Modified Ground Plane Multi-Band Rectangular Microstrip Antennas with Reduced Cross Polar Radiation

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Abstract—New designs of dual and triple band rectangular microstrip antennas employing modified ground plane profiles are proposed. Slots introduced in the ground plane not only tune the higher order mode resonance frequency of the radiating patch but also alter the current distributions on the ground which yields multi-band response showing reduced cross polar level radiation pattern. Dual and triple band antennas yield 1 to 2% of impedance bandwidth at each frequency with gain around 1.5 to 2 dBi. Also in the multi-band design, 35% reduction in patch size against the conventional half wavelength counterpart is obtained. Further resonant length formulation at modified patch modes is presented which gives closer prediction of calculated frequency than the simulated value. The proposed multi-band design can find applications in personal communications systems requiring frequency agile capabilities.

1. INTRODUCTION

In modern era, compact antennas with multi-band operating capability have great prospect to accomplish requirements of wireless devices. Several techniques have been reported in the literature to attain dual- or multi-band characteristics. Multi-band antennas can be realized using multi-resonators or multi-layer structures, wherein additional resonant patches are electromagnetically coupled with the fed patch [1–4]. Here appropriate dimensions and spacing among the patches lead to multi-band response. Although such antennas exhibit high gain, they may be not suitable to accommodate inside modern wireless devices. Loading schemes such as inclusion of stubs, shorting pins, and slot cut techniques also yield multi-band operation [5–10]. Main advantage of short and slot loading technique is the miniaturization unlike the stub loading technique. Shorting pins give compactness but have impact on the antenna gain accompanied with high cross polar radiation. The defected ground plane structures (DGS) have gained importance in the antenna design where slots are loaded on the ground to obtain benefits like size reduction, gain enhancement, and frequency tuning [11–16]. The DGS method also has been reported to yield reduced cross polar radiation specifically at the fundamental mode.

In this paper, novel designs of dual and triple band rectangular microstrip antennas (RMSAs) backed by modified rectangular ground plane are proposed. As reported in papers, defects imbibed in the ground plane generally reduce the cross polar radiation at fundamental mode frequency. Present study highlights the cross polar reduction at higher order modes of a microstrip antenna (MSA) by employing slots on the ground plane. The MSA is equivalent to a parallel plate capacitor, where patch and ground plates are coupled through modal fringing fields [1, 2]. Thus changes in ground plane are reflected on the patch as well. Slots on the ground plane create perturbations in current distribution on patch, which leads to increased current path length and thus results in resonance frequency reduction for the same patch dimension. Initially, a dual-band RMSA design realized by etching two rectangular slots on the ground plane, which lies below and near RMSA radiating edge, is presented. These slots bring higher order TM_{30} mode frequency closer to the fundamental TM_{10} mode frequency, to realize

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dual-band response showing a similar radiation pattern. In the first and second bands, dual-band RMSA provides 20 and 40 MHz of bandwidth (BW) ($\sim 1.5\%$), respectively with broadside gain of 3 and 1.5 dBi. Further additional slots are inserted in dual-band DGS MSA at zero potential location of TM_{20} mode current distribution to achieve frequency tuning. Due to these additional slots, current distribution at TM_{20} mode frequency is perturbed which results in reorientation of vector current directions. Thus, radiation pattern at TM_{20} mode frequency is also transformed towards broadside direction yielding triple band response due to TM_{10}, TM_{20}, and TM_{30} modes. Here additional slots, which alter TM_{20} mode frequency, lead to increment in the cross polarization levels at TM_{30} mode. The cross polar at TM_{30} mode is lowered by employing triangular and semi-elliptical cut ground plane profiles, and it gives cross polar levels less than -30 dB. This cross polar level reduced triple band antenna exhibits nearly 2% impedance bandwidth (BW) with 2 dBi of broadside gain and 35% size reduction against its conventional half wavelength counterpart. Modal analysis and resonant length formulations are provided in the paper which exhibits operation of antenna and is useful in carrying out a similar antenna design. Slot theory demonstrating the effect of shape and position of slot on the antenna performance is discussed in detail in the present paper which is not discussed in detail in most of the multi-band antenna designs using DGS. The antenna proposed here was initially studied using CST simulation software version 2019, using a Taconic substrate with $\varepsilon_r = 3$, $\tan\delta = 0.002$ and substrate thickness 'h' of 1.6 mm [17]. MSA is fed using a coaxial SMA connector of inner probe with radius of 0.6 mm. For experimental validation, vector network analyser ZVH-8, spectrum analyzer FSC 6, and RF source SMB 100A were used. The measured results are found closely matching the simulated ones.

2. DUAL BAND MSA WITH PAIR OF VERTICAL SLOTS ON GROUND PLANE

A multi-band RMSA with various defects on the ground plane is shown in Fig. 1(a). The dimensions referred in the paper are in 'mm', and frequencies are expressed in 'MHz'. The final optimum structure
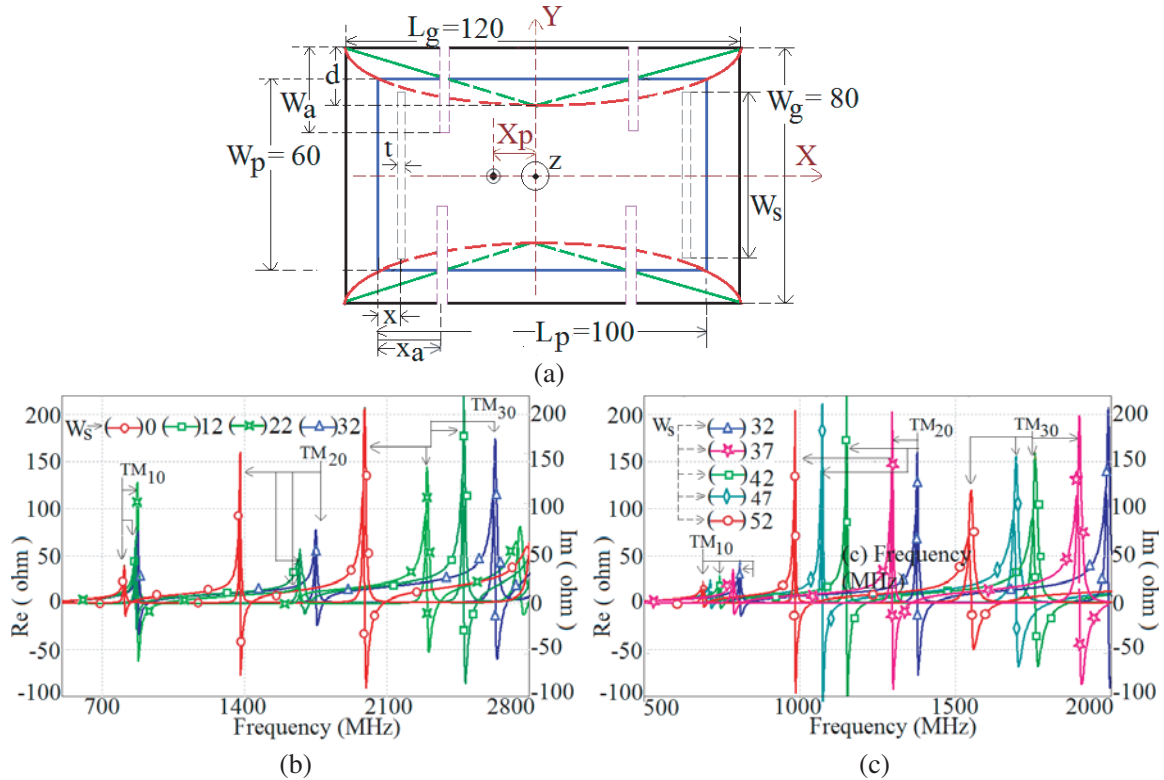

