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A Compact-Size Wideband Optically-Transparent Water Patch Antenna Incorporating an Annular Water Ring

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ABSTRACT A wideband optically-transparent water patch antenna with a compact size is proposed. Both the water patch and the water ground plane are made of distilled water to realize the highly optical transparency. Particularly, by simply incorporating an annular water ring under the water patch, the center frequency can be reduced from 2.3 GHz to 1.95 GHz, while the corresponding size of the water patch can be reduced by 28%. Both the simulation and the measurement are carried out for verification. The measured results turn out that a wide impedance bandwidth of 41.8% with SWR < 2, the maximum gain of 1.56 dBi, radiation efficiency up to 78% and stable monopolar radiation pattern with linear polarization can be achieved. Additional, the effects of the annular water ring on the antenna performance are analyzed and discussed.

INDEX TERMS Water patch antenna, transparent antenna, compact size, monopolar radiation pattern, annular water ring.

I. INTRODUCTION

Antennas with novel materials have attracted more interests in research institutions and technical companies. Various novel materials are utilized, including textiles, plasmonic and fabric substrates, liquid metals, glass, ethyl acetate [1]–[9]. Among all these materials, water becomes popular for its unique merits, such as low in material cost, easy access, liquid and flexible configuration, highly optical transparency [10]. Generally, water can be divided into two categories. One is salt water or sea water and another one is distilled water or pure water. Distilled water can be viewed as a pure dielectric substrate with high dielectric constant at microwave frequencies, which could be utilized to design dielectric resonator antennas (DRA) [11], [12]. Salt water can serve as a conductor since it has some degree of conductivity to support the current flowing inside. Thus, salt water is often utilized to form monopole or loop antennas, especially for maritime environments [13]–[15].

Dense dielectric patch antenna (DDPA) was proposed in 2013 [16]. Based on the basic patch antenna concept with the top metallic patch replaced with a thin dielectric substrate of relative high dielectric constant, the DDPA was achieved with similar performance as the conventionally metallic patch antenna. For millimeter-wave applications, the DDPA shows better characteristics in efficiency over metallic patch antennas since the caused conductor loss can be reduced [17]. Regarding the application at microwave frequencies, the DDPA can be applied to construct patch antennas composed of novel materials to address various challenges of sophisticated wireless communications in the future. Basically, water is a kind of material with relative high permittivity of about 80 at microwave frequencies at room temperature [18]. Therefore, water can be regarded as one of the liquid dense dielectric substrate for realizing the DDPA. The first patch antenna using distilled water was proposed in 2015 with the top metallic patch replaced by a pure water layer [19]. The working principle and results in [19] had demonstrated the successful realization of the concept of the water patch antenna. Following the prototype in [19], a transparent water patch antenna with both the patch and the ground plane made of distilled water was reported [20]. The obtained performance in [20] shows that the patch mode can be primarily excited and resonant in the middle substrate

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between the water patch and the water ground plane, resulting in the same working principle as the metallic patch antenna.

For a patch antenna with monopolar radiation pattern, the patch diameter is about one wavelength at its resonant frequency, which is physically larger and undesirable for many practical applications [21]–[30]. By etching slots on the patch or employing the folded patch, the total current length along the patch can be extended. Thus, a lower operating frequency and a compact patch size in terms of wavelength are achieved [31]–[34]. However, since no current exists inside distilled water, these approaches will not effectively work for water patch antennas. Incorporating a shorting pin close to the feeding probe is another simply approach to reduce the patch size due to the strong capacitive coupling effect between the shorting pin and the feeding probe [35]–[37]. However, this method will introduce additional metallic portions, decreasing the total optical transparency for the water patch antenna.

In this paper, a compact-size optically-transparent water patch antenna is proposed by simply incorporating an annular water ring under the water patch. It shows that with an annular water ring, the center frequency can be reduced from 2.3 GHz to 1.95 GHz, and the corresponding size of the water patch can decrease by 28%. Both the patch and the ground plane are made of distilled water to obtain the highly optical transparency. A wide impedance bandwidth of 41.8% with stable monopolar radiation pattern over the entire frequencies can be experimentally achieved.

