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Analysis of Broadband E-shaped Microstrip Antennas

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ABSTRACT
The broadband E-shaped microstrip antenna is realized by cutting pair of rectangular slots on one of the radiating edges of rectangular microstrip antenna. While designing an E-shaped antenna at given frequency, the slot length is taken to be nearly quarter wave in length. However this simpler approximation does not give closer results. In this paper, first a comparison of slot frequency calculated by using quarter wavelength approximation against simulated data for an optimized E-shaped antenna, is presented, which shows larger error. Further a detailed analysis to study the effects of slot on broadband response in E-shaped microstrip antenna is proposed. It is observed that slots do 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 distribution at TM_{02} mode thereby yielding broadside radiation pattern over complete bandwidth without any variations in the directions of principle planes. Further an analysis of rectangular slot cut rectangular patch is also presented. The rectangular slot reduces orthogonal TM_{01} mode frequency of the patch and along with its TM_{10} mode, yields broadband response. The proposed analysis gives an insight into the functioning of widely used E-shaped antenna, and it will help in designing them in given frequency band.

Keywords
Rectangular Microstrip Antenna, E-shaped microstrip antenna, Broadband microstrip antenna, Rectangular slot, Higher order mode

1. INTRODUCTION
The broadband microstrip antenna (MSA) is more commonly realized by cutting the slot of different shapes like, U-slot, V-slot, rectangular slots at an appropriate position inside the patch [1 – 5]. The slot is said to introduce an additional mode near the fundamental mode resonance frequency of un-slotted patch, when its length either equals half wave or quarter wave in length, to realize broadband response. The broadband E-shaped MSA is realized by cutting pair of rectangular slots on one of the edges of the rectangular MSA (RMSA) [6]. The E-shaped MSA yields BW of nearly 24% in 1600 MHz frequency band, with broadside radiation pattern and gain of more than 7 dBi over most of the BW. Two antenna designs for different spacing between the pair of slots were presented in [6]. A wide band E-shaped patch antenna for wireless mobile communication is reported [7]. Two antenna design yielding 21% and 32% bandwidth (BW) were discussed. The equivalent circuit for the equivalent RMSA and E-shaped MSA is presented. The equivalent circuit of E-shaped MSA consists of additional inductor which account for the surface current flow across the two parallel rectangular slots [7]. Using the space diversity concept, E-shaped patch antennas for high speed wireless networks like in WLAN applications in 5 to 6 GHz frequency band are proposed [8]. The antennas were compatible to be included in PCMCIA card of 0.5 cm thickness. A broadband and high gain 2 x 2 array of E-shaped patches is reported [9]. The individual E-shaped patches were fed using microstrip line fed equal power divider network. The reported E-shaped array yields impedance BW of more than 30% with gain of more than 10 dBi over most of the VSWR BW. For wireless applications, a wide-band circularly polarized E-shaped patch antenna is reported [10]. An effective BW of 9% in 2500 MHz frequency band was realized. As against the equal lengths of pair of rectangular slots in E-shaped MSA, pair of unequal length slots were used. The BW of E-shaped MSA has been increased by stacking two dipole re-radiators above the E-shaped patch which yields stable gain of around 8.4 – 8.7 dBi [11]. Using the circuit theory approach, an analysis of E-shaped MSA is reported [12]. The equivalent circuit model for an E-shaped patch is proposed in which to model the surface current flow across pair of slots, an inductor is added to the equivalent circuit of equivalent RMSA. The return loss plots for variation in realized BW against pair of slots parameters were given. However, design formulation for the mode introduced by the slot is absent. For substrate thickness more than $0.08\lambda_0$, various proximity fed broadband configurations of variations of E-shaped MSAs are proposed [13]. For substrate of thickness $0.0344\lambda_0$, the BW of suspended E-shaped MSA is increased by incorporating using L and C network which is integrated below the patch [14]. However the effects of using the folded ground plane and detail design procedure for proposed L and C network is not given. By using the symmetry of E-shaped MSA across the feed point axis, a compact rectangular slot cut RMSA is proposed [15, 16]. The compact configuration has slightly reduced BW as compared to that of equivalent E-shaped MSA. In most of the reported literature on E-shaped MSAs, while designing the MSA in given frequency band, slot length is taken to be approximately quarter wave in length and further other slot parameters like its width and spacing between them is optimized to achieve increase in BW. However this simpler approach of using slot length against quarter wavelength does not give closer results for different slot parameters. Also in the available literature the formulation for the slot frequency is not available. Therefore an analysis to investigate the effects of slot in E-shaped patch is needed.

