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Wideband Designs of U-Slot Cut Square Microstrip Antenna Using Modified Ground Plane Profile

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Abstract—Wideband designs of a U-slot cut square microstrip antenna using bow-tie and H-shape ground plane profiles are proposed on an electrically thinner substrate. The modified ground plane optimizes the input impedance at patch resonant modes on the thinner substrate, which yields wider bandwidth. Against the conventional ground plane design on substrate thickness $> 0.06\lambda_g$, the bow-tie shape ground plane offers $0.03\lambda_g$ reduction in total substrate thickness, 10% increment in the bandwidth with a peak broadside gain of 6.1 dBi. The design methodology to realize a similar configuration as per a specific frequency spectrum is presented, which yields similar response.

1. INTRODUCTION

Bandwidth (BW) in microstrip antenna (MSA) is increased by adding multiple resonant modes in the radiating patch [1]. Among the many techniques reported, a resonant slot cut design is the preferred one since it employs a single patch configuration [2]. In this technique, different slot shapes like U-slot, pair of rectangular slots, and their modified variations, such as a V-slot, half U-slot, and a single rectangular slot, have been selected [3–11]. To achieve optimum results, slot-cut wideband MSAs require a thicker air-suspended substrate ($> 0.06\lambda_g$). The increase of the probe length increases the unwanted radiation in the end-fire direction, surface wave excitation, and the antenna volume. MSAs using an inverted U-slot [12] or two U-slots [13] are reported, which offer a wideband response on a thinner microwave substrate. However, these configurations either yield a conical radiation pattern [12] or employ multiple slots offering narrow BW [13]. The wideband E-shape MSA embedded with a printed reactive circuit on a substrate of thickness $0.04\lambda_g$ gives only 9% of BW [14]. Thus, in the reported study simpler wideband designs of slot cut MSAs on electrically thinner substrates offering broadside radiation patterns are not discussed.

In this paper, wideband designs of a U-slot cut square MSA (SMSA) backed by either bow-tie or H-shape ground plane profile are proposed on an electrically thinner substrate in the 900 MHz frequency range. Using each of the ground plane profiles, a detailed parametric study to explain their effects on the antenna parameters against the realized BW is presented. On a thinner substrate ($h_t \sim 0.04\lambda_g$), the modified ground plane helps in achieving the impedance matching at U-slot cut patch resonant modes, which results in the formation of a loop inside Voltage Standing Wave Ratio (VSWR) = 2 circle in the Smith chart, to achieve wider BW. Optimum results are obtained using the bow-tie shape ground plane. Against the conventional square ground plane design, it yields more than 10% increase in the BW, supported by a $0.03\lambda_g$ reduction in total substrate thickness. The modified ground plane MSA exhibits a broadside radiation pattern with a peak broadside gain of 6.1 dBi. Thus, the present study describes a simple method to reduce the substrate thickness in a wideband slot cut MSA and offers higher BW than the conventional ground plane design. This kind of simpler design approach to realize wideband slot cut MSA on an electrically thinner substrate offering broadside pattern and gain

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characteristics has not been reported in the literature. A detailed comparison highlighting the technical novelty in the present design against the reported wideband designs is presented further in the paper. It clearly shows that in terms of the BW, substrate thickness, patch area, and gain together, the proposed design offers better results. As the main thrust of the proposed study is on realizing thinner substrate wideband slot cut design, the MSA design is not aimed at any particular wireless application. However, for realizing the same with reference to a specific application, resonant length formulation at U-slot cut patch modes and subsequent design methodology is presented that helps in achieving a similar design as per the specific wireless application.

2. WIDE BAND SMSAS USING MODIFIED GROUND PLANE PROFILE

The design of a U-slot cut SMSA backed by a bow-tie shape ground plane is shown in Figs. 1(a) and (b). To depict the relation between the H-shape ground plane and the bow-tie, the H-shape ground plane is also shown in Fig. 1(a). To realize a modified ground plane profile, a three-layer suspended configuration is selected in which two layers of FR4 substrate ($\varepsilon_r = 4.3$, $h = 0.16$ cm) are separated by an air gap of 'h_2' cm. The bottom FR4 layer consists of the modified ground plane. Initially on a total substrate thickness of 2.02 cm (air gap 'h_2' = 1.7 cm), using IE3D simulation SMSA length is optimized

