Performance Improvement of a Water-Based Transparent and Flexible Unidirectional Antenna

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***Abstract*—In this paper, a study has been devoted to design a water-based flexible, robust and transparent antenna having unidirectional radiation pattern. Simulation analysis is presented to exhibit the determining factors affecting antenna performance and further a method is demonstrated to improve the performance. The proposed antenna is designed by utilizing pure water, polymer and transparent-flexible e-textile sheet. The design concept of the antenna is based on the utilization of a reflector surface on one side of a dipole radiator to transform the omnidirectional radiation of the dipole to unidirectional pattern. The reflector is constructed from pure water enclosed inside a rectangular hollow cavity made from polydimethylsiloxane (PDMS) and the dipole radiator is made from transparent-flexible e-textile sheet. The impacts of the reflector's properties on antenna performance are investigated in this research to identify the optimum design parameters for performance improvement.**

***Index Terms*—compact, conformal, mesh, polydimethylsiloxane, robust, transparent, water.**

I. Introduction

Over the last couple of years, there has been tremendous growth in flexible electronics. Among flexible electronic devices, flexible antennas have gained enormous popularity in communication and sensing applications. With the emerging demands in various applications, new requirements have been demanded in antennas' characteristics. To meet these demands, new designs, materials, fabrication techniques and functionalization processes have emerged [1]. Recently, the demand for flexible and optically transparent antennas have increased. Optically transparent antennas are generally used in automobile windshields, touch screens, displays [2], solar panels [3], electromagnetic interference (EMI) shielding, camera lenses and satellites. When transparent antennas become concurrently flexible then their applications can be extended into wider spectrum, e.g., clinical sensing and wellbeing operations, wearable glasses [4] and other applications where antennas are to be attached to curved surfaces with unnoticeable appearance.

The realization of optically transparent antennas having conformal geometries are associated with the limitation of the unavailability of appropriate materials. The traditional transparent conductors are available in two major forms: (i) transparent conductive oxides (TCOs) (most commonly 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) [8] and silver-coated polyester (AgHT) film [9]) and (ii) meshed metals [10], [11]. Most of these conductors do not have mechanical resilience to withstand harsh physical deformations. Moreover, there is an inverse relationship between the optical transmittance and radio-frequency (RF) sheet resistance of these conductors, thus, high transparency cannot be achieved without sacrificing efficiency [8]. In addition, the costly manufacturing processes have hindered the large-scale commercial production of transparent antennas. Because of these apparent challenges, there is limited progress into the development of flexible and transparent antennas.

Apart from these traditional materials having limited scope in realizing robust, flexible and transparent antennas, water is an effective alternative. Water is a perfectly transparent, flexible, biocompatible, low-cost and widely available material. In literature, several research efforts have been emphasized towards the development of antennas using pure water [12], salt water [13] and a combination of these two for performance enhancement [14]. However, there is little insights into the development of robust, flexible and transparent antennas with unidirectional patterns and incorporating small dimensions. Many applications require a small antenna with a unidirectional radiation pattern, e.g., wearable applications, satellite communications and microwave imaging.

A recent research study has investigated a new type of transparent and flexible antenna using conductive mesh, pure water and polymer [15]. In this research, the high permittivity of water has been utilized to make a reflector surface, which was positioned at a certain distance apart from a dipole radiator. The reflector surface, made from pure water enclosed inside PDMS cavity, alters the bidirectional pattern of the dipole radiator to a unidirectional pattern, mimicking the broadside pattern of a microstrip patch antenna. This antenna was highly transparent, flexible, robust and involved a less-costly manufacturing process. The explored fabrication process was much simple and cost-effective than the traditional lithography, etching and inkjet printing processes. Motivated by this research approach, in this paper, a further research effort has been emphasized to investigate the factors affecting antenna characteristics and develop a method to improve the performance.

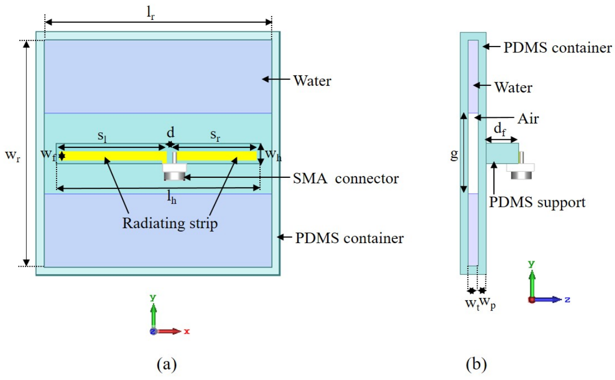

Fig. 1. Geometry of the proposed antenna-(a) top view, (b) side view.

TABLE I
DIMENSIONS OF THE WATER-BASED ANTENNA.