Figure 1. (a) Modified ground plane multi-band RMSA ($x = 15$ mm, $t = 2$ mm) and its (b), (c) impedance graphs for variation in slot width 'W_s'.

is evolved through the methodical approach initially starting from a simple rectangular patch backed by rectangular ground plane, followed by the slots near RMSA radiating edge and later transformed into two ground plane profiles namely, bow-tie shape and semi-elliptical shape ground planes. The design was initiated with a simple rectangular patch of chosen dimension to operate in TM_{10} mode at 900 MHz. Feed position of the antenna 'X_p' was selected at 15 mm from the origin. Simulation shows four resonant peaks including fundamental mode frequency and three higher order mode frequencies. The first peak is due to TM_{10} mode, and the next higher order modes for given feed location correspond to TM_{20}, TM_{30}, and TM_{02}. The radiation patterns at TM_{10} and TM_{30} resonant modes are broadside while at the other two modes they are conical patterns. Frequency ratio of the third mode with respect to first mode is larger, i.e., $f_{30}/f_{10} = 3$. Also cross polar radiation in TM_{10} mode frequency is very low but is considerably larger at TM_{30} mode. In order to obtain dual-band response, TM_{30} mode frequency is brought closer to fundamental mode frequency without altering the pattern at fundamental mode frequency. This is achieved by introducing two vertical slots on the ground plane in the close vicinity of radiating edges of RMSA. When slots are aligned orthogonal to the current direction, they modify modal surface currents on the patch which reduces respective frequency. Here positions of slots are specifically chosen such that they are placed below the maximum current location at TM_{30} mode on the ground plane but near minimum current location at TM_{10} mode. This imposes larger reduction in frequency at TM_{30} mode than TM_{10} mode as shown in Figs. 1(b), (c). A parametric study of variation in width of these slots is performed, and its effect on the resonant frequencies is observed. For width variation by 52 mm, TM_{30} mode frequency decreases from 2630 to 1486 MHz while fundamental TM_{10} mode frequency marginally changes. However, the impedance at TM_{10} mode is observed to be very small. The feed point is optimized to 'X_p' = 23 mm, to achieve impedance matching at two modes for the dual-band response. For 'W_s' = 52 mm, simulated frequencies of the dual-band DGS antenna are $f_{10} = 816$ MHz and $f_{30} = 1486$ MHz whereas respective measured frequencies are 812 and 1500 MHz as depicted in Fig. 2(a). In two bands BWs of nearly 20 and 40 MHz are obtained. The simulated and measured broadside gains in two bands are nearly 3 and 1.5 dBi, respectively as given in Fig. 2(a). Simulated and measured radiation patterns at both frequencies are broadside with E and H planes aligned along $\Phi = 0°$ and $90°$, respectively, as shown in Figs. 3(a)–(d). The fabricated dual-band DGS
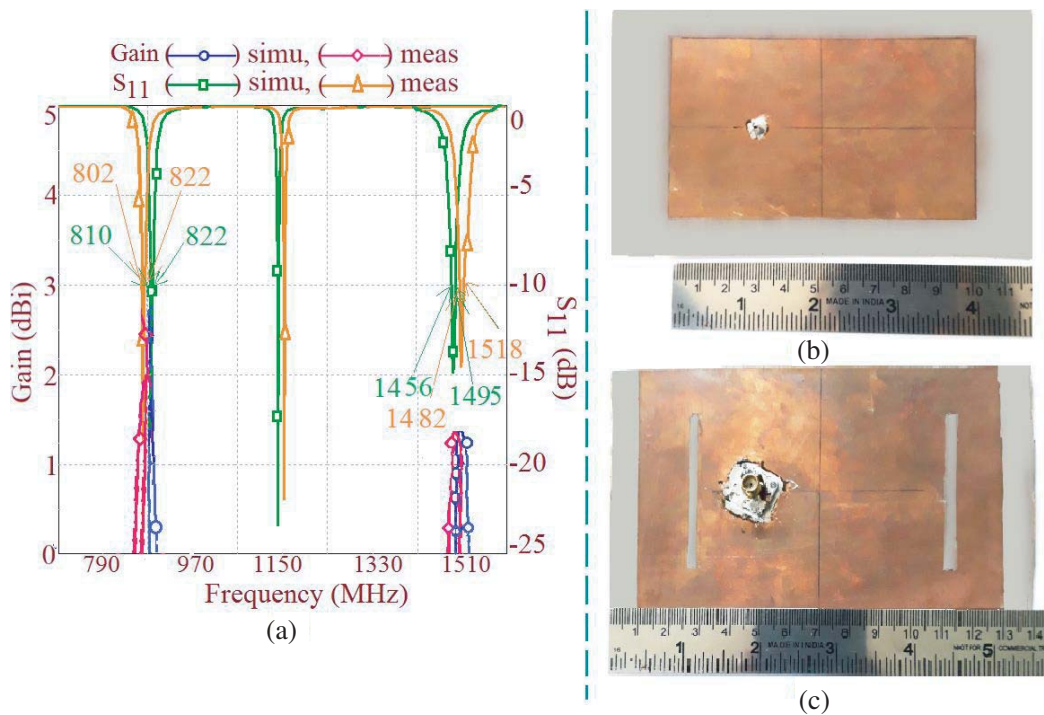

