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Quasi-Planar Composite Microstrip Antenna: Symmetrical Flat-Top Radiation With High Gain and Low Cross Polarization

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ABSTRACT In this paper, a quasi-planar composite microstrip antenna consisting of a single layer rectangular microstrip antenna along with two metallic posts (monopoles) has been studied theoretically and experimentally. The proposed antenna exhibits wide, symmetrical radiation (around 145°) in both principle planes, along with flat-top radiation in the entire bore sight region (72° along with bore sight) with high gain (8.5 dBi) and significantly low cross polarized radiation. More than 26 dB co-cross polarization isolation over an entire broadside direction is obtained. The present structure is very simple and easy to manufacture. The present investigation provides an insightful, visualization-based understanding of concurrent improvement of the radiation characteristics.

INDEX TERMS Cross polarization, flat-top radiation, microstrip antenna.

I. INTRODUCTION

In the present wireless world, with the expeditious growth of modern wireless communication, tiny antennas with wide beam, symmetrical radiation pattern, high gain and low cross-polarization are in the present research spotlight. Further, antennas with flat-top radiation pattern are in demand for ubiquitous wireless communication services, in base station for mobile communication and as efficient feeds for parabolic reflectors for the sake of uniform aperture illumination [1]–[6]. In fact, antennas with flat-top radiation pattern provide stable maximum gain along bore sight to improve signal strength within service coverage area [1]–[6].

RECTANGULAR MICROSTRIP ANTENNA (RMA) is a very much popular genre of tiny printed antennas for its light weight, small size with low fabrication cost. In general, linearly polarized (LP) RMA generates asymmetric radiation pattern along its broadside with relatively wider E-plane beam-width than the H-plane beam-width [7]. For instance, the E-plane beam-width of a RMA (fabricated on PTFE substrate with $\varepsilon_r = 2.33$) is around 80° while the same in H-plane is only 60°[7]. A conventional RMA does not possess a flat-top radiation pattern. Furthermore, RMA suffers from very poor co-polar to cross-polar radiation isolation (CP-XP isolation) particularly in its H-plane; the typical CP-XP isolation in the H-plane is around 8-10 dB at X band [7]. Also, RMA has poor gain (around 4-6 dBi).

In wide-angle scanning phased array applications, antenna with wide beam-width is preferably required [8]. Also, wide and symmetrical radiation pattern is always preferred in a point-to-multipoint wireless communication system. Although, RMA is an attractive contender for such applications, the narrow H-plane beam-width with asymmetrical 3D radiation pattern puts a major drawback in its use. A wide beam composite RMA configuration was reported in [9] with 88° and 64° 3 dB beam-width in E-plane and H-plane, respectively. However, the structure is complex to fabricate because of composite nature of dielectric which limits practical use. A shorted comb shaped antenna proposed in [10] exhibited around 100° 3 dB beam-width but suffered from the feeding problem and the maximization of the patch size for a resonant frequency. Moreover, the antenna exhibits asymmetric radiation patterns with respect to $\theta = 0°$ line which limits its use in practical applications. A two-layer stacked patch

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structure reported in [11] exhibits symmetrical radiation pattern in E and H planes with 60° beam-width in both planes. However, because of the stacking, the structure became bulky with no improvement in XP performance [11]. Earlier, non-planar microstrip-monopole antenna topology was reported in [12], where four finite height metallic rods were integrated with a circular microstrip antenna to achieve only broad 3 dB beam-width (170°) and circular polarization. The antenna structure reported in [12] is basically a composite antenna made up of cylindrical rods (monopole antenna) integrated with circular microstrip antenna. Any improvement in CP-XP isolation is not apparent [12]. Furthermore, none of the antennas reported in these works [8]–[12] exhibit flat-top radiation pattern.

Recently, a few research results have been reported on flat-top radiation pattern from antennas. Around 60° flat-top radiation pattern with 28 dB CP-XP isolation with 7.9 dBi gain has been obtained from LP double shell lens antenna in [1]. Four element linear and 8×8 planar array LP antenna have been proposed in [2], [3] to obtain 46° and 20° flat-top radiation pattern with side lobe level −20 dB and −15 dB respectively. The 3 dB beam-width in [2] is 60° in the principal planes. The techniques to develop flat-top radiation pattern and pencil beam have been discussed in [4]. Circular polarized array antenna with flat-top radiation pattern and dual patch with flat gain have been reported in [5], [6]. However, the angular range of flat-top sector is very small, and antenna structures are complex and expensive to fabricate [5], [6]. Additionally, the studies on symmetry in radiation patterns, broadening of beams and CP-XP isolation are not apparent from these works. It is also observed that flat-top radiation was achieved from non-planar antennas, high-profile antennas or volumetric antennas [1]–[6]. More importantly, no effort has been reportedly made to achieve flat-top radiation pattern from a simple, single element RMA. Also, the physics behind achieving flat-top radiation pattern have not explored in all these works.

Improved CP-XP isolation is very much required over wide angular range in numerous applications [7]; for instance, it is an issue of vital relevance in the design of fully polarimetric synthetic aperture radars for convenient polarimetric data calibration and in maritime surveillance applications [13], as well as in dual-polarized hybrid antenna array for 5G communication MIMO operation [14]. The widespread techniques for achieving good CP-XP isolation (around 22-30 dB) in LP antennas are employment of defected ground structures (DGS) [15], defected patch structure (DPS) [16] and shorted patch technique [17]. In recent years, DGS has been widely used in a number of applications for instance in designing RFID tag [18] and band pass filter [19]. However, DGS and DPS integrated RMAs experience complexity in probe feeding in view of the difficulty in placing the slots either on the ground plane or on the patch surface. Enhanced back radiation from such DGS structures is a severe limitation in wireless communication. Shorted patch technique conflicts with the miniaturization as the operating frequency increases thereby making it non-attractive for miniaturized wireless systems. Furthermore, the antennas proposed in these reports emphasizing only on CP-XP isolation [15]–[17] did not exhibit wide, symmetrical, flat-top radiation pattern.

The composite and non planar antennas such as magneto-electric dipole antennas [20], horn antenna integrated microstrip antennas [21], lens integrated microstip antennas [1], microstrip monopole antenna loaded with metamaterial superstrate [22], 3D printed fractal antenna [23] are very much popular and widely investigated in the recent years. Nevertheless, in some cases such as in surveillance application and satellite communication where, the user defined stringent performance criteria are to be met, antenna of one type is really difficult to meet the requirement. Therefore, two different types of structures with different characteristics may be employed which lead to a composite volumetric antenna structure. For instance, a microstrip antenna integrated with biconical antenna can be used in satellite digital multimedia broadcast [24]. In order to alleviate the lacunae of the earlier works and further to take care of the improvement of complete radiation performance, i.e., for improving the symmetry in radiation pattern, achieving flat-top radiation pattern in principal planes, widening 3 dB beam-width, and improving gain and CP-XP isolation in both the principal planes; in the present work, a simple, quasi-planar composite microstrip antenna (QPCMA) consisting of a single element RMA along with two metallic posts (monopoles) is proposed (Fig. 1). Around 90° of 3 dB beam-width in both the principal planes have been achieved from the proposed QPCMA. The novelty of the work is that the proposed antenna exhibits wide beam-width with 145° symmetry in radiation pattern in principal planes along with considerably high gain of 8.2 dBi (although using a FR-4 substrate) and around 26 − 40 dB CP-XP isolation concurrently. Further, the present QPCMA exhibits around 70° of flat-top radiation pattern with almost no ripple. Also, the physics behind the germination of flat-top radiation pattern from the proposed QPCMA have been explored thoroughly and accurately. Therefore, this is a new technique to improve CP-XP isolation from microstrip antenna without invoking any slots in ground plane or patch surface or putting shorting pins within the structure. To the best of the authors' knowledge the present work is probably the first work where, a linearly polarized single RMA integrated with two thin metallic posts is investigated for improving radiation characteristics with an emphasis on achieving flat top radiation pattern.

