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Wideband Designs of Sectoral Microstrip Antennas Using Parasitic Arc Shape Patches

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Abstract—Wide bandwidth and high gain designs of sectoral microstrip antennas gap-coupled with parasitic arc shape patches are proposed. In 1800 MHz frequency band, optimum response with bandwidth of more than 50% and peak gain of 10 dBi is obtained for 30° sectoral angle employing two gap-coupled arc shape patches. Further gap-coupled variations of slot cut single arc shape patch with 60° sectoral patch is presented. This design yields bandwidth of above 930 MHz (∼ 53%) with peak gain of more than 10 dBi. The comparison for the proposed gap-coupled sectoral variations with reported antennas is presented. Proposed gap-coupled sectoral configurations are single layer and thus simple in design and yet offers bandwidth and gain of larger than 50% and 10 dBi, respectively.

1. INTRODUCTION

Due to numerous advantages like low profile planar configuration, microstrip antennas (MSAs) are widely used in various communication applications ranging from personal communication systems to mobile applications and in satellite communication [1, 2]. While catering to these varied applications, MSA should offer larger gain and higher bandwidth (BW) so that larger area coverage is possible, and different frequency applications lying in nearby frequency spectrum can be accommodated. Many techniques have been reported to increase BW and gain. The impedance BW in MSA is increased by employing multiple resonant modes in the patch which is obtained either by employing parasitic patches in the same or stacked layer or by using modified feeding techniques like proximity feed and L-probe feed or by embedding resonant slots [3–8]. Amongst all slot cut designs have been widely used. However, wideband slot cut antennas are relatively complex in design as compared with simpler gap-coupling method. The antenna gain has been increased by increasing the effective aperture area [1, 2]. The multi-resonator gap-coupled technique increases BW and also adds to the gain [9]. By employing stacked configuration along with gap-coupled patches in the stacked layer, wideband and high gain MSA variations are reported which yields gain around 11 dBi [10–12]. The enhancement in gain is also realized by using either gap-coupled configuration of U-slot cut MSAs or array of U-slot cut patches fed using an L-probe feed employing power divider [13, 14]. The gain in dual band, wideband, and circularly polarized designs has been increased by using reflect arrays employing microstrip patches or the space fed arrays, and they give gain in excess of 12 to 15 dBi [15, 16]. Using array of gap-coupled rectangular MSA and vertex truncated triangular MSA, wideband and high gain design offering 12 dBi of gain is reported [17]. The design of a coaxially fed circular patch integrated with conical horn antenna is reported which gives gain of 12 dBi [18]. The design of a printed Yagi-Uda antenna is reported which yields peak gain of above 8 dBi [19]. Enhancement in Yagi-Uda antenna gain by 60% is realized by backing the same with electronic band gap structure [20]. Thus in the reported papers, multi-layer structure has been employed for gain enhancement, which requires larger antenna volume. This makes the design and fabrication relatively complex.

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This paper presents various wideband and high gain designs of a sectoral MSA gap-coupled with parasitic arc shape MSAs. Initially wide band designs of 30° sectoral MSAs with parasitic arc shape MSAs are discussed. Parametric study is presented for optimizing the configuration for BW against number of arc shape MSAs present in gap-coupled design. An optimum response in terms of gain and BW is obtained with two parasitic arc shape MSAs. For 30° sectoral angle, BW of larger than 1020 MHz ($> 54\%$) with peak gain of 10 dBi is obtained. Detailed study of further using two parasitic arc shape patches is presented for sectoral angle increasing from 30° to 70°. It is observed that with increase in angle, impedance BW decreases. For angles in the range of 30° to 50°, peak gain remains around 10 dBi; however, for larger angles, gain decreases. The reduction in gain is attributed to increased amount of orthogonal current variation over the arc shape patches. Hence for lower angles, i.e., 30° and 40°, optimum response in terms of gain and BW is obtained. Further wideband designs of 60° sectoral MSAs using single parasitic arc shape MSA employed with a pair of rectangular slots and its variations are presented. The slots on parasitic arc shape patch tune either TM_{02} or TM_{01} mode resonance frequency with reference to TM_{10} mode on the sectoral patch to give maximum BW of above 940 MHz ($\sim 54\%$). This gap-coupled slot cut variation also yields peak gain close to 10 dBi. Thus proposed configurations are planar in design, employ simple gap-coupled technique for BW as well as gain enhancement, hence they are simpler in design and implementation with reference to reported wide band high gain MSAs. The comparison explaining the same is presented further in the paper. The antenna configurations proposed in this paper are first studied using CST software [21]. In simulation and measurements, square ground plane of side length 40 cm has been used. an N-type connector having 0.32 cm inner wire diameter is used to feed the antennas. High frequency instruments, namely ZVH-8, FSC 6, and SMB-100A are used for the experimental validation of the proposed antennas. There is a good agreement obtained between simulated and measured results.

2. GAP COUPLED VARIATIONS OF 30° SECTORAL MSAS

The proximity fed design of sectoral MSA with angle 'α' is shown in Figs. 1(a), (b). Initially the design is investigated for 'α' = 30°. The patch is fabricated on an FR4 substrate ($\varepsilon_r = 4.3$, $h = 0.16$ cm), and it is suspended above the ground plane using an air gap of 'h_a' cm. For total substrate thickness ($h + h_a$) of 2.16 cm, sectoral patch radius 'r_p' is parametrically optimized for fundamental TM_{10} mode frequency of 1400 MHz. The radius is found to be 8 cm. To enhance the BW and gain, parasitic arc shape MSAs are gap-coupled along the edge of sectoral MSA as shown in Fig. 1(c). The arc shape

