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2016

Zou, M., Shen, Z., & Pan, J. (2016). Frequency-reconfigurable water antenna of circular polarization. *Applied Physics Letters*, 108(1), 014102-.

<https://hdl.handle.net/10356/82426>

<https://doi.org/10.1063/1.4939455>

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Citation: [Applied Physics Letters](#) **108**, 014102 (2016); doi: 10.1063/1.4939455

View online: <http://dx.doi.org/10.1063/1.4939455>

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Frequency-reconfigurable water antenna of circular polarization

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(Received 22 October 2015; accepted 21 December 2015; published online 6 January 2016)

A circularly polarized frequency-reconfigurable water antenna with high radiation efficiency is proposed based on the design concept of combining a frequency-reconfigurable radiating structure with a frequency-independent feeding structure. In this letter, a resonator made of distilled water and an Archimedean spiral slot are employed as the radiating and feeding structures, respectively. The operating frequency of the antenna can be continuously tuned over a very wide range while maintaining good impedance matching and circular polarization by changing the dimensions of the water resonator. A prototype antenna is designed, fabricated, and measured. Simulated and measured results demonstrate that the designed antenna exhibits a wide tuning frequency range from 155 MHz to 400 MHz with an average radiation efficiency of about 90% and good circular polarization. © 2016 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4939455>]

Fluidic materials have the attractive advantages of liquidity, reconfigurability, and stretchability over the solid ones.^{1–4} Recently, the fluidic metal materials were widely studied for applications in electronic devices and various liquid metal antennas were proposed in the literature.^{5–9} In these designs, the liquid metal materials (e.g., galinstan⁵ and eutectic gallium indium alloy⁹) are used as conductors to support the flow of electric current. Although liquid metal antennas exhibit excellent performance of flexibility,⁶ stretchability,⁵ and reconfigurability,⁹ their applications have two major limitations: (1) liquid metal materials are relatively expensive for commercial applications and (2) liquid metals may dissolve solid metals in contact with them, which may damage the reliability of electronic devices. Water is a special liquid material that is low in cost, easy to access, and safe to use. Besides, it also has the property of transparency. Salt water can be regarded as a good conductor at the high frequency (HF) and very high frequency (VHF) bands. Based on its good conductivity, a sea water monopole antenna operating at VHF band was recently reported.¹⁰ The conductivity of salt water is proportional to its salinity, and the saturated salt water has a conductivity of about 20 S/m. This low conductivity of salt water makes it difficult to design a salt water antenna with high radiation efficiency in the microwave frequency. Different from the liquid metal materials, pure water can be regarded as a liquid dielectric material with high permittivity, which makes it feasible for dense dielectric patch antenna¹¹ and dielectric resonator antenna.^{12,13} However, the loss tangent of distilled water is 0.01–0.025 over the frequency range from 200 MHz to 500 MHz, which leads to a relatively low radiation efficiency and somehow limits the practicability of pure water antennas.

In this letter, a circularly polarized (CP) frequency-reconfigurable water antenna with high radiation efficiency and stable radiation pattern is presented. We employ a water resonator mounted on the conducting ground as the

frequency-reconfigurable radiating structure and utilize an Archimedean spiral slot as the frequency-independent feeding structure. By combining them together we can realize a frequency-reconfigurable water antenna of circular polarization, which exhibits a very large tuning frequency range. Distilled water is poured into a special acrylic container to construct the water resonator. The water resonator has the following two advantages: (1) both the height and cross-sectional dimension of the water resonator can be varied to tune its resonant frequency and (2) the water resonator has a much smaller dielectric loss than the traditional water resonator, which makes it particularly suitable for serving as an efficient radiator. Loading effect of the radiating structure on the feeding structure is also studied, and it is demonstrated that the Archimedean spiral slot can be used as a frequency-independent feeding structure for water resonator of different dimensions. A prototype antenna is fabricated to verify the proposed design concept. Simulated and measured results show that the frequency-reconfigurable antenna has a wide CP tuning frequency range of 155 MHz–400 MHz. Moreover, a high radiation efficiency of about 90% is achieved, which is comparable to that of the fluidic metal antennas.

The construction of an antenna can be generally divided into two parts: radiating element and feeding structure, and its radiation performance depends upon both parts integrated together. The role of the radiating structure for a transmitting antenna is to gather energy from the feeding structure, and then radiates the energy into space as radio waves. An antenna's radiating structure has infinite numbers of resonant modes, and each resonant mode has its own resonant frequency and field distribution. Meanwhile, the far field radiation patterns of an antenna are determined by the field distributions of the resonant mode in the radiating structure. The feeding structure for a transmitting antenna is to excite a particular desired resonant mode in the radiating structure and also to realize a good impedance matching between the transmission line and the antenna so that energy can smoothly flow from the feed line to the radiating element.

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FIG. 1. Design concept of the proposed CP frequency-reconfigurable water antenna.

