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Cavity Field Modulation With Modulating Circular Patch Antenna Surface: A Key to Realize Reduced Horizontal Radiation and Omni-Present Improvement in Radiation Performance

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ABSTRACT Although, the circular microstrip antennas are the most popular tiny planar antennas, increased horizontal radiation in the E plane imposes a severe limitation in case of modern applications such as array or 5G MIMO configurations. Further, low broadside gain, high H plane cross polar radiation reduces the efficiency of antenna for different wireless applications. Therefore, in order to cope up with the ubiquitous development of tiny and efficient wireless communication devices, antenna structure is to be judiciously modified. Symmetrical modification on patch structure by loading a pair of thin strip on circular patch with shorting posts germinates a modified circular patch with excellent radiation performances. High gain of around 9.2 dBi with excellent polarization purity of 27 dB has been achieved with such structure. Further, an excellent radiation characteristic of reduced horizontal radiation (21 dB down than peak co-polar gain) with 92% efficiency has been revealed from the present antenna. A clear physical insight in to the observed characteristics has been thoroughly documented. The antenna is simple, easy to manufacture and measured results are in close agreement with simulated results.

INDEX TERMS Gain, horizontal radiation, microstrip antenna.

I. INTRODUCTION

Circular microstrip antenna (CMA) on dielectric substrate is well known tiny antenna and the most popular genre of printed antennas although it suffers from poor gain, low efficiency and poor polarization purity (PP). However, this circular microstrip antenna is still be the first choice for use in industry because of its simple design procedure and well-developed theory [1]. Beside these shortcomings, another major but less investigated shortcoming of such CMA is a strong radiation fields along horizontal direction i.e., along ground plane. This radiation is undeniably undesirable for many applications like 5G MIMO, array [2]–[4] configuration or in vector sensors [5], [6]. The far field coupling of antenna elements in an array is mainly due to the strong patch radiation along horizontal direction. Therefore, this can be only minimized by judicious design of antenna structure with reduced horizontal radiation.

The gain enhancement in circular patches has been investigated in [7]–[14]. The technique such as slot-loading with aperture coupling [7] and the use of 3 stacked ground plane with slot and shorting vias [8] have been adopted to achieve around 7.8 dBi gain with no improvement in PP (Co-polar to cross-polar radiation isolation). To further increase the gain from 7.2 dBi to 9 dBi with PP of 18-19 dB only, the annular ring antenna in [9] was loaded with shorting vias (with branch line couplers), while numerous shorting vias beneath the circular patch have been reported in [10]. Notably, a structure similar to [8]–[10] has been reported in [11], and it can achieve high gain of 11 dBi but suffers from poor polarization purity of 17 dB and a much-distorted radiation pattern with a high side-lobe level. To attain high gain of around 6.8 dBi to 8 dBi for patch antenna, various techniques have been investigated, such as the adaptation of circular dual-stacked dense dielectric patch [12], replacement of circular patch

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geometry by hexa-decagon circular patch [13], and the use of graphene-based patch [14]. However, improvement in PP is not apparent from these.

The improvement in PP is very important for modern wireless applications. Efforts to achieve high polarization purity have been reported by modifying the patch geometry [15], [16], use of shorting metal patch [17] or using of DGS [18] in which maximum CP-XP isolation of approximately 22 dB to 23 dB is achieved but with no improvement in gain profile.

However, all these reported works do not deal with the said significant issue like suppression of horizontal radiation of patch antenna at its E plane which is usually only 8-10 dB down than peak co-polar gain. This, indeed a key challenge to the antenna scientists and developers in the epoch of 5G MIMO or array antennas. Employment of micromachined cavity below the patch [2], circular patch with shorting plates [4], the use of superstrate [19] or making the substrate dielectric as band gap structure by printing various patterns on it [20], [21] have been found effective to reduce the horizontal gain of the antenna. Out of them except [2], [19], all the techniques are basically the surface wave elimination technique. However, it may be noted that, the surface wave eliminated antennas are much larger in dimension compared to conventional antenna which is detrimental to use in the era of miniaturization. On the contrary, micromachined patch is complex to design and manufacture and therefore not cost effective. Again, the use of radome (cover) absorbs and reflects radiation wave from antenna and cause transmission losses. Further, radome causes distortion of antenna main lobe in some cases. A plentiful works have been reported on planar antennas with employment of substrate integrated waveguide (SIW) [22] or different kind of meta surface [23] for reduction in RCS or mutual coupling or polarization conversion. However, there is lack of investigations where, efforts are given to make conventional CMA more efficient for omni-present improvement in radiation characteristics.

In order to address the lacunae of the earlier studies, in the present work, circular geometry of the patch has been symmetrically modified with a pair of thin rectangular strip. Further, 12 numbers of shorting pins are symmetrically placed at the corners of the patch as shown in Fig. 1(c). This is done with a view to partially eliminate the surface wave along with the gain reduction in horizontal direction.

The novelties of the present antenna may be listed as:

(i) Judicious choice of modification in circular patch geometry along with few shorting vias make the structure simple but can yield the improvement in complete radiation performances such as high co-polar broadside gain and efficiency, excellent PP along with reduction in horizontal radiation.

(ii) Unlike earlier works, here, the present structure reduces surface wave with much lesser patch dimension. Around 22% reduction in patch area is observed in comparison to surface wave eliminated antenna.

(iii) To the best of authors knowledge, this is the first report where, all the radiation parameters have been improved concurrently along with reduction in horizontal radiation.

(iv) The antenna has been thoroughly analyzed to provide readers a clear physical insight.

II. ANTENNA EVOLUTION AND ANALYSIS

A. STRUCTURAL EVOLUTION

A simple CMA of radial dimension a = 7 mm has been designed on Rodger's RT Duroid 5880 dielectric substrate (permittivity ε_r = 2.2, thickness h = 0.787 mm) and is denoted as Antenna 1 (Ant#1) as shown in Fig. 1(a). Next, two thin rectangular strips of dimension (2a × w_1) are loaded at the upper and lower sections of patch in such a way that the whole patch geometry will not be extended than the CMA of radial dimension a = 7 mm. It is named as Antenna 2 (Ant#2) and is shown in Fig. 1(b). As a last step, 12 shorting pins of diameter d (= 1.2 mm) with center-to-center spacing d_1 (= 1.5 mm) has been incorporated as shown in Fig. 1(c). That is the proposed antenna structure and it is named as Antenna3 (Ant#3).

