components and process. It could be easily implemented in HMIC and MMIC for size reduction and harmonics rejection.

REFERENCES

1. T. Hirota, A. Minakawa, and M. Muraguchi, Reduced-size branch-line and rat-race hybrids for uniplanar MMICs, IEEE Trans Microwave Theory Tech 38 (1990), 270–275.
2. H.R. Ahn, I.S. Chang, and S.W. Yun, Miniaturized 3-dB ring hybrid terminated by arbitrary impedances, IEEE Trans Microwave Theory Tech 42 (1994), 2216–2221.
3. T. Kangasvieri, I. Hautajarvi, H. Jantunen, and J. Vahakangs, Miniaturized low-loss Wilkinson power divider for RF front-end module applications, Microwave Opt Technol Lett 48 (2006), 660–663.
4. F.R. Yang, K.P. Ma, and T. Itoh, A uniplanar compact photonic-bandgap structure and its applications for microwave circuit, IEEE Trans Antennas Propag 47 (1999), 1509–1514.
5. Y.J. Sung, C.S. Ahn, and Y.-S. Kim, Size reduction and harmonic suppression of rat-race hybrid coupler using defected ground structure, IEEE Microwave Wireless Compon Lett 14 (2004), 7–9.
6. T.Y. Yum., Q. Xue, and C.H. Chan, Novel subharmonically pumped mixer incorporating dual-band stub and in-line SCMRC, IEEE Trans Microwave Theory Tech 51 (2003), 2538–2547.
7. J. Gu and X. Sun, Compact low-pass filter using spiral compact microstrip resonant cell, IEE Electron Lett 41 (2005), 1065, 1066.
8. J. Gu and X. Sun, Miniaturization and harmonic suppression rat-race coupler using C-SCMRC resonators with distributive equivalent circuit, IEEE Microwave Wireless Compon Lett 15 (2005), 880–882.

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COMPACT BROADBAND GAP-COUPLED RECTANGULAR MICROSTRIP ANTENNAS

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ABSTRACT: *Systematic investigations have been presented by splitting a single rectangular microstrip patch into equal, smaller elements along the width, keeping the length same. Of these, one of the elements is fed while others are gap coupled to its nonradiating edges. The rectangular patch is gradually splitted into 2–14 equal, smaller elements and in between coupling gaps are optimized for maximum bandwidth. Parametric study for the effect of gap and feed point location, along with radiation pattern, has also been carried out. A maximum bandwidth increment of over 10 times, compared with that of the original single rectangular patch is obtained for 14 numbers of equal strips. As the additional resonators (at same resonance frequency) are obtained from the original patch itself, the overall configuration remains compact. Experiments have been carried out, which are in good agreement with simulated results.* © 2006 Wiley Periodicals, Inc. Microwave Opt Technol Lett 48: 2384–2389, 2006; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.21976

Key words: *compact broadband microstrip antennas; gap coupled rectangular microstrip antenna; parasitic coupled patches*

1. INTRODUCTION

Use of additional resonators, gap coupled to the driven patch, is an effective method to increase the bandwidth (BW) of microstrip antenna (MSA) [1–3]. However, this technique makes use of separate parasitic elements, which have nearly same dimensions as the driven patch, causing the overall size of the configuration to increase significantly. A variation of this technique, wherein six and seven numbers of parasitic strip elements of unequal width coupled with unequal gaps to the nonradiating edges of the driven patch, has been reported [4, 5]. The width of the patches used is much smaller than conventionally designed rectangular MSA (RMSA), so that overall configuration remains compact. A BW increment of around 8 times is obtained [4, 5].

However, as these configurations involve number of parasitic elements, their design becomes quite tedious if different width of strips and different coupling gaps are taken. Also, there is no systematic study carried out on this compact structure in terms of number of strips and gaps for maximum BW and corresponding radiation characteristics. In this article, a detailed and systematic analysis has been presented, which helps in understanding the configuration and also to analyze the maximum BW increment attainable using this configuration.

For this purpose, a single RMSA has been divided into equal smaller and smaller strips along the width, keeping the length and overall metallic area same. Of these one of the patches in the centre is coaxially fed, while others are gap coupled to it. The configuration reduces to gap coupled, smaller, equal width resonators along the nonradiating edges at same resonant frequency. The dimensions of all the elements are kept same, for simplicity of analysis. The number of strips is gradually increased from 1 to 14 and the behavior of each of these configurations has been studied in detail. Parametric study for the effect of gap and feed point location has also been carried out, the results of which can be used for their effective design. Radiation patterns are also studied in detail. Simulation has been carried out using commercially available software, which is based on method of moments (MoM), IE3D [6]. Experiments have been carried out, which are in good agreement with simulation.

