# Analysis of Broadband Slot Cut Semi-Circular Microstrip Antennas

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## ABSTRACT
Broadband microstrip antenna is more commonly realized by cutting slot inside the patch. While designing slot cut antennas at a given frequency, slot length is taken to be either quarter wave or half wave in length. However this simpler approximation does not give closer result. In this paper, an analysis to study the effect of slot like, half U-slot and rectangular slot on the broadband response of Semi-circular microstrip antenna is presented. It was observed that the slot does not introduce any additional mode but reduces the resonance frequency of second order $TM_{21}$ mode of the patch and along with fundamental $TM_{11}$ mode yields broadband response. The slot also modifies the surface current directions at $TM_{21}$ mode and thereby yields broadside radiation pattern over the complete bandwidth. Further by studying the surface current distributions at modified $TM_{21}$ mode, the formulation of resonant length is proposed. The frequencies calculated using the proposed equations agrees closely with the simulated result with % error less than 5% over the complete slot length range.

## Keywords
Semi-circular microstrip antenna, Broadband microstrip antenna, Half U-slot, Rectangular slot, Higher order modes

## 1. INTRODUCTION
The simplest method to realize broadband microstrip antenna (MSA) is by fabricating the patch on lower dielectric constant thicker substrate in conjunction with the proximity feeding technique [1 – 3]. The thicker substrate reduces the quality factor of the cavity below the patch whereas the proximity feeding technique realizes impedance matching for substrate thickness more than $0.06\lambda_0$. More commonly broadband MSAs are realized by cutting the slot (U-slot, V-slot and rectangular slot) at an appropriate position inside the patch [4 – 8]. The slot when its length nearly equals either half wave or quarter wave in length then it introduces a mode near the fundamental mode of the patch, to yield broadband response. However while designing slot cut MSAs in given frequency range, this simpler approximation of slot length against the wavelength does not give closer results for different slot lengths and their position inside the patch. An analysis to study the effects of U-slot in dual band rectangular MSA is reported [9]. The formulation of resonant length at various frequencies in terms of slot and patch dimensions is given. However a clear description of the modes at the individual frequencies and the comparison of simulated and measured results against the calculated results obtained using proposed formulations were not given. An analysis to study the effects of slots in broadband slot cut rectangular MSA is reported [10, 11]. The resonance curve plots, surface current distributions and radiation pattern plots were studied for different slot lengths. It was observed that the slot does not introduce any additional mode but reduces the resonance frequency of higher order orthogonal $TM_{02}$ mode of the patch and along with fundamental $TM_{10}$ mode yields broadband response. The slot also modifies the surface current directions at higher order mode and thereby gives broadside radiation pattern over the complete bandwidth (BW) without any variations in the direction of principle planes. The Semi-circular MSA (SCMSA) is a compact variation of circular MSA (CMSA) and broadband slot cut configurations of CMSA and SCMSA are reported [1, 12, 13].

In this paper, firstly broadband designs of slot cut SCMSAs for two different slot dimensions, are discussed. In the two cases, quarter wavelength approximation of slot length against the observed slot frequency does not give closer match. Therefore to understand the effect of slot, an analysis of broadband half U-slot and rectangular slot cut SCMSAs is presented. The slot length is varied in steps and for each of the lengths, resonance curve plots, surface current distributions and simulated radiation pattern plots generated using IE3D software were studied [14]. It was observed that the slot reduces the resonance frequency of second order $TM_{21}$ mode of the patch and along with the fundamental $TM_{11}$ mode yields broadband response. The slot also modifies the surface current directions at modified $TM_{21}$ mode and aligns them in the same directions as that of the currents at $TM_{11}$ mode and it gives broadside radiation pattern over the complete BW. Further by studying the surface current distributions for different slot lengths, formulation of resonant length at modified $TM_{21}$ mode is proposed. The frequencies calculated using proposed formulations agrees closely with simulated results obtained using IE3D software (which agrees within 2% with the measured results) for the complete slot length range. Thus the proposed analysis gives an insight into the functioning of slot cut antennas and the formulations can be used to design the slot cut SCMSAs at the desired frequency.