II. PHYSICAL INSIGHT

A. EFFECT OF MONOPOLE HEIGHT ON IMPROVING CO-POLAR (CP) RADIATION PATTERN OF QPCMA

Following the aperture modeling technique [25], it is evident that any perturbation (like metallic post or monopole) placed at the radiating slot apertures, significantly modifies the field distribution which, in turn alters the radiation pattern of RMA. In this work, two metallic posts of 1.5 mm diameter acting like monopoles, are placed centrally near radiating

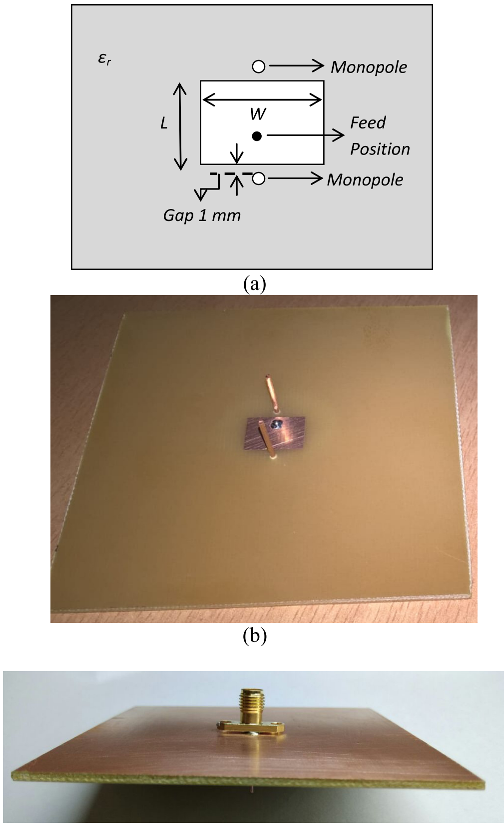

FIGURE 1. **Proposed QPCMA (a) 2-D top view schematic, (b) fabricated prototype (front-view), (c) fabricated prototype (back-view).**

edges of the patch of a RMA to realize a QPCMA (Fig. 1). These monopoles are parasitically coupled with the patch and the distance between patch edge and outer surface of the monopole is optimized to 1 mm for achieving best result. This pair of monopoles forms a linear array along the E-plane ($\phi = 0°$ plane) with inter radiator spacing $\sim\lambda_g/2$ ~9.5 mm and are excited with 180° out of phase fields from radiating edges of the patch. Hence, the array factor produces maxima along $\phi = 0°$ and 180° while, it exhibits null radiation along the H-plane ($\phi = 90°$ plane). From simulations [26], it is clear that if the monopoles are of length $\lambda_g/4 = 4.5$ mm; the monopole like radiation pattern dominates the overall CP radiation pattern of the QPCMA at E-plane (Fig. 2(a)). Hence, the peak gain in E-plane is slightly offset from the bore sight. It rolls off after the peak point (approximately around 60°) due to the composite effect of radiation from RMA with that of monopoles at E-plane.

When, height of the monopole increases to $\lambda_g/2 = 9.3$ mm; E-plane beam-width of the QPCMA becomes narrower than that of conventional RMA (Fig. 2(b)). This is expected as the radiation from $\lambda_g/2$ monopole is very less near the bore sight. However, the effect of monopole like radiation is still evident from the creation of one sided null in the CP radiation pattern of the QPCMA at E-plane. Unlike, conventional RMA, the E-plane beam-width of the QPCMA becomes narrower

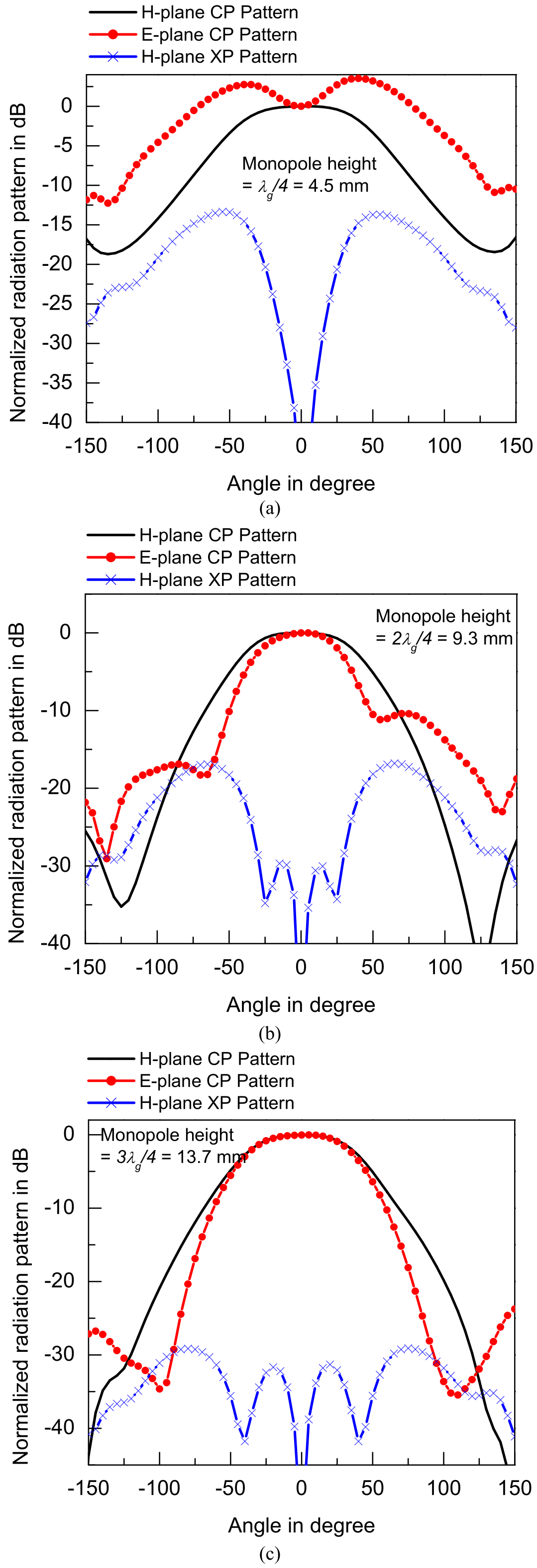

FIGURE 2. **E and H-plane radiation patterns of QPCMA for different monopole height: (a) for $\lambda_g/4$ monopole, (b) for 2 $\lambda_g/4$ monopole, (c) for 3 $\lambda_g/4$ monopole.**

at the cost of significant radiation near 90° elevation angle ($\theta = 90°$) (Fig. 2b). Unlike Fig. 2(a), the peak gain of the QPCMA at its E-plane occurs along bore sight because of the generation of very thin or pencil beam from $\lambda_g/2$ monopoles along the horizon i.e. along 90° elevations. Now, if the length of monopoles is increased beyond $\lambda_g/2$; it starts to develop certain lobes along the higher elevation angles. These lobes merge with the original E-plane radiation pattern of the RMA and broadens the overall E-plane beam-width of QPCMA. The radiation pattern of the QPCMA (Fig. 2c) shows that when, each monopole length is $3\lambda_g/4 = 13.7$ mm; it yields wide E-plane beam-width in comparison to the structure with $\lambda_g/2$ monopoles (Fig. 2b).