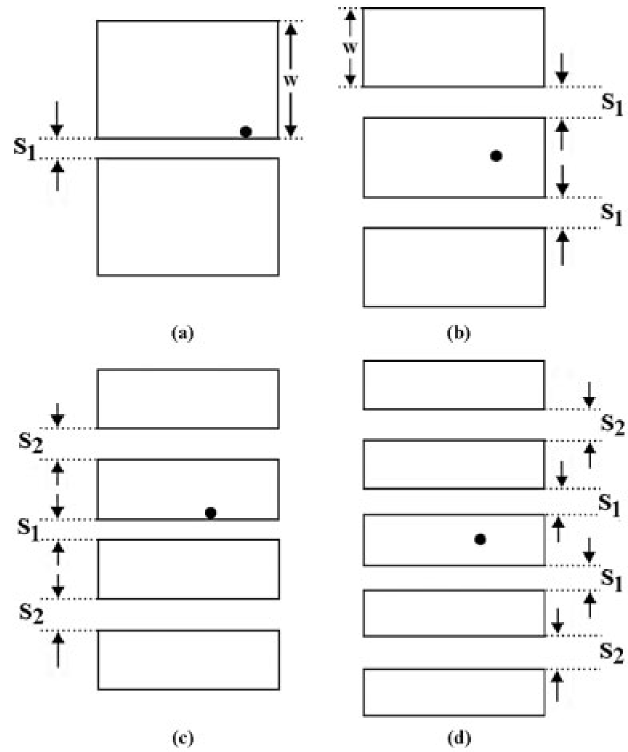

Figure 1 Gap coupled configurations formed by splitting single RMSA into (a) two patch, (b) three patch, (c) four patch, and (d) five patch configurations

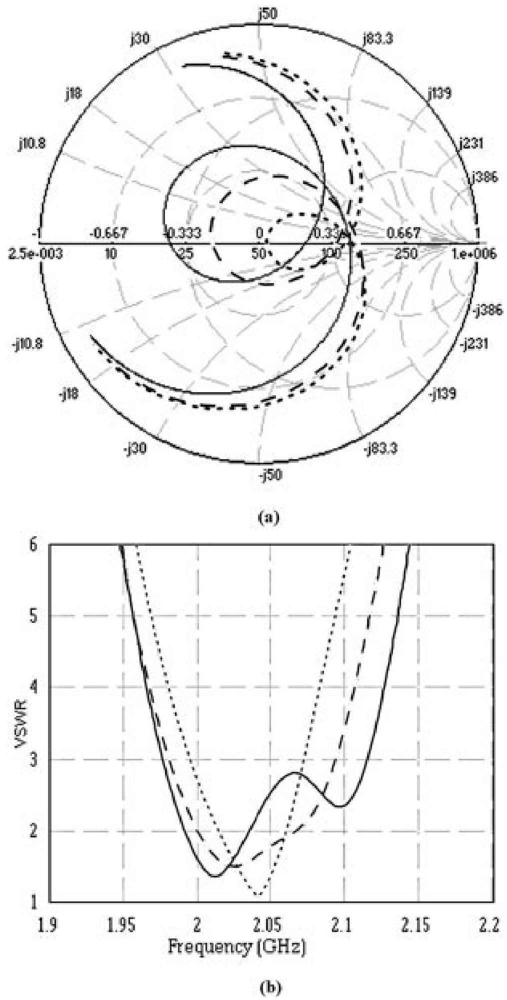

Figure 2 Effect of gap on (a) input impedance loci, (b) BW for two patch configuration for three different gaps (——) S_1 = 1 mm, (– – –) S_1 = 1.7 mm, (……….) S_1 = 4 mm

2. GAP COUPLED CONFIGURATIONS: PARAMETRIC STUDY

First, a single RMSA is designed to operate at 2 GHz, using the standard design formulas given in Ref. 3. The substrate parameters chosen are, $\varepsilon_r = 4.3$, $h = 1.59$ mm, and tan $\delta = 0.01$. The calculated length of a RMSA is $L = 35.0$ mm, and width, $W = 46.07$ mm. The RMSA is fed using N type connector with probe diameter $d = 3$ mm. BW of 35 MHz is obtained for the RMSA.

