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# Compact Gap-coupled Microstrip Antennas for Broadband and Dual Frequency Operations

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*Abstract:* **Microstrip antennas, when divided into two smaller elements, which resonate at the same frequency as the original undivided antenna, and then by suitably gap coupling these divided elements, broadband operation is obtained. In this paper, using this technique, broadband operation is studied and compared for three regular geometries of microstrip antennas viz. rectangle, circle and equilateral triangle. The bandwidth has been increased to more than double as compared to the original patch, keeping the overall size of the antenna nearly the same. Parametric studies for the effect of gap and feed point location, along with radiation characteristics have been investigated. By modifying the resonance frequencies of individual splitted elements, the same configurations are utilized to realize dual frequency response, which has also been investigated in detail. The experiments have been carried out to validate the simulation results.**

*Index Terms-* **Broadband microstrip antenna, rectangular microstrip antenna, circular microstrip antenna, equilateral triangular microstrip antenna,**

## I. INTRODUCTION

Numerous techniques have been devised to increase the bandwidth (BW) of microstrip antenna (MSA). One of these techniques uses additional parasitic resonators, which are gap-coupled to fed patch [1-7]. However, these techniques, uses parasitic resonators which have nearly the same dimensions as that of the original MSA, which leads to overall increase in size. If a MSA is divided into two smaller elements, which has nearly the same resonance frequency as that of the original MSA, then BW can be increased by suitably gap-coupling these splitted elements. This maintains nearly the same overall patch size. Likewise, gap-coupled broadband configurations for Circular Microstrip Antenna (CMSA) and Equilateral Triangular Microstrip Antenna (ETMSA), by dividing these MSAs into two equal semicircles and $30^0$-$60^0$-$90^0$ triangular MSA (TMSA), respectively, have been reported [6-7]. Similarly, a compact broadband gap-coupled rectangular MSA (RMSA) is formed by splitting the RMSA along its width into two equal RMSAs and gap-coupling them through a smaller gap. However, there has been no detailed, systematic and comparative study of these configurations as regards to the effect of different parameters such as gap and feed point location and also the effect on radiation pattern characteristics.

In this paper, detailed comparative investigations of three regular geometries viz. rectangle, circle and triangle has been presented. Parametric studies for the effects of different critical parameters like gap and feed point location has been carried out, and the results of which can be used for their effective design. The radiation characteristics of these configurations have also been investigated. If the resonance frequencies of the splitted elements are changed by changing their resonant length, then the separation between two resonances can be increased, making it possible to realize a dual frequency operation [7]. This new concept of dual frequency operation for these three configurations has also been investigated in detail. Simulations have been carried out using commercially available Method of Moments based IE3D software, followed by experimental verifications [8].

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## II. BROADBAND OPERATIONS

The MSA is divided into two equal elements in such a manner that these smaller divided elements have the same resonance frequency as the original antenna. These splitted elements are gap-coupled to yield broader BW. Three conventional MSAs viz. RMSA, CMSA and ETMSA, as shown in Fig. 1 (a – f), have been investigated as presented below.

### *A. Broadband RMSA*

The dimensions of RMSA designed to operate at 2 GHz on glass epoxy substrate (h = 1.59 mm, $\varepsilon_r$ = 4.3, and tanδ = 0.02) are; length L = 35 mm, and width W = 46.07 mm. The antenna is fed at x = 8.9 mm using N type co-axial connector having probe of diameter 3 mm [6]. This configuration when analyzed using IE3D, gives the BW of 48 MHz and directivity of 6.45 dBi.

The resonance frequency of RMSA primarily depends on its length. So, if the RMSA is divided into two equal smaller patches along its width, by keeping the length same, the divided patches will have nearly the same resonance frequency as that of the original RMSA. One of these smaller elements is fed using the co-axial probe, while the other is gap-coupled to fed patch as shown in Fig. 1(b). This slightly increases the total area as compared to single RMSA. The divided antenna now has two resonances, which results in a loop getting formed in the input impedance locus. The loop size depends upon the coupling between two patches, or the gap size, while its position depends on the feed point [1-6]. For small gap of S = 0.2 mm, as the coupling is more, the loop size is maximum possible that can be accommodated inside the VSWR = 2 circle, yielding the maximum BW of 145 MHz. The loop size is not very big as the loss tangent of the substrate is 0.02, which is relatively high. Further increase in the gap, reduces loop size, causing the BW to decrease, as can be seen from Table 1, which illustrates the effect of gap on resonance frequency, BW and directivity (D). The maximum BW achieved in this gap-coupled RMSA is approximately three times more than that of the single RMSA. For maximum BW, the feed point distance increases as compared to that for single RMSA. This is because, two elements are radiating, which decreases the radiation resistance and the feed point is shifted towards the higher impedance region. But, as the gap increases, the feed point shifts towards the centre, which is due to decreased coupling. With increase in the gap, overall size of the configuration increases leading to decrease in resonance frequency and increase in directivity.