In this paper, first reported broadband designs of E-shaped MSA are discussed [6]. The reported two E-shaped MSAs yield BW of 408 MHz (24.8%) and 376 MHz (23.6%) on air substrate of thickness 1.57 cm and 1.43 cm, respectively. For the same reported configuration, by further optimizing spacing between pair of slots and feed point location, an increased BW of 687 MHz (36.5%) is realized. From practical implementation purpose the antenna is optimized on air substrate of thickness 1.6 cm. Further to investigate the broadband response in E-shaped MSA, an analysis of this newly optimized E-shaped MSA is carried out. In the optimized MSA, using quarter wave length approximation the slot frequency for given pair of slot length is found to be 1286 MHz which neither lies in the operating BW nor it coincides with the observed resonance peaks in resonance curve plot. Therefore an analysis of E-shaped MSA by studying resonance curve plots, surface current distributions and simulated radiation pattern plots for equivalent RMSA and E-shaped MSA with different slot dimensions, generated using IE3D software is carried out [17]. It was observed that pair of slots does not introduce any additional mode near the fundamental mode frequency of the RMSA but reduces the orthogonal TM_{02} mode frequency of the patch and along with TM_{10} mode yields broadband response. The slot also modifies surface current distribution at TM_{02} mode and aligns them in the same direction as that of the currents at TM_{10} mode. Thereby it yields broadside radiation pattern over complete BW without any variations in the direction of principle planes. The aspect ratio (L/W) in the above equivalent RMSA of E-shaped MSA is higher (1.62), which leads closely spaced orthogonal frequencies. The similar analysis is also carried out using RMSA having smaller L/W ratio, which shows similar response. Further similar analysis for compact variation of E-shaped MSA, a single slot cut RMSA (half E-shaped MSA) is proposed. In this configuration, slot reduces TM_{01} mode frequency of the equivalent RMSA and along with TM_{10} mode yields broadband response. Thus the proposed analysis gives an insight into the functioning of E-shaped MSAs and will help them in designing at given frequencies.

2. BROADBAND E-SHAPED MSA

The reported configuration of broadband E-shaped MSA is shown in Fig. 1(a, b) [6]. In the reported design in [6], the patch is oriented such that its longer dimension is along x-axis. In this paper, from an analysis point of view, longer patch dimension is aligned along y-axis. This configuration, using air dielectric of substrate thickness 1.57 cm and 1.43 cm, yields BW of 408 MHz (24.8%) and 376 MHz (23.6%), respectively as shown in Fig. 1(c) [6]. For the same patch dimension, by varying separation between pair of slots (Y) and feed point location (x_f), the reported E-shaped MSA is optimized for larger BW than the reported one, as shown in Fig. 1(d). In the optimized configuration various parameters are, h = 1.6 cm, Y = 2.8 cm, l = 5.3 cm and w = 1.0 cm. The simulated BW is from 1537 to 2224 MHz (687 MHz, 36.5%). The simulated response is experimentally verified and the measured BW is from 1520 to 2236 MHz (716 MHz, 38.1%).

The slot in E-shaped MSA is said to introduce a mode near the fundamental patch mode (i.e. TM_{10}/TM_{01} depending upon L/W ratio) and when the spacing between these two frequencies is optimized it yields broadband response. The resonance curve plot indicating the two modes (peaks) in the broadband response in the above optimized E-shaped MSA is shown in Fig. 1(e). It shows peaks at 1011 and 1708 MHz. The surface current distribution at these two peaks is shown in Fig. 2(a, b). At 1701 MHz, surface currents show one half wavelength variations along patch length due the patch TM_{10} mode. At first peak, surface currents are found to be circulating around slot length. As per the reported literature on E-shaped MSA, at slot mode, currents are found to be circulating around the slot. Thus the resonance at 1011 MHz is due to the slot mode.