## 2. BROADBAND SLOT CUT SCMSAs
Broadband half U-slot and rectangular slot cut SCMSAs are shown in Fig. 1(a – c). The SCMSA is suspended in air of thickness (h) 2.1 cm ($0.06\lambda_0$) and is fed using the N-type connector of inner wire diameter 0.32 cm. The SCMSA radius is selected such that it operates in $TM_{11}$ mode at frequency of around 1000 MHz. The half U-slot cut SCMSA is optimized for broader BW for two different vertical slot lengths ($L_v$ = 1.5 and 2.5 cm) and resonance curve plots for them are shown in Fig. 1(d). Similarly broadband rectangular slot cut SCMSA is optimized for two values of slot position (Y) and resonance curve plots for the optimized designs are shown in Fig. 1(e).

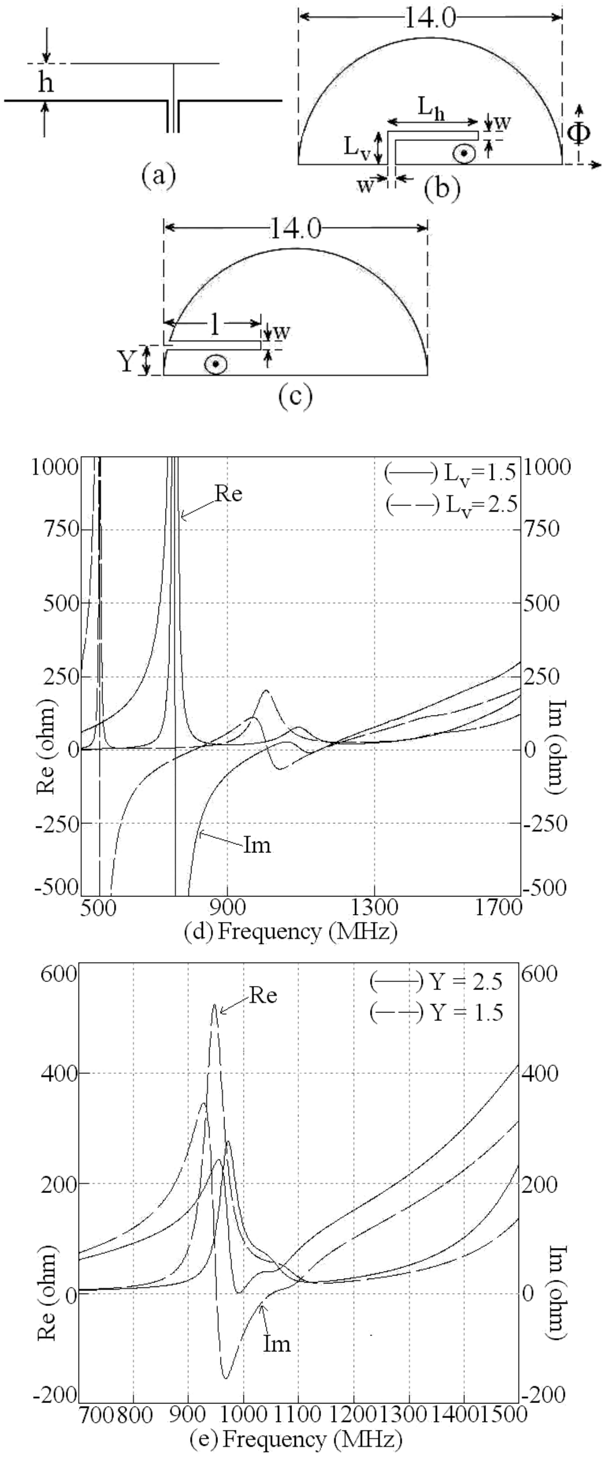


**Fig. 1 (a) Top and (b) side views of half U-slot and (c) rectangular slot cut SCMSA and resonance curve plot for (d) half U-slot cut and (e) rectangular slot cut SCMSA**

