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RESEARCH PAPER

Design and characterization of an efficient multi-layered circularly polarized microstrip antenna

PRAVIN R. PRAJAPATI, AMALENDU PATNAIK AND KARTIKEYAN M. V.

A novel asymmetric "+" shaped fractal slotted circularly polarized microstrip antenna with a Yagi–Uda structure is proposed. Four asymmetric plus shape slots are embedded symmetrically in the center of all four quadrants of a square patch. To suppress undesirable higher modes, dumbbell-shaped defected ground structure (DGS) is introduced at the ground layer of the antenna. We introduce a method to compensate the reduction in gain occurring due to the presence of DGS, without changing in the overall size of the antenna. A 3 dB axial ratio bandwidth of 4 MHz at center frequency of 862 MHz, 10 dB impedance bandwidth of 13.20 MHz and a gain of 4.25 dB is achieved with the proposed antenna. A laboratory prototype of the proposed antenna is made to cross-verify the simulation results. Very good agreements between the two are obtained. The proposed antenna may prove useful for International Mobile Telecommunication application for designing high-gain arrays.

Keywords: Active array antennas and components, Power amplifiers and linearizers

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I. INTRODUCTION

In many developing countries and countries with large areas of low population density, the cost-effective implementation of International Mobile Telecommunication (IMT) and the propagation characteristics of frequency bands below 1 GHz result in larger cells. The choice of microstrip antenna arrays used in these application areas due to its low-profile nature suffers from the poor gain characteristics [1, 2]. One of the effective techniques for gain enhancement of microstrip antennas, that is most suitable for array applications, is the use of multilayered Yagi–Uda concept [3–5]. The use of this technique does not change the overall size of the array. Design rules of microstrip Yagi and dipole Yagi are very similar, even though multilayered coupling mechanism and configuration of both Yagi antennas are different. The element, which is connected to the source, is known as the driven element. Other parasitic elements (known as directors/reflectors) receive energy through mutual coupling. The parasitic element, which is kept below the driven patch in multilayered Yagi antenna and has a larger size, is known as *reflector*. The reflector acts as a concave mirror and reflects the signal from the back side to the front side and thus helps to reduce back lobe. A parasitic element, which is placed above the driven element and has a shorter size as compared with driven patch and reflector, is known as *director*. The director acts as a convex lens and increases directivity by increasing field strength in the forward direction.

Furthermore, circularly polarized (CP) antennas are preferred in telecom applications because these antennas provide greater flexibility in alignment angle between transmitter and receiver and reduce polarization mismatch loss at the receiver [6]. Single feed CP microstrip antennas (CPMAs) have usually less complex design as compared to dual feed CPMAs [7–9]. Single feed CPMA design requires a perturbation in the patch radiator at a suitable location relative to feed location to excite two orthogonal modes, which have almost equal amplitude and an odd multiple of 90° phase shift for realization of CP radiation. Various methods for generation of CP printed antennas have been reported in the literature. The truncation of corner [10], use of fractal boundary [11, 12], slot [13, 14], defected ground structure (DGS) [15–17], fractal geometry [18], etc. are usually applied to realize circular polarization. The technique reported in [14] is one of the simplest and versatile methods of creating CP radiation in single feed microstrip antennas because it reduces the size of the antenna also.

This paper deals with the design of a circularly polarized, improved gain microstrip antenna for possible use in IMT application at 862 MHz. In line with the technique reported in [14], asymmetric "+" shaped slots are used to create CP radiation, in addition to the multi-layered Yagi–Uda concept for gain enhancement. To reduce the effect of higher order modes, DGS was used. The DGS in microstrip

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antennas are prone to increase back radiations which in turn reduces the gain in the desired direction.

The core contribution of the authors lies at this point where the space of the slots were used innovatively to insert fractal antennas to enhance the gain of the antenna [19–21].

The paper is organized as follows. Section II describes the constructional details of the antenna. In Section III, we present the results and cross-verification of it with the measurement. Finally, Section IV offers concluding remarks.

II ANTENNA DESIGN

A) Design geometry

Figure 1(a) shows the exploded view of the proposed antenna and Fig. 1(b) shows a cross-sectional view of the proposed antenna. The design process started with the creation of the slotted driven patch for getting circular polarization. Four asymmetrical "+" shaped slots were placed in four different quadrant centers of the square patch as shown in Fig. 2. This patch is the driven patch and co-axial feed was used to excite it. The feeding location is shown in Fig. 2. The dimensions of the square patch and the ground plane area are 78×78 and $120 \times 120\ mm^2$, respectively. In the next step of the design, layers of Yagi–Uda structure, that is, reflector and directors were added in order to increase the directivity of the antenna. The reflector patch was located below the driven patch and two director patches were placed above the driven patch. The dimension ratio between the first director patch and the driven patch is 0.85 and that of the second director patch and driven patch is 0.95. The dimensional ratio between the reflector patch and driven patch is 1.09. The inexpensive commercially available FR4 substrate having a dielectric constant (ϵ_r) of 4.4, height of 1.524 mm and loss tangent of 0.0024 has been used for substrate layers one, two, and three. The foam substrate having a dielectric constant (ϵ_r) of 1.18, height of 2.5988 mm and loss tangent of 0.0002 was used for substrate layers four and five. The reason for the selection of a substrate with a high dielectric constant ($\epsilon_r = 4.4$) for layers, one to three is to have compact patch size and the substrate with a low dielectric constant ($\epsilon_r = 1.18$) for layers, four and five is to facilitate radiation. The dimensions of the patch, reflector, directors and slots were optimized by CST Microwave Studio Version 12 [22].

