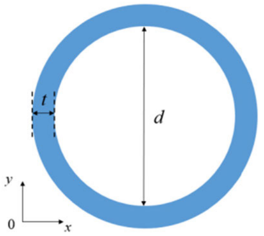
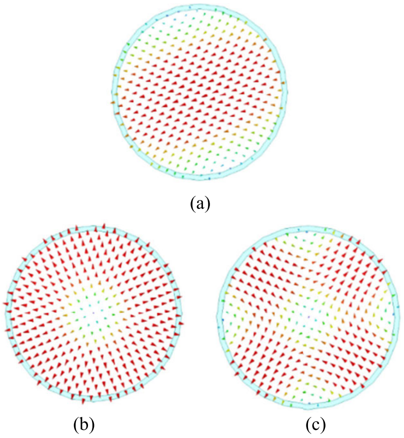


FIGURE 1. Cross section of the proposed water cylindrical waveguide.


(a)

(b)

(c)

FIGURE 2. Transverse E-field distributions of the first three modes in proposed water cylindrical waveguide. (a) HE_{11} mode. (b) TM_{01} mode. (c) HE_{21} mode.

A model of the water cylindrical waveguide is simulated using Ansys HFSS 14.0. The parameters used in the simulation are chosen as $t = 2$ mm, $d = 60$ mm. The first three modes of the water waveguide are HE_{11} mode, TM_{01} mode and HE_{21} mode. The transverse E-filed distributions of these modes are shown in Fig. 2. It can be seen that these modes are similar to those in a traditional metallic cylindrical waveguide. It should be noted that TM_{01} mode shown in Fig. 2(b) mode is axial-symmetric, which can be used to achieve conical radiation beam. According to the multimode simulations, the normalized phase constant (β/k_0) and attenuation constant of these modes are shown in Figs. 3 (a) and (b), in which, □β is the phase constant of the water waveguide and k_0 is the wavenumber in free space.

Fig. 4 shows the configuration of a water cylindrical waveguide with a reconfigurable feed system made of water. A coaxial probe is protruding in the center of the bottom of waveguide. A metallic cone is employed to facilitate the matching between the coaxial probe and circular water waveguide. Two tubes aiming to orient along different

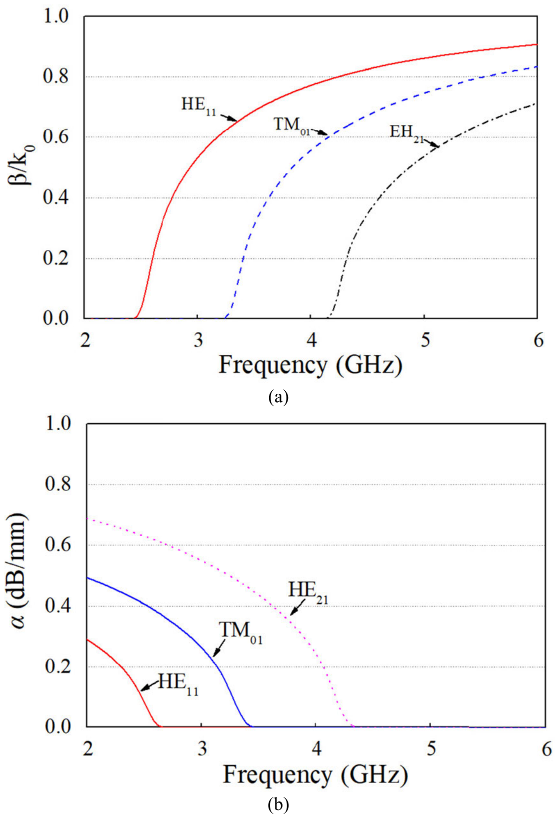


FIGURE 3. Simulated results of (a) normalized phase constant and (b) attenuation constant of the first three propagation modes excited in proposed water waveguide.

