Proximity fed gap-coupled half E-shaped microstrip antenna array

AMIT A DESHMUKH^{1,*} and K P RAY²

¹Department of Electronics and Telecommunication Engineering, D. J. Sanghvi College of Engineering, Vile –Parle (W), Mumbai 400 056, India

²Society for Applied Microwave Electronics Engineering and Research, Indian Institute of Technology Campus, Powai, Mumbai 400 076, India
e-mail: amitdeshmukh76@gmail.com; kpray@rediffmail.com

MS received 23 December 2013; revised 19 April 2014; accepted 24 August 2014

Abstract. Broadband gap-coupled array configuration of proximity fed rectangular microstrip antenna with half E-shaped microstrip antennas are proposed. The rectangular slot in half E-shaped patch reduces the orthogonal TM_{01} mode resonance frequency of equivalent rectangular patch and along with TM_{10} modes of fed and parasitic rectangular patches, yields broader bandwidth of more than 470 MHz ($> 45\%$). An improvement in radiation pattern and gain characteristics over the bandwidth is obtained by gap-coupling half E-shaped patches along all the edges of proximity fed rectangular patch, which yields bandwidth of nearly 510 MHz ($\sim 49\%$). Further to enhance the gain, a gap-coupled 3×3 array configuration of half E-shaped patches with proximity fed rectangular microstrip antenna is proposed. The gap-coupled array configuration yields bandwidth of more than 530 MHz ($> 50\%$) with broadside radiation pattern and peak gain of 11 dBi.

Keywords. Rectangular microstrip antenna; broadband microstrip antenna; half E-shaped microstrip antenna; proximity feeding; higher order mode.

1. Introduction

The simplest method to realize broadband microstrip antenna (MSA) is by using multi-resonator gap-coupled configuration and further by fabricating them on lower dielectric constant thicker substrate (Kumar & Ray 2003; Garg *et al* 2001; Bhartia & Bahl 1980). Due to an increase in effective aperture area, gap-coupled MSAs have higher gain. For substrate thickness, more than $0.05\lambda_0$, the antenna bandwidth (BW) in multi-resonator configurations is limited by the feed probe inductance. In such cases, broader BW is realized by using proximity feeding technique which is easier to implement in thicker substrates (Cock & Christodoulou 1987; Wong 2002). Without increasing the patch size, broadband MSA is realized by cutting the slot of different

*For correspondence

shapes like U-slot, V-slot, rectangular slot, etc., at an appropriate position on the edges or inside the patch (Wong 2002; Huynh & Lee 1995; Lee *et al* 2010; Guo *et al* 1998; Weigand *et al* 2003). In these MSAs, slot is said to introduce a resonant mode near the fundamental mode of the patch when its length either equals half wave or quarter wave in length. The coaxial or proximity fed slot cut MSAs yield bandwidth (BW) of more than 30% in 1000 MHz frequency band whereas they yield BW of more than 50%, when designed at frequencies above 3 to 5 GHz. A single slot cut MSA yields gain of around 6 to 8 dBi which has been increased by using their array configurations (Wang *et al* 2008; Lau *et al* 2011). In slot cut MSA arrays, individual patch elements are fed using microstrip line power divider network which are relatively complex in design and losses in the same reduces antenna gain. By cutting pair of rectangular slots on one of the radiating edges of rectangular MSA (RMSA), an E-shaped MSA is realized (Wong & Hsu 2001). By using its symmetry across the feed point axis, a compact half E-shaped MSA is obtained (Chair *et al* 2005; Deshmukh & Kumar 2005). As compared to E-shaped MSA, half E-shaped MSA yields 50% reduction in patch size with nearly the same BW. While designing slot cut MSAs at given frequencies, simpler approximation of slot length against wavelength, does not give closer results. An analysis of broadband ψ -shaped MSA is reported (Deshmukh & Ray 2013). The ψ -shaped MSA is derived from E-shaped MSA by cutting an additional pair of slot on the other edge of the patch. The slots cut to realize E-shaped and further ψ -shaped MSA does not introduce any additional mode but it reduces the resonance frequencies of TM_{20} and TM_{21} modes of equivalent RMSA and along with its TM_{01} mode yields broader BW. The ψ -shaped and E-shaped MSA in 1000 MHz frequency band yield gain of around 9 dBi (Deshmukh & Ray 2013). To increase its gain using their gap-coupled array configuration will require larger overall patch size.

