A Conformal and Transparent Frequency Reconfigurable Water Antenna

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***Abstract*—This paper presents a design of water-based flexible, optically transparent and frequency reconfigurable antenna having a unidirectional radiation pattern. The proposed antenna incorporates a dipole radiator on top of a reflector plane that makes the radiation unidirectional. The reflector is constructed from pure water enclosed inside a circular cavity made of polydimethylsiloxane (PDMS), which consists of several ring chambers arranged concentrically. Frequency tuning operation is achieved by an innovative mechanical tuning mechanism involving controlling the water configuration inside the circular cavity. Depending upon the presence or absence of the water in different chambers, the resonance frequency changes accordingly while maintaining the radiation pattern unidirectional. Detail simulation investigation of the proposed technique is presented in this paper.**

***Index Terms*—Conformal, polymer, reconfigurable antenna, reflector, transparent, water.**

I. INTRODUCTION

The rapid development of 5G technology and Internet-of-Things (IoT) has brought a lot of opportunities and concurrently imposes some significant challenges. The growing number of network infrastructures impose significant visual impact to the environment. To minimize this problem, engineers have adopted some innovative approaches, e.g., creating naturalistic cellular towers or incorporating camouflaging layouts around the towers [1]. However, in densely populated cities, these techniques are not feasible because of the limited availability of free spaces. Integrating optically transparent antennas on the buildings and infrastructures, such as glasses, windscreens, solar cells and displays can be an effective alternative solution for providing network access points without deteriorating aesthetics of the nature [1].

In many of the above-mentioned applications, antennas are required to be fit on curved or non-flat surfaces. To properly fit on these surfaces, antennas should have conformal geometries [2], [3]. Flexible-transparent antennas can be dynamically mounted on any surface with nearly unnoticeable appearance and thus, becomes a potential form of unobtrusive access points [2]. In addition to unobtrusive cellular networks, flexible-transparent antennas can be applied in diverse applications, for example, in wireless-body-area-network, security and tracking. For wearable applications, specially for healthcare monitoring and security services, it is highly essential to conceal the appearance of the antennas from patients' sights to enhance the reliability of operations. Flexible-transparent antennas can be mounted on wearer's body with minimum visual impacts, serving this purpose effectively [2].

However, there are some significant realization challenges with flexible-transparent antennas [4]. The realization of such antennas completely depends on unconventional materials and fabrication techniques. Some popular materials used for transparent antenna fabrication include transparent conductive thin films (e.g., indium-tin-oxide (ITO) [5], multi-layered indium zinc tin oxide (IZTO/Ag/IZTO) [4], fluorine-doped tin oxide (FTO) [6], aluminum-zinc-oxide (AZO) [7], Gallium-doped zinc oxide (GZO) [1] and silver-coated polyester (AgHT) film [8]) and metallic meshes [9], [10]. Despite the achieved transparency, most of these materials however still suffer from mechanical robustness issue, for instance, against repetitive deformations, thus may not be suitable for applications requiring conformality or bendability. Moreover, these materials need relatively costly and complex manufacturing processes.

As a solution to the above, we have recently introduced a unique approach utilizing water, polymer, and transparent conductive fabric composite for the development of flexible and transparent antennas [11], [12]. The high permittivity of water has been utilized to make a transparent reflective surface which was positioned at a certain distance from the radiator to achieve a unidirectional pattern [11], [12], [13].

The forthcoming wireless networks will also require highly intelligent adaptive systems to embrace the 'big data'era. Flexible and transparent antennas whose characteristics can be reconfigured in the fast-changing operating environment will be an ideal solution for the next-generation wireless communication systems. The most common way to achieve antenna reconfigurability is by incorporating RF switches, e.g., varactor diodes [11], [14], PIN diodes [15], photoconducting switches [16], etc. These antennas are often referred as active reconfigurable antennas. Another approach is by introducing a mechanism to physically change the antenna geometry [17], [18]. Such reconfigurable antennas are therefore called as passive reconfigurable antennas. While the active types are faster in terms of reconfigurability, they require additional bias networks which are often associated with extra losses. In this paper, we have investigated the possibility of developing a flexible and transparent passive reconfigurable antenna using our proposed materials and approach in [11], [12].

