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A Water Dense Dielectric Patch Antenna

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Abstract
A novel water dense dielectric patch antenna (DDPA) fed by an L-shaped probe is proposed and investigated. In contrast to the water antennas in the literature, including the water monopole and the water dielectric resonator antenna, the operation mechanism of the proposed water DDPA is similar to the conventional metallic patch antenna. The antenna is excited in a mode like the TM_{10} mode of the rectangular patch antenna. An L-shaped probe, which is widely used for the conventional patch antenna, is used to excite the water DDPA. A study on the bandwidth performance of the proposed design reveals that wide bandwidth can be achieved for the antenna by choosing a thick supporting substrate between the water patch and the ground plane. A prototype is fabricated to confirm the correctness of the design. An impedance bandwidth of 8%, maximum gain of 7.3 dBi, radiation efficiency up to 70%, and symmetrically unidirectional patterns with low backlobe and low cross polarization levels are obtained. Furthermore, owing to the transparency of the water patch, the proposed water DDPA can be conveniently integrated with the solar cells to realize a dual-function design. Measurements on the prototype demonstrate that the existence of the solar cells does not significantly affect the performance of the antenna and vice versa.

I. INTRODUCTION
Various liquid materials, such as mercury [1], [2], eutectic gallium indium (EGaIn) [3], liquid crystal [4], [5], and water [6], [7], have been utilized for realization of antennas owing to their many interesting properties, such as liquidity, transparency, and so on. Among these materials, water has become the most popular one recently because of low cost, easy access, and safety. Generally, the use of water for designing antennas can be divided into two kinds - the salt water and the pure water. The salt water is usually used as a conductor to support current flow. Different water monopoles have been designed based on this idea [8], [9]. On the other hand, the pure water is commonly applied as a dielectric to construct dielectric resonator (DR) antennas [10]–[12]. However, the high dielectric loss of the water degrades the radiation efficiency of these antennas.

Recently, a new kind of patch antenna designated as the dense dielectric patch antenna (DDPA) was introduced [13]. Compared with the conventional patch antenna, the metallic patch is replaced by a thin dielectric patch of high permittivity for the DDPA. As the permittivity of the dielectric patch is much larger than that of the supporting substrate, waves can be trapped between the dielectric patch and the ground plane. Therefore, the interface can be proximately seen as an electric wall. The result in [13] demonstrates that a cavity mode is still excited in the region between the dielectric patch and the ground plane. This indicates that the operating principle of the DDPA is similar to that of the metallic patch antenna.

As well known, at room temperature, the pure water is a dielectric with very high permittivity at microwave frequencies [10]. Hence, by applying the idea of the DDPA, a novel DDPA made of water is proposed in this paper. Different from other reported water antennas, the water patch in this antenna works as neither a conductor for current flow nor a dielectric resonator. It is just used for providing a boundary condition similar to an electric wall. Combining with the ground plane, the required cavity mode can be excited. Moreover, different from the reported DDPA, an L-shaped probe, which is widely used for conventional metallic patch antennas [14], is applied to feed the water dielectric patch antenna. The L-probe provides the convenience of fabrication for the design because it does not need to connect physically to the water patch. Furthermore, owing to the transparency of the pure water, the proposed antenna is optically transparent. Therefore it can be successfully integrated with solar cells to realize a dual-function device. Owing to the merits of low profile, simple structure, transparency, and good performance, the proposed L-probe fed water DDPA would be a promising candidate for many wireless applications.

INDEX TERMS Water patch, pure water, liquid antenna, dense dielectric patch antenna, L-probe.
The rest of the paper is organized as follows. Section II describes the geometry and design considerations of the proposed antenna. The simulated and measured results and the discussions are detailed in Section III. Finally, a conclusion is given in Section IV.

II. ANTENNA GEOMETRY AND DESIGN

The geometry of the proposed water DDPA with an L-probe feed is shown in Fig. 1. In order to realize the design, two boxes made of plexiglass are stacked together. The plexiglass has a thickness of 4 mm and a dielectric constant of 3.4. The top smaller rectangular box with a width of $W_P$, a length of $L_P$, and a height of $H_P$ is filled with pure water to construct the water dielectric patch, while the bottom larger square box with a height of $H_A$ is empty and is used as a supporting structure. Therefore, the substrate between the water patch and the ground plane is air in this design. A square metallic ground plane of length $W_G$ is installed at the bottom surface of the large box, where the L-shaped probe is mounted. The height and length of the L-probe are $L_V$ and $L_H$ respectively. There is a spacing $S$ between the edge of the water patch and the position of the L-probe. A short section of coaxial cable with an SMA connector is connected to the L-probe for measurement. It should be noted that the dimensions shown in Fig. 1 do not include the thickness of the plexiglass box.