At each stage, the performance of the antenna was observed through simulations. As expected, in-line with the fact that, discontinuities in the passive electromagnetic structures lead to the occurrence of higher order modes, at this stage of simulation it was found that the antenna is radiating higher order modes (as shown in Fig. 10). These higher order modes degrade the reception quality of the receiver connected to the antenna. In order to block these modes, in the third stage of design, a dumbbell-shaped DGS was introduced in the ground layer placed below the reflector layer separated by a thick layer of dielectric [16, 17, 23, 24]. The reason of using the thick layer of dielectric is to ensure minimal effect of the DGS on the radiation pattern of the antenna. The location and dimensions of the DGS are shown in Fig. 3. The simulation at this stage revealed a decreased gain compared with the previous observation. The decrease in the gain is because of the back radiation that is occurring due to the presence of the DGS. Because the structure was already of four layers, so instead of further increasing the antenna height wise, in the last step of design, the space in the "+" shaped slots was utilized to embed self-similar "+" shape fractal antennas as shown in Fig. 4.

B) Realization of CP by embedding asymmetrical "+" shape slots

The concept of CP generation is in-line with the concept explained in [14]. First of all, bigger slot S1 (upper right slot, Fig. 2) was embedded and axial ratio (AR) characteristics was studied. To reduce AR, second slot S2 (lower right slot), which has a slightly less slot area, was embedded. It was

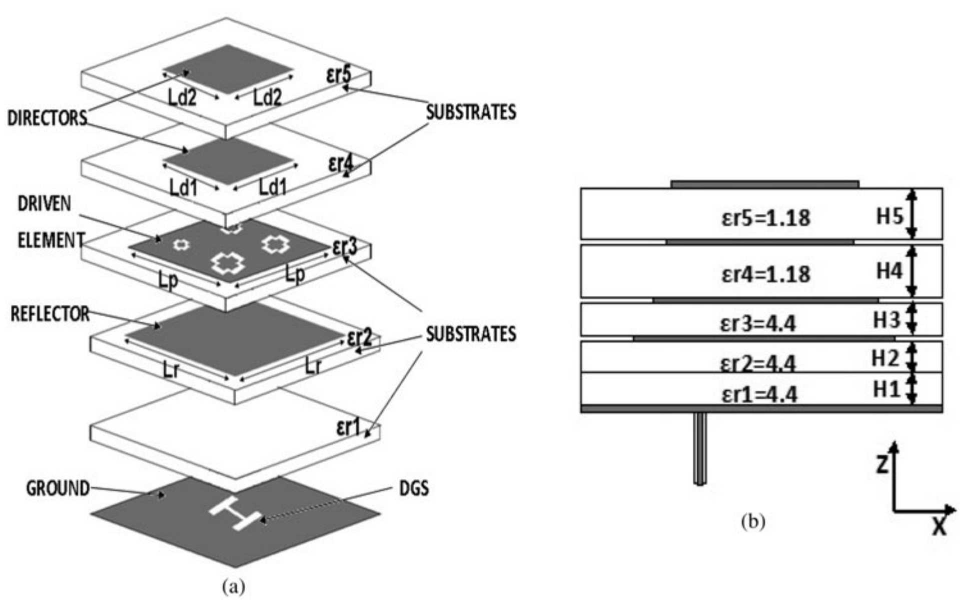

Fig. 1. (a) The structure of asymmetrical CP "+" shape fractal slotted Yagi–Uda patch antenna (ACPPSYA) (b) cross-sectional view of proposed antenna. H1, H2, H3 = 1.524 mm, H4, H5 = 2.5988 mm.

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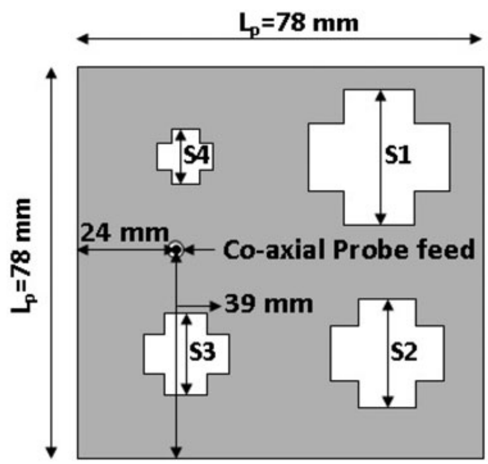

Fig. 2. Top view of 0th iteration "+" shape slotted driven patch, slot parameters: S1, S2, S3, and S4 are 20.20, 20.197, 15.836, and 11.317 mm, respectively.