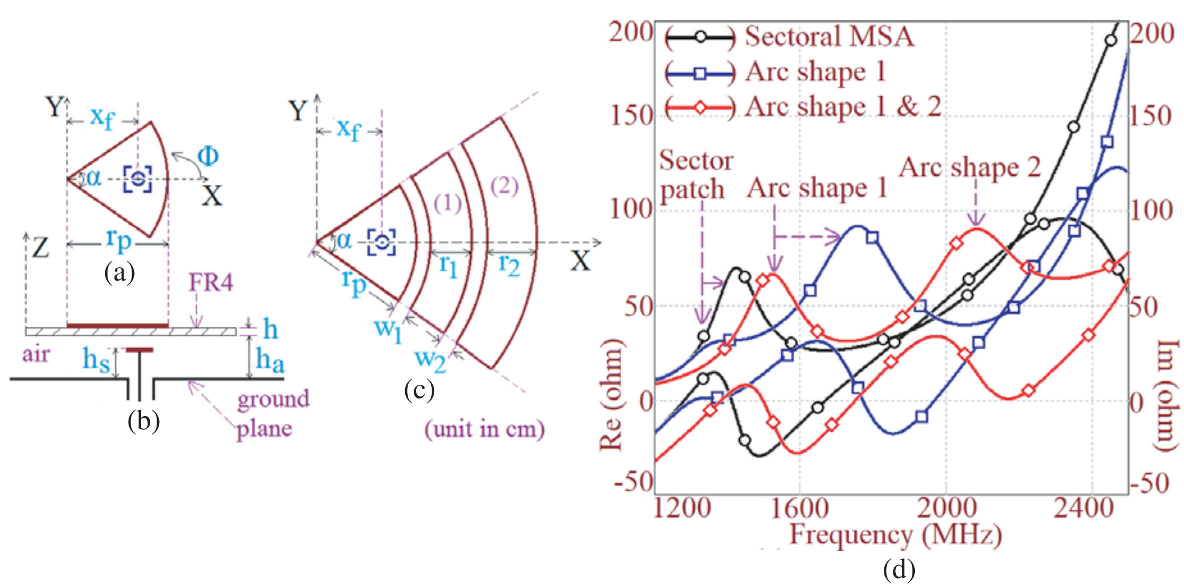


Figure 1. (a), (b) Proximity fed sectoral MSA, (c) gap-coupled configuration of sectoral MSA with arc shape MSAs and their (d) resonance curve plots showing the addition of modes with parasitic MSAs.

geometry is selected as it lies along the perimeter of the fed sectoral MSA that also ensures maximum coupling of electromagnetic energy from the fed to parasitic patches. The addition of parasitic arc shape MSAs '1' and '2' add to additional resonant modes as shown in Fig. 1(d) which will increase the BW.

To realize maximum BW, parametric study has been carried out on arc shape MSA's radius 'r_1' and 'r_2' and the spacing between sectoral MSA and arc shape MSAs, 'w_1' and 'w_2'. The antenna parameters in the optimum gap-coupled design with single arc shape MSA are $r_1 = 5.1$, $w_1 = 0.9$, and $x_f = 6.0$ cm. Similarly, antenna parameters in the gap-coupled design with two Arc shape MSAs are $r_1 = 5.1$, $r_2 = 4.1$, $w_1 = 0.6$, $w_2 = 0.3$, and $x_f = 6.0$ cm. The return loss (S_{11}) plots for gap-coupled designs, gain variation over BW for single and gap-coupled antenna, and pattern plots for gap-coupled

