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A Way to Address Inherent Weakness in Conceiving the Ground Plane Geometry for a Microstrip Antenna

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ABSTRACT This work presents an insight into the nature of ground plane (GP) current of a microstrip patch which is truly adverse in terms of generating cross-polar (XP) fields and minimally contributing to the primary radiation. This study also uses a theoretical basis in exploring a simple solution to mitigate the high XP values, specifically over the diagonal planes (D-planes). This actually turns out to be an engineered GP by clipping off its four corners. This has been thoroughly studied for a set of representative patch geometries and experimentally verified. A consistent XP reduction by 12-13 dB over D-planes has been ensured without affecting the impedance matching or antenna gains. This eventually results in cross-polar discrimination (XPD) of the order of 25-31 dB uniformly over the full range of operating bandwidth. In addition, the design is advantageous in terms of reduction in antenna size or the deployment area. Such a simple low-cost design appears as truly improved alternative to a typical standalone microstrip radiator for practical applications.

INDEX TERMS Polarization purity, diagonal plane radiation, microstrip antenna.

I. INTRODUCTION

MICROSTRIP patch suffers from high cross-polarized (XP) radiations [1] across its orthogonal ($\varphi = 90°$) and diagonal ($\varphi = 45°$) planes, peaking over the diagonal axes [2], [3], [4], [5]. Most of the research addressed $\varphi = 90°$ plane using different techniques such as balanced feed [6], [7], Electronic Band Gap (EBG) [8], [9], or defects on the ground planes [10], [11], [12]. Bulky shaped ground was also tried [13], [14] for the same. Orthogonal higher modes are the known XP sources which were intelligently maneuvered by the above techniques. But they cannot help in reducing XP over the diagonal planes (D-planes). Linearization of surface current by ground plane (GP) engineering was reported recently as D-plane XP measure [15], [16].

Noticeably, all of them overlooked yet another feature in the GP surface current, which also can help in a simpler way. The size of the GP indeed is a factor that controls the antenna gain, both co-polar (CoP) and XP levels. Smaller GP ($< 0.7\lambda$) results in lower XP but at the cost of lower gain and higher back radiation. But a practical design typically targets in the maximum achievable gain. It requires a moderately large GP ($\sim \lambda$) [17] which in turn cause proportionately high XP.

This work indeed identifies some adverse GP current distribution which never helps the primary radiation, rather in contrast causes derogatory effects. This investigation also applies a theoretical insight to explore a useful solution to improve an optimum gain antenna design by reducing the acute D-plane XP issues. This eventually leads to a profiled GP which is simple to realize without any rigorous calculation or mechanical processes. This, indeed, is the most attractive and useful aspects of this work.

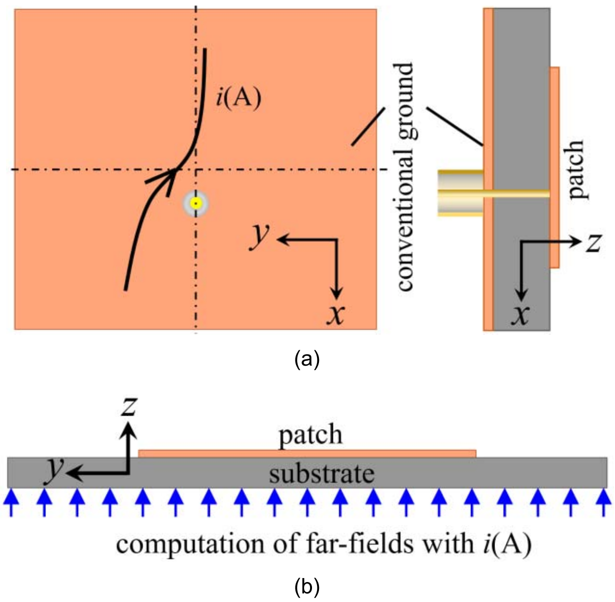


FIGURE 1. **(a) Schematic representation of the conduction current on a conventional ground, (b) the source current *i*(A) applied to an identical patch-substrate configuration.**