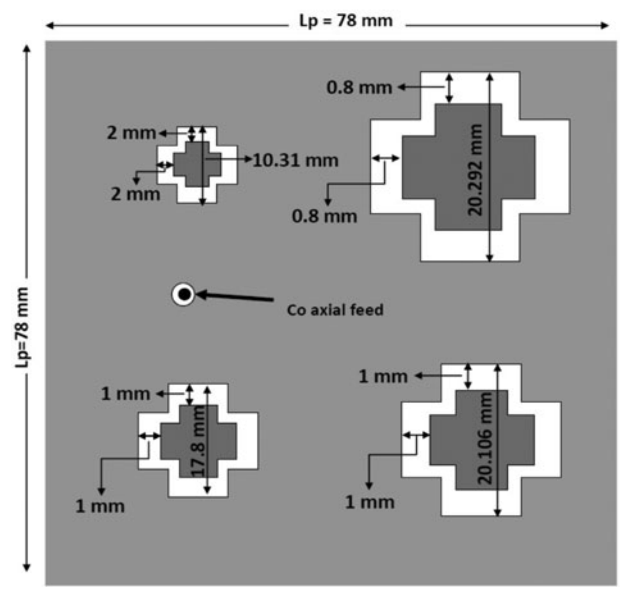

Fig. 4. The design dimensions of 1st iteration "+" shape slotted driven patch.

seen that after embedding second slot S2, AR was increased from 28.8 to 40 dB at 862 MHz center frequency as shown in Fig. 5. This is because the generated orthogonal field components have large amplitude difference and not having a phase difference near to odd multiplier of 90° due to the almost symmetrical arrangement of two slots on the patch. Asymmetrical slots help to generate almost equal amplitude and odd multiplication of 90° phase shift between orthogonal near degenerate resonant modes for realization of circular polarization. After embedding third slot S3 (lower left slot), the AR was reduced to 5.7 dB and the same was reduced to 2 dB after embedding forth slot S4 (upper left slot) at 862 MHz frequency. After adding 1st iteration fractal "+" shape in all "+" shape slots, AR reduced to 1.06 dB, which is further reduced to 0.7 dB after embedding dumbbell DGS at the ground plane at center frequency of 862 MHz frequency as shown in Fig. 5.

Figure 6 presents the simulated amplitude ratio and phase difference of two orthogonal modes at bore-sight that are responsible for of circular polarization. In the desired frequency of operation, E_θ/E_ϕ remains in 1–2.4 and the phase

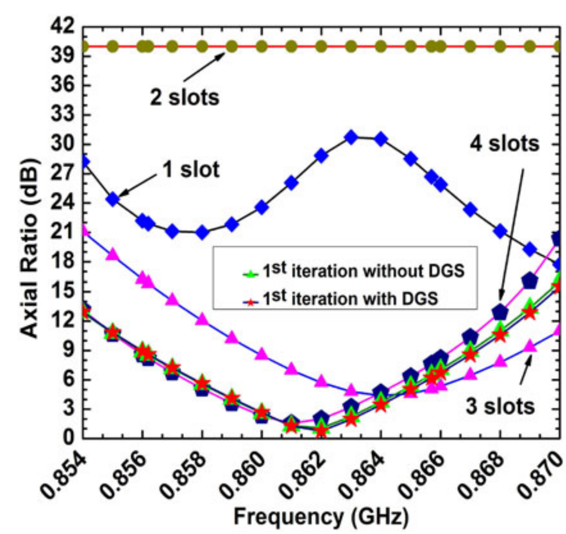

Fig. 5. Effect of embedding "+" shape slots on AR of the proposed antenna.

difference nearly ±90° or odd multiples of that, which conform the circular polarization [6].

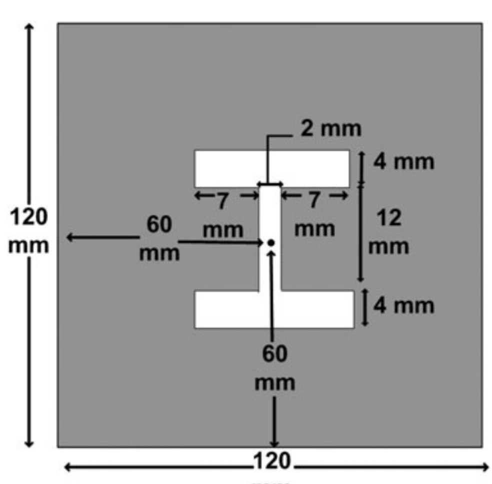

Fig. 3. The design and location of dumbbell-shaped DGS in ground layer (not to scale).

C) Effect of variation of directors and reflector size on the gain of the antenna

Generally, according to Yagi–Uda antenna design rules, the dimension ratio of the reflector patch to the driven element patch should be nearly between 1.1 and 1.3, depending on the substrate thickness and values of the dielectric constant. The dimension ratio between the director patch and the driven element patch should be between 0.8 and 0.95. Figure 7 shows the effect of variation of directors and reflector size on the gain of the antenna. According to the result of parameter sweep, the size ratio of the reflector to driven patch of 1.09 that of the first director to driven patch of 0.85 and driven that of the second director to driven patch of 0.95 was selected for getting maximum gain.

