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Triangular slotted ground plane: a key to realizing high-gain, cross-polarization-free microstrip antenna with improved bandwidth

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Abstract: A simple rectangular microstrip antenna with triangular slotted ground plane has been studied both theoretically and experimentally to improve shortcomings like low gain (5–6 dBi), narrow bandwidth (3%–4%), and poor copolarization (CP) to cross-polarization (XP) isolation, i.e. polarization purity (typically 10–12 dB), of conventional rectangular microstrip patch antennas. By placing two pairs of triangular shaped slots on the ground plane just below the nonradiating edges of the patch, high gain (around 9 dBi) and more than 22 dB polarization purity over a wide elevation angle has been achieved. The proposed antenna covers almost the full X band of frequency from 9.55 GHz to 11.43 GHz while resonating at 10.35GHz (i.e. impedance bandwidth of 17%), so the proposed antenna offers improved gain, impedance bandwidth, and polarization purity simultaneously as compared to conventional rectangular microstrip antennas. Parametric studies have been documented to achieve the optimum defect dimension. The specialty of the proposed antenna is that the gain and radiation pattern is quite stable in the entire operating frequency band, along with its attractive gain, impedance bandwidth, and polarization performance. The simulated and measured results show close resemblance to each other. The proposed geometry is quite simple and easy to fabricate and therefore may be ideal for applications where high gain, stable radiation characteristics, and wide impedance bandwidth along with high copolarization to cross-polarization isolation over wide elevation angles are required.

Key words: Rectangular microstrip antenna, gain, impedance bandwidth, copolarization, cross-polarization

1. Introduction

Modern wireless communication devices demand tiny broadband antennas with high gain, wide impedance bandwidth, and high polarization purity and hence the rectangular microstrip antenna (RMA) is an obvious choice for researchers working in the field of low-profile antennas. However, a few drawbacks like low gain (5–6 dBi), narrow bandwidth (3%–4%), and poor copolarization (CP) to cross-polarization isolation (XP) are unavoidable with conventional RMAs [1, 2]. Many research results were reported in [3–5] for enhancing the performance of such antenna characteristics. Although RMAs mainly radiate linearly polarized (copolarization) electrical fields in the broadside direction, some amount of orthogonal radiation also takes place, which is popularly known as cross-polarized (XP) radiation. The XP radiation becomes worse in its H-plane compared to that of the E-plane [6, 7]. Therefore, it restricts the use of RMAs as smart antennas in the field of modern RF and wireless communication, where high gain over the wideband and high polarization purity are required. Therefore, designing a simple RMA that can handle all these limitations for the purpose of wireless communication application is an important challenge to the antenna research community.

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It is noticed in the literature that the XP becomes prominent for the probe-fed design when the dielectric constant decreases and the substrate thickness increases [6]. The first higher order orthogonal mode (TM_{02}) is mainly attributed to cross-polarized radiation while the copolarized radiation is caused by the dominant (TM_{10}) mode in RMAs. In the TM_{02} mode electric fields from the nonradiating edges of the patch become very strong and significantly increase the XP radiation. The radiation from the corners of the patch at its primary dominant TM_{10} mode is also a key reason for XP radiation from RMAs.

Researchers have reported different techniques like aperture coupled dual polarization [8, 9], modification of feed structure [10–14] and ground plane [15, 16], and use of composite substrates [17, 18] to improve the input and radiation characteristics of RMAs. Around 7.5 dBi gain and 24% impedance bandwidth with 23 dB of CP-XP isolation were obtained in [8, 9]. However, all these structures suffer from complexity in fabrication and feeding mechanisms. Matched line feeding, stacked patch structure with the "mirrored pair", and shorted square patch were adopted in [10–14] for obtaining broader band and lower XP radiation. In almost all the designs reported in [10–14], the gain of the antenna is low. Moreover, the reported structures are not only complex but also bulky. Modification of the ground plane structure to reduce XP radiation was explored in [15,16]. In [15] a W-shaped ground plane was proposed to attain 14 dB of XP isolation in the H-plane along with 12% impedance bandwidth and 9.5 dB gain only in broad side direction, while in [16] 10–-15 dB cross-polarization isolation, 24% impedance bandwidth, and almost 8 dBi gain were achieved by a probe-fed patch antenna with a novel U-shaped ground plane. However, ground plane modification requires a complex manufacturing process. Simple single layer microstrip antennas (MAs) with air dielectric were reported in [17, 18], where about 7.5–8.5 dBi gain and poor polarization purity of 9 dB along with 5% impedance bandwidth were achieved. Fully and discretely shorted nonradiating edges have been employed in RMAs for minimization of XP fields as reported recently in [19, 20]. Polarization purity of about 25 dB is revealed from these reports, but both the structures suffer from poor impedance bandwidth of 5% and 11%, respectively. A complex structure by modifying feed and patch geometry in RMAs was reported in [21] for broad bandwidth of 21.15% and high gain of 9.5 dBi with poor polarization purity of only 12 dB in its H-plane. Wide band E (30%), U (27%), and ψ (54%) shaped patch antennas were reported in [22–24], where information about gain and polarization purity was not apparent. A recent article [25] showed the use of a shorted comb shaped patch for the improvement of XP radiation. In [25], the author reported CP-XP isolation of 35 dB, but the structure suffers from a major drawback of increased size. Hence, the structure is not suitable for miniaturized devices.