It may be noted that the length of monopole does not have an influence on the H-plane beam-width of the QPCMA as the array factor exhibits null radiation along the H-plane ($\phi = 90°$ plane). However, it can be observed that the H-plane beam-width of QPCMA is wider compared to that of conventional RMA. This H-plane beam-width is consistently wide for all lengths of monopole as seen from Figs. 2(a), (b) and (c). In all the cases, the H-plane CP radiation pattern becomes 40% wider (yielding 85° beam-width) than that of conventional RMA fabricated on conventional RT-Duroid or PTFE substrate with $\varepsilon_r = 2.33$.

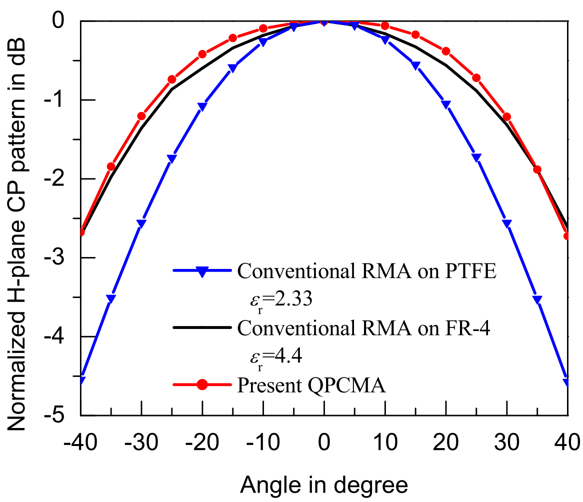

FIGURE 3. Normalized H-plane CP profile of conventional RMA with PTFE substrate ($\varepsilon_r = 2.33$), conventional RMA with FR−4 substrate ($\varepsilon_r = 4.4$) and the present QPCMA with FR-4 substrate ($\varepsilon_r = 4.4$).

In general, a RMA fabricated on higher dielectric constant (like FR-4) exhibits wider beam-width in comparison to the same fabricated on lower dielectric constant substrate (Fig. 3). Here, QPCMA structure is fabricated on higher dielectric constant substrate (FR-4). Along with the same, as the monopoles are placed near the radiating edges of the patch; it localizes more H-fields at the vicinity of the monopoles. This result into the reduction of E-fields at the vicinity of the monopole causing a non-uniform distribution of E-field along the radiating slot aperture width (contained in H-plane).Therefore, this non-uniform distribution of fields along the radiating slot aperture width (contained in H-plane of QPCMA) widens the beam-width of QPCMA more at its H-plane [9], [25]. In fact, the non-uniform distribution of field at any plane of aperture antennas results in wide beam-width at corresponding plane [27], [28].

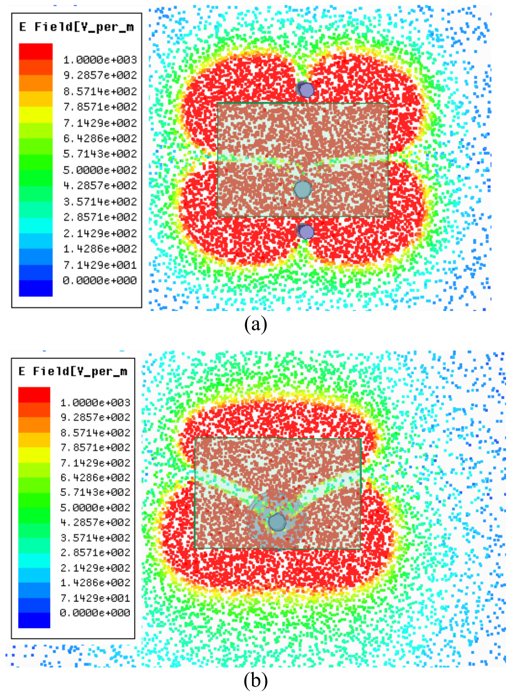

FIGURE 4. Field distribution over the substrate for (a) QPCMA with FR-4 substrate, (b) conventional RMA with FR-4 substrate.

The field distribution over the substrate for both the present QPCMA and conventional RMA with FR-4 substrate is presented in Fig. 4. This confirms the observation of this non-uniform distribution of fields along the radiating slot aperture width (Fig. 4(a)). From the figure, it may also be noted that the fringing E-fields are extended in both lateral and longitudinal directions as they are mitigated at the central region of radiating edge because of the presence of monopoles there. This effectively increases the H-plane dimension QPCMA (as fringing width ΔW increases). Therefore, the use of FR-4 substrate, the non-uniform distribution of field along the radiating slot aperture width (H plane) causes wide beam-width at the H-plane of the QPCMA.

Now, if we concentrate on the overall radiation pattern of the QPCMA structure, it is observed from Fig. 2(c) that in both the principal planes (E and H-plane), beam-widths of the structure with 3 $\lambda_g/4$ monopoles are symmetrical and significantly wide 3 dB beam-widths of 90°. Around 140° to 150° symmetry in principal E and H-planes are observed from Fig. 2(c). It is very motivating to observe that the CP radiation patterns are quite flat about 70° along the bore sight (Fig. 2(c)). Commonly, the flat-top radiation pattern can be obtained from array configuration by manipulating the amplitude and phase excitation of individual elements. This in fact increases radiation in the desired front direction while eliminates the side lobes slightly off side from the desired direction. However, in present investigation, the merging of monopole lobes at higher elevation angle with the E-plane lobe of RMA is exploited to achieve such flat-top radiation patterns. Also, the flat-top region in the radiation patterns is of all most no ripple.

B. EFFECT OF MONOPOLE LENGTH ON UPPRESSING CROSS-POLAR (XP) RADIATION FROM QPCMA

It is observed from fig. 2 that as soon as we introduce the monopoles; CP-XP isolation in the radiation pattern of QPCMA improves. In fact, these monopoles mitigate the electric fields at their vicinity and intensify the magnetic fields in the same region (Fig. 4 (a)). It results in a uniform field distribution between the lower and upper half sections of the QPCMA at its non-radiating edges (Fig. 4(a)) whereas, the field distribution is highly non-uniform between the lower and upper half sections of conventional RMA [29] (Fig.4(b)). Consequently, CP-XP isolation improves [29]. As the monopole length is increased from $\lambda_g/4$ to 3 $\lambda_g/4$; CP-XP isolation improves from 14 dB to 28 dB (Fig. 2). Following the current distribution of the monopole, it may be noted that the magnetic field near the base of monopole is maximum for monopole length of odd multiple of $\lambda_g/4$ than monopole length of even multiple of $\lambda_g/4$. Hence, the electric fields are not too less at the vicinity of the monopoles in case of the structure with $\lambda_g/2$ length.

TABLE 1. Radiation properties of the QPCMA with different monopole heights: Patch length $L = 8$ mm, width $W = 12$ mm, substrate permittivity $\varepsilon_r = 4.4$, substrate height $h = 1.58$ mm.