It is found in our studies that since the operating mechanism of the proposed water patch antenna is similar to the conventional metallic patch antenna, they own analogous design rules as well. The design procedure of the patch antenna has been available in the literature [15], [16]. Besides, a parametric study of the DDPA was also given in [13], so it is not necessary to address them in details here. According to the result in [13], the aperture coupled DDPA with a thin substrate has a narrow bandwidth of 1%. However, it is well known that the L-probe fed patch antenna [14] is a wideband antenna structure. Therefore, it is worthwhile to investigate the bandwidth performance of the novel water dielectric patch antenna.

| TABLE 1. Dimensions of three water dielectric patch antenna designs (units: mm). |
|---------------------------------|------|------|------|
| Design I | Design II | Design III |
| $H_A$ | 10 | 20 | 30 |
| $L_P$ | 190 | 160 | 130 |
| $W_P$ | 80 | 80 | 80 |
| $L_V$ | 5.9 | 15.9 | 25.9 |
| $L_H$ | 57 | 52 | 33 |
| $S$ | 15 | 35 | 33 |
| $H_A$ | 5 | 5 | 5 |
| $W_G$ | 350 | 350 | 350 |

| TABLE 2. Performances of three water dielectric patch antenna designs. |
|-----------------------------|------|------|------|
|                          | Design I | Design II | Design III |
| $f_0$ (GHz)               | 0.93 | 0.92 | 0.9 |
| BW (|$|$ |$|$ $<$ |$|$ -10 dB) | 7.5% | 10.7% | 22.6% |
| Max Gain (dBi)            | 7.4 | 8.3 | 8 |

The bandwidth of the patch antenna is mainly determined by the height of the supporting substrate. To confirm this expectation, three water DDPA with different heights of the air substrate are considered. The center frequency of the operating band is set at 0.9 GHz in this study. The heights of the three designs are 10, 20, and 30 mm, corresponding to 0.03 $\lambda_0$, 0.06 $\lambda_0$, and 0.09 $\lambda_0$ at 0.9 GHz respectively. The permittivity and the loss tangent of the pure water are set as 81 and 0.04 based on the results in [17]. The performances of the designs are simulated with the assistance of a full-wave electromagnetic solver - Ansoft HFSS [18]. By tuning the dimensions of the three designs for good impedance matching, the final values of the geometrical parameters are listed in Table 1. The performances of the three designs are given in Table 2. Obviously, the impedance bandwidth significantly increases with the height of the air substrate. For design I with $H_A$ = 10 mm, the bandwidth is 7.5%, while the
bandwidth of design III with $H_A = 30$ mm is 22.6% both with $|S_{11}| < -10$ dB. From these results, it can be concluded that the L-probe feed is an effective method to widen the bandwidth of the proposed water dielectric patch antenna when the air substrate is thick enough, but a good matching with relatively narrow bandwidth can still be achieved when the substrate is thin. The maximum antenna gains of the three designs are also shown in Table 2, which indicates that the gain of the water dielectric patch antenna with a thick substrate is slightly higher than the counterpart of the design with a thinner substrate. Therefore, it can be seen from the above analysis that for any requirement of practical applications, a proper height of substrate may be selected to achieve the desirable bandwidth.

### III. RESULTS AND DISCUSSION

In order to demonstrate the correctness of the proposed design, a prototype of design I in Section II was fabricated and measured. The input characteristic of the antenna was measured by applying an Agilent Network Analyzer E5701C, while the radiation performance was measured by a Satimo Starlab near-field measurement system.