In half U-slot cut SCMSA, first peak in the resonance curve corresponds to $TM_{11}$ mode whose frequency is reduced due to $L_v$. The second peak corresponds to slot mode and for $L_v$ = 1.5 and 2.5 cm, its frequency was found to be, 1091 MHz and 1011 MHz, respectively. The total inner slot length ($L_h$ – w + $L_v$) for two slot dimensions was found to be 7.9 cm and 11.8 cm. The frequencies calculated by equating this length to quarter wavelength, are 949 MHz and 635 MHz. These two frequencies are not close to the frequencies observed in resonance curve plots. In rectangular slot cut SCMSA, slot length is taken to be quarter wave in length. In the optimized designs, first peak in the resonance curve corresponds to $TM_{11}$ mode. The second peak frequency due to slot mode was found to be 1040 and 1068 MHz, for Y = 1.5 and 2.5 cm, respectively. The slot length in the two cases is 5.9 and 6.0 cm. By using quarter wave length approximation, the frequencies for these lengths are 1271 and 1250 MHz, which are not close to the observed frequencies in the resonance curve. Thus simpler quarter wave length approximation of slot length does not give accurate results. Therefore to understand the functioning of slot cut SCMSAs, an analysis of slot cut SCMSA is carried out as discussed in the following section.

## 3. ANALYSIS OF SLOT CUT SCMSAs

The above equivalent SCMSA was simulated using IE3D software and the resonance curve plot for the same is shown in Fig. 2(a). The first peak at 980 MHz corresponds to $TM_{11}$ mode and the next peak at 1556 MHz corresponds to $TM_{21}$ mode. The surface current distribution at these two frequencies is shown in Fig. 2(b, c).

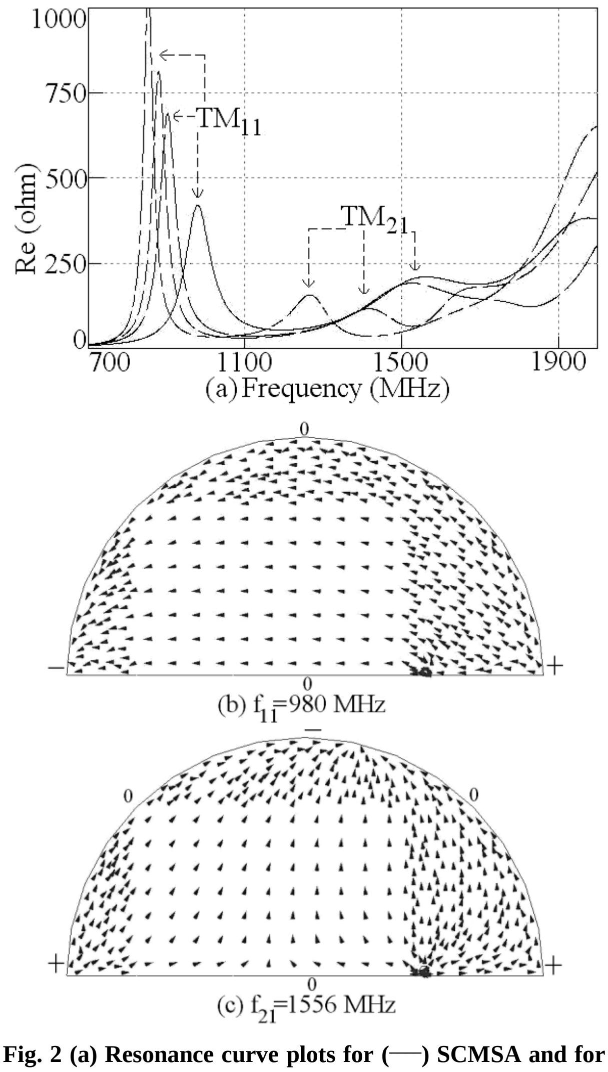


**Fig. 2 (a) Resonance curve plots for (—) SCMSA and for $L_v$ = 1.5 and (— —) $L_h$ = 3 cm, (– – –) $L_h$ = 4 cm, (— - —) $L_h$ = 5 cm and surface current distribution at (b) $TM_{11}$ and (c) $TM_{21}$ modes for SCMSA**

