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Thinner substrate wideband designs of proximity fed rectangular microstrip antennas for GSM band applications

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Abstract

Proximity feeding is the simplest technique to achieve wideband response in a microstrip antenna on a thicker substrate. However, the bandwidth is limited on a thinner substrate due to the capacitive impedance offered by the feeding strip. This paper presents wideband designs of proximity fed rectangular microstrip antennas loaded with printed open Ring shape or C-shape resonators, while using a thinner substrate. On substrate thickness of $0.053\lambda_g$, the proposed design yields a bandwidth of 214 MHz (23.62%) with a broadside radiation pattern and peak gain of 8.0 dBi. Against the thicker substrate proximity fed design, a reduction of $\sim 0.03\lambda_g$ in thickness is obtained. With the obtained antenna characteristics, the proposed design is useful in 800–1000 MHz, GSM band applications.

Introduction

Microstrip antenna (MSA) finds many applications in wireless systems, attributed to their advantages like low profile, planar design [1]. The MSA bandwidth (BW) is increased by employing a lower dielectric constant thicker substrate [1, 2]. However, probe inductance limits the BW in thicker substrate antennas. In such designs, modified feeding techniques are employed, and among them, proximity feeding is the simplest method [3, 4]. While maintaining the single patch configuration, the MSA BW is increased by employing the resonant slot [5–10]. In coaxially fed wideband slot cut MSAs, substrate thickness greater than $0.06\lambda_c$ is needed, which increases the antenna volume. Here, λ_c refers to the wavelength at the center frequency of the reflection coefficient (S_{11}) BW. For substrate thickness greater than $0.08\lambda_c$, BW in slot cut MSA is increased by employing the proximity feed [11, 12]. The thinner substrate design employing a resonant slot is reported but it requires dual feeds with a differential feeding [10]. A thinner substrate slot cut antennas employing a modified ground plane profile are reported [13, 14]. They yield BW in excess of 25%, on a substrate thickness in the range of $0.04–0.06\lambda_c$. However, these designs have lower peak gain attributed to the increased back-lobe radiation. Thinner substrate modified ground plane designs offering BW in excess of 70% are reported [15–17]. But these configurations employ modifications in the patch and the ground plane, thus leading to a complex design. While using a printed circuit element placed below the E-shape MSA, a wideband design on a thinner substrate is obtained [18]. This design offers 8% BW, but details about the design of the printed element are not discussed.

In this paper, wideband designs of proximity fed rectangular MSA (RMSA) on a thinner substrate, by employing printed Ring shape or C-shape resonators placed below the patch, are proposed. A technique of non-contact proximity feeding has been reported in the literature to enhance the BW in conventional and slot cut patches. But it requires substrate thickness $\geq 0.07\lambda_c$. On a thinner substrate, the capacitive impedance offered by the feeding strip limits the MSA BW. This paper presents a technique that achieves BW improvement on a thinner substrate, while considering the proximity feeding. The initial study in this paper highlights the limitation of the proximity feeding technique to achieve maximum BW, against a reduction in the substrate thickness. To achieve a BW improvement on a thinner substrate, proximity fed RMSA is loaded with either an open-loop printed Ring shape resonator or C-shape resonator. Resonators are present below the patch, thereby not increasing the antenna dimensions. An improvement in the BW is achieved through the coupling between the TM_{10} mode on RMSA and TM_{20r} modes on printed resonators. The proximity fed RMSA designs individually loaded with Ring shape resonator or C-shape resonator elements are discussed. Among all, the design consisting of three C-shape resonators achieves maximum BW. On a total substrate thickness of $0.053\lambda_c$, the antenna offers a simulated BW of 214 MHz (23.62%) with a broadside gain of greater than 6 dBi. Considering the substrate thickness, the results achieved in terms of BW and gain are improved ones against the reported wideband designs offering broadside