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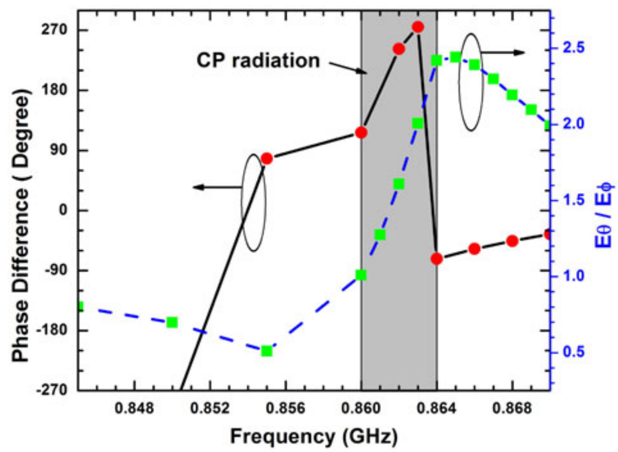

Fig. 6. Simulated amplitude ratio of electric field and phase difference (degree) of two orthogonal components of the electric field of the proposed antenna.

III. RESULTS AND DISCUSSION

A set of laboratory prototypes, one being "+" shape 1st iteration slotted patch, two directors, one reflectors and one ground with dumbbell-shaped DGS was fabricated. Figure 8 shows the fabricated driven patch and ground layer with dumbbell DGS. The antenna was fed with a 50 Ω subminiature type-A connector. The frequency characteristics were measured using a 20 GHz Rohde & Schwarz (model 1127.8500 ZVM) Vector Network Analyzer.

With the addition of Yagi–Uda structure in asymmetrical "+" shape CP antenna, the gain increase from 3.75 to 4.27 dB (13% improvements) at 862 MHz center frequency as shown in Fig. 9. To suppress higher modes, dumbbell-shaped DGS was embedded in the ground layer of the antenna, due to which the gain of the antenna was reduced. The reduction of the gain due to DGS was compensated by adding "+" shape slotted fractal antenna. According to the Bebinet's principle [25], each fractal slot acts as a separate antenna, which leads to an increment in the gain the antenna. The 1st iteration Yagi–Uda antenna with DGS not only compensate the reduction of gain, but also give some more gain at 862 MHz center frequency as compared with 0^{th} iteration Yagi–Uda antenna without DGS.

The effect of incorporation of DGS on higher modes is shown in Fig. 10. The 0^{th} iteration Yagi antenna without DGS generates three bands. The dimensions of DGS were selected in such a way that it should give a band-stop behavior at higher frequency, which includes 3rd band. The undesired lower band has been suppressed due to change in the dimension of driven patch after introducing DGS. However, the desired band (860–864 MHz) remains unaffected after introducing DGS.

The measured and simulated S_{11} of the proposed antenna are shown in Fig. 11. Simulated S_{11} has a value of −27.2 dB