II. ANTENNA CONFIGURATION

The proposed antenna configuration is shown in Fig. 1, with detailed dimensions given in Table. 1. The fabricated prototype is given in Fig. 2. The compact water patch antenna consists of four main portions: a water patch layer, a water ground plane layer, an annular water ring and a disk-loaded metallic probe. All the utilized water in the proposed configuration is distilled water, which is a kind of low-cost and optically transparent material. Both the water patch and the water ground plane are in circular shape for obtaining an omnidirectional radiation pattern. A disk-loaded probe is employed in the center position to capacitively excite the antenna. The probe connects to a coaxial cable of 50 ohm impedance. The thickness of the disk is 1.0 mm. The inner conductor of the coaxial cable acts as the vertical portion of the disk-loaded probe. In order to ensure the EM waves can be effectively transmitted into the middle substrate (plexiglass), the coaxial cable is arranged to entirely penetrate through the water ground plane into the middle substrate. The entire configuration is enclosed by a transparent container comprising the plexiglass. Particularly, a cylindrical hollow air cavity is left in the middle substrate for placing the disk-loaded probe. The measured dielectric constant and the dielectric loss tangent of the used plexiglass at room temperature are shown in Fig. 3. The measured dielectric constant and dielectric loss tangent of used distilled water had been carried out with results shown in [20]. For enhancing the accuracy, both the frequency-varying value of the dielectric

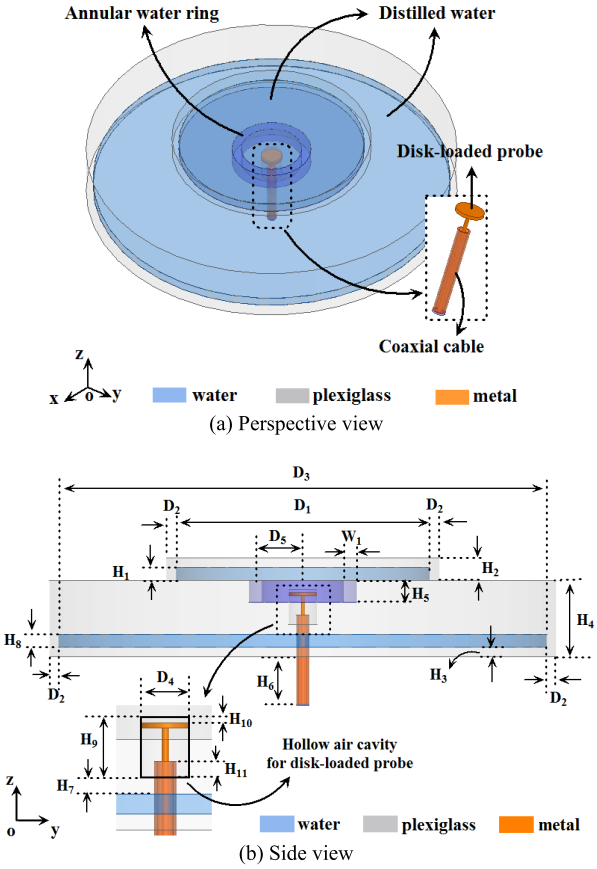

FIGURE 1. Configuration of the proposed compact-size water patch antenna: (a) Perspective view, (b) Side view.

TABLE 1. Dimension of the proposed compact-size water patch antenna.

