Analysis and design of broadband U-slot cut rectangular microstrip antennas

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Abstract. Broadband microstrip antenna using variations of U-slot has been widely reported. However, in most of the reported work, an in-depth explanation about the mode introduced by U-slot and procedure to design U-slot cut antennas at any given frequency is not explained. In this paper, first an extensive analysis to study the broadband response in symmetrical and a new configuration of asymmetrical U-slot cut rectangular microstrip antennas is presented. The U-slot tunes higher-order orthogonal mode resonance frequency of the patch with respect to fundamental mode to realise wider bandwidth. Further formulation in resonant length at modified patch modes in symmetrical U-slot cut antenna is proposed. Frequencies calculated using these formulations show closer agreement with simulated and measured results. Using proposed formulations, a procedure to design U-slot cut antenna at different frequencies over 800–4000 MHz range which shows broadband response is explained. Thus, the proposed work gives an insight into the functioning of widely used U-slot cut antennas and the formulations will be helpful for designing at any given frequency.

Keywords. Rectangular microstrip antenna; broadband microstrip antenna; U-slot; higher-order mode; resonant length formulation.

1. Introduction

Since its invention for the first time in 1995 [1], use of U-slot to realise wide-band microstrip antenna (MSA) has been widely reported [1–9]. In U-slot cut MSA, a patch is fed using coaxial feed, which is placed concentric with respect to the U-slot, and the slot is cut in the patch centre. Thus, while optimising on a thicker substrate ($h \sim 0.06$ to $0.08\lambda_0$), the U-slot is reported to compensate the probe inductance due to longer feed, leading to better input impedance matching [1–9]. Further increase in the bandwidth (BW) of U-slot cut MSA is obtained by cutting asymmetrical U-slot or by cutting second U-slot inside the first one [10, 11]. Due to the presence of three resonant modes, asymmetric U-slot cut MSA yields higher BW. However, across the BW, it shows orthogonal variation in surface current directions over the patch [10]. As compared to single U-slot, dual U-slot cut MSA yields nearly 5% to 10% increase in antenna BW [11]. As per the reported papers, an additional resonant mode is introduced by U-slot, when the total slot length equals half wavelength [1–11]. However, at dual-resonant modes in U-slot cut patch, the surface currents are found to be originating from

inside the slot and hence better approximation of length can be obtained by equating the inner edge of U-slot length to half the wavelength. Based upon half wavelength approximation, formulation for U-slot resonant length, in terms of patch and slot dimension, is reported [3, 12]. However, comparison of calculated U-slot frequency against simulated and measured values has not been given. Also for the given total U-slot length, effects of variation in aspect ratio in U-slot on the slot frequency is not explained. Furthermore, formulation for resonant modes in U-slot cut MSA that will help them to design similar configurations at any given frequency is not available in the reported literature. Therefore, the optimisation process to design U-slot cut antennas relies on the parametric study.

In this paper, an extensive analysis to study the broadband response in symmetrical and asymmetrical U-slot cut rectangular MSA (RMSA) is presented first. The optimised configurations as reported in [10] are used in the present study. Using IE3D simulations [13], an equivalent RMSA and the U-slot cut RMSAs have been analyzed by studying their simulated resonance curve plots, surface current distributions and the radiation pattern plots. The proposed analysis clearly brings out that U-slot does not introduce any additional resonant mode; on the contrary, it modifies the existing modes of the patch. In symmetrical