B. EVOLUTION ANALYSIS: RESONANT FREQUENCY

A conventional circular patch of radial dimension a fabricated on a dielectric substrate (permittivity ε_r) resonates at fundamental TM_{11} mode with a resonant frequency f_r as

$$f_r = \frac{1.84c}{2\pi a\sqrt{\varepsilon_r}} \Rightarrow {}^{\lambda_g}\!/_{2} = 1.7a \tag{1}$$

Now, this TM_{11} mode has one circumferential field variation and hence the semi-circular arc length of patch (S') should be $\lambda_g/2$ (Fig. 2(a)). Now,

$$S' = \pi a = 3.14a \neq {}^{\lambda_g}\!/_{2} \text{ rather } S' \triangleright {}^{\lambda_g}\!/_{2} \tag{2}$$

Therefore, $\lambda_g/2$ is corresponding to circumferential length somewhat lesser than S'. Let us consider a new radius a' for which

$$\pi a' = {}^{\lambda_g}\!/_{2} = 1.7a \Rightarrow a' = 0.54a \tag{3}$$

Therefore, resonant frequency of conventional circular patch may be calculated as

$$f_r = {}^{c}\!/_{\lambda_0} = \frac{c}{2\pi a'\sqrt{\varepsilon_r}} = \frac{c}{2\pi \times 0.54a\sqrt{\varepsilon_r}} \tag{4}$$

In the present investigation a CMA of radius a = 7 mm is considered and, in that case, a' = 3.8 mm. Therefore, considering the smaller radial circle of radius a' = 4 mm, a rectangular strip of width w_1 = 3 mm and length (2a) = 14 mm has been placed at lower and upper section of the main patch (a = 7 mm) as shown in Fig. 2(a). Therefore, the current path will be modified (Fig. 3(a)) and hence we may write

$$\pi a' + 2w_1 = {}^{\lambda_g}\!/_{2} \Rightarrow f_r = {}^{c}\!/_{\lambda_0} = \frac{c}{2\sqrt{\varepsilon_r}\,[\pi a' + 2w_1]} \tag{5}$$

and the resonant frequency of the particular structure becomes 5.65 GHz. As per simulation through Ansoft's High

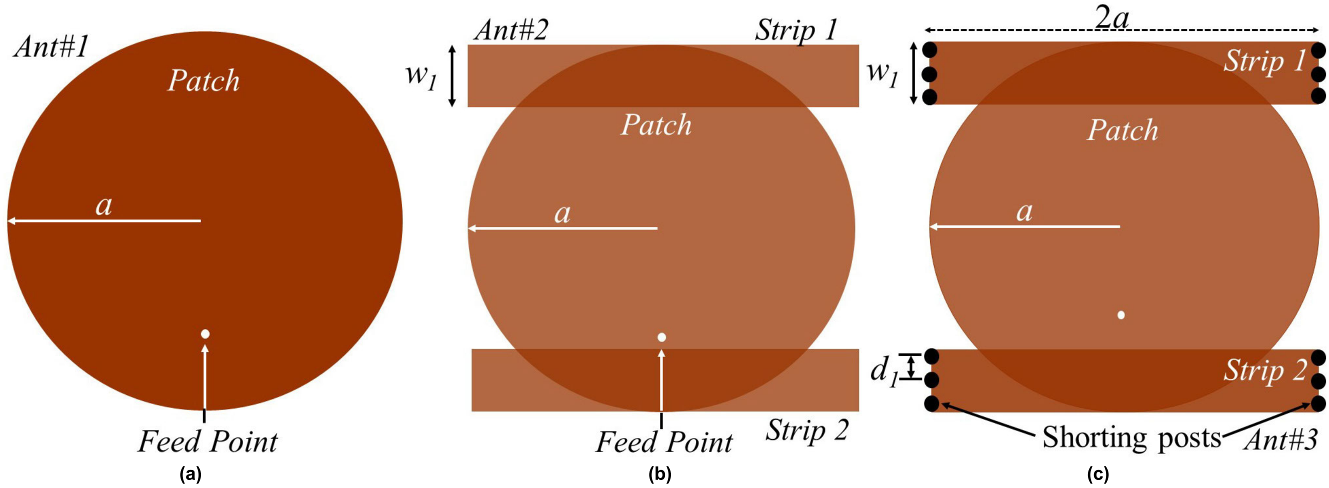

FIGURE 1. Antenna evolution (a) Ant#1, (b) Ant#2, and (c) Ant#3.

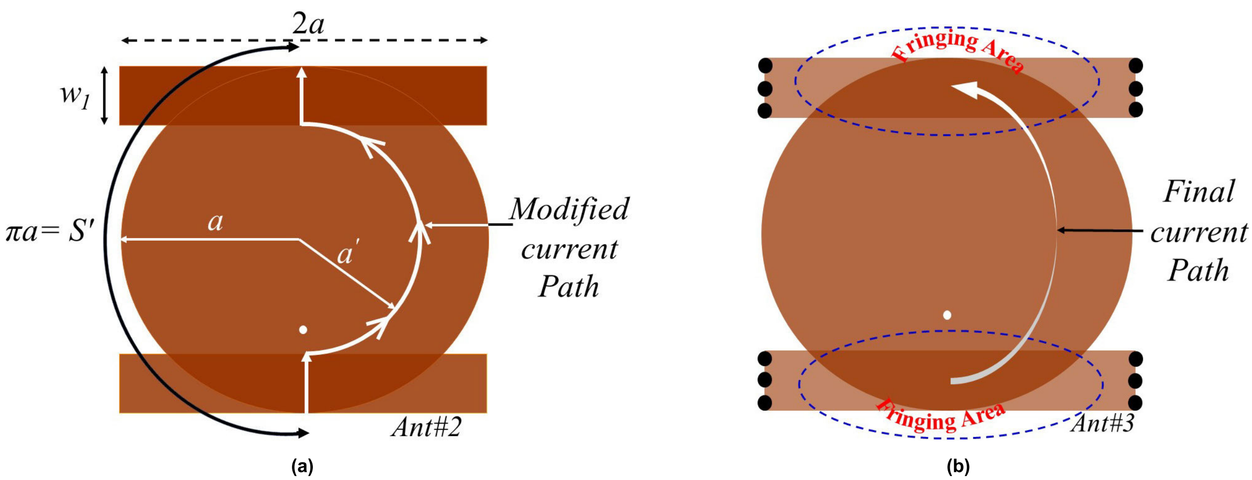

FIGURE 2. Schematic representation of electric surface current path on patch (a) Antenna#2 and (b) Antenna#3.