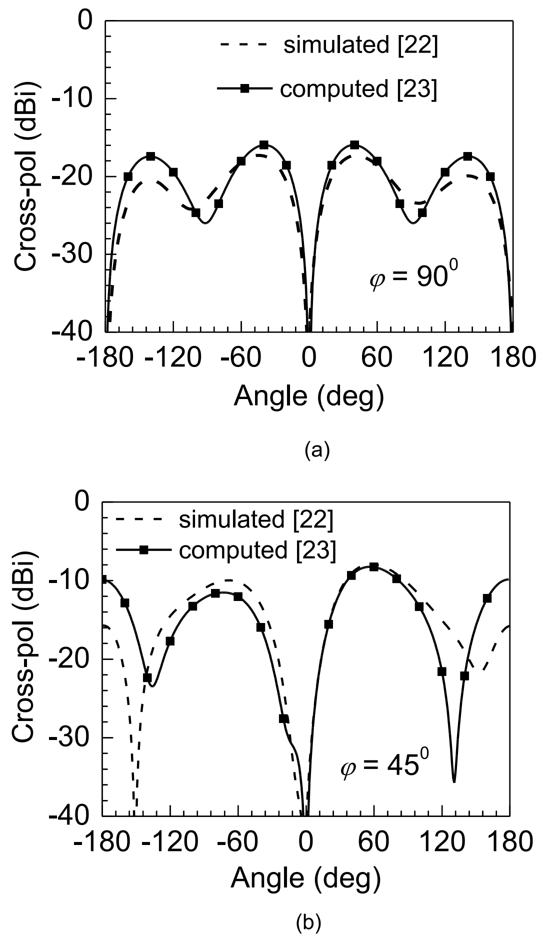


FIGURE 2. **Simulated and computed cross-polar radiation over (a) H-plane, (b) D-planes of a typical S-band rectangular microstrip patch.**

The present demonstration is actually a proof of concept which uses two representative geometries, e.g., rectangular and circular patches in S- and C-bands, respectively. About 12-13 dB reduction in XP level across the D-planes has been experimentally demonstrated. This leads to a uniform XP isolation over the full azimuth without affecting the primary radiations. Thus, any standalone design henceforth would follow the proposed method of clipping instead of a conventional GP. This, in addition, results in a reduction in the total GP area by nearly 25%. The proposed design can be directly applied to onboard SMD (surface mounted device) base-station [18] and air-borne [19], [20] antennas for improved polarization purity.

II. THEORY AND NEW APPROACH

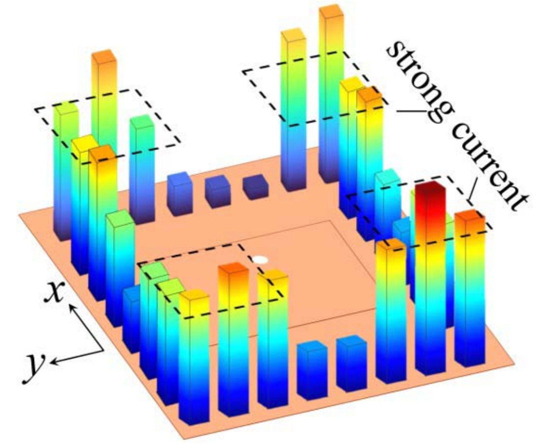
The sources of XP fields, particularly over the D-plane, have become a growing concern in recent times [5]. To effectively mitigate the XP radiation over this D- and H-planes, it is imperative to gain a deeper understanding of the near-field characteristics or surface current of the antenna, and establish a clear correlation between the near-fields and their interaction with the far-field XP radiation. A comprehensive and systematic approach to identifying the sources of XP, their location on the antenna surface, and the methods for synthesizing them to minimize XP radiation have been thoroughly discussed in the subsequent subsections.

A. GP CURRENTS: CANDIDATES OF XP SOURCES

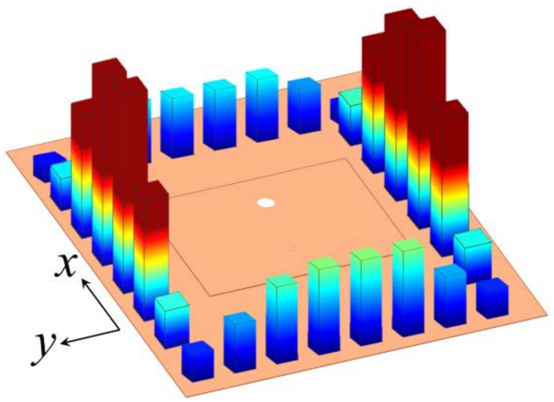
The inspiration for this study stems from a recent work [21]. It shows that the far-field co-polar radiation of a Dielectric Resonator Antenna (DRA) can be precisely manipulated by synthesizing the GP current. In the present study, we adopted a similar procedure as outlined in [21]. However, it is important to note that our research diverges from the study mentioned in [21], as our primary focus lies in investigating the correlation between the far-field XP radiation and the GP conduction current.

A scheme of the adopted technique (briefly sketched in Fig. 1) is as follows: (i) A standard S-band microstrip patch is simulated using a commercial tool [22] and the far-field data are designated as 'simulated data'. (ii) Its GP current *i*(A) is extracted as a ***fsm*** data file using [23], (iii) This ***fsm*** data file is applied to the lower surface of the substrate of the same antenna without considering GP and any kind of excitation, as depicted in Fig. 1(b). The far-field data obtained by this process are designated as 'computed data'.