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configuration, U-slot reduces the resonance frequency of higher-order TM_{20} mode, which, along with TM_{01} mode, yields broader BW. In an asymmetrically cut configuration, U-slot optimises the spacing of higher-order TM_{02} and TM_{11} modes with respect to TM_{10} and TM_{01} modes to yield broadband response. In symmetrical configuration, U-slot modifies surface current distribution at TM_{20} mode to yield broadside radiation pattern over the BW. In asymmetrical configuration, due to the presence of TM_{10} , TM_{01} , TM_{11} and TM_{02} modes, the antenna shows higher cross-polar level radiation pattern. Further, by studying the variation in TM_{01} and TM_{20} mode frequencies and respective surface current distributions against the U-slot lengths, a formulation in resonant length in symmetrical U-slot cut RMSA is proposed. The frequency calculated using proposed formulations agrees closely with the simulated and measured frequency. Furthermore, using the proposed formulation, a procedure to design symmetrical U-slot cut RMSA over 800–4000 MHz frequency band using air, foam and suspended glass epoxy substrate is presented. It yields a broadband response with formation of loop inside $VSWR = 2$ circle. Thus, the proposed study gives an insight into the functioning of U-slot cut RMSA and can serve as a tutorial for designing symmetrical U-slot cut RMSA in the desired frequency range. This is the novelty of the proposed work as a similar study for U-slot cut antennas is not available. Although a similar analysis to study the broadband response in U-slot cut RMSA has been reported in ref. [14]. However, the configurations studied in ref. [14] were symmetrical variations of U-slot cut RMSA. In comparison, the proposed work gives the detailed analysis of symmetrical as well as asymmetrical U-slot cut RMSAs. Additionally, in this paper, formulations for U-slot cut patch modes and design procedure to realise similar antenna at different frequency is presented, which is not given in ref. [14].

2. U-slot cut RMSAs

The symmetrical U-slot cut RMSA is shown in figure 1a [10]. The units of the dimensions and frequencies referred throughout the text and shown in figures are in cm and MHz, respectively. For probe diameter of 0.25 cm, on foam substrate ($\epsilon_r = 1.06$, $h = 1.0$ cm), a U-slot cut RMSA yields BW from 1970 to 2700 MHz as shown in figure 1b [10]. In unsymmetrical U-slot position, suspended RMSA gives 31% of BW (1900–2600 MHz) as shown in figure 1c and d [10]. The BW increases to 35% when the same configuration is optimised on full foam substrate of thickness 1.16 cm [10]. The above two U-slot cut RMSAs were simulated using IE3D software and their input impedance and resonance curve plots are shown in figure 1e and f. In symmetrical U-slot cut RMSA, a single loop and two resonant modes (f_1 and f_2) are observed. The surface current distribution at two modes is directed along the patch width, as shown in figure 2a and b.

As surface currents are originating from inside the U-slot, the inner slot length is equated to half the wavelength. For the MSA shown in figure 1a, the inner U-slot length is 9.36 cm, which gives slot frequency of 1560 MHz. This frequency is neither close to ' f_1 ' nor ' f_2 '. Two loops and three resonant peaks (f_1 , f_2 and f_3) are observed in asymmetrical U-slot cut RMSA. The current distributions are shown in figure 2c to e. At first two modes, currents are directed along the x - and y -axis and they are reported due to patch modes [10]. The third mode is due to U-slot, which shows current directed along the patch width [10]. Length of inner edge of U-slot in asymmetrical configuration is 6.2 cm, which gives U-slot frequency of 2410 MHz. This frequency is higher than the reported U-slot frequency (2312 MHz) [10]. The effects of variation in aspect ratio in U-slot on the slot frequency and impedances are studied. The resonance curve plots for varying ' L_h ' and ' L_v ' are shown in figure 2f and g. In each of these variations, the total slot length ($L_h + L_v$) is kept constant. According to half wavelength approximation, as the total slot length is unchanged the U-slot mode frequency should remain unchanged. However, in wider slots (increase in L_h), impedance at U-slot mode and its frequency increases (f_2 in symmetrical and f_3 in asymmetrical MSA), whereas it decreases in narrower slots. Thus, assumption of half wavelength approximation for U-slot resonant length is incorrect. Also, the reported work does not explain about the impedance behaviour at the U-slot mode. Hence, to understand the functioning (i.e. to get an insight about mode due to U-slot) in symmetrical and asymmetrical slot cut RMSAs, their analysis is presented in the following sections.