### *B. Broadband CMSA*

The CMSA designed at 2 GHz using the glass epoxy substrate and fed at x = 7.6 mm, has the BW of 45 MHz and directivity of 6.35 dBi [6]. The resonance frequency of CMSA primarily depends on its diameter. So, if a CMSA is equally divided along its diameter into two semi-circular MSAs, the resulting patches will have nearly same resonance frequency as the original CMSA [9]. Of these two semicircular MSA, one is fed using co-axial probe while the other is gap-coupled, as shown in Fig. 1 (d). The effect of gap on BW is summarized in Table 2. The maximum BW of 127 MHz is obtained for smaller gap and it is 2.8 times that of the original CMSA. The feed point for these gap-coupled configurations, as before, has to be shifted away from centre as compared to single CMSA. In this case also as the gap increases, the overall size of the patch increases leading to increase in directivity and decrease in resonance frequency.

### *C. Broadband ETMSA*

An ETMSA is designed at 2 GHz on glass epoxy substrate [6]. The calculated side length is 47.6 mm. The BW and directivity are 40 MHz and 6.31 dBi, respectively. The resonance frequency of the ETMSA depends on the median (height). So, if an ETMSA is divided into two equal half along the median, then the splitted elements ($30^0$-$60^0$-$90^0$ triangle) will have nearly same resonance frequency as the original ETMSA [10]. With two number of elements, number of resonances increase to two and a loop gets formed in the input impedance locus. But in this case the effect of gap on BW is slightly different than that in previous two cases, as voltage (current) variation along the median of the ETMSA is not exactly two half cycles. In this case, it is observed that for small gap S = 0.2 mm, loop size is also small as shown in Fig. 2 (a) and hence BW of only 78 MHz is obtained, as shown in Fig. 2 (b). With increase in gap to 1 mm, the loop size also increases, increasing the BW to 101 MHz, which is maximum possible for this configuration as shown in corresponding VSWR plot in Fig. 2 (b). The maximum BW in this configuration is 2.5 times that of the original ETMSA. With further increase in gap, loop size reduces decreasing the BW as can be seen from Fig. 2 (b). The detailed results are given in Table 2. Also, the feed point has to be shifted upwards, as compared to single ETMSA as is seen from Table 2. The increase in the gap, increases antenna directivity.

*D. Experimental Verifications*

Experiments are performed for these three gap-coupled configurations. For RMSA, with gap between two elements as 1.7 mm, and feed point at x = 9.2 mm, the measured and simulated VSWR are shown in Fig. 3(a). The measured BW is 107 MHz with centre frequency of 2.073 GHz, while the simulated BW is 119 MHz with centre frequency of 2.057 GHz. For CMSA, the gap between two elements is taken as S = 3.3 mm and feed point at x = 9.5 mm. The measured and simulated VSWR are shown in Fig. 3(b). The measured BW is 77 MHz with a centre frequency of 2.044 GHz, while simulated BW is 94 MHz with a centre frequency of 2.039 GHz. For ETMSA, the gap between two elements is taken as S =1 mm, with feed point, x = 21.01 mm. The measured and simulated VSWR plots are shown in Fig. 3(c). The measured BW is 121 MHz with centre frequency of 2.011 GHz, while simulated BW is 101 MHz with a centre frequency of 2.016 MHz. Minor differences in simulated and measured responses for all the configurations is attributed to the dielectric constant variation of commercial grade FR-4 substrate and also to the fabrication errors.

*E. Radiation Characteristics*

Radiation characteristics have been studied in detail for these gap-coupled configurations. It is observed that, the radiation pattern in E-plane remains in the broadside direction over the BW, but in H-plane towards higher frequencies the pattern tends to tilt slightly away from the broadside direction. This is because, the overall patch dimension remains unchanged in the E-plane, but it changes along the H-plane due to the gap-coupled parasitic elements, and thus there exits an asymmetry in the configuration with respect to the feed point axis. In H-plane, at lower band edge and centre frequencies, the beam maximum is almost in broadside direction. However at upper band edge frequency, for RMSA, the beam maxima shifts to $-40^0$ from broadside with a level of around 5 dB less at broadside as compared to beam maxima. For CMSA, the beam maxima shifts to $-35^0$ from broadside with power level of around -4 dB along the broadside, while for ETMSA it shifts to $-45^0$ from broadside, with a level of around -3 dB along the broadside. The measured and simulated radiation patterns at centre frequencies, for three configurations discussed in the previous section, are shown in Fig. 4. The radiation patterns in E-plane are in the broadside, whereas there is only slight variation in H-plane. Also, the cross-polar levels in case of RMSA and CMSA are well below -20dB, but for ETMSA cross-polar levels are higher. The measured and simulated beam widths are in reasonable agreement.

## III. DUAL FREQUENCY OPERATIONS

Dual frequency operation is realized by increasing the difference between resonance frequencies of the individual splitted elements and by appropriately modifying the feed point location.