At $TM_{11}$ mode, surface currents show one half wave length variations along patch diameter and the perimeter. The radiation pattern at $TM_{11}$ mode is in the broadside direction with E-plane aligned along $\Phi = 0^0$. At $TM_{21}$ mode, surface current shows half wavelength variation along patch diameter and two half wavelength variations along patch perimeter. At $TM_{21}$ mode maximum of surface currents are vertically directed inside the patch, hence radiation pattern shows E-plane aligned along $\Phi = 90^0$, as shown in Fig. 3(a). The half U-slot is cut inside this patch and resonance curve plots for $L_v$ = 1.5 cm and for varying $L_h$ are shown in Fig. 2(a). The increase in $L_h$ is parallel to the surface currents at $TM_{11}$ mode, hence decrease in its frequency is smaller. However the surface currents at $TM_{21}$ mode are orthogonal to the slot length and hence with an increase in $L_h$, $TM_{21}$ frequency reduces and it comes closer to $TM_{11}$ mode frequency. The surface current distributions and simulated radiation pattern for $L_h$ = 4 and 6 cm are shown in Figs. 3(b, c) and 4(a, b), respectively. With an increase in $L_h$, surface currents at $TM_{21}$ mode are modified and they are aligned along horizontal directions inside the patch. This changes E-plane direction from $\Phi = 90^0$ to $0^0$ at the modified $TM_{21}$ mode.

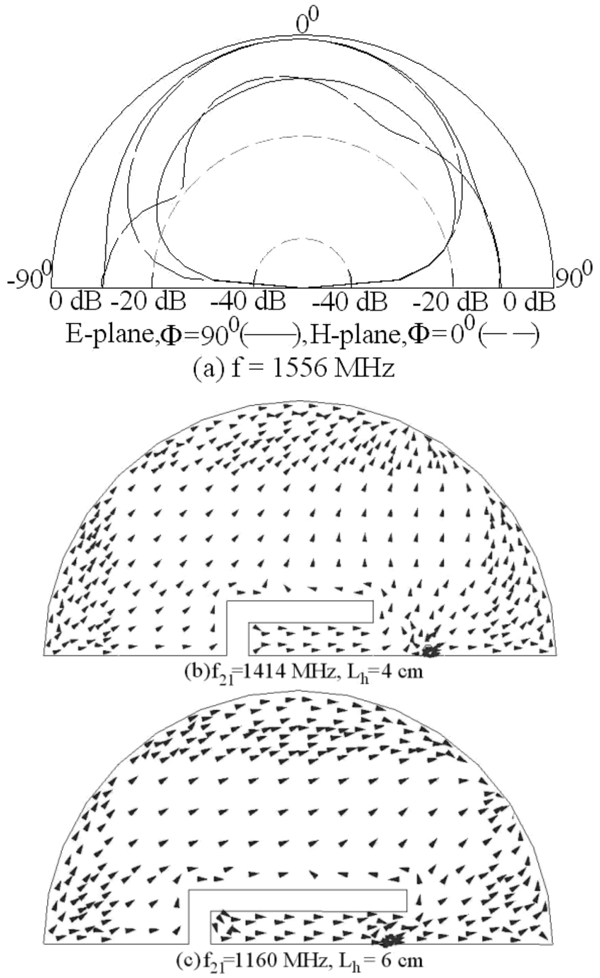


**Fig. 3 (a) Radiation pattern at $TM_{21}$ mode for SCMSA and surface current distribution for different $L_h$ for half U-slot cut SCMSA**

Thus half U-slot does not introduce any mode but reduces $TM_{21}$ mode frequency and when its spacing with respect to $TM_{11}$ mode frequency is optimized, then it yields broadband response. Due to half U-slot, surface currents at $TM_{21}$ mode is horizontal which leads to the E-plane direction along $\Phi = 0^0$ over the complete BW. Similar analysis is carried out for rectangular slot cut SCMSA as shown in Fig. 1(c). The resonance curve plots for varying slot length and surface current distribution for two slot lengths are shown in Figs. 4(c) and 5(a, b), respectively.