Application of a slot in the ground plane to adopt low XP radiation in RMAs was first reported in [26], where polarization purity of 5–8 dB was achieved in the broadside direction with no evidence of improvement of gain and input impedance bandwidth by placing a dot shaped slot on the ground plane. Arc shaped [27] and L-shaped [28] slotted ground plane integrated microstrip antennas revealed about 12–15 dB CP-XP isolation as compared to conventional MAs with no information about the improvement of gain and bandwidth. Around 25 dB polarization purity with 5% impedance bandwidth was achieved by placing a rectangular slot in the ground plane in [29]. Followed by [29], some more reports [30–33] investigated RMAs with bracketed shaped slot [30], rectangular shaped dumbbell shaped slot [31], cross shaped slot [32], and circular headed dumbbell shaped slot [33] over the ground plane, respectively. However, in those reports, neither gain nor bandwidth (BW) was improved. Therefore, the application of slot integrated ground structure seems to be a powerful technique to address the cross-polarized radiation issue. Nevertheless, the simultaneous improvement of polarization purity as well as gain and bandwidth still remains a key issue for the antenna research community.

In the present investigation a simple single layer triangular slotted ground plane integrated RMA has been proposed for concurrent improvement of gain, impedance bandwidth, and XP performance. The available literature [1, 34] suggested that for RMAs, CP to XP radiation becomes less when the aspect ratio of the patch is around 1.5. Therefore, an RMA with such aspect ratio has been utilized for the present investigation. Two pairs of triangular shape slots are placed beneath the corner of the rectangular patch to redistribute the electric fields in the corners of the patch as well as in the nonradiating edges (Figure 1a (top view), Figure 1b (bottom view)) to improve all three parameters without hampering the radiation characteristics of the dominant mode. The specialty of the present structure is provided by the proper selection of slot geometry in the ground plane. It is done with a view to modulating the cavity field in such a way that fields will be more concentrated near the radiating edge compared to that of the conventional structure. In the present structure of investigation, average gain of 8.7 dBi, impedance bandwidth of 17%, and 18–22 dB polarization purity in the H-plane are observed. Moreover, the radiation patterns in both the principle planes are stable in the whole operating frequency band. Therefore, the proposed investigation is a noteworthy report that can address three issues of RMAs simultaneously.

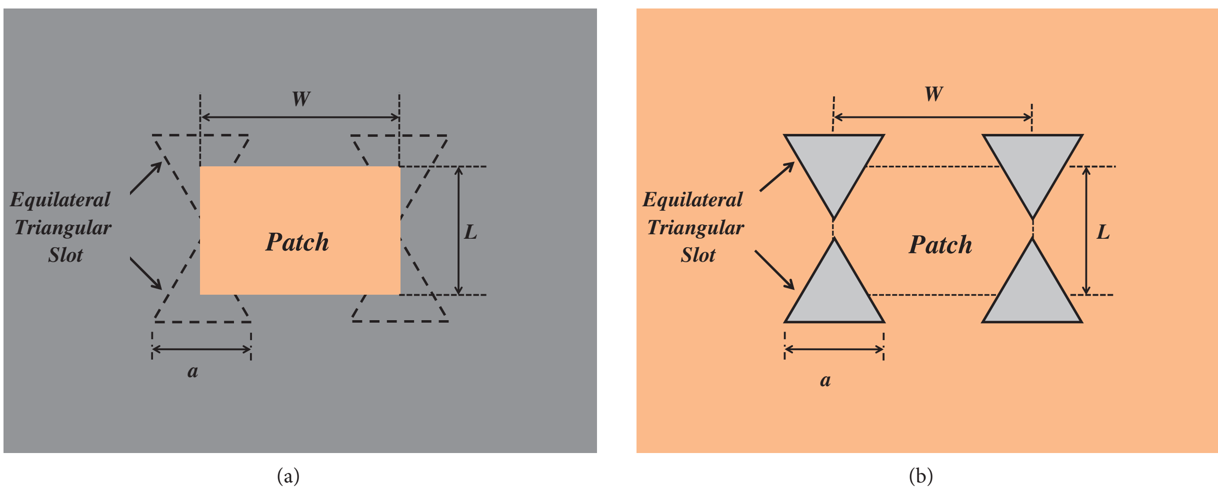


Figure 1. Schematic representation of proposed triangular slotted ground plane integrated RMA: (a) top view, (b) bottom view

2. Theoretical overview and parametric study

In general, the patch and ground plane of the RMA form an electric wall (PEC) while four open boundaries are considered to be magnetic walls (PMC). Therefore, the slot in the ground plane definitely causes changes in fields and this in turn alters both the input and the radiation characteristics of the RMA.

First the basic rectangular microstrip antenna is designed to operate in the X-band by using [35] and is given by:

$$f_{r,nm} = \frac{c}{2\sqrt{\varepsilon_{reff}}}[(\frac{n}{L+2\triangle L})^2 + (\frac{m}{W+2\triangle W})^2]^{\frac{1}{2}}, \quad (1)$$

where $\triangle L$ is fringing length, $\triangle W$ is fringing width, and ε_{reff} is effective dielectric constant. The values of $\triangle L, \triangle W$, and ε_{reff} have been calculated from [35].

Two pairs of equilateral triangular shaped slots with side arm length a (Figures 1a and 1b) are placed on the ground plane just beneath the corners of the patch. The position of the slot on the ground plane is designed in such a way as to align the center of the triangular slot coincident with the corner of the patch. This is done with a view to altering the electric field near patch corners. As the arm length (a) of the triangle is increased from 5.2 mm to 12.06 mm, bandwidth increases significantly, as shown in Figure 2.

For a ranging from a = 10.4 mm to a = 12.06 mm, the impedance bandwidth is almost the same (i.e. 17%). Further increase of slot size (a) may hamper the electric fields beneath the patch, which in turn degrades the copolarization performance of the proposed antenna. The gain variation with respect to slot dimension is also shown in the same figure. As the slot size increases initially gain increases and settles down at 8.7 dBi (a = 8.7 mm and a = 10.4 mm). If the dimension is increased further (i.e. towards a = 12.06 mm), it degrades the CP gain performance of the proposed triangular slotted ground plane integrated RMA.