Frequency Structure Simulator HFSS v.14 [24], the frequency is 6.13 GHz. Original patch with a = 7 mm resonates at 8.4 GHz. Therefore around 32% reduction of resonant frequency can be achieved with such new structure (Antenna#2).

Now, shorting pins of diameter 1.2 mm with center-to-center spacing $d_1 = 1.5$ mm has been incorporated as shown in Section-IIA (Fig. 1(c)) as discussed. As soon as the shorting pins are placed, current lines in Antenna#3 are again modified as is shown in Fig. 2(b) (schematic) and Fig. 3(b) (simulated). Fig. 2(b) and Fig. 3(b) reveal that the surface current on patch is similar to conventional CMA.

C. EVOLUTION ANALYSIS: CAVITY FIELD MODULATION WITH MODULATING PATCH SURFACE GEOMETRY

The patch surface and ground plane as PECs and peripheral regions as PMCs develop the cavity beneath the patch and the resonant field inside the cavity critically depends on the patch surface geometry. As such, this cavity fields may be judiciously modulated to yield optimized performance from patch antenna. Here, along with patch surface geometry, the shorting posts also play a vital role to modulate the cavity fields.

In fact, the magnetic fields around the shorting pins in Antenna#3 force the electric fields to concentrate at central region of radiating edges and hence fringing increases at radiating edges. Therefore, close inspection of Fig. 4 and Fig.5 reveal that, the incorporation of shorting pins (Antenna#3) modulates the cavity fields in such a way that the electric fields reside beneath the main circular disc plate (a = 7 mm) rather than distributed beneath the whole antenna patch plate as is the case for Antenna#2. Fig. 4 and Fig. 5 clearly depicts the fact. Although, structurally, Antenna#1 and Antenna#3 are different still, the cavity fields and consequently the fringing between Antenna#1 and Antenna#3 has a close resemblance as is clear from Fig. 4 (a) and Fig. 4(c). Fig. 5(a) and Fig. 5(c) confirms the observation in terms of electric vector.

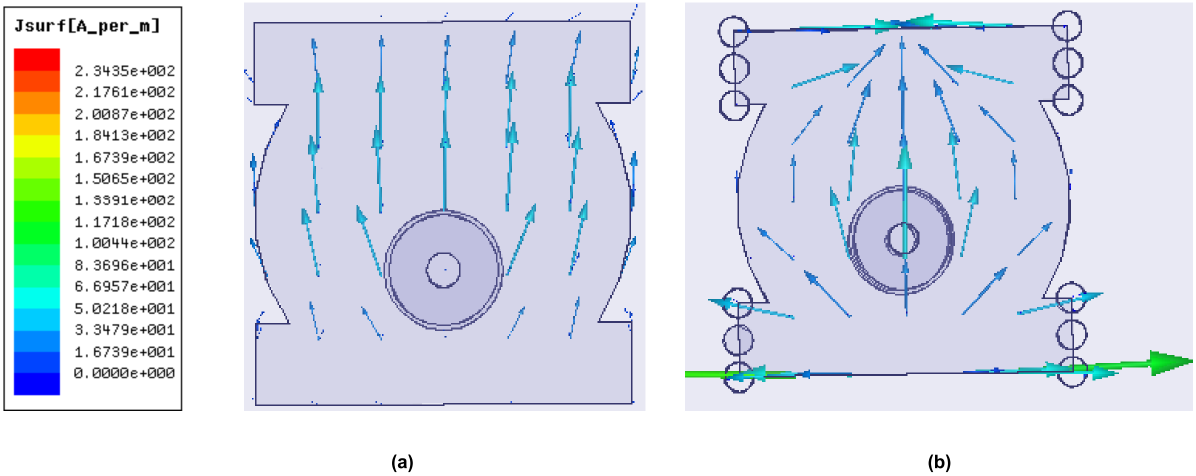

FIGURE 3. Simulated electric surface current path on patch (a) Antenna#2 and (b) Antenna#.

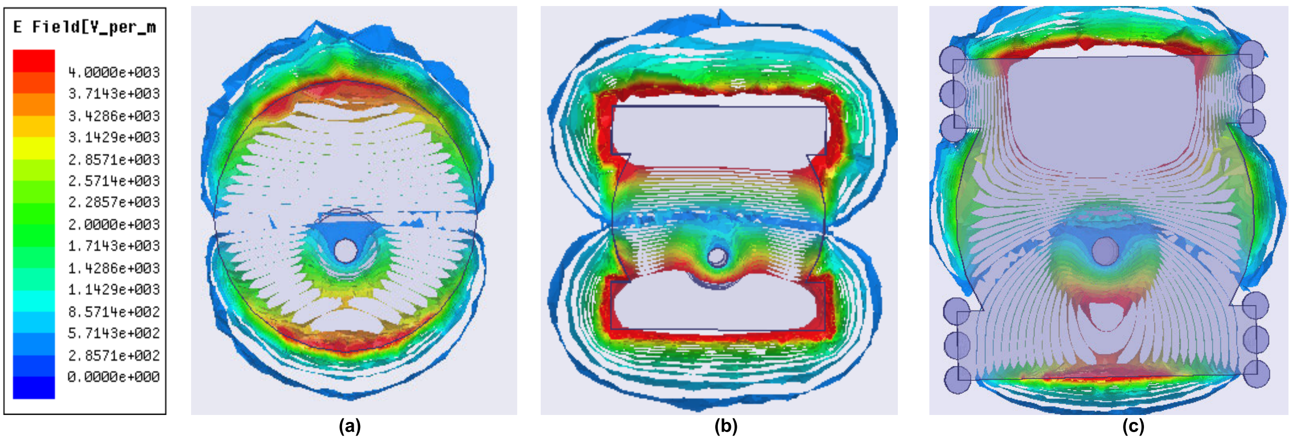

FIGURE 4. Simulated electric field magnitude over substrate (a) Antenna#1, (b) Antenna#2, and (c) Antenna#3.