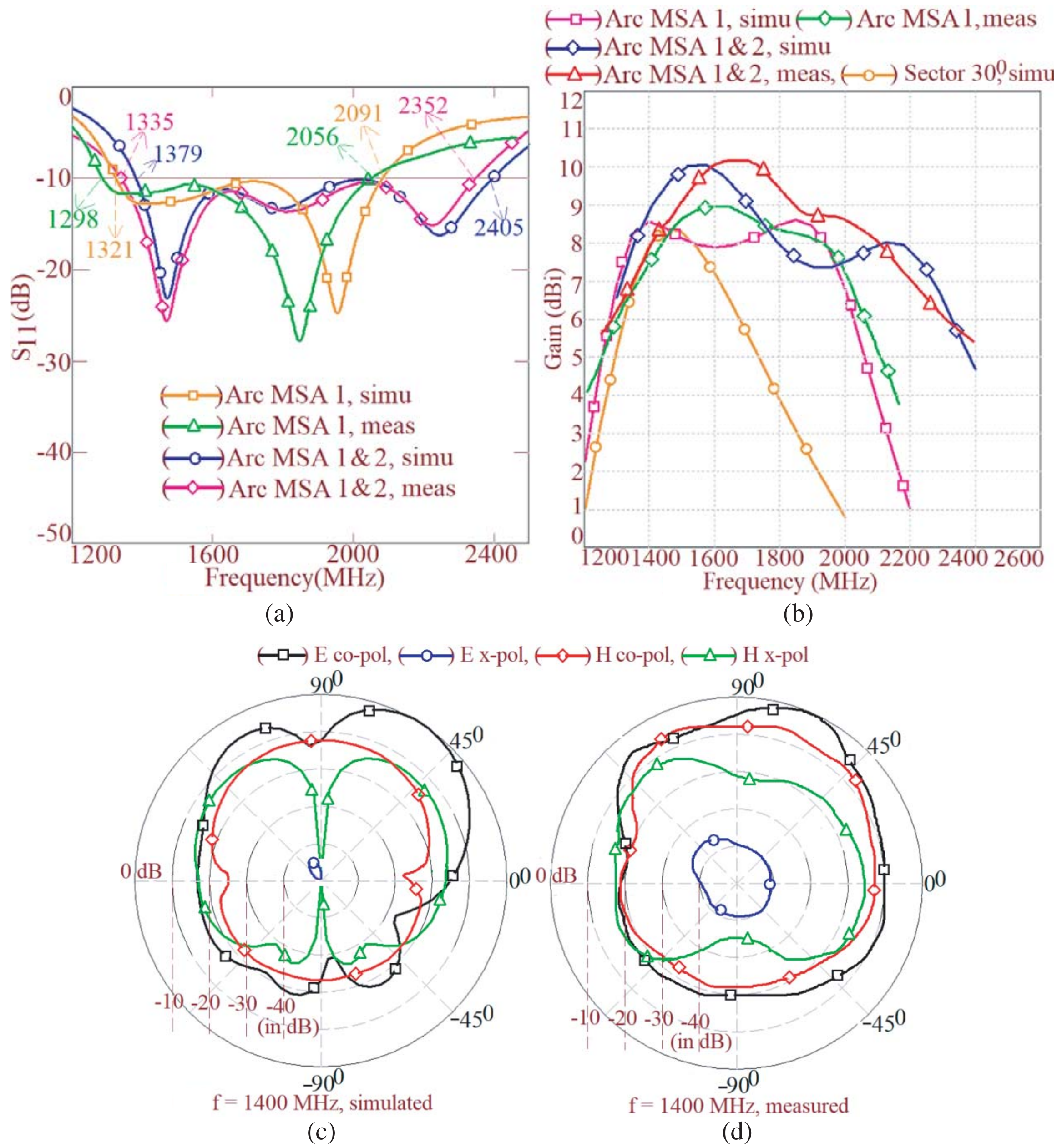


Figure 2. (a) Return loss plots for gap-coupled designs using 30° Sectoral MSA, its (b) gain variation over BW and (c), (d) radiation pattern plot nearer to band start frequency for 30° sectoral MSA gap-coupled with two arc shape MSAs.

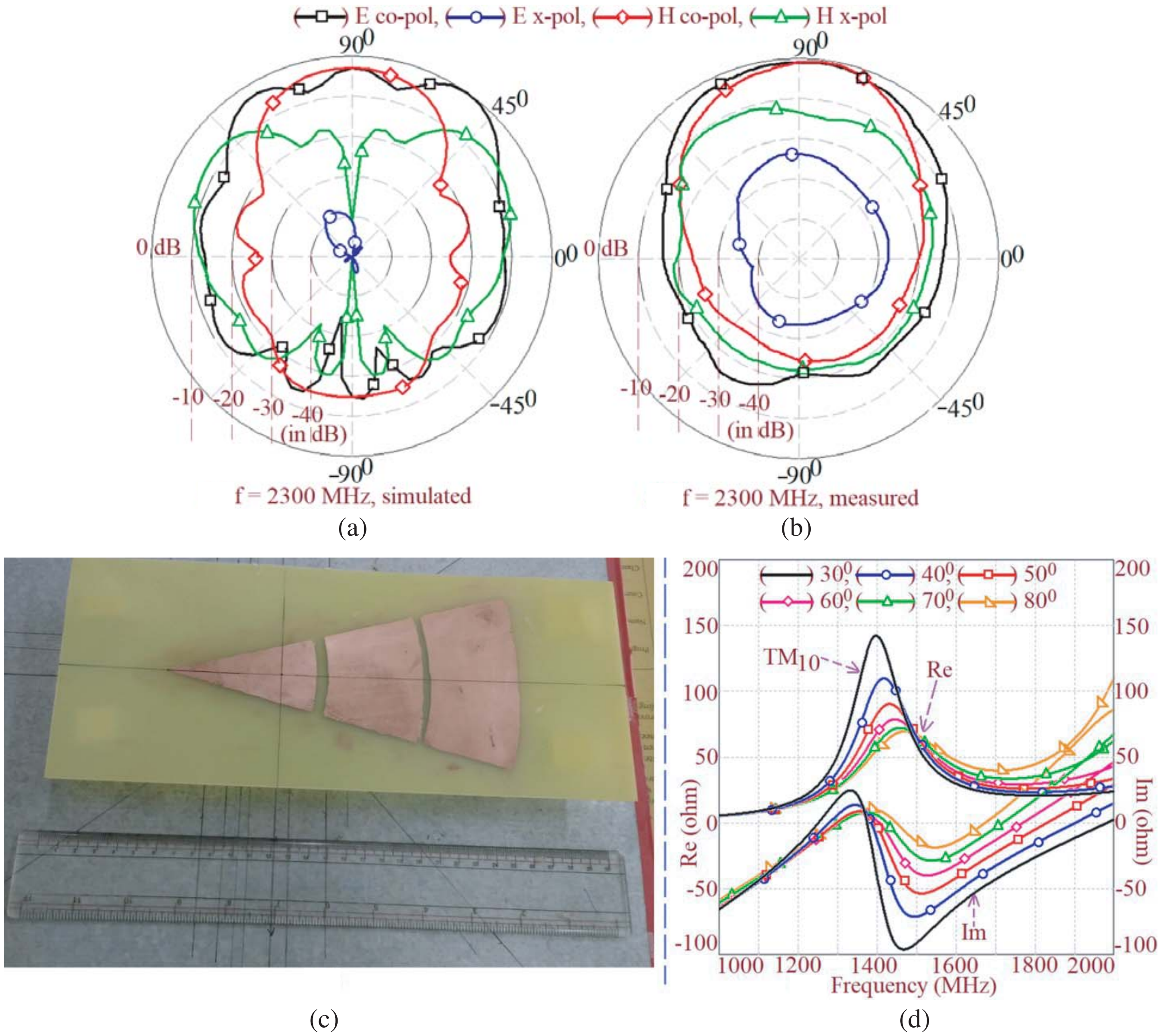


Figure 3. (a), (b) Radiation pattern nearer to band stop frequency and (c) fabricated prototype for 30° sectoral MSA gap-coupled with two arc shape MSAs, (d) variation in fundamental mode resonance frequency for sectoral MSA against angle.