In case of RMSA, the length of one of the elements is kept same as that of the original patch, which is 35 mm, while the length of the other element is varied from smaller to larger values and the results are summarized in Table 3. Also, it is observed that the response of configuration is different when bigger patch is fed, than when smaller patch is fed. When smaller patch is fed, the loop in the impedance loci gets formed at lower frequencies than when bigger patch is fed as can be seen from Fig. 5

(a), which gives the comparative input impedance loci in smith chart for above two cases. The loop corresponds to the frequency of the parasitic patch. As the frequency ratio depends upon the resonant length, it almost remains same in both the cases, as shown in Fig. 5 (b). However, it is observed that when the smaller patch is fed, it is difficult to obtain a proper matching, because of this the bandwidths in two frequency bands is less as compared to that obtained by feeding the bigger patch. To yield satisfactory dual frequency response, the range of second element length is from 33.5 mm to 36.5 mm as given in Table 3 and the maximum frequency ratio is 1.07. If difference exceeds the above range then satisfactory dual frequency response can not be realized. When the difference between the two lengths is more then there is larger separation between two centre frequencies, and the optimum BWs at individual frequency can not be realized because of improper impedance matching. The BWs at two dual band frequencies are optimum when the two lengths differ by small amount, leading to smaller separation between the two frequencies. The maximum BW of 52 and 41 MHz at two frequencies are obtained when the two elements have same lengths of 35 mm, with the frequency ratio of 1.05. The directivity is 6.52 dBi at lower frequency and the value is 8.49 dBi at higher frequency. The higher directivity at second frequency is due to smaller wavelength. Even though, for some cases, the lengths of the two splitted elements are same, dual frequency operation is obtained by appropriately shifting the feed point towards centre, so as to reduce the coupling between two resonances. The radiation patterns remain in broadside in both the planes at both the dual band frequencies.

Similarly for CMSA and ETMSA, the diameter of two semicircular elements and the median, respectively are changed, to vary the resonance frequencies and the results are summarized in Tables 4 and 5, respectively. Similar behaviour to that in the case of RMSA is observed. In case of CMSA, the range of radius that yielded satisfactory dual frequency response is between 19.84 mm to 21.84 mm, with a maximum frequency ratio of 1.08. The smallest frequency ratio that is obtained is 1.06 with BWs of 44 and 37 MHz, when two elements have same radius of 20.74 mm. It has directivity of 6.39 dBi at first frequency and 8.78 dBi at second frequency.

However, in case of ETMSA, it is observed that maximum frequency ratio that is obtained is only 1.05 for the case when the side lengths of two splitted elements are 49.6 mm and 47.6 mm. The range of side lengths of the second element that yielded satisfactory dual frequency response is from 46.1mm to 49.6 mm. The BWs of more than 35 MHz are obtained in both the frequency bands, when both the elements have side length of 47.6 mm and the directivity of 6.34 dBi at lower frequency and 6.36 dBi at higher frequencies. For ETMSA, it is observed, in comparison with RMSA and CMSA, the directivity in two frequency bands are similar, in all the cases.

Experiments have been performed for two cases of dual frequency operations of a splitted CMSA configurations and splitted ETMSA configurations. The glass epoxy substrate is used. In case of CMSA the radius of smaller elements in two configurations are $R_1$ = 21.04 mm and $R_2$ = 20.74 mm, with bigger element fed. The gap between two elements is taken as S = 0.2 mm, while feed point is taken as x = 7.0 mm. The comparative $S_{11}$ (in dB) plot for these two cases are shown in Fig. 6. The measured centre frequencies in two bands are $f_{r1}$ = 1.992 GHz, and $f_{r2}$ = 2.129 GHz, while the simulated centre frequencies are $f_{r1}$ = 1.988 GHz, and $f_{r2}$ = 2.113 GHz. In case of ETMSA, the two side lengths are $L_1$ = 47.6 mm, and $L_2$ = 48.1 mm, with smaller element fed at 20.31 mm. The measured dual band frequencies are $f_{r1}$ = 1.961 GHz, and $f_{r2}$ = 2.053 GHz, while the simulated frequencies are $f_{r1}$ = 1.969 GHz, and $f_{r2}$ = 2.054 GHz.

## IV. CONCLUSIONS

Detailed, systematic and comparative investigations have been presented for broadband and dual frequency operations, for RMSA, CMSA and ETMSA by equally splitting these antennas into two smaller elements.

Parametric studies for the effect of gap and feed point, along with radiation characteristics have been investigated. In case of gap-coupled RMSA, a BW increment of 3 times over that of single RMSA has been obtained, while for CMSA, BW increment of 2.8 times and for ETMSA, BW increment of 2.5 times has been obtained. The smallest gap, yields maximum BW for RMSA and CMSA, whereas for ETMSA, BW is less for smallest gap and increases when gap is increased. For all three geometries, the radiation pattern remains in broadside direction at all the frequencies in E-plane, but in H-plane it tends to tilt away from broadside at higher frequencies. For ETMSA, the cross-polar levels are more as compared to other two geometries. Detailed investigation for dual frequency operation has been presented by systematically varying the dimensions of the splitted elements. When the dimensions of two elements differ by large amount, then the separation between the dual band frequencies is more yielding larger frequency ratio, but BWs at two frequencies are less. The BWs are more when difference between the dimensions of two elements is less, but then the separation between the centre frequencies is also less, yielding smaller frequency ratio. The maximum frequency ratio that has been obtained in case of RMSA is 1.07, while in case CMSA it is 1.08. But for ETMSA, a maximum frequency ratio of only 1.05 has been obtained. These configurations can be used when small dual frequency ratio is required.