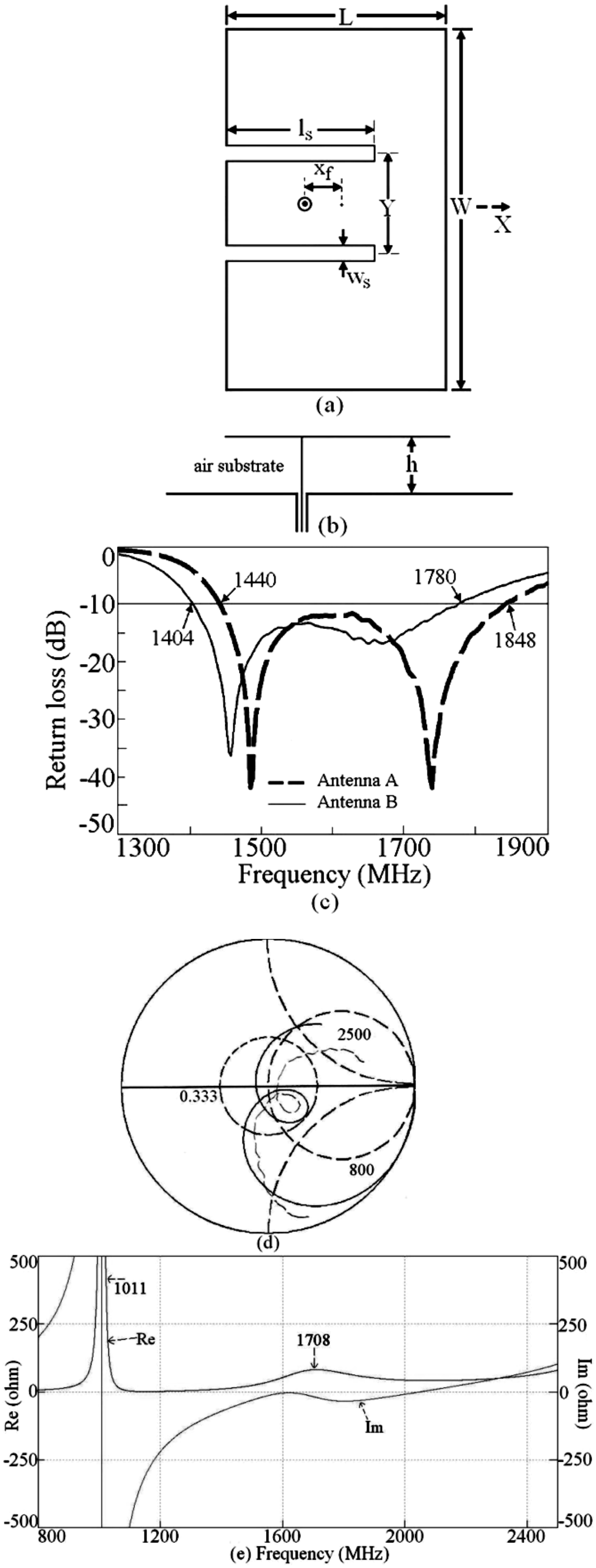

Fig. 1 (a) Top and (b) side views of E-shaped MSA, its (c) return loss plots [6], (d) input impedance, (──) simulated, (─ ─) measured and (e) simulated resonance curve plots for optimized E-shaped MSA

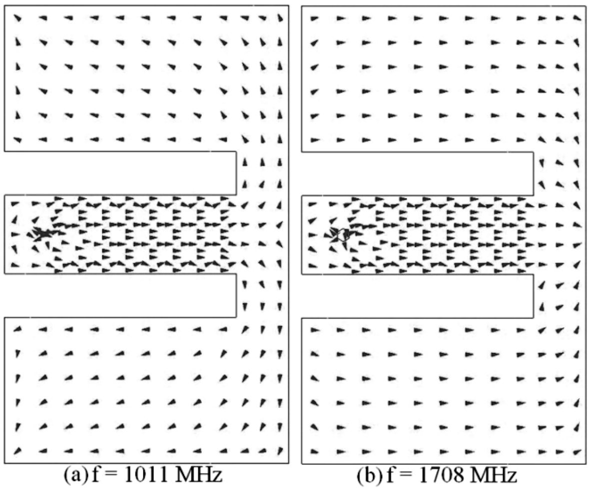

Fig. 2 (a, b) Surface current distribution at two peaks for E-shaped MSA

As per the reported literature on E-shaped MSA, slot length equals quarter wavelength with an additional length which account for additional surface current travel towards shorted end of slot [18]. This additional length was found to be approximately 10% of slot length. The slot length in above optimized E-shaped MSA is 5.3 cm. By using the quarter wavelength approximation, the corresponding frequency is 1286 MHz. This frequency neither lies in the operating BW nor it coincides with any of the observed resonant peaks. Thus the quarter wave length approximation for slot length does not give accurate results and hence to get an insight into the broadband behavior of E-shaped MSA, its analysis is presented as discussed below.