Now we demonstrate the polarization purity of the proposed RMA. To find the optimum defect size of the proposed antenna, normalized H-plane XP performance is examined and shown in Figure 3. It is seen that as the value of a increases, XP performance improves, and minimum CP-XP isolation is obtained when a = 10.4 mm, which is –22 dB over a wide elevation angle of $\pm 130^o$. Further increase of a (i.e. a = 12.06 mm) degrades the XP performance of the proposed structure.

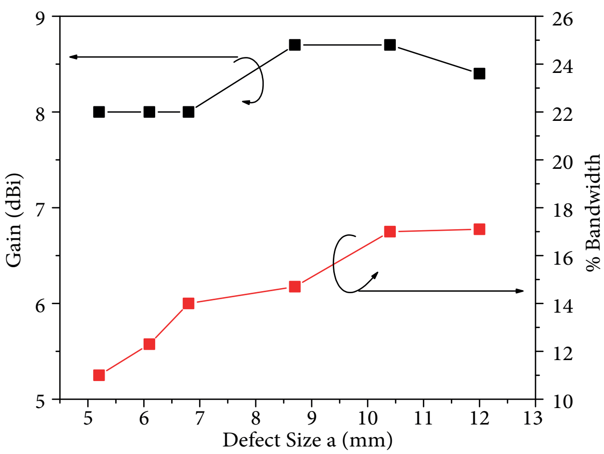


Figure 2. Variation of gain and % bandwidth of triangular slotted ground plane integrated RMA as a function of slot size.

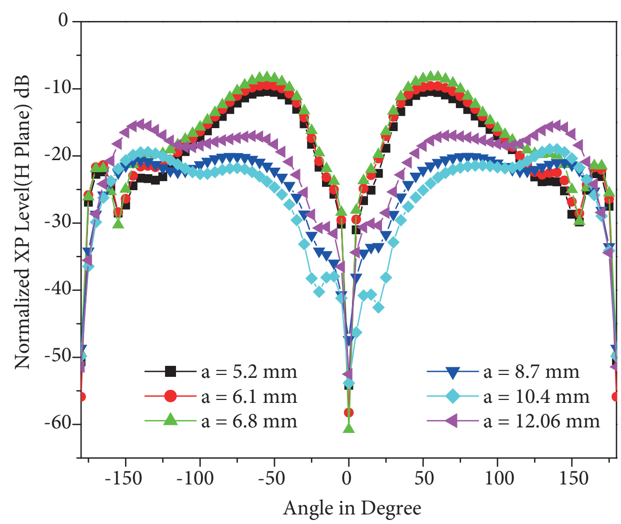


Figure 3. Simulated normalized H-plane XP pattern for different slot sizes of proposed triangular slotted ground plane integrated RMA.

Therefore, the triangular slot with arm length a = 10.4 mm is chosen for the optimum dimension of the slot. About 8.7 dBi gain, 17% impedance bandwidth, and 22 dB CP-XP isolation over a wide elevation angle have been achieved from the proposed structure.

Now we focus on the physical insight into the concurrent improvement of impedance bandwidth, gain, and XP performances of the proposed antenna.

The present antenna with its optimum defect size produces much higher bandwidth compared to classical RMAs. In fact, as losses increase with the increase of the size of the slot in the ground plane, bandwidth improves. In fact, increment of loss lowers the cavity quality factor (Q) and hence improves the bandwidth. The relation between the impedance bandwidth and the quality factor may be written as [1]:

$$Bandwidth(BW) = \frac{1}{Q_T}, \tag{2}$$

$$\frac{1}{Q_T} = \frac{1}{Q_R} + \frac{1}{Q_C} + \frac{1}{Q_D}, \tag{3}$$

$$Q_T \cong \frac{1}{Loss}, \tag{4}$$

where Q_T, Q_r, Q_d, and Q_c are total quality factor, quality factor due to radiation, quality factor due to dielectrics, and quality factor due to conductor, respectively.

Furthermore, it may be noted that the gain of the present structure is also relatively higher than that of the conventional RMA, which is about 5–6 dBi [1]. In fact, the field distribution beneath the patch is critically dependent on the defect geometry at the ground plane. Nevertheless, for termination of the electric fields, the ground plane is necessary. In case of the triangular slotted ground plane integrated structure, due to the absence of ground plane in some regions beneath the patch, the fringing is modified. This in turn produces a more uniform distribution over the aperture compared to conventional RMAs (Figure 4a), as shown in Figure 4b, where the magnitude of electric field distribution over the substrate in the present antenna (a = 10.4 mm) is depicted.