Parameter	H_1	H_2	H_3	H_4	H_5
Value (mm)	4	7	3	23.5	7
Parameter	H_6	H_7	H_8	H_9	H_{10}
Value (mm)	20.5	3	3.5	11	1
Parameter	H_{11}	D_1	D_2	D_3	D_4
Value (mm)	3	80	3	154	9
Parameter	D_5	W_1			
Value (mm)	15	4			

constant and dielectric loss tangent of distilled water and plexiglass have been considered in the simulation process. All the used value of plexiglass and distilled water in the simulation are in the case of room temperature of approximately 20 °C in accordance with the practical experimental condition. The size of the water patch and the water ground plane is 0.52 λ_0 × 0.52 λ_0 and 1.0 λ_0 × 1.0 λ_0 respectively. The thickness of middle substrate is 0.11 λ_0 (λ_0 refers to one wavelength in air at the center frequency of 1.95 GHz).

III. ANTENNA WORKING PRINCIPLE

A. ELECTRIC FIELD DISTRIBUTION

Because almost no current exist inside distilled water, only the distributions of electric field are studied in order to

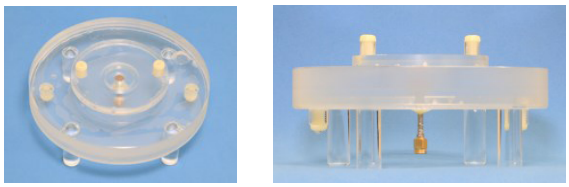

FIGURE 2. Prototype of the proposed compact-size water patch antenna: (a) Perspective view, (b) Side view.

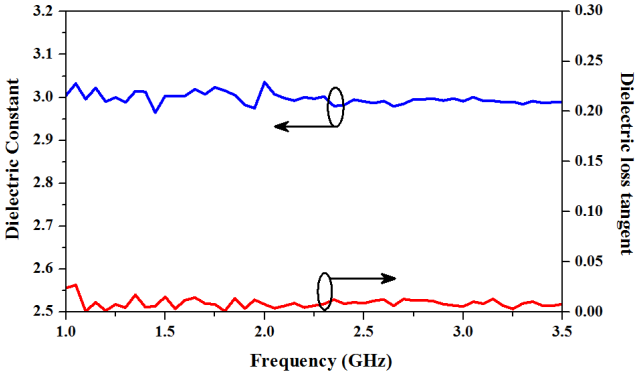

FIGURE 3. Measured dielectric constant and dielectric loss tangent of the plexiglass at room temperature used in the proposed compact-size water patch antenna.

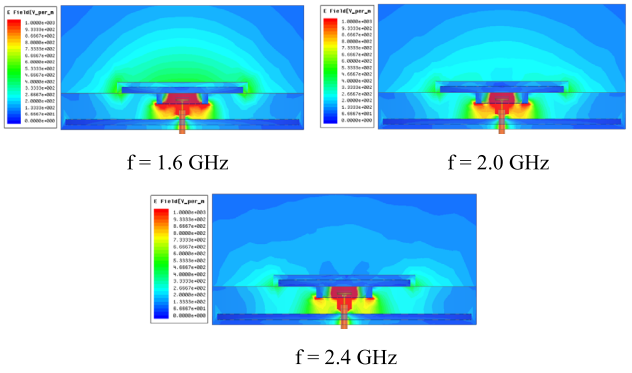

FIGURE 4. Simulated magnitude distributions of the electric field in the E-plane of the proposed compact-size water patch antenna across the entire frequencies.

investigate the working principle, and the performance is shown in Fig. 4 and Fig. 5.

The magnitude distributions of electric field in the E-plane are shown in Fig. 4. The majority of electric fields are confined between the water patch and the water ground plane, with very few electromagnetic (EM) waves inside distilled water. This is due to the higher dielectric constant of distilled water (∼80) and lower dielectric constant of plexiglass (∼3) at room temperature, leading to an internal reflection for most excited EM waves in the middle substrate on the boundary surface of water. Thus, the DRA mode of water will be reduced. The EM waves mainly resonant in the middle substrate of plexiglass, and then radiate into the free space through an annular open slot at the edge of the water patch.

