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

Zonunmawii, Abhijyoti Ghosh, L. Lolit Kumar Singh, Sudipta Chattopadhyay
Department of Electronics and Communication Engineering, Mizoram University, Aizawl, India
Corresponding author: abhijyoti_engineer@yahoo.co.in

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 (Copol 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 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 \(\varepsilon_r = 2.2\), 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 \((2a \times w_1)\) 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 are 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 $\varepsilon_r$) resonates at fundamental $TM_{11}$ mode with a resonant frequency $f_r$ as

$$f_r = \frac{1.84c}{2\pi a \sqrt{\varepsilon_r}} \Rightarrow \frac{\lambda_g}{2} = 1.7a$$

(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,

$$S' = \pi a = 3.14 a \neq \frac{\lambda_g}{2} \text{ rather } S' > \frac{\lambda_g}{2}$$

(2)

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

$$\pi a' = \frac{\lambda_g}{2} = 1.7a \Rightarrow a' = 0.54a$$

(3)

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

$$f_r = \frac{c}{\lambda_0} = \frac{c}{2\pi a' \sqrt{\varepsilon_r}} = \frac{c}{2\pi \times 0.54a \sqrt{\varepsilon_r}}$$

(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

$$\pi a' + 2w_1 = \frac{\lambda_g}{2} \Rightarrow f_r = \frac{c}{\lambda_0} = \frac{c}{2\pi \sqrt{\varepsilon_r} [\pi a' + 2w_1]}$$

(5)

and the resonant frequency of the particular structure becomes 5.65 GHz. As per simulation through Ansoft’s High 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 \( a = 7 \text{ mm} \) 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.

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

Following the (6), the area of the structure in case of Antenna#2 may be written as,

\[
A_p = \pi w^2 + 2 \left[ 2\alpha w_1 - \frac{\alpha^2}{2} \left( a - w_1 \right) \sqrt{a^2 - (a - w_1)^2} \right] 
\]  

(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 \( \text{mm}^2 \) and the capacitance of this patch plate in Antenna#2 becomes
It may be noted that, to excite such 10 GHz frequency, the surface wave eliminated antenna has larger radius than present $a=7 \text{ mm}$ patch. The surface wave eliminated antenna radius $a_2$ may be calculated as [25]

$$a_2 = \frac{1.84}{\beta_{TM0}}$$

(11)

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 $f = 6.13 \text{ GHz}$ 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 $f = 7.9 \text{ GHz}$. 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 $f = 10.01 \text{ GHz}$ is 10 dBi while polarization purity (PP) is 30 dB. It may be noted that, Antenna#3 has somewhat wider radiation beam at it’s 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,

$$

\text{TABLE I}

\begin{tabular}{|c|c|c|}
\hline
Patch configuration & Simulated $f_r$ (GHz) & Computed $f_r$ (GHz) \\
\hline
Antenna#1 & 7.9 & 8.4 \\
Antenna#2 & 6.13 & 5.7 \\
Antenna#3 & 10.01 & 9.7 \\
\hline
\end{tabular}

Where, $\beta_{TM0}$ 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]

$$

\frac{\beta_{TM0}}{k_0} = \left[1 + \left(k_0 h \right)^2 \right]^{1/2}

(12)

$$

Therefore, it yields that, for designing surface wave eliminated antenna or RSW antenna, the required patch radius is $a_2 = 8.8 \text{ mm}$ with patch area of $243.28 \text{ mm}^2$. Contrarily, the present patch area is $190 \text{ mm}^2$. 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 $f = 6.13 \text{ GHz}$ 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 $f = 7.9 \text{ GHz}$. 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 $f = 10.01 \text{ GHz}$ is 10 dBi while polarization purity (PP) is 30 dB. It may be noted that, Antenna#3 has somewhat wider radiation beam at it’s 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,
\[ \mathbf{\vec{p}} = j \omega \mathbf{\vec{P}} \]  
(13)

Where,
\[ \mathbf{\vec{P}} = (\varepsilon_r - 1) \varepsilon_0 \mathbf{E} \]  
(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 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.

![Effect of polarization current in horizontal radiation at E plane.](image)

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

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.

**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

\[ f_r = \frac{1}{2 \pi \sqrt{LC}} \]  
(15)

Where approximate value of \( C \) can be the patch capacitance and may be written as

\[ C = \frac{\varepsilon_0 \varepsilon_r}{h} A_p \text{ and } L = \frac{1}{(4\pi^2 f^2 C)} \]  
(16)

![Approximate circuit model (a) Conventional CMA, (b) proposed antenna](image)

FIGURE 8. Approximate circuit model (a) Conventional CMA, (b) proposed antenna.