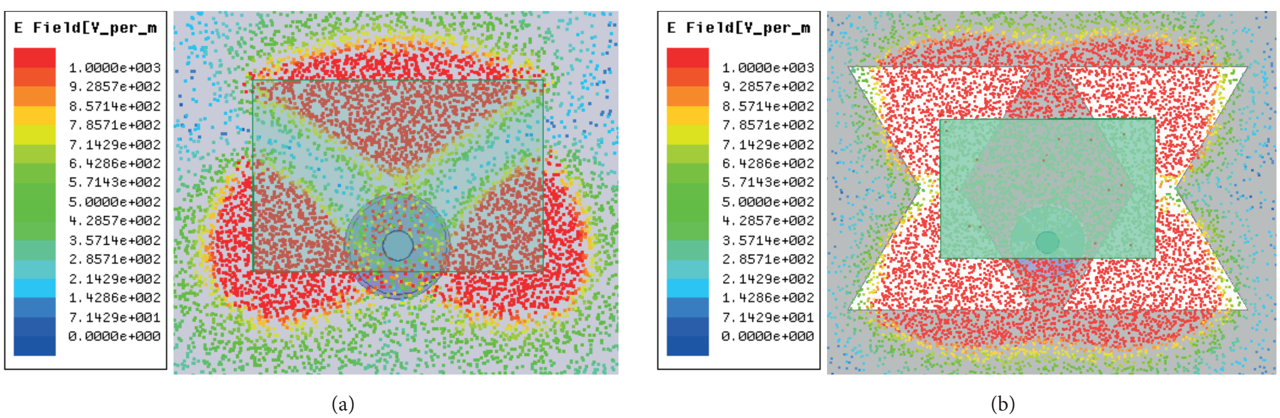


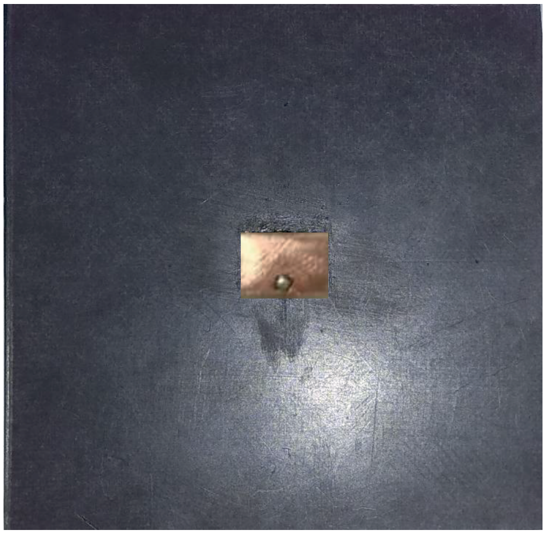
Figure 4. Electric field distribution on the substrate for (a) conventional RMA and (b) proposed triangular slotted ground plane integrated RMA.

Therefore, the present antenna gives much higher gain compared to other low-profile antennas, which is quite striking for antenna researchers.

It is interesting to note that the field distribution over the substrate (Figure 4b) is quite symmetric between the lower and upper half sections of the patch. Consequently, XP performance of the present antenna improves as indicated in [36].

3. Proposed structure

A rectangular microstrip antenna of length L = 8 mm and width W = 12 mm has been designed on PTFE substrate of size 80×80 mm^2, height (h) = 1.575 mm, and permittivity (ε_r) = 2.33. Four equilateral triangle type slots have been placed below the patch in such a way that the center of each slot coincides with the four corners of the patch. The Table shows the optimized size of the slot as well as the patch dimensions. The schematic antenna structure is shown in Figure 1 and the optimized fabricated structure is shown in Figure 5a (top view) and Figure 5b (bottom view).



(a)

(b)

Figure 5. Fabricated triangular slot ground plane integrated RMA: (a) top view, (b) bottom view.

Table. Detailed parameters of the proposed RMA of thickness h = 1.575 mm, ε_r = 2.33.

L (mm)	W(mm)	a(mm)	$f_{r_{10}}$ (GHz)
8	12	10.4	10.35

4. Results and discussion

The simulated (HFSS v.14) and measured results obtained from the conventional and triangular slotted ground plane integrated RMA are presented in this section. The fed positions for the conventional one and the prototype are 2.4 mm and 3.1 mm, respectively, from the center of the metal patch. The reflection coefficient profile of both antennas is shown in the Figure 6.

The conventional RMA resonates at 10.33 GHz while the proposed RMA resonates at 10.35 GHz (measured). The increment of fringing fields near the radiating edges may be attributed to such a slight shift in resonant frequency. Improvement of bandwidth is clearly apparent from Figure 6. About 17% impedance bandwidth (9.55 GHz to 11.43 GHz) is achieved by the proposed structure (both simulated and measured) while the same is only 3%–4% [1] for the conventional RMA.

Figure 7 shows the radiation pattern of the proposed antenna at its H-plane in dominant mode frequency. The H-plane XP performance has been improved surprisingly as a consequence of the placement of the optimized slot in the ground plane. As the E-plane radiation pattern does not change very much, it is not shown. The gain of the proposed structure is 8.7 dBi at center frequency. Minimum CP-XP isolation is about 22 dB while the same for the conventional RMA is only 12 dB near the entire broadside region. It is observed that the improved polarization purity in the case of the proposed antenna is significantly improved over a wide elevation angle ($\pm 130^o$).

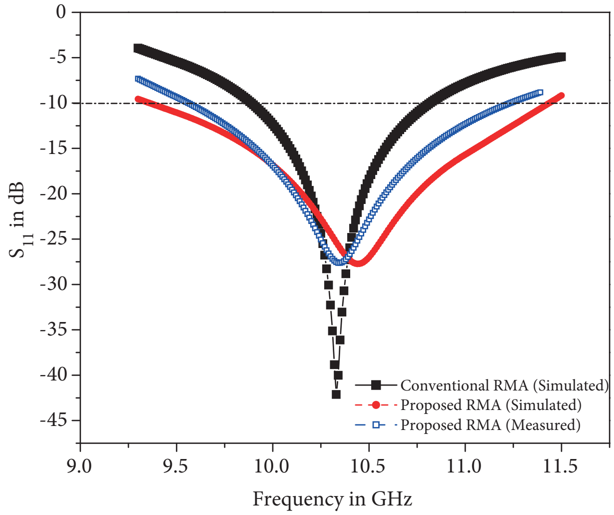


Figure 6. Reflection coefficient profile of conventional and proposed triangular slot ground plane integrated RMA.