Figure 2. (a) Return loss and gain plots and (b), (c) fabricated prototype of DGS dual band RMSA.
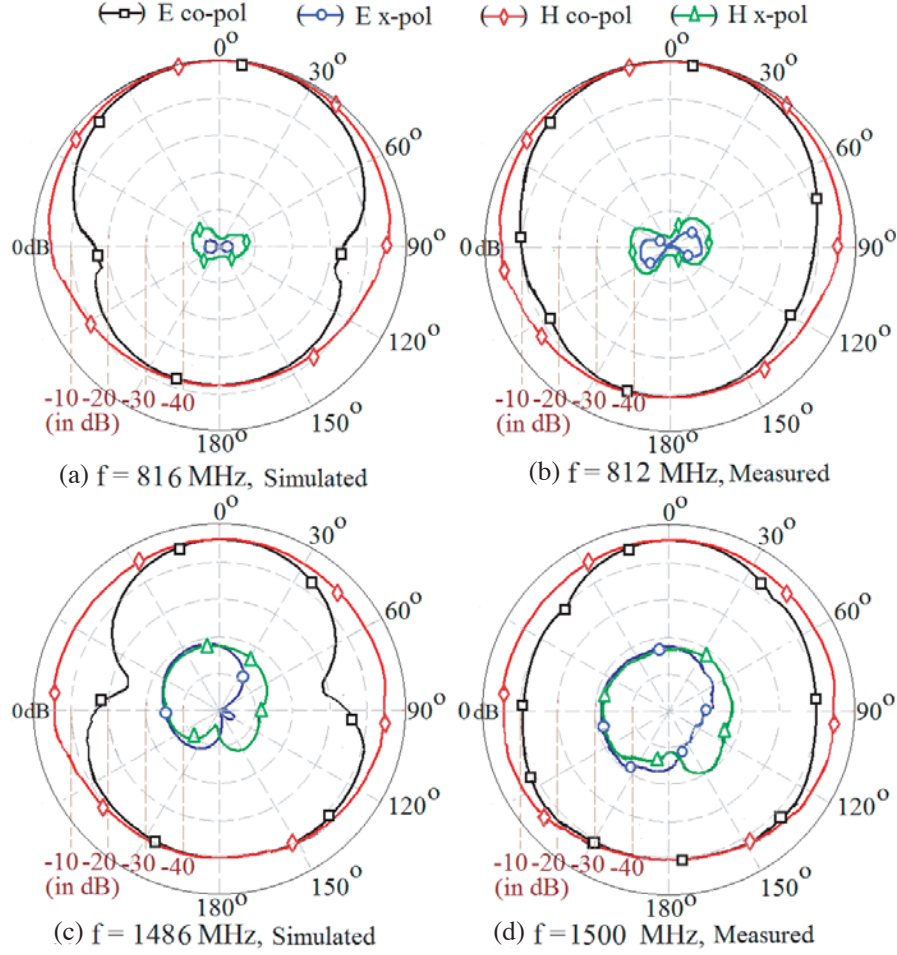
Figure 3. Radiation pattern at dual frequencies for DGS dual band RMSA.

antenna is shown in Figs. 2(b), (c). Further resonant length formulation for the proposed DGS MSA at dual modes is presented.

Resonant length formula is computed by considering a pair of slots placed near the radiating edge, beneath the patch. The surface current plots as shown in Figs. 4(a), (b) are studied for increasing slot width 'W_s' for formulating the resonant length equation at TM_{10} and TM_{30} modes, as given in Eqs. (1) and (2), respectively. As currents exhibit sinusoidal variations, sine term has been considered in both the equations. The effective dielectric constant (ε_{re}) is calculated by using an equation as given in [18]. The perturbation in resonant length is a function of slot position on the ground below the patch as well as its relative width with reference to the patch width. This effect is accounted in the second term on right hand side in Equations (1) and (2). The frequency is calculated using a resonance frequency equation for RMSA as reported in [18]. Further % error between simulated and calculated frequencies is calculated, plotted in Figs. 4(c), (d) at two modes. For different values of 'W_s', close prediction between two results is observed.

$$L_e = L_p + 1.1 \times (W_s) \times \left(\frac{W_s}{W_p}\right) \sin\left(\pi x/L_p\right) + 2h/\sqrt{\varepsilon_{re}} \tag{1}$$

$$L_e = L_p + 1.1 \times W_s \times \left(\frac{W_s}{W_p}\right) \sin\left(3\pi x/L_p\right) + 2h/\sqrt{\varepsilon_{re}} \tag{2}$$

Although dual-band response is obtained, due to vertically oriented slots, transverse current components are higher at TM_{30} mode which relatively increases cross polar radiation at higher order mode. By applying the triangular and semi-elliptical slot cuts on the ground plane, radiation pattern is improved

to a larger extent. This is shown by using the parametric study carried out by varying slot depth 'd' as mentioned in Fig. 1(a) and as shown in Figs. 5(a), (b) and Figs. 6(a), (b). For a triangular cut DGS antenna, 'd' refers to the height of triangle while in a semi-elliptical cut DGS antenna structure, 'd' represents minor axis of ellipse, major axis being patch length. By changing the value of slot depth, current distributions on the patch is altered. They become nearly unidirectional thus lowering cross polar radiation.
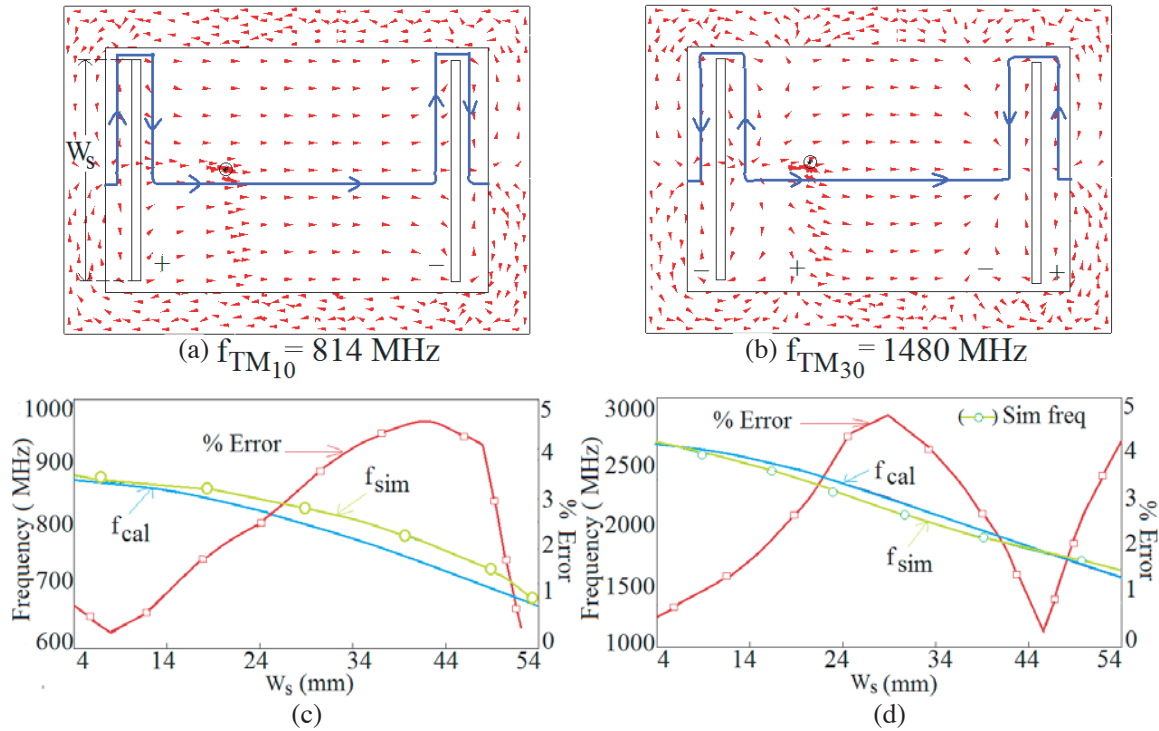