Parameter	Description	Value (mm)
l_r	Length of the water layer	56
w_r	Width of the water layer	56
w_t	Thickness of the water layer	2.5
w_p	Thickness of the PDMS container	2
l_h	Length of the PDMS support	50
w_h	Width of the PDMS support	5
d_f	Distance from reflector surface to radiator	8
s_l	Length of the left dipole strip	26
s_r	Length of the right dipole strip	20
w_f	Width of the dipole strip	2
d	Gap between two strips of the dipole	2
g	Gap between two water layers	15

II. Antenna Topology and Design Considerations

The explored research investigation of this paper is motivated by our previous water-based antenna as demonstrated in [15] where a water layer, enclosed by a PDMS cavity, worked as a reflector plane and provided a unidirectional radiation pattern by altering the bidirectional pattern came from a dipole radiator. The high permittivity of water was utilized to create an electric wall [16], which acts as the dielectric reflector. This antenna [15] achieved a peak gain of 3.84 dBi and an efficiency of 50% at 2.45 GHz. With dimensions of ~0.49 λ_0 × 0.49 λ_0 × 0.11 λ_0, this is the smallest flexible and transparent unidirectional water antenna. The proposed design in this paper is a modified version of the previous design. The proposed idea is to use water only at the two opposite edges of the PDMS cavity, leaving air at the middle of the cavity. This new concept increases antenna efficiency and gain. The geometry of the proposed new design is illustrated in Fig. 1. This geometry is exactly the same as the previous design [15] except the implementation of an air gap in the PDMS cavity. The new antenna is also realized with the same material as before, i.e., the dipole is made from transparent mesh, VeilShield from Less EMF Inc. (thickness = 0.057 mm, sheet resistance = 0.1 Ω/sq, transparency = 72%), pure water is used as the reflector and PDMS (relative permittivity = 2.7 and loss tangent varied from 0.008 to 0.07 in the frequency 0.5 to 10 GHz [17]) is used to hold the water and the dipole due to its excellent mechanical resilience [18]. Pure water is an ideal transparent liquid [19], so the demonstrated antenna has excellent transparency. Moreover, the girded monofilament threads of VeilShield form strong integration with PDMS [17], [20] and preserve this integration in multiple bending operations [21], [22], [23]. Thus, the antenna achieves very high transparency and robustness.

The next section describes the numerical analysis of the antenna to show the effects of using water at two edges of the cavity instead of filling the whole cavity with water.

III. Numerical Investigation

The principal goal of this research is to study the parameters affecting antenna performance and identify optimum parameters for providing improved performance. Our previous study [15] investigated the effects of water layer length, width, thickness and distance from radiator on the gain and efficiency of the antenna. It was revealed that antenna gain and efficiency were increased with the increase of water layer length, width, thickness and distance from the radiator. However, optimum parameters were selected to achieve satisfactory gain and efficiency while keeping the size small. In this work, we intend to improve the gain and efficiency of the antenna while preserving the same small dimensions. To improve the performance, at first it is required to identify the losses contributed by different materials and find ways to minimize the losses. It can be noted that total power loss in the antenna can be minimized by decreasing the loss tangent of PDMS. This can be done by mixing glass microspheres with PDMS [24]. However, it will affect flexibility and transparency. Another option for alleviating the loss is to reduce the power lost in the water. If water is used at the two opposite sides of the PDMS cavity while leaving a space in between then loss contributed by water will be significantly reduced. However, the radiation pattern should be observed carefully so that the unidirectional pattern is still preserved with this new reflector topology.

To investigate the effects of the air gap width on antenna performance, a study was conducted in CST Microwave Studio 2017. The initial dimensions of the water antenna for this study are shown in Table I. The overall dimensions of the antenna are exactly the same as the previous antenna [15]. In simulations, the air gap, g was varied from 15 to 30 mm and the corresponding changes in antenna parameters, i.e., resonance frequency, gain, radiation efficiency and radiation pattern, were observed.

The magnitude of the input reflection co-efficient, $|S_{11}|$, of the antenna for varying the air gap is shown in Fig. 2. It can be seen that antenna resonance frequency changes with the variation of the gap between the two water layers (air

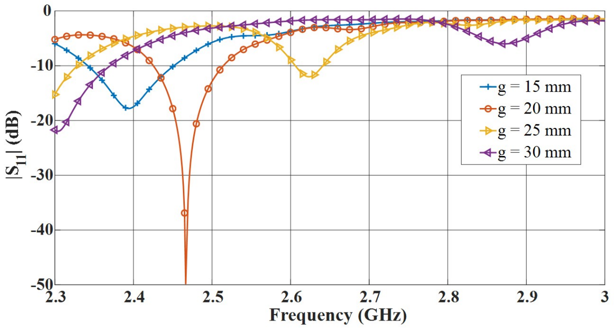

Fig. 2. $|S_{11}|$ of the proposed antenna for various air gaps (g).