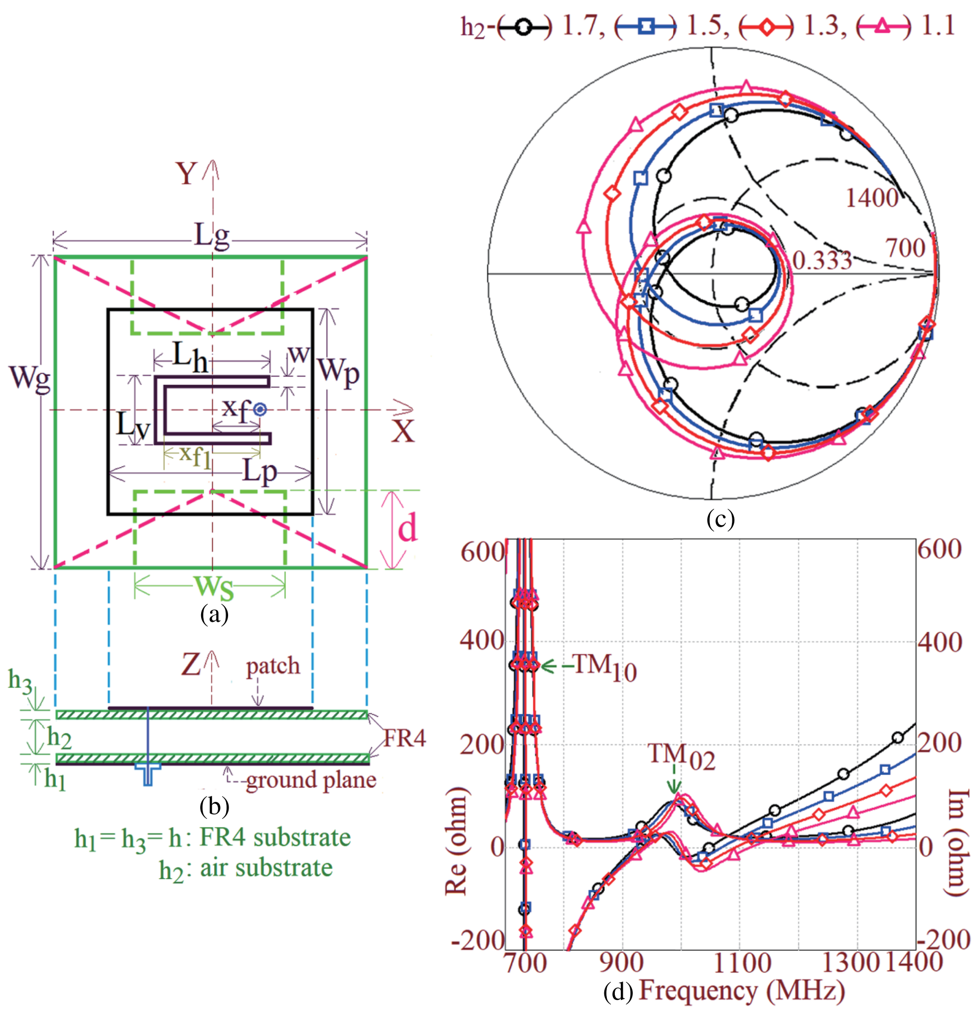

Figure 1. (a) Top and (b) side views of U-slot cut SMSA backed by Bow-tie and H-shape ground plane, (c) smith chart and (d) resonance curve plots for variation in 'h_2' for bow-tie shape ground plane design.

for $f_{\mathrm{TM10}} = 900\,\mathrm{MHz}$. Inside the square patch, the U-slot of dimension 'L_h' × 'L_v' × 'w' cm is cut in the patch center with coaxial feed placed inside the U-slot area. The U-slot cut SMSA is optimized for the BW using the parametric study for the slot dimensions and the feed position 'x_f', from the patch center. As the optimization process for U-slot cut SMSA describing resonant modes and relevant current distribution is well described in the literature [3, 7, 15], it is not presented here. The U-slot cut SMSA yields simulated BW of 147 MHz (14.9%) with a peak broadside gain of 7.7 dBi.

In U-slot cut SMSA, wider BW is attributed to the optimum spacing of patch TM_{02} mode against the fundamental TM_{10} mode, and the wideband response resides around this modified TM_{02} mode frequency [3, 7, 15]. At modified TM_{02} mode, as current vectors are aligned along the patch length, a broadside radiation pattern is observed over the BW with a lower cross polar radiation. With reference to this modified frequency, the antenna's electrical substrate thickness is $0.07\lambda_g$. The thicker substrate increases the probe length and thus the cross polar radiation in the end-fire direction. As described in the parametric study presented in [15], due to the higher capacitive impedance offered by the slot, the wideband U-slot cut antenna cannot be optimized on a thinner substrate. Therefore, using the conventional MSA design approach, wideband response with a broadside radiation pattern cannot be realized in U-slot cut antennas on a thinner substrate. An equivalent circuit of MSA is a parallel resonant circuit [1]. To explore the possibility of realizing wideband response on a thinner substrate, modifications in the ground plane profile are considered here. This is because the modifications in the ground plane will alter the impedance of the antenna cavity, which can realize a wideband response on a thinner substrate. Therefore, the effects of the bow-tie shape ground plane are studied first. Starting with the optimum design of U-slot cut SMSA on a square ground plane, a parametric study showing the Smith charts and resonance curve plots for the decrement in air gap 'h_2' followed by an increase in bow-tie ground plane parameter 'd' are shown in Figs. 1(c), (d) & 2(a), (b), respectively.

With the decrease in 'h_2', i.e., an air gap between the two FR4 layers, probe length decreases which reduces the probe inductance. The reduction in the inductive component leads to a capacitive nature of the impedance loop in the smith chart. Due to this, for lower 'h_2' impedance response cannot be optimized inside the VSWR = 2 circle. With the decrease in 'h_2', TM_{02} mode frequency marginally increases, which is attributed to the reduction in fringing field length. An increase in the ground plane parameter 'd' realizes the bow-tie structure. The resonance frequency of TM_{02} mode marginally decreases with an increase in 'd', but the resistance curve at the same becomes wider. This indicates the lossy nature of the antenna cavity. These losses are due to the bow-tie shape of the ground plane. With an increase in 'd', the loop size in the smith chart decreases, and it is positioned more towards the VSWR = 2 circle. Thus for different 'h_2' ($h_t = 2h + h_2$) and by optimizing 'd', U-slot length, and the coaxial feed position in each case, the bow-tie shape ground plane antenna is optimized for the BW. The plot of the impedance BW and peak broadside gain against the total substrate thickness (h_t) is shown in Fig. 2(c). With the decrease in 'h_t' and bow-tie shape of the ground plane, radiating fields do not add to the broadside direction, which reduces peak broadside gain. However, as the antenna cavity becomes lossy, MSA BW increases. Hence while the optimum design is considered, there exists a trade-off between the BW obtained for a substrate thickness reduction and the gain reduction. An optimum design is considered the one that offers a substantial amount of increase in the BW supported with a reduction in total substrate thickness, for gain reduction of not more than 1.5 dBi, against the conventional ground plane design on thicker substrate. Based on this, an optimum configuration is selected for $h_t = 1.22\,\mathrm{cm}$ ($h_2 = 0.9\,\mathrm{cm}$), and antenna parameters for the same are $L_p = w_p = 11.3\,\mathrm{cm}$, $w_g = L_g = 15\,\mathrm{cm}$, $L_h = 6.6\,\mathrm{cm}$, $L_v = 3.4\,\mathrm{cm}$, $w = 0.4\,\mathrm{cm}$, $x_f = 0.2\,\mathrm{cm}$, $d = 4.0\,\mathrm{cm}$. The results for the optimum design are shown in Fig. 3(a). Simulated and measured BWs for reflection coefficient (S_{11}) $< -10\,\mathrm{dB}$ are 250 MHz (26.6%) and 256 MHz (27.58%), respectively.

The antenna is optimized with a total substrate thickness (h_t) of 1.22 cm, which is $0.04\lambda_g$ in thickness with reference to the patch modified TM_{02} mode frequency. The antenna offers a peak broadside gain of 6.1 dBi with a broadside radiation pattern across the entire BW as shown in Figs. 3(b)–(e). The E-plane is aligned along $\Phi = 0°$. As the surface currents at modified TM_{02} mode are directed along the patch length, the cross polar levels are less than 15 dB as compared to the co-polar levels. Against the thicker substrate square ground plane design, the antenna with a bow-tie shape ground plane offers more than 10% BW improvement with a $0.03\lambda_g$ reduction in the substrate thickness. Thus, using a simpler ground plane modification, an increase in the BW of U-slot cut SMSA on the thinner