## REFERENCES

[1] Kumar, G., and Gupta, K. C.: ‘Broadband microstrip antennas using additional resonators gap coupled to the radiating edges’, IEEE Trans. Antennas Propagation, 1984, 32, pp.1375-1379

[2] Kumar, G., and Gupta, K. C.: ‘Non radiating edges and four edges gap coupled with multiple resonator, broadband microstrip antennas’, IEEE Trans. Antennas Propagation, 1985, 33, pp. 173-178.

[3] Ray, K. P. and Kumar, G., “Multi- frequency and broadband hybrid- coupled circular microstrip antennas”, *Electon. Lett.*, vol. 33, no. 6, pp. 437-438, Mar. 1997.

[4] Ray, K. P. and Kumar, G. and Lodwal, H. “Hybrid coupled broadband triangular microstrip antennas”, *IEEE Trans. Antennas Propagation*, vol. 51, pp. 139-141, Jan. 2003.

[5] Garg, R., Bhartia, P., Bahl, I., and Ittipiboon, A.: ‘Microstrip antenna design handbook’ (Artech House, Norwood, MA, 2001)

[6] Kumar, G., and Ray, K. P.: ‘Broadband microstrip antennas’ (Artech House, Boston, 2003)

[7] Ray, K. P.: ‘Broadband dual frequency and compact microstrip antennas’, Ph.D thesis, Indian Institute of Technology, Bombay, India, 1999.

[8] IE3D 9.21, Zeland Software Inc., Fremont, CA, 2002.

[9] Ray K. P., and Kumar, G.: ‘Multiport network model for fundamental and higher order modes of semicircular microstrip antennas’, Microwave & Optical Tech. Letters, 2001, 28 (4), pp 237-241.

[10] Satpathy, S., Kumar, G. and Ray, K. P.: ‘Compact shorted variations of triangular microstrip antennas’, Electronics Letters, 1998, 34 (8), pp. 709-711.

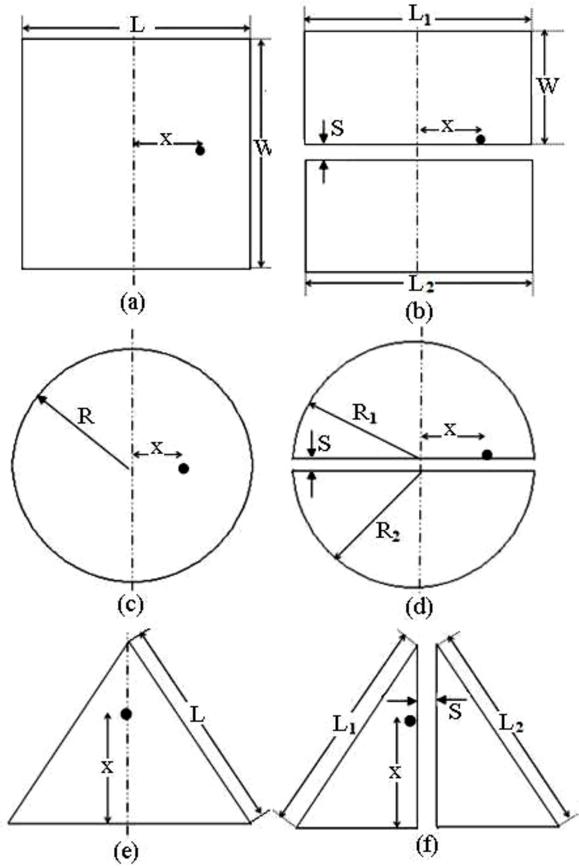


**Figure 1:** Gap coupled MSAs; (a) single RMSA, (b) two splitted gap-coupled RMSAs, (c) single CMSA, (d) two splitted gap-coupled CMSAs, (e) single ETMSA, (f) two gap-coupled splitted ETMSAs.