2.1. Two Equal Gap Coupled Patches

The RMSA, thus designed, is divided into two equal strips along the width keeping the length same. Of these, one of the patches is fed, while other is gap coupled to it as shown in Figure 1(a). As the number of radiating patches now increases to two, two closely spaced resonances are observed when compared with only one resonance for a single RMSA. This results in a formation of a loop in the impedance locus on the Smith Chart. The size of the loop depends on the coupling gap, while its position on the Smith Chart depends on the feed point location [1–3]. For small value of gap $S_1 = 1$ mm, coupling between patches is tight and thus loop is considerably bigger extending beyond the VSWR = 2 circle yielding a BW of only 45 MHZ as can be seen in Figure 2. As S_1 is increased to 1.7 mm, loop size reduces, yielding a BW of 68 MHz, which is maximum for this configuration as loop is maximum possible that can be accommodated inside the VSWR = 2 circle. With further increase in S_1 to 4 mm, the loop size further reduces and also it moves outside the VSWR = 2 circle, again resulting in low BW of only 46 MHz. Smith Chart plot of input impedance loci for three values of S_1 is shown in Figure 2(a), while the respective VSWR plots are shown in Figure 2(b). Performance of the configuration is also summarized in Table 1 for S_1 varying from 0.2 to 4 mm. A maximum BW of 68 MHz is obtained, for $S_1 = 1.7$ mm, which is 1.9 times higher than that of a single RMSA at approximately same resonance frequency. It is observed that the feed point has to be shifted to right compared with that of a single RMSA. This is as expected because now two elements are radiating, which decreases the radiation resistance.

TABLE 1 Effect of Gap Width on BW for 2, 3, 4, and 5 Patch Gap-Coupled Configurations[a]

No. of Elements	Width W (mm)	Gap Widths S (mm)	Feed Point x (mm)	Center Frequency f_r (GHz)	BW (MHz)	Directivity (dBi)
2	23.04	$S_1 = 0.2$	8.5	2.008	40	6.485
		$S_1 = 1.0$	9.0	2.014	45	6.523
		$S_1 = 1.7$	10.2	2.034	68	6.611
		$S_1 = 3.0$	10.3	2.036	60	6.720
		$S_1 = 4.0$	10.4	2.038	46	6.848
3	15.36	$S_1 = 0.2$	7.5	2.003	36	6.455
		$S_1 = 2.0$	8.0	2.016	41	6.509
		$S_1 = 4.3$	9.5	2.061	67	6.723
		$S_1 = 6.0$	9.5	2.068	55	6.831
4	11.52	$S_1 = 1.7$	9.0	2.105	191	7.692
		$S_2 = 2.8$				
		$S_1 = 1.7$	9.0	2.103	169	8.183
		$S_2 = 3.8$				
		$S_1 = 2.7$	9.0	2.102	141	8.103
		$S_2 = 4.8$				
5	9.21	$S_1 = 3.2$	8.5	2.115	134	7.142
		$S_2 = 6.5$				
		$S_1 = 3.2$	8.5	2.111	109	7.053
		$S_2 = 8.5$				
		$S_1 = 4.2$	8.5	2.120	110	7.194
		$S_2 = 10.5$				

[a] $L = 35$ mm, $\varepsilon_r = 4.3$, $h = 1.59$ mm, tan $\delta = 0.01$.