#### A. WATER DIELECTRIC PATCH ANTENNA WITH METALLIC GROUND PLANE

The fabricated prototype is depicted in Fig. 2. A water valve made of plastic is installed at a corner of the small plexiglass box for water injection. From the side view of the prototype shown in Fig. 2(b), it is seen that the whole antenna structure maintains a low profile. The height of the whole antenna including the thickness of the plexiglass box is 19 mm, corresponding to 0.059 $\lambda_0$ at 0.93 GHz. The antenna under test is illustrated in Fig. 2(c). In our design, the $xoz$ and $yoz$ planes are the E- and H- planes respectively.

The simulated electric field distributions across the antenna are shown in Fig. 3. It can be seen that the electric field in the air substrate between the water patch and the ground plane is much stronger than the field in the water dielectric patch. The field is radiated from the two open ends of the water dielectric patch. Therefore, it is confirmed that the proposed water dielectric patch design works as a patch antenna instead of a DR antenna. In addition, from the vector distribution given in Fig. 3(b), it is seen that the antenna works in TM$_{10}$ mode, which is the fundamental mode of the traditional rectangular metallic patch antenna.

The measured and simulated $|S_{11}|$ and gain of the fabricated prototype are shown in Fig. 4, which are in good agreement. The simulated and measured bandwidth of the antenna are 7.05% (from 0.89 to 0.95 GHz) and 8.02% (from 0.88 to 0.96 GHz) respectively with $|S_{11}| < -10$ dB. Considering the air substrate of 0.03 $\lambda_0$, the bandwidth of the water dielectric patch antenna is similar to that of the conventional metallic patch antenna. The simulated and measured gains of the antenna are up to 7.4 and 7.34 dBi, respectively. The 3-dB gain bandwidths are 17.0% and 18.5% by simulation and measurement respectively, which are wider than the impedance bandwidth. In addition, both the simulated and measured radiation efficiencies of the antenna as shown in Fig. 5 are up to 70% and larger than 60% over the operating band. Since the proposed antenna works in a patch mode and
only a small portion of the energy penetrates into the water dielectric patch, the loss in the water does not remarkably degrade the efficiency of the antenna. Therefore, good gain performance can be obtained. 

Symmetrically unidirectional patterns are obtained in both the E- and H-planes. The measured backlobe is smaller than $-20 \, \text{dB}$, while the measured cross polarization level is also lower than $-20 \, \text{dB}$. Besides, the beamwidth of the measured radiation pattern is slightly larger than the simulated one in the H-plane, which is mainly due to the fabrication and measurement tolerances.

In order to better justify the operation principle of the proposed antenna, a comparison of the simulated $|S_{11}|$ of antennas with and without the water dielectric patch is illustrated in Fig. 7. It is seen that the impedance matching is totally different when the water dielectric patch does not exist, which demonstrates that the radiation is not mainly contributed by the L-probe feed.

B. WATER DIELECTRIC PATCH ANTENNA INTEGRATED WITH SOLAR CELLS

Owing to the use of pure water as the radiating patch, the proposed antenna is optically transparent. Hence, the antenna structure can be conveniently integrated with solar cells to realize a dual-function device. Fig. 8 exhibits the photograph of the prototype, in which six pieces of solar cells are attached.
above the ground plane. Compared with the meshed patch antenna in [19], the proposed design has better transparency. In fact, it is hard to notice the existence of the water dielectric patch antenna. In order to demonstrate the influence of the solar cells on the performance of the antenna, the dimensions of the water dielectric patch antenna with solar cells are kept the same as those shown in Section III-A.

The simulated and measured $|S_{11}|$ and gain of the proposed water dielectric patch antenna integrated with solar cells are shown in Fig. 9. It is seen that reasonable agreement is obtained. The simulated and measured bandwidth of the water dielectric patch antenna integrated with solar cells are 5.1% (from 0.88 to 0.93 GHz) and 7.6% (from 0.87 to 0.94 GHz) with $|S_{11}| < -10$. The measured result is slightly larger than the simulated one, which is mainly due to the alignment tolerance of solar cells. The simulated and measured maximum gains of the antenna are 7.1 and 6.7 dBi, respectively. The simulated and measured 3-dB gain bandwidths are 16.4% (from 0.84 to 0.99 GHz) and 18.7% (from 0.83 to 0.99 GHz), which are also larger than the impedance bandwidth. The simulated and measured radiation efficiencies are shown in Fig. 10. The simulated radiation efficiency is up to 68%, while the measured one is up to 60%. Over the whole operating band, the radiation efficiency is larger than 55%. The measured result is 8% smaller than the simulated counterpart. By analyzing the simulated model and the prototype, the main reason for the discrepancy can be concluded as the uncertainty of the loss tangent of silicon cells used. Moreover, the bonding film, thin metallic strips, and the glass substrate comprising the solar cells also affect the radiation efficiency of the antenna.