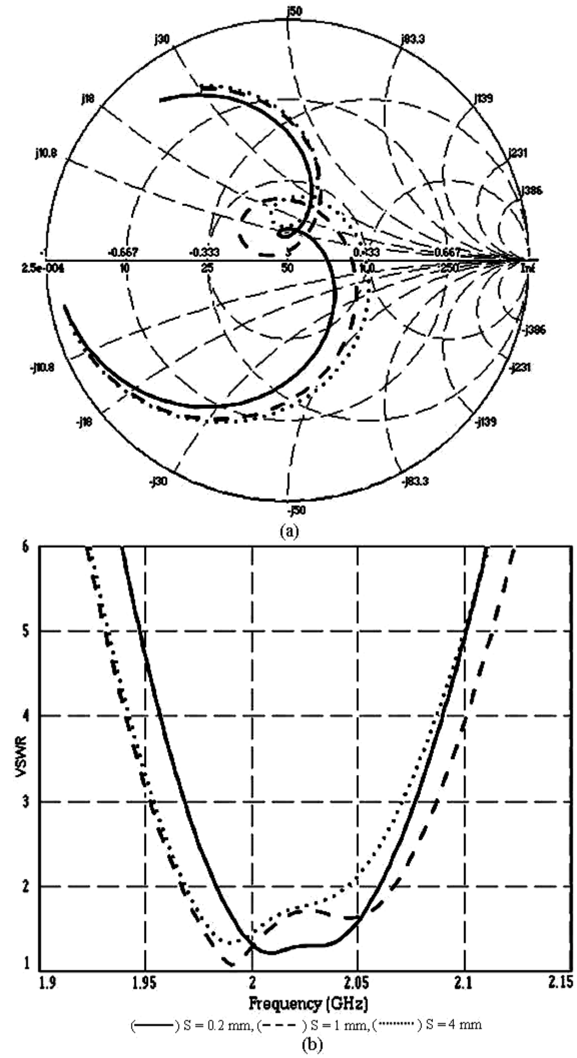


**Figure 2:** (a) Input impedance loci, (b) VSWR plots for effects of different values of gaps on performance of two splitted ETMSAs.

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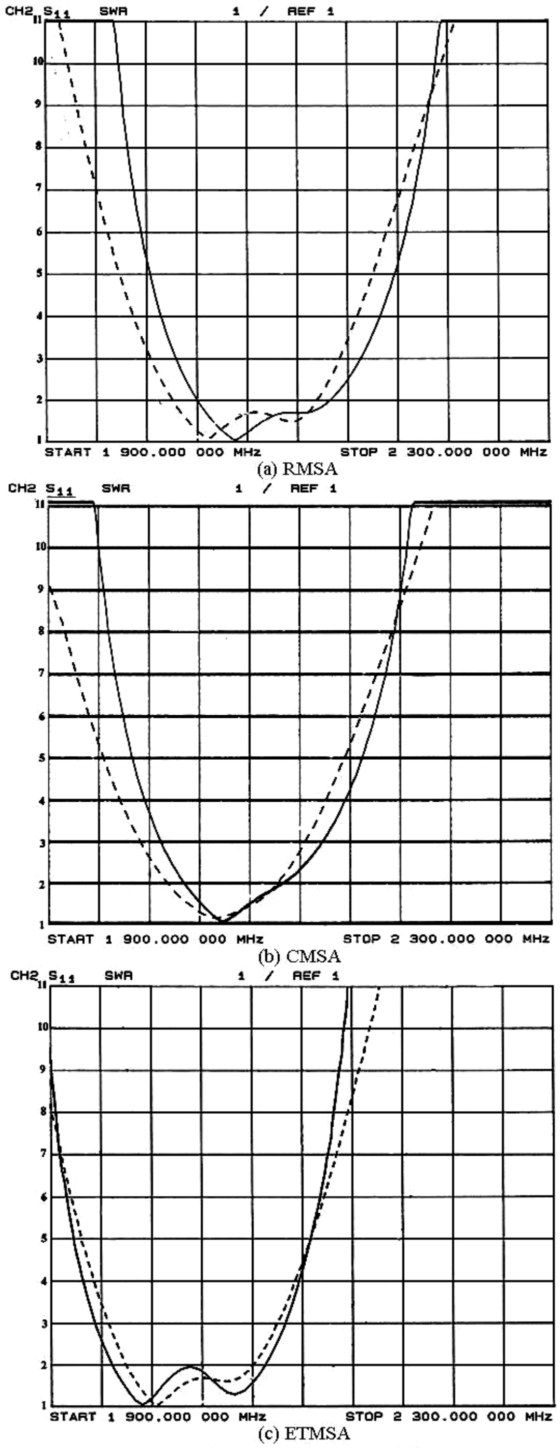


**Figure 3:** Measured and simulated VSWR plots for broadband response for; (a) two gap-coupled RMSAs, (b) two gap-coupled CMSAs and (c) two gap-coupled ETMSAs

