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Wideband and Compact Regular Shape Microstrip Antennas Employing Rectangular Slots Cut Bow-Tie Shape Ground Plane

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Abstract—Wide bandwidth compact rectangular and equilateral triangular microstrip antennas employing slots cut bow-tie shape ground plane profile are proposed. Amongst all the designs, patch employing three rectangular slots cut bow-tie shape ground plane yields optimum results. Using the rectangular patch, against conventional ground plane design, increase in bandwidth by 20%, resonance frequency, substrate thickness, and patch area reduction by 32%, $0.034\lambda_g$, and 61.12%, are respectively achieved. In equilateral triangular patch design, a three rectangular slots cut bow-tie shape ground plane configuration shows bandwidth increase by 30%, and substrate thickness, fundamental mode frequency, and patch size reduction by $0.027\lambda_g$, 16.4%, and 36.28%, respectively. Proposed antennas exhibit radiation pattern in the broadside with a gain of more than 5 dBi.

1. INTRODUCTION

With the advances in wireless communication, the requirement for an antenna that requires smaller size and offers wider bandwidth (BW) has increased. With its many advantages, microstrip antenna (MSA) is preferred in many wireless applications [1]. Reduction in the size of an MSA is obtained by employing techniques like shorting post or the slot. But these compact designs offer narrow gain and BW [2–5]. In conventional half-wavelength and compact MSAs, the BW is increased by cutting the resonant slots [4–19]. Slot-cut wideband MSAs require thicker substrates, larger patch size, and thus increase the antenna volume. The MSA BW is also increased by modifying the ground plane profile [20–23]. These designs do not provide a reduction in the patch size. Thus, reported work on wideband compact MSAs does not provide a solution that offers wider BW with broadside radiation characteristics supported by the reduction in substrate thickness and patch size.

Wideband designs of rectangular MSA (RMSA) and equilateral triangular MSA (ETMSA) using the modified ground plane profile, offering reduce patch size, are presented in this paper. Modified ground plane is obtained by first cutting single rectangular slot on ground plane followed by a bow-tie shape of the same. To obtain a further reduction in the frequency, additional rectangular slots are cut. In these designs, slots yield a reduction in fundamental mode frequency, and bow-tie shape of the ground plane achieves an impedance matching for a thinner substrate to provide the wideband response. Amongst various rectangular patch configurations proposed, RMSA employing three rectangular slots cut bow-tie shape ground plane yields optimum result. It gives impedance BW of more than 45% on the substrate with thickness of $0.066\lambda_g$. As against conventional ground plane design, the optimum design offers a 20% BW increment, $0.034\lambda_g$ reduction in the substrate thickness, 32% reduction in patch fundamental mode resonance frequency, and more than 60% reduction in patch area. In ETMSA designs, as against conventional ground plane design, the patch backed by three rectangular slots cut bow-tie shape ground plane offers increment in the BW by 30%, supported with substrate thickness,

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fundamental mode frequency, and patch size reduction by $0.027\lambda_g$, 16.4%, and 36.28%, respectively. Both the optimum antennas offer radiation pattern maximum in a broadside with a gain above 5 dBi across the entire BW. In reported wideband MSAs, reduction in the antenna volume is not achieved. Against this, the proposed study does not just present a wideband configuration but offers reduction in the patch size. This is the technical novelty in the proposed MSAs. Formulation in resonant length followed by methodology to design proposed MSAs in the give spectrum is presented. This is useful in designing similar wideband compact MSAs at the given patch frequency. MSAs presented in this study are initially optimized using IE3D software [25]. Following which experimental verification is carried out inside the Antenna Laboratory, using ZVH-8, FSC 6, and SMB 100A instruments.

2. RMSA EMPLOYING SLOTS CUT BOW-TIE SHAPE GROUND PLANE PROFILE

Proximity-fed RMSA employing rectangular slots cut bow-tie shape ground plane profile is shown in Figs. 1(a), (b). A three-layer suspended configuration is used. In this configuration, two layers of FR4 substrate ($\varepsilon_r = 4.3$, $h = 0.16$ cm) are distanced by an air gap of h_a cm. The patch is fabricated on the top FR4 layer whereas the modified ground plane profile is realized on the bottom FR4 layer. RMSA is fed using the proximity strip of dimensions '$L_{pf} \times W_{pf}$' cm. For substrate thickness of 2.42 cm ($h_a = 2.1$ cm) and rectangular ground plane with dimension $L_g = 10$, $W_g = 12$ cm, the length of RMSA is optimized for the TM_{10} mode frequency of 1200 MHz. Dimensions for this frequency are calculated to be $L_p = 8.5$, $W_p = 10.2$ cm. The electrical substrate thickness for this TM_{10} mode frequency is $0.102\lambda_g$. Respective simulated and experimental BWs in proximity-fed RMSA are 295 MHz (23.22%) and 312 MHz (24.64%).

To achieve the resonance frequency reduction, a slot is cut at the maxima of modal currents at the fundamental mode. Here the slot is either placed on the patch or at the center point on the ground plane below the patch. Increment in the input impedance for the slot on patch is higher than the slot on ground plane [24]. The higher impedance will pose problems for the input impedance matching. Hence, a slot on the ground plane is considered in this study. The effects for variation in ground plane slot dimension on the patch resonant mode frequency are studied. Resonance curve plots for the same against the increasing W_s are provided in Fig. 1(c). The slot lengthens modal current lengths on the ground plane. Through the fringing fields present between the ground plane and patch, these current modifications are linked to the current components on the patch, as given in Figs. 1(d), (e). This reduces the TM_{10} mode frequency. Because of this reduction in frequency, the wideband response around the TM_{10} mode is formed in the lower frequency region. For each slot width, substrate thickness (air gap) is increased such that total antenna thickness nearly remains $0.1\lambda_g$. Here λ_g is calculated with reference to reduced TM_{10} mode frequency. The presence of a ground plane rectangular slot increases the back-lobe radiation that reduces the broadside antenna gain. Thus there exists a trade-off for the reduction in TM_{10} mode frequency against the peak gain reduction. An optimum configuration is considered, the one that offers a substantial increase in the BW for peak broadside gain remaining above 6 dBi. This is obtained for $W_s = 7.6$ cm. Results for the same are given in Fig. 1(f). Antenna parameters in this optimum design are $L_s = 0.5$, $L_{pf} = W_{pf} = 1.0$, $x_f = 0.7$, $h_a = 2.4$, $h_f = 2.3$ cm. Simulated and experimental BWs for $S_{11} < -10$ dB are 260 MHz (23.59%) and 274 MHz (24.88%), respectively. Gain over the BW is more than 6 dBi with a peak value of 6.4 dBi. Radiation pattern at the band start and stop frequencies as given in Figs. 2(a)–(d) as well as over the entire BW is in the broadside direction, showing cross-polar level lower than -15 dB against the co-polar component of radiation. The E & H-planes of radiation are directed along $\Phi = 0^\circ$ and 90°, respectively. The TM_{10} mode frequency of RMSA employing slot cut ground plane is 1053 MHz. The total substrate thickness is 2.72 cm, which is $0.099\lambda_g$ in terms of the TM_{10} mode frequency. Thus for the same substrate thickness, a slot-cut ground plane design offers a 166 MHz (13.6%) reduction in the frequency. With the same substrate thickness, using the conventional ground plane, dimensions of proximity-fed RMSA for TM_{10} mode frequency of 1053 MHz are $L_p = 9.7$ and $W_p = 11.6$ cm. It offers a simulated BW of 235 MHz (21.1%). Against this antenna, a slot-cut ground plane design offers 3% additional BW, with a patch area reduction of 22.95%.

The substrate thickness in the compact slot cut ground plane design is $0.1\lambda_g$. Here on a reduced substrate thickness, as the impedance matching cannot be realized, RMSA employing slot-cut ground