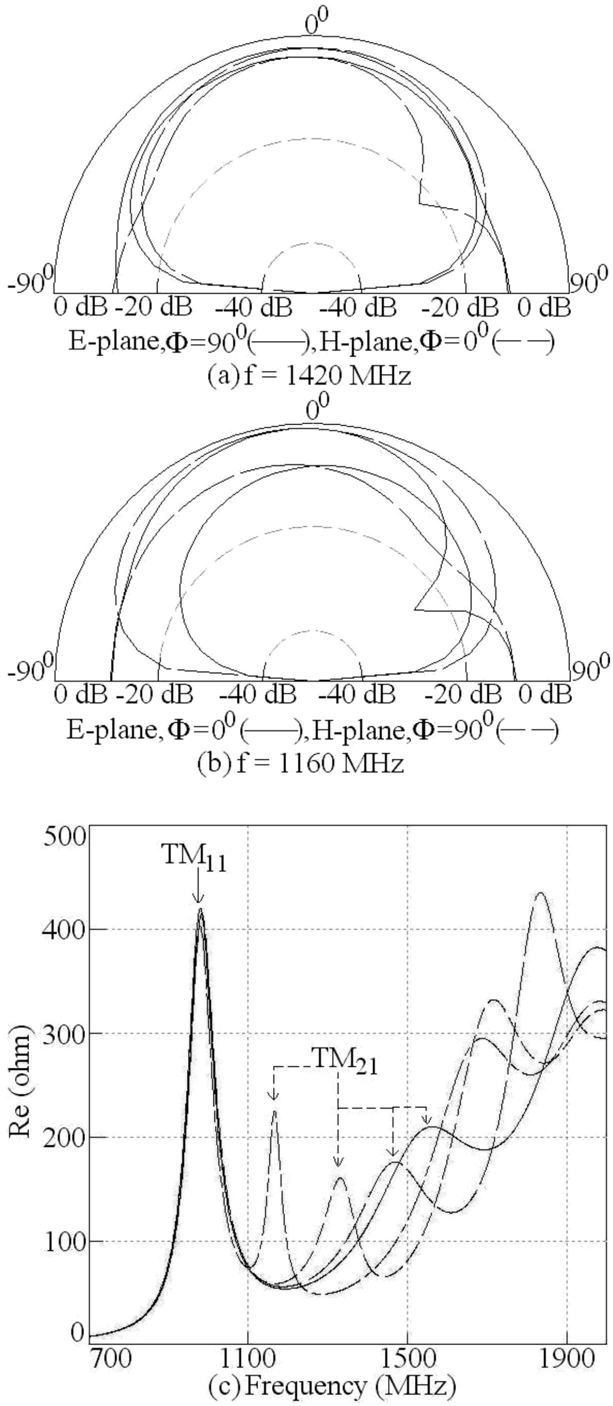


**Fig. 4 Radiation pattern for half U-slot cut SCMSA for (a) $L_h$ = 4 cm, (b) $L_h$ = 6 cm and (c) resonance curve plots for rectangular slot cut SCMSA, Y = 1.5 cm and w = 0.6 cm and, (——) l = 0 cm, (— —) l = 3 cm, (– – –) l = 4 cm, (— - —) l = 5 cm**

With an increase in slot length, $TM_{11}$ frequency remains constant whereas $TM_{21}$ mode frequency reduces. The surface currents at modified $TM_{21}$ mode are also aligned along the horizontal direction inside the patch. This changes E-plane direction from $\Phi = 90^0$ to $0^0$. Thus in this case also the slot realizes tuning of $TM_{21}$ frequency with respect to $TM_{11}$ mode frequency to realize broader BW. Similar results are obtained for rectangular slot cut SCMSA with slot cut inside the patch as shown in Fig. 5(c). Further by studying the surface current distribution at modified $TM_{21}$ mode, formulation of resonant length is proposed as discussed in the following section.