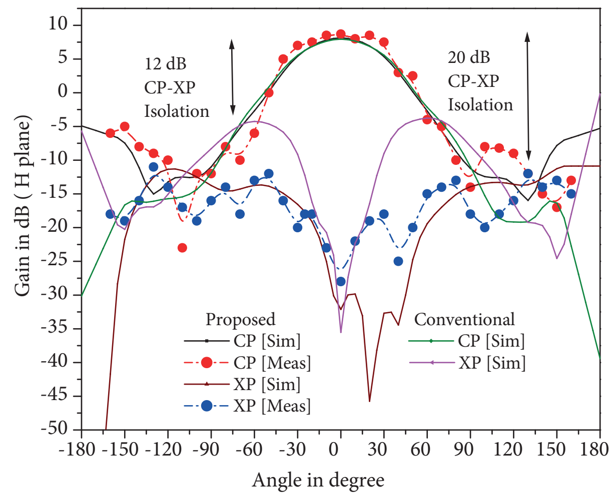


Figure 7. Radiation pattern (H-plane) conventional and proposed triangular slot ground plane integrated RMA at corresponding center frequency.

The antenna should maintain its gain and minimum CP-XP isolation throughout its impedance bandwidth. Figure 8 shows the variation of gain as well as minimum CP-XP isolation of the proposed RMA structure over its whole operating bandwidth. Gain maintains its value from 7 to 8.7 dBi and minimum CP-XP isolation is between 18 and 22 dB within the whole impedance bandwidth, which is quite appreciable.

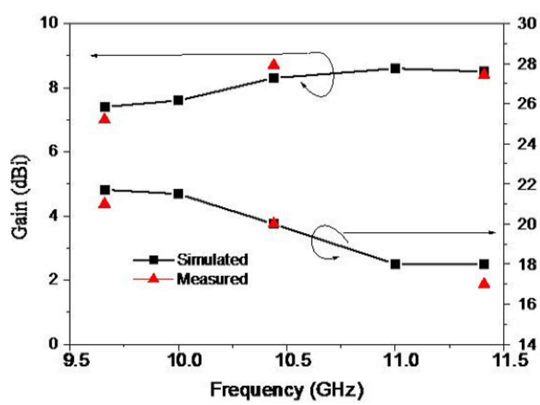


Figure 8. Variation of gain and minimum CP-XP isolation of triangular slot ground plane integrated RMA in the operating frequency band.

The stability of the profile of the radiation pattern is an important issue for a broadband RMA. Therefore, the radiation pattern of the proposed structure has been studied at two different frequencies other than the center frequency within the operating bandwidth of the proposed antenna (at 9.66 GHz and 11.41 GHz) and this is shown in Figures 9a and 9b. The radiation patterns at the frequencies other than the center frequency seem to be very stable, which confirms the stable and efficient performance of the proposed RMA in its whole operating band.

It is noted that the measured results slightly deviate from the simulated results as presented in the graphical representations. However, this level of deviation is due to fabrication error and is tolerable for the antenna community.

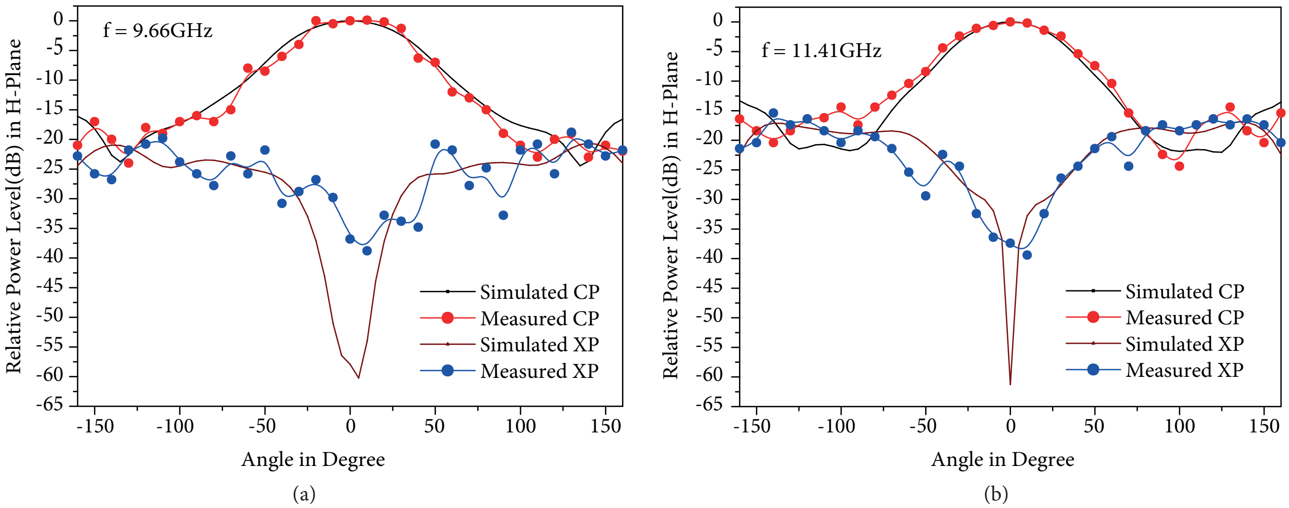


Figure 9. H-plane radiation pattern of proposed triangular slot ground plane integrated RMA at frequencies other than center frequency: (a) 9.66 GHz and (b) 11.41 GHz.