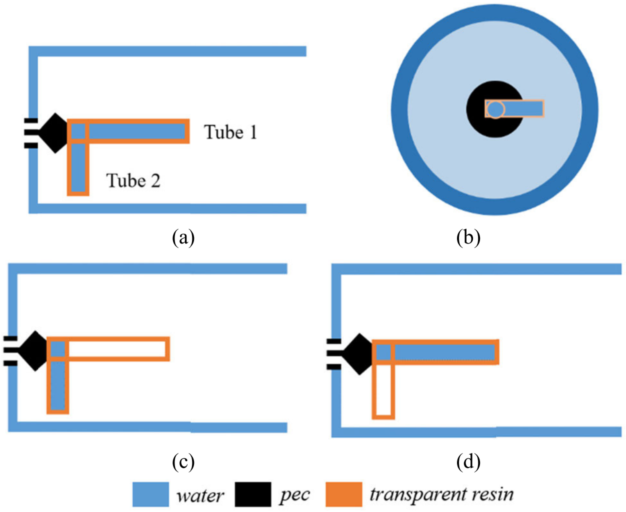


FIGURE 4. Configuration of a water cylindrical waveguide with the proposed reconfigurable water feed system (a) Side view (b) Top view (c) State A (d) State B.

directions are placed on the top of the metallic cone to control the excited mode. When the normal Tube 2 is filled with water, as shown in Fig. 4(c), the feed system works in State A, and the fundamental mode HE_{11} mode is excited. When the axial Tube 1 is filled with water, as shown in Fig. 4(d), the feed system works in State B, and an axial-symmetric mode is excited. Fig. 5 shows the transverse E-field distributions of the water cylindrical waveguide when the feed system is working in these two states. It is clear that when working in different states, different modes are excited and propagated in the water cylindrical waveguide.

TABLE 1. Dimensions of the proposed water short backfire antenna.

Parameter	D_m	D_s	d_1	d_2	l
Value/mm	150	50	60	5	15
Parameter	d_c	W	S_1	S_2	h_1
Value/mm	9	50	50	20	6
Parameter	h_2	h_3	t		
Value/mm	4	20	2		

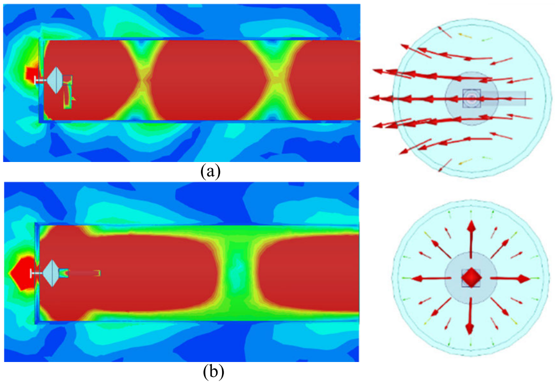


FIGURE 5. Simulated magnitude and vector distribution of electric field of the water cylindrical waveguide when feed system working in (a) State 1 and (b) State 2.

B. CONFIGURATION OF THE PROPOSED WATER ANTENNA

Fig. 6 shows the configuration of the proposed function-reconfigurable water short backfire antenna. The water walls are held by a container with interlayer made of transparent resin with a dielectric constant of 2.8. The container is fabricated by 3D printing technology and its thickness t is 2 mm. According to simulated results, the effect of the resin container can be neglected because its dielectric constant is quite small compared with that of the water wall. A probe with metallic cone is employed to feed the antenna. Detailed dimensions are shown in Table 1.

Due to the fluidity of water, the water antenna can be easily reconfigured. By controlling the water flow to fill different layers, the existence of the side wall of the water short backfire antenna can be switched. When the side walls are filled with water, the water antenna works as a pattern-reconfigurable short backfire antenna. When the side walls are empty, which makes the antenna looks like a water patch antenna, it works as a frequency-tunable antenna.

III. FUNCTION I: A WATER SHORT BACKFIRE ANTENNA WITH PENCIL BEAM

Fig. 7 shows the configuration of the proposed function-reconfigurable water short backfire antenna working in Function I as a water short backfire antenna with pencil beam. As shown in Section II, we can switch the excited mode of the water antenna by controlling the water flow to fill different tubes of the feed system. When the water is filled as shown in Fig. 7, HE_{11} mode is excited and a pencil radiation beam is obtained. Fig. 8 shows the magnitude and vector of the