2.2. *Three Equal Gap Coupled Patches*

Now, similarly the single RMSA is equally divided into 3 elements (keeping the overall metallic patch area same). The central patch is fed, while other two are gap coupled to its nonradiating edges as shown in Figure 1(b). It is observed that if gaps for two parasitic elements are taken different then it becomes difficult to fulfill the matching criteria, resulting in low BW. So the two gaps [i.e., S_1 in Fig. 1(b)] are taken same, which also makes the configuration symmetrical about the axis through feed point. Because of this symmetry, the coupling seen by parasitic elements is same and hence these radiate at same frequency, resulting in only two resonances being observed even though now the number of resonators in the system is three, thus only a single loop gets formed, in the impedance loci, on the Smith Chart. The effect of gap on BW is similar as that in the previous case as shown in Table 1. Table 1 gives the variation of BW of three splitted patches with two equal coupling gaps S_1, varying from 0.2 to 6 mm. The maximum BW obtained in this case is 67 MHz, for S_1 = 4.3 mm, which is slightly less than the configuration with two splitted patches. This is because now as the two parasitic elements radiate at same frequency, because of the symmetry of the configuration, coupling increases resulting in very large loop size when compared with configuration with two strips. The coupling can be reduced by increasing the gap size, but it is observed that by increasing the gap width, loop size reduces but also the impedance loci, on the Smith Chart, moves upward (i.e. toward inductive side), making it difficult to accommodate the loop completely inside the VSWR = 2 circle. Thus, increased coupling makes it difficult to obtain proper matching, thereby yielding low BW for configuration with three strips [7]. This is also the reason that value of S_1, for optimum BW, is significantly more than the previous case of two gap coupled patches. The feed point when compared with previous case has to be shifted toward centre. This is because width of the individual element decreases, increasing the input impedance.

2.3. *Four Equal Gap Coupled Patches*

Again, the single RMSA is similarly divided into four equal smaller elements as shown in Figure 1(c). In this case, as the configuration is asymmetrical about the axis through feed point, four resonances corresponding to four elements are obtained, as all the elements radiate at slightly different frequency. This results in three loops getting formed, in the impedance loci, on the Smith Chart as shown in Figure 3(a). However, the topmost and bottommost patches [Fig. 1(c)] radiate at frequencies that are only slightly different so these two gaps [i.e. S_2 in Fig. 1(c)] are taken same. It is observed that for proper matching, the gaps for the patches farther away from the fed patch have to be taken more than that of those which are nearer. Table 1 shows the effect of three combinations of gaps S_1 and S_2, on BW. It is observed that BW is maximum for smallest gap sizes for which matching is obtained. The maximum BW of 191 MHz is obtained for the combination of S_1 = 1.7 mm and S_2 = 2.8 mm, which is significantly more than previous cases. The feed point shifts to left when compared with three patch configuration. If gap sizes are increased further, BW decreases.

2.4. *Five Equal Gap Coupled Patches*

Continuing in similar manner, the RMSA is divided further to obtain configuration with five gap coupled strips as shown in Figure 1(d). As for three patch configuration, in this case also if gaps between strips are taken all unequal, then it is difficult to obtain proper matching. So the gaps for similarly placed parasitic elements are taken equal, making the configuration symmetrical. Also, because of same gaps, the coupling seen by similarly placed parasitic elements is same, hence these radiate at same frequency resulting in only three resonances, even though now there are five resonators in the configuration. In the impedance loci, only two loops get formed because of three resonances, as shown in Figure 3(b). The maximum BW obtained for this case is only 134 MHz, which is considerably less than the configuration with four gap-coupled strips. The reason for less BW is increased coupling, which makes it difficult to obtain proper matching. In this case also the feed point has to be shifted to left, as the input impedance of thinner strips becomes higher.