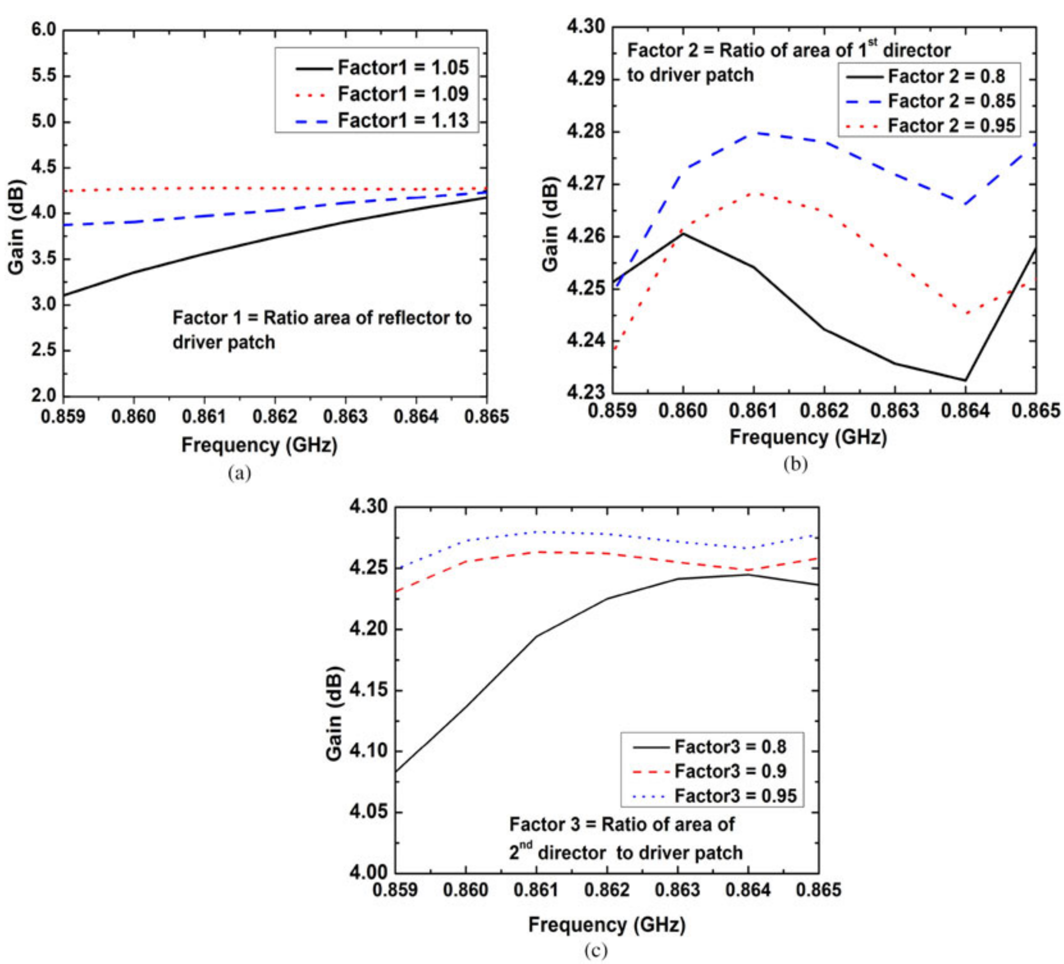

Fig. 7. Effect of variation of directors and reflector size on gain of the antenna.

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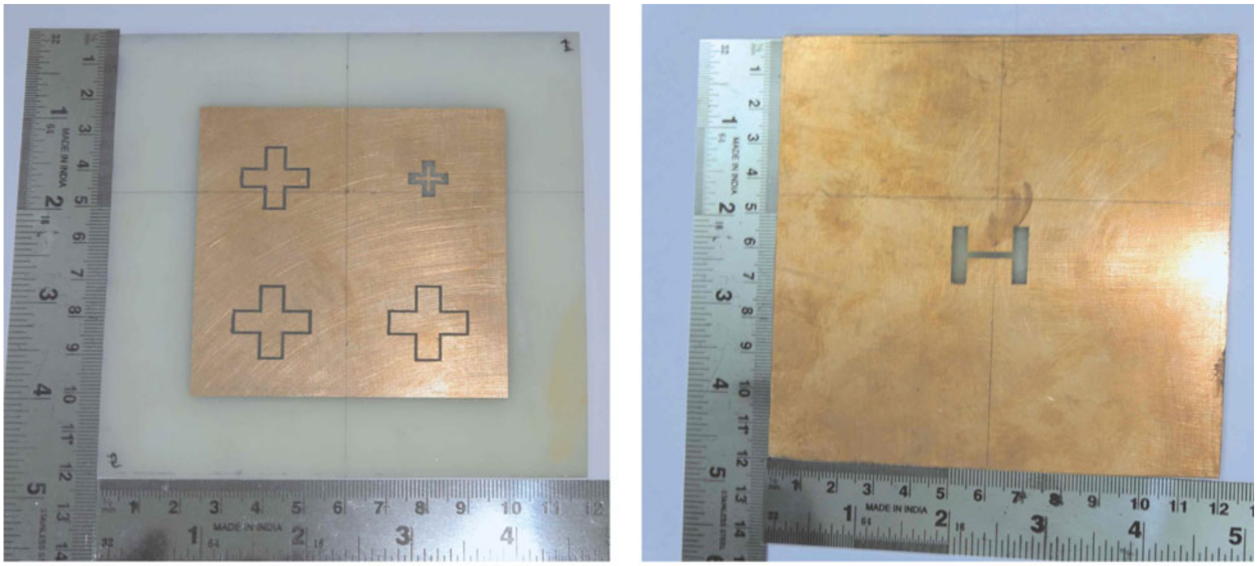

(a) (b)

Fig. 8. Fabricated layers (a) driven patch (b) ground layer with dumbbell-shaped DGS.

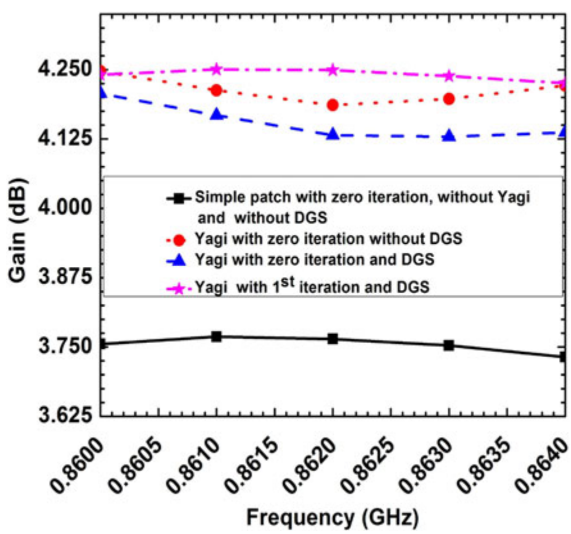

Fig. 9. Simulated gain comparison with and without Yagi antenna and 0[th] to 1st iteration with/without DGS conditions.