Now, when we insert shorting pins beneath the patch plate, an inductance \( L_j \) comes between the electrodes (patch and ground plane) of the capacitor. This \( L_j \), comes parallel to the anti-resonant circuit of patch. Also, the incorporation of shorting pins change the dielectric constant of the substrate from \( \varepsilon_r \) 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 effective 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 \( L_j \) and the new dielectric capacitance \( C_d \) can be obtained from [26], [27] as

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

and

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

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

\[ C_i = C_0 + C_d \]  
(19)

Where, \( C_0 \) is the portion of patch capacitance of Antenna#3 when dielectric is removed [27]. Hence, \[ C_i = \left[ \frac{\varepsilon_0 \pi a^2}{h} \right] + [(\varepsilon_r)_N - 1] \frac{\varepsilon_0 \pi a^2}{h} \]  
(20)

In the context of Section II D, the current through this pin inductance \( L_j \) 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

$$L_{eq} = \frac{L_1 + L_2}{L_3}$$

And the resonant frequency will be

$$f_r = \frac{1}{\sqrt{\mu_0 L_{eq} C_{eq}}}$$

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 \((\varepsilon_r)_{eff} = 1.7\) (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 \(\times 3\) mm 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 \(\times\) 50 mm (\(\approx 1.5\lambda_0 \times 1.5\lambda_0\)). 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.

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 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.

![Figure 9](image1.png)

**FIGURE 9.** Fabricated prototype (a) Top view (b) bottom view

![Figure 10](image2.png)

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

![Figure 11](image3.png)

**FIGURE 11.** Simulated and measured H and E plane radiation patterns of proposed Antenna#3

![Figure 12](image4.png)

**FIGURE 12.** Simulated magnitude of electric field at the substrate.
The variation of antenna gain as function of angle $\theta$ 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 $\pm 25^\circ$. Contrarily, this gain decrement is comparatively slower in case of H plane where the measured gain varies from 9.2 dBi to 6 dBi within $\pm 40^\circ$. 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$^\circ$ in E plane while the same for H plane is 80$^\circ$.

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-II. This confirms the consistency and superiority of the present structure over others.

**TABLE II**

| 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   | 9.2        | 27                           | 92             | 20                                                         | Simple modified CMA for reduced horizontal radiation along with high gain, excellent PP and efficiency. |

ACKNOWLEDGMENT

We thank Prof. Debashis Guha and Dr. J. Y. Siddiqui from the Institute of Radio Physics and Electronics, Calcutta University, India, for their insightful advice. We would like to thank Dr. C. Kumar, SAC-ISRO, for always encouraging our research endeavours.

REFERENCES

1. M. U. Khan, M. S. Sharawi, and R. Mittra, “Microstrip patch antenna miniaturization techniques: a review”, IET Microwaves, Antennas & Propagation, Vol. 9, No. 9, pp. 913-922, June, 2015.
2. M.A. Khayat, J. T. Williams, D. R. Jackson, and S. A. Long, “Mutual coupling between reduced surface wave microstrip antennas,” IEEE Transactions on Antennas and Propagation, Vol.48, Issue. 10, pp.1581-1593, Oct, 2000.
3. J-G. Youk, L. P. B. Katehi, “Micromachined microstrip patch antenna with controlled mutual coupling and surface waves,” IEEE Transactions on Antennas and Propagation, Vol.49, Issue. 9, pp.1282-1289, Sep. 2001.
4. Zonunmawii, A. Ghosh, L. K. Singh, S. Chattopadhyay, C-Y-D. Sim, “Reduced-Surface-Wave-Inspired Circular Microstrip Antenna for Concurrent Improvement in Radiation Characteristics”, IEEE Antenna & Wave Propagation Letter, Vol. 20, Issue 5, pp. 858-862, May. 2021.
5. A. Nehorai, and E. Paldi, “Vector-sensor array processing for electromagnetic source localization,” IEEE Transaction on Signal Processing, Vol.42, Issue 2, pp.376-398, Feb. 1994.
6. J. Li, P. Stoica, and D. Zheng, “Efficient direction and polarization estimation with a COLD array,” IEEE Transactions on Antennas and Propagation, Vol.44, Issue. 4, pp.539-547, Apr. 1996.
7. S. K. Padhi, N. C. Karma, C. L. Law, and S. Aditya, “A Dual Polarized Aperture Coupled Circular Patch Antenna Using a C-Shaped Coupling Slot, IEEE Transactions on Antennas & Propagations, Vol.51, No.12, pp.3295-3298, 2003.
8. Y. Yusuf, H. Cheng, X. Gong, “Co-designed substrate-integrated waveguide filters with patch antennas,” IET Microwaves, Antennas and Propagation, Vol.7, No.7, pp.493-501, 2013.