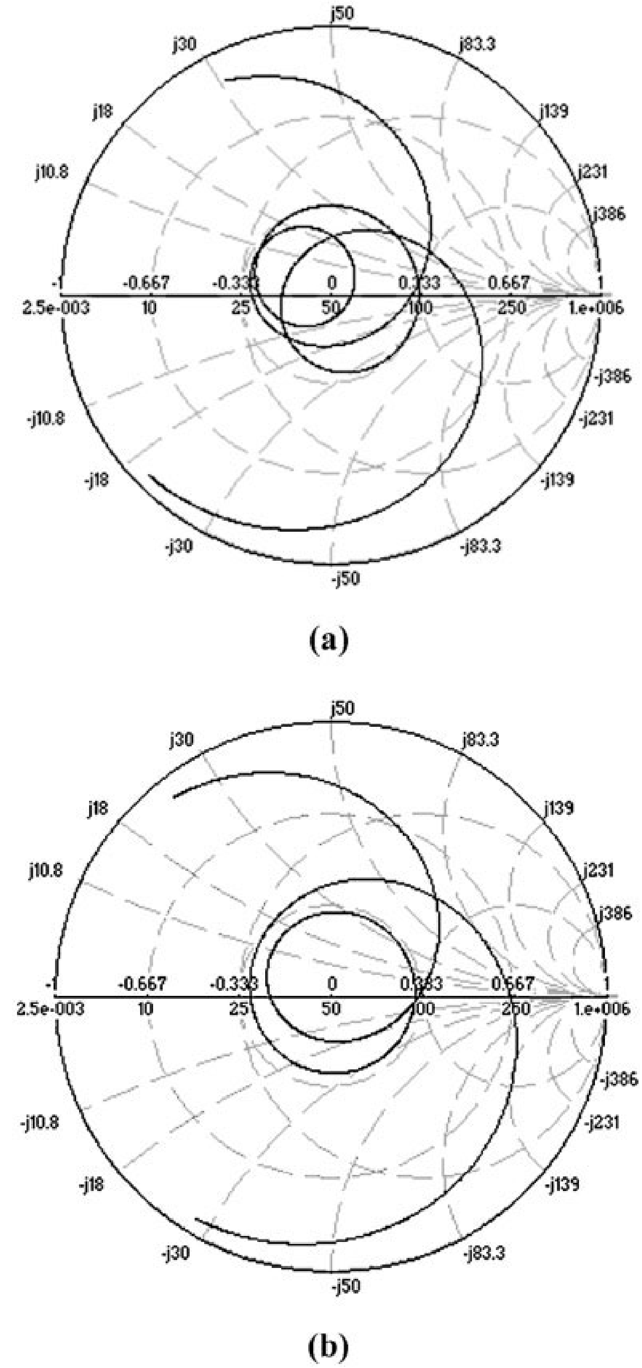

Figure 3 Input impedance loci for (a) four patch configuration, S_1 = 1.7 mm, S_2 = 2.8 mm and (b) five patch configuration, S_1 = 3.2 mm, S_2 = 6.5 mm

TABLE 2 Details of Various Parameters for Configurations with Odd Number of Patches[a]

No. of Elements	Width W (mm)	Gap Widths S (mm)	Feed Point x (mm)	Center Frequency f_r (GHz)	BW (MHz)	Directivity (dBi)
1	46.07	—	7.2	2.003	35	6.454
3	15.36	$S_1 = 4.3$	9.5	2.061	67	6.723
5	9.21	$S_1 = 3.2$ $S_2 = 6.5$	8.5	2.115	134	7.142
7	6.58	$S_1 = 2.2$ $S_2 = 4.1$ $S_3 = 6.1$	8.3	2.154	206	7.7
9	5.12	$S_1 = 2.0$ $S_2 = 3.7$ $S_3 = 4.5$ $S_4 = 6.7$	8.1	2.186	245	8.402
11	4.19	$S_1 = 1.8$ $S_2 = 3.0$ $S_3 = 4.0$ $S_4 = 4.7$ $S_5 = 6.0$	8.0	2.212	284	8.342
13	3.54	$S_1 = 1.8$ $S_2 = 2.9$ $S_3 = 3.3$ $S_4 = 4.1$ $S_5 = 4.7$ $S_6 = 5.3$	7.5	2.229	314	8.84

[a] $L = 35$ mm, $\varepsilon_r = 4.3$, $h = 1.59$ mm, $\tan \delta = 0.01$.

In general, similar behavior is observed, as the RMSA is splitted into more numbers of smaller strips. Configurations with even number of patches behave differently than those with odd number. However, for both, with increase in number of elements number of resonances increase and so does the BW. But, in general, the BW increment for configurations with odd number of patches is less than those with even. Also, for optimized matching, gap sizes are more in former case. Table 1 shows the effect of

TABLE 3 Details of Various Parameters for Configurations with Even Number of Patches[a]

No. of Elements	Width W (mm)	Gap Widths S (mm)	Feed Point x (mm)	Center Frequency f_r (GHz)	BW (MHz)	Directivity (dBi)
2	23.04	$S_1 = 1.7$	10.2	2.034	68	6.611
4	11.52	$S_1 = 1.7$ $S_2 = 2.8$	9.0	2.105	191	7.692
6	7.68	$S_1 = 1.2$ $S_2 = 2.3$ $S_3 = 4.7$	8.8	2.152	252	7.573
8	5.76	$S_1 = 1.2$ $S_2 = 1.8$ $S_3 = 3.5$ $S_4 = 4.0$	8.4	2.185	308	7.742
10	4.61	$S_1 = 1.1$ $S_2 = 1.6$ $S_3 = 3.0$ $S_4 = 3.4$ $S_5 = 3.7$	8.0	2.21	347	8.965
12	3.84	$S_1 = 1.1$ $S_2 = 1.9$ $S_3 = 2.6$ $S_4 = 3.1$ $S_5 = 3.8$ $S_6 = 4.1$	7.8	2.225	360	8.698
14	3.29	$S_1 = 1.3$ $S_2 = 1.9$ $S_3 = 2.4$ $S_4 = 3.2$ $S_5 = 3.3$ $S_6 = 4.2$ $S_7 = 5.1$	7.5	2.24	370	9.147