3. ANALYSIS OF BROADBAND E-SHAPED MSA

The equivalent RMSA dimensions in optimized E-shaped MSA are, L = 6.5 cm and W = 10.5 cm. This gives higher aspect ratio i.e. W/L = 1.6. The higher aspect ratio will realize higher gain but also leads to closely spaced orthogonal frequencies. Using the resonance frequency equation for RMSA, various calculated resonant mode frequencies are, f_{TM10} = 1657 MHz, f_{TM01} = 1163 MHz, f_{TM11} = 2023 MHz, f_{TM02} = 2325 MHz, f_{TM20} = 3311 MHz, f_{TM12} = 2855 MHz, f_{TM21} = 3510 MHz. The RMSA is simulated for feed point location shown in Fig. 1(a) and its resonance curve plot is shown in Fig. 3(a). The resonant peaks due to TM_{10} (1679 MHz), TM_{02} (2185 MHz) and TM_{12} (2821 MHz) are observed in the resonance curve as the impedance matching is realized at these modes. The surface currents at TM_{10} mode are aligned along patch length and it shows broadside radiation pattern with E-plane aligned along $\Phi = 0^0$. The surface currents at TM_{02} mode, as shown in Fig. 4(a), shows two half wavelength variation along patch width. It has conical radiation pattern i.e. maximum in end-fire direction with E-plane aligned along $\Phi = 90^0$ as shown in Fig. 4(d). Inside this RMSA, pair of slot was cut to realize E-shaped patch and resonance curve plots for varying slot length 'l_s' are shown in Fig. 3(a, b). For this length variation, feed point is located at x_f = -1.5 cm and values of 'Y' and 'w' are 2.8 and 1.0 cm, respectively.

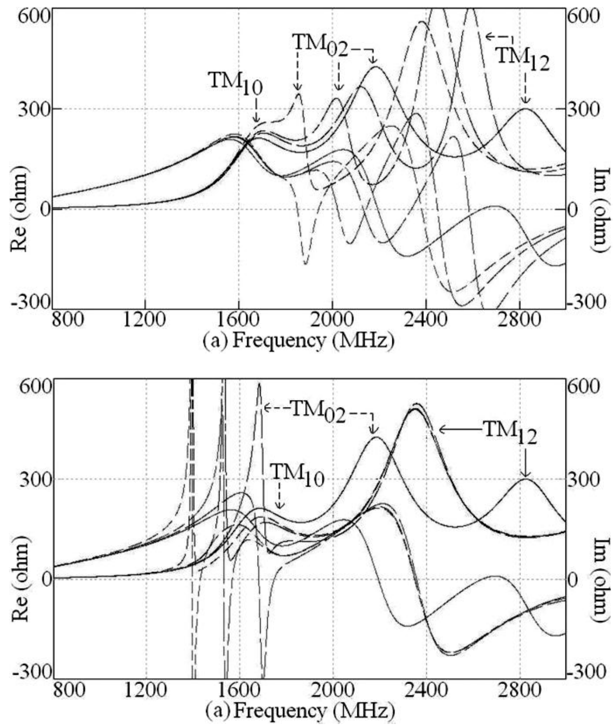

Fig. 3 Resonance curve plots for (a) (──) $l_s = 0$, (─ ─) $l_s = 1.5$, (─ ─ ─) $l_s = 2.0$, (- - -) $l_s = 2.5$, (b) (──) $l_s = 0$, (─ ─) $l_s = 3.0$, (─ ─ ─) $l_s = 3.5$, (- - -) $l_s = 4.0$, for E-shaped MSA

The pair of slots increase the surface current lengths at that mode for which its length is orthogonal, whereas frequency remains nearly unchanged for those modes at which surface currents are parallel to the slot length. Thus the TM_{10} mode frequency remains nearly constant whereas TM_{02} mode frequency reduces. The pair of slot modifies the surface currents at TM_{02} mode and with an increasing slot length, it aligns them along the patch length, as shown in Fig. 4(b, c). Due to increased amount of horizontally directed surface currents, with slot length, radiation pattern shows maximum in the broadside direction as shown in Fig. 4(e). However, for larger slot length ($l_s \geq 4.5$ cm), equal and anti-parallel components of surface currents along patch length, at modified TM_{02} mode cancels their radiation in the broadside direction. Hence due to surface currents along patch width, radiation pattern shows maximum radiation in the end-fire direction as shown in Fig. 4(f). The surface currents at modified TM_{02} mode, encircles around slot length as shown in Fig. 4(b, c). Hence, maximum current location lies near the shorted end of slot. Therefore when 'x_f' is reduced from 1.5 to 0.5 cm, the impedance at modified TM_{02} mode increases as shown in Fig. 5(a). Since at this feed location impedance at TM_{10} mode is smaller, a distinct peak due to the same mode is not present. Further broadband response is realized when the spacing between TM_{10} and modified TM_{02} mode is optimized such that the loop formed due to coupling between them lies inside VSWR = 2 circle. This is obtained for l_s = 5.3 cm and realized BW is from 1537 to 2224 MHz. As seen from the resonance curve, the resonance frequency of modified TM_{02} mode is lower than 1537 MHz and hence the surface currents over the complete operating BW remain in the horizontal direction. This gives radiation pattern in broadside direction with E-plane aligned along $\Phi = 0^0$, over the entire BW.