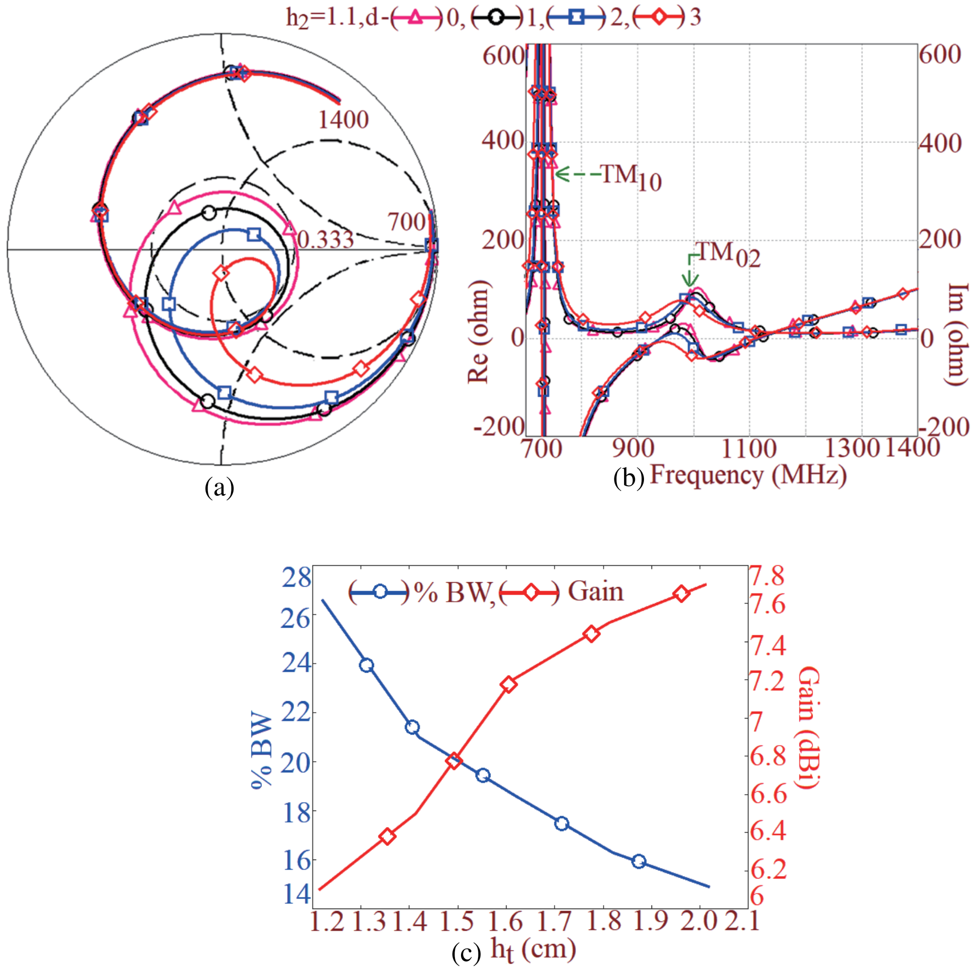

Figure 2. (a) Smith chart and (b) resonance curve plots for variation in 'd' for Bow-tie shape ground plane, and (c) % BW and broadside peak gain plots against total substrate thickness for U-slot SMSA backed by Bow-tie shape ground plane.

substrate is achieved here. Due to the thinner substrate and the bow-tie nature of the ground plane, peak broadside gain has been reduced by 1.6 dBi, which is a small reduction.

The design of the U-slot cut SMSA backed by an H-shape ground plane profile is shown in Fig. 1(a). A similar parametric study is carried out for the H-shape ground plane parameters, 'h_2', 'w_s', and 'd' that back the U-slot cut SMSA. It shows similar variations in the frequencies of the patch resonant modes and the impedances at them, to that observed in the bow-tie shape ground plane design. Parametric study in U-slot length leads to the optimum design for different 'h_2'. An optimum configuration is considered the one in which for 1.5 dBi reduction in the broadside gain, a substantial increase in the BW with the reduction in substrate thickness is obtained. Based on this, antenna parameters in the optimum design are $L_p = w_p = 11.3$ cm, $w_g = L_g = 15$ cm, $h_2 = 1.1$ cm, $L_h = 6.6$ cm, $L_v = 3.8$ cm, $w = 0.4$ cm, $x_f = 0.2$ cm, $w_s = 8.0$ cm, $d = 3.0$ cm, and results for the same are shown in Fig. 4(a). The simulated and measured BWs are 313 MHz (32.62%) and 307 MHz (32.37%), respectively. In this design, MSA is optimized on a total substrate thickness (h_t) of 1.42 cm, which is $0.051\lambda_g$ in thickness with reference to the patch modified TM_{02} mode frequency, lying inside the BW. The antenna offers a peak broadside gain of 5.9 dBi. The radiation pattern is in the broadside direction across the entire BW with E-plane aligned along $\Phi = 0°$, as shown in Figs. 4(b)–(e). Over the complete BW, cross polarization levels are less than 15 dB as against the co-polar levels, observed in the broadside direction. Thus, compared to the thicker substrate square ground plane design, using the H-shape ground plane,