[a] $L = 35$ mm, $\varepsilon_r = 4.3$, $h = 1.59$ mm, $\tan \delta = 0.01$.

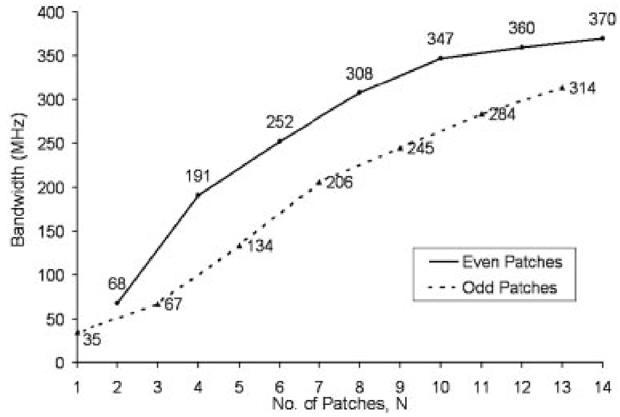

Figure 4 Comparative plot for BW increment for configurations with even and odd number of patches

coupling gap on BW for configurations consisting up till five patches. Tables 2 and 3 summarize the various parameters for maximum BW of the configurations with odd and even numbers of splitted elements, respectively, while Figure 4 shows comparative plot for BW increment for even and odd number of elements. The maximum number of elements is restricted to 14 because beyond this the N type feed probe diameter extends beyond the width of the individual strip.

Experiments have been performed for two cases of configurations with 11 and 12 strips. The substrate parameters are $\varepsilon_r = 4.3$, $h = 1.59$ mm, and tan $\delta = 0.01$, and the configurations are fed using N type coaxial connector with probe diameter $d = 3$ mm. The gaps and feed point are taken as specified in Table 2 for configuration with 11 strips and Table 3 for configuration with 12 strips. Comparative plots for measured and simulated VSWR, for both these cases, are shown in Figure 5. For the case of configuration with 11 strips, measured BW is 281 MHz with centre frequency of 2.229 GHz, while the simulated BW is 284 MHz with centre frequency of 2.212 GHz. For the case of configuration with 12 strips, the measured BW is 341 MHz with centre frequency of 2.234 GHz, while the simulated BW is 360 MHz with centre frequency of 2.225 GHz. There is good agreement between simulated and measured results. Minor differences can be attributed to fabrication errors and variation in dielectric constant of the commercial grade substrate.

3. RADIATION PATTERNS

Radiation pattern has been studied in detail for all the configurations over the range of frequencies for which VSWR $\leq$2. Following observations are made based on the studies. The E plane radiation pattern remains in the broadside throughout, whereas for some cases, the H plane radiation pattern shows variation with frequency. This is because dimension of the patch remain unchanged along the E plane, but along the H plane, it changes as the parasitic strips are arrayed along the H plane. In the H plane, for even number of elements from 2 to 8, the maxima of the radiation pattern shifts away from broadside at higher frequency of the BW. This is because configurations with even number of strips are asymmetrical with respect to feed point and as frequency increases, radiation from parasitic patches experience phase delay when compared with driven patch, leading to shift in beam maxima. However for configuration with odd number of patches, pattern remains in broadside over the BW, which is due to symmetry of these configurations and also BW is less compared with configurations with even number of elements. For configurations with more than 10 gap coupled strips, the pattern remains in broadside direction over the BW in both the planes. When the number of strips become more than three, side lobes start appearing in H plane at higher frequency because of increased effective aperture. This is also reflected in increased directivity as shown in Tables 1–3.