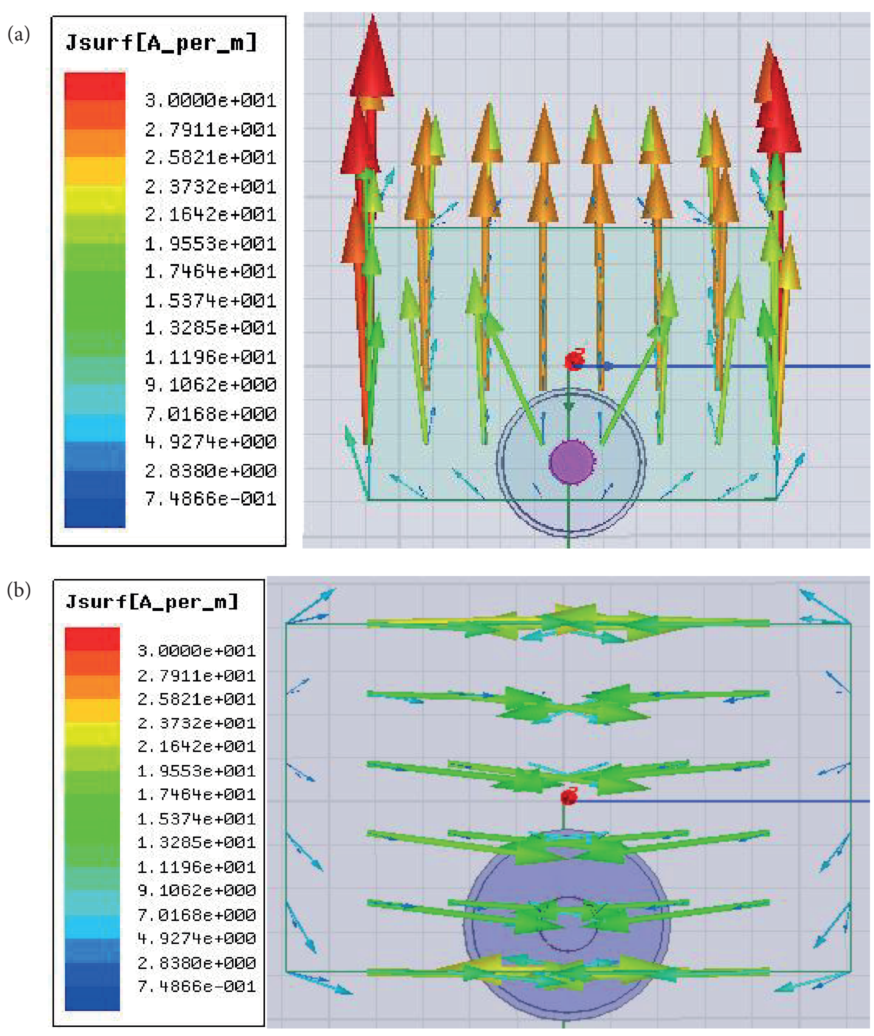


Figure 10. Surface current distribution of conventional RMA over the patch corresponding to (a) dominant TM_{10} mode and (b) first higher order orthogonal TM_{02} mode.

For more confirmation of the theory, the distributions of surface current on the patch for both the conventional structure and proposed structure have been studied. Figure 10 shows the electric current distribution on the patch for the conventional RMA in dominant mode (TM_{10}) (Figure 10a) and the first higher order orthogonal mode (TM_{02}) (Figure 10b), which is mainly responsible for cross-polarization. In the case of the conventional RMA (Figure 10a) the surface current flows along the length of the patch, while in the case of the first higher order orthogonal mode (Figure 10b) current flows along the patch width and this current is definitely orthogonal to the current flow in TM_{10} mode. The surface current is maximum at the patch corners in TM_{10} mode, which is clear from Figure 10a.

As soon as the slot is introduced the strong electric fields at the corner of the patch disappear, which helps to enhance the XP performance of the proposed structure (Figure 11a). The radiation from the nonradiating edges of the patch in TM_{02} mode (Figure 11b) is also responsible for cross-polarization. Figure 11b also shows that the slot along the nonradiating edges eliminates the electric field near the nonradiating edges due to the first higher order orthogonal mode. Hence, the surface current distribution only along the length persists, which again helps to improve the XP performance of the proposed structure.