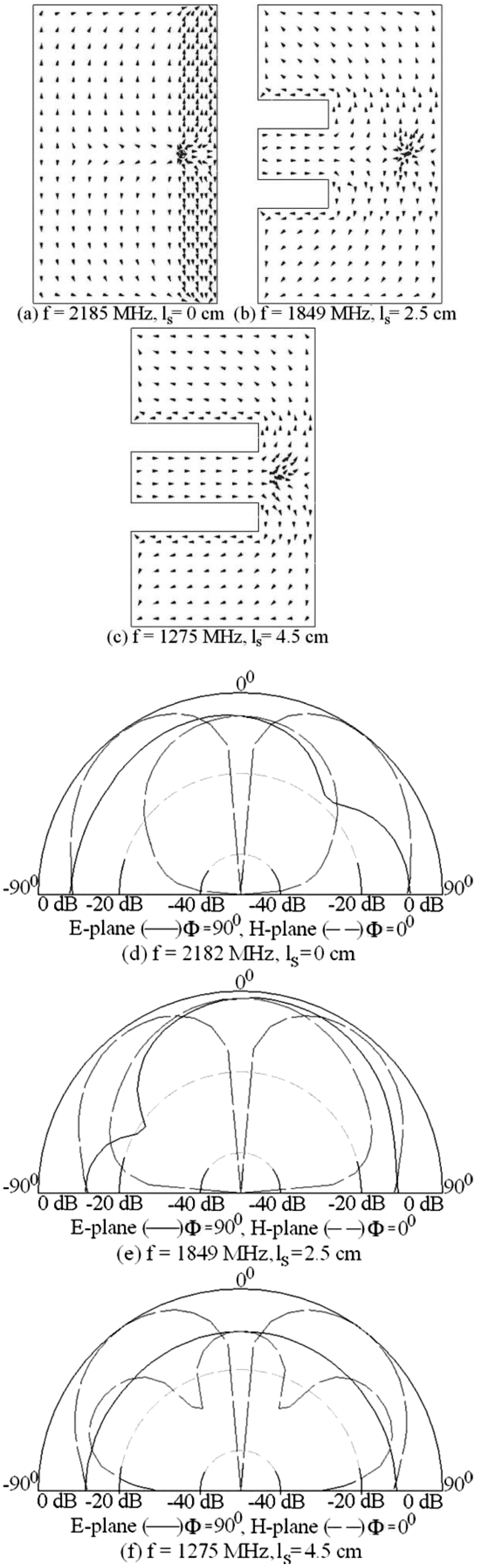

Fig. 4 (a – c) Surface current distribution and (d – f) radiation pattern for E-shaped MSA for different slot lengths

Thus pair of rectangular slots in E-shaped patch does not introduce any mode but reduces TM_{02} mode frequency and along with TM_{10} mode, yields broadband response. In the above E-shaped MSA, the aspect ratio (W/L) for equivalent RMSA is 1.6. Similar analysis is carried out for E-shaped MSA with smaller aspect ratio, in 900 MHz frequency range. For this analysis, E-shaped MSA reported in [16] is used as shown in Fig. 5(b, c). In the reported design, E-shaped patch is fabricated on glass epoxy substrate which is suspended above the ground plane with an air gap of 2.0 cm. The MSA has simulated BW of 176 MHz (20.2%) whereas the measured BW is 172 MHz (19.9%) [16].

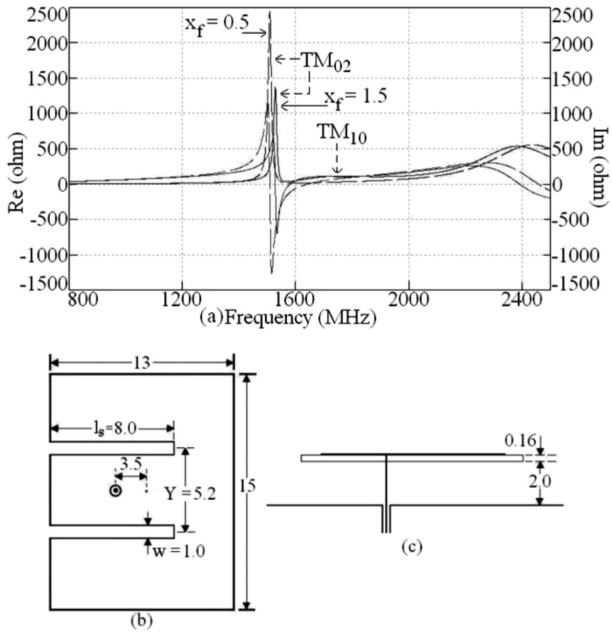

Fig. 5 (a) Resonance curve plot for varying x_f, (b) top and (c) side views of E-shaped MSA in 900 MHz range [16]