The simulated and computed data for both D- and H-planes have been compared in Fig. 2. It is evident that the computed data closely match the simulated data. The observation, thus, ensures the pivotal role of the GP current as the XP generating source. It eventually indicates a way of minimizing XP radiation by appropriate synthesis of GP current distribution.



(a): J_y



(b): J_x

FIGURE 3. 3D simulated plot indicating GP current components J_x and J_y at the exact location (5 mm inside the edge): (a) J_y (A/m^2), (b) J_x (A/m^2). Color scale: red is maximum and blue is minimum.

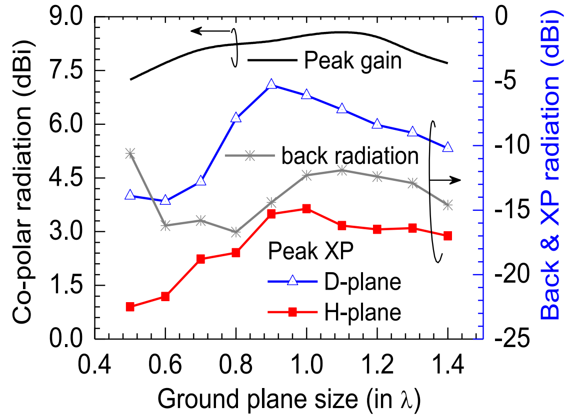


FIGURE 4. Variation of peak gain, peak XP and back radiation as a function of ground plane (square) size for a conventional S-band rectangular patch.

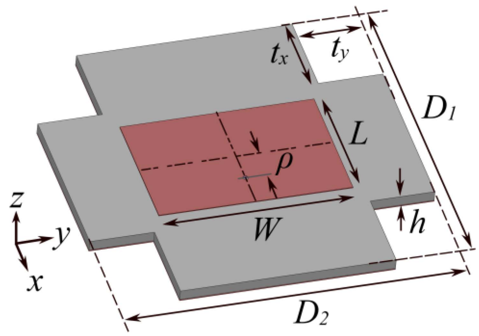


FIGURE 5. The proposed geometry after strategic clipping.

B. CONCENTRATION OF ADVERSE CURRENT COMPONENTS ON GP SURFACE

This is a new set of investigations to search and identify the localized concentration of the targeted or adverse current components. It partially relates to Ludwig's theoretical framework [24] as discussed in [15]. It expresses the fields across the H-plane and D-planes as:

$$E^H_{cross} = E(\theta, \varphi)\cos\theta\ \widehat{i_y} \quad (1)$$

$$E^D_{cross} = 0.5\ E(\theta, \varphi)\left[(1 + \cos\theta)\widehat{i_y} - (1 - \cos\theta)\widehat{i_x}\right] \quad (2)$$

where, $\widehat{i_x}$, $\widehat{i_y}$ are source current polarization vectors, θ and φ represent the elevation and azimuth angles, respectively. Associated XP generating currents J_s (= $\nabla\times \mathbf{H}$, with $|\boldsymbol{H}| = |\boldsymbol{E}/\eta)$ aligns with the source current polarization vector $\hat{\imath}_s$ and relates to $\boldsymbol{E}_{\text{cross}}$ as

$$|\boldsymbol{J}_s| = |(\nabla \times \boldsymbol{E}_{cross})|/\eta \quad (3)$$

Equation (1) thus implies $\boldsymbol{J}_s = \boldsymbol{J}_y$ as the source for H-plane XP radiation, but that for D-plane (Equation (2)) appears as a combination of $\boldsymbol{J}_y$ and $\boldsymbol{J}_x$, although $\boldsymbol{J}_y$ is the primary contributing factor. This theory gives an insight in handling the XP issue by minimizing $\boldsymbol{J}_y$.

We, therefore, believe that a careful investigation of the localized concentration of $\boldsymbol{J}_y$ and $\boldsymbol{J}_x$ would help one in handling the situation in a more scientific way.

Keeping this in view, we executed a comprehensive analysis using [22] and some representative results have been furnished through Fig. 3. This helps estimating both $\boldsymbol{J}_x$ and $\boldsymbol{J}_y$ around the boundary line (5 mm inward the edge). High $\boldsymbol{J}_y$ values are apparent near the GP corners, whereas $\boldsymbol{J}_x$ is adequately low. Therefore, one can surmise that, the corners areas are derogatory in terms of XP radiating source. The engineers should give more attention to the GP corners to study their contribution and impact on the antenna performance.