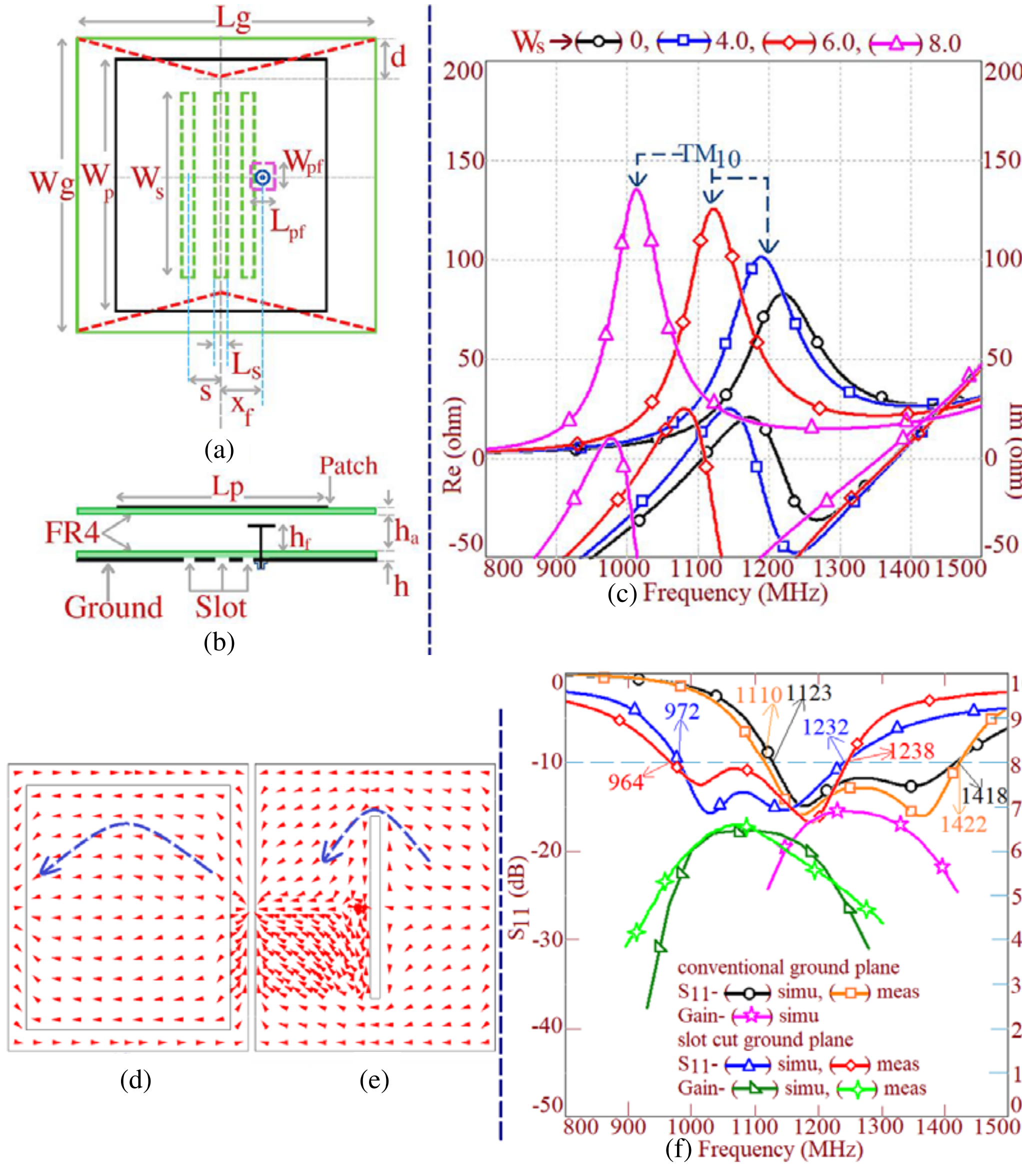


Figure 1. (a), (b) RMSA employing rectangular slots cut bow-tie shape ground plane, its (c) resonance plots against increasing W_s, $L_s = 0.5\,\text{cm}$, surface currents on the (d) patch and (e) ground plane for $W_s = 8\,\text{cm}$, (f) reflection coefficient (S_{11}) BW and broadside gain plots for optimum designs.

plane does not yield optimum BW. Hence to realize the same on smaller substrate thickness, the bow-tie shape of the ground plane is considered as given in Figs. 1(a), (b). Resonance plots for RMSA employing rectangular slot cut and bow-tie shape ground plane and surface currents plot at the modified TM_{10} mode in the bow-tie shape design are provided in Figs. 2(e), (f). In the bow-tie shape designs reported in [26–28], the reduction in patch fundamental mode frequency is not achieved. As against that in the proposed design, the presence of a rectangular slot before the realization of bow-tie shape of the ground increases perturbation in current vector lengths that reduces the resonance frequency. With the reduction in the substrate thickness, a parametric study against the variation in ground plane depth 'd' to achieve wider BW is carried out. Since this study for bow-tie shape of the ground is well elaborated in [26], it is not presented here. With a bow-tie shape of the ground, broadside peak value of the gain decreases, but it provides BW improvement on a thinner substrate. An optimum design is considered, the one where peak antenna gain is above 6 dBi. This is realized for the antenna parameters as $h_a = 2.0$,

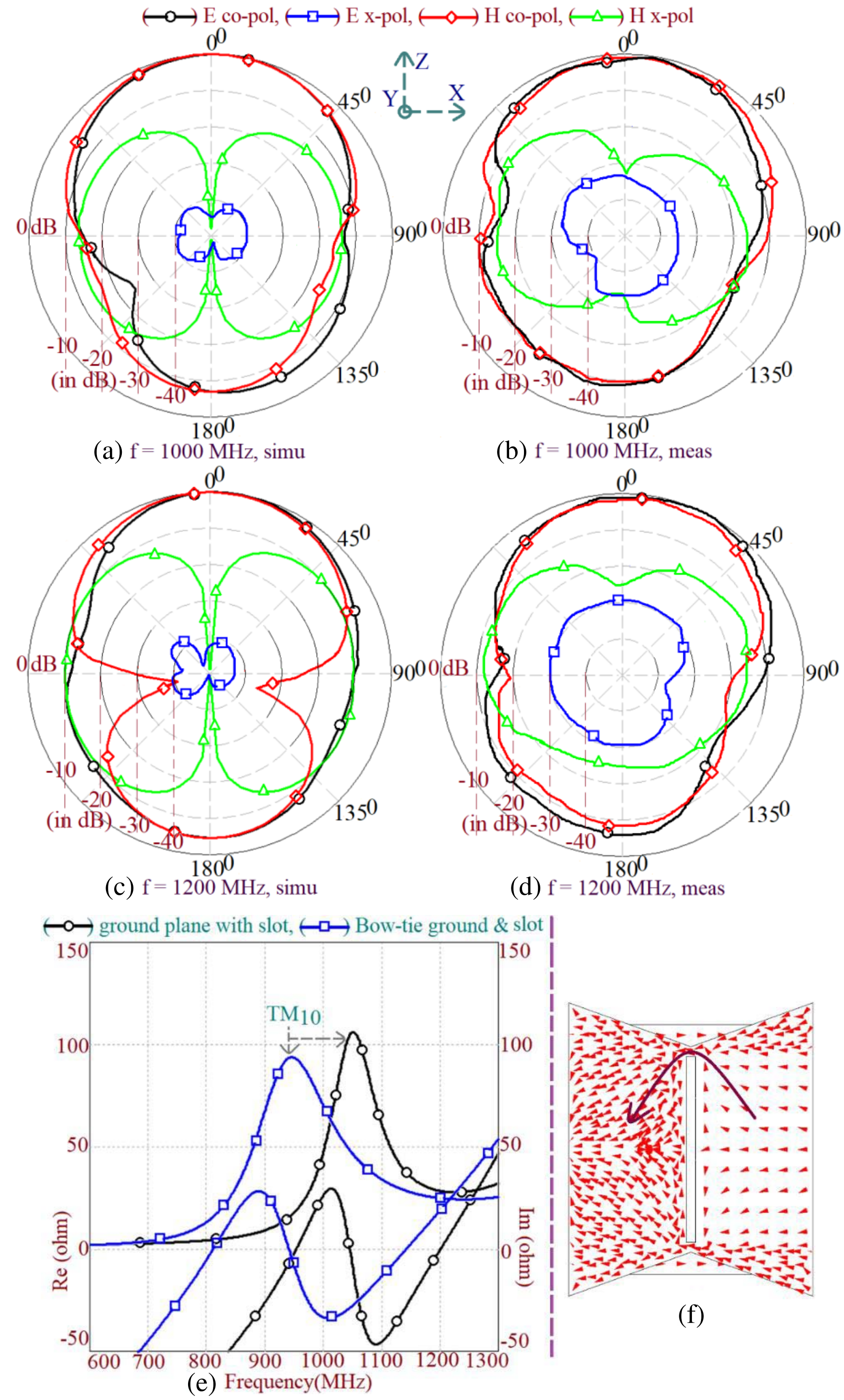


Figure 2. (a)–(d) Polar radiation pattern plots at the band start and stop frequencies of the BW for RMSA employing center rectangular slot cut ground plane, (e) resonance curve plot & (f) ground plane modal current for RMSA employing center rectangular slot cut bow-tie shape ground plane.

$h_f = 1.9$, $d = 1.8$, $L_s = 0.5$, $W_s = 7.6$, $L_{pf} = W_{pf} = 1.4$, and $x_f = 1.7$ cm. Simulated and experimental BWs are 337 MHz (33.32%) and 342 MHz (34.16%), respectively as mentioned in Fig. 3(a). Gain across the S_{11} BW is larger than 5 dBi with a maximum value of 6.1 dBi. The TM_{10} mode frequency in