The simulated and measured radiation patterns at the center frequency of the operating band are given in Fig. 11, which are in good agreement. The radiation patterns are unidirectional and symmetrical. The backlobe of the antenna is lower than $-20$ dB, while the cross polarization level is almost less than $-20$ dB. Comparing the results for the antenna without the silicon cells, it is found that the existence of the solar cells does not negatively affect the radiation pattern of the water dielectric patch antenna.

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In order to clearly study the influence from the solar cells, a comparison between the water dielectric patch antennas with and without solar cells is summarized in Table 3. First, the solar cells would slightly decrease the bandwidth of the proposed antenna. However, by fine tuning of the dimensions and the position of the L-probe, it is believed that the performance of the bandwidth can be recovered. Second, due to the dielectric loss of the silicon substrate, the existence of solar cells also slightly degrades the radiation efficiency of the design. However, it should be noted that the radiation
efficiency still achieves 60% and the gain is also close to 7 dBi, which is acceptable for many practical applications.

FIGURE 12. Equivalent circuit of the output power measurement.

C. LIGHT TRANSMITTANCE OF WATER DIELECTRIC PATCH

In light of practical applications, it is also important to know the influence of the water dielectric patch antenna on the performance of the solar cell. The parameter of the light transmittance defined in [20] is applied here to evaluate the impact from the water dielectric patch, which can be expressed as

\[
\text{Transmittance} = \frac{P_{\text{out, w/patch}}}{P_{\text{out, w/o patch}}} \quad (1)
\]

where \(P_{\text{out, w/patch}}\) and \(P_{\text{out, w/o patch}}\) are the output power of the solar cell when there is with and without the water dielectric patch, respectively. Therefore by calculating the transmittance, the loss of the optical power caused by the water dielectric patch can be seen.

A circuit as illustrated in Fig. 12 is used for measuring the output power of the solar cell, in which the voltage and current of the load resistor are measured by two multimeters. Measurement setups with and without the water dielectric patch are shown in Fig. 13. The two setups are tested under the same light source. Here, only one piece of solar panel is measured for brevity.

FIGURE 14. Measured output power of the solar panel and transmittance of the water dielectric patch antenna.

The measured results with different load resistors ranged from 15 Ω to 12 kΩ are given in Fig. 14. First, it is seen that the output power of the solar cell increases with the load resistance. Particularly, it almost increases exponentially for load resistors varying from 2 kΩ to 12 kΩ. Hence, the case with a large load resistance would be desirable in practical applications. On the other hand, the light transmittance of the water dielectric patch is around 80% when the output power of the solar cell is relatively low. However, with the enhancement of the output power, the light transmittance also improves to larger than 90%, which demonstrates that the proposed water DD patch antenna has limited influence on the performance of the integrated solar cells.

IV. CONCLUSION

A novel water dense dielectric patch antenna fed by an L-shaped probe has been proposed. In contrast with the reported water monopoles and the water dielectric resonator antennas, the proposed water dielectric patch antenna constructed by pure water owns the similar working principle compared with the traditional metallic patch antenna. The L-probe feed has also been applied to the water dielectric patch antenna. The bandwidth performance of the proposed antenna has been investigated, which demonstrates that by increasing the thickness of the supporting substrate between the water dielectric patch and the ground plane, wide bandwidth similar to the L-probe fed metallic patch antenna can be realized. A prototype was designed, fabricated, and measured to verify the design. An impedance bandwidth of 8.0% for an air substrate of 0.03λ₀, a gain up to 7.3 dBi, and radiation
efficiency higher than 60% has been obtained. The radiation pattern of the prototype is symmetrical with low backlobe and low cross polarization level. Owing to the transparency of the water dielectric patch, the proposed design can be conveniently integrated with solar cells. A prototype has been successfully realized, which shows that both of the antenna and the solar cell work well when they combine together. Therefore, the proposed dual-functional device would be an attractive candidate for practical applications.

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