Electrical length of monopole	E-plane 3 dB beam-width	H-plane 3 dB beam-width	CP-XP isolation in dB	Symmetry in principal planes	Flat-top range in the beam
$2\lambda_g/4$	70^0	86^0	17	30^0	45^0
$2.3\lambda_g/4$	74^0	86^0	21	40^0	50^0
$2.5\lambda_g/4$	78^0	88^0	25	60^0	60^0
$2.7\lambda_g/4$	82^0	87^0	28	95^0	68^0
$3\lambda_g/4$	90^0	90^0	26	145^0	72^0

It, in turn, cannot produce a uniform field distribution between the lower and upper half sections of QPCMA at its non-radiating edges [29] and hence, CP-XP isolation does not improves. The effects of increasing the length of monopoles beyond $\lambda_g/2$ on the overall radiation properties (Table-I); corroborates the observed phenomenon. As the height of monopole increases gradually from $\lambda_g/2$ to 3 $\lambda_g/4$; base feed current increases and hence the magnetic fields near the base of monopole increases. Therefore, electric field reduces at the vicinity of the monopole at the cost of increased electric fields at the upper patch corners which, improves the CP-XP isolation [29]. Moreover, the excellent symmetry between the E and H-plane radiation patterns for the QPCMA with monopole length 3 $\lambda_g/4$ is also the reason for improved CP-XP isolation.

C. EFFECT OF MONOPOLE SPACING ON CP AND XP RADIATION PATTERNS OF QPCMA

In the present QPCMA structure, the monopoles are placed at close proximity of the radiating edges. This is done with a view to couple the fields efficiently from radiating edges

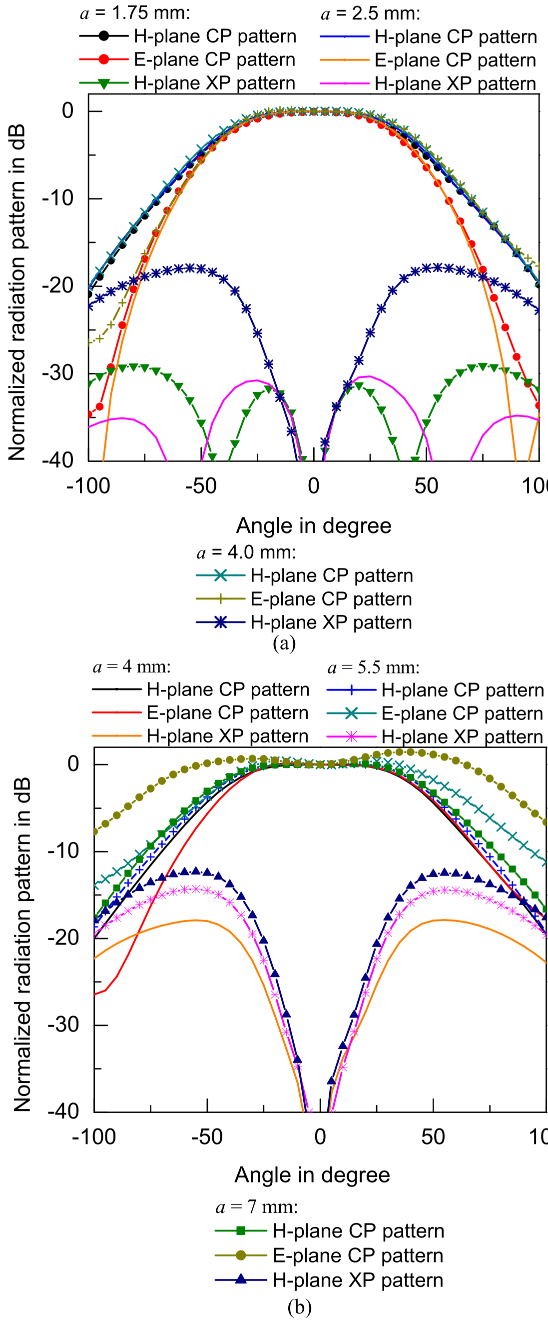

FIGURE 5. Normalized radiation pattern of the present QPCMA for different spacing (*a* values) between monopole and the radiating edges of RMA.

of the patch to the monopole. The distance from the post surface to radiating edge is 1 mm i.e. the distance from each radiating edge to centre of each post is $a = 1.75$ mm. This yields an asymmetric distribution of fields along radiating slot aperture width (Fig. 4(a)) and uniform field distributions between lower and upper half section of patch which causes wide symmetrical flat-top radiation patterns in conjunction with low XP radiation in the present QPCMA structure with monopole length 3 $\lambda_g/4$ as discussed elaborately in section II A and II B.

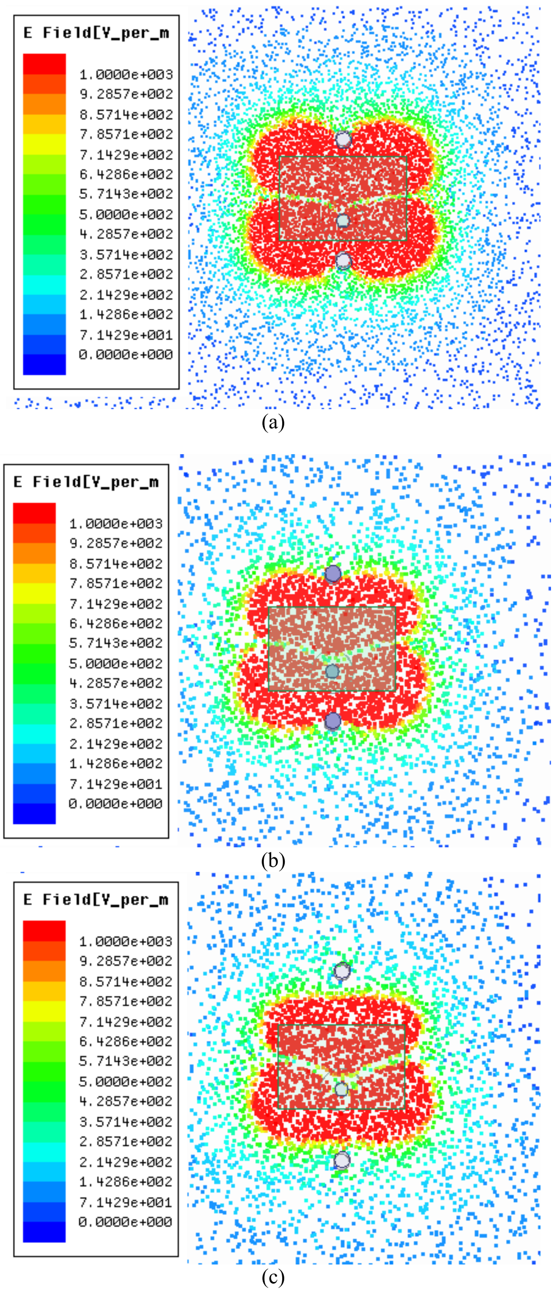

FIGURE 6. **Field distribution over the substrate for QPCMA with (a) $a = 2.5$ mm, (b) $a = 4$ mm, (c) $a = 5.5$ mm.**

Now, if we increase the distance of monopole from the radiating edge of patch i.e. if a increases, initially, the radiation patterns does not degrade much. However, significant distortion is noted in the radiation pattern for higher values of a. The radiation patterns for QPCMA for different a values are depicted in Fig. 5. It is found that if the monopoles are at a distance $a = 2.5$ mm, there is no significant change in radiation patterns of the QPCMA. Hence, the QPCMA with $a = 2.5$ mm, also exhibits high-gain symmetrical, wide beam-width and flat-top radiation pattern with low XP radiation. This is because of the extension of fringing fields at patch radiating edges which, efficiently couples the fields to the monopoles. Hence, this extended fringing fields interact with the monopoles in a similar manner (like $a = 1.75$ mm) which in turn cause no change in radiation characteristics of QPCMA. The magnitude of electric field distribution is depicted in Fig. 6(a) for the QPCMA with $a = 2.5$ mm is to a certain extent similar to that of the QPCMA with $a = 1.75$ mm (Fig. 4(a)).