3. Analysis of U-slot cut RMSA

The equivalent RMSA dimensions in symmetric U-slot cut RMSA are $L = 7.1$ cm and $W = 5.2$ cm, which gives $W/L = 0.732$. The RMSA is simulated for two feed-point locations (' x_f ' = 1.5, ' y_f ' = 1.5), as shown in figure 3a and their resonance curve plots are shown in figure 3b. With feed at point 'A', resonance curve shows excitation of TM_{01} and TM_{20} modes [1]. In addition to these modes, TM_{10} and TM_{11} modes are present when feed is placed at point 'B' [1]. The surface currents at TM_{01} mode show one half-wavelength variations along patch width; hence, radiation pattern at TM_{01} mode is broadside with E-plane directed along $\Phi = 90^\circ$. At TM_{20} mode, surface currents show two half-wavelength variations along patch length as shown in figure 3c. Hence, radiation pattern at the same is conical, with E-plane directed along $\Phi = 0^\circ$ as shown in figure 3d. Inside this RMSA, U-slot of dimension ' L_h ' and ' L_v ' is cut as shown in figure 3e. The slot dimensions are increased in steps and their effects on modal frequencies are studied, as shown in their resonance curve plots in figure 4a and b.

An increase in horizontal U-slot length (L_h) is orthogonal to surface currents at TM_{01} mode. But decrease in its

Figure 1. (a) Symmetric U-slot cut RMSA, its (b) return loss plots for two probe diameters, (c) asymmetric cut U-slot RMSA and its (d) return loss plots [10], simulated (e) input impedance and (f) resonance curve plots for U-slot cut RMSAs.

frequency is smaller as the U-slot is not placed near the patch center. The TM_{20} mode frequency remains almost constant, as surface currents at them are parallel to horizontal U-slot length. An increase in vertical U-slot length

' L_v ' increases perturbations in the surface current at TM_{01} and TM_{20} modes, which reduces their frequencies. The surface current distribution at modified TM_{20} mode for two different values of ' L_v ' is shown in figure 4c and d. With

Figure 2. Surface current distributions at resonant modes for (a, b) symmetric and (c–e) asymmetrically cut U-slot RMSAs, resonance curve plots for variation in U-slot dimensions for (f) symmetric and (g) asymmetric cut U-slot RMSAs.

increase in ' L_v ', the current contribution increases along the patch width. Hence, in larger ' L_v ', nearly uni-directional current variation is achieved, which gives a broadside radiation pattern at modified TM_{20} mode, with E-plane directed along $\Phi = 90^\circ$, as shown in figure 4e. Broader BW will be realised when a loop formed due to coupling between TM_{01} and TM_{20} modes lies inside the $\text{VSWR} = 2$ circle. The input impedance locus for ' L_v ' = 3.9 cm and $y_f = 3.0$ cm is shown in figure 4f. The loop position (as shown by the arrow) is not optimised inside the $\text{VSWR} = 2$ circle. At modified TM_{20} mode, surface currents originate

from inside the U-slot. Therefore, input impedance is higher inside the slot. The input impedance plots for decreasing feed point location (y_f) are shown in figure 4f. When the feed is placed inside the U-slot, input impedance increases and the loop position shifts towards higher-resistance region in the Smith chart. This optimises its position inside the $\text{VSWR} = 2$ circle to yield broadband response. Thus, from earlier study, it is inferred that U-slot tunes the spacing between TM_{01} and TM_{20} mode frequencies and position of feed point optimises the impedance at respective modes to yield broader BW.

Figure 3. (a) Equivalent RMSA, its (b) resonance curve plots for two feed-point locations, its simulated (c) surface current, (d) radiation pattern plot at TM_{20} mode and (e) U-slot cut RMSA.