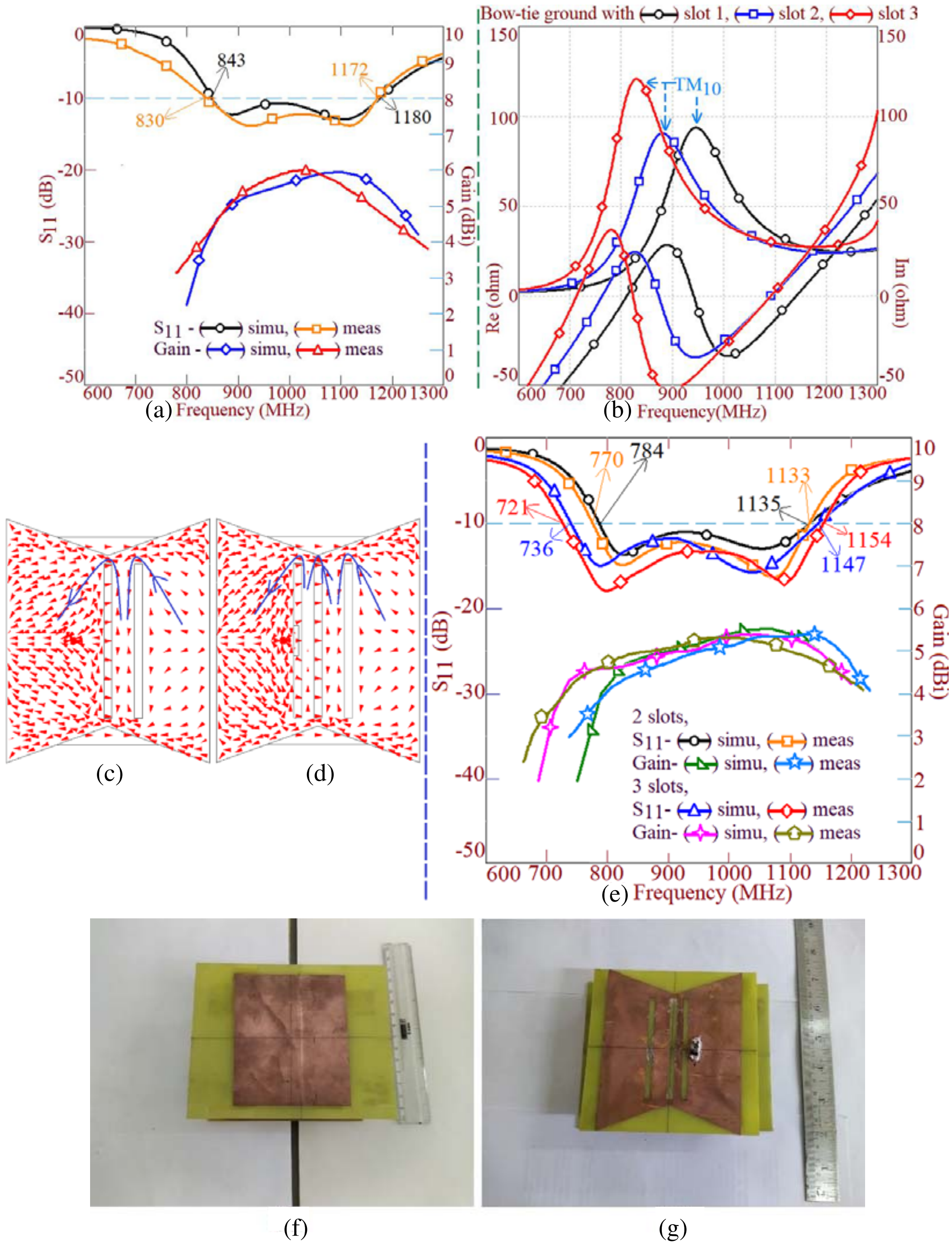


Figure 3. (a) S_{11} BW and broadside gain plots for RMSA employing slot cut bow-tie shape ground plane, (b) resonance plots, (c), (d) vector currents plots on ground at fundamental mode and (e) optimum results for 2 and 3 slots cut design with bow-tie shape ground plane profile, (f), (g) fabricated prototype for RMSA employing 3 slots cut design with bow-tie shape ground plane profile.

RMSA employing rectangular slot cut bow-tie shape ground plane is 950 MHz. Here the total substrate thickness is 2.32 cm, which is $0.076\lambda_g$ in terms of the modified ground plane TM_{10} mode frequency. Against the original rectangular ground plane design, a slot cut bow-tie shape ground plane offers an increase in BW by 10% with 22% (269 MHz) reduction in TM_{10} mode frequency. With the total substrate thickness of 2.32 cm, dimensions of RMSA for $f_{10} = 950$ MHz employing conventional ground plane are $L_p = 11.8$ & $W_p = 14.2$ cm. It offers a simulated BW of 69 MHz (7.27%). As against this, the proposed design offers 27% BW increment with a 48.26% reduction in patch area.

The reduction in patch fundamental mode frequency is further obtained by embedding additional rectangular slots on either side of the slot in center, as mentioned in Figs. 1(a), (b). Firstly, a rectangular slot is added on left side of the slot in the center, i.e., the opposite side of the proximity feed. This configuration is referred to as 2 slots cut design. The later additional slot is added on right side of the slot in the center. This design is referred to as 3 slots cut design in the following text. For $W_s = 7.6$ cm, resonance curve plots for single and multiple slots cut bow-tie shape ground plane designs & modal current distribution on ground plane are shown in Figs. 3(b)–(d). The addition of slots further perturbs the current path on the ground that reduces TM_{10} mode resonance frequency. By optimizing the proximity strip parameters, optimum BW is obtained, and their results are shown in Fig. 3(e).

For optimum design employing 2 slots, various antenna parameters are $h_a = 2.0$, $h_f = 1.9$, $d = 1.8$, $L_s = 0.5$, $W_s = 7.6$, $s = 1.5$, $L_{pf} = W_{pf} = 1.5$, and $x_f = 1.7$ cm. Respective simulated and experimental BWs in this design are 351 MHz (36.58%) and 363 MHz (38.15%). Antenna shows broadside radiation pattern across the entire BW. Gain is above 5 dBi across most of the S_{11} BW with a maximum value of 5.4 dBi. The total substrate thickness in this design is 2.32 cm, which is $0.071\lambda_g$ in thickness with respect to modified TM_{10} mode frequency of 877 MHz in 2 slots cut configuration. Thus two slots cut bow-tie shape ground plane antenna offers 15% increase in the BW supported with a 28% (342 MHz) reduction in TM_{10} mode frequency. Using conventional ground plane, RMSA dimensions for $f_{10} = 877$ MHz on the total substrate thickness of 2.32 cm are $L_p = 12.6$ & $W_p = 15.12$ cm. It offers simulated BW of 52 MHz (5.8%). As against this RMSA, two slots cut design offers a 32% BW increase supported by a 54.5% reduction in the patch area.

For optimum 3 slots cut design various antenna parameters are $h_a = 2.0$, $h_f = 1.9$, $d = 1.8$, $L_s = 0.5$, $W_s = 7.6$, $s = 1.5$ (second slot position), $s = 1.0$ (third slot position), $L_{pf} = W_{pf} = 1.5$, and $x_f = 1.7$ cm. Respective simulated and experimental BWs are 411 MHz (43.65%) and 433 MHz (46.18%). Antenna broadside gain is around 5 dBi across most of the S_{11} BW with a maximum value of 5.2 dBi. Polar radiation pattern plots at the band start and stop frequencies as provided in Figs. 4(b)–(e) and over the entire BW are in the broadside direction with a cross-polar radiation component lower than -14 dB as against co-polar level. Modified TM_{10} mode frequency in this design is 828 MHz. With respect to this resonance frequency, the substrate thickness is $0.066\lambda_g$. Thus three slots cut bow-tie shape ground plane design offers 20% increase in BW supported with 32% (391 MHz) reduction in TM_{10} mode frequency and $0.034\lambda_g$ reduction in substrate thickness. RMSA dimensions for $f_{10} = 828$ MHz on total substrate thickness of 2.32 cm are $L_p = 13.6$ & $W_p = 16.4$ cm. It offers simulated S_{11} BW of 40 MHz (4.78%). As against this RMSA, three slots cut design offers more than a 40% BW increase supported by a 61.13% reduction in the patch area.

Thus slots cut bow-tie shape ground plane designs offer substantial amount of increase in antenna BW and provide resonance frequency reduction, thus the patch area. By nearly 2 dBi, antenna broadside gain has reduced as against conventional ground plane design. But across the entire BW stable gain characteristics are observed. Fabricated prototype for the three slots cut bow-tie shape ground plane RMSA & measurement setup for polar pattern and broadside gain are shown in Figs. 3(f), (g) and 4(a), respectively. Radiation pattern and gain were measured inside the Antenna laboratory. In this reference wideband larger gain Horn antennas were employed. For the better accuracy, broadside antenna gain is measured using a three-antenna method.