Next, as we increase the separation (increase a values), radiation pattern of QPCMA particularly in the H-plane XP starts to degrade significantly. The radiation pattern of QPCMA for $a = 4$ mm, incorporated in the same plot (Fig. 5(a)) shows noteworthy increase in H-plane XP radiation and hence fails to improve the CP-XP isolation. Close inspection of Fig. 5 also shows some asymmetry between the E and H-plane CP patterns of QPCMA in case of $a = 4$ mm. It is found that the E and H-plane CP patterns of QPCMA are symmetric in right side while the same is not true in the left side of the radiation pattern plot. The magnitude of electric field distribution is depicted in Fig. 6(b) for the QPCMA with $a = 4$ mm. Although, an asymmetric distribution of fields along radiating slot aperture width is maintained to some extent, still there is an asymmetry in field distribution between lower and upper half section corners of the patch which degrades the CP-XP isolation [29] of the QPCMA with $a = 4$ mm.

The radiation patterns for the QPCMA for values $a \geq 4$ mm are illustrated in Fig. 5(b). It is found that for higher values of a (=5.5 mm or 7 mm), the QPCMA exhibits the radiation pattern like conventional RMA. This is expected because the monopoles are far away from radiating edges and hence the extended fringing fields cannot interact with the monopoles. Therefore, the composite effect on radiation pattern of QPCMA is not apparent. The E-field magnitudes in case of QPCMA with $a = 5.5$ mm is portrayed in Fig. 6(c) which is similar to conventional RMA (Fig. 4(b)) and confirms the observations.

Hence, the monopoles of length $3\,\lambda_g/4$ are placed at close proximity ($a = 1.75$ mm) to the radiating edge of the patch for obtaining best performance for further investigations.

III. THEORETICAL LOOK INTO FLAT-TOP RADIATION AND HIGH WIDE ANGLE GAIN

A. FLAT-TOP RADIATION

It is clear from Section II A that the $3_{\lambda g}/4$ monopole has a critical influence in the overall E-plane radiation pattern of QPCMA. On the contrary, the H-plane beam-width of QPCMA is already wide due to non-uniform electric field variation at slot aperture as discussed in same section IIA. Therefore, it is necessary to look into the physics behind the beam-width widening of QPCMA in its E-plane.

For a conventional RMA, $E\theta$ and $E\varphi$ components of the far-field radiation pattern can be expressed as [7]

$$[E_\theta]_{RMA} = 2\cos\phi \frac{\sin\left(k_0 W \sin\theta \sin \phi/_2\right)}{\left(k_0 W \sin\theta \sin\phi/_2\right)} \times \cos\left(\frac{k_0 L \sin\theta\cos\phi}{2}\right) \quad (1a)$$

and

$$[E_\phi]_{RMA} = 2\cos\theta \sin\phi \frac{\sin\left(k_0 W \sin\theta \sin{\phi}/_{2}\right)}{\left(k_0 W \sin\theta \sin{\phi}/_{2}\right)} \times \cos\left(\frac{k_0 L \sin\theta \cos\phi}{2}\right) \quad (1b)$$

where $W = 1.5L$; $L = \lambda_g/2$ and $k_0 = 2\pi/\lambda_g$ For a simple metallic post or monopole antenna of length l, $E\theta$ component of the far-field radiation pattern is

$$[E_\theta]_{\sin gle\_monopole} = \frac{\cos(kl\cos\theta) - \cos(kl)}{\sin\theta} \quad (2)$$

Two monopoles constitute a linear array along $\phi = 0°$ and the array factor will be

$$F = \frac{\sin(k_0 d \sin\theta\cos\phi + \delta)}{\sin\left[\frac{1}{2}(k_0 d \sin\theta\cos\phi + \delta)\right]} \text{ where } \delta = \pi \text{ and } d \cong {\lambda_g}/_{2} = 2\sin\left(\frac{\pi}{2}\sin\theta\cos\phi\right) \quad (3)$$

Hence, contribution from monopoles can be computed as

$$[E_\theta]_{monopole} = \left[\frac{\cos(kl\cos\theta) - \cos(kl)}{\sin\theta}\right] \times \left[2\sin\left(\frac{\pi}{2}\sin\theta\cos\phi\right)\right] \quad (4)$$

In E-plane, $\phi = 0°$ and in H-plane, $\phi = {\pi}/_{2}$

In case of array of two dissimilar sources, the total field pattern factor may be written as [30] for E-plane,

$$[E_\theta]_{TOTAL} = [E_\theta]_{monopole} + [E_\theta]_{RMA} \quad (5)$$

and for H plane,

$$[E_\theta]_{TOTAL} = [E_\theta]_{monopole} + [E_\phi]_{RMA} \quad (6)$$

The computed field components radiation patterns in E and H-plane show wide and flat-top radiation pattern in both planes. This is clearly due to the effect of monopole as clear from equation (4). Also, a close inspection of equation 2 reveals that when the length of monopole is greater than 3 $\lambda_g/4$, it develops higher elevation lobes which is superposed with the radiation pattern of conventional RMA and hence, the proposed QPCMA develops wide flat-top radiation pattern.

The computed E-plane pattern for conventional RMA and the present QPCMA using above equations is depicted in Fig. 7. The above analysis can also be done with the simple pattern multiplication method. However, it is not shown in this paper.

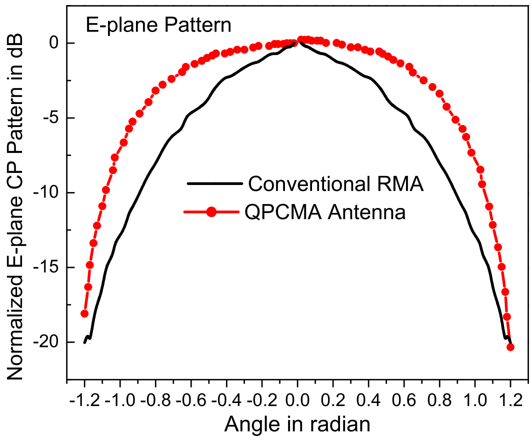

FIGURE 7. Computed E-plane pattern for conventional and present QPCMA.

B. HIGH WIDE ANGLE GAIN

The modulation of near field distribution to obtain enhanced radiation performance is a useful technique which has been currently adopted in some very recent investigations [31], [34]. In general, a RMA produces non-uniform aperture field distribution over the substrate (Fig. 4(b)). This leads to poor aperture efficiency and poor gain of such antenna [33], [34]. Unlike conventional RMA, the presence of two monopoles in case of QPCMA modulate the field distribution in such away (as discussed above) that the E-fields extend in both lateral and longitudinal directions near the corners of the patch as shown in Fig 4 (a).This in turn, results in a uniform aperture distribution over the substrate and hence the gain of the QPCMA is much improved [33], [34]. On the contrary, the field distribution of conventional RMA shown in Fig. 4(b) reveals non-uniform field distribution over the aperture and hence the aperture efficiency decreases and reveals low gain. [33], [34].

Furthermore, in QPCMA, due to the tapering of fringing fields at the central part of the radiating edges (Fig 4(a)), the fields are extended in both lateral and longitudinal directions which increase the effective fringing length ΔL and fringing width ΔW which increases the effective aperture $(L + 2\Delta L)(W+2\Delta W)$.

Therefore the gain of the QPCMA antenna [33], [34]

$$G = \varepsilon_{ap} \frac{4\pi\,(L + 2\Delta L)\,(W + 2\Delta W)}{\lambda^2}$$

increases due to the increments of ΔL, ΔW and also the aperture efficiency ε_{ap}.