Therefore, the capacitance of the structure changes which is manifested on the change in dielectric constant due to the incorporation of shorting pins.

Now, the patch plate area (A_P) of the structure in case of Antenna#2 may be written as,

$$A_P = \pi a^2 + 2\left[2aw_1 - \left\{\frac{a^2}{2}\theta_0 - (a-w_1)\sqrt{a^2-(a-w_1)^2}\right\}\right] \tag{6}$$

Again, the patch plate area of Antenna#3 is similar to Antenna#2. Therefore, the calculated area from (6) may be used to find the static capacitance of Antenna#3 with new dielectric constant (due to inner portion of the shorting pins).

Following the (6), the area of the structure becomes 190 mm^2 and the capacitance of this patch plate in Antenna#2 becomes

$$C_P = \frac{190}{h}(\varepsilon_r)_N \tag{7}$$

where, $(\varepsilon_r)_N$ becomes new dielectric constant due to the incorporation of shorting pins. Based on the discussions above, this C_P with new dielectric constant is equivalent to the capacitance (C_O) of original circular disc patch ($a = 7$ mm). Now,

$$C_O = \frac{\pi a^2}{h}\varepsilon_r = \frac{153}{h}\varepsilon_r \tag{8}$$

As the cavity fields beneath the patch in case of Antenna#1 and Antenna#3 has close resemblance, equating these two capacitances,

$$(\varepsilon_r)_N = 0.8\varepsilon_r = 1.7 \tag{9}$$

Now, due to incorporation of shorting pins at far end side of patch structure, major part of the current producing radiation follows the locus of conventional circular patch as is depicted in Fig. 2(b) and Fig. 3(b). Therefore, resonance frequency may be calculated by (4).

Therefore, the new resonant frequency becomes

$$f_r = \frac{c}{2\pi \times 0.54a\sqrt{(\varepsilon_r)_N}} = 9.7GHz \tag{10}$$

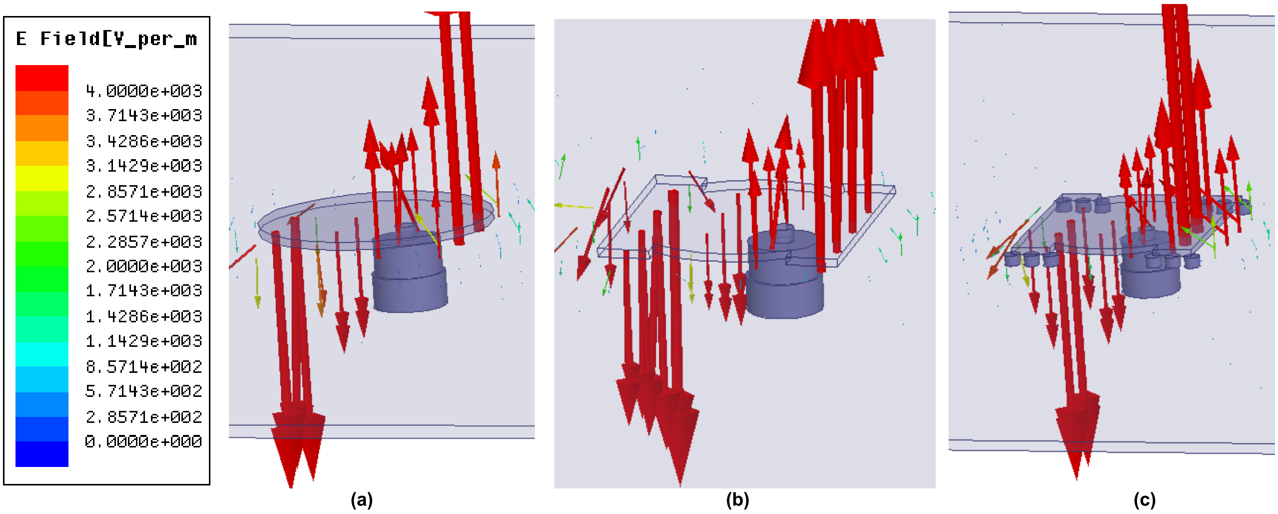

FIGURE 5. Simulated electric field vector over substrate (a) Antenna#1, (b) Antenna#2, and (c) Antenna#3.

TABLE 1. Comparison of simulated and computed resonance frequency using proposed theory.

Patch configuration	Simulated f_r (GHz)	Computed f_r (GHz)
Antenna#1	7.9	8.4
Antenna#2	6.13	5.7
Antenna#3	10.01	9.7

The simulated resonance frequency for Antenna#3 is10.01 GHz.

Simulated and computed resonance frequencies are documented in Table 1.

It may be noted that, to excite such 10 GHz frequency, the surface wave eliminated antenna has larger radius than present $a = 7$ mm patch. The surface wave eliminated antenna radius a_2 may be calculated as [25]

$$a_2 = {}^{1.84}/_{\beta_{TM0}} \tag{11}$$

where, β_{TM0} is the propagation constant of first surface wave mode that is TM_0 surface wave. And, k_0 is the wave number of structure. The relation between them may be written as [25]

$$^{\beta_{TM0}}/_{k_0} = \left[1 + (k_0 h)^2\right] \tag{12}$$

Therefore, it yields that, for designing surface wave eliminated antenna or RSW antenna, the required patch radius is $a_2 = 8.8$ mm with patch area of 243.28 mm^2. Contrarily, the present patch area is 190 mm^2. Therefore, 21.9% reduction in patch area has been achieved with the present design in comparison to complete surface wave eliminated patch.