MSA with two arc shape MSAs are shown in Figs. 2(a)–(d) and 3(a), (b).

The BW as given by 30° sectoral MSA is 440 MHz (28.7%), whereas its gap-coupled design with arc shape MSA yields simulated and measured BWs of 770 MHz (45.13%) and 758 MHz (45.2%), respectively. Addition of single arc shape MSA increases the BW by more than 15%, but peak antenna gain nearly remains constant. With the addition of two arc shape MSAs, realized simulated and measured BWs are 1026 MHz (54.22%) and 1017 MHz (55.17%), respectively. These BWs are nearly 30% more than the BW obtained from 30° sectoral MSA. The average and peak gain response offered by this design is better than the two patch design. The antenna offers average gain of around 9 dBi with peak gain of above 10 dBi. The fabricated prototype of 30° sectoral MSA with arc shape MSAs is shown in Fig. 3(c). Further effects of variation in sectoral angle 'α' on the impedance BW and gain in the gap-coupled design with two arc shape MSAs are investigated. Variation in the fundamental mode frequency of sectoral patch against different angles is studied first, and resonance curve plots for the same are shown in Fig. 3(d).

With increase in angle it is observed that frequency of sectoral patch increases, and the impedance at the same decreases. The decrease in impedance is attributed to increase in effective width of sectoral patch with sectoral angle. This effective increase in width also reduces fringing field extension length towards the patch edges which increases its frequency. Based on this, formulation in resonant length for fundamental TM_{10} mode in sectoral MSA is realized against varying angle as given in Eqs. (1)–(7). Here the area of sectoral patch (A_{sector}) is equated to the area of a rectangular patch of length 'r' using which equivalent rectangular patch width (W_{sector}) is calculated. This is further used to calculate fringing field extension length (dr) which decreases with the angle. Further, frequency as calculated using Eq. (7) at TM_{10} mode closely matches simulated frequency as obtained using CST software.

$$l_c = r\left(\pi\alpha/180\right) \quad (1)$$

$$A_{sector} = \pi r^2 \left(\left(\pi/\alpha/180\right)/2\pi\right) \quad (2)$$

$$W_{sector} = A_{sector}/r \quad (3)$$

$$\varepsilon_{re} = (\varepsilon_r + 1/2) + (\varepsilon_r - 1/2)\left(1/\sqrt{1 + 12h_t W_{sector}}\right) \quad (4)$$

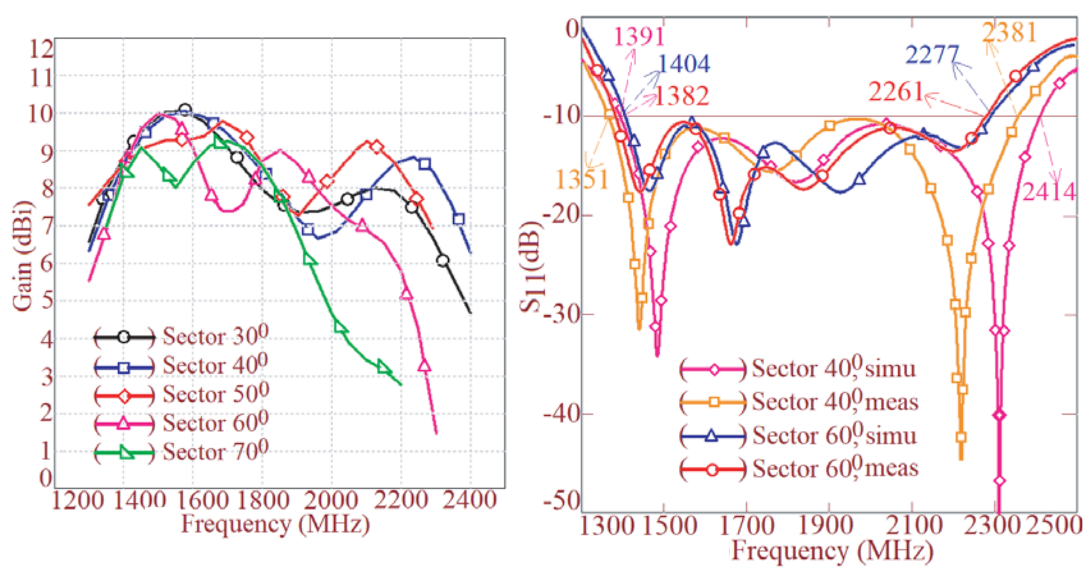
$$r_1 = \left|\sin\left(\pi\left(2r - l_c\right)/3r\right)\right| \quad (5)$$

$$dr = 1.25\left(\left(h + h_a\right) r_1/\sqrt{\varepsilon_{re}}\right) \quad (6)$$