The resonance frequencies of various modes for this equivalent RMSA are, f_{TM10} = 850 MHz, f_{TM01} = 767 MHz, f_{TM11} = 1145 MHz, f_{TM02} = 1530 MHz, f_{TM20} = 1702 MHz, f_{TM12} = 1754 MHz, f_{TM21} = 1865 MHz. The RMSA is simulated for the feed point shown in Fig. 5(b) and its resonance curve plot is shown in Fig. 6(a). The resonance curve shows peaks due to TM_{10} (842 MHz), TM_{02} (1467 MHz) and TM_{12} (1709 MHz) modes. The pair of rectangular slots of dimension 'l_s' and 'w_s' were cut inside this patch and the resonance curve plots for Y = 5.2 cm, w_s = 1.0 cm and varying 'l_s' are shown in Figs. 6(a, b). Similar to the above E-shaped MSA, the TM_{10} mode frequency nearly remains constant whereas TM_{02} mode frequency reduces. Since TM_{12} mode frequency depends upon both the patch dimensions, its frequency also reduces. The slot modifies the surface current distributions at TM_{02} mode and with an increasing slot length, aligns them along patch length. The broadband response is realized when the spacing between TM_{10} and modified TM_{02} mode is optimized which yields formation of loop due to coupling between them, inside VSWR = 2 circle. This is realized for l_s = 8 cm. For this slot length the modified TM_{02} mode frequency is less than 700 MHz, and over the realized BW the surface currents are varying along patch length. Therefore over the complete BW, radiation pattern remains in broadside direction without any variations in the directions of principal planes. By using the symmetry of E-shaped MSA across the feed point axis, compact rectangular slot cut RMSA is reported [15, 16]. To understand the broadband response in this compact RMSA, its analysis is presented as given below.

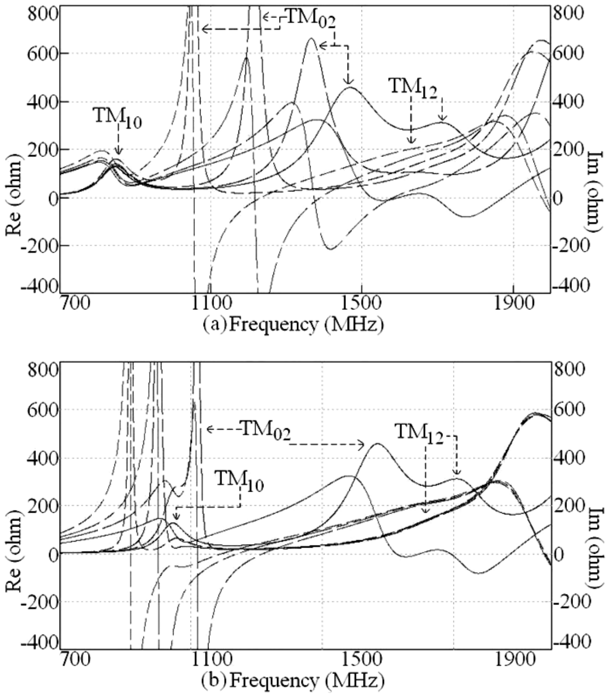

Fig. 6 Resonance curve plots for (a) (—) RMSA, (— —) l_s = 2.0, (— - —) l_s = 3.0, (— — —) l_s = 4.0, (b) (—) RMSA, (— —) l_s = 5.0, (— - —) l_s = 6.0, (— — —) l_s = 7.0 for E-shaped MSA in 900 MHz frequency range

4. ANALYSIS OF BROADBAND RECTANGULAR SLOT CUT RMSA

The broadband rectangular slot cut RMSA as reported in [16] is used in the present analysis as shown in Fig. 7(a).The compact configuration optimized on total substrate thickness of 2.16 cm, (2.0 cm air and 0.16 cm glass epoxy) yields simulated BW of 133 MHz (15.2%) whereas measured BW is 127 MHz (14.6%). The antenna shows broadside radiation pattern with higher cross-polarization levels towards higher frequencies of BW. To understand the broadband response the slot cut antenna is analyzed for varying slot lengths. For the equivalent RMSA, various resonant modes frequencies are, f_{TM10} = 850 MHz, f_{TM01} = 1302 MHz, f_{TM11} = 1555 MHz, f_{TM02} = 2605 MHz, f_{TM20} = 1702 MHz, f_{TM12} = 2740 MHz, f_{TM21} = 2142 MHz. The RMSA is simulated for the feed point location as shown in Fig. 7(a) and its resonance curve plot is shown in Fig. 7(b). The plot shows peaks due to TM_{10} (859 MHz), TM_{01} (1239 MHz) and TM_{11} (1559 MHz) modes. These frequencies are closer to the above calculated frequencies. At TM_{11} mode, the surface currents show one half wavelength variations along patch length as well as width. On one of the edges of RMSA, a slot of dimension 'l_s' and w = 1.0 cm, is cut and resonance curve plots for varying slot length and surface current distribution at modified TM_{01} mode for different slot length is shown in Fig. 7(b – e). The increase in slot length is parallel to the surface currents at TM_{10} mode, hence decrease in its frequency is negligible. The slot length is orthogonal to the surface currents at TM_{01} mode hence it reduces its frequency. The TM_{11} mode frequency also reduces as its frequency depends upon both the patch dimension. The surface currents at TM_{01} mode are aligned along patch width, which gives broadside radiation pattern with E-plane aligned along $\Phi = 90^0$. With an increasing slot length more and more amount of surface currents are aligned along patch length, which contribute to the radiation along $\Phi = 90^0$. The broadband response is realized when the spacing between modified TM_{01} and TM_{10} mode is optimized such that the loop formed due to the coupling between them lies inside VSWR = 2 circle in the input impedance plot. This is obtained for l_s = 8 cm as reported in [16]. For l_s = 8 cm, the modified TM_{01} mode frequency is lower than 600 MHz. Therefore over the entire operating BW, the surface current distribution remains along patch length which gives broadside radiation pattern without any variations in the direction of principle planes.