D. EVOLUTION ANALYSIS: RADIATION CHARACTERISTICS

The simulated gain and cross polarization of Antenna#1 and Antenna#2 at their H plane are depicted in Fig. 6 (a). The gain of the Antenna#2 at $f = 6.13$ GHz is 6.25 dBi while PP is 10 dB. Contrarily, Antenna#1 has peak gain of 7.64 dBi and the PP is 18 dB at $f = 7.9$ GHz. It may be noted that, Antenna#2 has somewhat flat-topped radiation beam which is good for certain applications. However, PP is poor with broadside profile of cross polar radiation which may affect the main co-polar beam.

The simulated gain and cross polarization of Antenna#1 and Antenna#3 at their H plane are depicted in Fig. 6(b). The gain of the Antenna#3 at $f = 10.01$ GHz is 10 dBi while polarization purity (PP) is 30 dB. It may be noted that, Antenna#3 has somewhat wider radiation beam at its H plane with high gain in comparison to Antenna#1.

The E plane radiation characteristics of Antenna#1, Antenna#2 and Antenna#3 is depicted in Fig. 6(c). The comparison of E plane radiation performance amongst all three antennas reveals that, Antenna#3 has best performance in terms of gain and PP. Notably, radiation along horizontal direction in Antenna#3 has significant improvement in comparison to Antenna#1 and Antenna#2.

The strong radiation fields along the horizontal direction at the E plane of patch antenna is actually due to the polarization current (J_P) as,

$$\bar{J}_P = j\omega\bar{P} \tag{13}$$

where,

$$\bar{P} = (\varepsilon_r - 1)\,\varepsilon_0\bar{E} \tag{14}$$

Therefore, the problem of horizontal radiation in E plane is much prominent in case of patch with dielectric substrate in comparison to air substrate. In air substrate, the suppression of radiation along horizontal direction is manifested through the gain enhancement at the zenith of the patch. Contrarily, the problem of strong horizontal radiation is not the issue in H plane. In the Fig. 7, x-z plane is E plane while y-z plane is H plane. At the patch radiating edges (where the electric field is maximum and consequently the dielectric polarization and hence the polarization current) is counter-phased between the

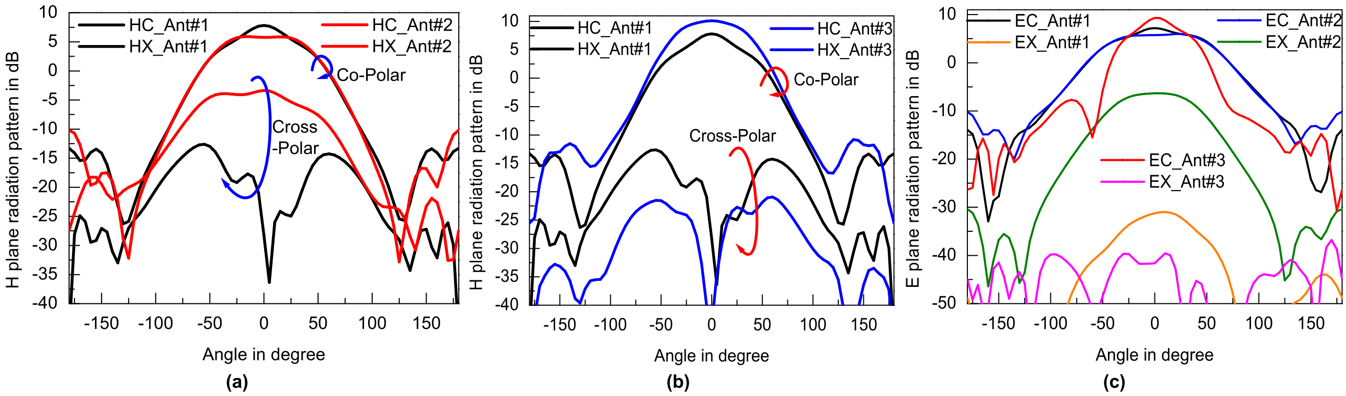

FIGURE 6. **Comparison of H plane radiation pattern (a) Antenna#1 and Antenna#2, (b) Antenna#1 and Antenna#3, and (c) Comparison of E plane radiation patterns of Antenna#1, Antenna#2, and Antenna#3.**

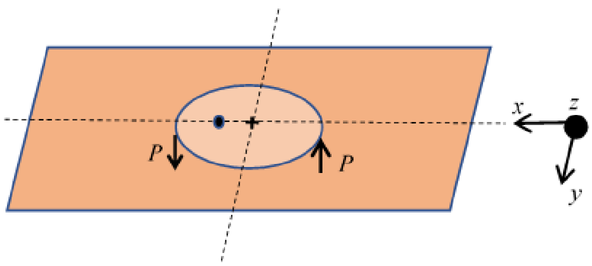

FIGURE 7. **Effect of polarization current in horizontal radiation at E plane.**

lower and upper half section of patch. Therefore, the effect on the horizontal radiation along H plane is cancelled while it is prominent in E plane due to the path difference travelled by radiation field arises due to polarization current as is clear from Fig. 7.

Now, near the radiating edges of the patch, if shorting pins are incorporated, it compensates this polarization current by counter-phased conduction current through shorting pin. With this in view, 12 numbers of shorting pins are incorporated at four extreme sides of Antenna#2 which, gives birth to Antenna#3. Therefore, the radiation along horizontal direction becomes 20 dB down than peak co-polar gain in case of Antenna#3 while the same is only around 8-9 dB in Antenna#1 and Antenna#2.

This, suppression of radiation field along horizontal direction in Antenna#3 in turn enhances broadside radiation and hence gain increases. The incorporation of shorting pins in Antenna#3 concentrates the fields near the radiating edges of patch structure and hence fringing increases there. This may also be attributed for higher gain in Antenna#3. Furthermore, incorporation of shorting pin reduces the effective dielectric constant of the substrate. Hence, surface wave reduces and as a result gain and efficiency increases.

It may be noted that, the incorporation of shorting pins reduces orthogonal component (y directed) of fringing electric fields as is confirmed from Fig. 4 in Antenna#3. In fact, because of structural modification as well as the incorporation of shorting pin, locus of current path has been modulated as is shown in Fig. 2(b) and Fig. 3(b). It results in low cross polarized radiation in the proposed Antenna#3.