A typical S-band patch has been optimized in terms of its GP dimension in Fig. 4. The peak gain varies from 7.7 dBi to 8.6 dBi with a maximum when the GP$\sim$1.1λ, λ being the operating wavelength in free space. Other related parameters such as back radiation and XP over both D- and H-planes have also been examined in Fig. 4. The D-plane XP is relatively high with a maximum around at GP $\sim$ 0.9λ. Compact GP is always a preferred case and thus, GP < 0.9λ could be a practical choice revealing considerable gain with lower XP. The back radiation plot in Fig. 4 endorses the idea and indicates GP $\sim$ 0.8λ with the lowest back radiation value. Considering all such information, GP $\sim$ 0.8λ has been used for this study.

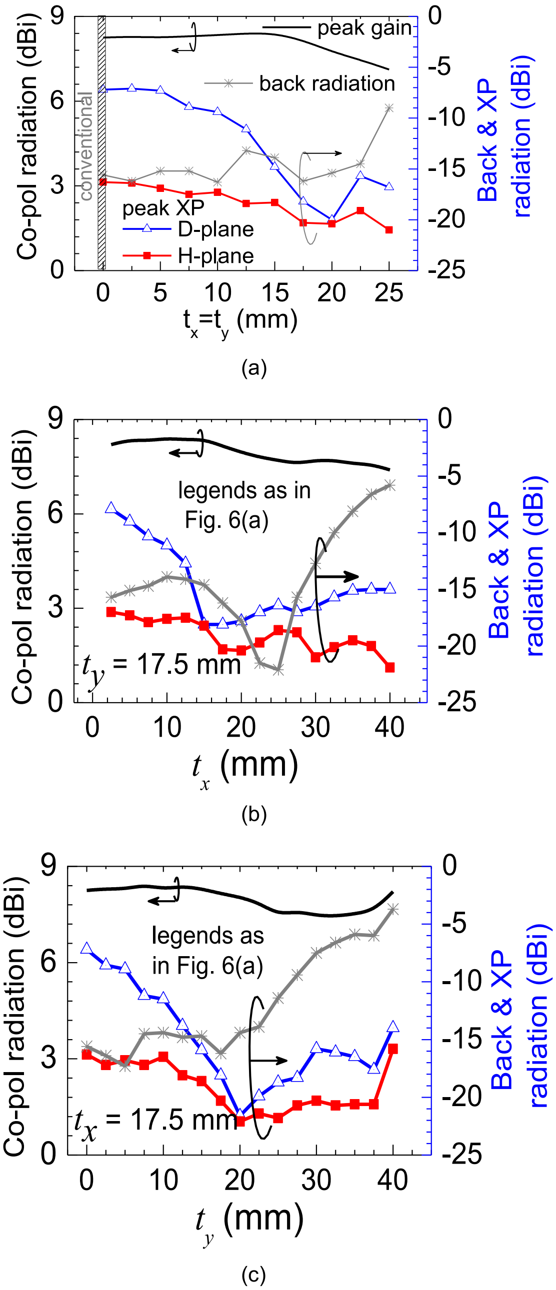


FIGURE 6. Variation of peak gain, XP, and back radiation as function of truncation parameters t_x and t_y: (a) t_x (= t_y) variation, (b) t_x variation with t_y = 17.5, (c) t_y variation with t_x = 17.5. Other parameters: $D_1 = D_2 = 80$, $W = 45$, $L = 30$, $\rho = 7$, $h = 1.575$, $\varepsilon_r = 2.33$. All parameters in mm.

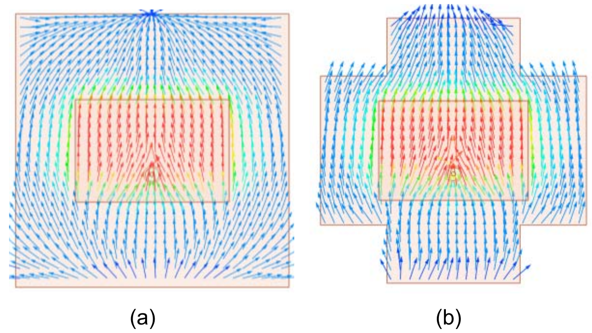


FIGURE 7. Ground plane conduction current: (a) conventional geometry, (b) proposed geometry. Both in identical color scale. Red: maximum, blue: minimum. Parameters as in Fig. 5.