4. Analysis of asymmetrical U-slot cut RMSA

For asymmetrical U-slot cut patch, its equivalent RMSA ($L = 4.85$ and $W = 4.58$ cm) is simulated for different feed positions, as shown in figure 5a and respective resonance curve plots are shown in figure 5c. For feed at point 'A', resonant peaks due to TM_{10} (2044 MHz) and TM_{02} (3886 MHz) modes are observed. When the feed is

placed at point 'B', peaks due to TM_{01} (2122 MHz) and TM_{20} (3784 MHz) modes are observed. When the feed is placed at point 'C', TM_{10} , TM_{01} and TM_{11} (3004 MHz) modes are observed. In the reported asymmetric U-slot cut RMSA, feed is placed along the horizontal axis, that is, at ' $x_f = 1.4$ ' [10]. Therefore, in the present analysis, same feed position with respect to U-slot is selected, as shown in figure 5b. The resonance curve plots for ' $x_f = 1.4$ cm

Figure 4. (a, b) Resonance curve plots for $y_f = 3.0$ and varying slot dimensions, surface current distribution at modified TM_{20} mode for $L_h = 2.4$ and (c) $L_v = 1.9$ and (d) $L_v = 3.9$, simulated (e) radiation pattern plot at modified TM_{20} mode for $L_h = 2.4$, $L_v = 3.9$ and (f) input impedance plots for varying feed-point location in U-slot cut RMSA.

and for increasing U-slot dimensions are shown in figure 5d and e. Since the feed is along x -axis, resonance plot for RMSA show peaks due to TM_{10} and TM_{02} modes. In U-slot, first a rectangular slot of length ' L_h ' is cut. This

slightly reduces TM_{02} mode frequency as the slot length is orthogonal to its modal surface currents. With increase in vertical slot length (L_v), TM_{10} and TM_{02} mode frequencies reduce. Due to asymmetrical position of U-slot with

Figure 5. (a) RMSA, (b) asymmetric U-slot cut RMSA, (c) resonance curve plots for RMSA for different feed point locations and (d, e) resonance curve plots for varying U-slot dimension for asymmetric U-slot cut RMSA.

respect to patch centre, slot-cut RMSA becomes an asymmetrical configuration for larger ' L_v ', due to which TM_{01} and TM_{11} modes also appear in the resonance curve plot. With further increase in ' L_v ', perturbation in surface current lengths increases at all the resonant modes, which reduces their frequencies. The surface current distribution at observed resonant modes for ' L_v ' = 0.9 and 2.4 cm are shown in figure 6a to g. Across various resonant modes, due to asymmetrical U-slot, surface currents are not oriented either along patch width or along the length. This gives bi-directional surface current variation over the slot-

cut patch. Input impedance and resonance curve plots for $L_v = 2.4$ cm and for varying feed point locations are shown in figure 7a to d. The plots in figure 7a and b shows variation in feed point along the horizontal axis (x_f), whereas that in figure 7c and d shows variation in the same along vertical axis (y_f).

Inside U-slot, surface currents at modified TM_{01} and TM_{11} modes vary along the horizontal and vertical directions, respectively. Hence, with decrease in ' x_f ', impedance at modified TM_{01} mode reduces, whereas that at modified TM_{11} mode marginally increases. Similarly, with increase

Figure 6. Surface current distribution at observed resonant modes for asymmetric U-slot cut RMSA for $L_v =$ (a–c) 0.9 cm and (d–g) 2.4 cm.

in ‘ y_f ’, impedance at modified TM_{01} mode remains constant, whereas at TM_{11} mode, it reduces. This variation in impedances at respective modes changes their loop size in the input impedance plots. Broader BW is obtained when spacing between modified TM_{01} and TM_{11} modes is optimised with respect to TM_{10} mode. This is obtained for ‘ L_v ’ = 2.4 cm. Further feed position optimises the impedance at TM_{01} and TM_{11} modes to control their loop size that realises wider BW. In asymmetric U-slot cut RMSA,

due to bi-directional variations in surface currents over TM_{10} , TM_{01} and TM_{11} resonant modes, polarisation of the radiated E-field vector changes over horizontal (x -axis) to vertical (y -axis) directions and radiation pattern shows higher cross-polarisation level. Hence, although asymmetrical U-slot cut RMSA yields higher BW, due to pattern variation and higher cross polar component, it may not be useful as compared with symmetrical U-slot cut configuration.

Figure 7. Input impedance and resonance curve plots for asymmetric U-slot cut RMSA for variation in (a, b) x_f and (c, d) y_f .