Figure 4. (a), (b) Vector surface current distributions at two modes for dual band DGS MSA and its (c), (d) dual frequencies and error plots at TM_{10} mode and TM_{30} modes.
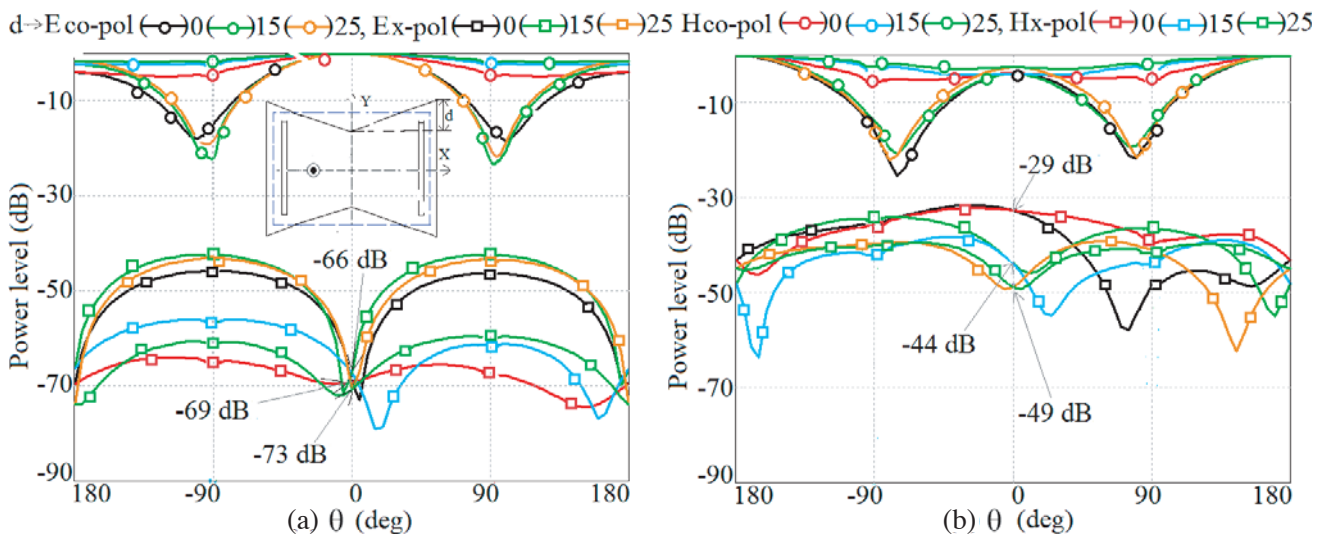

Figure 5. Radiation patterns for slot cut depth 'd' = 0, 15 and 25 mm in modified ground dual band MSA with triangular cut profile at (a) TM_{10} and (b) TM_{30} mode frequencies.
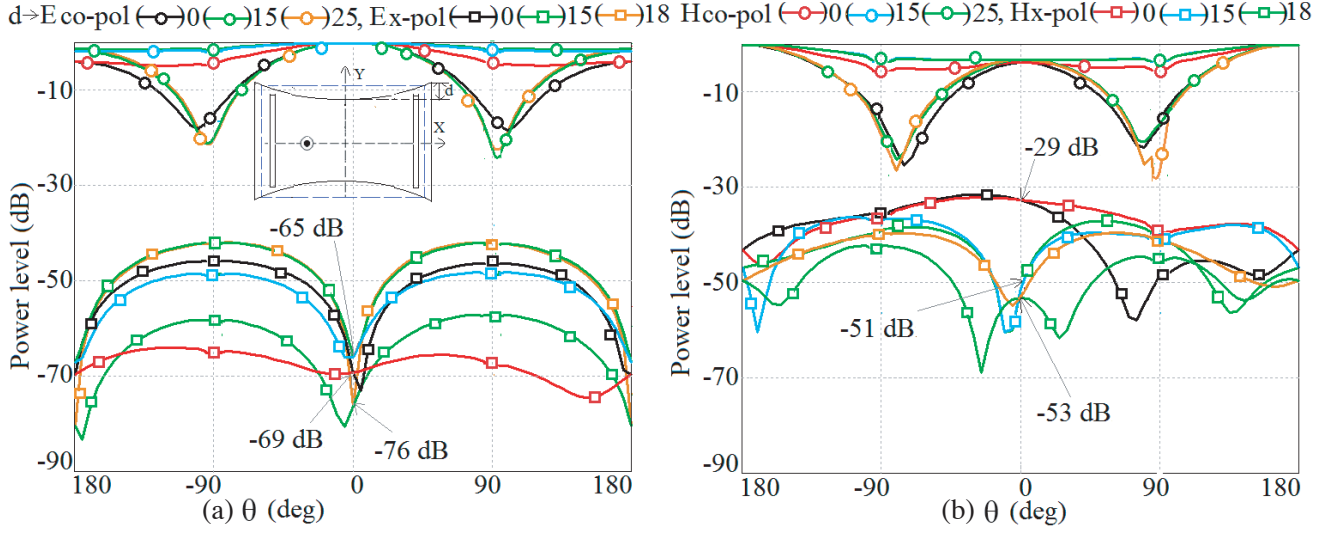
Figure 6. Radiation pattern for slot depth 'd' = 0, 15 and 25 mm in modified ground dual band MSA with semi-elliptical cut profile at (a) TM_{10} and (b) TM_{30} modes.

It can be seen that cross polar radiation in broadside direction for TM_{10} mode frequency for 'd' = 25 mm is reduced to -73 dB for triangular cut ground, whereas for semi-elliptical cut ground it is -76 dB. Cross polar reduction in the broadside direction at TM_{30} mode frequency for triangular and semi-elliptical profiles at 'd' = 25 mm is -49 dB and -53 dB, respectively. Thus semi-elliptical cut ground profile shows reduced cross polar components in radiation pattern. Greater reduction in semi-elliptical cut ground plane on contrary to triangular cut is attributed to the reorientation of current distributions with less vertical current components attaining the unidirectional current flow.