Figure 6 shows the measured and simulated E and H plane radiation patterns for 11 patch configuration at lower band edge, centre, and upper band edge frequencies. In E plane, single main beams are formed except for reduction in beamwidth with increase in frequency. In H plane, only one main lobe is formed at lower and higher band edge frequencies whereas two additional symmetric side lobes are formed at centre frequency. This is because at centre frequency radiation from all the strips are in phase leading to lower beam width and increased directivity, whereas radiations from all the strips are not in phase at two band edge frequencies, leading to larger beam width even when effective aperture is more at higher band edge frequency along the H plane. It is seen from Figure 6 that measured beam widths, in both E and H planes, are in reasonable agreement with corresponding simulated values at

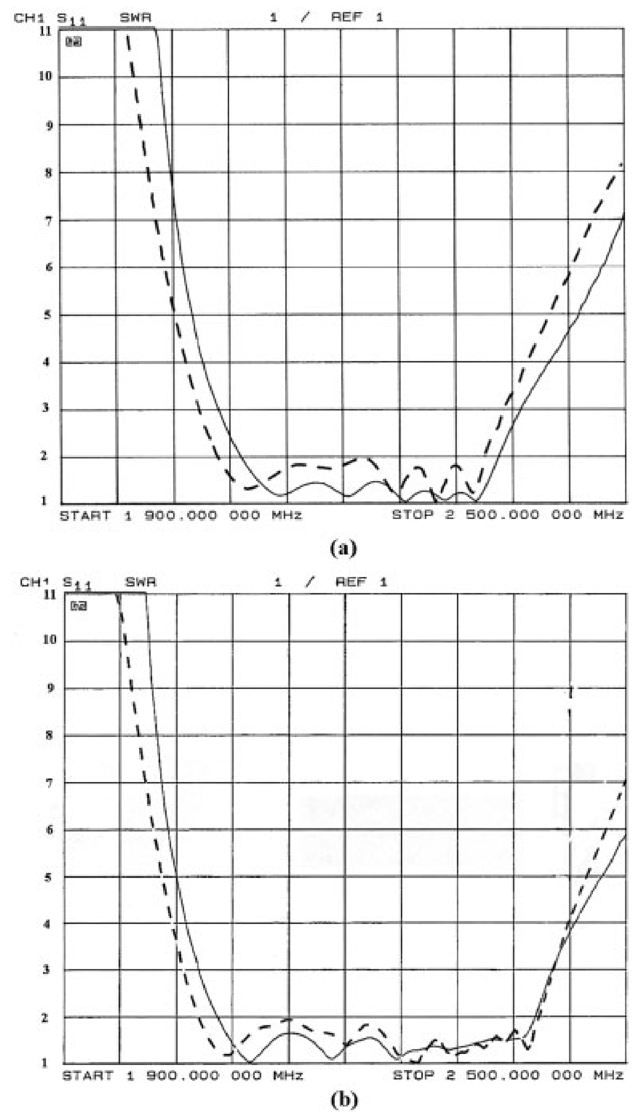

Figure 5 Comparative plot for measured and simulated VSWR for (a) configuration with 11 strips; (b) configuration with 12 strips; (——) measured, (– – –) simulated