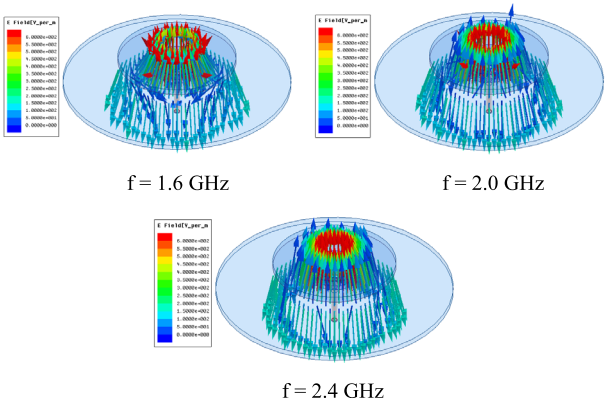

FIGURE 5. Simulated direction distributions of the electric field in the middle substrate of the proposed compact-size water patch antenna across the entire frequencies.

The direction distributions of electric field in the middle substrate of plexiglass are illustrated in Fig. 5. In order to generate a monopolar radiation pattern for a patch antenna, the TM_{02} mode needs to be excited. The electric field distributions of the TM_{02} mode for a patch antenna shows a sinusoidal distribution of one wavelength with the maximum electric field occurs at center and edge positions [22]. As seen from Fig. 5, the electric field distributions in the proposed water patch antenna is the same as in the metallic patch antenna operating at TM_{02} mode, demonstrating that the patch mode is primarily excited.

B. FREQUENCY DECREASE BY ANNULAR WATER RING

By simply incorporating an annular water ring in the middle substrate with the patch size unchanged, the center frequency can be reduced from 2.3 GHz to 1.95 GHz. As shown in Fig. 4 and Fig. 5, distilled water actually provides a kind of boundary with almost the same function of perfect electric conductor (PEC) to confine the EM waves. Besides, as the antenna radiation is from the circle edge of the water patch, the water patch along with the water ground plane can be actually regarded as a kind of transmission line to guide the propagation of excited EM waves in the middle substrate (plexiglass). Thus, the performance of frequency decrease of the water patch antenna can also be characterized using the transmission line theory.

Usually, the patch antenna with monopolar radiation pattern can be modelled as a transmission line with one wavelength in length at its resonant frequency. As shown in Fig. 6, the EM waves propagate along the transmission line consists of the water patch and the water ground plane, and then radiate at the edge of the water patch. The edge serves as an open slot of the transmission line, which can be modelled as a parallel circuit composed of shunt capacitance C and shunt conductance G. The water patch can be modelled as a section of transmission line of characteristic impedance Z_{water}. The disk-loaded probe gives the input excitation in the center position. When incorporating an annular water ring under the water patch, the characteristic impedance of

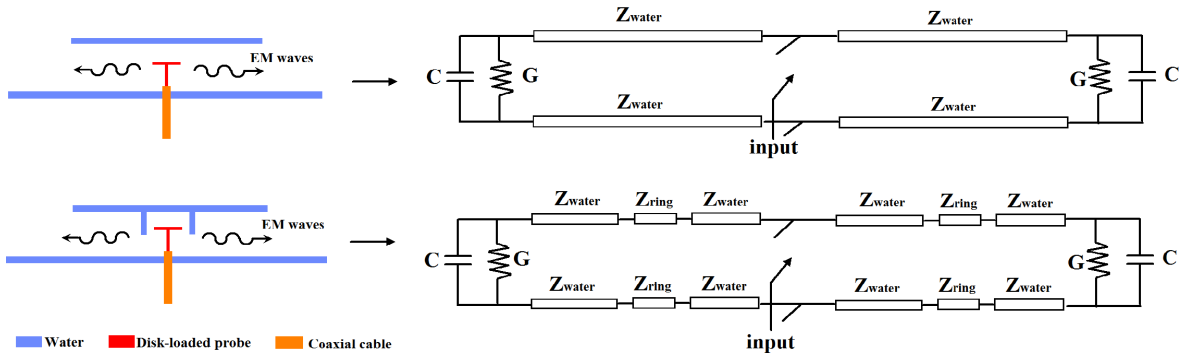

FIGURE 6. Equivalent circuit of the cross-section view of the proposed water patch antenna without and with an annular water ring.