3. TRIPLE-BAND MSA USING MODIFIED GROUND PLANE

In order to achieve frequency varying characteristics in the dual-band antenna as shown in Fig. 1(a), two additional slots are inserted at the minimum current position of TM_{30} mode, i.e., nearly at one sixth of the patch length distance from the center, on either sides. Slots at these locations have no effect on TM_{30} mode frequency. Resonance curve plots for varying slot width 'W_a' is shown in Fig. 7(a). TM_{10} and TM_{20} mode frequency decreases with 'W_a', but TM_{30} mode frequency remains constant. This achieves tuning of the first band (TM_{10}) frequency without affecting second band, i.e., TM_{30} mode.
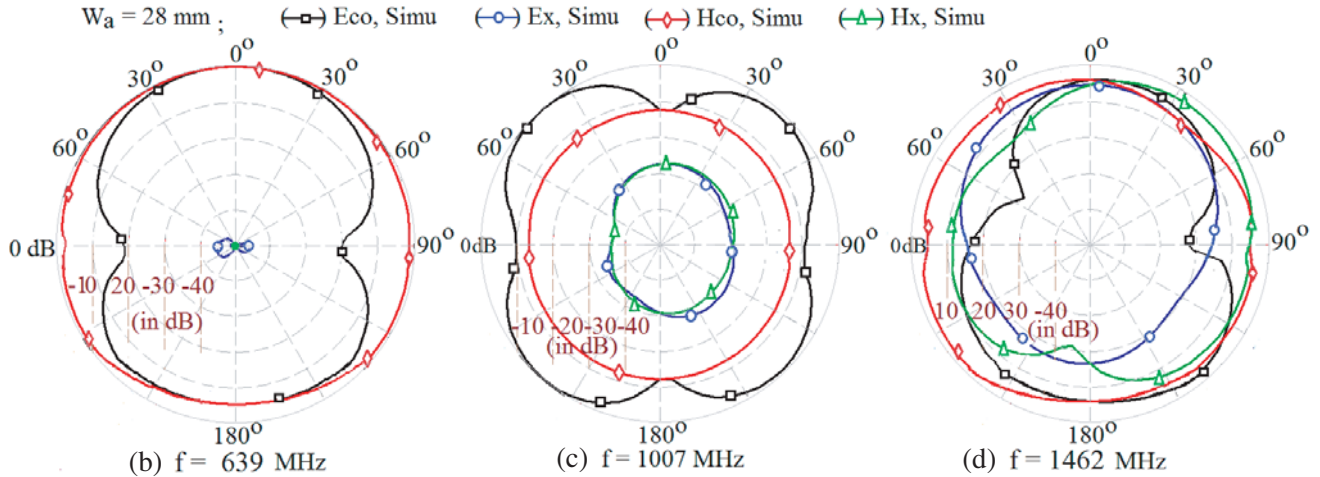
(b) f = 639 MHz   (c) f = 1007 MHz   (d) f = 1462 MHz
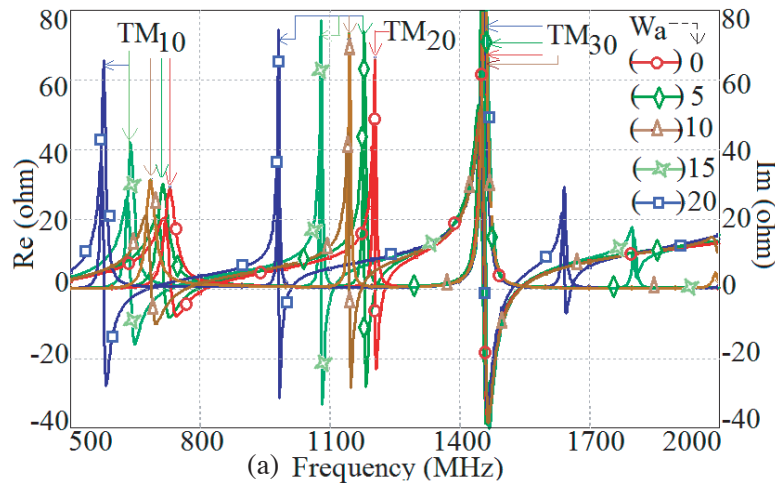
Figure 7. (a) Resonance curve plots showing variation in three modal frequencies against 'W_a', simulated radiation pattern at (b) TM$_{10}$, (c) TM$_{20}$ and (d) TM$_{30}$ resonant modes for DGS RMSA with additional vertical slots of width 'W_a'.

For 'W_s' = 52 and 'W_a' = 20 mm, simulated frequencies of RMSA backed by additional slots cut ground plane are $f_{10} = 639$ MHz, $f_{20} = 1007$ MHz, and $f_{30} = 1462$ MHz, respectively. The simulated radiation pattern plots at three modes are shown in Figs. 7(b)–(d). The insertion of additional slots increases the vertical current components and thus results in higher cross polar radiation at the third frequency (TM$_{30}$ mode). The pattern at TM$_{20}$ mode is conical. However, because of the slots, current vector reorientation at TM$_{20}$ mode takes place which increases its broadside level. However, maximum is still present in the direction away from the broadside axis. Thus with additional slot, fundamental mode frequency of MSA can be controlled without affecting other bands. Further formulation of resonant
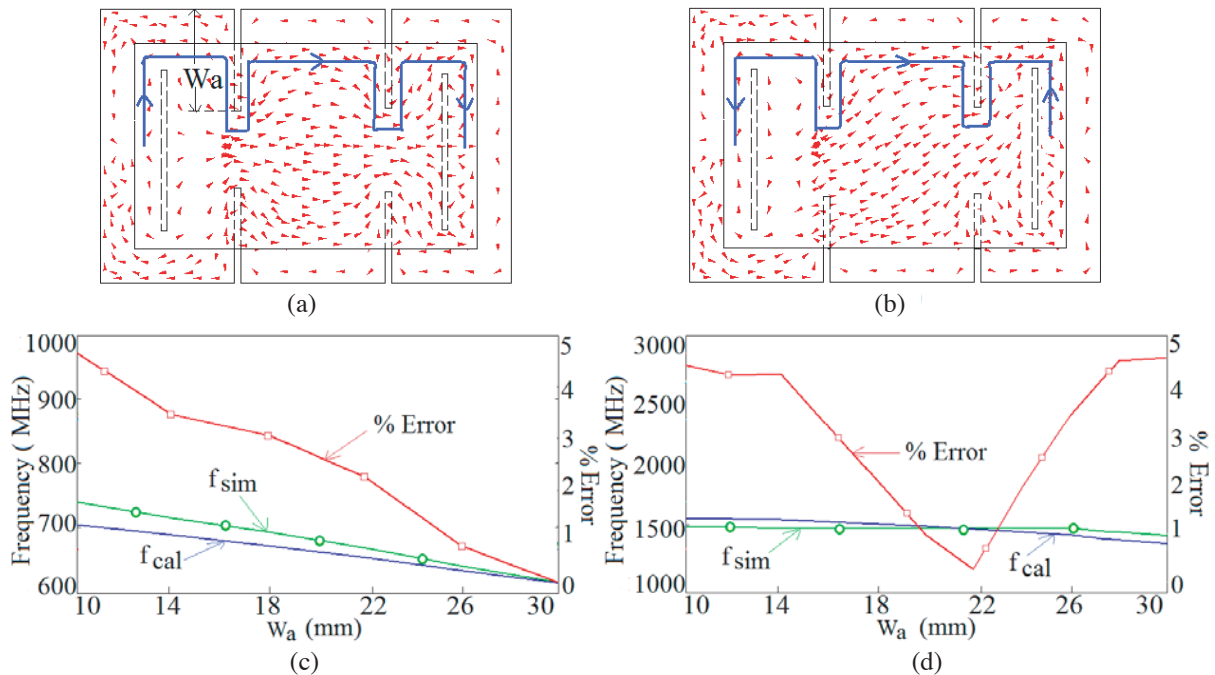

Figure 8. (a), (b) Current distribution for slot width 'W_a' = 20 mm at TM$_{10}$ mode and TM$_{30}$ mode, (c), (d) frequency and their % error plots for DGS RMSA with addition slots of width 'W_a'.

length at TM_{10} and TM_{30} modes is presented to add the effects of slot width 'W_a'. Here the effects of slot width 'W_a' are added to the effective resonant length at respective modes as given in Eqs. (1) and (2) accounting for width 'W_s'. The surface current distributions as shown in Figs. 8(a), (b) are studied for different 'W_a', and based on variations in current vectors respective mode resonant lengths are formulated as given in Equations (3) and (4) for TM_{10} and TM_{30} modes, respectively. Further frequency as calculated using following equations matches closely with simulated value as shown in Figs. 8(c), (d).