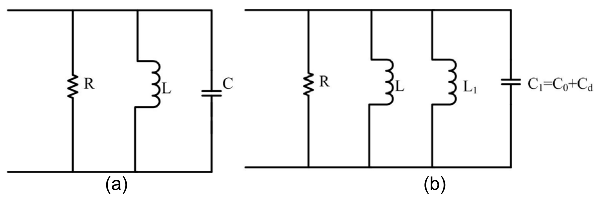

FIGURE 8. **Approximate circuit model (a) conventional CMA and (b) proposed antenna.**

E. CIRCUIT MODEL APPROACH

A simple CMA is a parallel resonant circuit consisting of resonant input resistance R, patch inductance L and the patch capacitance C between two electrodes (patch and ground plane) as is shown in Fig. 8(a). The resonant frequency of the patch in terms of circuit theory can be written as

$$f_r = {}^{1}\!\big/_{2\pi\sqrt{LC}} \tag{15}$$

where approximate value of C can be the patch capacitance and may be written as

$$C = \frac{\varepsilon_0 \varepsilon_r}{h} A_p \text{ and } L = {}^{1}\!\big/_{(4\pi^2 f^2 C)} \tag{16}$$

Now, when we insert shorting pins beneath the patch plate, an inductance L_1 comes between the electrodes (patch and ground plane) of the capacitor. This L_1, comes parallel to the anti-resonant circuit of patch. Also, the incorporation of shorting pins change the dielectric constant of the substrate from ε_r to $(\varepsilon_r)_N$ as is discussed in Section II C. Therefore, a new dielectric capacitance C_d has come up replacing the conventional dielectric capacitance of patch. The new dielectric capacitance C_d is the capacitance only due to the presence of new dielectric with dielectric constant $(\varepsilon_r)_N$. It may be noted that, once the shorting pins are introduced, the antenna structure (Antenna#3) is behaving like a simple circular patch of radius $a = 7$ mm irrespective of patch plate geometry as is discussed and validated in previous Sections II B and II C.

The pin inductance L_1 and the new dielectric capacitance C_d can be obtained from [26], [27] as

$$L_1 = \frac{\mu_0}{2\pi}\left(\ln\left[\frac{a}{d/2}\right] - \frac{3}{4}\right)h \tag{17}$$

and

$$C_d = \left[(\varepsilon_r)_N - 1\right]\frac{\varepsilon_0 \pi a^2}{h} \tag{18}$$

Therefore the whole patch capacitance of Antenna#3 can be written as [27]

$$C_1 = C_0 + C_d \tag{19}$$

where, C_0 is the portion of patch capacitance of Antenna#3 when dielectric is removed [27]. Hence,

$$C_1 = \left[\frac{\varepsilon_0 \pi a^2}{h}\right] + \left[(\varepsilon_r)_N - 1\right]\frac{\varepsilon_0 \pi a^2}{h} \tag{20}$$

In the context of Section II D, the current through this pin inductance L_1 must be compensated by the polarization current through new dielectric capacitance C_d. Then only, the horizontal radiation from antenna in E plane can be reduced as is discussed in Section II D.

Therefore, the new equivalent circuit for Antenna#3 is as shown in Fig. 8(b). The equivalent inductance and capacitance of Antenna#3 can be written as

$$L_{eq} = {}^{LL_1}/_{(L + L_1)} \text{ and } C_{eq} = C_1 \tag{21}$$

And the resonant frequency will be

$$f_r = {}^{1}/_{2\pi\sqrt{L_{eq}C_{eq}}} \tag{22}$$

Considering patch of radius $a = 7$ mm, pin diameter $d = 1.2$ mm, substrate thickness $h = 0.787$ mm and new effective dielectric constant of $(\varepsilon_r)_N = 1.7$ (equation 9), patch plate area $A_p = 190$ mm (equations 6 and 7); the calculated f_r for Antenna#3 is 9.3 GHz which is very close to that obtained in equation (10). The simulated and measured resonant frequency of same antenna (10.01 GHz and 10.02 GHz respectively) is documented in results section (Section IV, Fig. 10) which shows good agreement with the predicted results by both the cavity model and circuit model approaches.

III. PROPOSED STRUCTURE

First, a simple CMA with 0.5 mm copper strip having radius $a = 7$ mm is chosen and two rectangular thin strips of dimension 14 mm × 3mm are loaded at the upper and lower sections of patch as shown in Fig. 1(b). It is then fabricated on RT-5880 (dielectric constant $\varepsilon_r = 2.2$ and thickness $h = 0.787$ mm) substrate. The dimensions of substrate and ground plane are chosen to be 50 mm × 50 mm ($\sim 1.5\lambda_0 \times 1.5\lambda_0$). Next, 12 shorting pins of diameter d (=1.2 mm) with center-to-center spacing d_1 (= 1.5 mm) has been incorporated at the sides of two thin rectangular strips as shown in Fig. 1(c). The patch is fed at 1.5 mm from the centre point (Fig. 1). An equivalent conventional CMA of radius 5.5 mm having same resonant frequency has also been fabricated on RT-5880 (dielectric constant $\varepsilon_r = 2.2$ and thickness $h = 0.787$ mm) substrate for comparison. The fabricated prototype of the proposed patch is shown in Fig. 9.

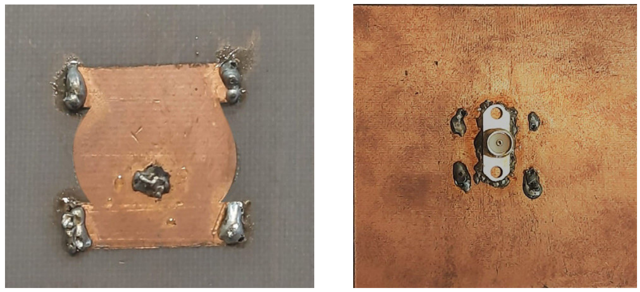

FIGURE 9. Fabricated prototype (a) top view and (b) bottom view.