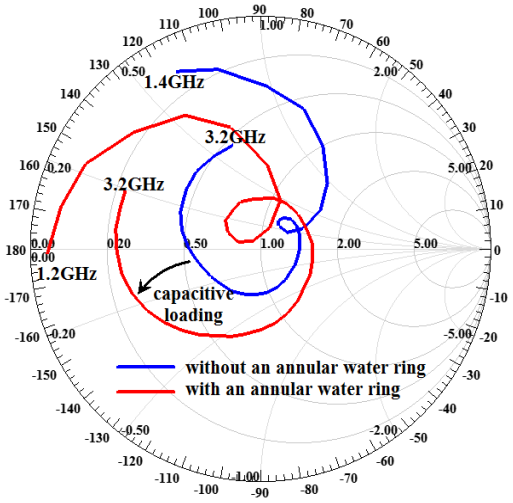

FIGURE 7. Comparison of the input impedance variation on smith chart for the proposed water patch antenna with and without an annular water ring.

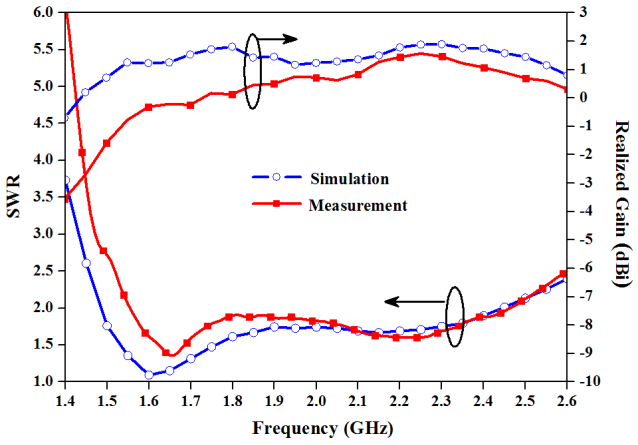

FIGURE 8. Simulated and measured SWRs and realized gains for the proposed compact water patch antenna.

the transmission line with water ring changes into Z_{ring}, resulting in the variation of total input impedance. Incorporating an annular water ring will decrease the gap distance between the water patch layer and the water ground plane layer, leading to an increased shunt capacitive C. Thus, Z_{ring} actually shows more capacitive than Z_{water},which is equivalent to the capacitive coupling to the original equivalent circuit of water patch.The locus of input impedance on smith chart for the proposed water patch antenna have been shown in Fig. 7. It shows that by incorporating an annular water ring, the locus has a counter-clockwise shift, demonstrating the effect of capacitive coupling. At the frequencies below the resonance of the water patch antenna, the inductive reactance of the input impedance can be compensated by the capacitive coupling of the water ring, resulting in a lower operating bandwidth.

IV. PERFORMANCE AND DISCUSSION

Both the simulation and the measurement have been carried out for verification. The S-parameter was measured by Agilent E5071C network analyzer and the radiation pattern, gain and efficiency were measured by SATIMO complex antenna measurement system.

A. BANDWIDTH AND GAIN

The simulated and measured results of SWR and gain are illustrated in Fig. 8. The measured and simulated impedance bandwidth with SWR < 2 is 41.8% (from 1.57 to 2.4 GHz) and 46.2% (from 1.5 to 2.4 GHz), respectively. The simulated gain varies from 0.7 to 1.8 dBi, and the measured gain ranges between -0.3 and 1.56 dBi. The difference between the simulated and measured gain is due to the inevitable measurement system error and fabrication error. Also, some possible air bubbles existing inside distilled water will cause some uncertainty deviations. The gain is not as high as in the metallic patch due to the dielectric loss of distilled water and a smaller size of the water ground plane.