$$L_{eff} = L_e + 2.2 \times (W_a) \times \left(\frac{W_a}{W_p/2}\right) \sin\left(\pi x_a/L_p\right) + 2h/\sqrt{\varepsilon_{re}} \tag{3}$$

$$L_{eff} = L_e + 2.2 \times W_a \times 2\left(\frac{W_a}{W_p}\right) \sin\left(3\pi x_a/L_p\right) + 2h/\sqrt{\varepsilon_{re}} \tag{4}$$

4. LOW CROSS POLAR LEVEL TRIPLE BAND MSA USING MODIFIED GROUND PLANE

As it is noticed in the design of triple frequency RMSA with additional slots on the ground plane, cross polar component is very high at TM_{30} mode. Also pattern is still conical at TM_{20} mode frequency. In order to reduce cross polar level of triple frequency RMSA, ground plane is further modified by cutting triangular slots and is thus transformed into a bow-tie shape ground plane as shown in Fig. 1(a) and Fig. 9(a) inset. Effects of variation in slot depth 'd' on the cross polar levels in radiation pattern is
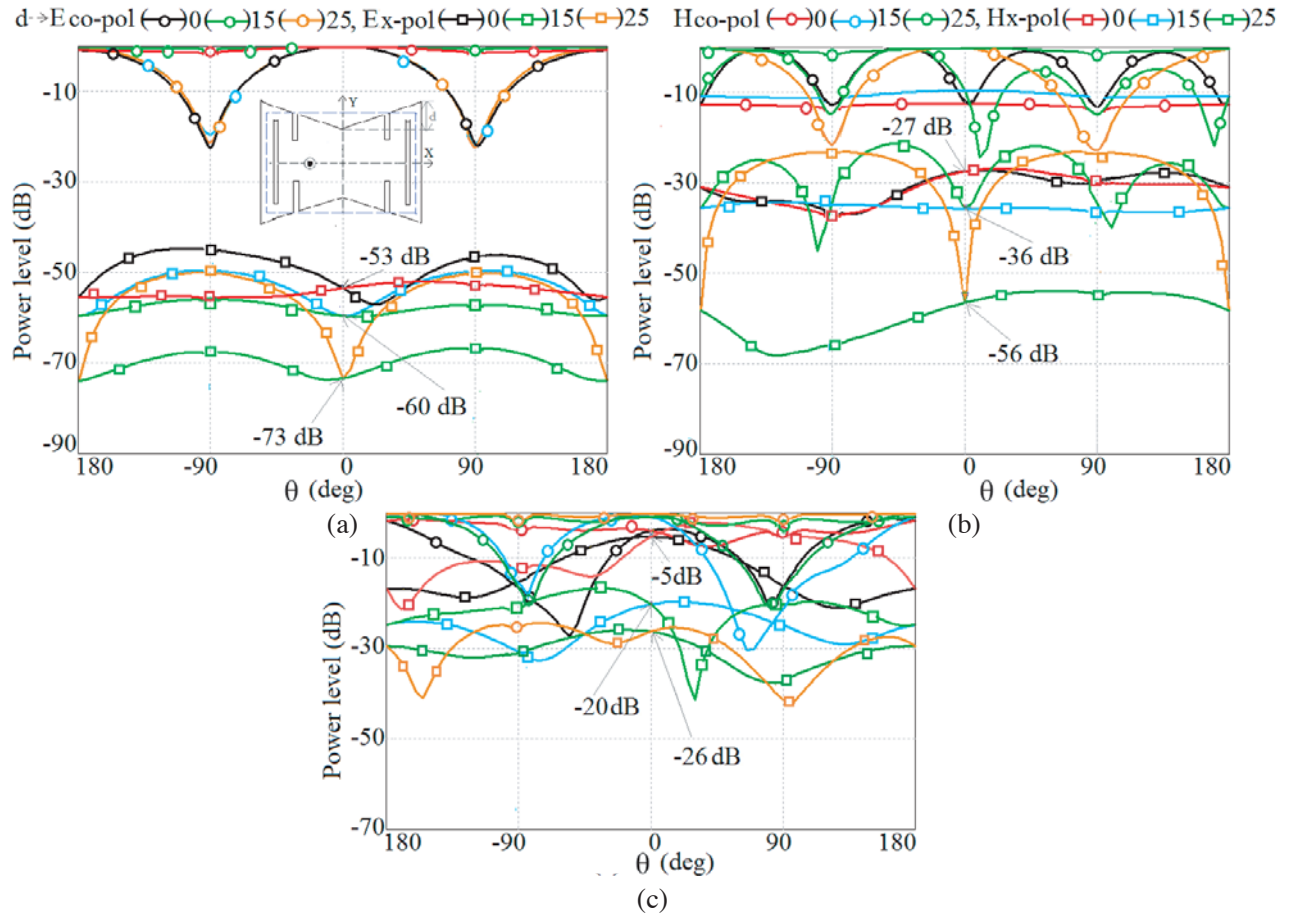

Figure 9. Radiation pattern plots for triangular slot cut ground plane profile with depth 'd' = 0, 15 and 25 mm for triple band modified ground RMSA at (a) TM_{10}, (b) TM_{20} and (c) TM_{30} mode.
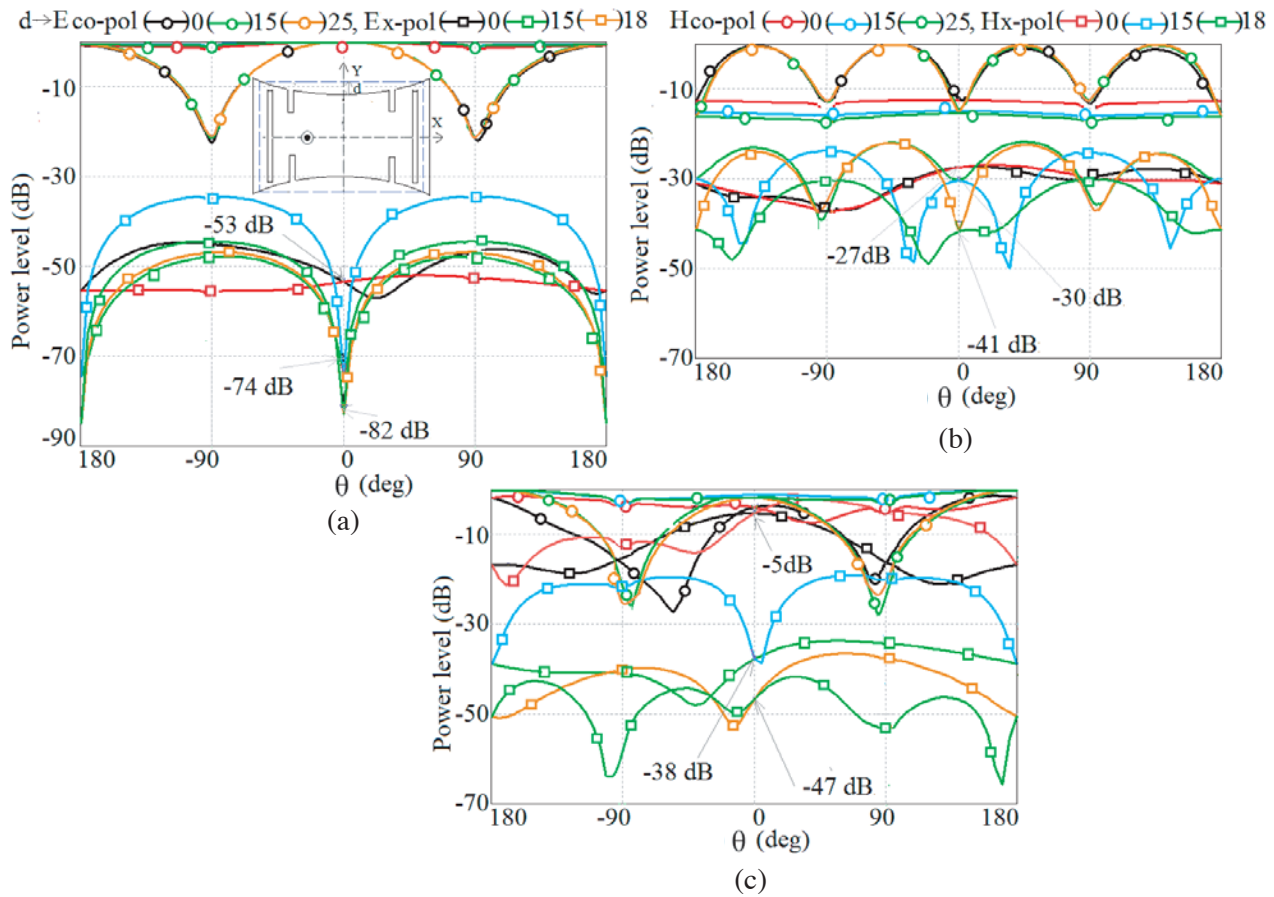
Figure 10. Radiation pattern plots for with semi-elliptical slot cut ground plane profile with depth 'd' = 0, 15 and 18 mm for triple band modified ground RMSA at (a) TM$_{10}$, (b) TM$_{20}$ and (c) TM$_{30}$ mode.