3. DESIGN METHODOLOGY FOR MODIFIED GROUND PLANE RMSAS

Resonant length at TM_{10} mode in RMSA using conventional ground plane on the thicker substrate is given by using a close form Equations (1) & (2). In this equation, h_t represents the total substrate thickness, and 'c' is the velocity of light in free space. An effective dielectric constant (ε_{re}) in a three-layer suspended configuration is calculated using Equation (3). In this equation, $h_1 = h_3 = h$, i.e., FR4 thickness, and $h_2 = h_a$, i.e., the air gap thickness. For the RMSA dimensions given above, backed by a conventional ground plane, the calculated TM_{10} mode resonance frequency is 1223 MHz, which matches

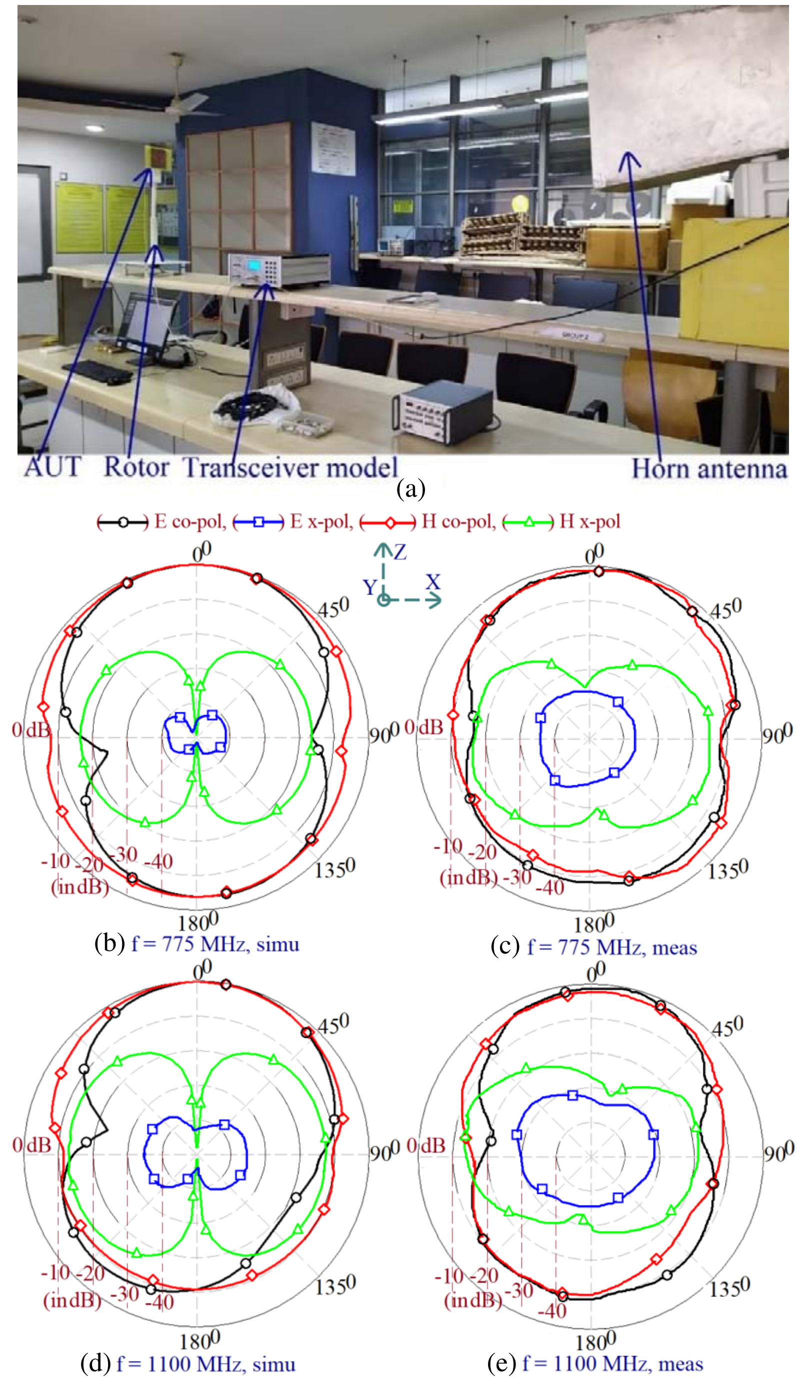


Figure 4. (a) Setup for radiation pattern measurement and (b)–(e) polar pattern plots at the band start and stop frequencies of the BW for RMSA employing 3 slots cut bow-tie shape ground.

closely with its simulated value of 1219 MHz.

$$L_e = L_p + 2\left(0.7h_t/\sqrt{\varepsilon_{re}}\right) \tag{1}$$

$$f_{10} = c/2L_e\sqrt{\varepsilon_{re}} \tag{2}$$

$$\varepsilon_{re} = \frac{\varepsilon_{r1}\varepsilon_{r2}\varepsilon_{r3}\left(h_1+h_2+h_3\right)}{h_1\varepsilon_{r2}\varepsilon_{r3}+h_2\varepsilon_{r1}\varepsilon_{r3}+h_3\varepsilon_{r1}\varepsilon_{r2}} \tag{3}$$

In rectangular slot cut ground plane design, the slot increases perturbation in resonant length at the TM_{10} mode as given in Equation (4), which reduces frequency. In the optimum slot cut configuration above, $W_s = 0.894L_p$, $W_p = 1.2L_p$. Using these relations, Equation (4) is simplified as given in (5). Frequency is calculated by using Equation (3) for $L_e = L_{es}$. The calculated frequency for the above antenna parameters is 1043 MHz, which is very close to the simulated value of 1053 MHz.

$$L_{es} = L_p + 2\,(0.7h_t/\sqrt{\varepsilon_{re}}\,) + (W_s/3.5)\,(W_s/W_p) \tag{4}$$
$$L_{es} = L_p + 2\,(0.7h_t/\sqrt{\varepsilon_{re}}\,) + 0.19L_p \tag{5}$$

The modified TM_{10} mode resonant length because of the bow-tie shape ground plane is given by Equation (6). With reference to the optimum design above, the relation between various antenna parameters as $d = 0.212L_p$, $W_s = 0.894L_p$, and $W_g = 1.412L_p$ is used to simplify Equation (6) as mentioned in Equation (7). Modified frequency is calculated using Equation (2) with $L_e = L_{es1}$. Calculated frequency is 967 MHz against the simulated value of 950 MHz.

$$L_{es1} = L_p + 2\,(0.7h_t/\sqrt{\varepsilon_{re}}\,) + 0.19L_p + (dW_s/W_g - 2d) \tag{6}$$
$$L_{es1} = L_p + 2\,(0.7h_t/\sqrt{\varepsilon_{re}}\,) + 0.19L_p + 0.192L_p \tag{7}$$

Further, the effects of the second ground plane slot are added in the resonant length as mentioned in Equation (8). The fifth term present on the right-hand side of Equation (8) is for the contribution because of the second slot. With reference to the optimum design above, by using the relation $W_s = 0.894L_p$, Equation (8) is simplified to Equation (9). For antenna parameters present in above optimum design, the frequency calculated using Equation (2) with $L_e = L_{es2}$ is 879 MHz. This value matches closely with the simulated frequency of 877 MHz.

$$L_{es2} = L_p + 2\,(0.7h_t/\sqrt{\varepsilon_{re}}\,) + 0.19L_p + 0.192L_p + W_s/6 \tag{8}$$
$$L_{es2} = L_p + 2\,(0.7h_t/\sqrt{\varepsilon_{re}}\,) + 0.19L_p + 0.192L_p + 0.149L_p \tag{9}$$

In the three slots cut design, the resonant length L_{es3} is given by using Equations (10) & (11). As slot 3 is added after the introduction of slot 2, modification in the resonant length is not the same as that for the second slot. Hence corresponding modification in the length is accounted for by the last term on the right-hand side of Equations (10) & (11). For antenna parameters present in above optimum design, the frequency calculated is 821 MHz. This value matches closely with the simulated value of 828 MHz. Using these formulations, a procedure to design a modified ground plane RMSA is explained further. In terms of S_{11} BW, the total substrate thickness, and reduction in the patch area, the RMSA employing 3 slots cut bow-tie shape ground plane gives optimum results. Hence the procedure to design a similar configuration at a given TM_{10} mode frequency of patch with modified ground plane is presented.

$$L_{es3} = L_p + 2\,(0.7h_t/\sqrt{\varepsilon_{re}}\,) + 0.19L_p + 0.192L_p + W_s/10 \tag{10}$$
$$L_{es3} = L_p + 2\,(0.7h_t/\sqrt{\varepsilon_{re}}\,) + 0.19L_p + 0.192L_p + 0.149L_p + 0.0894L_p \tag{11}$$

Initially, the desired TM_{10} mode frequency of bow-tie shape ground plane employing three slots is specified. By using Equation (12), the total substrate thickness 'h_t' at this TM_{10} mode frequency is calculated. h_t equals $2h + h_a$, where 'h' is the substrate thickness of the FR4 layer. While calculating the thickness, the initial value of ε_{re} is not known. Hence an approximation of ε_{re} as 1.1 is selected to start with. This approximation is based on the value of ε_{re}, present in the above optimum design for the mentioned antenna parameters. From the calculated value of h_t, the value of h_a that is practically realizable is selected. Using this value of h_a and for $h_1 = h_2 = h$, ε_{re} is calculated again by using Equation (3). Since the recalculated value is marginally different from the initial approximation, the same is used in further calculations. Using Equation (13) effective patch length 'L_{er}' at a given TM_{10} mode frequency is obtained. Patch length 'L_p' is obtained by using Equation (14). By rearranging terms in Equation (11), Equation (14) is realized. RMSA width W_p is selected as $1.2L_p$. Ground plane dimensions are taken as, $L_g = 1.176L_p$, $W_g = 1.2L_g$. The three rectangular slot dimensions are selected as $W_s = 0.894L_p$ & $L_s = 0.053W_s$. The slot dimension in bow-tie shape is selected as, $d = 0.212L_p$. Slot position on the left side is selected as $0.176L_p$, and on right side of the center, position of the slot is taken as $0.118L_p$. Here, the right side refers to the side of the patch where the proximity feed is present. Square proximity strip of length $L_{pf} = 0.176L_p$ is positioned at a distance of $x_f = 0.2L_p$ from the patch center and at a thickness of $h_s = 0.059\lambda_{g10}$ from the ground plane. Here $h_s = h_f + h$, as mentioned in Figs. 1(a), (b). The λ_{g10} refers to wavelength at the patch TM_{10} mode frequency in the suspended dielectric substrate.