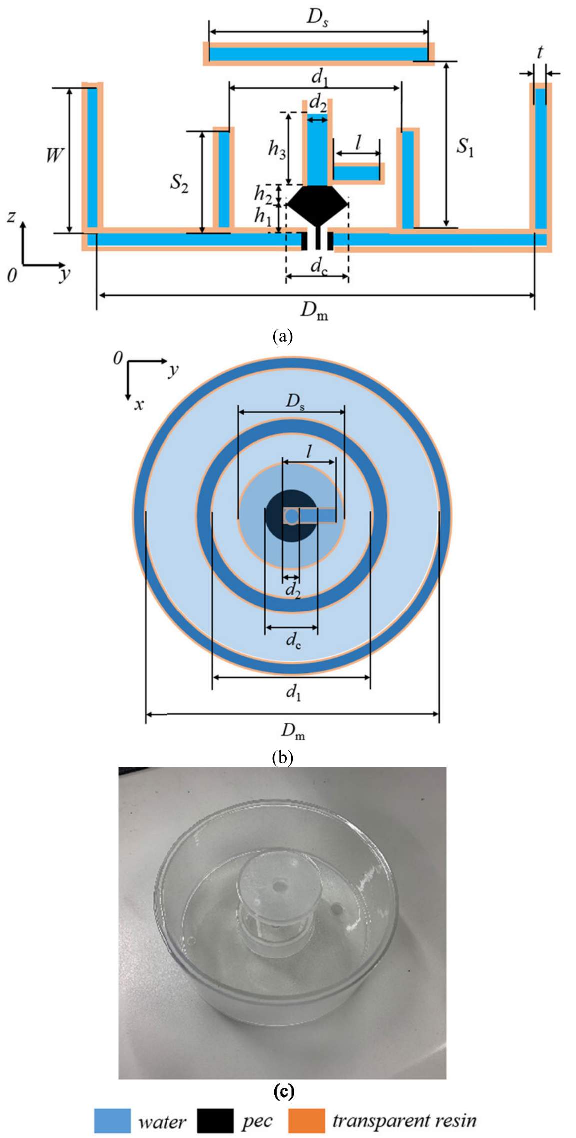


FIGURE 6. Configuration of the proposed function-reconfigurable water short backfire antenna. (a) Side view. (b) Top view. (c) Photo.

electric field distribution of the proposed water short backfire antenna when working in Function I.

Simulated and measured reflection coefficients of the proposed water short backfire antenna working in Function I are shown in Fig. 9. The simulated impedance bandwidth is 13.0% (3.6 GHz to 4.1 GHz) and the measured result is 11.7% (3.6 GHz to 4.05 GHz). Measured and simulated radiation patterns of the water short backfire antenna working in Function I is shown in Fig. 10. It can be seen that a pencil-beam radiation pattern is obtained when working in Function I. Good agreement between the measured and simulated results is obtained as well. Fig. 11 shows the simulated and measured gains and the simulated radiation efficiency of the proposed water short backfire antenna with pencil beam. It can be seen that maximum gains of 10.8 dBi is obtained, radiation efficiency better than 70% over the operating band is achieved as well.

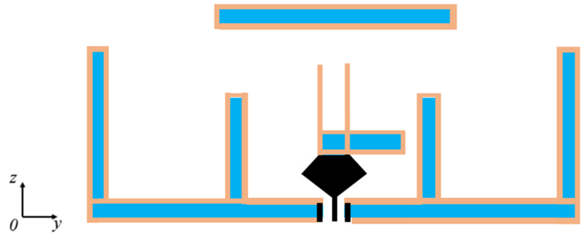


FIGURE 7. Configuration of the proposed function reconfigurable water short backfire antenna working in Function I.

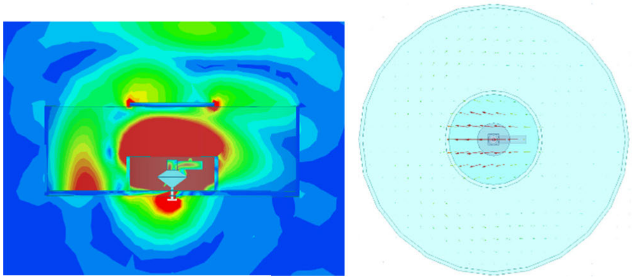


FIGURE 8. Simulated magnitude and vector distribution of electric field of the proposed water short backfire antenna working in Function I.

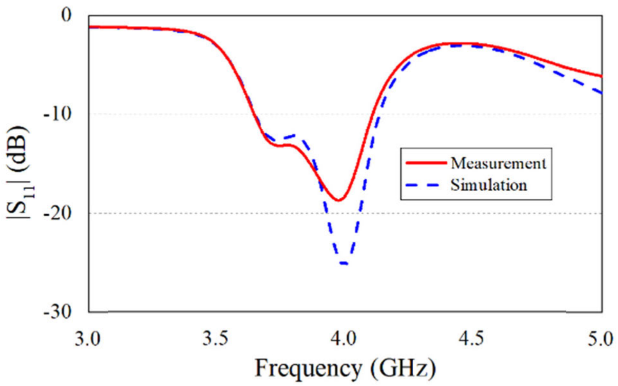


FIGURE 9. Measured and simulated reflection coefficients of the proposed water short backfire antenna working in Function I.