studied as shown in Figs. 9(a)–(c). At TM$_{10}$ mode, with an increment in parameter 'd' by 25 mm of the modified ground plane, the cross polar level in broadside direction decreases by 20 dB. At TM$_{20}$ mode, this reduction is from -27 to -56 dB whereas at TM$_{30}$ mode, it is reduced from -5 to -26 dB. For modified bowtie shape ground plane embedded with vertical slots on the ground plane. Simulated triple frequencies observed for $d = 25$ mm are $f_{10} = 579$ MHz, $f_{20} = 982$ MHz, and $f_{30} = 1457$ MHz, respectively.

The results are further improved by changing the ground plane to a semi-elliptical slot cut ground plane as explained in Fig. 1(a) and shown in Fig. 10(a) inset. Effects of variation in slot depth 'd' on the cross polar levels in the radiation pattern are shown in Figs. 10(a)–(c). The cross polar level at each mode drops significantly. Using semi-elliptical ground plane profile, at TM$_{10}$ mode, with an increment in 'd' from 0 to 18 mm, cross polar levels in broadside direction decreases from -53 to -82 dB. At TM$_{20}$ mode this reduction is from -27 to -41 dB whereas at TM$_{30}$ mode, it is reduced from -5 to -47 dB. Beyond 18 mm reduction in cross polar component is smaller, hence results are shown till $d = 18$ mm. The optimum results for $d = 18$ mm are shown in Fig. 11(a). Simulated frequencies of optimum triple band DGS antenna are observed at $f_{10} = 595$ MHz, $f_{20} = 947$ MHz, and $f_{30} = 1417$ MHz, and measured frequencies are observed at $f_{10} = 583$ MHz, $f_{20} = 950$ MHz, and $f_{30} = 1421$ MHz, respectively. The simulated and measured BWs at three bands are around 11 (1.8%) MHz, 10 MHz (1.3%), and 25 MHz (1.5%), respectively. At three bands antenna broadside gains are around 1.5 to 2 dBi. The smaller gain than the dual-band antenna design is attributed to modified ground plane profiles realized for the cross polar reduction. The fabricated antenna design is shown in Figs. 11(b), (c). Simulated and measured radiation patterns for the antenna are given in Figs. 12(a)–(f).
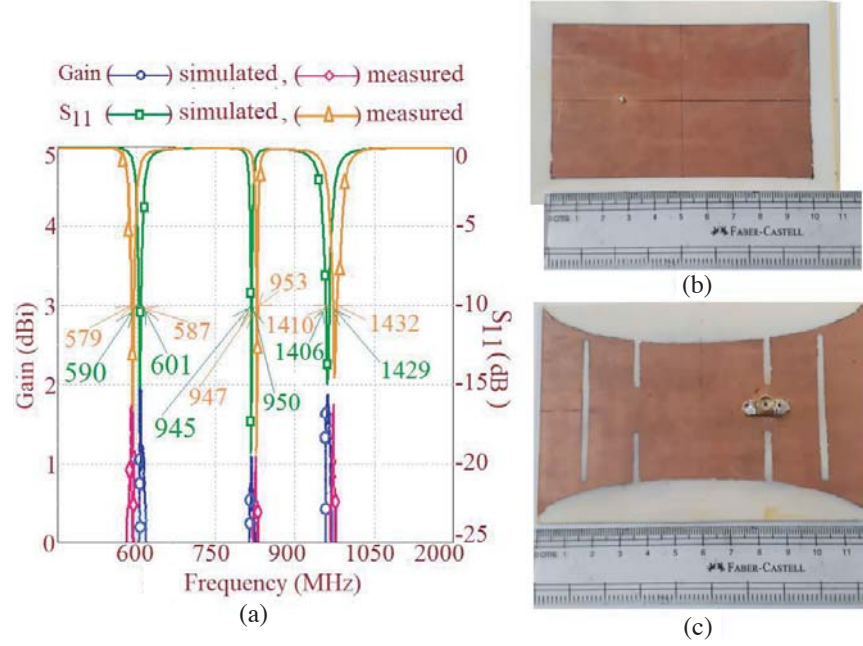
Figure 11. (a) Return loss and broadside gain plots and (b), (c) fabricated prototype for dual band DGS MSA with semi-elliptical cut ground plane profile.
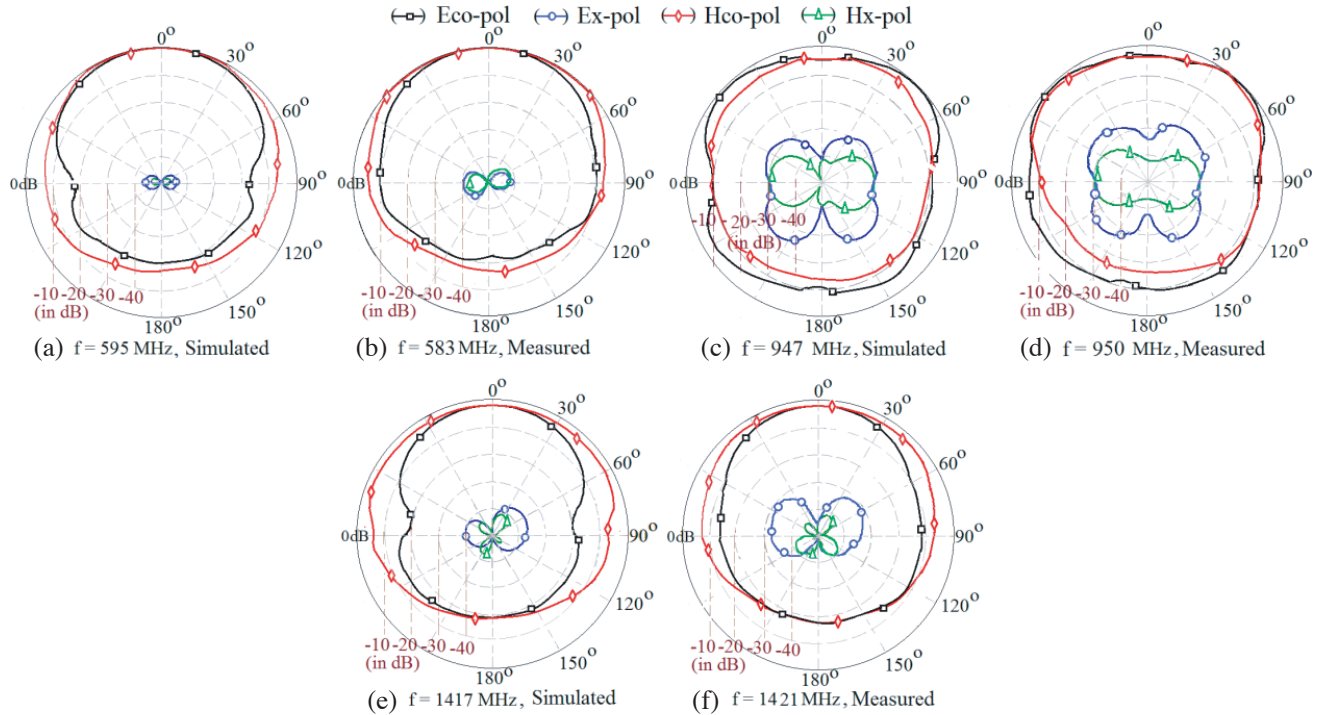
Figure 12. Radiation pattern plots for triple band DGS MSA with semi-elliptical slot cut ground plane profile.