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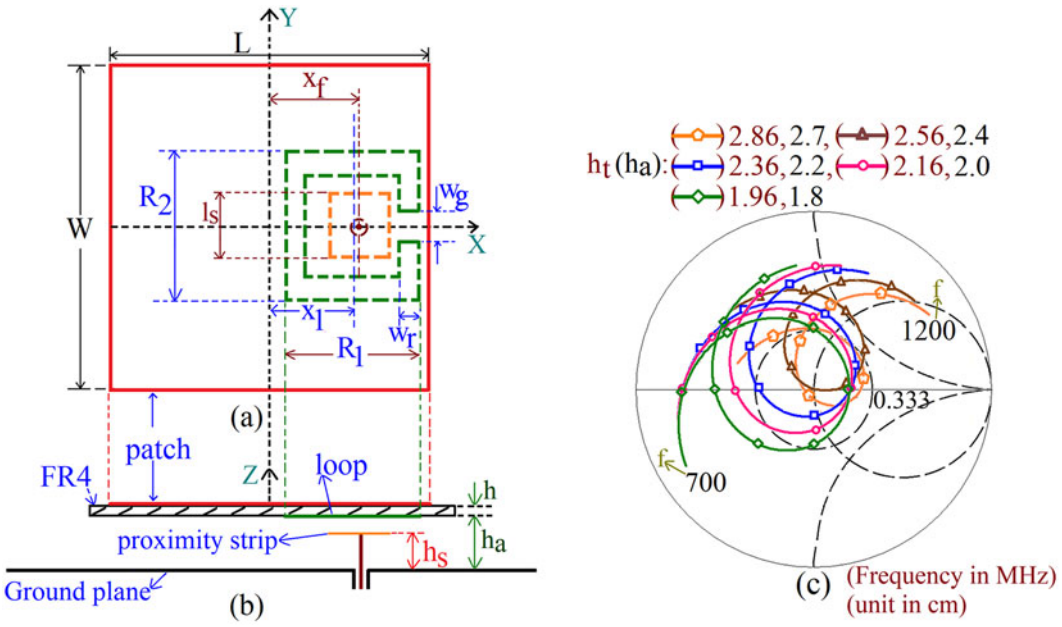


Figure 1. (a, b) Proximity fed RMSA loaded with resonant Ring shape loop, and (c) effect of reducing the substrate thickness on the S_{11} BW in proximity fed RMSA.

radiation characteristics. Also, the proposed work puts forward a technique to increase the BW in proximity fed designs, while employing a thinner substrate. To highlight the novelty aspect, a detailed tabular comparison against the reported MSAs is discussed ahead in the paper. With the obtained antenna characteristics, the proposed wideband design can find applications in the GSM band (800–1000 MHz). The antennas proposed in this paper are initially optimized using CST software [19] followed by an experimental verification. In the reflection coefficient (S_{11}) BW, radiation pattern and broadside gain measurements, ZVH–8, SMB 100A, FSC6 are used. The measurement is carried out inside the Antenna Laboratory in which wideband high-gain Horn antennas were used as the reference antennas. A good agreement is obtained between the simulated and the measured results.

Wideband proximity fed RMSA loaded with printed ring shape resonator

Wideband configuration of proximity fed RMSA loaded with printed open Ring shape resonator is shown in Fig. 1(a, b). Initially, rectangular patch is designed for the TM_{10} mode frequency of 875 MHz, using air-suspended FR4 substrate (h = 0.16 cm, $\varepsilon_r = 4.3$), with an air gap (h_a) of 2.7 cm; thus realizing total substrate thickness of the antenna as 2.86 cm ($0.085\lambda_{g10}$). The λ_{g10} refers to the wavelength at the TM_{10} mode frequency. The RMSA dimensions are calculated as, L = 13 cm and W = 15 cm. RMSA is fed using a square proximity strip of length "l_s" = 2.2 cm, placed at a substrate thickness of "h_s" = 2.5 cm above the ground plane and at a feed position of "x_f" = 3.5 cm from the patch center. In the proximity feed design, electromagnetic coupling arising from the fringing fields of the strip excites the resonant mode on the patch that yields simulated S_{11} BW of 174 MHz (20.2%). The BW obtained is a function of proximity strip parameters, i.e. strip length and its thickness above the ground plane. To assess the effects of air gap and the proximity feed thickness, parametric study for the decrease in the total substrate thickness is carried out and smith chart for the same is provided in Fig. 1(c).