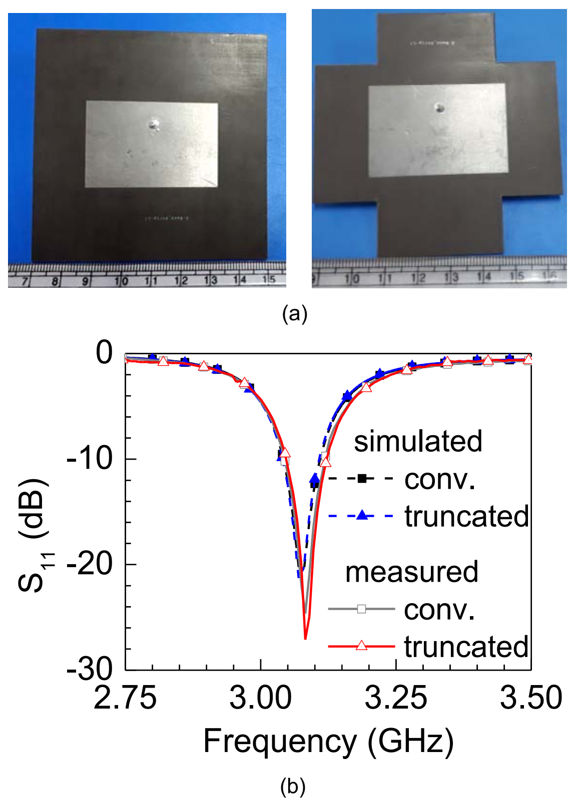


FIGURE 8. (a) Prototypes of rectangular patch with a conventional and a profiled ground plane, and (b) comparison of their S_{11} characteristics Parameters as in Fig. 6.

As per theory, the predominant $\boldsymbol{J}_y$ around the GP corners may be completely avoided to improving the XP scenario and as such four corners of the ground has been strategically clipped off. This is schematically shown in Fig. 5. Each removed area measures $t_x \times t_y$. They need to be optimized aiming optimum benefit. The study, therefore, begins with t_x (= t_y) variation with $D_1 = D_2 = 80$ mm (0.8λ) for an S-band rectangular patch as shown in Fig. 6(a). It estimates the changes of the antenna peak gain, peak XP, and back radiation as the function of t_x, t_y.

Here, $t_x = t_y = 0$ represents the conventional case for which the patch radiates as maximum as 8.25 dBi. The parameter t_x (= t_y) has been gradually increased revealing distinct impact on XP: it falls significantly over D-planes and monotonically in H-plane. But the design strategy should follow a thumb rule that the corner truncation should not have any impact on the input impedance or resonance. This has been the basis of t_x and t_y variations in Fig. 6. No change in peak gain is observed up to $t_x = t_y = 15$ mm (0.15λ). The lowest XP corresponds to $t_x = t_y = 20$ mm, which causes peak gain about 0.7 dB down. A tradeoff, therefore, may be suggested as $t_x = t_y = 17.5$ mm before adjusting t_x vs t_y values. A study presented in Fig. 6(b and c) helps in identifying fine

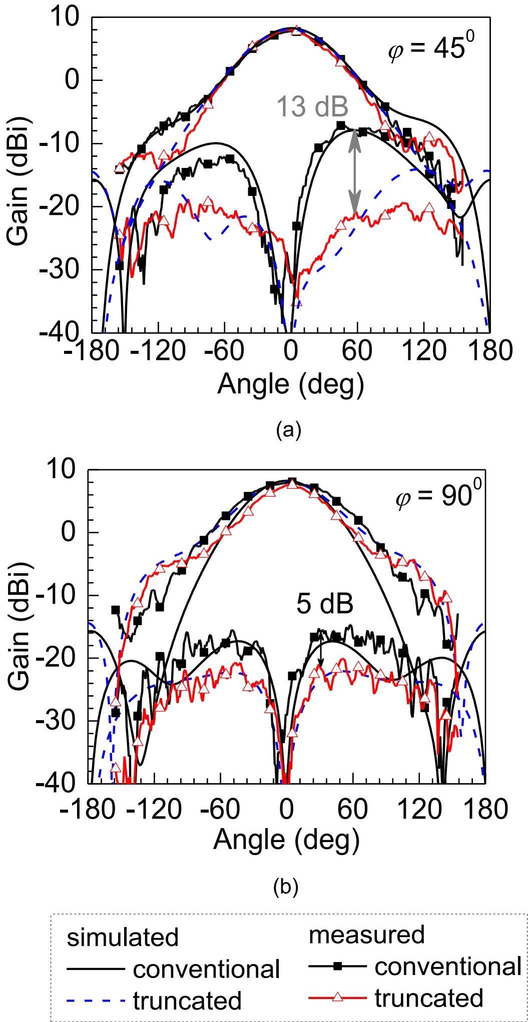


FIGURE 9. Measured radiation patterns of the rectangular prototype compared with its conventional counterpart: (a) D-plane; (b) H-plane. Parameters as in Fig. 6.