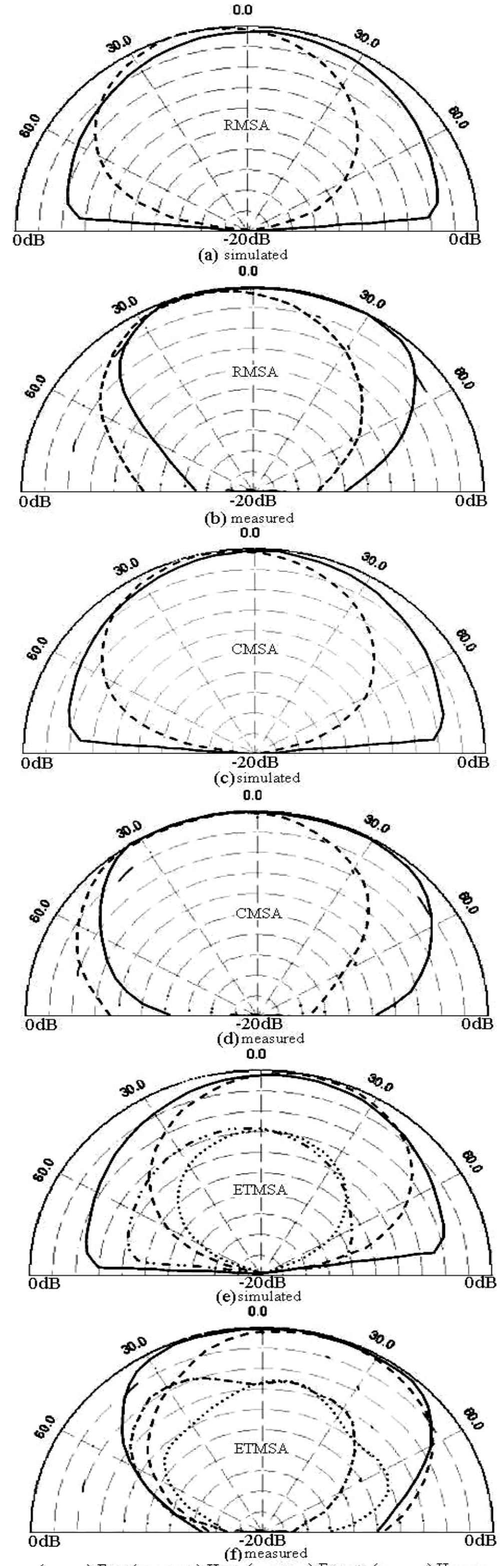


**Figure 4:** Radiation pattern at centre frequency for two splitted gap-coupled (a, b) RMSA, (c, d) CMSA and (e, f) ETMSA

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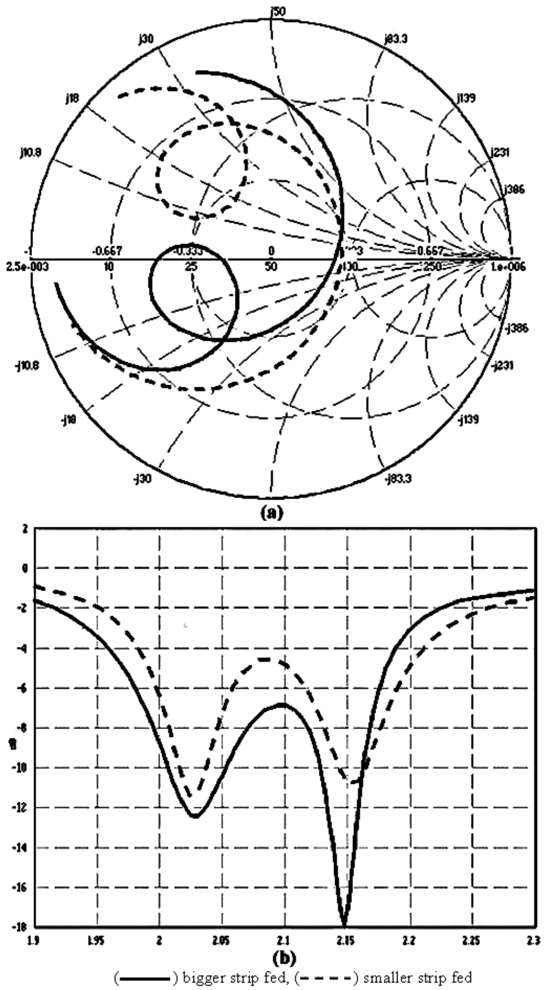


**Figure 5:** (a) Input impedance loci, (b) $S_{11}$ plot of two splitted RMSAs with lengths of two strips as 35 and 34 mm, by feeding both bigger and smaller strip,