$$h_t = 0.066\,(c/f_{10}\sqrt{\varepsilon_{re}}\,) \tag{12}$$
$$L_{er} = c/2f_{10}\sqrt{\varepsilon_{re}} \tag{13}$$
$$L = (L_e - (1.4h_t/\sqrt{\varepsilon_{re}}\,))\,/1.6204 \tag{14}$$

Using this procedure, RMSA employing 3 slots cut Bow-tie shape ground is designed for $f_{10} = 1200$ MHz and its various antenna parameters are, $L_p = 5.8$, $W_p = 7.0$, $L_g = 6.8$, $W_g = 8.2$, $d = 1.25$, $W_s = 5.2$, $L_s = 0.3$, $s = 1.0$, $s = 0.7$ (slot on the right side), $h_s = 1.36$, $h_f = 1.2$, $x_f = 1.2$, $L_{pf} = W_{pf} = 1.3$ cm. Antenna is fabricated and measurement is carried out. Respective simulated and experimental BW is 603 MHz (46%) and 622 MHz (46.8%). Simulated value of TM_{10} mode frequency observed in this design is 1152 MHz, which is closer to the desired frequency. The re-designed antenna shows similar pattern and gain response to that observed in the original design above. Since the results were similar, to avoid repetition, plots for the re-designed antenna are not shown. Thus, using the proposed design methodology, variations of RMSA employing modified slot cut ground plane can be designed around a given TM_{10} mode frequency. This frequency can be as per the desired wireless application.

4. ETMSA EMPLOYING MODIFIED GROUND PLANE PROFILE

ETMSA employing slots cut bow-tie shape ground plane is given in Figs. 5(a), (b). Side length 'S' in ETMSA is calculated by equating its area to the RMSA area, selected above. Based on this equivalence, 'S' is found to be 14.2 cm. Using ground plane dimension of $L_g = 13.8$ & $W_g = 15.7$ cm and substrate thickness of 2.92 cm ($h_a = 2.6$ cm), this ETMSA is resonant in its TM_{10} mode frequency of around 1000 MHz. Electrical substrate thickness is $0.0964\lambda_g$ at this resonant frequency. Proximity-fed ETMSA yields respective simulated and experimental BWs of 137 MHz (13.84%) and 145 MHz (14.68%), as given in Fig. 5(f). In ETMSA, maximum current location at TM_{10} mode lies around the centroid of the geometry. Hence exactly below the centroid point on ETMSA, a slot of length L_s & width W_s is cut on the ground plane, as shown in Fig. 5(a). Slot on the ground alters modal currents on the ground plane as explained in Figs. 5(d), (e). These modifications are linked to the perturbation of the patch currents that reduces TM_{10} mode frequency as mentioned in Fig. 5(c). With an increase in W_s, a wideband response is obtained in the lower frequency spectrum. Hence to keep the same value of electrical substrate thickness, an air gap is increased for every W_s. By considering the trade-off between the reduction in resonance frequency, increase in the BW against decrease in the broadside gain, an optimum design is selected. For this design antenna parameters are $S_x = 4.1$, $X_f = 5.6$, $L_s = 0.4$, $W_s = 8.2$, $W_{pf} = L_{pf} = 1.5$, $h_a = 2.8$, $h_f = 2.5$, $S = 14.2$ cm. For $S_{11} < -10$ dB, simulated and experimental BW are 163 MHz (17.56%) and 179 MHz (19.42%), respectively as provided in Fig. 5(f). Peak broadside gain in conventional ground plane ETMSA is 7 dBi. Against this, slot-cut ground plane ETMSA gives the peak broadside gain of 6.7 dBi. Radiation pattern plots near the band edge frequencies & across the BW is in the broadside direction showing cross-polar levels less than -15 dB, as given in Figs. 5(g), (h) & 6(a), (b). The TM_{10} mode frequency in slot cut ground plane design is 893 MHz. Against conventional ground plane design, slot-cut ground plane MSA offers 4% increase in BW and a 7.84% reduction in the frequency. At $f_{10} = 893$ MHz, with the total substrate thickness of 3.12 cm ($0.095\lambda_g$), ETMSA backed by conventional ground plane has $S = 15.8$ cm. It gives a simulated BW of 118 MHz (12.92%). Against this, a slot cut ground plane design offers 4% additional BW with a reduction in patch area by 19.31%.

To yield wider BW on thinner substrate, the ground plane profile employing bow-tie shape is considered as provided in Fig. 5(a). With an introduction of bow-tie shape, the perturbation in surface currents increases. This reduces TM_{10} mode frequency, as shown in Figs. 6(c), (d). An optimum design is considered, the one that provides substantial increment in the BW and reduction in fundamental mode frequency for the peak gain to be around 6 dBi. Based on this, antenna parameters for the optimum configuration are $X_f = 6.5$, $L_s = 0.4$, $W_s = 8.2$, $W_{pf} = L_{pf} = 1.5$, $h_a = 2.2$, $h_f = 2.1$, $d = 3.5$ cm. Respective BWs observed in simulation and experimentation are 273 MHz (29.72%) and 283 MHz (31.15%), as shown in Fig. 6(e). The total substrate thickness is 2.52 cm, which is $0.0745\lambda_g$ in terms of the TM_{10} mode frequency (866 MHz) of the optimum design. Thus as against the initial

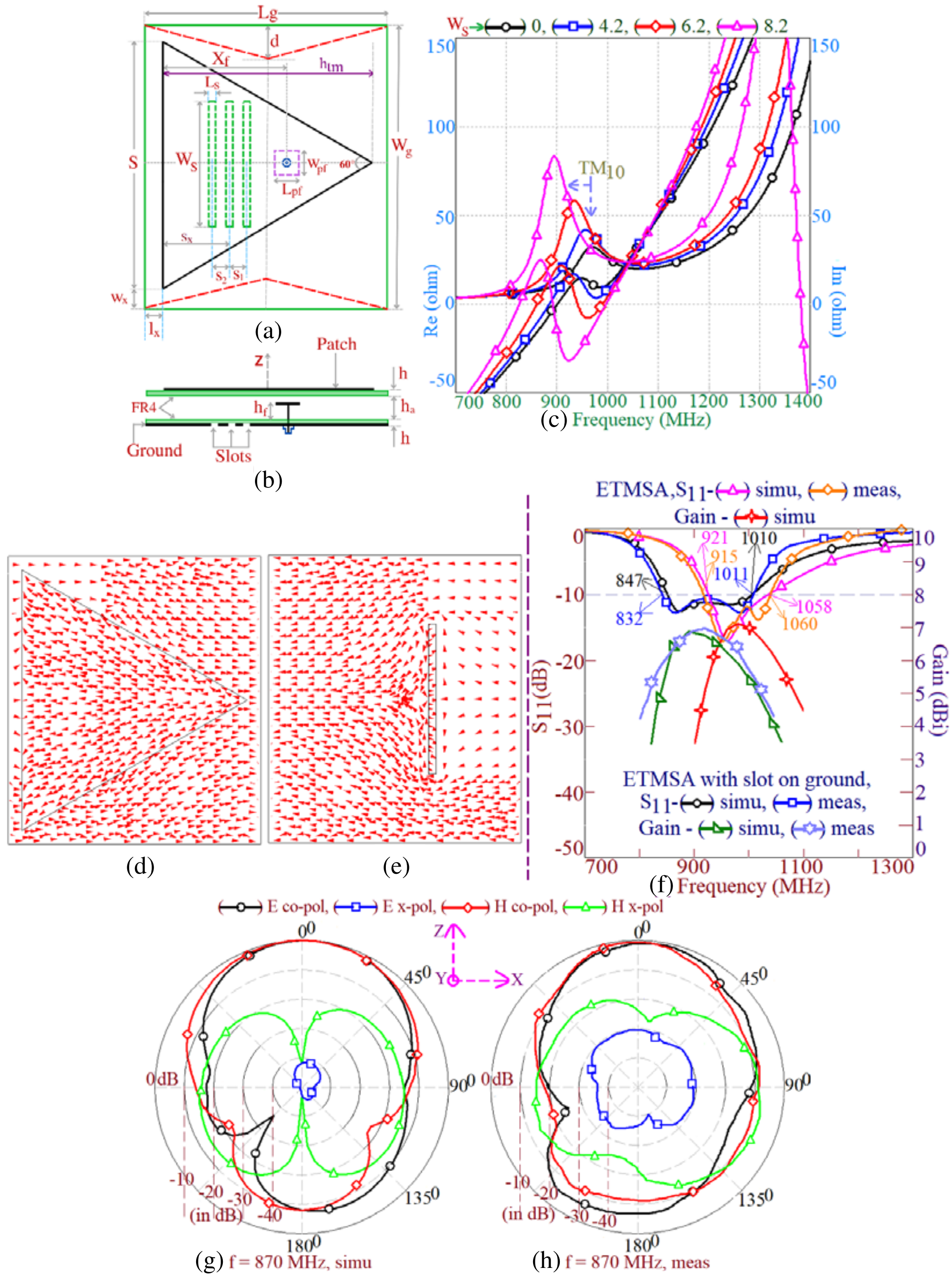


Figure 5. (a), (b) ETMSA employing modified ground plane profile, its (c) resonance plot for $L_s = 0.4\,\mathrm{cm}$ and varying W_s, TM_{10} mode current distribution with the slot on (d) patch and (e) ground plane, (f) optimum results and (g), (h) polar pattern plots at the band start frequency of the S_{11} BW.