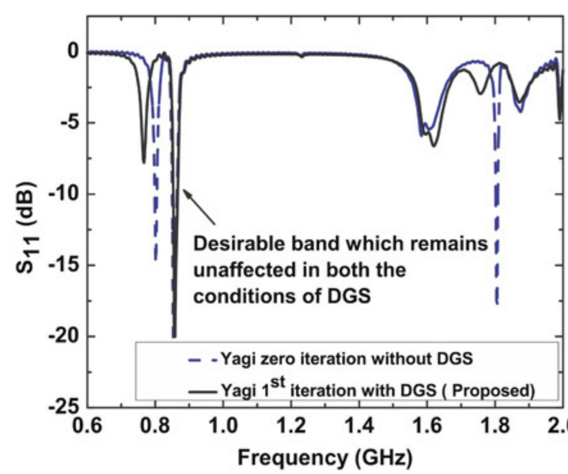

Fig. 10. Comparison of simulated return loss for demonstrating the effect of DGS.

at 862 MHz and measured one has value of −21.13 dB at 842 MHz. Due to fabrication error and misalignment of layers, there is a minor center frequency shift of 20 MHz occurred.

The gain of the proposed antenna was measured in an anechoic chamber. Figure 12 shows measured gain in obtained AR band. It shows that the proposed antenna has a gain of 3.9 to 4.3 dB in AR and resonance band, which is very much near to a simulated gain of 4.25 dB.

Figure 13 shows that by embedding 1st iteration fractal layer at all four plus slots in the driven patch and dumbbell-shaped DGS at ground layer, 3 dB AR bandwidth was increased from 3.85 to 3.93 MHz as compared with 0[th] iteration Yagi antenna without DGS.

The AR should be less than 3 dB at the operating frequency range for good circular polarization. The AR at bore-sight

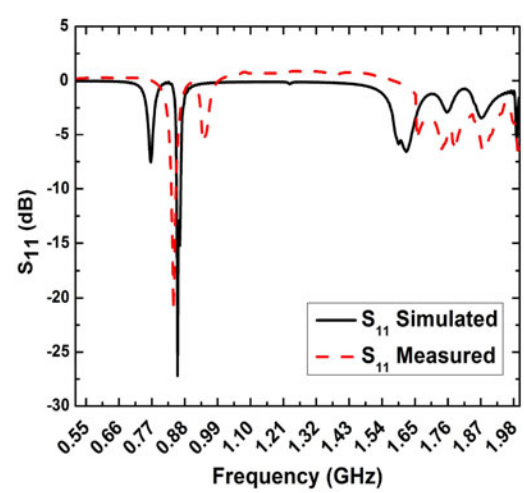

Fig. 11. Measured and simulated S_{11} of the proposed antenna.

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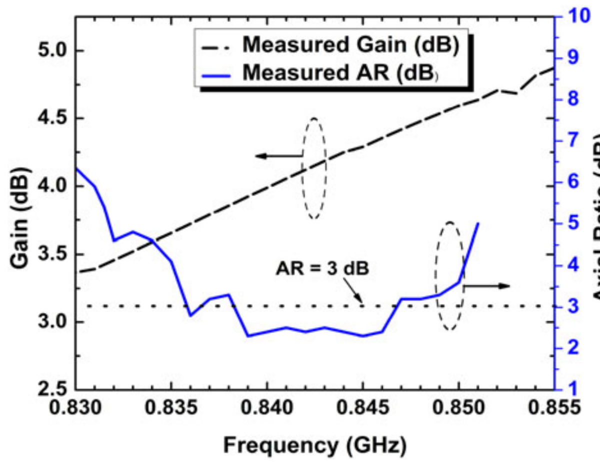

Fig. 12. Measured gain and measured AR of the proposed antenna.

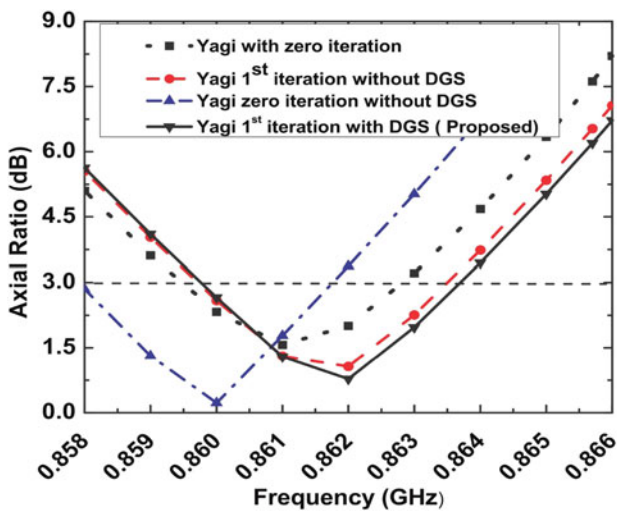

Fig. 13. Simulated AR for different configurations of the antenna.

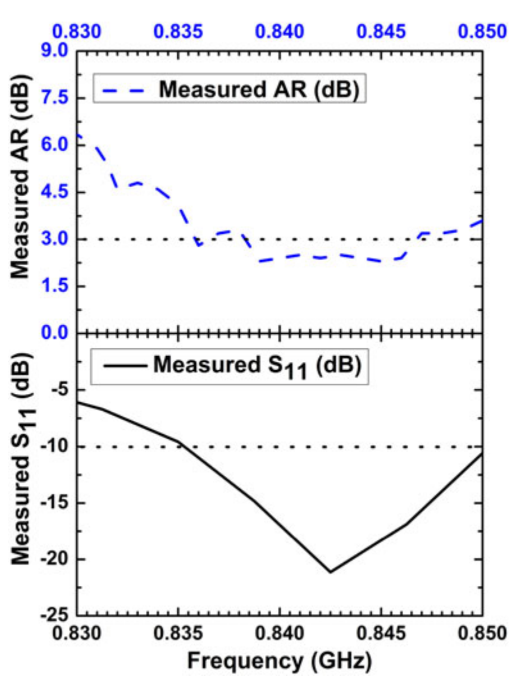

Fig. 14. Measured AR and measured return loss of the proposed antenna.