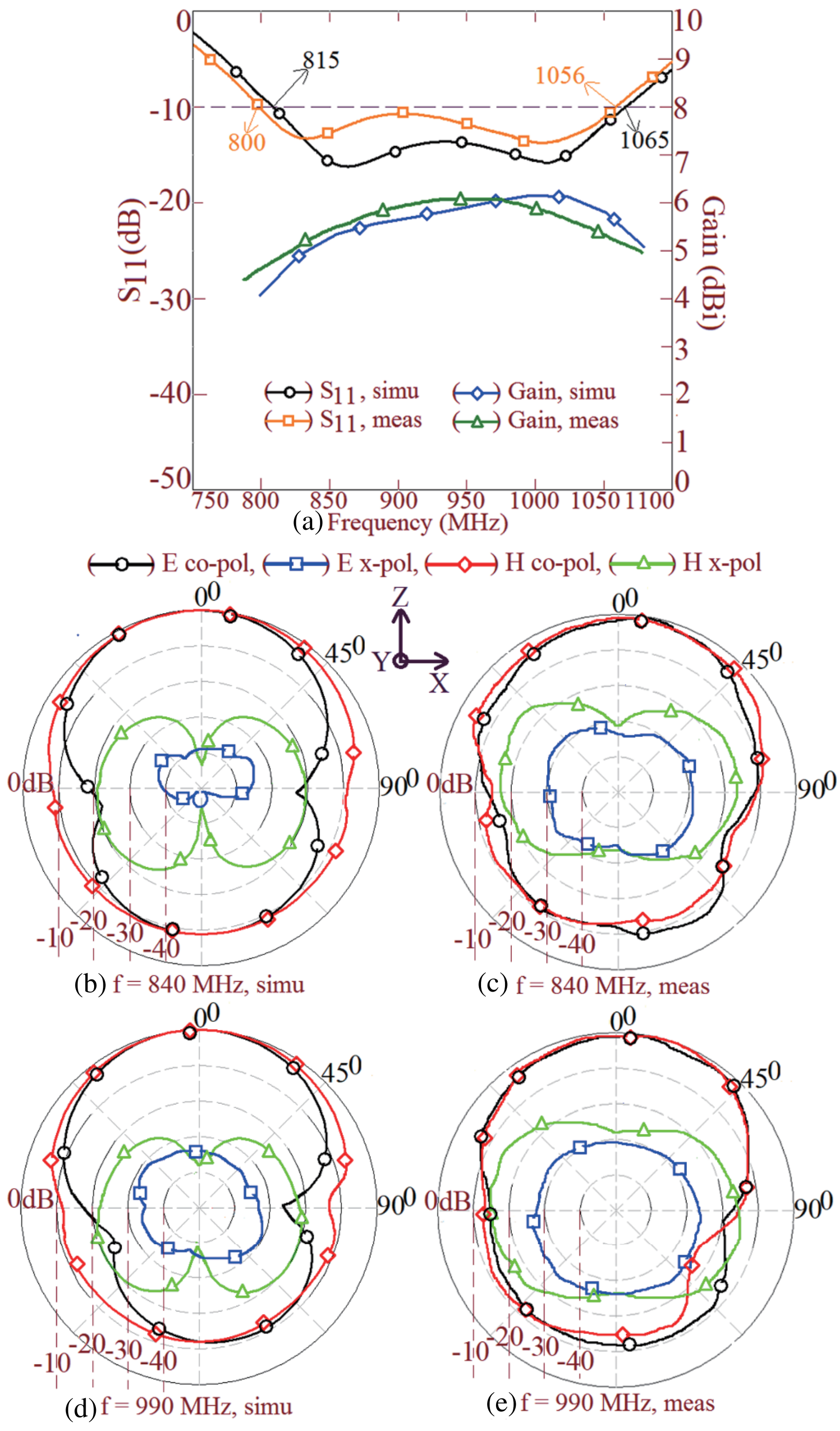

Figure 3. (a) Reflection coefficient and gain plots for U-slot cut SMSA backed by bow-tie shape ground plane and its radiation pattern plots nearer to the band (b), (c) start and (d), (e) stop frequencies of the BW.

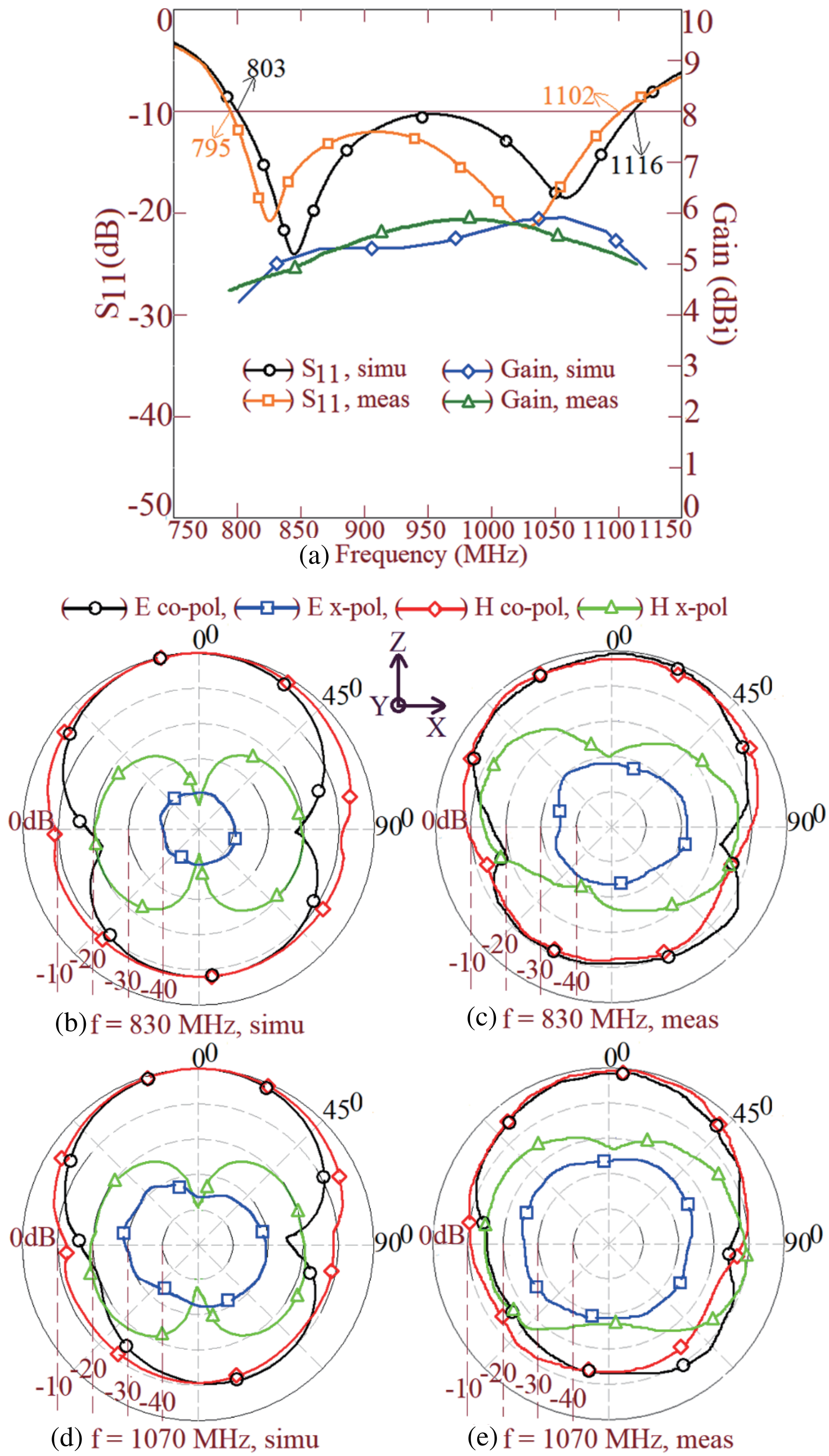

Figure 4. (a) Reflection coefficient and gain plots for U-slot cut SMSA backed by H-shape ground plane and its radiation pattern plots nearer to the band (b), (c) start and (d), (e) stop frequencies of the BW.