9. S. Kojima, N. Shinohara, T. Mitani, “Integration of a Via-Loaded Annular-Ring Reduced-Surface-Wave Antenna and a Branch-Line Coupler,” IEEE Access, Vol. 8, pp. 133645-133653, 2020.

10. S. M. Rathod, R. N. Awale, K. P. Ray, S. S. Kakatkar, “Directivity Enhancement of a Circular Microstrip Antenna with Shorting Port,” IETE Journal of Research, 2019 DOI: 10.1080/03772063.2019.1612285.

11. J.-H. Ou, J. Huang, J. Liu, J. Tang, and X. Y. Zhang, “High-Gain Circular Patch Antenna and Array with Introduction of Multiple Shorting Pins,” IEEE Transactions on Antennas & Propagations (early Access), 2020. DOI:10.1109/TAP.2020.2983793.

12. K. Xu and J. Shi, “High-efficiency dense circular dielectric patch antenna with frequency selectivity,” IET Electronic Letters, Vol. 54, No. 14, pp.861-862, 2018.

13. K. K. Naik and P. A. V. Sri, “Design of Hexadecagon Circular Patch Antenna with DGS at Ku Band for Satellite Communications,” Progress In Electromagnetics Research M, Vol. 63, pp. 163–173, 2018.

14. Md. A. K. Khan, T. A. Shaem, M. A. Alim, “Graphene patch antennas with different substrate shapes and materials,” Optik, Vol.202, 2020, DOI: 10.1016/j.ijleo.2019.163700.

15. A. Ghosh, S. K. Ghosh, D. Ghosh and S. Chattopadhyay, “Improved polarization purity for circular microstrip antenna with defected patch surface,” International Journal of Microwave and Wireless Technologies, Cambridge University Press and the European Microwave Association, UK, Vol. 8, No.1, pp. 89 – 94, 2016.

16. S. Chattopadhyay, S. Chakraborty, “A Physical Insight Into the Influence of Dominant Mode of Rectangular Microstrip Antenna On Its Cross-Polarization Characteristics and Its Improvement With T-Shaped Microstrip Antenna”, IEEE Access, USA, Vol. 6, No. 1, 2018, pp. 3594-3602.

17. D. Ghosh, S. K. Ghosh, S. Chattopadhyay, “Physical and Quantitative Analysis of Compact Rectangular Microstrip Antenna with Shorted Non radiating Edges for Reduced Cross Polarized Radiation Using Modified Cavity Model,” IEEE Antennas & Propagation Magazine, USA, Vol.56, No.4, 2014, pp. 61–72.

18. D. Guha, M. Biswas, and Y. M. M. Antar, “Microstrip Patch Antenna with Defected Ground Structure for Cross Polarization Suppression,” IEEE Antennas and Wireless Propagation Letters, vol. 4, pp. 455-458, 2005.

19. N. G. Alexopoulos, and D. R. Jackson, “Fundamental superstrate (Cover) effects on printed circuit antennas,” IEEE Transactions on Antennas and Propagation, Vo.32, Issue 8, pp.807-816, Aug. 1984.

20. S. D. Cheng, R. Biswas, E. Ozbay, S. M. C. Calmønt, G. Tuttle, and K.-M. Ho “Optimised dipole antennas on photonic bandgap crystals,” Appl. Physics Letters, Vol.67, No. 23, pp. 3399-3401, Dec. 1995.

21. R. Coccioni, T. Itoh, “Design of photonic bandgap substrates for surface wave suppression,” in Proc. MTT-S Int. Microwave Symposium Digest, Baltimore, MD, USA, 1998, pp. 1259-1262.

22. S.-J. Li, J. Gao, X. Cao, Z. Zhang, and D. Zhang, “Broadband and high-isolation dual polarized microstrip antenna with low radar cross section,” IEEE Antennas and Wireless Propagation Letters, 13, pp. 1413-1416.

23. S. J. Li, Y. B. Li, H. Li, Z. X. Wang, C. Zhang, Z. X. Gao, R. Q. Li, X. Y. Cao, Q. Cheng, and T. J. Cui, “A thin self-feeding janus metasurface for manipulating incident waves and emitting radiation waves simultaneously,” Annalen der Physik, vol. 532, no. 5, pp. 1-13, 2020.

24. High Frequency Structure Simulator; HFSS v.14. Pittsburgh, PA, USA, Ansoft Corporation, 2014.

25. R. Garg, P. Bhartia, I. Bhal, and A. Ittipiboon, Microstrip Antenna Design Handbook. Norwood, MA, USA: Artech House, 2001

26. F. E. Terman, “Electronic and Radio Engineering,” McGraw Hill, Singapore, 1955

27. M.M. Nikolic, A.R. Djordjevic, A. Nehorai, “Rectangular Microstrip Antenna with Suppressed Radiation in Horizontal Direction and Reduced Coupling,” IEEE Transactions on Antennas and Propagation, Vo.53, No. 11, pp. 3469-3476, 2005.