Fig. 1 illustrates the design concept of the proposed frequency-reconfigurable water antenna. The frequency-reconfigurable radiating structure is made of distilled water, whose operating frequency is tunable by adjusting the water dimension. Good frequency-reconfigurable radiating structure should have stable field distributions and high radiation efficiency when its resonant frequency is varied. The frequency-independent feeding structure made of an Archimedean spiral slot is fixed and its performance does not change with the operating frequency of the antenna. Therefore, by using a frequency-independent feeding structure to excite the frequency-reconfigurable radiating structure, a frequency-reconfigurable antenna with wide tuning frequency range and stable radiation patterns can be achieved.

Resonators¹⁴ made of dielectric material of high relative permittivity can be used as a compact radiating structure of an antenna.¹⁵ Such dielectric resonators are often mounted on a conducting ground, though the ground plane can have a significant influence on the antenna's radiation. The resonant frequencies of a dielectric resonator are determined by the shape and dimensions of the resonator as well as the permittivity of the material. Moreover, the employed material should have a low loss tangent because a high dielectric loss will degrade the antenna's radiation efficiency, where radiation efficiency is the ratio of radiated power to the input power delivered to the antenna. The radiation efficiency is one of the key parameters of an antenna to judge how good and effective a structure can be used as a radiator. Conventional dielectric resonators are fabricated from solid materials with high hardness (e.g., the ceramics), which makes it difficult to tune their dimensions and thus their resonant frequencies.

Water is a very flexible and transparent fluidic dielectric that can be employed to realize a frequency-reconfigurable resonator. Resonant frequencies of the water resonator can be varied by changing the dimensions of water resonator without deteriorating the near-field distributions and corresponding far-field radiation patterns of the resonant modes. Among all kinds of water, distilled water has the lowest loss tangent and thus is the most suitable for constructing water resonator. Relative permittivity and loss tangent of distilled water are functions of the operating frequency.¹⁶ Distilled water has a relative permittivity of about 78, and it has a lower loss tangent at lower frequency. The fundamental mode of a rectangular water resonator mounted on a ground

plane is TE_{111}^x/TE_{111}^y mode, where the superscript x/y means the electric field of the resonant mode has no x/y component and the subscript indicates the numbers of field extrema in the x -, y -, and z -directions. Radiation efficiency of the TE_{111}^x/TE_{111}^y mode can be calculated based on the dielectric waveguide model method.¹⁵ Calculated results indicate that the radiation efficiency of conventional water resonator antenna is lower than 50% in the operating frequency band of 200 MHz–500 MHz. Therefore, a method to decrease the dielectric loss of water resonator is necessary before water can be directly used to construct an efficient radiating structure.

Introducing a thin substrate with low-permittivity between the ground plane and resonator is an efficient way to increase the bandwidth of a dielectric resonator antenna. In our design, a low loss substrate of low permittivity is utilized to increase the radiation efficiency of water resonator by decreasing the effective loss tangent and effective permittivity of water resonator. In addition, the water resonator must be held in a container due to its liquidity. As shown in Fig. 2, we use an acrylic ($\epsilon_{ra} = 2.7$) box as the water container, whose bottom layer acts as the low-permittivity insert. The acrylic box has 7 layers in the cross-section, with an

FIG. 2. Structure of the proposed CP frequency-reconfigurable water antenna. (a) 3D view. (b) Side view.

innermost side length of l_1 , outermost side length of l_7 , and equal spacing of Δl between the adjacent layers. The 7 acrylic layers have the same height of h_2 and thickness of t . The square water resonator is frequency-reconfigurable because its width l can be changed from l_1 to l_7 at an interval of $2\Delta l$ and its height h can be continuously tuned from 0 to h_2 . As described below, the water resonator has a low dielectric loss and can be used as an efficient radiating structure.

An Archimedean spiral slot etched on the ground plane is utilized as the frequency-independent feeding structure to excite the fundamental TE_{111}^x and TE_{111}^y modes of the water resonator. The Archimedean spiral slot is in the form of $\rho = a\varphi$, where a is the growth rate and φ changes from $\pi/2$ to φ_{max} . The two Archimedean spiral slot arms are connected by a linear slot. The spiral slots and linear slot have the same width of w to simplify the design. A coaxial line is used to feed the antenna with its inner and outer conductors soldered to the two sides of the linear slot, respectively.

It is well known that Archimedean spirals have wide-band performance and produce circular polarization due to their self-complementary structure. However, in this design, the Archimedean spiral slot is loaded by the water resonator on the top side, and the dielectric loading changes the effective relative permittivity ϵ_{eff} seen by the Archimedean spiral slot. Thus, the frequency response of the feeding structure also depends on the loading effect of the water resonator on the Archimedean spiral slot, and ϵ_{eff} should be stable within the tuning frequency range to realize a frequency-independent feeding structure. ϵ_{eff} is determined by the location and electrical size of the water resonator, which is in turn defined by its dimension relative to the operating wavelength. In this design, the water resonator has a very small electrical size and is separated from the Archimedean spiral slot by an acrylic layer with a low relative permittivity of $\epsilon_{ra} = 2.7$. Therefore, the water resonator has a small effect on ϵ_{eff} due to the existence of the acrylic layer. Moreover, although the physical size of the water resonator changes with the operating frequency, its electrical size remains approximately constant when the operating frequency is varied. Consequently, the Archimedean spiral slot sees a stable effective permittivity when the operating frequency of the antenna changes, and the Archimedean spiral slot loaded with the water resonator can therefore be regarded as a frequency-independent feeding structure.