In each variation, the air gap thickness is reduced, and subsequently strip thickness is lowered. In equivalent circuit form, the proximity strip in combination with the probe inductance provides a series combination of inductor and capacitor [1]. Against the decrease in the substrate thickness, probe inductance reduces, thus making the capacitive effect more dominant. With this for smaller h_s, the loop formed does not lie completely inside VSWR = 2 circle, thereby reducing the S_{11} BW. As noted from Fig. 1(c), this effect is prominent for substrate thickness less than $0.07\lambda_{g10}$. In [18], one such technique to increase the BW in thinner substrate antennas using coaxial feed was discussed. But the method presented is complex, as no details about the design of the printed circuit element used to reduce the thickness were elaborated. To enhance the BW on thinner substrate, while using the proximity strip, two techniques are presented in this work, which are simpler in design and implementation. In the first such design, printed Ring shape resonator loop is coupled with the proximity fed RMSA as shown in Fig. 1(a). The printed loop is placed below the rectangular patch, thus not increasing the overall patch size. The RMSA dimensions are maintained the same as specified earlier, while air thickness is chosen as "h_a" = 1.6 cm, making the total substrate thickness of the antenna as 1.76 cm ($0.053\lambda_{g10}$). The RMSA is fed using a square proximity strip of side length "l_s" = 2 cm, which is placed at "h_s" = 1.5 and "x_f" = 3.5 cm. For these substrate parameters, RMSA offers simulated BW of 80 MHz (9%), which is lower than that observed above in thicker substrate design. To analyze the effects of printed Ring shape loop dimension, parametric variations are carried out and resonance curve plots showing the variations in real and imaginary part of input impedance against variation in Ring dimensions "R_1," "R_2," and its position "x_1" for a given width "w_r," are shown in Fig. 2(a–c).

In the resonance curve two modes are observed. To identify the modes, surface current distribution at them was studied, as provided in Fig. 2(d, e). The first mode corresponds to TM_{10} mode. At the second mode, currents exhibit two half wavelength variation along the total Ring shape length. With this variation, resonant mode in Ring shape resonator is referred to as TM_{20r},

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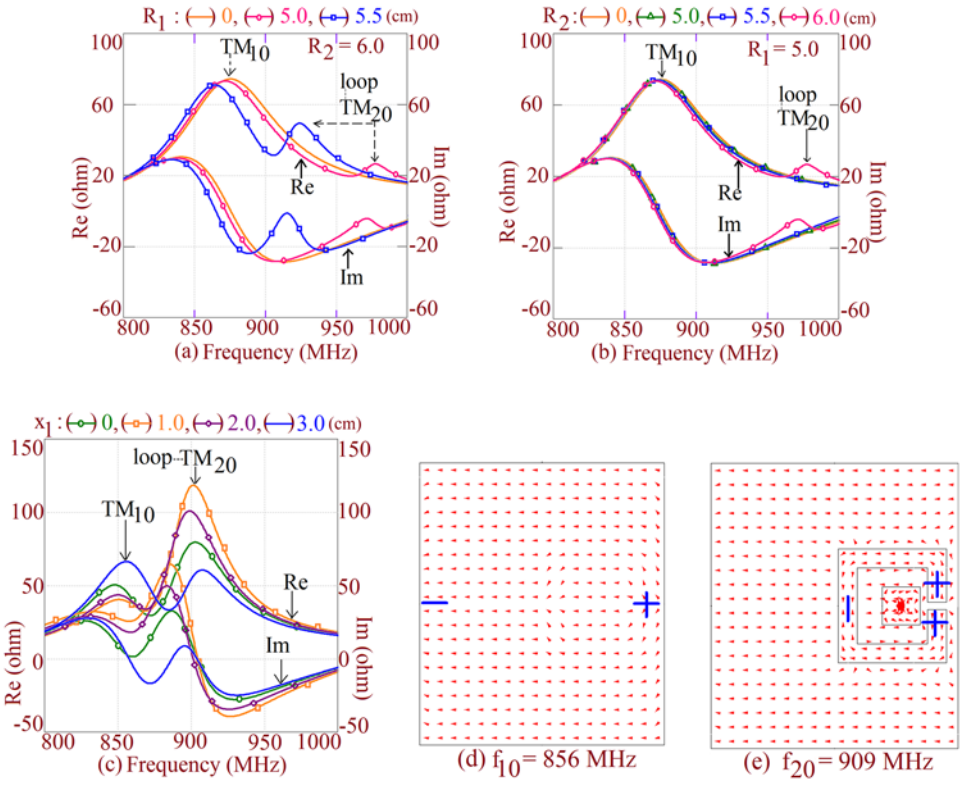


Figure 2. Resonance curve plots for the variation in (a) "R_1," (b) "R_2," (c) "x_1," and (d, e) surface current distributions of proximity fed RMSA loaded with Ring shape resonator.