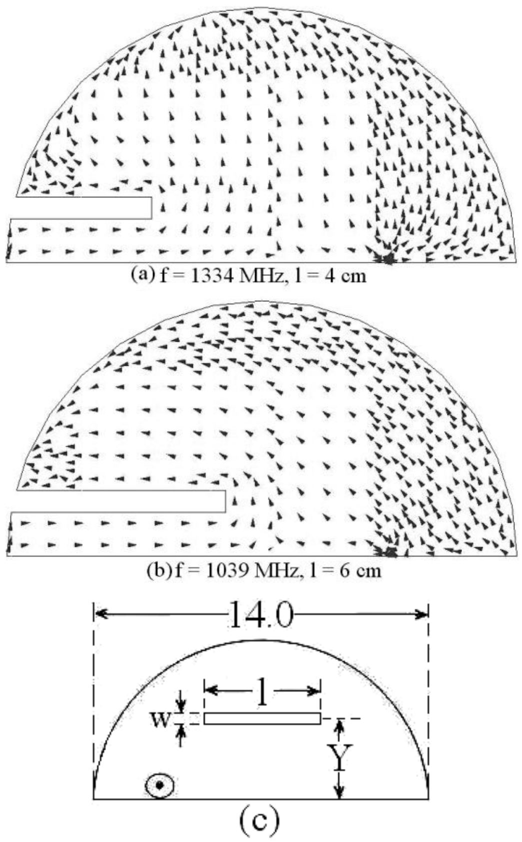


**Fig. 5 (a, b) Surface current distribution for modified $TM_{21}$ mode for rectangular slot cut SCMSA and (c) rectangular slot cut SCMSA (slot cut inside patch)**

## 4. Formulation of resonant length for slot cut SCMSA

The resonance frequency for CMSA is given by using equation (1). As the decrease in $TM_{11}$ mode frequency with slot length is smaller, its formulation in terms of slot dimension is not proposed. To formulate the resonant length at $TM_{21}$ mode, patch radius is modified in terms of the slot dimension. The formulation at modified $TM_{21}$ mode for half U-slot cut SCMSA is given by using equations (2) – (4).

$$f_r = \frac{K_{mn} c}{2r\pi\sqrt{\varepsilon_{re}}} \quad (1)$$

Where, c = velocity of light = 3 x $10^8$ (m/s)

$K_{mn}$ = $m^{th}$ root of $n^{th}$ order Bessel function = 3.05424, for $TM_{21}$ mode

$$r_e = r + 0.9L_v + 1.6\left(\frac{L_h}{25r}\right) \quad (2)$$

$$f_r = \frac{3.05424c}{2r_e\pi\sqrt{\varepsilon_{re}}} \quad (3)$$

$$\%\ \text{error} = 100\left(\frac{f_r - f_{ie3d}}{f_{ie3d}}\right) \quad (4)$$

The equation for effective patch radius ($r_e$) is derived based on the variation in $TM_{21}$ mode frequency with respect to slot length. The frequency is calculated by using equation (3) and the % error between the calculated and simulated values is calculated by using equation (4). For different values of $L_v$, plots of frequencies and % error are shown in Fig. 6(a – c).