Therefore, the gain of the present QPCMA configuration is high. It is also found that the present QPCMA with 2 $\lambda_g/4$monopole exhibits wide beam-width in H-plane and narrow beam-width in the E-plane.

The close look of Fig. 8 for the CP profile of the structure in both E and H-planes corroborate the observation. It is important to note that though their peak gain is high (around 8.3 dBi) and is maintained in the H-plane over wide elevation angle $\theta = -34°$ to $+34°$, E-plane gain rolls off within a few degrees (around ~22°). Hence, it is a challenging work to widen the E-plane beam-width of the antenna with stable high gain in wide angular range. As discussed earlier, the lobes of 3$\lambda_g/4$ monopole at high elevation angle ($\theta = 15°$-$45°$) (as can be obtained from equation (2)) merges with the E-plane radiation pattern of the RMA and this results in wide E-plane beam-width in the QPCMA. However, to obtain

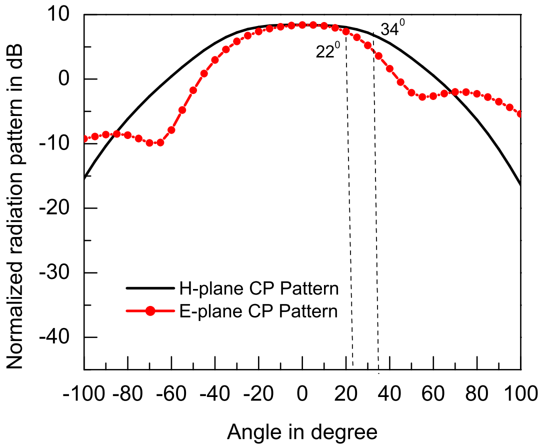

FIGURE 8. Radiation pattern of QPCMA with $a = 1.75$ mm and monopole length $l = 2\ \lambda_g/4$.

the stable peak gain over wide elevation angle (within $\theta = \pm 35°$) at E-plane, the portion of high elevation lobe (within $\theta = 22° - 35°$) of monopole array (which merges with the E-plane radiation pattern of the RMA) should have sufficient gain of around 8-9 dBi.

Now, the directive gain of a monopole at specified direction can be obtained from [28] as

$$D_{m\theta} = \frac{2f(\theta)}{\int_0^{\pi/2} f(\theta)\sin\theta d\theta} \tag{7}$$

where $f(\theta)$ is the pattern factor and can be calculated from (2) as

$$f(\theta) = \left[\frac{\cos\left({}^{3\pi}/_{2}\cos\theta\right)}{\sin\theta}\right]^2 \tag{8}$$

Now,

$$\begin{aligned}\int_0^{\pi/2} f(\theta)\sin\theta d\theta &= \frac{1}{2}\int_0^{\pi} f(\theta)\sin\theta d\theta \\ &= \frac{1}{2}\left\{\begin{aligned}&0.5772 + \ln(kl') - C_i(kl') \\ &+ \tfrac{1}{2}\sin(kl')\left[S_i(2kl') - 2S_i(kl')\right] \\ &+ \tfrac{1}{2}\cos(kl')\Big[0.5772 + \ln\left(\tfrac{kl'}{2}\right) \\ &\qquad + C_i(2kl') - 2C_i(kl')\Big]\end{aligned}\right\} \\ &= 0.883\end{aligned} \tag{9}$$

where $l' = 2l$.

Therefore,

$$D_{m\theta} = 2.27\left[\frac{\cos\left({}^{3\pi}/_{2}\cos\theta\right)}{\sin\theta}\right]^2 \tag{10}$$

Now, in E-plane, the normalized array factor of $N = 2$ elements 3 $\lambda_g/4$ monopole array can be written from (3) as

$$F_n = \frac{F}{N} = \sin\left(\frac{\pi}{2}\sin\theta\right) \tag{11}$$

Therefore, from (11), the radiation intensity can be written as

$$U = F_n^2 = \left[\sin\left(\frac{\pi}{2}\sin\theta\right)\right]^2 \tag{12}$$

In the upper hemisphere, the average radiation intensity of array of monopoles separated by a distance $d = \lambda_g/2$ is given by [28]

$$U_0 = \frac{\pi}{4Nkd} = \frac{1}{4N\frac{2}{\lambda_g}\frac{\lambda_g}{2}} = \frac{1}{4N} = \frac{1}{8} \tag{13}$$

Directive gain of the array as a function of elevation angle θ

$$D_\theta = \frac{U}{{}^1/_{4N}} = \frac{\left[\sin\left(\frac{\pi}{2}\sin\theta\right)\right]^2}{{}^1/_{4N}} = 8\left[\sin\left(\frac{\pi}{2}\sin\theta\right)\right]^2 \tag{14}$$

Therefore, overall directive gain at a particular direction (θ) in case of array of monopoles can be written as

$$D = D_{m\theta}D_\theta = 18.16\left[\frac{\cos\left({}^{3\pi}/_{2}\cos\theta\right)}{\sin\theta}\right]^2\left[\sin\left(\frac{\pi}{2}\sin\theta\right)\right]^2. \tag{15}$$

Hence, using above equation (15), the overall gain of the monopole array in the angular region $\theta = 22°$ to $34°$ varies from 8 dBi to 11 dBi.

Therefore, the monopole array has sufficient gain in the angular region 22° to 34° where, the E-plane gain of the RMA rolls off. This merges with the E-plane radiation pattern of RMA resulting in stable wide angle gain in case of present QPCMA.

C. INVESTIGATION OF THE PERFORMANCE OF THE QPCMA WITH LOW LOSS SUBSTRATE

Conventional RMA at high frequency is significantly vulnerable to losses and hence, the use of a substrate with high loss tangent is usually not preferred. Consequently, to examine the validity of the present QPCMA in low loss substrate, the antenna has been designed on RT-5870 at X band and the radiation pattern is illustrated in Fig. 9. It is found that the gain of the QPCMA with RT-5870 increases by 1.2 dB compared to the same with FR4 substrate. In fact, the antenna gain enhances with lower dielectric constant substrate [34] because the E-fields are loosely bound to the substrate which contributes in CP radiation. This may be attributed for higher gain of QPCMA with low loss substrate. On the contrary, as the E-fields are loosely bound to the substrate, it contributes in XP radiation also and hence XP radiation increases. However, around 25 dB of CP-XP isolation is revealed for QPCMA with RT−5870 substrate. It may also be noted from Fig. 9 that the QPCMA exhibits symmetry in radiation patterns of around 110° in principle planes with 69° flat-top regions. The QPCMA with RT- 5870 at X-band