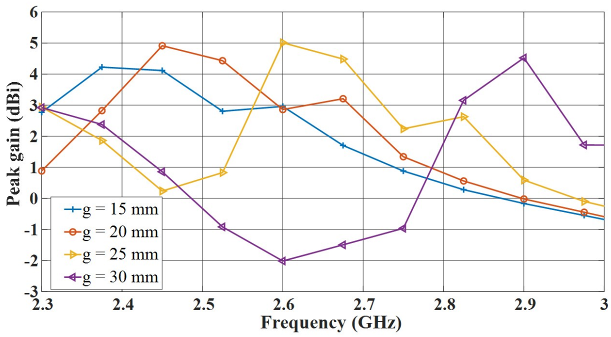

Fig. 3. Peak gain vs frequency for various air gaps.

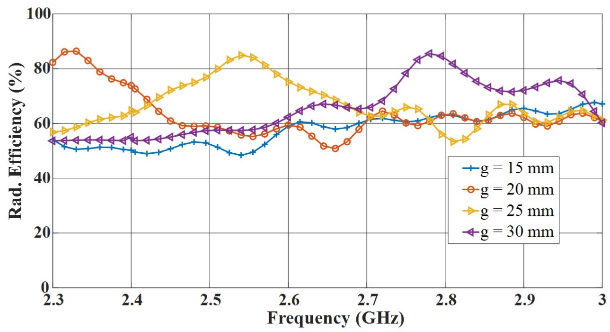

Fig. 4. Radiation efficiency vs frequency for various air gaps.

gap, g). From this result, it is revealed that a frequency reconfigurable antenna can also be developed from this approach by tuning the air gap.

The gain of the antenna is shown in Fig. 3 for different air gaps. It is evident that the peak gain at the corresponding resonance frequency increases with the increase of the air gap for up to 25 mm and then decreases subsequently due to the poor impedance matching (see Fig. 2). However, matching can be improved by optimizing dipole width, w_f.

The radiation efficiency of the antenna is shown in Fig. 4 for different air gaps. It is evident that radiation efficiency increases with the increase of air gap.

The far-field radiation patterns of the antenna at the

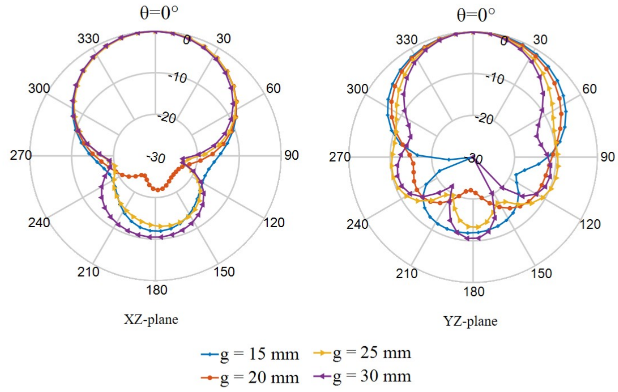

Fig. 5. Radiation patterns (in dB scale) of the proposed antenna for various air gap at the corresponding resonance frequency.

TABLE II
PERFORMANCE OF THE WATER-BASED ANTENNA FOR VARYING AIR GAP.

g (mm)	Res. Freq. (GHz)	Gain (dBi)	Rad. Effi. (%)	F/B (dB)
15	2.4	4.15	50.2	11.8
20	2.46	4.9	60	21.8
25	2.62	5.01	71	12.9
30	2.9	4.5	72	10.4

corresponding resonance frequencies are shown in Fig. 5 for different air gaps. It is revealed that front-to-back ratio changes with the change of air gap due to the variation of the surface area of the reflector.

The performance of the antenna for various air gaps are summarized in Table II. Here, resonance frequency for various air gaps, and gain, radiation efficiency and front-to-back (F/B) ratio at the corresponding resonance frequency are listed.

From Table II, it is ascertained that an efficient antenna can be developed by optimizing the air gap while keeping constant overall antenna dimensions. After optimization (s_l = 27.5 mm, s_r = 21.5 mm, l_h = 51 mm and g = 20 mm), it is obtained that resonance frequency can be tuned to 2.45 GHz with the achieved peak gain of 5.16 dBi and radiation efficiency of 70%. In [15], the peak gain and efficiency at 2.45 GHz were 3.84 dBi and 50%, respectively. So, it is revealed that about 1.32 dB improvement in gain and 20% improvement in efficiency can be achieved by incorporating an air gap in the water of the cavity compared to the whole cavity filled with water.

IV. CONCLUSION

A study has been conducted in this paper to design a flexible and transparent unidirectional antenna using water, polymer and transparent mesh. Detail numerical investigations have been presented to analyze the factors affecting antenna performance. It is demonstrated that using water at the two opposite sides in the PDMS cavity instead of totally fill the cavity by water subsequently minimizes the loss and increases efficiency. However, appropriate water layer width should be maintained to preserve satisfactory front-to-back ratio for the unidirectional pattern. The simulation results exhibit that about 5.16 dBi peak gain and 70% efficiency can be achieved at 2.45 GHz with this proposed design. It is also revealed that gain is increased by about 1.32 dB and radiation efficiency is increased by about 20% as compared to the water antenna where entire PDMS cavity was filled with water. The performance of the proposed design is promising as compared to other flexible and transparent antennas reported in the literature.

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