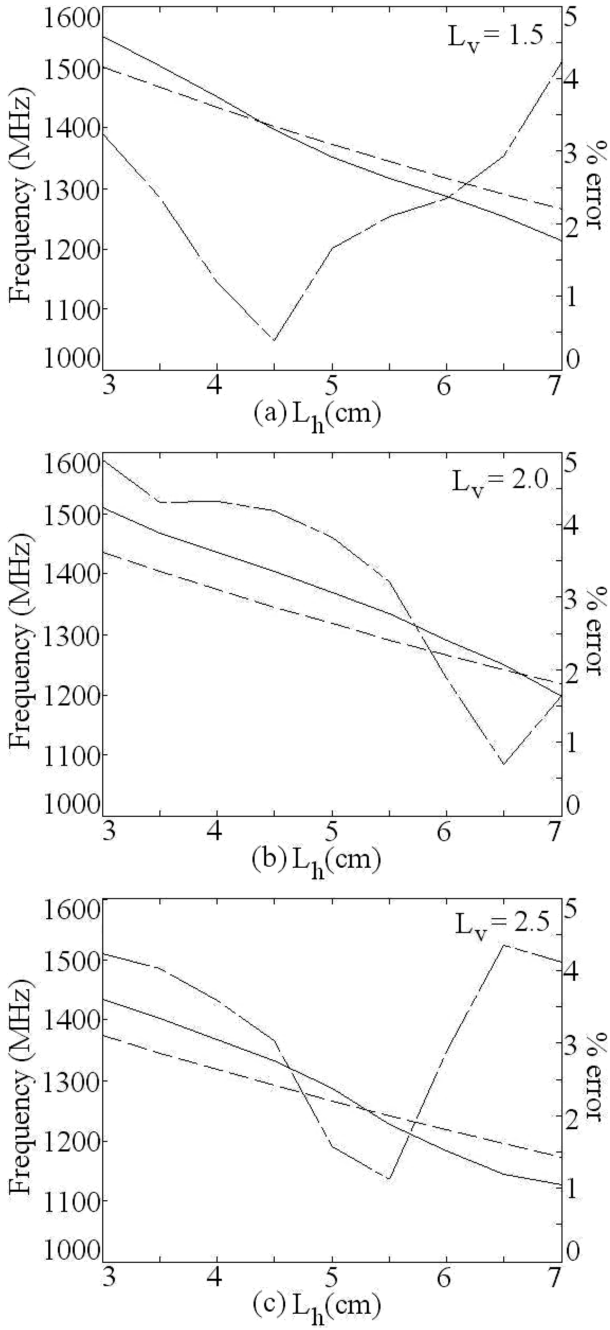


**Fig. 6 (a – c) Resonance frequency and % error plots for half U-slot cut SCMSA, (──) simulated, (‒ ‒ ‒) calculated, (──‒ ‒──) % error**

For the complete slot length range a closer agreement between calculated and simulated frequencies with % error less than 5% is obtained. For the rectangular slot cut CMSA (Fig. 1(c) and 5(c)) the decrease in $TM_{11}$ mode frequency is negligible. For the configuration in Fig 1(c), formulation of resonant length at modified $TM_{21}$ mode in terms of slot length (l) is given by using equations (5). The frequency and % error between simulated and calculated values are calculated by using equations (3) and (4), respectively. The plots of the same are shown in Fig. 7 (a – c).

$$r_e = r + Y + 1.5\left(\frac{l}{25r}\right) \quad (5)$$

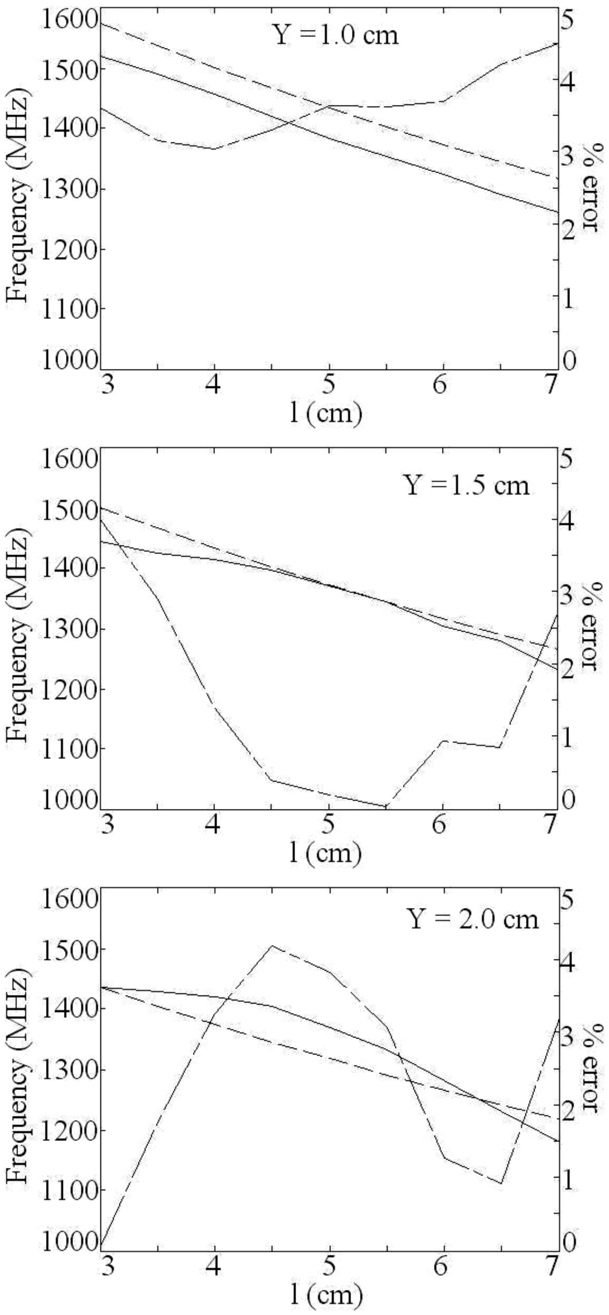


**Fig. 7 (a – c) Resonance frequency and % error plots for rectangular slot cut SCMSA, (—) simulated, (- - -) calculated, (— - —) % error**