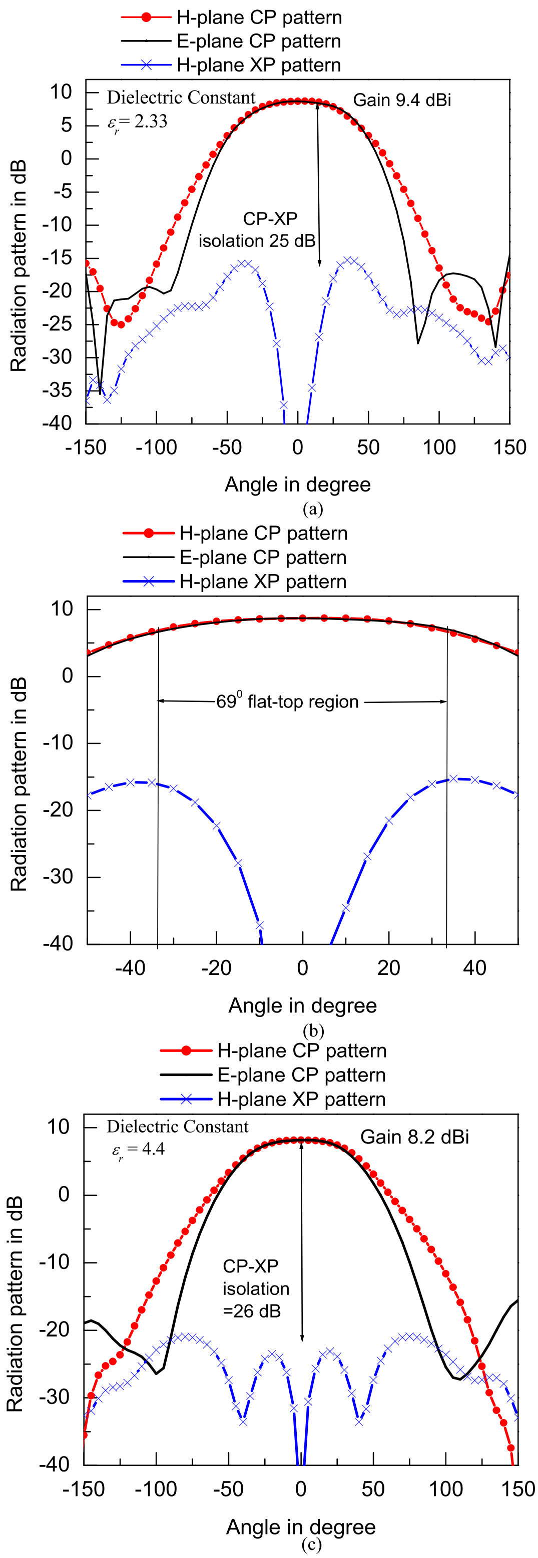

FIGURE 9. **Simulated radiation pattern of QPCMA with different substrate (a) low loss substrate (RT-Duroid, $\varepsilon_r = 2.33$), (b) same as (a) to depict the flat-top region, (c) low loss substrate (FR-4, $\varepsilon_r = 4.4$).**

also exhibits wide 3 dB beam-width of 89° which is similar to the same with FR-4 substrate. Therefore, it may be concluded that the QPCMA works well with both the low loss and high loss substrate except some degradation in peak gain for high loss substrate.

In general, the FR-4 substrates are used up to 1-2 GHz. In fact, the dielectric loss tangent increases with frequency in most of the cases. However, the loss tangent of FR-4 is typically constant from 1 to 10 GHz [35]. Therefore, to manufacture low cost antenna, FR-4 may be used by sacrificing gain of the antenna. Furthermore, it may be noted that for such substrate, the gain may be low, but it has lower XP radiation and definitely the wide beam-width.

IV. RESULTS AND DISCUSSIONS

A. PROPOSED STRUCTURE

First, a RMA with dimension $(L \times W) = 7.8 \times 12$ mm^2 has been fabricated on grounded FR-4 dielectric substrate with dimension is 90 mm × 90 mm (5 λ_g × 5 λ_g) ($\varepsilon_r = 4.4$, height $h = 1.58$ mm) (fig. 1). The antenna has been fed at 2.1 mm from the centre of the patch. Then, two grooves of diameter 1.5 mm have been cut in the substrate at the central part of radiating edges at a distance of 1 mm from the respective edges. Two conducting copper sticks of length $3\lambda_g/4$=13.5 mm and diameter 1.5 mm are inserted through grooves resulting in proposed QPCMA (fig. 1b, 1c).

B. MEASURED RESULTS

The measured results obtained for the proposed QPCMA prototype have been documented in this section. The resonant frequency of the proposed QPCMA is 8.04 GHz with around 7% impedance bandwidth (from 7.8 GHz to 8.3 GHz) (Fig. 10).

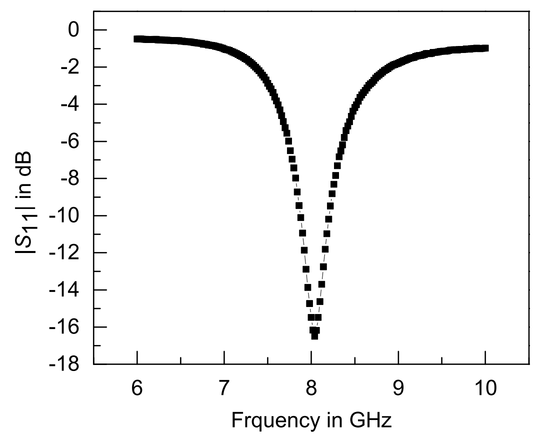

FIGURE 10. **Measured reflection coefficient profile of the proposed QPCMA.**

Fig. 11 shows the H and E-plane radiation patterns of the proposed QPCMA along the bore sight at two frequencies within its operating band. The H-plane XP radiation pattern is plotted in the same figure. There is no significant change in E-plane XP radiation. Therefore, we refrain from giving E-plane XP radiation pattern in the manuscript for brevity. The measured 3-dB and 10-dB beam-width of the QPCMA are around 90° and 125°, respectively in both the principal