In this paper, to realize higher BW and gain, gap-coupled array configurations of proximity fed RMSA with compact half E-shaped MSAs are proposed. The proposed MSAs will not involve power divider network and use proximity feeding and gap-coupled technique, hence they are easy to implement. As compared to E-shaped MSA, half E-shaped MSA is used as it reduces the overall patch size and gives higher BW as compared to RMSA. Firstly, broadband proximity fed RMSA in 1000 MHz frequency band and its gap-coupled configurations with parasitic RMSAs which are gap-coupled along with radiating as well as non-radiating edges are discussed. The gap-coupled proximity fed RMSAs yield BW of more than 350 MHz. To further enhance the BW, half E-shaped MSAs were gap-coupled along the edges of proximity fed RMSA. In first configuration, two half E-shaped MSAs were gap-coupled along the non-radiating edge of proximity fed RMSA whereas in second configuration, four half E-shaped MSAs were gap-coupled along all the edges of proximity fed RMSA. The analysis to study the effect of rectangular slot in half E-shaped MSA is presented. The slot reduces TM_{01} mode resonance frequency of equivalent RMSA and along with TM_{10} modes of fed and parasitic RMSAs, yields broader BW. In first configuration, BW of more than 470 MHz ($> 45\%$) is obtained whereas second configuration yields BW of more than 500 MHz ($\sim 49\%$). The rectangular slot in half E-shape MSA modifies surface currents directions at orthogonal TM_{01} mode and aligns maximum amount of surface currents along the patch length, i.e., in the same direction as that of the surface currents at TM_{10} mode. Thereby it gives broadside radiation pattern over the BW with out any variations in the directions of E and H-planes. Although the increase in BW from two half E-shaped MSA configuration to four half E-shaped MSA configuration is smaller, the latter configuration shows better radiation pattern characteristics due to symmetrical structure. Both of these gap-coupled half E-shaped MSA configurations will help in gaining of more than 7 dBi over most of the BW. Further, to enhance the gain, additional half E-shaped MSAs are gap-coupled along the diagonal axis of four gap-coupled half E-shaped MSAs, thereby realizing 3×3 array of half E-shaped

MSAs with proximity fed RMSA. The 3×3 array yields BW of nearly 530 MHz ($> 50\%$) with broadside radiation pattern and peak gain close to 11 dBi. The proposed MSAs were first optimized on air substrate (which realizes maximum radiation efficiency) using IE3D software (IE3D 2000). In first simulation an infinite ground plane is used (since it requires lesser computation time). To simulate infinite ground plane effect in the measurement, a square ground plane of side length 80 cm is used, which is more than six times the substrate thickness in all the directions with respect to patch edges (Kumar & Ray 2003). The maximum size of gap-coupled antenna array is 37×22 cm. To investigate the antenna performance on finite ground plane, simulation and measurement were also carried out using finite square ground plane of side length 50 cm, which showed closer match in terms of impedance response but with higher back lobe radiation, to that of 80 cm ground plane. In the following sections simulations and measured results with square ground plane of side length 50 cm are given. In measurements antennas were fabricated using copper plate having finite thickness (which is also considered in IE3D simulations) and were supported in air using foam spacer support which was placed towards antenna corners. The foam spacers were also used to maintain the required air gap between fed and parasitic patches. The antennas were fed using N-type connector of 0.32 cm inner wire diameter and antenna response was measured using R & S vector network analyzer. The pattern was measured in minimum reflection surroundings with required minimum far field distance between reference antenna and gap-coupled array configurations.

2. Proximity fed RMSAs

The proximity fed RMSA is shown in figure 1(a, b). To realize larger BW thicker air substrate of $h = 3.0$ cm ($0.095 \lambda_0$) is selected. The RMSA length (L) is calculated such that its TM_{10} mode resonance frequency is around 950 MHz. To realize compact configuration, RMSA width (W) of 7 cm is selected. The coupling strip is placed below the patch at substrate thickness of 2.8 cm ($0.09 \lambda_0$). By optimizing strip dimensions and its position below the patch, simulated BW of 240 MHz (24%) is realized, whereas the measured BW is 238 MHz (23.8%). To further increase the BW and gain, parasitic RMSAs having different lengths along the two co-ordinate axis were gap-coupled along radiating as well as non-radiating edges of proximity fed RMSA, as shown in figure 1(c). This gives three resonance frequencies which can lead to three loops in the input impedance locus as shown in figure 1(d). The simulated BW is 363 MHz (36%) whereas the measured BW is 358 MHz (35%). The radiation pattern over the BW is in the broadside direction with cross-polarization levels less than 15 dB as compared to that of the co-polar level. The antenna gain is more than 7 dBi over the BW. The resonance curve plot for optimized gap-coupled proximity fed RMSAs is shown in figure 1(e). It shows three peaks due to TM_{10} modes on proximity fed and parasitic RMSAs. The resonance curve also shows additional peak in higher frequency region. The surface currents at this frequency are varying along the patch width inside the parasitic RMSAs which are gap-coupled along the non-radiating edges, as shown in figure 1(f). This indicates the excitation of TM_{01} mode in them. Although at this frequency TM_{01} mode in parasitic RMSAs gap-coupled along patch length is also present but due to larger air gap the coupling to them is weak. Hence surface current variations for them are not distinctly observed. To increase the BW, this mode frequency is optimized with respect to TM_{10} mode frequencies of fed and parasitic RMSAs. For this, rectangular