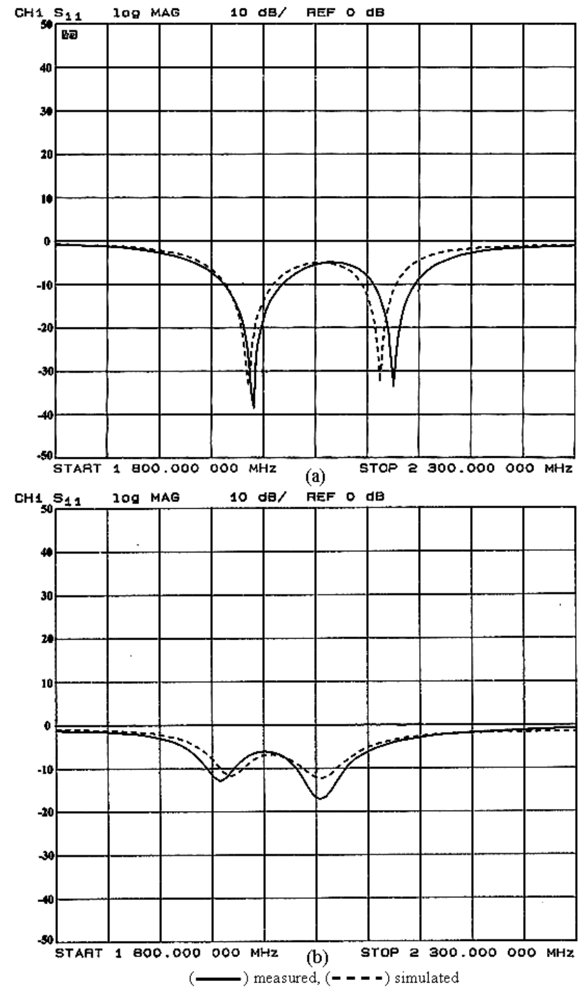


**Figure 6:** Measured and simulated $S_{11}$ plots for dual frequency response of (a) splitted CMSAs configuration with $R_1$ = 21.04 mm, $R_2$ = 20.74 mm, (b) splitted ETMSAs configuration with $L_1$ = 47.6 mm, $L_2$ = 48.1 mm

**Table 1:** Effect of coupling gap on performance of splitted RMSA configurations
(L = 35.0 mm, h = 1.59 mm, εr = 4.3, tanδ = 0.02)

| | W (mm) | S (mm) | x (mm) | $f_r$ (GHz) | BW (MHz) | Directivity (dBi) |
|---|---|---|---|---|---|---|
| Single RMSA | 46.07 | - | 8.9 | 1.999 | 48 | 6.45 |
| Two Splitted RMSA | 23.04 | 0.2 | 11.7 | 2.059 | 145 | 6.68 |
| | 23.04 | 1.0 | 9.7 | 2.059 | 132 | 6.79 |
| | 23.04 | 1.7 | 9.2 | 2.057 | 119 | 6.89 |
| | 23.04 | 3.0 | 8.2 | 2.048 | 103 | 7.16 |
| | 23.04 | 5.0 | 8.2 | 2.048 | 78 | 7.36 |

**Table 2:** Effect of coupling gap on performance of splitted CMSA and ETMSA configurations
(R = 20.74 mm, h = 1.59 mm, εr = 4.3, tanδ = 0.02, L = 47.6 mm)

| | S (mm) | x (mm) | $f_r$ (GHz) | BW (MHz) | D (dBi) | | S (mm) | x (mm) | $f_r$ (GHz) | BW (MHz) | D (dBi) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Single CMSA | - | 7.6 | 1.998 | 45 | 6.35 | Single ETMSA | - | 19.91 | 2.005 | 40 | 6.31 |
| Two Splitted CMSA | 0.2 | 11 | 2.057 | 127 | 6.54 | Two Splited ETMSA | 0.2 | 20.61 | 2.022 | 78 | 6.46 |
| | 1 | 10 | 2.043 | 125 | 6.56 | | 1 | 21.01 | 2.016 | 101 | 6.45 |
| | 2.2 | 9.5 | 2.041 | 112 | 6.60 | | 2 | 21.01 | 2.013 | 101 | 6.48 |
| | 3.3 | 9.5 | 2.039 | 94 | 6.68 | | 3 | 21.01 | 2.009 | 90 | 6.52 |
| | 5 | 9.0 | 2.03 | 75 | 6.83 | | 4 | 21.01 | 2.006 | 78 | 6.63 |
| | | | | | | | 6 | 21.01 | 2.005 | 50 | 6.67 |

**Table 3:** Dual frequency response of splitted RMSA configuration, with $L_1$ as fed element (W = 23.04 mm, h = 1.59 mm, εr = 4.3, tanδ = 0.02)

| $L_1$ (mm) | $L_2$ (mm) | S (mm) | x (mm) | $f_{r1}$ (GHz) | $RL_1$ (dBi) | $BW_1$ (MHz) | $f_{r2}$ (GHz) | $RL_2$ (dBi) | $BW_2$ (MHz) | $f_{r2}/f_{r1}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 35 | 33.5 | 0.5 | 9.7 | 2.034 | -10.81 | 38 | 2.172 | -11.17 | 20 | 1.07 |
| 33.5 | 35 | - | - | - | - | - | - | - | - | - |
| 35 | 34 | 0.5 | 9.7 | 2.031 | -12.43 | 52 | 2.146 | -17.67 | 37 | 1.06 |
| 34 | 35 | 0.5 | 8.2 | 2.027 | -11.51 | 26 | 2.154 | -10.84 | 27 | 1.06 |
| 35 | 35 | 0.5 | 8.2 | 2.01 | -22.9 | 52 | 2.117 | -20.03 | 41 | 1.05 |
| 36 | 35 | 0.5 | 9.7 | 1.977 | -12.74 | 50 | 2.087 | -17.07 | 36 | 1.06 |
| 35 | 36 | 0.5 | 8.2 | 1.973 | -11.13 | 22 | 2.099 | -11.7 | 30 | 1.06 |
| 36.5 | 35 | 0.5 | 9.7 | 1.955 | -11.35 | 39 | 2.084 | -11.03 | 18 | 1.07 |
| 35 | 36.5 | - | - | - | - | - | - | - | - | - |