conventional ground plane antenna, ETMSA employing slot cut bow-tie shape ground plane offers 16% BW improvement, 10.62% reduction in the TM_{10} mode frequency, and $0.0219\lambda_g$ reduction in substrate thickness. At $f_{10} = 893\,\mathrm{MHz}$ and with substrate thickness of 2.52 cm employing conventional ground plane, ETMSA requires $S = 16.4\,\mathrm{cm}$. It offers simulated BW of 65 MHz (7.23%). Against this, bow-tie

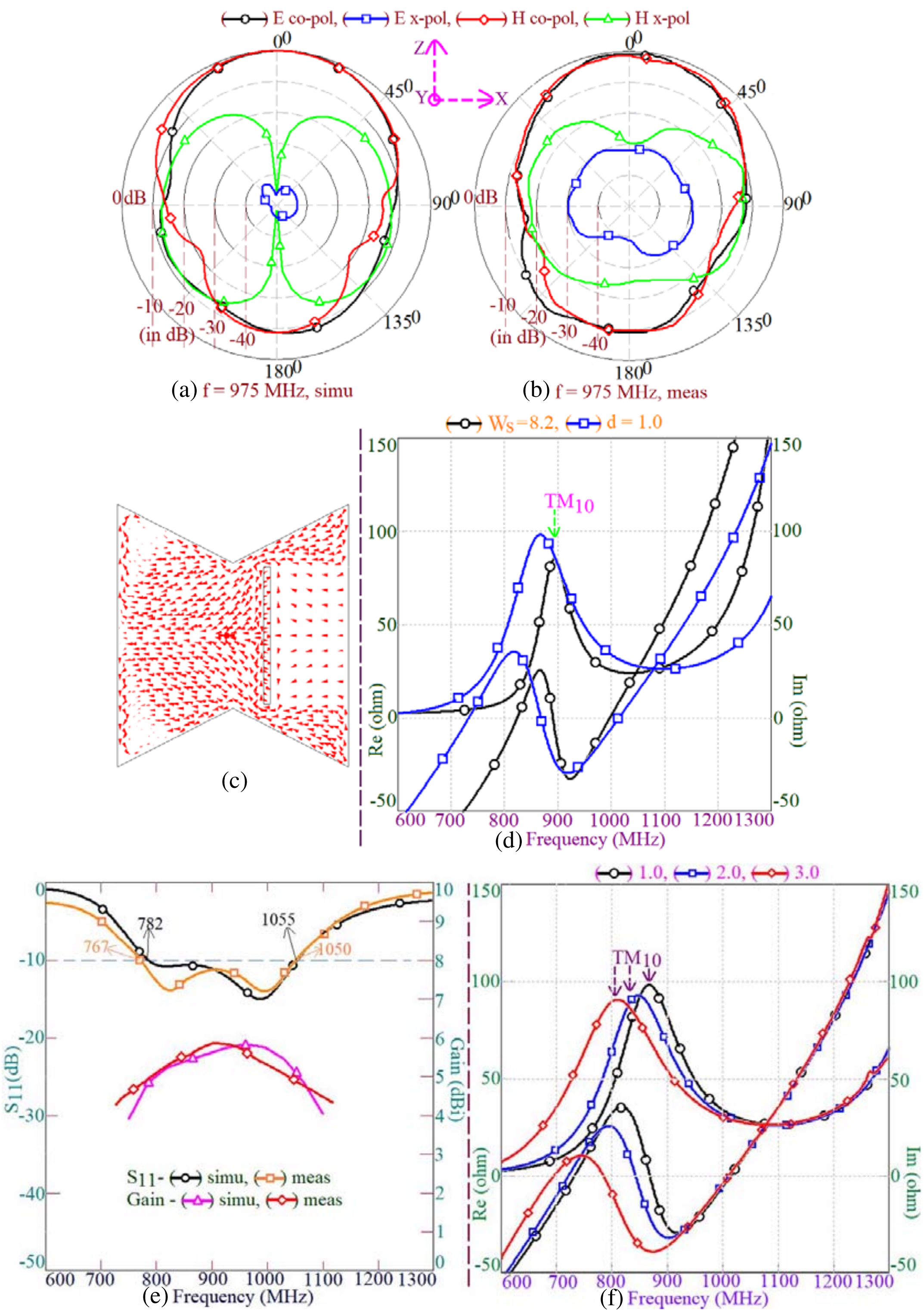


Figure 6. (a, b) Radiation pattern at the band stop frequency of S_{11} BW for ETMSA employing slot cut ground plane, (c) modal current distribution, (d) resonance curve plots, and (e) optimum BW & gain results for ETMSA employing slot cut bow-tie shape ground plane, (f) resonance curve plots for ETMSA employing multiple slots cut bow-tie shape ground plane.

shape design offers 23% additional BW with a patch area reduction by 25%. Further reduction in TM_{10} mode frequency is achieved by cutting additional slots as shown in Fig. 5(a). Similar to the above, 2 slots and 3 slots cut designs are studied. Slots are placed on either side of the slot in the center, i.e., around the ETMSA centroid point. Initially, a slot is added on left side of the first slot, referred to as 2 slots cut design. Next, the third slot is added on right side of the first slot, referred to as 3 slots cut design. The right side refers to the patch side where the proximity strip is present.

As provided in Figs. 7(a), (b), slots perturb surface current components on the ground plane at ETMSA TM_{10} mode that reduces its frequency as shown in Fig. 6(f). For the optimum configuration, broadside gain of greater than 5 dBi is considered. An optimum BW is realized by changing the proximity strip parameters. Antenna parameters in the optimum design using 2 slots are $S_x = 4.1$, $S_2 = 1.0$, $X_f = 6.5$, $L_s = 0.4$, $W_s = 8.2$, $W_{pf} = L_{pf} = 1.5$, $h_a = 2.2$, $h_f = 2.1$, $d = 3.5$ cm. Respective BWs as noted in simulation and measurement are 308 MHz (34.37%) and 318 MHz (35.61%), as shown in Fig. 7(c). Antenna exhibits broadside pattern and gain characteristics across the entire BW with a maximum gain value of 5.9 dBi. In this design, the total substrate thickness is 2.52 cm, which is $0.073\lambda_g$ in terms of TM_{10} mode frequency (846 MHz) in the 2 slots cut design. Compared to the conventional ground plane antenna, ETMSA employing 2 slots cut bow-tie shape ground offers 20% BW improvement, 12.69% reduction in the TM_{10} mode frequency, and $0.0234\lambda_g$ reduction in the substrate thickness.

For $f_{10} = 846$ MHz and with substrate thickness of 2.52 cm using a conventional ground plane, ETMSA requires $S = 17$ cm. It gives the simulated BW of 59 MHz (6.8%). As against this, bow-tie shape design offers 28% additional BW supported with reduction in the patch area by 30.1%.

Antenna parameters present in the optimum design using 3 slots are $S_x = 4.1$, $S_2 = 1.0$, $S_1 = 1.0$, $X_f = 6.5$, $L_s = 0.4$, $W_s = 8.2$, $W_{pf} = L_{pf} = 1.5$, $h_a = 2.2$, $h_f = 2.1$, $d = 3.5$ cm. Simulated and experimental BWs are 381 MHz (43.97%) and 393 MHz (45.88%), respectively as provided in Fig. 7(c). The total substrate thickness is 2.52 cm, which is $0.069\lambda_g$ in terms of the TM_{10} mode frequency (810 MHz) of 3 slots cut configuration. Against the original conventional ground plane antenna, a 30% BW improvement, 16.4% reduction in TM_{10} mode frequency, and $0.0274\lambda_g$ reduction in the total substrate thickness are achieved. At $f_{10} = 810$ MHz in ETMSA, which is backed by a conventional ground plane, 'S' equals 17.7 cm on the total substrate thickness of 2.52 cm. It gives simulated BW of 53 MHz (6.144%). As against this, the slots cut bow-tie shape design offers 39% additional BW with a patch area reduction by 36.28%. The antenna exhibits broadside radiation pattern across the complete BW, as shown in Figs. 7(d)–(g). The E-plane is aligned along $\varphi = 0°$. Across the entire S_{11} BW, gain remains above 5 dBi with the maximum value of 5.7 dBi. Amongst all configurations, three slots cut bow-tie shape ground plane design of ETMSA shows optimum results for the BW increment, reduction in fundamental mode frequency, and the patch size. The fabricated antenna for three slots cut design is provided in Figs. 8(a), (b).