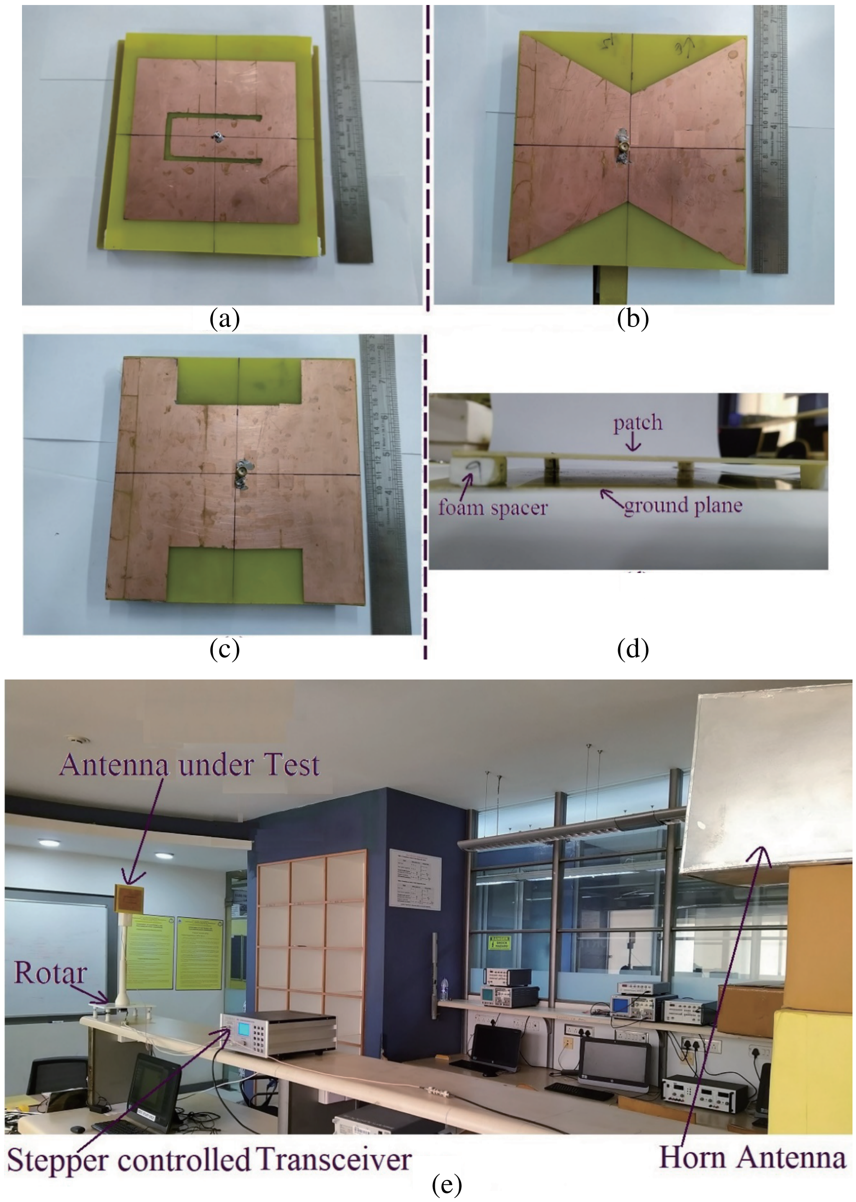

Figure 5. Fabricated prototype showing (a) U-slot cut SMSA. (b) Bow-tie and (c) H-shape ground plane and (d) side view of the antenna, (e) experimental setup to measure the antenna radiation pattern.

the antenna offers more than 15% BW improvement but with nearly $0.02\lambda_g$ reduction in the substrate thickness. Thus, between the two-ground plane profiles, in terms of BW increment, substrate thickness reduction, and the broadside gain, bow-tie shape ground plane design offers optimum results.

The fabricated prototypes of the two ground plane designs showing the patch, ground plane profile, and side view of the configuration are shown in Figs. 5(a)–(d). The pattern measurement setup is shown in Fig. 5(e). Measurement was carried out using the automated pattern measurement setup, as well as using RF source 'SMB 100A', Spectrum analyzer 'FSC 6', and Vector network analyzer 'ZVH-8'. In the pattern and broadside gain measurements, a reference wideband high gain Horn antenna is used. Far-field distance of more than '$2D^2/\lambda_0$' is maintained between the antenna under test and the reference Horn antenna. Here 'D' is the largest dimension of the Horn antenna. In the vicinity of the measurement setup and along the line joining the two antennas, metallic objects are not present. Further with reference to the central measuring desk, where the antennas are placed, the distance of the surrounding objects is more than 7λ, where 'λ' is measured with reference to the lower frequency of the BW. With this distance, the reflection from the surrounding objects is reduced, and thus measurement setup does match up with the ideal environment to the best possible extent. The radiation pattern as observed in the simulation and measurement is in the broadside direction. The variations in the two plots are observed specifically in the cross-polar levels. The cross-polar measurement is sensitive to the reflected signal that occurs from the surrounding objects. As the measurement in the lab is not completely reflection free, the cross polar levels observed in the simulation and measurement differ. The antenna gain is measured using the three-antenna method, as it is the accurate procedure to be used inside the laboratory. It also minimizes the errors in the gain measurement that can arise due to the variations in the gain of the reference Horn antennas.

3. DESIGN METHODOLOGY FOR MODIFIED GROUND PLANE DESIGNS

In this section, resonant length formulation and subsequent design methodology are presented for the wideband design of U-slot cut SMSA backed by bow-tie and H-shape ground plane profiles. In U-slot cut patch, the wideband response is due to the optimum spacing between TM_{10} and TM_{02} resonant modes. To formulate the resonant length at these two modes, the surface current distributions are extensively studied for different slot lengths. Initially, the resonant length formulation is presented for U-slot cut SMSA backed by the bow-tie shape ground plane. The U-slot consists of two sections, i.e., horizontal 'L_h' and vertical 'L_v' slot lengths. The length 'L_v' is orthogonal to the TM_{10} mode surface currents, whereas current vectors were seen to be circulating the length 'L_h'. By considering these two effects, resonant length at TM_{10} mode is formulated as given in Equation (1).