$$f_{10} = 30/2\left(r + dr\right)\sqrt{\varepsilon_{re}} \quad (7)$$

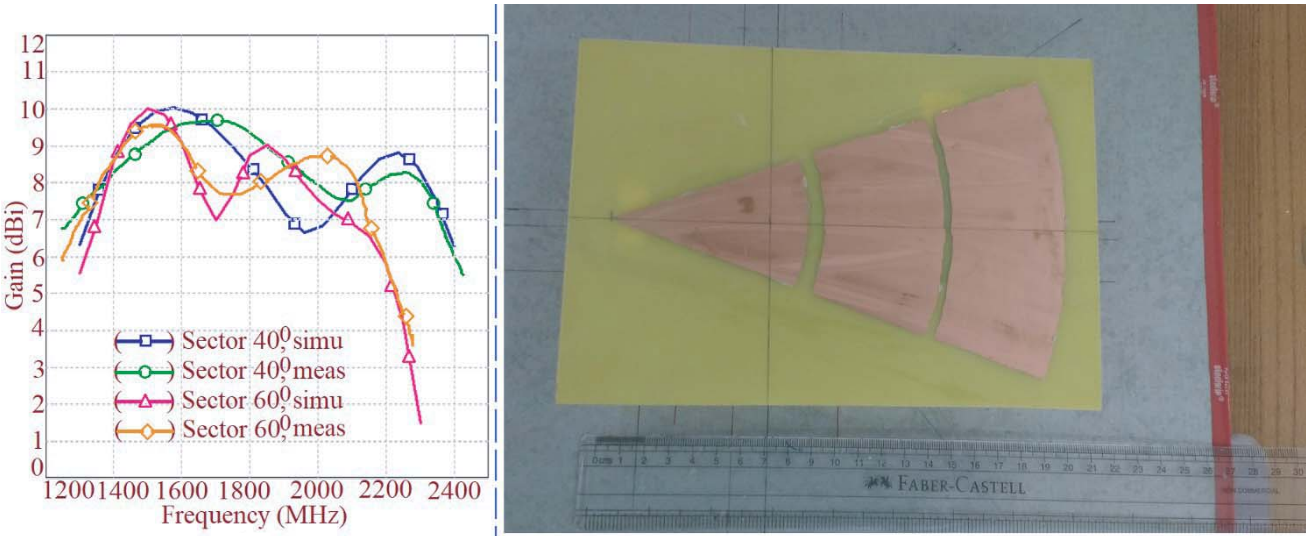
In above equations, the antenna dimensions are in cm, and f_{10} is calculated in GHz. Further gap-coupled design of sectoral MSA for angle increasing from 30° to 70° is optimized for BW and gain using two parasitic arc shape MSAs. For each angle, dimensions of 'r_1' and 'r_2' in arc shape MSAs are kept the same as that optimized for $\alpha = 30°$. Also the angle in parasitic arc shape MSA is kept equal to the angle of respective fed sectoral MSA. With increase in angle, simulated BW in gap-coupled antenna decreases. This reduction is more for angle larger than 50°. Also with increase in angle, average and peak antenna gains decrease as shown in Fig. 4(a). The reduction in gain is attributed to increase in orthogonal current variations over parasitic arc shape MSAs for higher angles. The optimum results in terms of BW for gap-coupled antennas for $\alpha = 40°$ and 60° are shown in Figs. 4(b) and 5(a), (b).

The simulated and measured BWs realized in 40° gap-coupled design are 1023 MHz (53.77%) and 1030 MHz (55.2%), respectively. Respective simulated and measured BWs realized in 60° gap-coupled design are 873 MHz (47.4%) and 879 MHz (48.26%). The peak antenna gain in both the configurations is close to 10 dBi with average gain of around 8 dBi. As the gap-coupled arc shape patches are present on



(a) (b)

Figure 4. (a) Gain variation over BW for gap-coupled MSAs against varying angle and (b) return loss plots for sectoral MSA gap-coupled with arc shape MSA for 40° and 60° angles.



(a) (b)

Figure 5. (a) Gain variation over BW for 40° and 60° sectoral MSA gap-coupled with arc shape MSAs and (b) fabricated prototype for 40° sectoral MSA gap-coupled with arc shape MSAs.

right hand side of fed sectoral MSA, maximum of the pattern is present at 25° away from the broadside direction. The gains presented using simulation and measurements are also in the same direction. Thus due to relatively narrow sectoral and arc shape patches, gains and BWs obtained in 30° and 40° sectoral gap-coupled designs are the optimum.

3. GAP COUPLED AND SLOT CUT VARIATIONS OF 60° SECTORAL MSAS

In all these gap-coupled variations, three resonant modes are present. With three patches in the gap-coupled design, antenna gain decreases for angle larger than 50° because of the orthogonal currents. To improve the BW and gain characteristics for these angles, single arc shape MSA is gap-coupled to the fed sectoral MSA. Further a slot is introduced to realize additional resonant mode to increase the overall BW. Thus using a single parasitic patch and slot, various gap-coupled designs using 60° sectoral MSA as fed patch are realized as shown in Figs. 6(a)–(d).

As seen above, gap-coupled design with single arc shape MSA (Fig. 6(a)) yields BW of around 760 MHz (> 45%). By dividing single arc shape MSA into two 30° arc shape MSAs (Fig. 6(c)), BW increases to around 823 MHz (47.94%). Thus dividing the parasitic patch yields 3% increase in the BW. Alternatively, slot of length 'l_s' and width 'w_s', when being introduced in arc shape MSA (Fig. 6(b)), tunes next higher order TM_{02} mode frequency in arc shape MSA with reference to TM_{10} modes in sectoral and arc shape patches as shown in Fig. 7(a). These modal identifications have been done by studying their surface current distributions for the cases with and without rectangular slot. The optimum spacing between respective modal frequencies is realized for 'l_s' = 1.7 cm, 'w_s' = 0.4 cm, and 'y' = 2.5 cm, and it yields simulated and measured BWs of 915 MHz (51.83%) and 921 MHz (52.92%), respectively, as shown in Fig. 7(b). Further to increase BW of gap-coupled 30° arc shape MSAs with 60° sectoral MSA, rectangular slots are introduced as shown in Fig. 6(d). The slot lengths selected on 30° arc shape MSAs are unequal. They reduce the frequency of orthogonal TM_{01} mode in 30° patch to yield increase in the BW. The maximum BW is obtained for 'l_s' = 1.7, 'l_{s1}' = 2.2, 'w_s' = 0.4, and 'y' = 2.5 cm as shown in Fig. 7(b). The BW realized using simulation is 931 MHz 52.8%), and that obtained using measurement is 940 MHz (54.02%).