also represented as "loop TM_{20}" in Fig. 2(a–c). With the variation in lengths R_1, R_2 that constitutes a total Ring shape length, frequency of TM_{20r} mode reduces, and it gets tuned with respect to the TM_{10} mode frequency of the RMSA. For the wideband response, impedance tuning at the two modes is also needed. Here, position of Ring shape resonator (x_1) from the RMSA center optimizes the impedance at two modes to achieve a wideband response. The antenna dimensions in the optimum wideband design are "R_1" = 5.7, "R_2" = 6.0, "w_r" = 1.0, "w_g" = 0.4, and "x_1" = 3.0 cm, and their results are provided in Fig. 3(a). The simulated and measured S_{11} BW is 135 MHz (15.16%) and 137 MHz (15.47%), respectively. Antenna offers broadside radiation pattern across the entire BW as mentioned in Fig. 3(c–h), with cross-polar radiation level less than 15 dB as compared with the co-polar level. The E-plane of radiation is aligned along $\Phi = 0^0$. Antenna gain over the S_{11} BW is more than 6 dBi with a maximum value of 8.1 dBi. With reference to the TM_{10} mode frequency of RMSA, above mentioned BW is obtained for substrate thickness of 1.76 cm, i.e. $0.053\lambda_{g10}$.

For the same substrate thickness, impedance locus plots for proximity fed RMSA and that loaded with a Ring shape resonator loop are provided in Fig. 3(b). For RMSA, loop is not formed inside VSWR = 2 circle. This does not yield maximum BW. But when RMSA is loaded with a Ring shape resonator then an additional loop due to the TM_{20r} mode is formed inside the VSWR = 2 circle that increases the BW by 6%, on a thinner substrate, while using the proximity feed. Fabricated antenna showing RMSA and Ring shape resonator is provided in Fig. 4(a, b).

Wideband proximity fed RMSA loaded with printed C-shape resonators

Design of proximity fed RMSA loaded with C-shape resonators is shown in Fig. 5(a–c). The C-shape resonators are placed below the patch and on the other side of FR4 substrate. Three variations of the design are investigated. First one with single C-shape resonator, followed by two and three resonators, each having different length R_i, where i = 2, 3 & 4. The vertical dimension R_1 and resonator width w_r is same across all the C-shape resonators.

The C-shape resonator is simpler in fabrication against the open Ring shape resonator. Furthermore, in the geometry of C-shape against the Ring shape resonator, surface currents at TM_{20r} mode are larger in contribution along the length, as shown in Fig. 5(d), hence the same is selected. In each design, for h_a = 1.6 cm, by employing parametric variations for the C-shape dimensions, an optimum S_{11} BW is obtained that results in the optimum spacing of TM_{20r} modes with reference to the TM_{10} mode. Results for all the designs are provided in Figs. 6 and 7.

In the optimum design consisting of single C-shape resonator placed below the proximity fed RMSA, resonator dimensions are R_1 = 4.4, R_2 = 8.6, w_r = 1.0, x_1 = 2.45 cm. It offers simulated and measured S_{11} BW of 129 MHz (14.63%) and 131 MHz (14.96%), respectively.

The broadside antenna gain is more than 6 dBi over the complete BW with a maximum value of 8 dBi. A single C-shape resonator offers equivalent BW to that given by Ring shape resonator. The addition of second C-shape resonator adds to another TM_{20r} resonant mode and its optimum spacing with respect to