By using the relation between 'L_v' and 'L_h', as presented in the above U-slot cut design using a bow-tie shape ground plane, the resonant length equation is further simplified as given in Equations (2) & (3). The modified TM_{10} frequency as calculated using Equation (4) for the patch parameters in the optimum design above is 690 MHz, which matches closely with the frequency of 689 MHz as observed in the simulation. The 'ε_{re}' in Equation (4) is the effective dielectric constant in a three-layer suspended substrate, which is calculated by using Equation (5). In the following equations, 'c' is the velocity of light in free space, and 'h_t' represents the total substrate thickness. It equals $h_1 + h_2 + h_3$, where h_1, h_2, h_3 are the substrate thicknesses, and ε_{r1}, ε_{r2}, ε_{r3} are the dielectric constants of the three layers. Layer 2 is of air substrate, and layers 1 & 3 are of FR4 substrate. Patch dimensions mentioned in all the equations are in 'cm', and frequency is in 'GHz', thus c is taken as 30. The proposed formulations are originally derived in the present study.

$$L_{10s} = L + (2h_t/\sqrt{\varepsilon_{re}}) + (L_v/6) + 0.8L_h \quad (1)$$

$$L_v = 0.515L_h \quad (2)$$

$$L_{10s} = L + (2h_t/\sqrt{\varepsilon_{re}}) + 0.9L_h \quad (3)$$

$$f_{10s} = c/2L_{10s}\sqrt{\varepsilon_{re}} \quad (4)$$

$$\varepsilon_{re} = (\varepsilon_{r1}\varepsilon_{r2}\varepsilon_{r3}\,(h_1 + h_2 + h_3)\,/h_1\varepsilon_{r2}\varepsilon_{r3} + h_2\varepsilon_{r1}\varepsilon_{r3} + h_3\varepsilon_{r1}\varepsilon_{r2}) \quad (5)$$

The resonant length at TM_{02} mode is formulated by using Equation (6). As noted from the surface current distribution, the currents at modified TM_{02} mode originate from inside the U-slot. This effect on modal currents is formulated by using the third term on the right-hand side of Equation (6). Since the square patch is considered in the design, instead of patch width 'W', length 'L' is mentioned in Equation (6). The frequency for the modified TM_{02} mode is calculated by using Equation (7). For the antenna parameters in the above optimum design for U-slot cut SMSA with a bow-tie shape ground plane, the frequency as calculated using Equation (7) is 958 MHz, which is near the simulated frequency of 966 MHz. Using these equations at two resonant modes, the design methodology to realize wideband MSA in the given frequency range is presented ahead.

$$W_{02s} = L + (2h_t/\sqrt{\varepsilon_{re}}) + 2.2L_h \quad (6)$$

$$f_{02s} = c/W_{02s}\sqrt{\varepsilon_{re}} \quad (7)$$

The design methodology is presented for the given center frequency 'f_c' of the wideband response in U-slot cut SMSA backed by a bow-tie shape ground plane. For this frequency, the thinner substrate value 'h_t' is calculated by using Equation (8). In this equation, the initial value of the effective dielectric constant 'ε_{re}' is unknown. Hence, an approximation for 'ε_{re}' as 1.3 is considered. This initial approximation depends upon the frequency of operation as that decides the thinner substrate value. When the desired frequency of operation is above 2000 MHz, the initial approximation of 'ε_{re}' = 1.4–1.5, will give an accurate result in the redesigning procedure. From the calculated value of 'h_t' using (8), for $h_1 = h_3 = 0.16$ cm (FR4 substrate thickness), a practically realizable value of h_2, i.e., air gap thickness, is decided. Using these substrate thickness values, 'ε_{re}' is recalculated by using Equation (5). It is observed that the recalculated value of 'ε_{re}' differs by a small margin from the initial approximation. As noted above, the modified resonant lengths at TM_{10} and TM_{02} modes, (i.e., L_{10s} & W_{02s}) include the effects of U-slot lengths. Hence to calculate these lengths, the frequency relation among 'f_c', 'f_{02s}', and 'f_{10s}' that exist in the optimum wideband design above is used to calculate modified lengths at the resonant modes, as given in Equations (9)–(12).

$$h_t = 0.0417c/f_c\sqrt{\varepsilon_{re}} \tag{8}$$

$$f_{02s} = 1.032f_c \tag{9}$$

$$f_{10s} = 0.736f_c \tag{10}$$

$$W_{02s} = c/f_{02s}\sqrt{\varepsilon_{re}} \tag{11}$$

$$L_{10s} = c/2f_{10s}\sqrt{\varepsilon_{re}} \tag{12}$$

After calculating modified patch dimensions at TM_{10} and TM_{02} mode frequencies using Equations (11) & (12), two variables namely the patch length and U-slot dimensions are to be evaluated. As the design employs a square patch, Equations (3) & (6) for modified patch length and width at modified TM_{10} and TM_{02} modes are similar, except for the difference in the contribution of U-slot length, 'L_h'. Therefore, the U-slot horizontal length 'L_h' is calculated by using Equation (13), which considers the difference between w_{02s} and L_{10s} values as obtained using Equations (11) & (12) for the given 'f_c'. Further, the patch length 'L' is calculated by using Equation (14). Since the square patch is considered in the design, $W = L$. A square ground plane is present in the original design. Hence, the ground plane dimensions are selected as $L_g = w_g = 1.327L$. The bow-tie slot depth is selected as $d = 0.354L$. The vertical U-slot length is calculated by using Equation (2). The U-slot width is selected as $0.061L_h$, whereas the coaxial feed is placed at a distance 'x_{f1}' $= 0.47L_h$ from the open circuit edge of the U-slot. Using this design formulation, a U-slot cut SMSA backed by a bow-tie shape ground plane is designed for $f_c = 1200$ MHz, and its antenna parameters are, $h_1 = h_3 = 0.16$ cm, $h_2 = 0.6$ cm, $L = 8.7$ cm, $L_g = 11.5$ cm, $d = 3.1$ cm, $L_h = 4.8$ cm, $L_v = 2.5$ cm, $w = 0.3$ cm, $x_{f1} = 2.4$ cm. The simulated and measured values of the BW for $S_{11} \leq -10$ dB are 297 MHz (25.24%) and 306 MHz (26.18%), as shown in Fig. 6(a). The center frequencies of the BW in the simulation and measurement are 1176 and 1169 MHz, respectively. These frequency values are close to the desired center frequency of 1200 MHz.

$$L_h = |W_{02s} - L_{10s}|/1.3 \tag{13}$$

$$L = L_{10s} - (2h_t/\sqrt{\varepsilon_{re}}) - 0.9L_h \tag{14}$$

In the design of the U-slot cut SMSA backed by H-shape ground plane, the resonant length at TM_{10} mode is given by using Equation (15). The contribution in the modified resonant length due to U-slot lengths is added by using the third and fourth terms on the right-hand side of Equation (15). By using the relation between 'L_h' and 'L_v' as present in the above optimum design of H-shape ground plane, resonant length at TM_{10} mode is further simplified, as given in Equations (16) & (17). The modified resonance frequency due to the U-slot is calculated by using Equation (4). For the above optimum U-slot cut design, this frequency is calculated to be 684 MHz which matches closely with the simulated frequency of 689 MHz. At modified TM_{02} mode, the resonant length is given by using Equation (18). For the substrate parameters present in the H-shape ground plane design above, 'ε_{re}' is calculated using Equation (5). The modified resonant frequency is calculated by using Equation (7). Here, the calculated frequency is found to be 992 MHz which matches closely with the simulated value of 977 MHz. For $f_c = 1200$ MHz, redesigning procedure is explained for the U-slot cut SMSA backed by H-shape ground plane.