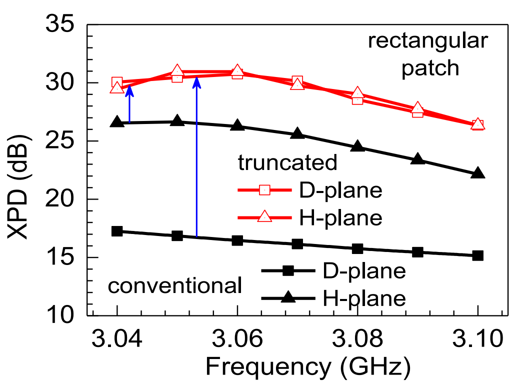


FIGURE 10. XPD values compared with the conventional antennas over the entire operating band. Parameters as in Fig. 6.

TABLE 1. Proposed investigation compared with earlier reported works.

Investigation		XP Suppression (dB) H-plane	XP Suppression (dB) D-plane	Peak Gain (dBi)	Antenna surface area (λ^2)	Comments
Balance feeding	[6]	15	*	5.23	1.05	Complicated fabrication. Cannot suppress D-plane XP.
EBG	[8]	8	*	#	1.8	Complicated design. Cannot suppress D-plane XP.
	[9]	20		#	0.65	
GP Engineering	[15]	4-5	5-6	8.0	1.1	Not effective in terms of gain along with uniform XP reduction.
	[16]	13	10	7.6	0.67	
Present		**5**	**13**	**8.1**	**0.52**	Effective across all radiation planes, best and uniform XPD, compact size, easy to implement.

* D-plane not addressed; # data not available.

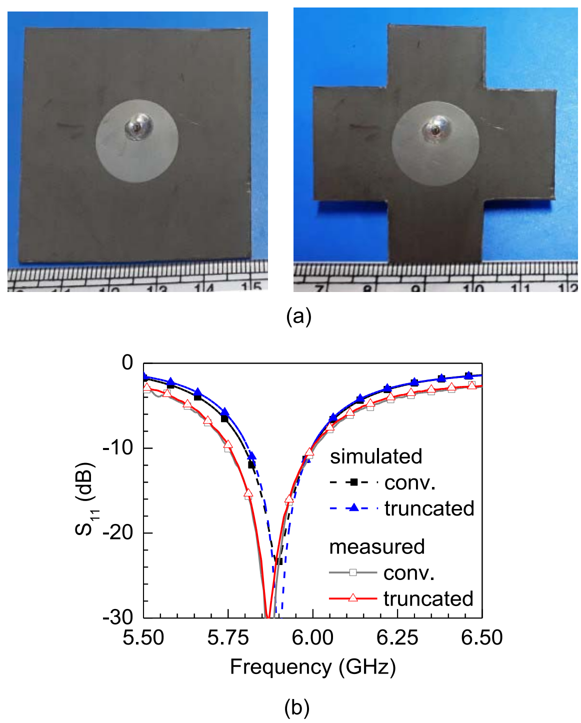


FIGURE 11. Photos of the circular patch with the conventional and truncated GP and (b) Comparison of the measured and simulated S_{11} characteristics of the circular parch. Patch radius = 9, $D = 50$, $t_x = 14$, $t_y = 13$, all parameters in mm and $\varepsilon_r = 2.33$.

tuning between t_x and t_y. They examine the impact of each variable keeping the other fixed and the results are self-explanatory. They reveal $t_y = 20$ mm with $t_x = 17.5$ mm as the optimum choice in terms of reduction in XP maintaining antenna gain almost unaffected.

The impact of such GP clipping can be viewed from the comparison of surface current distributions on two different geometries depicted through Fig. 7. The simulated portrays were captured with identical phase and intensity.