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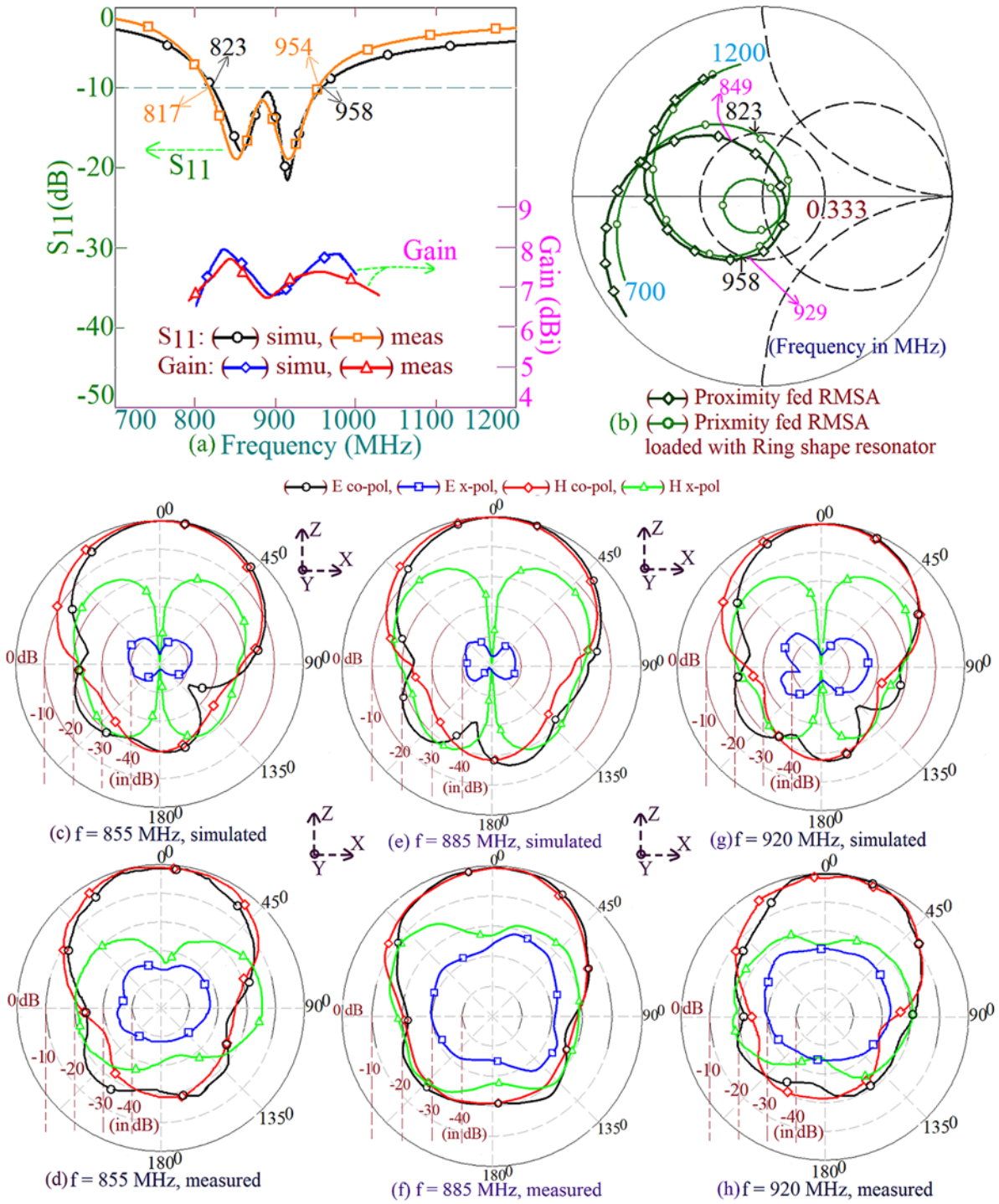


Figure 3. (a) S_{11} BW and gain plots, (b) smith chart for the optimum design, and (c–h) radiation pattern plots over the S_{11} BW for proximity fed RMSA loaded with Ring shape resonator.

RMSA's TM_{10} and C-shape TM_{20r} modes, yields increment in the BW. An optimum response is obtained for $R_1 = 4.4$, $R_2 = 8.6$, $R_3 = 7.2$, $w_r = 1.0$, $y = 3.0$ cm, and corresponding simulated and measured S_{11} BW are 176 MHz (19.47%) and 189 MHz (20.89%), respectively. The antenna offers similar broadside gain characteristics to that offered in single C-shape resonator design. A single and dual C-shape resonator designs offer broadside radiation pattern across the BW with E-plane aligned along $\phi = 0^0$. The cross-polar level remains below 15 dB as compared with the co-polar level of radiation. An increment in the BW is further achieved by employing three C-shape resonators of unequal dimensions. The dimensions (R_i) of the individual resonator are kept different to achieve maximum BW. Here, while employing parametric study in each resonator lengths, optimum BW is obtained. For the three C-shape resonator dimensions as, $R_1 = 4.4$, "R_2" $= 8.6$, $R_3 = 7.2$, $R_4 = 7.9$, $w_r = 1.0$, $y_1 = y_2 = 5.0$ cm, respective simulated and