Figure 1. (a) Top view and (b) side view of proximity fed RMSA, (c) gap-coupled proximity fed RMSAs, (d) input impedance plot, (—) simulated, (---) measured, (e) resonance curve plot and (f) surface current distribution at TM_{01} mode.

slot is cut on one of the radiating edges of parasitic RMSAs which were gap-coupled to the proximity fed RMSA. This realizes compact half E-shaped MSA, as discussed in the following section.

Figure 2. (a) Proximity fed RMSA gap-coupled to RMSAs and half E-shaped MSAs, (b) resonance curve plot for $l =$ (—) 0 cm, (---) 1 cm, (- - -) 2 cm, (- · - ·) 3 cm and (c) surface current distribution for $l = 3.0 \text{ cm}$.

3. Broadband gap-coupled half E-shaped MSAs

The proximity fed RMSA gap-coupled to RMSAs and half E-shaped MSAs is shown in figure 2(a). In parasitic MSAs, an equal patch and slot dimensions along the two co-ordinate axis are taken. To understand the effect of slot, slot length in half E-shaped MSA is increased in steps of 1 cm and for each of the case resonance curve plot, surface current distributions were studied.

Figure 3. (a) Input impedance and VSWR plots, (—) simulated, (---) measured, (b) fabricated prototype for proximity fed RMSA gap-coupled to RMSAs and half E-shaped MSAs.

The resonance curve plots for this variation are shown in figure 2(b). Since surface currents at TM_{01} mode are orthogonal to slot length, its frequency reduces with an increase in 'l' and comes closer to TM_{10} mode frequencies of proximity fed and gap-coupled RMSAs. The surface current distribution for $l = 3.0$ cm is shown in figure 2(c). The currents at TM_{01} mode are primarily directed along patch width. However, due to the rectangular slot, more and more amount of surface currents are re-oriented along the patch length. The optimum BW is realized when the loop formed due to modified TM_{01} mode frequency which lies inside $VSWR = 2$ circle. This is obtained for slot length of 3.2 cm. The optimized input impedance and VSWR plot on 50 cm ground plane is shown in figure 3(a). The simulated BW is 490 MHz (48.8%) whereas the

Figure 4. (a–c) Radiation pattern and (d) gain variation over BW for proximity fed RMSA gap-coupled to RMSAs and half E-shaped MSAs.

Figure 5. (a) Proximity fed RMSA gap-coupled to half E-shaped MSAs, (b) input impedance and VSWR plots, (—) simulated, (---) measured, and (c) fabricated prototype.

measured BW is 502 MHz (45.3%). The fabricated prototype of the configuration is shown in figure 3(b). The measured radiation pattern and gain variation over the BW using 50 cm ground plane is shown in figure 4(a–d). The E and H-planes are aligned along $\Phi = 0^\circ$ and 90° , respectively. The pattern is in the broadside direction with cross-polarization levels less than 12 dB as compared to the co-polar levels. The back-lobe radiation is less than 10 dB as compared to the bore sight radiation. The antenna gain is more than 7 dBi over the operating BW with peak gain very close to 9.5 dBi. Towards the higher frequencies of BW, TM_{01} mode in parasitic half E-shaped MSA is dominant. This increases surface current contribution along patch width, which in turn increases cross polar levels and reduces antenna gain. To realize symmetrical structure

Figure 6. (a–c) Radiation pattern and (d) gain variation over BW for proximity fed RMSA gap-coupled to half E-shaped MSAs.