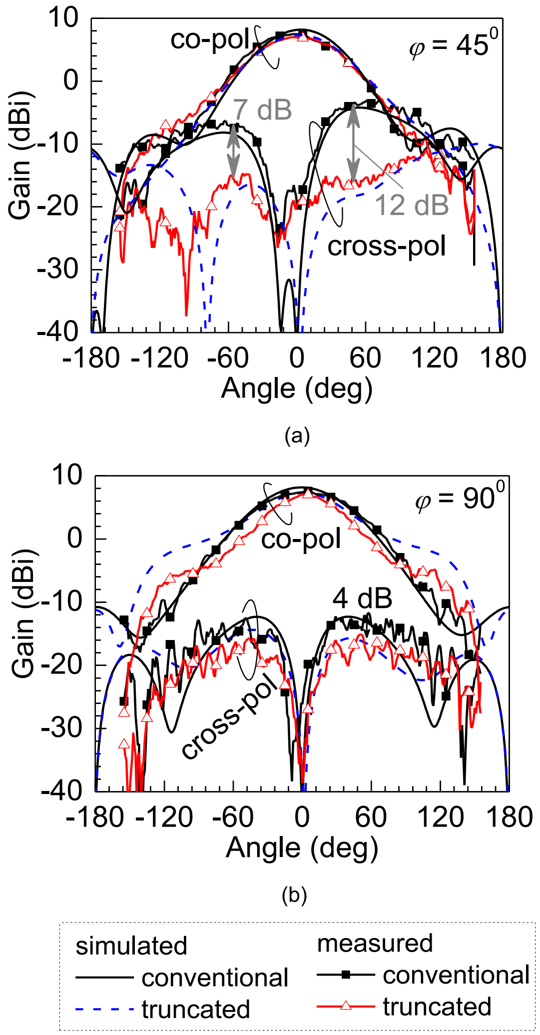


FIGURE 12. Measured radiation patterns of the circular prototype compared with its conventional counterpart: (a) D-plane; (b) H-plane. Parameters as in Fig. 11.

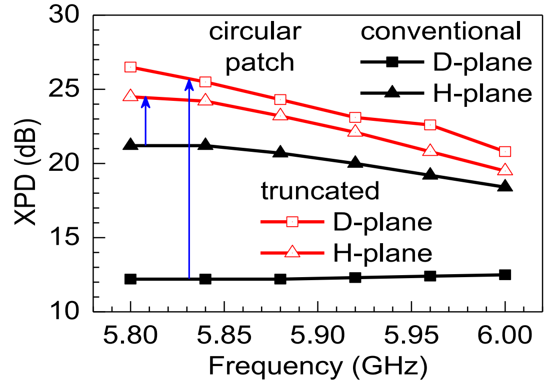


FIGURE 13. XPD values compared with the conventional antennas over the entire operating band. Parameters as in Fig. 11.

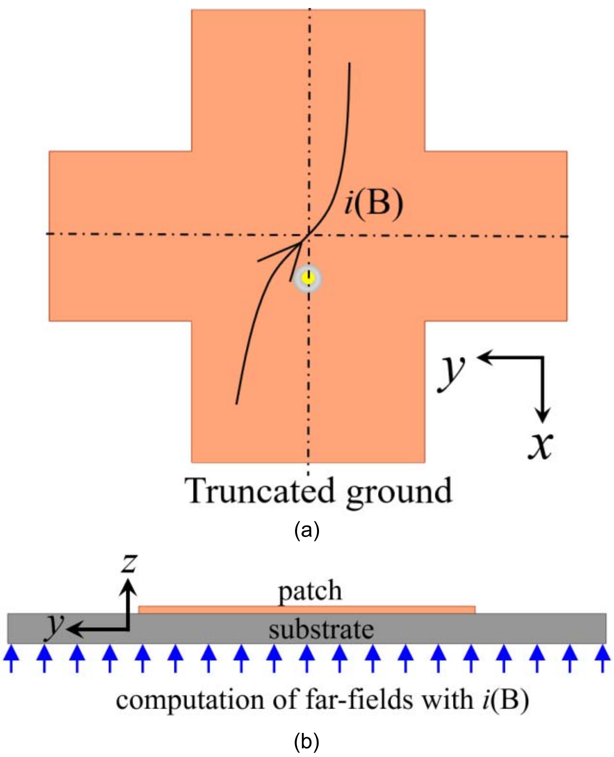


FIGURE 14. (a) Schematic representation of conduction currents *i*(B) on truncated ground, (b) the source current *i*(B) applied to an identical patch and substrate configuration. Parameters as in Fig. 6.

Minimization of $\boldsymbol{J}_y$ and hence improve linearization of surface current along x-axis are clearly visible. This eventually should impact on the polarization purity of the radiated fields as experimentally studied in the following section.

III. PROTOTYPES AND MEASUREMENTS

A set of S-band prototypes, shown in Fig. 8(a), were measured using Agilent's N9926A FieldFox Network Analyzer and an automated anechoic chamber. Measured S_{11} values are compared in Fig. 8(b). The simulated predictions have also been incorporated revealing excellent mutual agreement. They also ensure that the proposed geometry has a minimal impact on the input impedance or patch resonance. Fig. 9 compares its measured and simulated radiation characteristics over D- and H-planes. The observation is quite significant. The experimental data closely follows the simulated one. The co-polar patterns remain almost identical. However, the scenario is completely different for XP radiation. The measured data ensures the predicted reduction in XP level by 13 dB over D-plane and 5 dB over the H-plane. The order of suppression appears asynchronous and dependent on the specific radiation planes. This may be attributed to the localized concentration of $\boldsymbol{J}_y$ on the GP surface. This indeed means large $\boldsymbol{J}_y$ around $\varphi = 90°$ axis influences H-plane XP predominantly and in contrast, a large $\boldsymbol{J}_y$ around $\varphi = 45°$ (GP corner) predominantly influences the D-plane XP [15]. The present case of study addressing corner $\boldsymbol{J}_y$, therefore, results in significantly prominent impact in reducing the XP values over the D-plane compared to that over H-plane.