The variations in gain for gap-coupled designs presented in Figs. 6(a)–(d) are shown in Figs. 8(a), (b). The average gain in all the designs is around 8 dBi. However, the peak gain observed in slot cut antennas is above 10 dBi. The measured gain plots in slot cut designs are in good agreement with

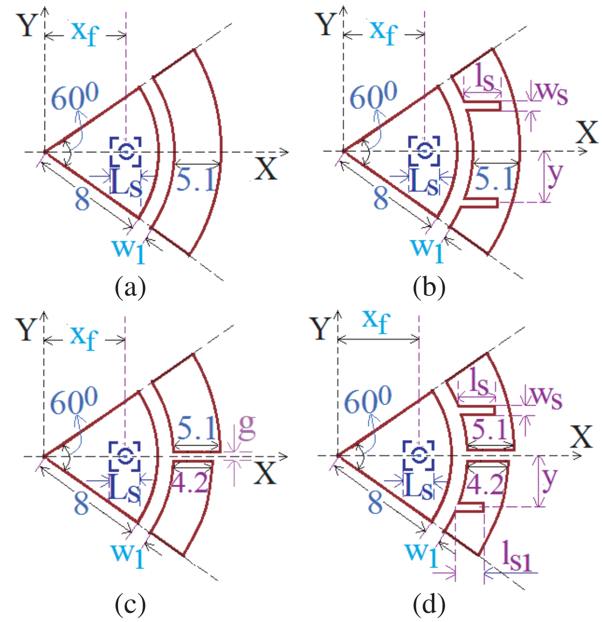


Figure 6. (a)–(d) Various gap-coupled designs of 60° sectoral MSA with slot cut arc shape MSA.

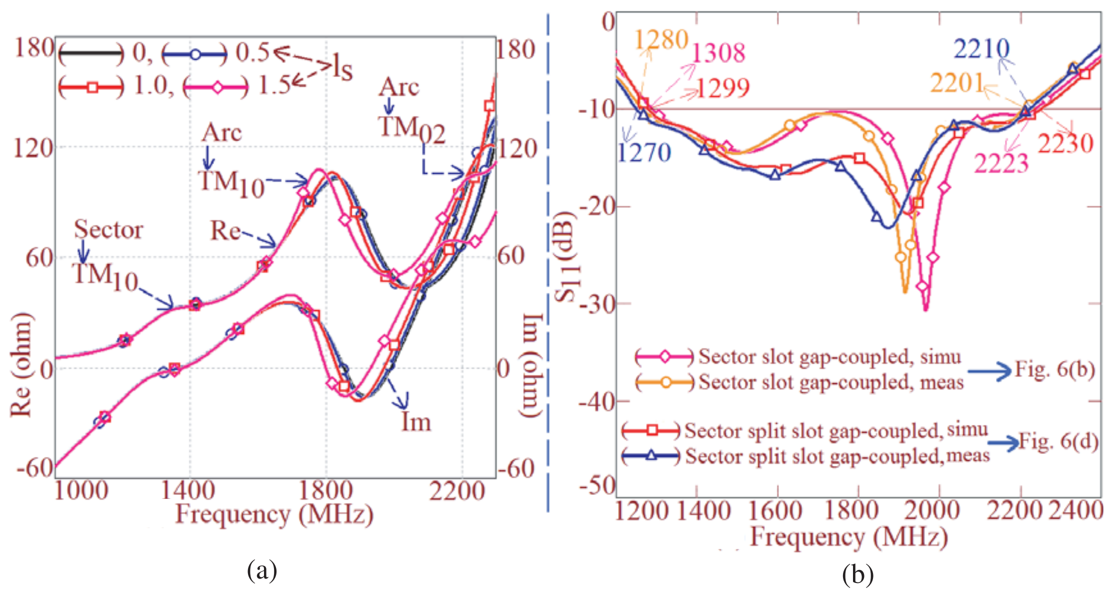


Figure 7. (a) Resonance curve plots showing variation in modal requencies against increase in slot length for slot cut Arc shape MSA gap-coupled with 60° Sectoral MSA, (b) return loss plots for gap-coupled variations of slot cut Arc shape MSAs with 60° Sectoral MSA.

simulated ones. The radiation pattern near band edge frequencies of the BW for slot cut arc shape MSA gap-coupled to 60° sectoral MSA is shown in Figs. 8(c)–(f). The pattern shows maximum of radiation away from broadside direction by nearly 20°, which is due to patches gap-coupled along one side of the sectoral MSA. The fabricated prototype of slot cut gap-coupled antennas is shown in Figs. 9(a), (b). Similar gap-coupled slot cut designs are also investigated for 50° and 70° angles. However, designs with 60° sectoral MSA yields optimum result in terms of BW and gain.