$$L_{10s} = L + (2h_t/\sqrt{\varepsilon_{re}}) + (L_v/8) + 0.8L_h \tag{15}$$

$$L_v = 0.576L_h \tag{16}$$

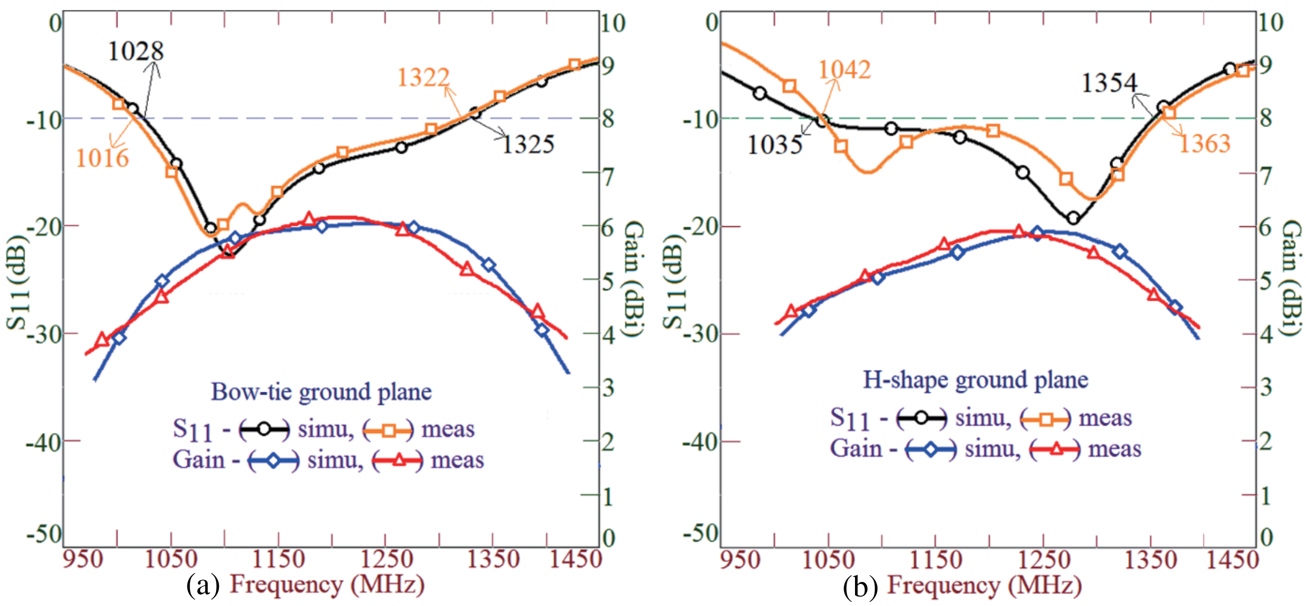

Figure 6. S_{11} BW and gain plots for re-designed configuration of U-slot cut SMSA backed by (a) Bow-tie and (b) H-shape ground plane for $f_c = 1200$ MHz.

$$L_{10s} = L + (2h_t/\sqrt{\varepsilon_{re}}) + 0.872L_h \tag{17}$$
$$W_{02s} = L + (2h_t/\sqrt{\varepsilon_{re}}) + 2L_h \tag{18}$$

At this frequency, the total substrate thickness is calculated by using Equation (19). Similar to the above procedure, initially ε_{re} is assumed to be 1.3. For h_1 & h_3 = 0.16 cm, the value of h_2 (air gap) is selected such that it is practically realizable. The frequencies of modified TM_{10s} and TM_{02} modes are calculated by using Equations (20) and (21), respectively. The modified resonant lengths at the two modes are calculated by using Equations (11) and (12). Using these two lengths, the horizontal U-slot length is calculated by using Equation (22). The square patch length is calculated by using Equation (23). Equation (23) is obtained by rearranging Equation (17). The square ground plane dimension is selected as $L_g = 1.327L$. The vertical U-slot length is calculated by using Equation (16), whereas the U-slot width is selected as $w = 0.061L_h$. The coaxial feed is placed at a distance of 'x_{f1}' $= 0.409L_h$ from the open circuit edge of the U-slot. The H-shape slot dimensions on the ground plane are selected as $d = 0.266L$, $w_s = 0.708L$. Using these design formulations, a U-slot cut SMSA backed by H-shape ground plane is designed for $f_c = 1200$ MHz, and its antenna parameters are $h_1 = h_3 = 0.16$ cm, $h_2 = 0.8$ cm, $L = 8.5$ cm, $L_g = 11.3$ cm, $d = 2.6$ cm, $w_s = 6.0$ cm, $L_h = 5.6$ cm, $L_v = 3.2$ cm, $w = 0.4$ cm, $x_{f1} = 2.3$ cm. The result for the redesigned antenna is shown in Fig. 6(b). The simulated and measured values of the BW are 319 MHz (26.71%) and 321 MHz (26.69%), respectively. The center frequency of the BW in the simulation and measurement are 1195 and 1202 MHz, respectively. These values are close to the desired frequency of 1200 MHz.

$$h_t = 0.051c/f_c\sqrt{\varepsilon_{re}} \tag{19}$$
$$f_{02s} = 1.02f_c \tag{20}$$
$$f_{10s} = 0.719f_c \tag{21}$$
$$L_h = |W_{02s} - L_{10s}|/1.128 \tag{22}$$
$$L = L_{10s} - (2h_t/\sqrt{\varepsilon_{re}}) - 0.872L_h \tag{23}$$

In the proposed design methodology, it is observed in some of the antenna parameters that non-integer or practically not realizable values are obtained. Hence, while the antenna is designed, these values are rounded off to the nearest possible integer. These modified antenna parameters can lead to a variation in the output response. Therefore, for getting the optimum wideband response, small parametric optimization is needed in some of the antenna parameters like coaxial feed position. The wideband resonant slot cut antenna is a single patch configuration and thus has many applications in wireless communication. However, they require substrate thickness $\geq 0.07\lambda_g$. Hence the main thrust of the proposed work was on realizing wideband slot cut designs on a thinner substrate. Therefore, the proposed designs were not aimed at any specific wireless application. However, by using the proposed resonant length formulation and the subsequent design methodology, a thinner substrate wideband U-slot cut SMSA can be realized around the given center frequency of the BW as per the specific wireless application. The wideband designs proposed in this paper, with the antenna characteristics like BW $> 25\%$ and peak gain of 6 dBi on a thinner substrate, can find a variety of applications like GSM frequency bands (T-GSM-810, GSM-850, P-GSM-900, E-GSM-900, R-GSM-900, T-GSM-900).