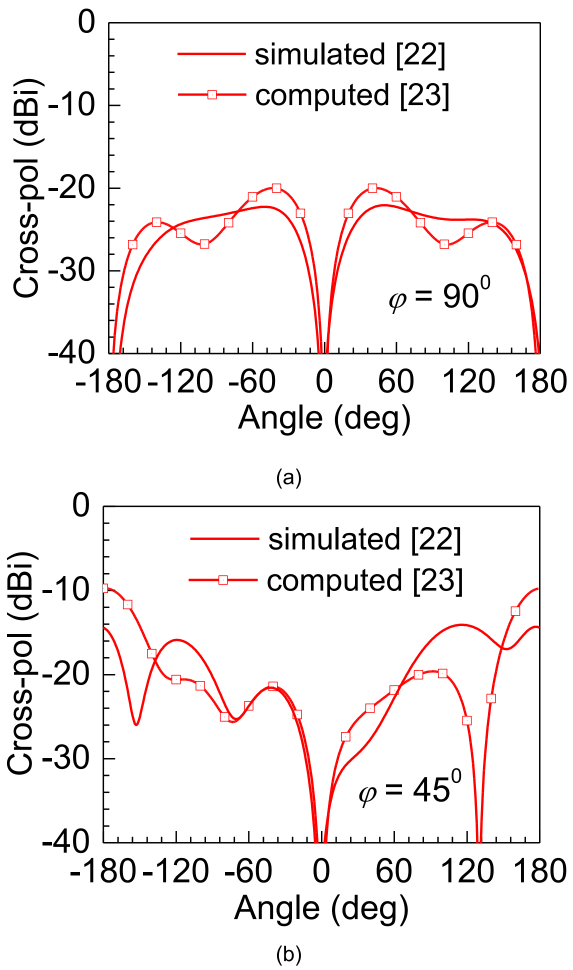


FIGURE 15. Simulated and computed cross-polar radiation over (a) H-plane, (b) D-planes. Parameters as in Fig. 6.

The ultimate impact can be visualized from the comparison of co-to-cross polar discrimination (XPD) portrayed over the operating band in Fig. 10. The proposed geometry is much improved in terms of XPD values (by 25 dB - 31 dB) which appear consistent and uniform over both H- and D-planes.

A comparison of the proposed design with some representative earlier techniques is provided in Table 1. Their salient features are self-explanatory. Very few earlier attempts could really address D-plane XP suppression [15], [16]. The present one is more compact and more straight forward in terms of design but revealing a relatively improved XPD values.

IV. VERSATILITY OF THE PROPOSED TECHNIQUE

Above conjecture and observations have been reconfirmed through a set of studies with circular patches in C-band. An identical PTFE substrate (62 mil, RT Duroid 5870) has been used and the prototypes are shown in Fig. 11(a). Here also, t_x and t_y values were chosen within the limit that do not affect antenna input impedance or resonance. This has been experimentally verified in Fig. 11(b). Simulated S_{11} values closely agree with the measurement and indicate no relative change when the GP is clipped off. Fig. 12 examines their radiation characteristics over D- and H-planes. The measured data closely corroborate with the simulated predictions and ensures distinct suppression in XP level by about 12 dB in D-plane and 4 dB in the H-plane. A circular patch follows the same trend like a rectangular geometry and maintains uniform XPD over the entire bandwidth as examined in Fig 13. It also reveals significant improvement particularly in D-plane. The overall XPD over the band varies from 26 dB to 20 dB.

V. CONCLUSION

The computational technique in Fig. 1 has been verified for the proposed antenna as well. The current distribution, represented as *i*(B) in Fig. 14(a), has been subsequently applied to the lower surface of the substrate as illustrated in Fig. 14(b). The dimensions and shapes in Fig. 14(b) have been kept identical to that in Fig. 1(b). The far-field results are compared in Fig. 15. The simulated data closely align with the computed data over both D- and H-planes. This close correspondence between computation and simulation provides strong support to our investigation. It confirms that the distinctive characteristics of XP are conveyed through the current distribution on GP surface, thereby validating our approach for achieving the desired GP current distribution through GP profiling.

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