---

**Zonumnaawii** was born in 1988. She received the B.E. degree in Electronics and Communication Engineering from Dr. Ambedkar Institute of Technology, Bangalore, India in 2010, and M. Tech in Electronics and Communication Engineering from Lovely Professional University, Punjab in 2012. She is currently working as an Assistant Professor in the Department of Electronics and Communication Engineering, Mizoram University (A Central University, Govt. of India), Mizoram, India. She has more than 7 years of experience in teaching. She is currently pursuing the Ph.D. degree in Electronics & Communication Engineering at Mizoram University, Mizoram, India. Her research interest includes the characterization of microstrip antenna of different shapes, shorted patch antenna etc.

**Abhijyoti Ghosh** currently working as an Assistant Professor in the Department of Electronics and Communication Engineering, Mizoram University (A Central University, Govt. of India), Aizawl, Mizoram, India. Before joining Mizoram University, he served at Department of ECE, Siliguri Institute of Technology, West Bengal as faculty member. He has done his B.E. (Electronics & Telecommunication Engineering) from North Maharashtra University in 2005, M.Tech. (Mobile Communication and Network Technology) from West Bengal University of Technology, Kolkata, West Bengal, in 2007 and Ph.D. (Tech.) from National Institute of Technology, Silchar, India in 2019. His area of research includes microstrip and integrated antennas, defected ground structures, computer aided design of patch antennas and signal processing. He regularly serves as the reviewer of IEEE Antennas and Propagation Magazine, International journal of RF and Microwave Computer Aided Engineering, Wiley, IEEE Access, and many more. He has more than 50 publications in referred international journals, international and national conferences. He has contributed in several chapters in different edited research hand books also. He is Life Member of Indian Society for Technical Education (ISTE), member, International Association of Computer Sciences & Information Technology (IACSIT), Singapore.
Lourembam Lolit Kumar Singh is presently working in the Dept. of Electronics & Communication Engg., Mizoram University (A Central University, Govt. of India), Mizoram, India as Professor. Before joining to Mizoram University, he worked in the Dept. of Electronics and Communication Engg., NERIST, Nirjuli, Itanagar from 2001 to 2010 as Assistant Professor. He obtained B.E (Electronics & Telecommunication Engg.) from B.N. College of Engg., Pusad (Amravati University) Maharashtra in 2000, M.E (Electronics & Telecommunication Engg.) from Jadavpur University, Kolkata in 2008 and pursuing Ph.D in Jadavpur University, Kolkata. He has published more than 20 research articles in refereed journals and conferences. His present area of interest is Microstrip Antennas. He is member of the Institution of Electronics & Telecommunication Engineers (IETE), Associate member of Institutions of Engineers (IE), Life Member of Indian Society for Technical Education (ISTE).

Sudipta Chattopadhay received his B.Sc (Physics Honours) from University of Calcutta and did B.Tech, M. Tech and Ph.D from Institute of Radio Physics and Electronics, University of Calcutta in 1999, 2001, and 2011, respectively. Since then he started his independent research in the field of Antenna Engineering. He is currently working as Professor at Department of Electronics and Communication Engineering, Mizoram University (A Central University, Govt. of India), Mizoram, India. Before joining Mizoram University, he served Siliguri Institute of Technology, West Bengal, India for 16 years as faculty member. His area of research includes microwave antennas, microstrip and integrated antennas, defected ground structures, and computer aided design of patch antennas.

He regularly serves as the reviewer of IEEE Antennas and Propagation Magazine, IEEE Transactions on Antennas and Wireless Propagation, IEEE Antennas and Wireless Propagation Letters, IET Microwave Antennas and Propagation Journal, UK, International journal of RF and Microwave Computer Aided Engineering, Wiley, International journal of Microwave and Wireless Technologies, Cambridge and also for Taylor and Francis Journal. He has more than 80 publications in refereed international journals and international conferences. He has contributed in several chapters in different edited research hand books and also worked as sole Editor in the hand book of “Trends in Research on Microstrip Antenna”.

His research and formulations are cited in different Research Hand books as well as in well-known undergraduate text book of “Antennas and Wave Propagation” by J. D. Kraus et. al, 4th Edition, Tata Mc Graw Hill. He is an Associate Editor of IEEE Access, Wiley journal- International journal of RF and Microwave Computer Aided Engineering. He is listed in Marquis Who’s Who in the World, USA, 26th Ed, 2009 and also listed in 2000 Outstanding Intellectuals of the 21st Century, UK, 2010.