B. RADIATION PATTERN

The simulated and measured radiation pattern over the entire bandwidth is shown in Fig. 9. The monopolar radiation pattern is achieved with the small cross-polarization and a wide beamwidth. In the E-plane, the conical beam radiation pattern is obviously obtained. The direction of the maximum radiation intensity occur at elevation angle of around 78 degree. The omnidirectional radiation pattern in the H-plane is achieved with quite small cross-polarization of less than -20 dB.

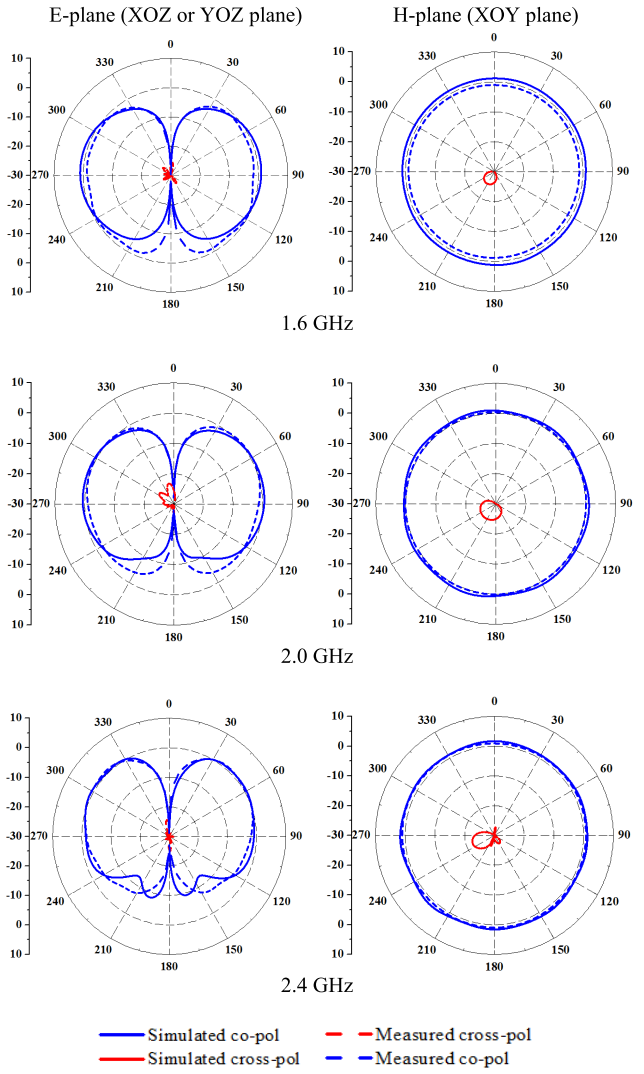

FIGURE 9. Simulated and measured radiation pattern in the E-planes (elevation planes) and H-planes (azimuth planes) across the operating bandwidth.

C. EFFICIENCY

The simulated and measured radiation efficiency are shown in Fig. 10. The simulated radiation efficiency ranges from 80% to 90%, while the measured radiation efficiency varies between 70% and 78%. The difference between them is mainly caused by the fabrication tolerance and some possible tiny air bubbles inside distilled water, causing deviation of distilled water volume between the simulation and the measurement. Since the most EM waves resonant in the middle substrate with lower dielectric loss rather than being absorbed by distilled water, good efficiency can be obtained accordingly.

D. DISCUSSION ON ANNULAR WATER RING

The annular water ring is the crucial portion to the size reduction and overall bandwidth because it can significantly affect the input impedance. Therefore, the height (H_5) and width (W_1) of the annular water ring are studied and analyzed.

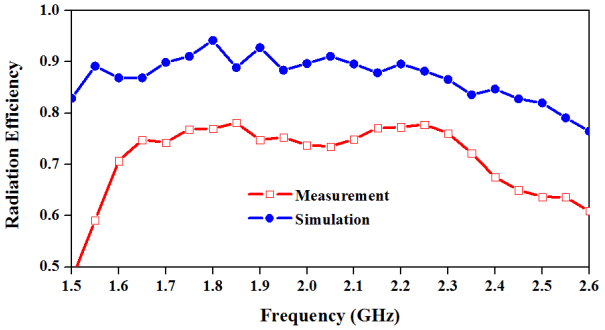

FIGURE 10. Simulated and measured radiation efficiencies for the proposed compact-size water patch antenna.