Radiation pattern at each resonant mode is in the broadside direction. Cross polar radiation in the broadside direction at TM_{10}, TM_{20}, and TM_{30} mode frequencies for semi-elliptical profiles at $d = 18$ mm is -82 dB, -41 dB, and -47 dB, respectively. Thus semi-elliptical cut ground profile shows reduced cross polar components in radiation pattern. Conventional microstrip antenna offers approximately 3 to 5 dBi

gain accompanied with large cross polar radiation. By modifying ground plane, cross polar levels are significantly reduced with little compromise on the antenna gain.

The proposed antenna is compared with other variations of multi-band antennas reported in literature and summarized in Table 1. Stacked patches are utilized [3] which yields dual-band operation. Although large BW is obtained here, structural complexity of the antenna is increased. Dual-band antenna [4] is realized using two patch radiators suspended over ground plane, but resulting structure has relatively thick substrate about 0.09λ. Miniaturized dual-band antennas are achieved by incorporating multiple ground slots [8, 9] and result in 64% and 46% size reduction, respectively. However, the reason for multiple slots on patch is not explained in both papers. Also level of cross polar component in E

Table 1. Comparison of different reported antennas with proposed antennas.

Antenna structure Shown in	f_{c1}, BW (MHz)	f_{c2}, BW (MHz)	f_{c3}, BW (MHz)	Area saving	Gain (dBi)	Cross polar levels in broadside direction
RMSA with two slots	812, 20	1500, 40	-	10%	3, 1.5	TM_{10} -69 dBi TM_{30} -32 dBi
Tunable DGS MSA	639, 11	1007, 10	1462, 11	30%	-	TM_{10} -53.8 dBi TM_{30} -8.48 dBi
Bowtie ground tunable DGS MSA	579, 9	982, 10	1457, 10	36%	-	TM_{10} -71.6 dBi TM_{30} -39 dBi
Semi-elliptical slot cut tunable DGS MSA	583, 11	950, 10	1415, 25	35%	2, 1.2, 2	TM_{10} -81 dBi TM_{20} -42 dBi TM_{30} -46 dBi
Ref. [3]	2400, 280	5620, 960	-	-	-	< -10 dBi
Ref. [4]	2400, 175	5250, 600	-	-	7, 6	-20 dBi at each modes
Ref. [7]	926, 115	1934, 535	-	-	-	Omnidirectional
Ref. [10]	2400, 175	5250, 383	-	13%	7.5, 7.2	< -20 dBi
Ref. [11]	2500, 105	3470, 80	5750, 259	-	0.2, 0.1, 0.6	< -10 dBi
Ref. [12]	2385, 327	5400, 604	-	-	3, 4	-20 dBi at each modes
Ref. [13]	9750, 280	12150, 800	13490, 900	30%	0.46, 4.2, 4	-10 dBi at each modes
Ref. [14]	3150	4470	-	38%	-	Poor pattern
Ref. [15]	2500	3500	5500	-	0.2, 0.4, 4.76	Omnidirectional in H Plane
Ref. [16]	2400	3600	6150	-	2	< -10 dBi

and H planes is not shown. Compact patch antenna with dual-band characteristics [7, 10] is obtained by combination of the shorting pins and slot loading. Although reduction in size is achieved, suspended configuration and shorting pins make the structure complex. Multiple strips are employed [12] with defected ground plane to achieve dual band response along with benefits of size reduction and enhanced BW. However, isolation between co- and cross-polar levels in both E-plane and H-plane is only more than -20 dB. An alternative defected ground multi-band patch antenna [13] realized by cutting three U-shaped slots on patch shows significant size reduction due to the presence of slots, but cross polar levels depicted in paper are quite large making it unsuitable for any application. Though many such configurations [14–16] are seen in literature yielding multi-band response, none of the reported configurations explain evolution of their structure or modal investigation of the antenna. Also none of the reported papers have presented mathematical formulation to aid in the design of similar antennas at any desired resonant frequency. As seen from Table 1, proposed multi-band antenna is simple and conformal and offers low cross polar radiation levels as compared to reported counterparts. Due to back lobe radiation, although gain in reported antennas is on lower side, they can be used in personal communication applications requiring frequency agility.

5. CONCLUSIONS

Novel low cross polar designs of dual and triple band defected ground microstrip antennas are proposed. Modal analysis with mathematical formulations is provided to exhibit evolution of the proposed antenna structures. A pair of slots etched near the radiating edges below the patch tunes TM_{30} mode frequency and yields dual-band response. Frequency tuning is achieved by incorporating another pair of slots on ground which alters TM_{10} and TM_{20} mode frequency with reference to TM_{30} mode. Modifications in the ground plane geometry by incorporating semi-elliptical cuts reduces cross polar levels at higher order modes in addition to the fundamental mode, and cross polar radiations are suppressed to below -40 dB at higher order TM_{30} mode. TM_{10}, TM_{20} and TM_{30} modes contribute to triple band response having a similar radiation pattern in broadside direction with 1–2% impedance BW and maximum broadside gain o around 2 dBi.

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