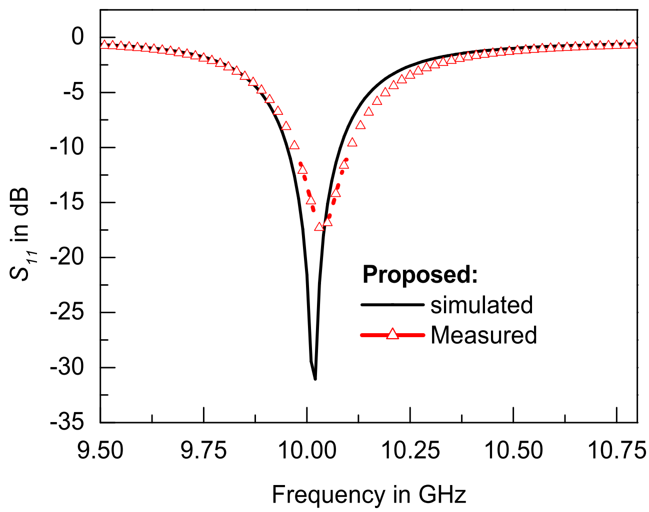

FIGURE 10. Simulated and measured reflection coefficient profiles of proposed Antenna#3.

IV. RESULTS AND DISCUSSIONS

The fabricated prototypes (conventional CMA of radius 5.5 mm and the proposed patch) have been measured and the results are documented. In Fig. 10, the simulated and measured reflection coefficient profiles for the proposed antenna (Antenna#3) are presented. The proposed antenna resonates at 10.02 GHz with an impedance bandwidth from 9.94 GHz to 10.14 GHz. The equivalent conventional CMA of radius 5.5 mm also resonates at same 10.02 GHz frequency although not shown in figure to avoid clumsy plot.

The complete H and E plane radiation patterns of the proposed antenna has been presented in Fig. 11 (a) and Fig. 11 (b) respectively. The complete radiation pattern of equivalent conventional CMA has also been incorporated in the respective plot for comparison. Fig. 11 depicts that; the measured

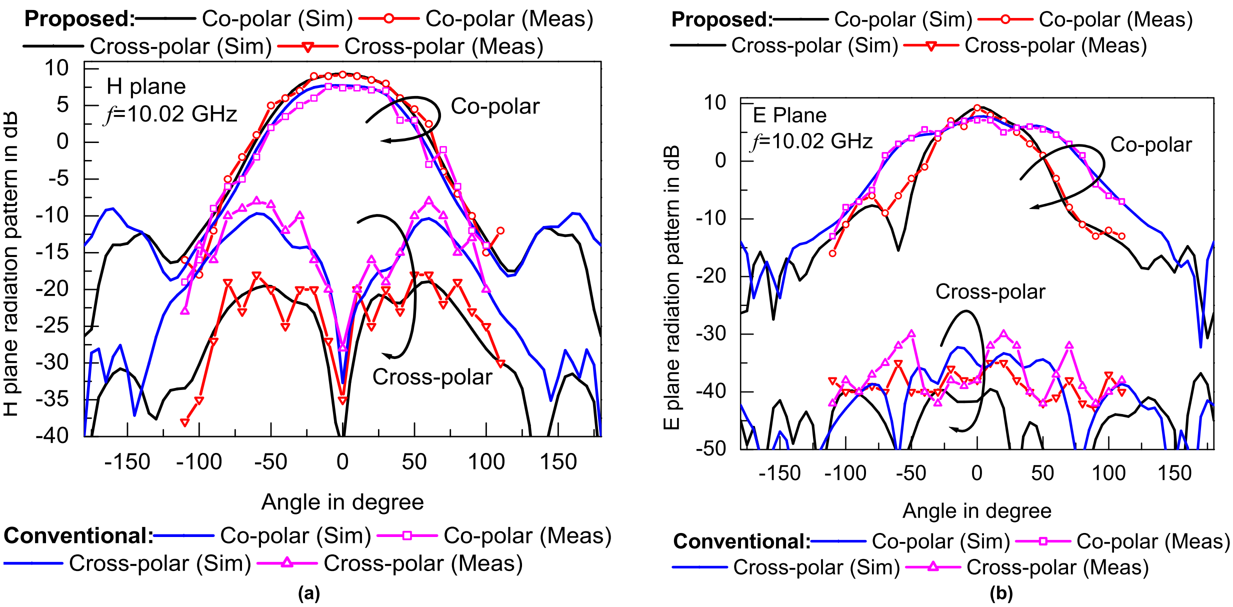

FIGURE 11. Comparison of simulated and measured radiation patterns of conventional Antenna#1 and proposed Antenna#3 (a) H plane and (b) E plane.

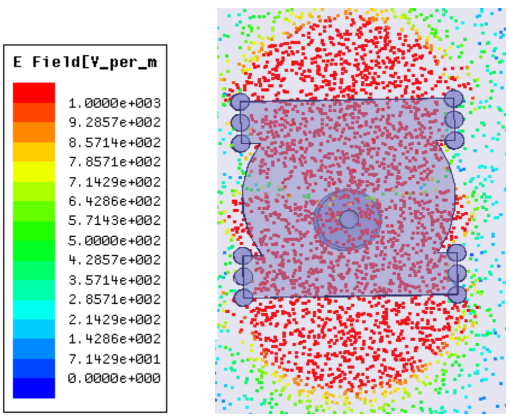

FIGURE 12. Simulated electric field magnitude over substrate in proposed Antenna#3.

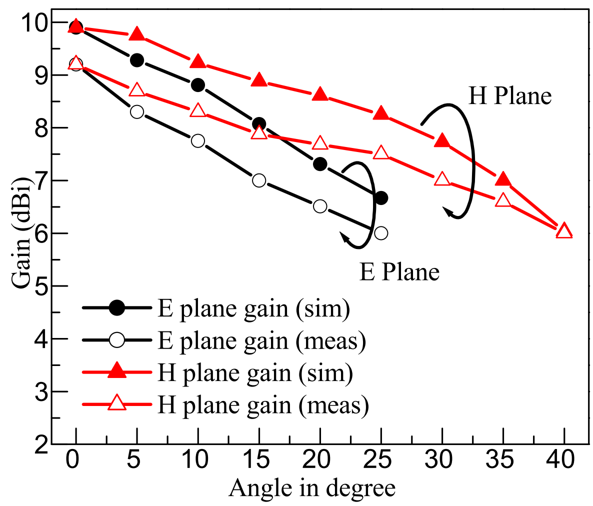

FIGURE 13. Variation of gain of proposed antenna at both principal planes within its 3 dB beam widths.

gain of the proposed antenna is 9.2 dBi while the simulated gain is 9.6 dBi. Contrarily, equivalent conventional CMA has measured gain of 6.8 dBi while the simulated one is 7.4 dBi. Therefore, 2.4 dB improvements in gain can be achieved with the proposed antenna in comparison to conventional CMA resonating at same 10.02 GHz frequency.