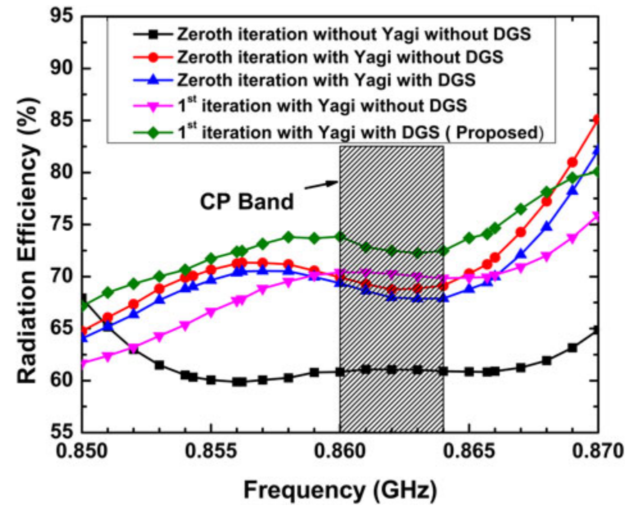

Fig. 15. Simulated vector current distributions of the proposed antenna at 862 MHz for four different time instants ωt = (a) 0°, (b) 90°, (c) 180°, (d) 270°.

was measured in an anechoic chamber. The measured 3 dB AR bandwidth is 10 MHz (837–847 MHz), out of which antenna gives 10 dB return loss between 836 and 850 MHz as shown in Fig. 14. The minimum measured AR value of 2.3 dB achieved at 839 MHz frequency.

The comparison of simulated radiation efficiency in different design stages of the antenna is shown in Fig. 15. It can be seen that at the center frequency, with a simple patch (0^{th} iteration, without Yagi and without DGS) only 61.06% radiation efficiency is achieved. With the incorporation of Yagi–Uda structure with two directors, radiation efficiency increased to 68.76%. Yagi with 0^{th} iteration with DGS antenna has less gain as compared with that of without DGS because DGS radiates at the back side. Fractal layers are embedded in plus slots, not only enhance the gain, but also enhance the radiation efficiency. After embedding DGS with 1st iteration Yagi antenna (proposed), the efficiency of antenna was further increased to 72.45% at 862 MHz center frequency.

The vector current distribution on the surface of the proposed antenna at 862 MHz, in different time instants, $\omega t = 0°$, 90°, 180° and 270° illustrated in Fig. 16. The left-hand circular polarized (LHCP) behavior of the antenna in the $+z$-direction can be clearly marked from the figure.

The simulated and measured radiation patterns (LHCP and right-hand circular polarized (RHCP)) of the proposed antenna in the *E*-plane and the *H*-plane are plotted in Fig. 17. Polarization type of LHCP and 3 dB beam width of 98.3° at the *E*-plane and that of 98.7° at the *H*-plane have been achieved.

The radiating patch size of the proposed antenna is compared with the earlier reported patch antennas operated in the same ultra-high frequency range (860 to 960 MHz). The radiating patch size of the proposed antenna is 75, 19.63, 54.25, and 13.64% compact as compared with [26–29], respectively.

IV. CONCLUSION

A novel "+" shape fractal slotted microstrip antenna is proposed for CP radiation. The advantages of DGS for