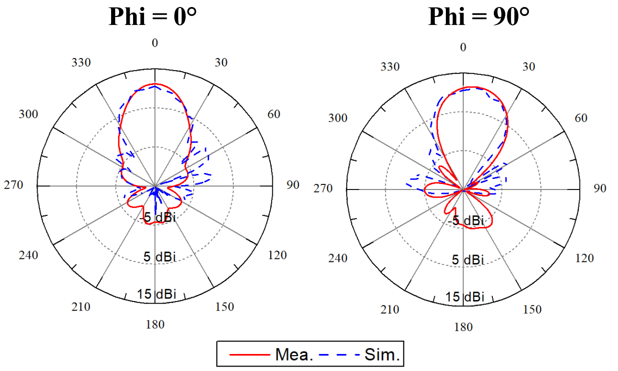


FIGURE 10. Simulated and measured radiation patterns of the proposed water short backfire antenna working in Function I.

IV. FUNCTION II: RECONFIGURABLE CONICAL ANTENNA

Fig. 12 shows the configuration of the proposed function-reconfigurable water short backfire antenna working in Function II as a water conical beam antenna with beam

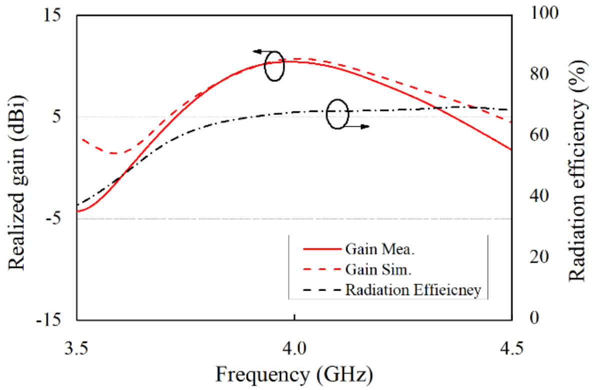


FIGURE 11. Radiation efficiency and measured and simulated gain of the proposed water short backfire antenna working in Function I.

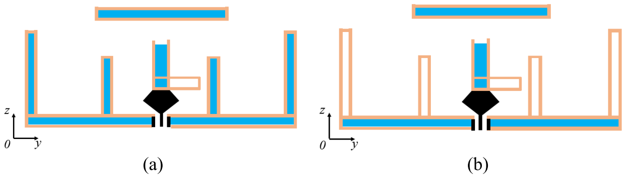


FIGURE 12. Configuration of the proposed function reconfigurable water short backfire antenna working in Function II with (a) State 1, and (b) State 2.

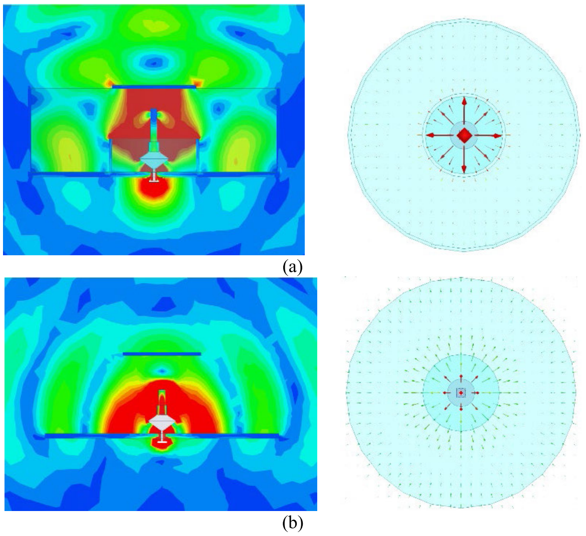


FIGURE 13. Simulated magnitude and vector distribution of electric field of the proposed water short backfire antenna working in Function I with (a) state 1, and (b) state 2.

angle reconfigurable. It can be seen that by controlling the water volume, we can change the height of the side wall. Hence, the beam-pointing angle can be changed. In order to facilitate the discussions, we simply consider two states and they are shown in Fig. 12(a) and Fig. 12(b). Fig. 13 shows the simulated magnitude and vector of the electric field distribution of the proposed water antenna in two states. It can be seen that a symmetrical mode is excited, which may produce a conical beam.