5. DESIGN METHODOLOGY FOR MODIFIED GROUND PLANE ETMSAS

Resonance frequency in ETMSA is governed by its side length. Effects of rectangular slots and bow-tie shape of the ground alter the current distribution at TM_{10} mode, which effectively changes its side length. The TM_{10} mode resonance frequency in ETMSA is given by using Equation (15). Here the second term on the right-hand side of Equation (16) gives fringing field extension length. For ETMSA with $h_t = 2.92$ & $S = 14.2$ cm, the calculated TM_{10} mode frequency is 982 MHz. This matches closely with a simulated value of 969 MHz. The slot alters the directions of TM_{10} mode currents on the ground, and its effect on patch side length is formulated using Equation (17). In the above optimum configuration of ground plane rectangular slot, $W_s = 0.5775S$. Using this relation, Equation (17) is simplified as given in Equation (18). For $S_e = S_{es}$, TM_{10} mode frequency because of the rectangular slot is calculated using Equation (15). For antenna parameters as present in the optimum slot cut ground plane design, the frequency calculated is 927 MHz. This matches closely with the simulated value of 893 MHz.

$$f_{10} = 2c/3S_e\sqrt{\varepsilon_{re}} \tag{15}$$

$$S_e = S + (2h_t/\sqrt{\varepsilon_{re}}) \tag{16}$$

$$S_{es} = S + (2h_t/\sqrt{\varepsilon_{re}}) + W_s/10 \tag{17}$$

$$S_{es} = S + (2h_t/\sqrt{\varepsilon_{re}}) + 0.05775S \tag{18}$$

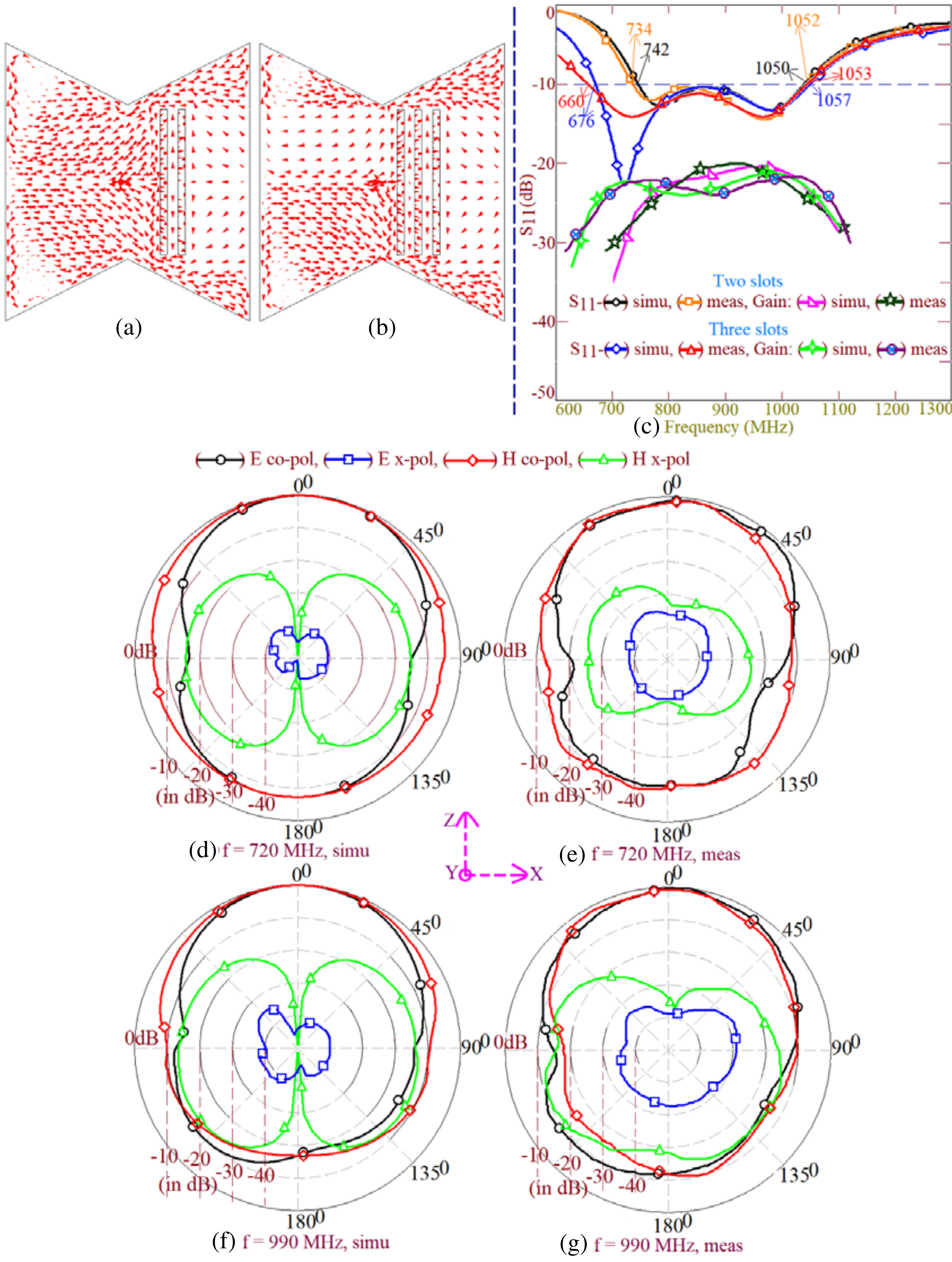
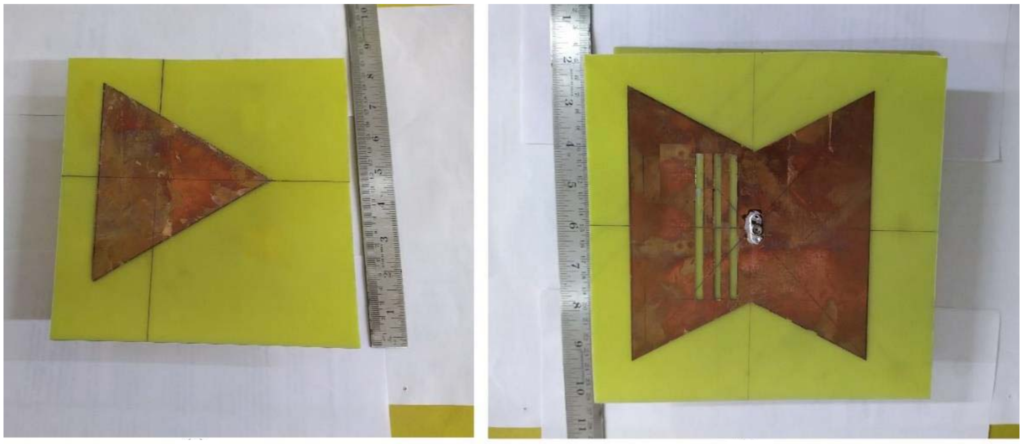


Figure 7. Surface current plots on the ground plane for (a) 2 and (b) 3 slots, (c) optimum BW and gain results for ETMSA employing 2 and 3 slots cut Bow-tie shape ground plane, and radiation pattern at the band (d), (e) start and (f), (g) stop frequencies of the BW for ETMSA employing by 3 slots cut Bow-tie shape ground plane.

Bow-tie shape of the ground plane modifies the TM_{10} mode current components. This modification on effective patch side length S_{eb} is formulated by using Equations (19) & (20). While simplifying Equation (19) into (20), the relation between antenna parameters as $W_s = 0.5775S$, $d = 0.2465S$ &



(a) (b)

Figure 8. Fabricated prototype showing (a) patch & (b) ground plane for ETMSA employing 3 slots cut bow-tie shape ground plane.

$W_g = 1.1056S$, which is present in the optimum configuration above is selected. For $S_e = S_{eb}$ and using Equation (15), the modified frequency is calculated. The calculated frequency is 884 MHz. It agrees closely with the simulated value of 866 MHz.

$$S_{eb} = S + (2h_t/\sqrt{\varepsilon_{re}}) + W_s/10 + (dW_s/1.5\,(W_g - 2d)) \tag{19}$$
$$S_{eb} = S + (2h_t/\sqrt{\varepsilon_{re}}) + 0.05775S + 0.155S \tag{20}$$

The addition of a second rectangular slot further alters surface current distribution at TM_{10} mode. Initially, a slot on left side of the first rectangular slot is added. Modified ETMSA side length 'S_{eb2}' due to the 2 slots and bow-tie shape of the ground is formulated by using Equations (21) & (22). While realizing Equation (22), a relation $W_s = 0.5775S$ that is present in the optimum design above is selected. By using Equation (15), modified frequency is calculated for $S_e = S_{eb2}$. Using 2 slots, calculated frequency is 853 MHz. This agrees closely with the simulated value of 846 MHz.

$$S_{eb2} = S + (2h_t/\sqrt{\varepsilon_{re}}) + 0.05775S + 0.155S + W_s/10 \tag{21}$$
$$S_{eb2} = S + (2h_t/\sqrt{\varepsilon_{re}}) + 0.05775S + 0.155S + 0.05775S \tag{22}$$

The contribution due to the third rectangular slot that is present on right side of the first slot is formulated using Equations (23) & (24). The modified TM_{10} mode frequency with three rectangular slots and bow-tie shape of the ground is calculated by using Equation (15) for $Se = S_{eb3}$. For the antenna parameters as present in the above optimum design, the frequency calculated is 816 MHz. It matches closely with the simulated value of 810 MHz. Amongst all the ETMSAs, design employing 3 slots cut bow-tie shape ground yields optimum results for the BW against frequency & patch size reduction. Therefore, by employing the proposed formulation, the procedure to design similar MSA is explained further.

$$S_{eb2} = S + (2h_t/\sqrt{\varepsilon_{re}}) + 0.05775S + 0.155S + 0.05775S + W_s/8 \tag{23}$$
$$S_{eb2} = S + (2h_t/\sqrt{\varepsilon_{re}}) + 0.05775S + 0.155S + 0.05775S + 0.0722S \tag{24}$$

The modified ground plane ETMSA is designed at the given TM_{10} mode frequency. At this frequency, the total substrate thickness 'h_t' is selected as given in Equation (25). h_t equals $2h + h_a$, where h is for the substrate thickness of FR4 layer, and h_a represents the air gap thickness. Similar to the above RMSA design, for calculating h_t, an initial approximation of $\varepsilon_{re} = 1.1$ is considered. A value of h_a, which is practically realizable is selected from the calculated value of h_t. Based on this 'ε_{re}' is recalculated using Equation (3), which is used in further calculations. The patch side length at the given TM_{10} mode frequency is calculated using Equation (26). This equation is realized by rearranging terms in Equation (24). Ground plane dimensions are selected as $W_g = 1.1056S$, $L_g = 0.972S$, $l_x = 0.0528S$.