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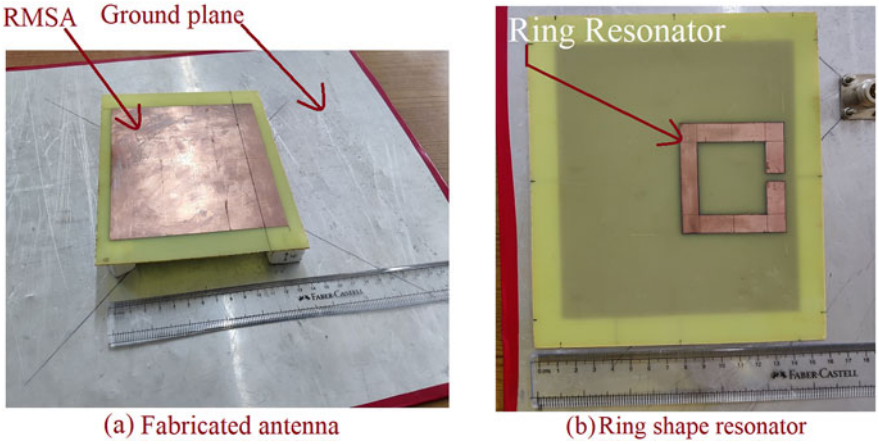


Figure 4. (a, b) Fabricated prototype of proximity fed RMSA loaded with Ring shape resonator.

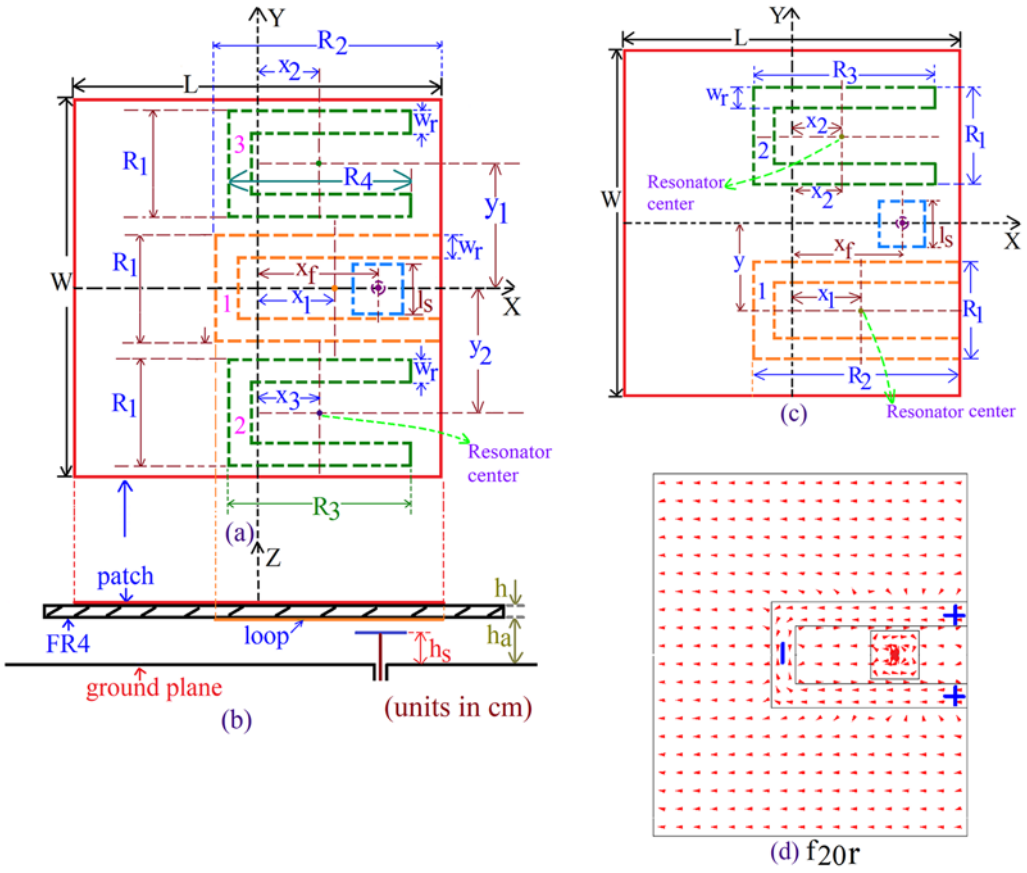


Figure 5. (a, b) Proximity fed RMSA loaded with odd number of C-shape resonators, (c) even number, and (d) surface current distribution at TM_{20r} mode on C-shape resonator.