Simulated and measured reflection coefficients of the proposed water antenna working in Function II with two states are shown in Fig. 14. It should be mentioned that with different heights of h_3 for the axial water cylinder, the operating frequency of the proposed antenna can be reconfigurable covering a wide frequency range as well. Fig. 15 shows the measured and simulated radiation patterns of the proposed water conical beam antenna working in two states. Good agreement between the measured and simulated results is obtained. It can be seen that the beam-pointing angle can be switched between 25° and 60° when operating in different states. Fig. 16 shows the simulated radiation efficiency and gain results of the proposed water conical beam antenna

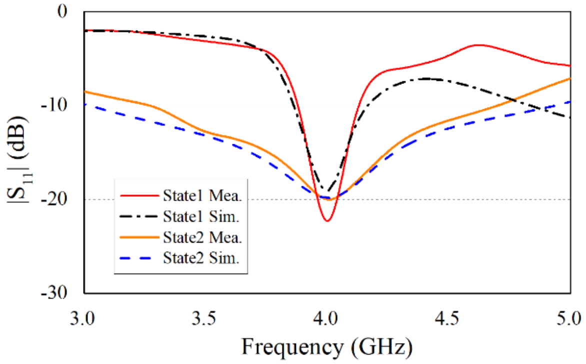


FIGURE 14. Measured and simulated reflection coefficients of the proposed water conical beam antenna working in two states.

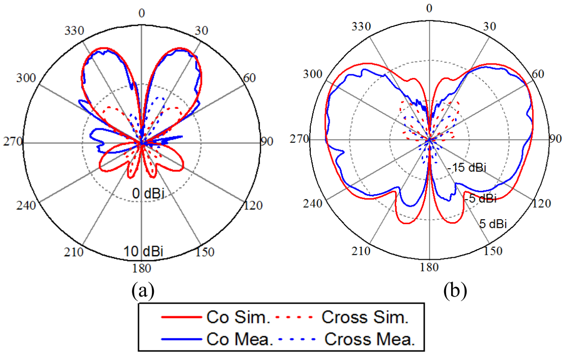


FIGURE 15. Simulated and measured radiation patterns of the proposed water conical beam antenna working in (a) State 1, and (b) State 2.

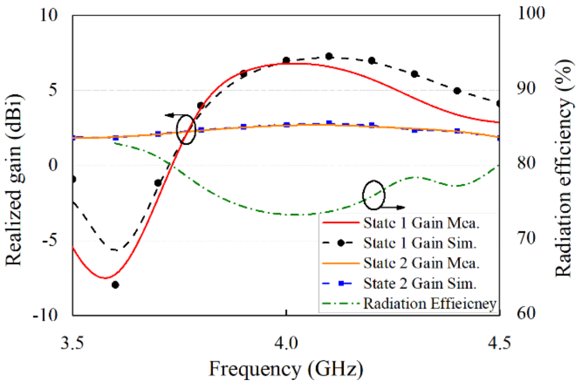


FIGURE 16. Measured and simulated gains and simulated radiation efficiency of the proposed water conical beam antenna working in two states.

working in two states. It can be seen that the maximum gain of 6.8 dBi for 25° and 2.7 dBi for 60° is obtained. The gain decreases when the beam-pointing angle beam increases because a much larger beamwidth is observed for a bigger beam-pointing angle. A radiation efficiency better than 70% over the operating band for both states are obtained as well.

V. CONCLUSION

A novel short backfire antenna made of water has been investigated in this paper. It has been found that by replacing the metallic wall of traditional metallic short backfire antenna with thin water layer, it can still bound electromagnetic waves like metallic reflectors. Based on the water short backfire antenna, a function-reconfigurable water short backfire antenna has been designed and constructed. The entire water short backfire antenna is enclosed by a transparent resin container and the water walls are all made of pure water, which is of low cost, easily available, and optically transparent. Measured results show that when working as a water short backfire antenna with pencil beam, the proposed antenna has an impedance bandwidth ($|S11| < -10$ dB) of 11.3% (3.6 GHz to 4.05 GHz). Maximum gain of 10.8 dBi is obtained. When working as a water conical beam antenna with beam angle reconfigurable, a conical beam is achieved and the beam angle can be switched between 25° and 60°. Maximum gain of 6.8 dBi for 25° and 2.7 dBi for 60° is obtained. The proposed antenna may be attractive for communication applications such as in flexible electronics or maritime environments.

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