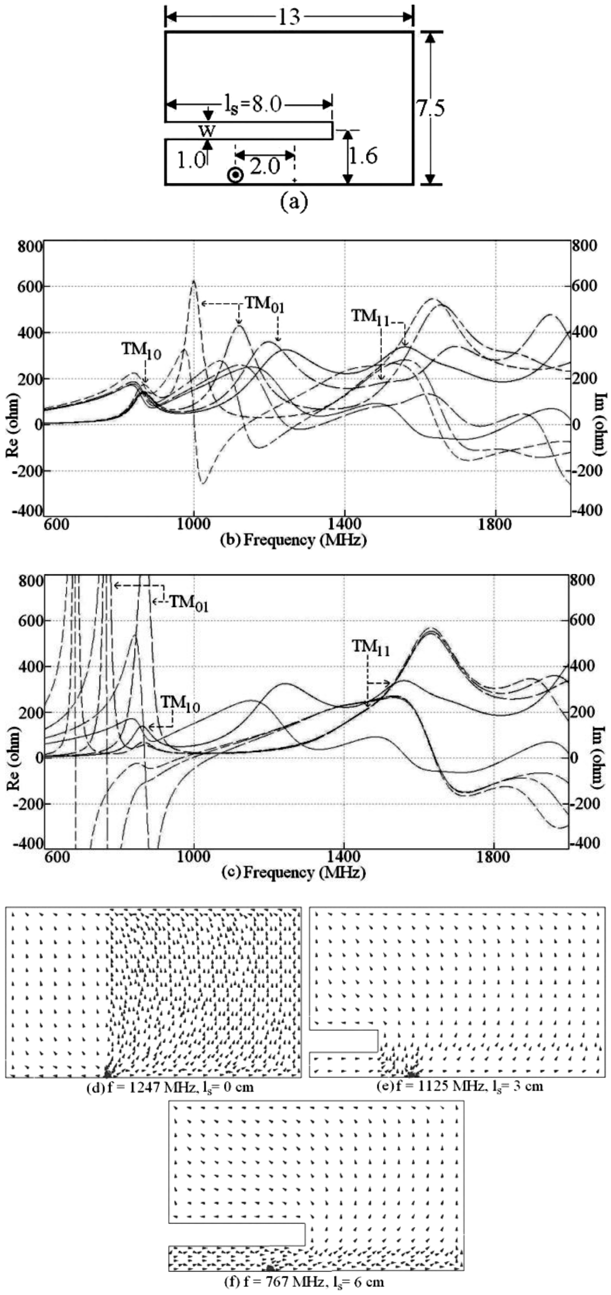

Fig. 7 (a) Rectangular slot cut RMSA, its resonance curve plots for (b) (—) l_s = 0, (— —) l_s = 2, (— - —) l_s = 3, (- - -) l_s = 4, (c) (—) l_s = 0, (— —) l_s = 5, (— - —) l_s = 6, (- - -) l_s = 7, and (d – f) surface current distribution at TM_{01} mode for different slot length

5. CONCLUSIONS

The reported broadband E-shaped MSA configurations are discussed. For the reported design, by optimizing slot position and its dimensions, an increase in BW of more than 680 MHz (>35%) is realized. While designing E-shaped MSA, it was observed that, quarter wavelength approximation of slot length against the frequency does not give closer results. Therefore an analysis of E-shaped MSA for varying slot dimension is presented. The analysis is presented for two different aspect ratios of equivalent RMSA. Through the analysis it was observed that slot does not introduce any additional mode but reduces the resonance frequency of orthogonal TM_{02} mode of the patch and when its spacing with respect to TM_{10} mode is optimized, it yields broadband response. In the optimized configuration, the modified TM_{02} mode frequency does not lie near the operating BW of E-shaped MSA and hence over the entire BW the surface currents are varying along patch length. This gives broadside radiation pattern over complete BW without any variations in the directions of principle planes. Further an analysis of compact variation of E-shaped MSA, rectangular slot cut RMSA (half E-shaped MSA) is proposed. In this configuration the slot reduces TM_{01} mode frequency of equivalent RMSA and along with TM_{10} mode yields broader BW. The proposed analysis in this paper, will give an insight into the functioning of widely use E-shaped patch antenna.