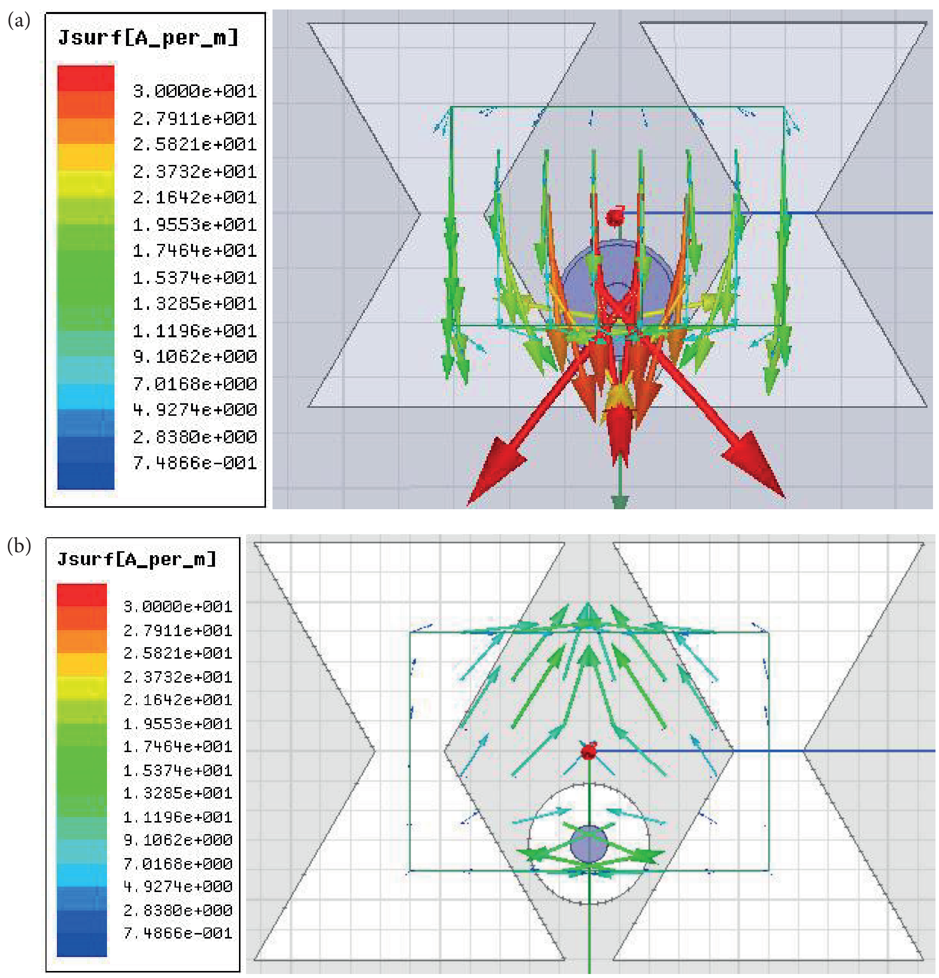


Figure 11. Surface current distribution of conventional RMA over the patch corresponding to (a) dominant TM_{10} mode and (b) first higher order orthogonal TM_{02} mode.

5. Conclusion

A simple and compact triangular slot ground plane integrated RMA is proposed for concurrent improvement of the gain, impedance bandwidth, and polarization purity over wide elevation angles. From the proposed structure, about 17% impedance bandwidth, stable radiation pattern with peak gain 8.7 dBi, and 18–22 dB polarization purity over broad elevation angles are achieved. The proposed antenna is very useful for wireless applications where high polarization purity over wide elevation angles along with stable gain and wide impedance bandwidth are required with such a simple and low-profile microstrip antenna.

References

[1] Garg R, Bhartia P, Bahl I, Ittipiboon A. Microstrip Antenna Design Handbook. Norwood, MA, USA: Artech House, 2001.

[2] Guha D, Antar YMM. Microstrip and Printed Antennas - New Trends, Techniques and Applications. Chichester, UK: John Wiley, 2011.

[3] Akgol O, Altintas O, Unal E, Karaaslan M, Karadag F. Linear to left-and right-hand circular polarization conversion by using a metasurface structure. International Journal of Microwave and Wireless Technologies 2017; 10 (1): 133-138. doi: 10.1017/S1759078717001192

[4] Alkurt FO, Altintas O, Atci A, Bakir M, Unal E et al. Antenna-based microwave absorber for imaging in the frequencies of 1.8, 2.45, and 5.8 GHz. Optical Engineering 2018; 57 (11): 113102. doi: 10.1117/1.OE.57.11.113102

[5] Dogan E, Unal E, Kapusuz D, Karaaslan M, Sabah C. Microstrip patch antenna covered with left handed metamaterial. Applied Computational Electromagnetics Society Journal 2014; 29 (2): 178-183.

[6] Petosa A, Ittipiboon A, Gagnon N. Suppression of unwanted probe radiation in wide band probe-fed microstrip patches. Electronics Letter 1999; 35 (5): 355–357. doi: 10.1049/el:19990269

[7] Huynh T, Lee KF, Lee RQ. Cross-polarization characteristics of rectangular patch antennas. Electronics Letters 1988; 24 (8): 463–464. doi: 10.1049/el:19880313

[8] Gao S, Li LW, Leong MS, Yeo TS. A broad-band dual-polarized microstrip patch antenna with aperture coupling. IEEE Transactions on Antennas and Propagation 2003; 51 (4): 898-900. doi: 10.1109/TAP.2003.811080

[9] Lai CH, Han TY, Chen TR. Broadband aperture coupled microstrip antennas with low cross polarization and back radiation. Progress in Electromagnetics Research Letters 2008; 5: 187–197. doi: 10.2528/PIERL08111805

[10] Li P, Lai HW, Luk KM, Lau KL. A wideband patch antenna with cross-polarization suppression. IEEE Antenna Wireless Propagation Letters 2004; 3: 211–214. doi: 10.1109/LAWP.2004.834937

[11] Chen ZN, Chia MYW. Broad-band suspended probe-fed plate antenna with low cross-polarization level. IEEE Transactions on Antennas and Propagation 2003; 51 (2): 345–346. doi: 10.1109/TAP.2003.809062

[12] Loffler D, Wiesbeck W. Low-cost X-polarised broadband PCS antenna with low cross-polarisation. Electronics Letters 1999; 35 (20): 1689-1691. doi: 10.1049/el:19991197

[13] Granholm J, Woelders K. Dual polarization stacked microstrip patch antenna array with very low cross-polarization. IEEE Transactions on Antennas and Propagation 2001; 49 (10): 1393-1402. doi: 10.1109/8.954928

[14] Baligar JS, Revankar UK, Acharya KV. Broadband two-layer shorted patch antenna with low cross-polarisation. Electronics Letters 2001; 37 (9): 547-548. doi: 10.1049/el:20010371

[15] Wong KL, Tang CL, Chiou JY. Broad-band probe-fed patch antenna with a W-shaped ground plane. IEEE Transactions on Antennas and Propagation 2002; 50 (6): 827-831. doi: 10.1109/TAP.2002.1017663

[16] Hsu WH, Wong KL. Broad-band probe-fed patch antenna with a U-shaped ground plane for cross-polarization reduction. IEEE Transactions on Antennas and Propagation 2002; 50 (3): 352-355. doi: 10.1109/8.999626