4. RESULTS DISCUSSION AND COMPARATIVE ANALYSIS

To reflect upon the new contribution in the proposed work, a comparison of the bow-tie shape ground plane design against the reported wide band configurations is presented in Table 1. The comparison is presented for the measured BW against the peak gain, patch area, and substrate thickness. The area and thickness are normalized with reference to the wavelength at the center frequency of the BW.

In the initial slot cut wideband designs [3, 4], BW is higher but it requires higher substrate thickness and patch size. As the parasitic patches are employed in the design reported in [5], it loses the

Table 1. Comparison of the proposed modified ground plane SMSA against reported Wideband MSAs.

MSA shown in	Meas. BW (MHz, %)	Peak Gain (dBi)	Patch Area (A_p/λ_c)	Substrate thickness (h_t/λ_c)
Fig. 1(a)	**256, 27.58**	**6.2**	**4.1**	**0.04**
Ref. [3]	470, 44.9	10	9.54	0.08
Ref. [4]	408, 24.82	7.2	3.74	0.076
Ref. [5]	1440, 26.2	—	3.38	0.114
Ref. [6]	590, 53.9	7.9	7.11	0.104
Ref. [7], U-slot RMSA	156, 17.4	7.8	6	0.057
Ref. [7], Half U-slot RMSA	130, 14.6	6.8	2.96	0.066
Ref. [8]	260, 13	7	7.301	0.037
Ref. [9]	600, 24	—	6.82	0.041
Ref. [10]	340, 6.1	10.7	7.382	0.022
Ref. [11]	880, 39.82	—	3.1	0.079
Ref [12]	2040, 68	10	2.244	0.023
Ref [13]	3100, 12	6.7	0.16	0.0792
Ref [14]	80, 9	7	5.4	0.04
Ref [16]	351, 39.1	6.2	4.077	0.0645
Ref [17]	6300, 40	10.5	2.344	0.119
Ref [18]	350, 6.8	7	0.8	0.04
Ref [19]	160, 16	8.83	3.94	0.0567
Ref [20]	450, 13.1	9.12	14.51	0.161
Ref [21]	1570, 60	11.1	3.13	0.183
Ref [22]	5.75%	—	4.84	0.068
Ref [23]	730, 13.19	9.7	2.87	0.055

compactness. Also in this design, with higher substrate thickness, obtained BW is smaller. The modified slot cut designs reported in [6] require substrate thickness greater than $0.07\lambda_g$. The U-slot cut designs reported in [7] offer lower BW on higher substrate thickness. As the third-order resonant mode contributes to the BW in the design reported in [8], the patch size is larger. The wideband design reported in [9] does offer a comparable value of the BW against the proposed design, but it requires multiple shorting posts for tuning the patch resonant modes. The antenna size in the slot cut design reported in [10] is larger whereas the design reported in [11] requires multiple rectangular slots and higher substrate thickness. The design reported in [12] offers BW above 50% on a thinner substrate. But it employs two U-slots and differential feeding, and thus yields a conical radiation pattern. The thicker substrate wideband MSA reported in [13] employs two U-slots but gives BW less than 15%. The design reported in [14] does offer the technique to realize wideband slot cut MSA on a thinner substrate. However, the reported technique is not simple in implementation. Also, the BW obtained for a substrate thickness around $0.04\lambda_g$ is less than 10% [14]. Using a similar ground plane profile, wideband designs are reported in [16]. In comparison to them, the proposed design requires smaller substrate thickness and employs a coaxial feeding technique against the proximity feed. The multi-resonator gap-coupled design in [17] requires higher electrical substrate thickness and uses a gap-coupled shorted mushroom shape structure. Against that the proposed design is a single patch wideband configuration. The staggered gap-coupled variation reported in [18] offers a much smaller impedance BW. The slot cut stacked patch design as reported in [19] employs L-probe feeding and offers lower BW on a thicker substrate. Using the stacked configuration of multiple U-slots cut fed patch along with the U-shape and square patch, a dual-band configuration offering BW of 13% and 26% in the dual bands is reported [20]. In this, antenna characteristics in the first band are decided by the fed U-slot cut patch. Therefore, in comparison to the BW obtained in the first band, the proposed design offers higher BW on smaller substrate thicknesses. A wideband slot cut design reported in [21] offers 60% BW. But in this design, the slot cut patch is fed using the differential feed that consists of the combination of a U-shape resonator and L-shape patches. This arrangement increases the design complexities to a large extent. The wideband gap-coupled design as reported in [22] offers smaller BW, whereas the dual edge shorted rectangular MSA reported in [23] requires a larger antenna size, as the wideband response is realized due to the coupling between shorted patch higher order TM_{11} and TM_{03} modes. Wideband modified ground plane designs discussed in [24] require thicker substrates than the proposed designs.

Thus, in comparison with the reported configurations, the proposed design is a single patch configuration. It offers higher BW on an electrically thinner substrate and has an appreciably higher value of the broadside gain with a broadside radiation pattern. In addition, the present work puts forward a simpler technique to reduce the substrate thickness in wideband slot cut antennas, which generally requires substrate thickness above $0.07\lambda_g$, while using the conventional ground plane. A similar technique to realize coaxially fed wideband slot cut designs on thinner substrates offering broadside pattern and gain characteristics is not reported in the literature, and thus this is the novelty in the proposed work. The design of the C-shape ground plane profile (i.e., slot only on the top horizontal edge of the ground plane) was also investigated during this wideband MSA design. As against the H-shape and Bow-tie shape ground plane profiles, the C-shape ground plane is an un-symmetrical configuration and thus does not offer improved results for the BW increment against the reduction in substrate thickness. Hence, the results for the C-shape ground plane profile are not presented here. Further, other shape ground plane profiles, like a slot in the center and below the patch as reported in [25] are not considered here, as they offer a reduction in the fundamental mode frequency to yield the compact structure. The main focus of the present study was on realizing wideband configurations for the given frequency but on an electrically thinner substrate. Lastly, using the proposed design methodology, a similar antenna can be designed in the given frequency band as per a specific wireless application.

5. CONCLUSIONS

Wideband designs of U-slot cut SMSA using bow-tie and H-shape ground plane profiles are proposed. The modified ground plane optimizes the impedance at the U-slot cut patch mode that achieves wider BW on an electrically thinner substrate. Amongst the two ground plane profiles, bow-tie shape ground offers an optimum result. Against the conventional square ground plane design, it offers more than

10% BW increment with nearly $0.03\lambda_g$ reduction in the substrate thickness. The modified ground plane antenna yields a broadside radiation pattern with a peak gain of 6.1 dBi. Thus, the present study proposes a simpler technique to reduce the substrate thickness in the slot cut wideband antennas, which also adds to the S_{11} BW.

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