measured S_{11} BW are 214 MHz (23.62%) and 220 MHz (24.42%). The broadside antenna gain is more than 6 dBi across the S_{11} BW with a maximum value of 8 dBi. The radiation pattern across the BW is in the broadside direction with cross-polar level less than 15 dB as compared with the co-polar level. The E-plane of radiation is aligned along $\Phi = 0^0$. On a total substrate thickness of 1.76 cm ($0.053\lambda_{g10}$), proximity fed RMSA yields simulated BW of 80 MHz (9%). Against these three C-shape resonators loaded proximity fed RMSA on the same substrate thickness offers nearly 15% increment in the S_{11} BW. Due to the capacitive impedance offered by the coupling proximity strip, BW in proximity fed RMSA on thinner substrate is less than 10%. The proximity feeding is the simplest method to enhance the MSA BW. In the literature, a simple technique to increase the BW of patch antenna employing proximity feed on thinner substrate showing broadside radiation characteristics, without using a modified ground plane structure, is not discussed. The proposed work addresses this research gap and presents a novel technique that employs printed resonators placed below the patch. This does not increase the patch size but provides S_{11} BW improvement on a substrate thickness of $\sim 0.05\lambda_c$. This is the new contribution in the proposed wideband MSAs.

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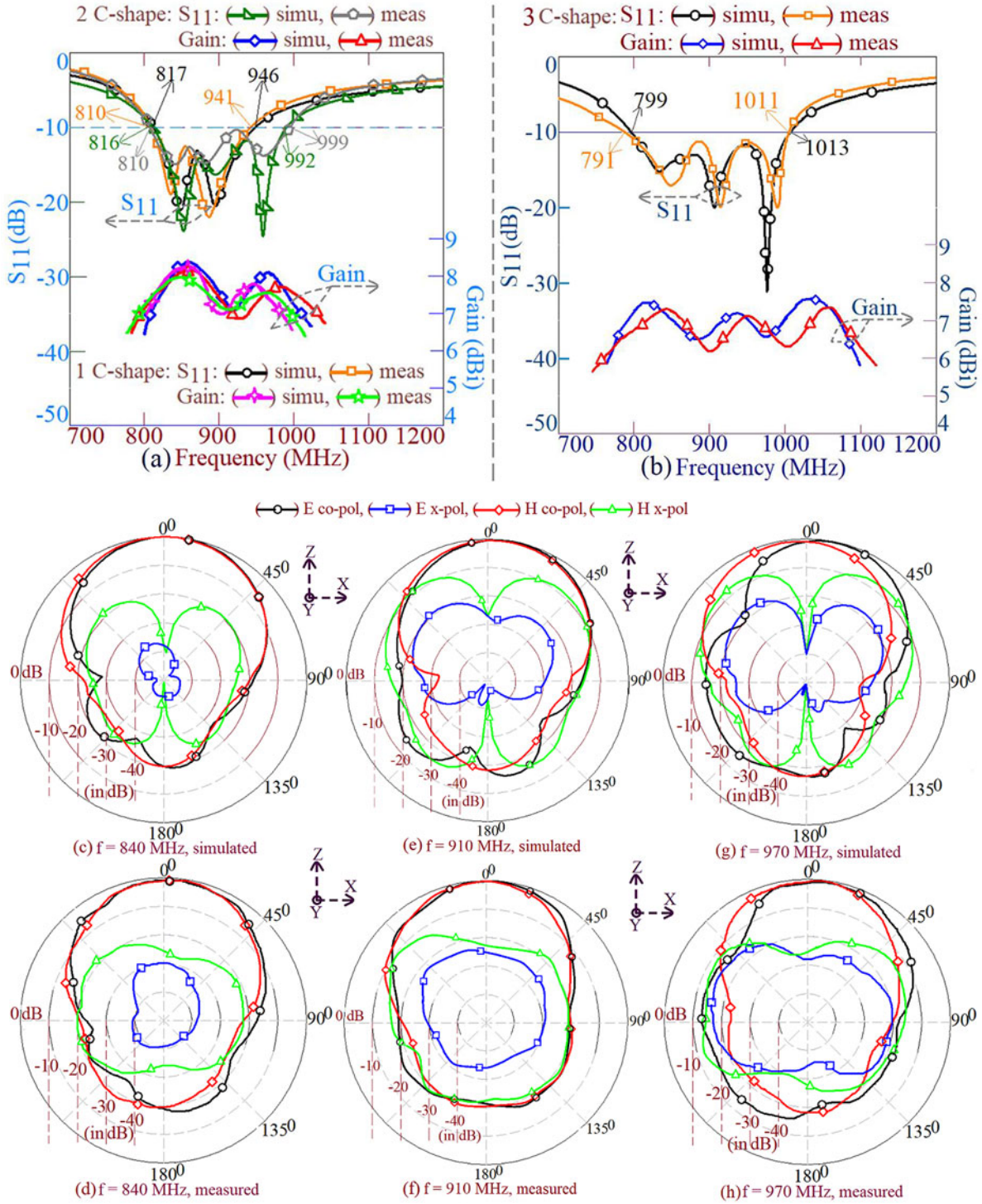