[17] Chattopadhyay S, Siddiqui JY, Guha D. Rectangular microstrip patch on a composite dielectric substrate for high gain wide-beam radiation patterns. IEEE Transactions on Antennas and Propagation 2009; 57 (10): 3324–3327. doi: 10.1109/TAP.2009.2029607

[18] Guha D, Chattopadhyay S, Siddiqui JY. Estimation of gain enhancement replacing PTFE by air substrate in a microstrip patch antenna. IEEE Antenna Propagation Magazine 2010; 52 (3): 92–95. doi: 10.1109/MAP.2010.5586581

[19] Ghosh D, Ghosh SK, Chattopadhyay S, Nandi S, Chakraborty D et al. A physical and quantitative analysis of compact rectangular microstrip antenna with shorted non-radiating edges for reduced cross-polarized radiation using modified cavity model. IEEE Antenna Propagation Magazine 2014; 56 (4): 61-72. doi: 10.1109/MAP.2014.6931658

[20] Poddar R, Chakraborty S, Chattopadhyay S. Improved cross polarization and broad impedance bandwidth from simple single element shorted rectangular microstrip patch: theory and experiment. Frequenz 2016; 70 (1-2): 1–9. doi: 10.1515/freq-2015-0105

[21] Islam MT, Shakib MN, Misran N. Design analysis of high gain wideband L-probe fed microstrip patch antenna. Progress in Electromagnetics Research 2009; 95: 397-407. doi: 10.2528/PIER09080204

[22] Yang F, Zhang X, Ye X, Samii YR. Wide-band E-shaped patch antennas for wireless communications. IEEE Transactions on Antennas and Propagation 2001; 49: (7) 1094-1100. doi: 10.1109/8.933489

[23] Sharma SK, Shafai L. Performance of a novel Ψ-shape microstrip patch antenna with wide bandwidth. IEEE Antenna Wireless Propagation Letters 2009; 8: 468-471. doi: 10.1109/LAWP.2009.2020184

[24] Tong KF, Luk KM, Lee KF, Lee RQ. A broad-band U-slot rectangular patch antenna on a microwave substrate. IEEE Transactions on Antennas and Propagation 2000; 48 (6): 1148–1152. doi: 10.1109/8.865229

[25] Pawar UA, Chakraborty S, Chattopadhyay S. A compact and grounded comb-shaped microstrip antenna: a key to realize enhanced radiation performance. International Journal of RF and Microwave Computer Aided Engineering 2017; 27 (6): 1 -11. doi: 10.1002/mmce.21101

[26] Guha D, Biswas M, Antar YMM. Microstrip patch antenna with defected ground structure for cross polarization suppression. IEEE Antenna Wireless Propagation Letter 2005; 4: 455-458. doi: 10.1109/LAWP.2005.860211

[27] Guha D, Kumar C, Pal S. Improved cross-polarization characteristics of circular microstrip antenna employing arc-shaped defected ground structure (DGS). IEEE Antenna Wireless Propagation Letters 2009; 8: 1367-1369. doi: 10.1109/LAWP.2009.2039462

[28] Kumar C, Guha D. Asymmetric geometry of defected ground structure for rectangular microstrip: a new approach to reduce its cross-polarized fields. IEEE Transactions on Antennas and Propagation 2016; 64 (6): 2503–2506. doi: 10.1109/TAP.2016.2537360

[29] Ghosh A, Ghosh D, Chattopadhyay S, Singh LLK. Rectangular microstrip antenna on slot type defected ground for reduced cross polarized radiation. IEEE Antenna Wireless Propagation Letters 2015; 14: 324-328. doi: 10.1109/LAWP.2014.2363563

[30] Kumar C, Guha D. DGS integrated rectangular microstrip patch for improved polarization purity with wide impedance bandwidth. IET Microwave Antenna Propagation 2014; 8 (8): 589-596. doi: 10.1049/iet-map.2013.0567

[31] Ghosh A, Chakraborty S, Chattopadhyay S, Nandi A, Basu B. Rectangular microstrip antenna with dumbbell shaped defected ground structure for improved cross polarised radiation in wide elevation angle and its theoretical analysis. IET Microwave Antenna Propagation 2016; 10 (1): 68–78. doi: 10.1049/iet-map.2015.0179

[32] Ghosh A, Chattopadhyay S, Chakraborty S, Basu B. Cross type defected ground structure integrated microstrip antenna: a novel perspective for broad banding and augmenting polarization purity. Journal of Electromagnetic Waves and Applications 2017; 31 (5): 461-476. doi: 10.1080/09205071.2017.1284610

[33] Chakraborty S, Chattopadhyay S, Substrate fields modulation with defected ground structure: a key to realize high gain, wideband microstrip antenna with improved polarization purity in principle and diagonal planes. International Journal of RF and Microwave Computer-Aided Engineering 2016; 26 (2): 174-181. doi: 10.1002/mmce.20950

[34] Abbas SMD, Paul S, Sen J, Gupta PR, Malakar K et al. Aspect ratio: a major controlling factor of radiation characteristics of microstrip antenna. Journal of Electromagnetic Analysis and Applications 2011; 3 (11): 452-457. doi: 10.4236/jemaa.2011.311072

[35] Chattopadhyay S, Biswas M, Siddiqui JY, Guha D. Rectangular microstrip with variable air gap and varying aspect ratio: improved formulations and experiments. Microwave Optical Technology Letters 2009; 51 (1): 169-173. doi: 10.1002/mop.24025

[36] Chattopadhyay S, Chakraborty S. 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 2018; 6: 3594-3602. doi: 10.1109/ACCESS.2018.2797358