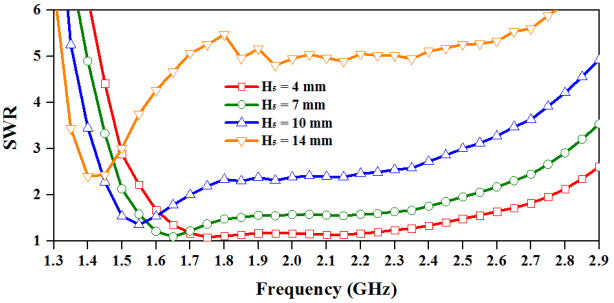

FIGURE 11. Simulated SWRs for the proposed compact-size water patch antenna with different height of the annular water ring (H_5).

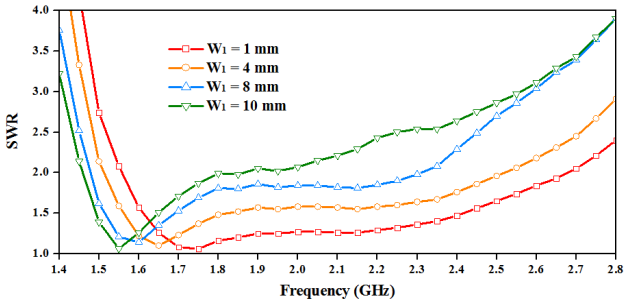

FIGURE 12. Simulated SWRs for the proposed compact-size water patch antenna with different widths of the annular water ring (W_1).

The results of SWR versus H_5 and W_1 have been shown in Fig. 11 and Fig. 12. It shows that increased H_5 and W_1 can result in the lower operating frequencies. This is mainly because a larger H_5 or W_1 will cause increased effect of capacitive coupling on the equivalent circuit of original water patch since the gap between the water ring and the water ground plane becomes smaller or longer. Besides, the change of H_5 and W_1 will result in obvious variation of bandwidth due to its capacitive coupling effect on the input impedance. However, a wide bandwidth can still be achieved by choosing suitable dimensions of the disk-loaded metallic probe.

A comparison between water patch antennas with and without an annular water ring is depicted in Fig. 13 and Table. 2. The dimensions of the disk and height of middle substrate are properly chosen for achieving the wideband characteristic. By adding an annular water ring, both the real

TABLE 2. Comparison of simulated results between water patch antennas with and without an annular water ring.

	Center Frequency	Diameter of water patch	Diameter of water ground plane	Imp. BW% (SWR < 2)
Water patch antenna without an annular water ring	2.3 GHz	80 mm (1.05 λg)	154 mm (2.01 λg)	52% (1.72 – 2.9 GHz)
Water patch antenna with an annular water ring	1.95 GHz	80 mm (0.89 λg)	154 mm (1.71 λg)	46.2% (1.5 - 2.4 GHz)

λg refers to the wavelength in terms of the middle substrate at center frequency in their respective passbands.
Imp. BW% refers to the impedance bandwidth in the simulation.

TABLE 3. Comparison of various monopolar patch antennas.