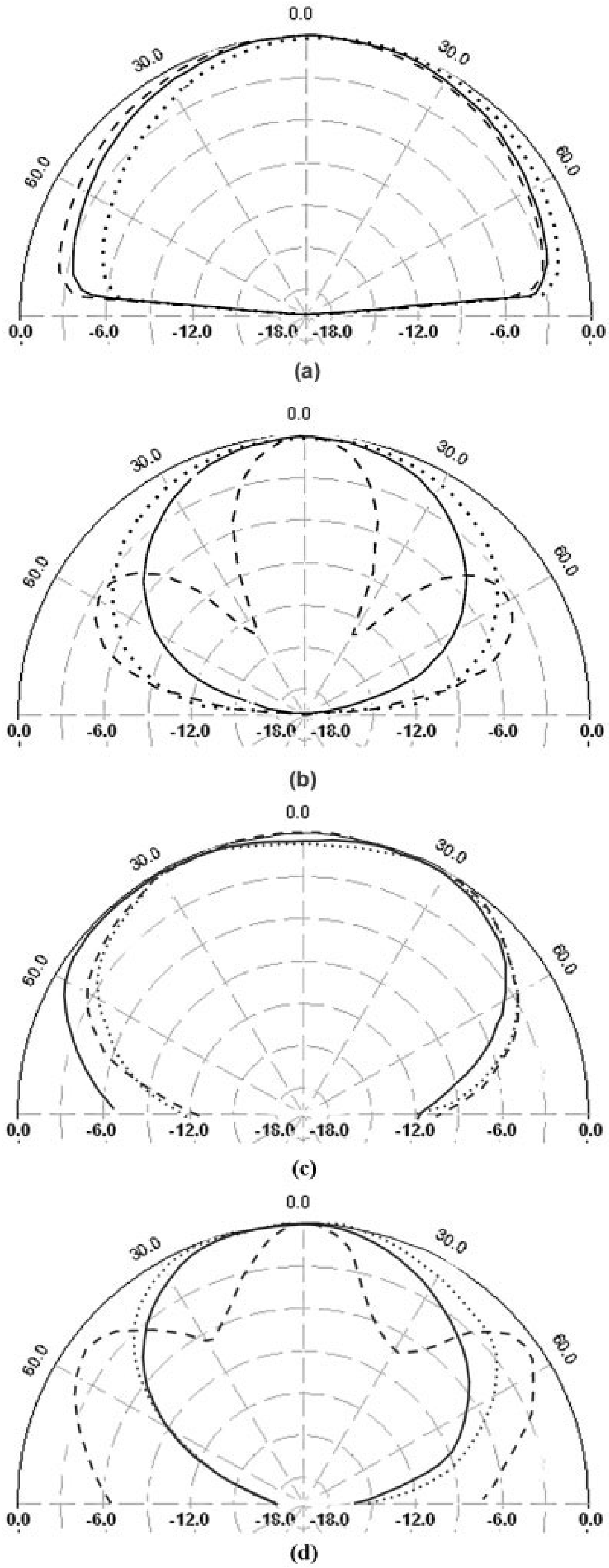

Figure 6 Radiation pattern for 11 patch configuration at three different frequencies (——) lower band edge, (– – –) centre, (……….) upper band edge; simulated (a) E plane; (b) H plane, measured; (c) E plane; (d) H plane

three frequencies. However, in the E plane, a slight dip of approximately 1 dB is observed along the broadside direction at lower and upper band edge frequencies. Also in the off main beam direction, there is difference in power levels between simulated and measured values. This could be due to reflection from other objects present in the laboratory.

4. CONCLUSIONS

Systematic study of gap coupled, multiple numbers of parasitic elements formed by splitting a single RMSA into numbers of equal, smaller strips along the width has been carried out. The number of parasitic elements is gradually increased and the behavior of each configuration has been studied in terms of BW and radiation pattern in detail. Configurations with even number of elements behaved differently from those with odd number. As regards to BW, significantly more BW has been obtained using even number of patches, but as regards to radiation pattern, configurations with odd number of elements have broadside radiation pattern throughout the BW. A maximum BW of 370 MHz has been obtained, for 14 patch configuration, which is 10.6 times that of a single RMSA, which has 35 MHz BW. Also as the parasitic elements are obtained from a single RMSA, the overall configuration is compact when compared with gap coupled full width RMSAs. Parametric study for the effect of gap and feed point location has also been presented, which can be used for their effective design at any other frequency with suitable scaling factor.

REFERENCES

1. G. Kumar and K.C. Gupta, Broadband microstrip antennas using additional resonators gap coupled to the radiating edges, IEEE Trans Antennas Propag 32 (1984), 1375–1379.
2. G. Kumar and K.C. Gupta, Non radiating edges and four edges gap coupled with multiple resonator, broadband microstrip antennas, IEEE Trans Antennas Propag 33 (1985), 173–178.
3. G. Kumar and K.P. Ray, Broadband microstrip antennas, Artech House, Boston, 2003.
4. C.K. Anandan and K.G. Nair, Compact broadband microstrip antennas, Electron Lett 22 (1986), 1064–1065.
5. C.K. Anandan, P.K. Mohanan, and K.G. Nair, Broadband gap coupled microstrip antennas, IEEE Trans Antennas Propag 38 (1990), 1581–1586.
6. IE3D 9.21, Zeland Software, Fremont, CA, 2002.
7. J. Ollikainen and P. Vainikainen, Radiation and BW characteristics of two planar multistrip antennas for mobile communication systems, In: IEEE Proceedings of Vehicular Technology Conference, Ontario, Canada, 1998, pp. 18–21.

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