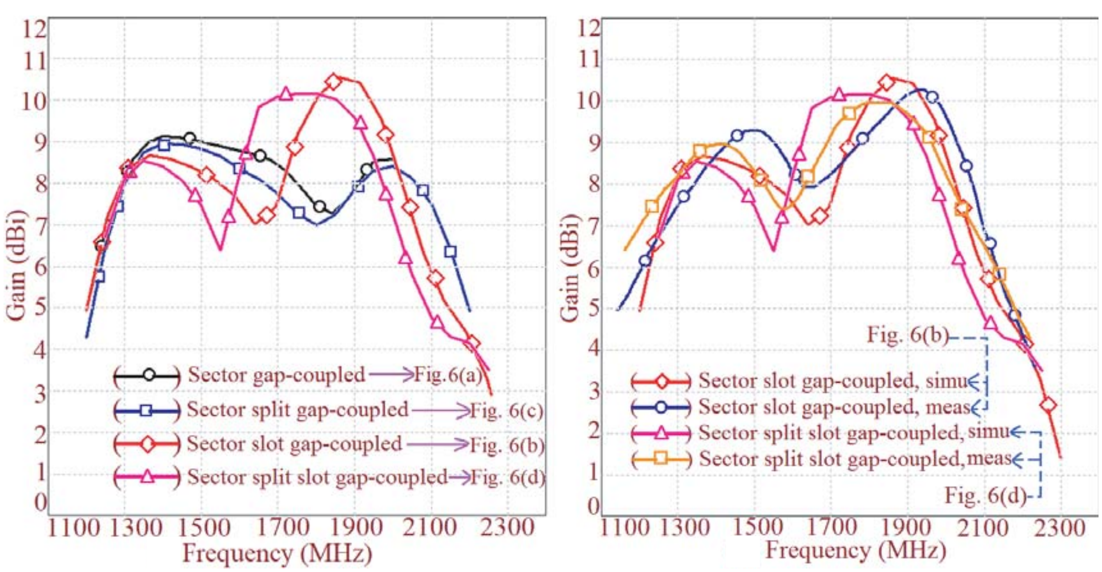
The comparisons of the proposed designs against reported wideband and high gain designs are provided in Table 1. In Table 1, the total patch area and substrate thickness are expressed in terms of

Table 1. Comparison for proposed wideband sectoral MSA variations against reported designs.

MSA shown in	Simu. BW (MHz, %)	Meas. BW (MHz, %)	Peak Gain (dBi)	Patch Area (cm^2, area/λ_c)	Substrate thickness
1(c), $\alpha = 30°$	1026, 54.22	1017, 55.17	10.1	86.8, 5.61	$0.139\lambda_c$
1(c), $\alpha = 40°$	1023, 53.77	1030, 55.2	10.0	114.65, 7.45	$0.140\lambda_c$
6(b), $\alpha = 60°$	915, 51.83	921, 52.92	10.4	93.06, 5.61	$0.127\lambda_c$
6(d), $\alpha = 60°$	931,52.8	940, 54.02	10.1	86.82, 5.23	$0.130\lambda_c$
Ref. [10], Stacked	820, 39	860, 41.5	12	59.93, 4.3	$0.133\lambda_c$
Ref. [10], 2×2 array	880, 41.5	950, 44	16.6	362.67, 26	$0.164\lambda_c$
Ref. [11]	—-	1093, 47	9.54	64.5, 5.12	$0.134\lambda_c$
Ref. [12]	5251, 39.63	5651, 42.65	6.08	0.95, 5.523	$0.23\lambda_c$
Ref. [13]	240 4.64	250, 4.85	12.16	48.15, 11.89	$0.04\lambda_c$
Ref. [14]	—-	710, 20	19.5	315.21, 38.4	$0.067\lambda_c$
Ref. [15]	899, 10.26	600, 8.1	23.7	756.25, 186.54	$5.42\lambda_c$
Ref. [16]	—-	8100, 54	11.45	4.58, 2.35	$0.791\lambda_c$
Ref. [18]	—-	1700, 5.2	12	1.4, 1.517	$1.007\lambda_c$
Ref. [19]	—-	600, 41.4	7.0	93.24, 4.833	$0.008\lambda_c$
Ref. [20]	—-	33.2, 1.38	8.53	115.78, 11.9	—-

the wavelength at the center frequency of the VSWR BW (λ_c). The proposed designs offer comparable BW and gain against the gap-coupled and stacked variations as reported in [10–12]. However, against these designs, the proposed antennas are planar in structure using single layer, and thus they are simpler to implement.

Due to four times of the patch area, the stacked 2×2 MSA array using shorted patches and a power divider as reported in [10] offers higher antenna gain than the proposed antennas. Compared with the gap-coupled U-slot cut rectangular MSAs reported in [13], due to use of proximity feeding,



(a) (b)