5. Formulation in resonant length for U-slot cut RMSA

Using half-wavelength approximation, formulation in resonant length at slot mode in symmetrical U-slot cut RMSA is reported [3, 12]. But as seen earlier, broader BW is realised due to modified TM_{02} mode. Hence, by modifying the resonant lengths at TM_{01} and TM_{20} modes, formulation for symmetric U-slot cut RMSA is proposed here. The surface current distributions at modified TM_{01} and TM_{20} modes are shown in figure 8a to f. The horizontal slot length ' L_h ' slightly reduces TM_{01} mode resonance frequency. The increase in TM_{01}

mode resonant length (W_e) or decrease in its frequency is formulated by using Eq. (1). The surface currents at TM_{01} mode show sinusoidal variation along patch width; hence, reduction in its frequency depends on the position of ' L_h '. The maximum reduction in frequency is obtained when horizontal slot is placed in the patch centre, that is, at $y = W/2$ as shown in figure 3e. To account for this effect, sinusoidal function is used in Eq. (1). With an increase in vertical U-slot length ' L_v ', surface currents at TM_{01} mode circulate around the vertical U-slot length. The circulation in currents increases with ' L_v ', which increases the perturbation in current lengths. Thus, increase in modified TM_{01} mode resonant length with

Figure 8. Surface current distributions for different slot length at (a–c) TM_{01} and (d–f) TM_{20} mode for U-slot cut RMSA.

Figure 9. Resonance frequencies and percentage error plots at (a) TM_{01} and (b) TM_{20} modes for U-slot cut RMSA.

respect to L_v (W_{ch}) is modeled using Eq. (2). Further, for $m = 0$ and $n = 1$, TM_{01} mode frequency is calculated by using Eq. (3). The percentage error between calculated (f_{calc}) and simulated (f_{ie3d}) frequencies is calculated using Eq. (4). The frequencies and percentage error plots are shown in figure 9a. For complete slot length range, closer approximation between two frequencies with less than 5% error is obtained. The reported U-slot cut RMSA was fabricated on foam substrate of 1.0 cm thickness. Its TM_{01} mode resonance frequency for different U-slot length was measured using ZVH-8 vector network analyser. The measured TM_{01} mode frequency also

shows closer match with simulated and calculated values as shown in figure 9a.

$$W_e = W + 2(0.7h) + \left(\left(yL_h/W \right) \sin(\pi y/W) \right) \quad (1)$$

$$W_{ch} = W_e + \left(L_v/W - L_v \right) \quad (2)$$

$$f_{mn} = c/2\sqrt{\epsilon_r} \sqrt{\left(m/L_e \right)^2 + \left(n/W_{ch} \right)^2} \quad (3)$$

$$\% \text{ error} = \left(f_{ie3d} - f_{calc}/f_{ie3d} \right) \times 100 \quad (4)$$

where $c = 3 \times 10^8$ (m/s), velocity of light in free space, ϵ_r = foam dielectric constant = 1.06, m & n = mode indices

At TM_{20} mode, surface currents are directed along the patch length. The slot width in horizontal section of U-slot (L_h) is orthogonal to TM_{20} mode surface currents. The increase in length due to the same is proportional to ratio of slot width to patch width (w/W). Hence, an effect of slot width (w) on TM_{20} mode resonant length (L_e) is formulated using Eq. (5). At modified TM_{20} mode, with increase in vertical U-slot length, currents show half-wavelength variations from inside and outside the U-slot and towards the opposite vertex point, along the patch width (figure 8d to f). In addition, it is observed from the parametric study for length variation that for smaller vertical U-slot length ' L_v ', decrease in TM_{20} mode frequency is larger and as ' L_v ' approaches W , reduction in frequency is smaller. To model this increase in length variation, second term on right-hand side of Eq. (6) is multiplied by using sinusoidal function. Modified TM_{20} mode resonant length (L_{eh}) with respect to increase in ' L_v ' is calculated by using Eq. (6). For $m = 2$ and $n = 0$, frequency and % error is calculated by using Eqs. (3) and (4) and they are plotted in figure 9b. Over the complete slot length range, less than 5% error is obtained.