Figure 7. (a) Proximity fed 3×3 half E-shaped MSA array, (b) input impedance and VSWR plots, (—) simulated, (---) measured and (c) fabricated prototype.

and to improve upon radiation pattern and gain characteristics, half E-shaped MSAs is gap-coupled along all the edges of proximity fed RMSA, as shown in figure 5(a). The slot length in all the parasitic half E-shaped MSAs was kept the same, which realizes same modified TM_{01} mode resonance frequency. A broader BW is realized by optimizing the spacing between all the MSAs, as shown in figure 5(b). The simulated BW is 514 MHz (48.5%) whereas the measured BW is 518 MHz (48%). The fabricated prototype of the configuration is shown in figure 5(c). Since the slot and parasitic patch dimensions are equal, an increase in the BW is smaller. However, as half E-shaped MSA are gap-coupled along all the edges of proximity fed RMSA, this configuration has better radiation pattern and gain characteristics as shown in figure 6(a-d).

Figure 8. (a–c) Radiation pattern and (d) gain variation over BW for proximity fed 3×3 half E-shaped MSA array.

Table 1. Comparison of various proximity fed gap-coupled RMSAs and half E-shaped MSAs.

Configuration of proximity fed	Simulated BW(MHz, %)	Measured BW(MHz, %)	Peak gain (dBi)
RMSA	240, 24	238, 23.8	7
Gap-coupled RMSAs	363, 36	358, 36	9.2
RMSAs and half E-shaped MSAs	490, 48.8	502, 45.3	9.5
half E-shaped MSAs	514, 48.5	518, 48	9.8
3×3 half E-shaped MSA Array	532, 51	528, 51	11

To further enhance the gain, additional half E-shaped MSAs are gap-coupled along the diagonal axis in the above gap-coupled configuration, thereby realizing 3×3 array of half E-shaped MSAs as shown in figure 7(a). To avoid the variation in the radiation pattern over the BW, dimensions of half E-shaped MSAs gap-coupled along the diagonal axis were kept the same. By optimizing the spacing, a broader BW as shown in figure 7(b) is obtained. The simulated BW is 532 MHz (51%) whereas the measured BW is 528 MHz (51%). The fabricated prototype of the array is shown in figure 7(c). The radiation pattern and gain over the BW are shown in figure 8(a–d). The pattern is in the broadside direction. The back-lobe radiation is less than 10 dB as compared to the bore sight level. The cross polarization levels increase towards the higher frequencies of the BW since the modified TM_{01} mode in all half E-shaped MSAs is present towards those frequencies. The 3×3 MSA array shows peak gain of nearly 11 dBi.

The results for all the gap-coupled configurations are given in table 1. The increase in BW over different gap-coupled configurations to 3×3 MSA array is nearly by 40 MHz. This is due to the equal dimensions of parasitic half E-shaped MSAs which give closely spaced TM_{10} and modified TM_{01} mode frequencies over proximity fed and gap-coupled MSAs. The higher BW could have been realized for different resonant frequencies (unequal patch dimensions) of respective modes over parasitic MSAs. However, it leads to higher amount of squint in the radiation pattern away from the broadside direction. In gap-coupled half E-shaped MSAs, the cross polarization levels are higher towards higher frequencies of BW. At these frequencies, TM_{01} mode in half E-shaped MSA is dominant which leads to vertical currents inside the patch that increases cross polar component and also affects the polarization purity in bore sight direction. With unequal dimensions of half E-shaped MSAs, the cross polarization levels will be further higher due to different resonance frequencies of TM_{01} modes amongst gap-coupled MSAs. With the antenna characteristics like, BW of more than 500 MHz with broadside radiation pattern and gain of more than 7 dBi, the proposed configurations can find applications in mobile communication environment in 800 to 1200 MHz frequency band.

4. Conclusions

The broadband proximity fed gap-coupled RMSAs are discussed which can give BW of more than 350 MHz. Further to increase the BW, gap-coupled array configurations of half E-shaped MSAs with proximity fed RMSA are proposed. The rectangular slot in half E-shaped MSA reduces the resonance frequency of orthogonal TM_{01} mode in parasitic RMSAs and along with TM_{10} modes of proximity fed and gap-coupled RMSAs, yields BW of around 500 MHz. The slot also modifies the surface current directions at TM_{01} mode and aligns them in the same direction as that of the currents at TM_{10} mode. Thereby it gives broadside radiation pattern over the BW with gain of more than 7 dBi. The gap-coupled configuration of four half E-shaped MSAs yields

better radiation pattern and gain characteristics as against that with two half E-shaped MSAs. Further, 3×3 gap-coupled array configurations of half E-shaped MSAs with proximity fed RMSA is proposed. It gives BW of more than 530 MHz ($> 55\%$) with peak gain of nearly 11 dBi. Due to the presence of modified TM_{01} mode towards higher frequencies of BW, cross polar levels are higher even in bore sight direction. However, they will be of advantage in multi-path propagation environment wherein signal loss due to polarization mismatch can be minimized.

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