The simulated magnitude of electric field at the substrate shown in Fig. 12 reveals a high concentration of fringing fields near radiating edges of patch as is discussed in section II D. This confirms the conjecture for higher gain of the structure discussed earlier. Fig. 11(b) shows that, the polarization purity in E plane radiation pattern is 44 dB while the same for conventional CMA at same frequency is 35 dB. However, the polarization purity in E plane is not a major concern as it is usually below 30 dB than the peak co-polar gain always. On the contrary, H plane cross-polarization is a major factor for linearly polarized antenna and it is usually high in conventional CMA. Fig. 11(a) confirms that, the H plane polarization purity of proposed patch is 27 dB while the same for conventional CMA is only 15 dB. About 12 dB improvement in co-polar to cross- polar radiation isolation is revealed from proposed patch than conventional CMA at same frequency at H plane.

The variation of antenna gain as function of angle θ at off bore sight direction has also been examined through simulation and measurements at the operating frequency $f = 10.02$ GHz. The resulting plot is depicted in Fig. 13. The gain variation is examined within its 3 dB beam width. In E plane, the measured gain is monotonically decreasing from 9.2 dBi to 6 dBi, while the same is 10 dBi to 6.88 dBi for simulated gain within $\pm 25°$. Contrarily, this gain decrement is

TABLE 2. Performance comparison of the present antenna with recently reported relevant works.

Reference	Gain (dBi)	Minimum CP-XP Isolation (dB)	Efficiency (%)	Max radiation to horizontal radiation isolation (E plane) (dB)	Remarks
[4]	8.5	25	93	---	Simple RSW inspired circular patch with pair of shorting strips makes concurrent improvements in gain, efficiency and polarization purity.
[7]	7.8	20	---	10	Four stacked planes with complex feeding.
[8]	8	---	91	13	Use of slots, numerous vias with 3 stack ground plane makes the structure too bulky.
[9]	7.25	18	73.5	16	Complex structure integrated with branch line coupler. Dual feed RSW inspired antenna.
[10]	9	13	69	10	RSW inspired simple circular patch with shorting four vias.
[11]	11	19	89	15	RSW inspired antenna with much distortion in radiation pattern and very high side lobes.
[12]	9.0	20	92	15	Use of multiple stacking with dual stacked dense dielectric circular patch make the structure too complex for manufacturing.
[13]	6.8	0	----	3	Hexadegagon circular patch with DGS makes significantly distorted radiation pattern).
[14]	7.8	----	63	7	Asymmetric E and H plane radiation beam makes the radiation property poor.
Present work	9.2	27	92	20	Simple modified CMA for reduced horizontal radiation along with high gain, excellent PP and efficiency.

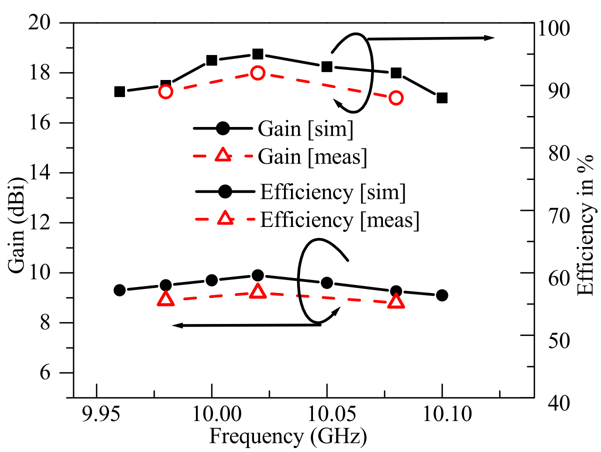

FIGURE 14. Variation of gain and efficiencies of proposed antenna as function of frequency in the operating band.

comparatively slower in case of H plane where the measured gain varies from 9.2 dBi to 6 dBi within ±40°. It may be noted that, the measured gain is around 0.8-1 dB lower than the simulated gain. This 0.8-1.0 dB decrement in measured gain is expected due to unavoidable cable and connector losses. Therefore, the 3 dB beam width of the proposed antenna is around 50° in E plane while the same for H plane is 80°.

The measured horizontal radiation arises from lateral surface wave is 20-21 dB down than peak co-polar gain in case of proposed antenna at it's both E and H plane. On the other hand, for conventional CMA, the same is only 10 dB down than peak co-polar gain in E plane and 20 dB down in H plane.

The measured efficiencies of the proposed antenna are 92% while the same for conventional CMA is 85%. The gain and efficiency variation as a function of frequency has been presented in Fig. 14. Minor degradation of measured gain and efficiency both in respect to simulation results are noted and it is expected due to practical and unavoidable loss factors as discussed above. It is noted that, measured gain varies from 8-9 dBi while the measured efficiency varies from 88 to 92%. However, it may be concluded that, gain and efficiency is merely constant over the whole operating band of the proposed antenna.

The performance of the proposed Antenna#3 has been compared with the available relevant literatures in Table-2. This confirms the consistency and superiority of the present structure over others.

V. CONCLUSION

A symmetrically modified circular microstrip antenna with a pair of thin strips has been proposed and investigated theoretically as well as experimentally. Excellent improvement in radiation performance with high gain of 9.2 dBi, 27 dB polarization purity with 92% efficiency have been obtained. Notably, a new feature of reduced horizontal radiation i.e., 21 dB down than peak co-polar gain has been achieved which is undeniably helpful for modern array or 5G MIMO configuration. The thorough investigation presented in the paper gives an insightful exploration of such new antenna structure. The proposed antenna will surely be helpful for modern scientific and research community looking for tiny planar structure with excellent radiation properties.

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