$$L_e = L + 2(0.8h) + (w/W)(w/2) \quad (5)$$

$$L_{eh} = L_e + \left(L_v/2\right) \left(L_v + W/4\right) \sin\left(\pi L_v/W\right). \quad (6)$$

6. Design of U-slot cut RMSAs

Further, using proposed formulations, U-slot cut RMSAs are designed in different frequency range. In the reported optimised U-slot cut RSA [10], modified f_{TM20} and f_{TM01} mode frequencies are 2279 and 1492 MHz, respectively, which gives f_{TM20}/f_{TM01} of 1.5. With respect to TM_{01} mode frequency (2182 MHz) of equivalent RSA, U-slot cut RSA is optimised on foam substrate of thickness $0.07\lambda_0$ [10]. The W/L ratio in RSA is 0.732. The U-slot width (w), horizontal U-slot length (L_h) and position of horizontal U-slot length (y) in terms of TM_{01} mode wavelength are $0.03\lambda_0$, $0.18\lambda_0$ and $0.064\lambda_0$, respectively. Using the aforementioned W/L ratio and foam substrate of thickness $0.07\lambda_0$, RSA dimensions for $f_{TM01} = 1000$ MHz are calculated as $W = 11$ cm and $L = 15$ cm. Using the U-slot parameters in terms of operating wavelength, various parameters at

1000 MHz are calculated as $w = 0.94$ cm, $L_h = 5.4$ cm, $y = 1.92$ cm. To realise broader BW, ratio of modified f_{TM20} and f_{TM01} mode frequencies should be around 1.5. Using proposed formulations, plots of modified TM_{01} and TM_{20} mode frequencies and their ratio are generated at 1000 MHz, as shown in figure 10a. Using the same, vertical U-slot length, which gives frequency ratio close to 1.5, is found out to be 9 cm. This U-slot cut RSA is simulated using IE3D software for $L_v = 9$ cm and its simulated input impedance plot is shown in figure 10b. The broadband response with formation of loop inside the VSWR = 2 circle is obtained. The simulated BW is 304 MHz (28.5%). The experiment was carried out and the measured BW is 320 MHz (28.8%), as shown in figure 10b.

Further using the proposed formulations, U-slot cut RMSAs are designed at 1500 and 4000 MHz and their respective antenna parameters are given in table 1. The frequency ratio plots at 1500 and 4000 MHz are shown in figure 10c and e. Using these plots, vertical U-slot length of 4.8 and 1.6 cm was selected for RSA in 1500 and 4000 MHz frequency range, respectively. The input impedance plots for re-designed antennas are shown in figure 10d and f. In both the cases, broadband response with formation of loop inside the VSWR = 2 circle is obtained. The simulated and measured BWs for 1500 MHz range are 495 MHz (30.3%) and 480 MHz (29.5%), whereas for 4000 MHz frequency the values are 1444 MHz (32.1%) and 1398 MHz (31.8%), respectively. The proposed formulations were further tested for air and suspended glass epoxy substrate ($\epsilon = 4.3$, $h = 0.16$ cm and $\tan \delta = 0.02$). The results for them are shown in figure 11a and b. The patch designed on air substrate yields simulated and measured BW of 356 MHz (33.4%) and 366 MHz (35%), respectively. The RSA designed on suspended glass epoxy substrate ($h = 2.0$ (air) + $0.16 = 2.16 \sim 0.07\lambda_0$) yields simulated and measured BW of 238 MHz (23%) and 246 MHz (23.3%), respectively. Lastly, the formulations were also used for designing U-slot cut RSA on varying thicker substrates. For $TM_{10} = 1000$ - MHz, U-slot cut RSA is designed for $h = 2.5$ cm ($0.083\lambda_0$) and 3.0 cm ($0.1\lambda_0$) and for $TM_{10} = 4000$ MHz, it is designed for $h = 0.7$ cm ($0.093\lambda_0$). Various antenna parameters for the same are given in table 2. The input impedance plots for the re-designed antennas are shown in figure 11c to e. In all the cases, broadband response with formation of loop inside the VSWR = 2 circle is obtained. At 1000 MHz, for $h = 2.5$ cm, simulated and measured BWs are 321 MHz (30.8%) and 334 MHz (31.8%),