	Material of patch	Substrate dielectric constant	Polarization	Center frequency (GHz)	Diameter of circular patch	Substrate thickness	Imp. BW% ($\|S_{11}\|$ < - 10 dB or SWR < 2)	Max. Gain (dBi or dBic)
[21]	Metal	2.55	LP	5.2	1.17 λ	0.04 λ	3.3%	4.2
[22]	Metal	2.33	LP	2.26	1.1 λ	0.037 λ	18%	6.0
[23]	Metal	2.65	LP	5.76	2.03 λ	0.047 λ	27.4%	6.0
[24]	Metal	1.0	LP	2.15	1.0 λ	0.172 λ	52%	5.0
[25]	Metal	1.0	LP	1.91	0.955 λ	0.13 λ	30%	6.5
[26]	Metal	2.94	LP	6.05	2.14 λ	0.05 λ	12.8%	5.7
[27]	Metal	2.94	CP	5.7	0.98 λ	0.1 λ	28%	4.9
[28]	Metal	2.33	LP	1.88	1.45 λ	0.06 λ	25.5%	5.9
[29]	Metal	2.2	CP	2.45	1.14 λ	0.042 λ	16.6%	1.1
[30]	Metal	1.0	LP	2.55	1.054 λ	0.051 λ	23.5%	6.9
This work	Water	3.0	LP	1.95	0.89 λ	0.19 λ	42%	1.56

λ refers to the wavelength of center frequency in the middle substrate for respective antennas.
Imp. BW% refers to the impedance bandwidth.

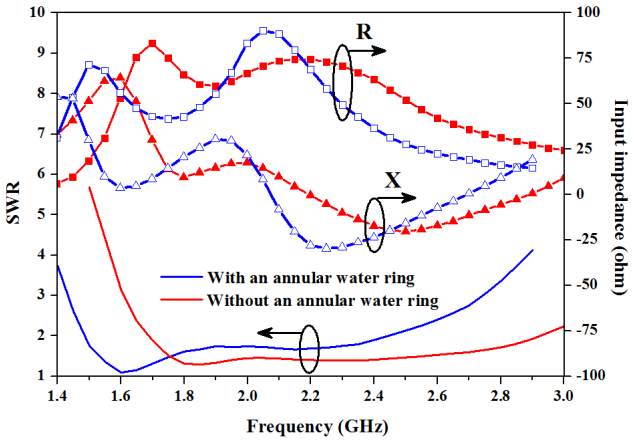

FIGURE 13. Simulated SWRs and input impedances for the water patch antennas with or without annular water ring.

and imaginary part of input impedance shift to lower frequencies with the center frequency decreasing to 1.95 GHz from 2.3 GHz. The corresponding size of the water patch is reduced by 28%. This is because the input reactance is inductive below 1.8 GHz for the water patch antenna without an annular water ring, as shown in Fig. 13. By incorporating an annular water ring, the capacitive effect of the annular water ring can significantly compensate a great number of inductive input reactance below 1.8 GHz, resulting in a resonance (zero crossing of input reactance) occurring at a lower frequency below 1.8 GHz. Thus, the center frequency is reduced and the size of water patch in terms of wavelength of center frequency is miniaturized.

E. COMPARISON AND DISCUSSION

A comparison of various reported monopolar patch antennas is illustrated in Table. 3. It shows that a thicker substrate or a lower dielectric constant of substrate can result in a wider bandwidth, as provided in [24] and [25]. In [23] and [26], an additional coupled annular ring was added to enhance the bandwidth so that their patch size are large. When comparing with the monopolar patch antennas composed of metal, the water patch antenna can also achieve a wide impedance bandwidth of over 40% if a thick substrate is used. The realized gain is up to 1.56 dBi, which is lower than most reported

monopolar metallic patch antennas due to the dielectric loss of distilled water at the operating frequencies.

V. CONCLUSION

A compact-size optically transparent water patch antenna is demonstrated in this paper. By simply incorporating an annular water ring under the water patch, the center frequency can be reduced from 2.3 GHz to 1.95 GHz, and the size of the water patch can be reduced by 28%. A disk-loaded probe is employed in the center position to excite the water patch antenna and also enhance the bandwidth. The water patch, the water ground plane and an annular water ring are all composed of distilled water, which is low material cost, easily available and 100% optically transparent. The entire compact water patch antenna is enclosed by the transparent plexiglass. The results turn out that a wide impedance bandwidth of 41.8% (from 1.57 to 2.4 GHz with SWR < 2), the maximum gain of 1.56 dBi, radiation efficiency up to 78%, and stable monopolar radiation pattern can be achieved.

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