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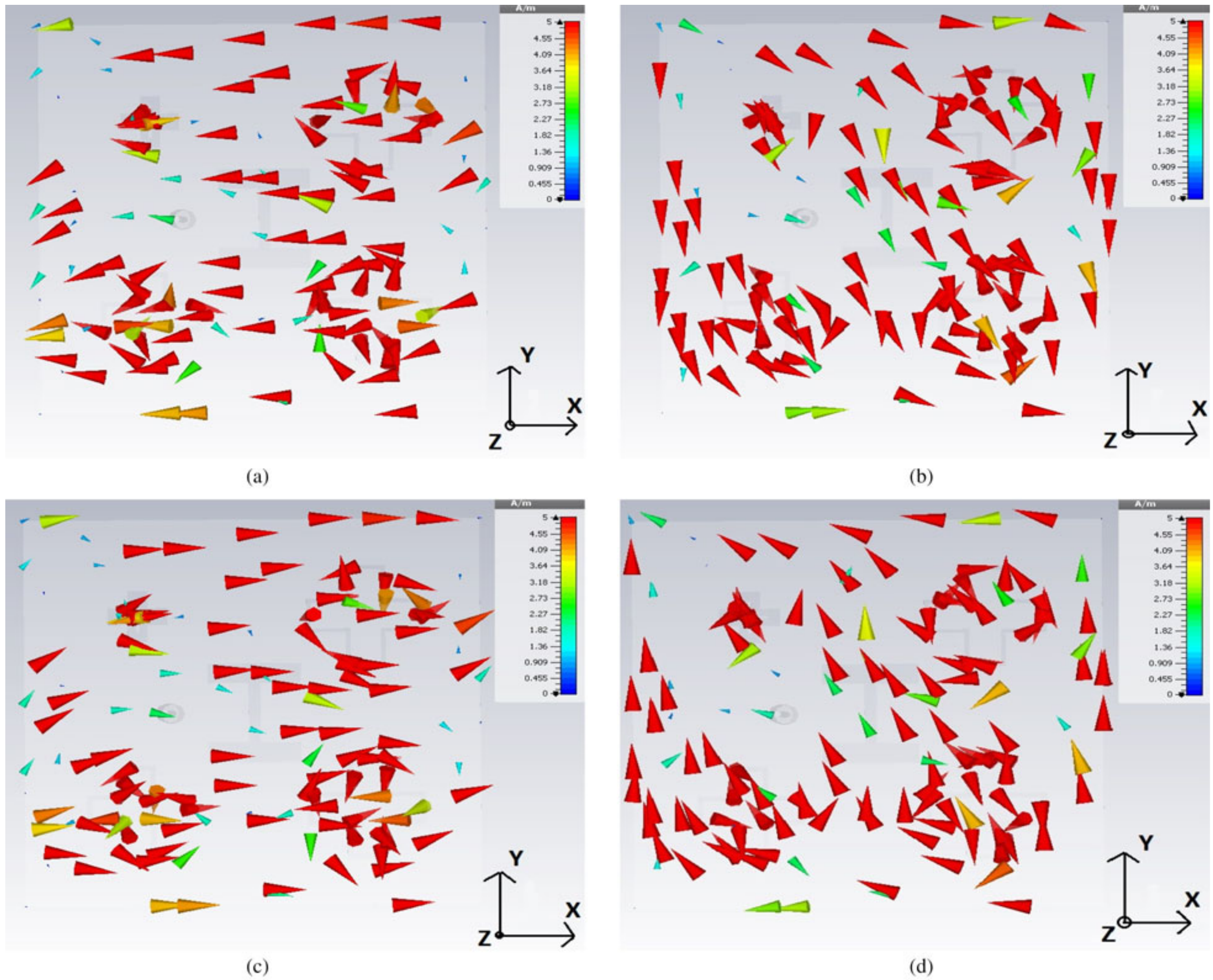

Fig. 16. Comparison of simulated radiation efficiency with different design stages of the antenna. (a) 0°, (b) 90°, (c) 180° and (d) 270°.

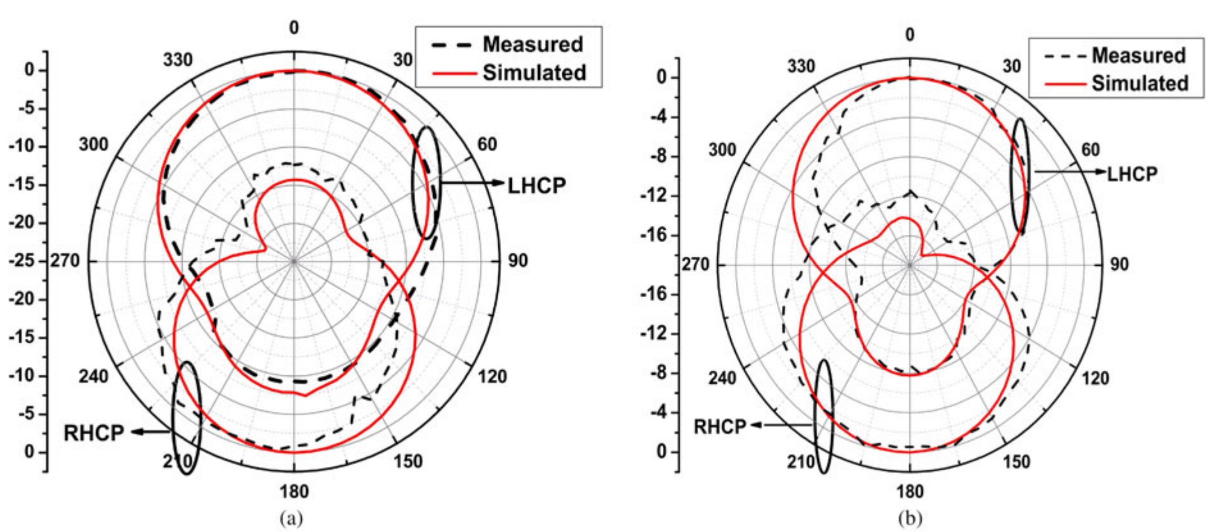

Fig. 17. Simulated and measured radiation patterns (a) *E*-plane [0.862 GHz (Sim.)/0.842 GHz (Meas.)] and (b) *H*-plane [0.862 GHz (Sim.)/0.842 GHz (Meas.)].

suppression of unwanted bands and enhancement of the AR bandwidth of the CP antenna are presented. Slots created for a generation of CP are better utilized in a novel way to compensate the decreased gain due to the presence of the DGS. The Yagi–Uda 1st iteration antenna with DGS gives a higher gain as compared with its 0th iteration counter-part. The proposed antenna is designed for IMT applications.

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