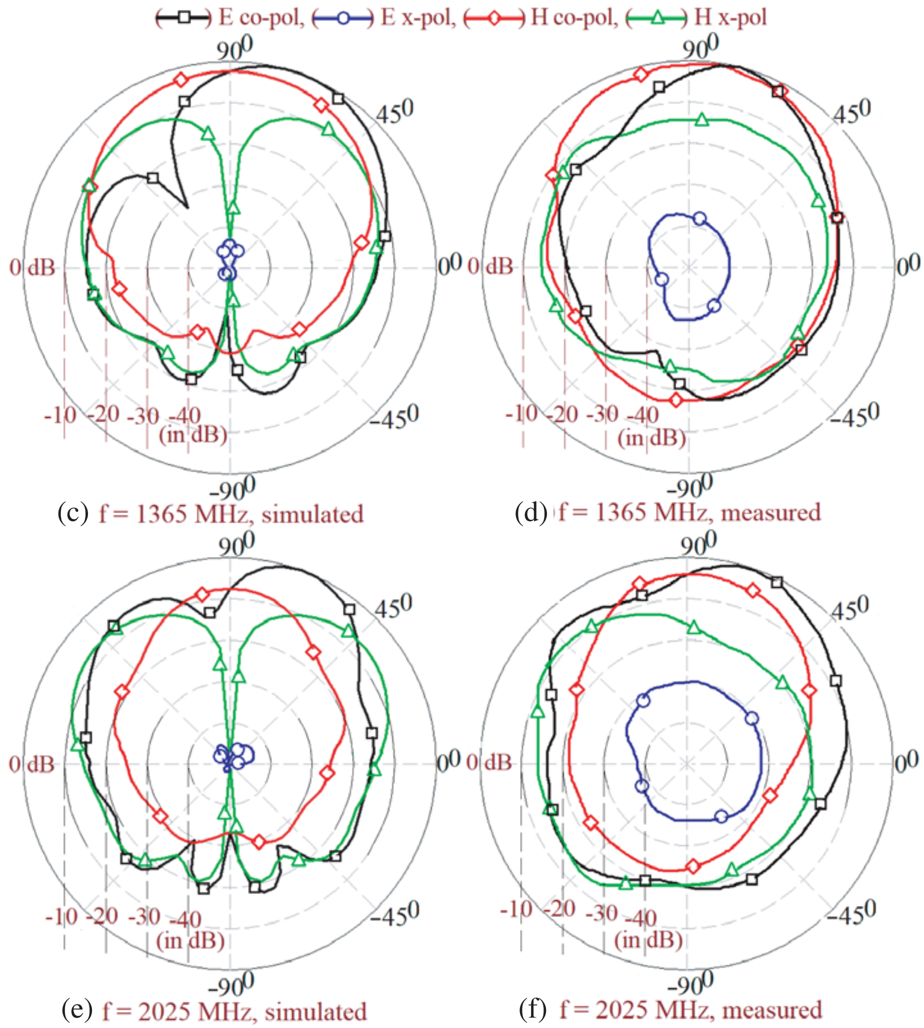
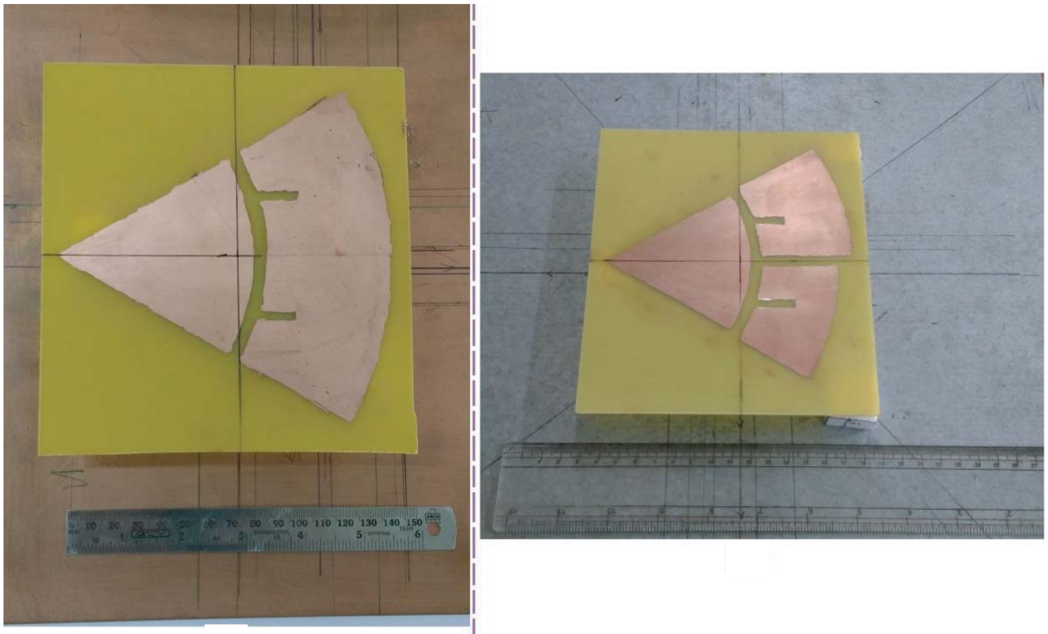


Figure 8. (a), (b) Gain variations for various slot cut gap-coupled designs and (c)–(f) radiation pattern plots nearer to band start and stop frequency for 60° Sector MSA gap-coupled with slot cut Arc shape MSA.

proposed design offers higher impedance BW with smaller patch size and showing comparable values of peak antenna gain. A larger gain in [14] than the proposed antennas is due to larger patch size. However, the design reported in [14] is complex in implementation since it requires a power divider network. The designs reported in [15] and [16] offer larger gain, but their structures are bulky and occupy larger volume as they use reflect array or space fed techniques for gain enhancement. Due to the use of conical horn, the gain realized in [18] is more, but the proposed configuration is planar and offers equivalent gain and BW values. Thus as against the reported techniques of gain and BW enhancement, the present paper proposes simpler planar gap-coupled configurations of sectoral MSAs with arc shape MSAs which offer equivalent BW and gain results against the reported designs. They do not require a power divider and have single layer in configuration which makes their fabrication simpler. A similar study of gap-coupled sectoral antennas was reported in [22]. However, in [22], detailed discussion on effects of variation in sectoral angle on BW and gain in three patch gap-coupled configuration was not presented. Also wideband designs using slot and single arc shape MSA were not discussed which offered nearly the same BW and gain responses as that obtained using two arc shape MSA designs. The gap-coupled designs for sectoral angle greater than 70° are not discussed in this paper, as gain decreases in those configurations due to higher orthogonal dimension in the arc shape patch.



(a) (b)

Figure 9. Fabricated prototype of (a) 60° sectoral MSA gap-coupled with slot cut arc shape MSA and (b) 60° sectoral MSA gap-coupled with slot cut 30° arc shape MSAs.

4. CONCLUSIONS

Simpler gap-coupled designs of sectoral MSA with parasitic arc shape MSAs are proposed for wideband and high gain characteristics. The wider BW is due to coupling between fundamental mode frequencies amongst fed and parasitic patches. The detailed study to explain effects of sectoral angle on the realized BW and gain is presented. The optimum response with BW greater than 50% with peak gain of 10 dBi is obtained for 30° and 40° sectoral angles in the fed sectoral MSA. Further using single arc shape parasitic patch embedded with a slot, wideband gap-coupled designs using fed Sectoral 60° MSA are proposed. These designs also yield equivalent BW and gain characteristics to that obtained in the configuration with two arc shape patches. As against reported papers, the proposed designs are single layer planar structures, do not require a power divider to feed individual patches, and thus they are simpler in implementation. Further they offer equivalent values of gain and BW against reported designs. These are the novelties in the present configurations.

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