Table 1. Parameters for U-slot cut RSA at different TM_{01} mode frequency.

f_{01} (MHz) and substrate	w , ($0.03\lambda_0$) (cm)	L_h , ($0.18\lambda_0$) (cm)	y , ($0.064\lambda_0$) (cm)	y_f , ($0.08\lambda_0$) (cm)	L (cm)	W (cm)
1000, foam	0.94	5.4	1.92	2.4	15	11
1500, foam	0.63	3.6	1.28	1.6	10	7.3
4000, foam	0.24	1.35	0.48	0.6	3.6	2.6

Figure 10. Dual frequency and ratio and input impedance plots for U-slot cut RSA at (a, b) 1000 MHz, (c, d) 1500 MHz and (e, f) 4000 MHz.

Table 2. Parameters for U-slot cut RSA at different TM_{01} mode frequency for different air substrate thickness.

f_{01} (MHz)	h (cm)	w , $(0.03\lambda_0)$ (cm)	L_h , $(0.18\lambda_0)$ (cm)	L_V , (cm)	y , $(0.064\lambda_0)$ (cm)	y_F , $(0.08\lambda_0)$ (cm)	L (cm)	W (cm)
1000	2.5	1.0	5.4	8.8	1.92	2.4	15	11
1000	3.0	0.6	3.6	8.4	1.28	1.6	14.5	10.6
4000	0.7	0.2	1.4	1.7	0.48	0.6	3.5	2.6

Figure 11. Input impedance plots for (a) air and (b) suspended glass epoxy substrate for U-slot cut RSA in 1000 MHz range, input impedance plots for U-slot cut RSA at 1000 MHz for $h =$ (c) 2.5 cm and (d) 3.0 cm and at 4000 MHz for (e) $h = 0.7$ cm.

respectively, whereas that for $h = 3.0$ cm, the two BWs are 333 MHz (31.4%) and 345 MHz (32.9%), respectively. At 4000 MHz, simulated and measured BWs are 1211 MHz (26.7%) and 1245 MHz, (27.7%), respectively. Thus, the proposed formulation can be used to design U-slot cut RMSA at any given frequency and for varying substrate thickness. Many papers on U-slot cut antennas are available in the literature, but proper explanations for antenna working are not included. The novelty of the proposed work lies in providing detailed explanation for slot resonant mode as well as the formulation and a design procedure for designing the U-slot cut antennas on thicker substrates at any given frequency.

7. Conclusions

A detailed analysis to study the broadband response in symmetric and asymmetric U-slot cut RMSAs is presented. In symmetrical configuration, U-slot reduces patch TM_{20} mode resonance frequency, which along with TM_{01} mode yields broader BW. The slot alters the surface current distribution at TM_{20} mode to give broadside radiation pattern over the BW. In an asymmetric configuration, U-slot optimises spacing of TM_{20} and TM_{11} modes with respect to TM_{10} and TM_{01} modes to yield broadband response. Due to orthogonal variations in surface currents over various resonant modes, radiation pattern shows higher cross-polar levels. Additionally, formulation in resonant length at modified TM_{01} and TM_{20} modes in symmetric U-slot cut RMSA is proposed. Frequencies calculated using these formulations give closer agreement with simulated and measured results. Using the proposed formulations, procedure to design U-slot cut RMSAs at different frequencies in 800–4000 MHz frequency band is presented, which yields broadband response with formation of loop inside the $VSWR = 2$ circle. Although papers on U-slot cut MSAs are widely available in the literature, modal explanations are not included. The proposed work gives an insight into the functioning of U-slot cut RMSAs, especially asymmetric configuration. Also the formulations at modal frequencies are proposed for symmetric U-slot patch, which will help in designing of similar configurations at any desired frequency.

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