II. Antenna Geometry and Operating Mechanism

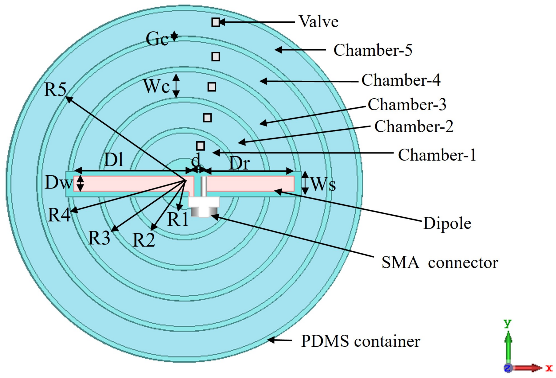
The topology of the proposed antenna is illustrated in Fig. 1. The radiator of the antenna is an off-centred-fed electric dipole. The dipole is made with Veilshield, the Less EMF Inc's transparent conductive fabric. VeilShield is 57 μm thin, has 0.1 Ω/sq sheet resistance and nearly 72% optical transparency. When the dipole is excited, it radiates omni-directionally. A circular water reflector, confined inside a polydimethylsiloxane (PDMS) cavity, is placed underneath the dipole. PDMS is a transparent (having more than 94% transparency [19]), flexible, robust [20], [21], [22], and hydrophobic polymer, which has a dielectric constant of 2.75 and an increasing loss tangent varies from 0.018 to 0.024 in 2 to 3.5 GHz frequency range [2], [20]. Pure water is nearly 100% transparent and has a dielectric constant of 78. The dipole is supported by a rectangular PDMS block. The high dielectric constant of the water creates a boundary condition [23] for the electromagnetic wave coming from the dipole and, thus, the water layer acts as a dielectric reflector, it reflects back the radiation towards +z-axis [12]. Hence, most of the radiation from the dipole confines towards +z-axis and the antenna becomes an unidirectional broadside antenna like typical microstrip patch antennas [12].

The circular PDMS cavity contains five hollow chambers (see Fig. 1). Each chamber has a valve through which water can be injected or exited. The presence or absence of water in each chamber affects the resonance characteristics of the antenna and, thus, is utilized as a frequency tuning mechanism of the antenna. This is further investigated in the next section. The dimensions of the antenna are shown in Table I. It can be noted that the proposed antenna is the smallest water-based flexible-transparent unidirectional reconfigurable antenna as reported in the literature.

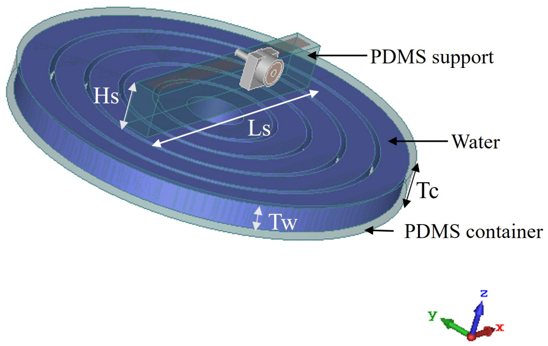
III. Performance Investigation

To evaluate the tuning performance of the antenna, four different antenna states described below are investigated using CST Microwave Studio 2020, and the corresponding resonance frequency, gain, radiation pattern, front-to-back ratio of the pattern and radiation efficiency are observed.

- State-1: All chambers are filled with water.
- State-2: Chamber 1 is empty and chamber 2-5 are filled with water.
- State-3: Chamber 1 and 2 are empty and chamber 3-5 are filled with water.



(a)



(b)

Fig. 1. Geometry of the proposed frequency reconfigurable antenna-(a) top view, (b) cross-sectional view.

TABLE I
Dimensions of the proposed water-based frequency reconfigurable antenna.

Parameter	Description	Value (mm)
R_1	Inner radius of chamber 1	5
R_2	Inner radius of chamber 2	11
R_3	Inner radius of chamber 3	17
R_4	Inner radius of chamber 4	23
R_5	Inner radius of chamber 5	29
W_c	Width of each chamber	5
T_w	Thickness of each chamber	4.5
T_c	Thickness of the container	6.5
G_c	Gap between adjacent chamber	1
L_s	Length of the PDMS support	46
W_s	Width of the PDMS support	5
H_s	Height of the PDMS support	8
D_l	Length of the left side of the dipole	23.5
D_r	Length of the right side of the dipole	17.5
D_w	Dipole Width	3
d	Separation between two sides of the dipole	2

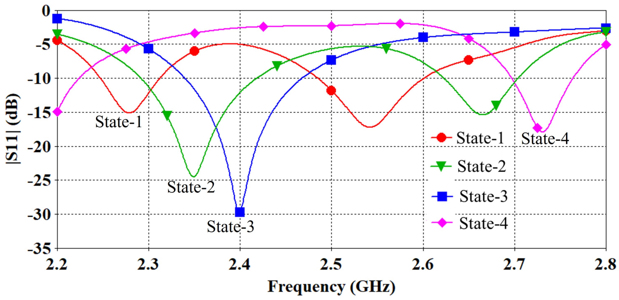


Fig. 2. $|S_{11}|$ of the proposed antenna for different antenna states.

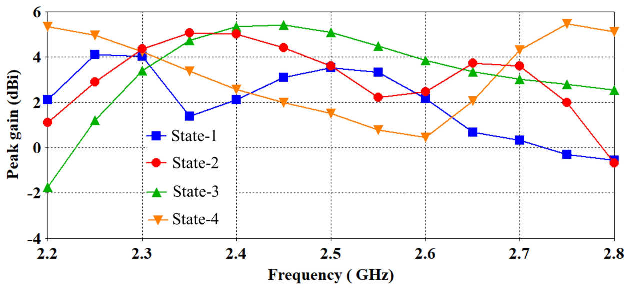


Fig. 3. Peak gain vs frequency for different antenna states.