A prototype of the proposed antenna shown in Fig. 3 is designed, fabricated, and measured to verify the design concept. The parameters for the prototype antenna are $l_1 = 50$ mm, $l_7 = 350$ mm, $\Delta l = 25$ mm, $h_1 = 10$ mm, $h_2 = 150$ mm, $t = 3$ mm, $a = 6$ mm, $w = 4$ mm, and $\varphi_{max} = 3.5\pi$.

An Agilent N9923A RF vector network analyzer is used to measure the reflection coefficient of the antenna, where the reflection coefficient Γ is the ratio between the reflected voltage wave and the incident voltage wave at the input terminal of the antenna. Usually, the reflection coefficient is expressed in dB as $20 \log |\Gamma|$, and it is not more than -10 dB for an effective antenna. As stated above, the width l of the square water resonator can be changed from 50 mm to 350 mm at an interval of 50 mm, and its height h can be continuously adjusted from 0 to 150 mm. A lot of antenna tuning states with different combinations of l and h are studied, and

FIG. 3. Photographs of the fabricated prototype antenna. (a) The acrylic box without water. (b) The Archimedean spiral slot. (c) 3D view of the prototype antenna partially filled with water.

4 sample states are selected to demonstrate the antenna's radiation performance. Fig. 4(a) shows the measured reflection coefficients for the 4 states, with the simulated results obtained from ANSYS high frequency structure simulator (HFSS). Very good agreements are observed between simulated and measured results. Good impedance matching is achieved for all of the 4 states, with corresponding center frequencies of 167 MHz, 201 MHz, 244 MHz, and 355 MHz, respectively.

Circularly polarized antennas are desired in many wireless communication systems because they can suppress the multipath interferences and are less sensitive to the orientations of transmitter and receiver. The CP performance of an antenna is defined by its axial ratio (AR), which ranges from 0 dB to ∞ . An antenna is regarded as a CP antenna when its $AR \leq 3$ dB with 0 dB indicating a perfect CP radiation. The simulated AR results of the water antenna in the broadside direction for the 4 states are shown in Fig. 4(b). It is clearly observed that CP operations are achieved for all of the 4 states. Each state has an axial ratio value of lower than 3 dB at the center frequency. Fig. 4(c) illustrates the radiation patterns of the antenna for the 4 states. The radiation patterns remain broadside and stable when the dimensions of the water resonator change because the modes excited in the water resonator are the same. Meanwhile, it can be seen from Fig. 4(d) that the antenna's right hand circularly polarized (RHCP) gain is about 6 dBi.

Fig. 5(a) shows the tuning frequency range of the antenna, with the corresponding height of the water resonator and its total volume of water required. The proposed antenna exhibits a continuous tuning frequency range from 155 MHz to 400 MHz by varying the dimensions of the water resonator. Meanwhile, the total volume of water decreases monotonously with the increase of the operating frequency. The antenna's radiation patterns across the entire tuning

FIG. 4. Results for the sample states of the proposed antenna. State 1: $l = 350$ mm and $h = 80$ mm; state 2: $l = 250$ mm and $h = 80$ mm; state 3: $l = 200$ mm and $h = 75$ mm; and state 4: $l = 150$ mm and $h = 50$ mm. (a) Simulated and measured reflection coefficients. (b) Simulated axial ratios at the broadside direction. (c) Simulated radiation patterns of the 4 states. (d) Simulated RHCP gains at the broadside direction.

FIG. 5. (a) Height of the water resonator and total volume of water contained in the resonator versus the operating frequency. (b) Simulated and measured radiation efficiencies versus the operating frequency.

frequency range are also studied, and it is found that the proposed antenna produces a stable RHCP radiation pattern within the whole tuning frequency range. The water antenna's radiation efficiency is measured based on the improved Wheeler cap method,¹⁷ in which the electrical dimensions of a metallic box are changed by varying the measurement frequency. Measured results versus the center frequency are compared with simulated ones obtained by HFSS, as shown in Fig. 5(b). Both simulations and measurements demonstrate that the antenna maintains a high radiation efficiency of about 90% when its operating frequency is tuned from 155 MHz to 400 MHz by changing the dimensions of the water resonator.

In conclusion, a frequency-reconfigurable water antenna of circular polarization has been presented in this letter. The design concept is based on combining a frequency-reconfigurable radiating structure with a frequency-independent feeding structure. The feasibility of using a water resonator mounted on the ground plane operating in its fundamental TE_{111}^x and TE_{111}^y modes as the frequency-reconfigurable radiating

structure and employing an Archimedean spiral slot as frequency-independent feeding structure has been demonstrated. A prototype antenna has been designed, fabricated, and measured. A wide tuning frequency range of 155 MHz–400 MHz is achieved with high radiation efficiency of about 90% and stable broadside pattern of circular polarization.

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