6. REFERENCES

[1] Wong, K. L. 2002. Compact and Broadband Microstrip Antennas, John Wiley & sons, Inc., New York, USA

[2] Huynh, T., and Lee, K. F. 1995. Single-Layer Single-Patch Wideband Microstrip Antenna, Electronics Letters, vol. 31, no. 16, (August 1995), 1310-1312.

[3] Deshmukh, Amit A., and Kumar, G. 2005. Compact Broadband U-slot loaded Rectangular Microstrip Antennas, Microwave and Optical Technology Letters, vol. 46, no. 6, (20th September 2005), 556 – 559.

[4] Wang, Y. J., Gan, Y. B., and Lee, C. K. 2002. A Broadband and Compact Microstrip Antenna for IMT-2000, DECT, and Bluetooth Integrated Handsets, Microwave and Optical Technology Letters, vol. 32, no. 3, (5th February 2002), 204 – 207.

[5] Sharma, S. K., and Shafai, L. 2009. Performance of a Novel Ψ-Shaped Microstrip Patch Antenna with Wide Bandwidth, IEEE Antennas & Wireless Propagation Letters, vol. 8, 468 –471.

[6] Wong, K. L., and Hsu, W. H. 2001. A Broadband Rectangular Patch Antenna with a Pair of wide slits, IEEE Transactions on Antennas & Propagation, Vol. 49, No. 9, (September 2001), 1345 – 1347.

[7] Yang, F., Zhang, X., Yc, X., and Sammi, Y. R. 2001. Wide-band E-shaped patch antennas for wireless communication, IEEE Transactions on Antennas & Propagation, vol. 49, no. 7, (July 2001), 1094 – 1100.

[8] Ge, Y. K., Esselle, P., and Bird, T. S. 2004. E-shaped patch antennas for high speed wireless networks, IEEE Antennas & Propagation Magazine, vol. 52, no. 12, (December 2004), 3213 – 3219.

[9] Denidni, T. A., and Hassaine, N. 2008. Broadband and high Gain E-shaped Microstrip antennas for high speed wireless networks, PIERS C, vol. 1, (2008), 105 – 111.

[10] Khidre, A., Lee, K. F., Yang, F., and Elsherbeni, A. 2010. Wideband Circularly polarized E-shaped patch antenna for wireless applications, IEEE Antennas and Propagation Magazine, vol. 52, no. 5, (October 2010), 219 – 229.

[11] Makarov, E. S., and Fedorov, S. M. 2012. Broadband E-shaped Microstrip Antenna with dipole re-radiators, Microwave and Optical Technology Letters, vol. 54, no. 8, (August 2012), 1785 – 1788.

[12] Pandey, V. K., and Vishvakarma, B. R. 2007. Analysis of an E-shaped patch Antenna, Microwave and Optical Technology Letters, vol. 49, no. 1, (January 2007), 4 – 7.

[13] Deshmukh, Amit A., and Ray, K. P. 2011. Broadband proximity fed modified Rectangular Microstrip Antennas, IEEE Magazine on Antennas and Propagation, vol. 53, no. 5, (October 2011), 41 – 56.

[14] Chen, Y., Yang, S., and Nie, Z. 2010. Bandwidth enhancement method for low profile E-shaped Microstrip Patch Antennas, IEEE Transactions on Antennas & Propagation, vol. 58, no. 7, (2010), 2442 – 2447.

[15] Chair, R., Mak, C. L., Lee, K. F., Luk, K. M., and Kishk, A. A. 2005. Miniaturized wide-band half U-slot and half E-shaped Patch Antennas, IEEE Transactions on Antennas & Propagation, vol. 53, no. 8, (2005), 2645 – 2652.

[16] Deshmukh, Amit A., and Kumar, G. 2005. Compact Broadband E-shaped Microstrip Antennas, Electronics Letters, vol. 41, no. 18, (1st September 2005), 989 – 990

[17] IE3D 12.1, 2004. Zeland Software, Freemont, USA

[18] Knorr, J. B., and Saenz, J. 1973. End effect in a shorted slot, IEEE Transaction on Microwave Theory and Techniques, (September 1973), 579 – 580.