For the entire slot length range a closer agreement between simulated and calculated frequencies is obtained. Similarly the formulation of resonant length for rectangular slot cut SCMSA wherein slot is cut inside the patch is proposed as given in equation (6). The plots of frequencies and % error are given in Fig. 8 (a – c).

$$r_e = r + Y + 1.3\left(\frac{l}{25r}\right) \quad (6)$$

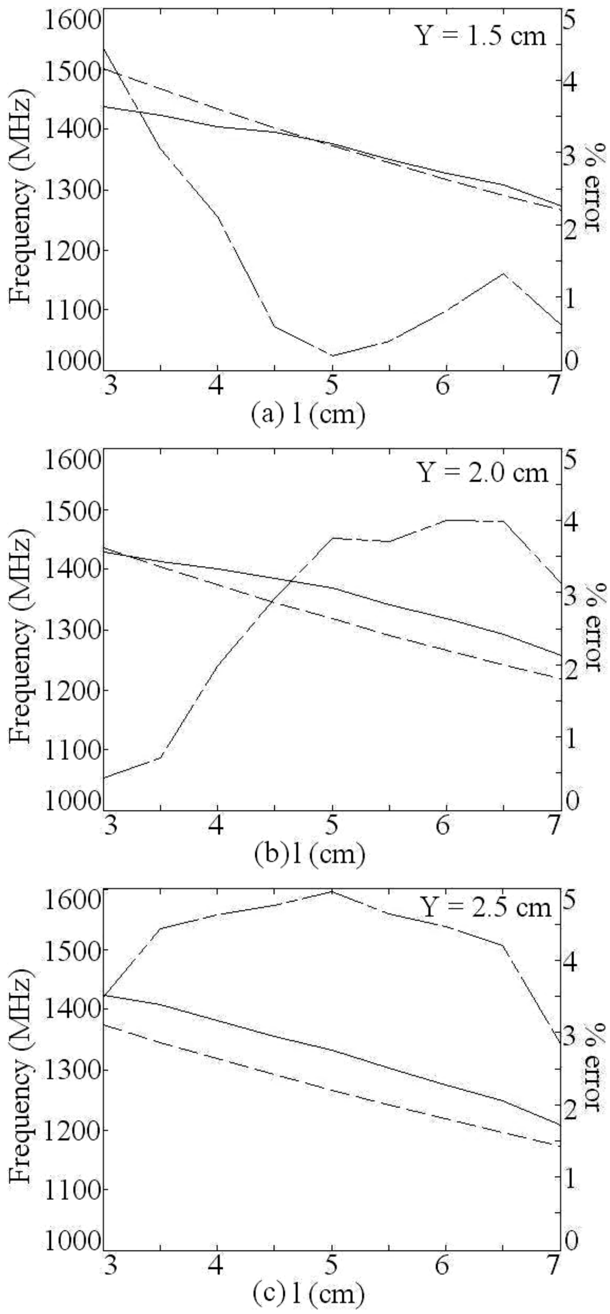


**Fig. 8 (a – c) Resonance frequency and % error plots for rectangular slot cut SCMSA (slot cut inside the patch), (—) simulated, (- - -) calculated, (— - —) % error**

For the complete slot length range, good agreement between the simulated and calculated values is obtained. Thus the proposed analysis gives an insight into the functioning of slot cut antennas and the proposed formulation can be used to design slot cut SCMSA in the given frequency band.

## 5. Conclusions

The broadband designs of slot cut SCMSAs are discussed. It was observed that the quarter wavelength approximation of slot length does not give closer result. Therefore to get an insight into the functioning of slot cut antennas, an analysis of slot cut SCMSAs is proposed. It was observed that the slot reduces second order $TM_{21}$ mode frequency of the patch and along with $TM_{11}$ mode yields broadband response. The slot also modifies the surface currents directions at $TM_{21}$ mode and thereby yields broadside radiation pattern over the complete BW with out any variations in the directions of principle planes. The resonant length formulation for modified $TM_{21}$ mode in terms of slot dimension is proposed. In all the slot cut antennas, the frequencies calculated using the proposed formulations agrees closely with the simulated results. The proposed study in the paper is novel and these formulations can be used to design the slot cut antennas in the desired frequency range.

## 6. REFERENCES

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