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**Table 4:** Dual frequency response of splitted CMSA configuration, with $R_1$ as fed element ( h = 1.59 mm, εr = 4.3, tanδ = 0.02)

| $R_1$ (mm) | $R_2$ (mm) | S (mm) | x (mm) | $f_{r1}$ (GHz) | $RL_1$ (dBi) | $BW_1$ (MHz) | $f_{r2}$ (GHz) | $RL_2$ (dBi) | $BW_2$ (MHz) | $f_{r2}/f_{r1}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 20.74 | 19.84 | 0.2 | 8 | 2.031 | -12.3 | 44 | 2.189 | -12.54 | 23 | 1.08 |
| 19.84 | 20.74 | - | - | - | - | - | - | - | - | - |
| 20.74 | 20.14 | 0.2 | 8 | 2.026 | -14.26 | 51 | 2.161 | -20.01 | 34 | 1.07 |
| 20.14 | 20.74 | 0.2 | 7 | 2.021 | -10.96 | 20 | 2.17 | -10.91 | 25 | 1.07 |
| 20.74 | 20.44 | 0.2 | 7 | 2.016 | -40.69 | 50 | 2.145 | -32.68 | 36 | 1.07 |
| 20.44 | 20.74 | 0.2 | 7 | 2.015 | -14.36 | 35 | 2.145 | -13.53 | 34 | 1.06 |
| 20.74 | 20.74 | 0.2 | 7 | 2.003 | -20.04 | 44 | 2.128 | -19.87 | 37 | 1.06 |
| 21.04 | 20.74 | 0.2 | 7 | 1.988 | -32.05 | 48 | 2.113 | -31.61 | 34 | 1.06 |
| 20.74 | 21.04 | 0.2 | 7 | 1.985 | -13.93 | 32 | 2.117 | -14.44 | 35 | 1.06 |
| 21.44 | 20.74 | 0.2 | 8 | 1.963 | -15.12 | 49 | 2.097 | -16.11 | 29 | 1.07 |
| 20.74 | 21.44 | 0.2 | 7.5 | 1.958 | -11.02 | 20 | 2.102 | -10.14 | 18 | 1.07 |
| 21.84 | 20.74 | 0.2 | 9 | 1.931 | -10.1 | 22 | 2.088 | -10.53 | 13 | 1.08 |
| 20.74 | 21.84 | - | - | - | - | - | - | - | - | - |

**Table 5:** Dual frequency response of splitted ETMSA configuration, with $L_1$ as fed element ( h = 1.59 mm, εr = 4.3, tanδ = 0.02)

| $L_1$ (mm) | $L_2$ (mm) | S (mm) | x (mm) | $f_{r1}$ (GHz) | $RL_1$ (dBi) | $BW_1$ (MHz) | $f_{r2}$ (GHz) | $RL_2$ (dBi) | $BW_2$ (MHz) | $f_{r2}/f_{r1}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 47.6 | 46.1 | 1.2 | 20.61 | 2.014 | -13.64 | 48 | 2.094 | -14.78 | 33 | 1.04 |
| 46.1 | 47.6 | - | - | - | - | - | - | - | - | - |
| 47.6 | 46.6 | 1.2 | 19.11 | 2.006 | -17.22 | 37 | 2.087 | -15.22 | 27 | 1.04 |
| 46.6 | 47.6 | - | - | - | - | - | - | - | - | - |
| 47.6 | 47.1 | 1.2 | 19.11 | 1.996 | -12.55 | 27 | 2.075 | -23.3 | 34 | 1.04 |
| 47.1 | 47.6 | 1.2 | 20.31 | 1.991 | 29 | -12.71 | 2.073 | -10.73 | 26 | 1.04 |
| 47.6 | 47.6 | 1.2 | 20.01 | 1.986 | 37 | -14.45 | 2.06 | -15.5 | 41 | 1.04 |
| 48.1 | 47.6 | 1.2 | 19.41 | 1.976 | 33 | -14.59 | 2.052 | -30.72 | 36 | 1.04 |
| 47.6 | 48.1 | 1.2 | 20.31 | 1.969 | 24 | -11.81 | 2.054 | -11.31 | 29 | 1.04 |
| 48.6 | 47.6 | 1.2 | 19.61 | 1.966 | 44 | -24.01 | 2.041 | -18.72 | 33 | 1.04 |
| 47.6 | 48.6 | - | - | - | - | - | - | - | - | - |
| 49.1 | 47.6 | 1.2 | 19.61 | 1.952 | 44 | -28.04 | 2.035 | -12.43 | 21 | 1.04 |
| 47.6 | 49.1 | - | - | - | - | - | - | - | - | - |
| 49.6 | 47.6 | 1.2 | 20.61 | 1.934 | 38 | -12.29 | 2.027 | -10.38 | 13 | 1.05 |
| 47.6 | 49.6 | - | - | - | - | - | - | - | - | - |