Here l_x represents the position of the ground plane with reference to the base of ETMSA, as mentioned in Figs. 5(a), (b). The height of the ETMSA (h_{tm}) is obtained using Equation (27). Ground plane slot dimensions are selected as $W_s = 0.5775S$, $L_s = 0.049W_s$, $S_1 = S_2 = 0.0813h_{tm}$. The bow-tie shape ground parameter d is taken as $0.2465S$. The proximity coupling strip is placed at a height of $h_s = 0.0637\lambda_{g10}$ from the bottom ground plane. Here λ_{g10} is the wavelength in suspended dielectric substrate at a mentioned TM_{10} mode frequency. Further, with reference to Fig. 5(b), $h_s = h + h_f$. Feeding strip is placed at the distance of $X_f = 0.528h_{tm}$ from the patch base, and its dimensions are selected as $L_{pf} = W_{pf} = 0.122h_{tm}$.

$$h_t = 0.069\left(c/f_{10}\sqrt{\varepsilon_{re}}\right) \tag{25}$$

$$S = \frac{\left(\left(2c/3f_{10}\sqrt{\varepsilon_{re}}\right) - \left(2h_t/\sqrt{\varepsilon_{re}}\right)\right)}{1.3427} \tag{26}$$

$$h_{tm} = 0.866S \tag{27}$$

Using the above guideline, ETMSA backed by 3 slots cut bow-tie shape ground is designed at TM_{10} mode frequency of 1200 MHz, and various antenna parameters obtained using the above mentioned procedure are $S = 9.1$, $L_g = 8.5$, $W_g = 10.1$, $l_x = 0.5$, $h_a = 1.4$, $h_f = 1.3$, $W_{pf} = L_{pf} = 1.2$, $X_f = 4.2$, $d = 2.25$, $W_s = 5.3$, $L_s = 0.3$, $S_1 = S_2 = 0.65$, $w_x = 0.5$ cm. Simulated and experimental BWs in the redesigned antenna are 561 MHz (43.64%) and 578 MHz (44%), respectively. The TM_{10} mode frequency observed in the simulation for the redesigned antenna is 1206 MHz. This is very near the desired frequency value. Redesigned antenna shows a similar pattern and gain response to that observed in the original design above.

6. RESULTS DISCUSSION AND COMPARATIVE ANALYSIS

To put forward the technical novelty in the proposed design, the comparison for optimum RMSA and ETMSA configurations against reported wideband configurations is presented in Table 1. The comparison is presented for the antenna parameters as measured BW, maximum gain, patch area, and substrate thickness. Patch area and substrate thickness mentioned in Table 1 are normalized with respect to wavelength (λ_c) at the center frequency of the measured BW. Due to this, the substrate thickness as mentioned in Table 1 for proposed designs is stated to be higher. As mentioned above, the same is with reference to patch fundamental mode frequency, which reflects the patch size reduction. Initial reported wideband designs using U-slot and pair of rectangular slots require larger patch size [6, 7]. Also they do not support reduction in the resonance frequency. Multiple slots cut antenna presented in [8] offers larger BW and gain but requires a thicker substrate. The slot cut MSA discussed in [9] yields smaller BW. The wideband MSA presented in [10] requires parasitic patches and offers smaller impedance BW. Wideband design discussed in [11], although yields higher BW and gain, shows variations in the polarization of radiated fields over the BW. E-shape MSA employing a printed reactive circuit on a thinner substrate reported in [12] offers smaller impedance BW. Wideband MSA using double U-slots gives higher BW on the thinner substrate [13]. However, this design selects differential feeding to feed the antenna and shows a conical radiation pattern across the BW. Wideband design in [14] employs parasitic shorted patches and requires a thicker substrate. The slot cut design discussed in [15] requires differential feeding and larger patch size since higher order TM_{30} and TM_{50} modes are present in realizing wider BW. Wideband shorted gap-coupled design discussed in [16] requires a larger patch size whereas designs discussed in [17, 18] require larger substrate thickness. The gap-coupled design discussed in [19] offers smaller BW. The modified ground plane designs presented in [20–23] offer BW greater than 100%. However, those designs employ multiple modifications on patch and the ground plane, thus increasing design complexity. Further, they do not offer reduction in resonance frequency and patch size. Also, details about the antenna working in terms of patch resonant modes and design methodology are not discussed. Wideband designs discussed in [26–28] do not provide a reduction in patch size or the frequency as bow-tie shape does not perturb the current distribution in the patch center where the maximum of modal current is present.

Against the reported wideband configurations, proposed work explains a technique to yield wider BW supported with reduction in patch resonant mode frequency (patch area) on an electrically thinner substrate. In the reported study, designs offering wider BW with a reduction in the antenna size and

Table 1. Comparison for proposed modified ground plane MSAs against reported wideband MSAs.

Configuration shown in	Meas. BW (MHz, %)	Peak Gain (dBi)	Patch Area (A_p/λ_c)	Substrate thickness (h_t/λ_c)
Figs. 1(a), (b) RMSA using Three slots cut Bow-tie shape ground plane	433, 46.18	5.2	2.8	0.07
Figs. 5(a), (b) ETMSA using Three slots cut Bow-tie shape ground plane	393, 45.88	5.5	2.55	0.074
Ref. [6]	470, 44.9	10	9.54	0.08
Ref. [7]	408, 24.82	7.2	3.74	0.076
Ref. [8]	3000, 53.6	10.2	2.1	0.124
Ref. [9]	350, 6.8	7	0.741	0.04
Ref. [10]	1440, 26.2	8.5	2.78	0.115
Ref. [11]	880, 39.82	9.2	3.1	0.08
Ref. [12]	80, 9	7	5.4	0.04
Ref. [13]	2040, 68	10	2.224	0.023
Ref. [14]	6300, 40	10.5	2.344	0.119
Ref. [16]	100, 4.0	4.6	9.982	0.02
Ref. [17]	650, 20.5	4.93	1.292	0.345
Ref. [18]	6300, 79.2	8.4	5.871	0.232
Ref. [19]	374, 5.75	—	4.84	0.068
Ref. [20]	5760, 99	3.66	0.6	0.05
Ref. [21]	7700, 110	4.5	1.83	0.06
Ref. [22]	9700, 131	3.5	1.104	0.062
Ref. [23]	6900, 86.79	4.1	1.223	0.065

substrate thickness are not discussed. Hence, novelty in the present work resides in the design of smaller size proximity fed wideband MSAs that offer broadside radiation characteristics. Although the peak broadside gain has been reduced by 2 dBi, over the entire S_{11} BW it remains above 5 dBi, which is an appreciably large value. Further, the MSA offers stable gain response across the entire BW. Design methodology is presented that helps in realizing similar wideband MSA as per the given fundamental mode frequency, which can coincide with the given wireless application.

While using conventional ground plane, due to the difference in structural geometry, surface currents on the triangular patch are not completely unidirectional. With this, the triangular patch design offers higher cross polar component than the rectangular patch. But in the proposed designs, cross polar component is not large while using rectangular and triangular patches. This is attributed to the shape of the modified ground plane [24]. Also, proposed configurations are a single patch designs employing a modified ground plane structure. Hence, the symmetry in the radiation pattern is not lost while going from rectangular to triangular patch geometry.

7. CONCLUSIONS

Wideband compact configurations of RMSA and ETMSA by employing rectangular slots cut bow-tie shape ground plane profile are proposed. Rectangular slots yield a reduction in the patch fundamental mode frequency, and bow-tie shape of the ground plane provides an impedance matching on a thinner substrate, to yield a wider BW. Designs of RMSA and ETMSA employing a three rectangular slots cut bow-tie shape ground plane structure provides optimum result. Compared with the original conventional ground plane design, the design employing RMSA shows 20% increase in the BW, 32.1% reduction in TM_{10} mode frequency, and more than $0.034\lambda_g$ reduction in substrate thickness. With reference to conventional ground plane design at the lower frequency, the proposed design offers 61.13% reduction in the patch area. ETMSA design offers a 30% increase in the BW, which is supported by a 16.4% reduction in patch size, $0.027\lambda_g$ reduction in the substrate thickness, and 36.28% reduction in the patch area. All these proposed designs exhibit broadside radiation pattern and gain characteristics, with a maximum gain above 5 dBi.

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