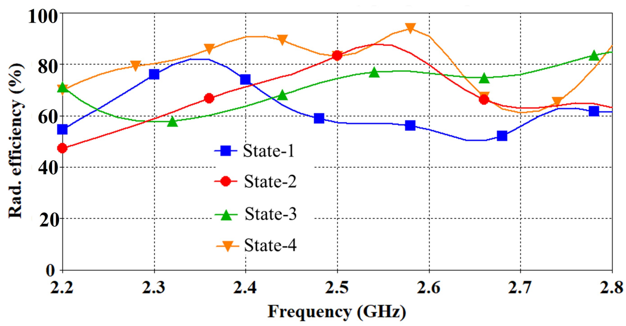


Fig. 4. Radiation efficiency vs frequency for different antenna states.

- State-4: Chamber 1-3 are empty and chamber 4 and 5 are filled with water.

The magnitude of the input reflection co-efficient, $|S_{11}|$, of the antenna for different states are shown in Fig. 2. It can be observed that by controlling the water distribution in the chambers, the antenna resonance frequency can be altered while maintaining an excellent impedance matching.

The gain of the antenna for different states are shown in Fig. 3. A maximum peak gain of 5.35 dBi is achieved for state 3, whereas a gain of higher than 4 dBi is maintained in other states.

The radiation efficiency of the antenna is illustrated in Fig. 4 for different states. It exhibits more than 60% radiation efficiency in each state at the corresponding resonance frequencies, demonstrating the excellent radiation performance of the antenna.

The far-field radiation patterns of the antenna at the

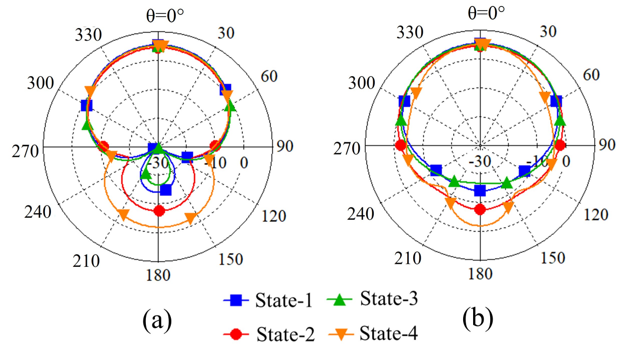


Fig. 5. Radiation patterns (in dB) of the proposed antenna for different antenna states at the corresponding resonance frequencies-(a) XZ-plane, (b) YZ-plane.

TABLE II
PERFORMANCE OF THE WATER-BASED ANTENNA FOR DIFFERENT ANTENNA STATES.

State	Res. Freq. (GHz)	Gain (dBi)	Rad. Effi. (%)	F/B (dB)
1	2.28	4.06	71.2	12.1
2	2.35	5.07	65.4	21.8
3	2.4	5.35	63.7	19.5
4	2.73	5	63.6	7.0

corresponding resonance frequencies for different states are shown in Fig. 5. It is revealed that in each state, maximum radiation goes towards +z-axis demonstrating broadside radiation.

The performance of the antenna for different states are summarized in Table II. Here, resonance frequency for various states of the chambers, corresponding peak gain, radiation efficiency and front-to-back (F/B) ratio are shown. From Table II, it is revealed that the resonance frequency of the proposed antenna can be tuned by simply controlling the water in different chambers of the circular PDMS container. Four different states of the chambers are studied. Maximum peak gain is achieved at state-3 where chamber 1-2 are empty and chamber 3-5 are filled with water. Maximum radiation efficiency is obtained at state-1 where all the chambers are filled with water. Maximum front-to-back (F/B) ratio is obtained at state-2 where chamber 1 is empty and all other four chambers are filled with water. It can be noted that at state-4, the F/B ratio is minimum (7 dB), it happens because in this state, only chamber 4 and 5 contain water, which does not act as perfect reflector, so radiation leaks towards -z-axis. From the numerical analysis of antenna, it is observed that the antenna has remarkable performance as a flexible-transparent reconfigurable antenna.

IV. Conclusion

This paper demonstrates a new design of frequency reconfigurable, flexible, transparent and unidirectional antenna incorporating pure water, polymer and transparent conductive fabric. Frequency tuning operation is achieved through a modification of water reflector configuration. It is observed that by creating sectional chambers in the PDMS-made water container and varying the water distribution in each chamber, the resonance frequency of the antenna can be altered. In all tuning states, excellent gain, radiation efficiency and unidirectional radiation characteristics are preserved. The proposed technology can be efficiently utilized to design flexible-transparent unidirectional antennas having reconfigurable characteristics in simple and cost-effective method. In future, detailed experimental explorations will be accomplished.

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