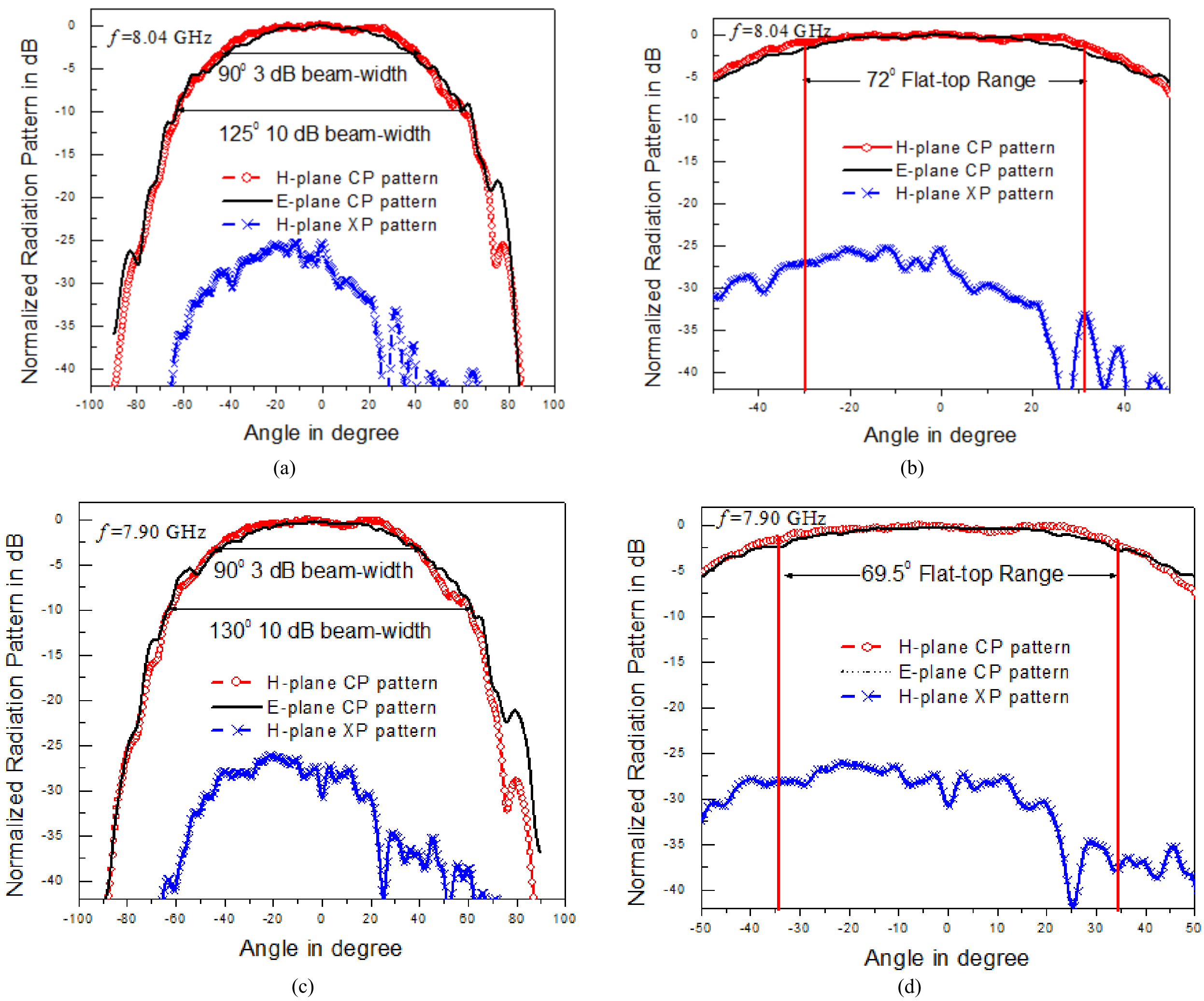

FIGURE 11. **Measured E and H-plane radiation patterns for QPCMA at different frequency. (a) Complete pattern at f = 8.04 GHz, (b) flat-top region at f = 8.04 GHz, (c) complete pattern at f = 7.9 GHz, (d) flat-top region at f = 7.9 GHz.**

planes at centre frequency f =8.04 GHz. The H-plane beam - width has been broadened by 50% while the same for E- plane is 13% compared to that of a conventional RMA. Around 145° symmetry in measured E and H-plane radiation patterns is clearly found from fig. 11 (a) and (c) at two frequencies in its operating band. The proposed QPCMA exhibits flat-top radiation in the entire bore sight region. At each frequency, the close view of the flat-top portion in the radiation patterns in the E and H planes is portrayed in figs 11 (b) and (d). Around 70° flat-top in the radiation pattern is revealed from the QPCMA in all the frequencies of operation with almost no ripple. The simulated and measured gain of the proposed QPCMA (fabricated on a grounded FR-4 substrate with $\varepsilon_r = 4.4$, height $h = 1.58$ mm) are 8.7 dBi and 8.2 dBi, respectively whereas, the measured gain of a conventional RMA is 4.5 dBi. The measured gain of the proposed QPCMA is reasonably stable and varies from 7.95 dBi to 8.2 dBi in the whole band and the peak CP-XP isolation is in the range of 26-40 dB in the whole operating band. Therefore, around 14-18 dB improvement in suppression of XP radiation is revealed from the proposed QPCMA than that of a conventional RMA. In order to examine the stability of peak gain and the polarization purity of the proposed QPCMA as a function of frequency, the measured values of these are presented in Fig. 12. It shows that the gain of the QPCMA is quite stable and varies from 7.95 dBi to 8.2 dBi in the whole band. On the contrary, minimum CP-XP isolation is in the range of 26-27 dB in the whole operating band.

In general, a conventional RMA with small ground plane generates symmetry in radiation patterns in E and H-planes. This symmetry in radiation patterns deteriorates with increase in ground plane dimensions. On the contrary, in case of QPCMA, the symmetry in radiation patterns have been achieved in large ground plane. This is evidently an advantage of this antenna in some practical applications where, the large device body is considered as ground plane. Therefore, the

TABLE 2. Comparison between radiation properties of the QPCMA with conventional RMA and earlier reported works.

References	Antenna type	Gain (dBi)	H-plane 3 dB beam width	E-plane 3 dB beam width	Symmetry between radiation patterns in principal planes	Peak CP-XP isolation in dB	Flat-top range in the radiation patterns	Remarks
-	Conventional RMA ($\varepsilon_r = 4.4$)	4.5	65^0	70^0	-	16	-	Planar structure
[1]	Double shell lens antenna fed by aperture coupled microstrip antenna		80		-	28	80^0 in H-plane, 60^0 in E-plane,	Volumetric antenna, ripple in flat-top region
[2]	Switched beam microstrip antenna array	16.6	56^0	5^0		25	46^0	Quasi planar antenna array
[5]	Circularly polarised bow tie array	>11.8	60^0	30^0		25	30^0 in E-plane	Quasi planar antenna array
[9]	Composite dielectric loaded RMA	7	64^0	88^0	-	17	-	Quasi planar structure
[12]	Circularly polarised microstrip monopole antenna	3.5	137^0	156^0	130^0	-	-	Quasi planar structure
[15]	Slot type DGS integrated RMA	-	55^0	60^0	-	25	-	Planar structure
[17]	Shorted RMA	7.5	60^0	70^0	-	27	-	Planar structure
[29]	T-shaped microstrip antenna	6.11	56^0	-	-	21	-	Planar structure
-	Present QPCMA	8.2	90^0	90^0	145^0	26	72^0 in both E and H-plane	Quasi planar structure

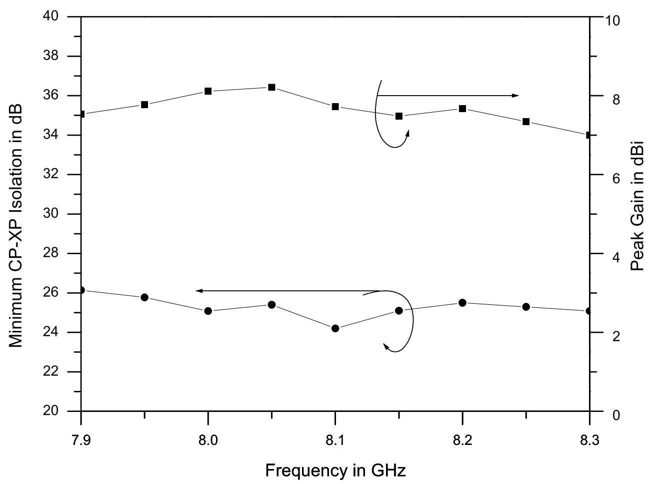

FIGURE 12. Measured gain and minimum CP-XP isolation as a function of frequency for QPCMA.

proposed QPCMA shows 7% impedance band width, wide-beam flat-top radiation pattern with 145° symmetry in principle planes with high gain (8.2 dBi) and improved CP-XP isolation (26-40 dB along wide elevation angle). The performance of QPCMA is compared with conventional RMA designed on FR-4 substrate ($\varepsilon_r = 4.4$) and earlier reported works in Table-II. It is apparent that the proposed QPCMA exhibits wide beam-width with 145° symmetry in radiation pattern in principal planes along with considerably high gain of 8.2 dBi (although using a FR-4 substrate) and around 26-40 dB CP-XP isolation concurrently. Additionally, the present QPCMA exhibits around 70° of flat-top radiation pattern with almost no ripple.

V. CONCLUSION

A compact QPCMA is proposed for high gain, flat-top, wide beam-width, symmetrical radiation pattern with excellent CP-XP isolation. The concurrent improvement of all the radiation properties with such low profile structure is absolutely new in the field of microstrip radiator till date. The reasons for the improvement in each parameter are thoroughly investigated, analyzed and documented in the present paper for insightful exploration of the structure. The proposed structure is extremely simple and trouble-free to construct.

The proposed antenna structure will surely be helpful for antenna community and find potential applications in the fields of modern wireless communications.

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