Figure 6. S_{11} BW and gain plots for proximity fed RMSA loaded with (a) one, two, (b) three C-shape resonators, and (c–h) radiation pattern plots over the S_{11} BW for proximity fed RMSA loaded with three C-shape resonators.

The S_{11} BW, broadside gain, and radiation pattern measurement setup are provided in Fig. 7. All these measurements are carried out inside the Antenna laboratory. The cable as seen in the S_{11} BW measurement is a low-loss cable. As the radiation pattern measurement is a relative plot of received power in the orthogonal planes, any amount of cable loss occurring has less effect. In the broadside gain and pattern measurement, reference wideband high-gain Horn antennas were used as the reference antennas. The RF source SMB 100A and spectrum analyzer FSC 6 are used in these measurements. A required minimum far-field distance calculated with reference to the highest frequency of the S_{11} BW is maintained between the reference Horn antenna and Antenna under test (AUT). Thus, for the obtained frequency results, minimum distance of 170 cm is needed. Around the measurement

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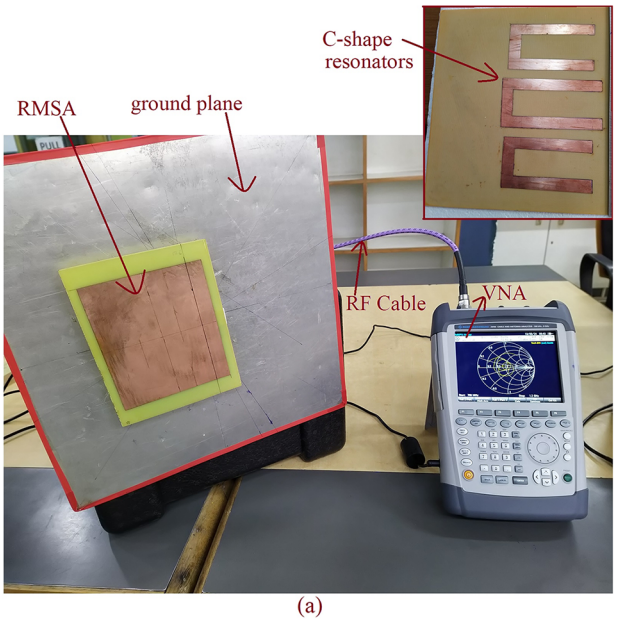




Figure 7. (a) S_{11} BW measurement setup and (b) gain measurement setup for proximity fed RMSA loaded with three C-shape resonators.

desk, minimum amount of metallic objects is present that ensures lower reflection from the surrounding objects. Also, the distance of the surrounding walls/objects is more than seven times the wavelength calculated with respect to lowest frequency of S_{11} BW. This gives path length of at least fourteen times the wavelength for any reflected wave coming from the surrounding objects. Due to this path length, reflected wave has lower effects against the direct wave present between the transmitter and receiver antenna. Broadside gain measurement is carried out using three-antenna method. This method is selected as it provides better accuracy for the measurements inside the laboratory. Also, it minimizes any loss or variations in the measurement due to the improper calibration of gain in the reference Horn antenna, as employed in the relative gain measurement employing single Horn antenna. These setup details provide fairly good measurements inside the antenna laboratory. The simulated radiation efficiency for the proposed designs was observed. Since the air-suspended FR4 substrate is employed, antenna radiation efficiency remains above 70% across the S_{11} BW.

To explain the wideband linear polarized radiation pattern response in proximity fed RMSA loaded with printed C-shape resonators, surface current distribution at the observed resonant modes in the optimum design of RMSA loaded with three C-shape

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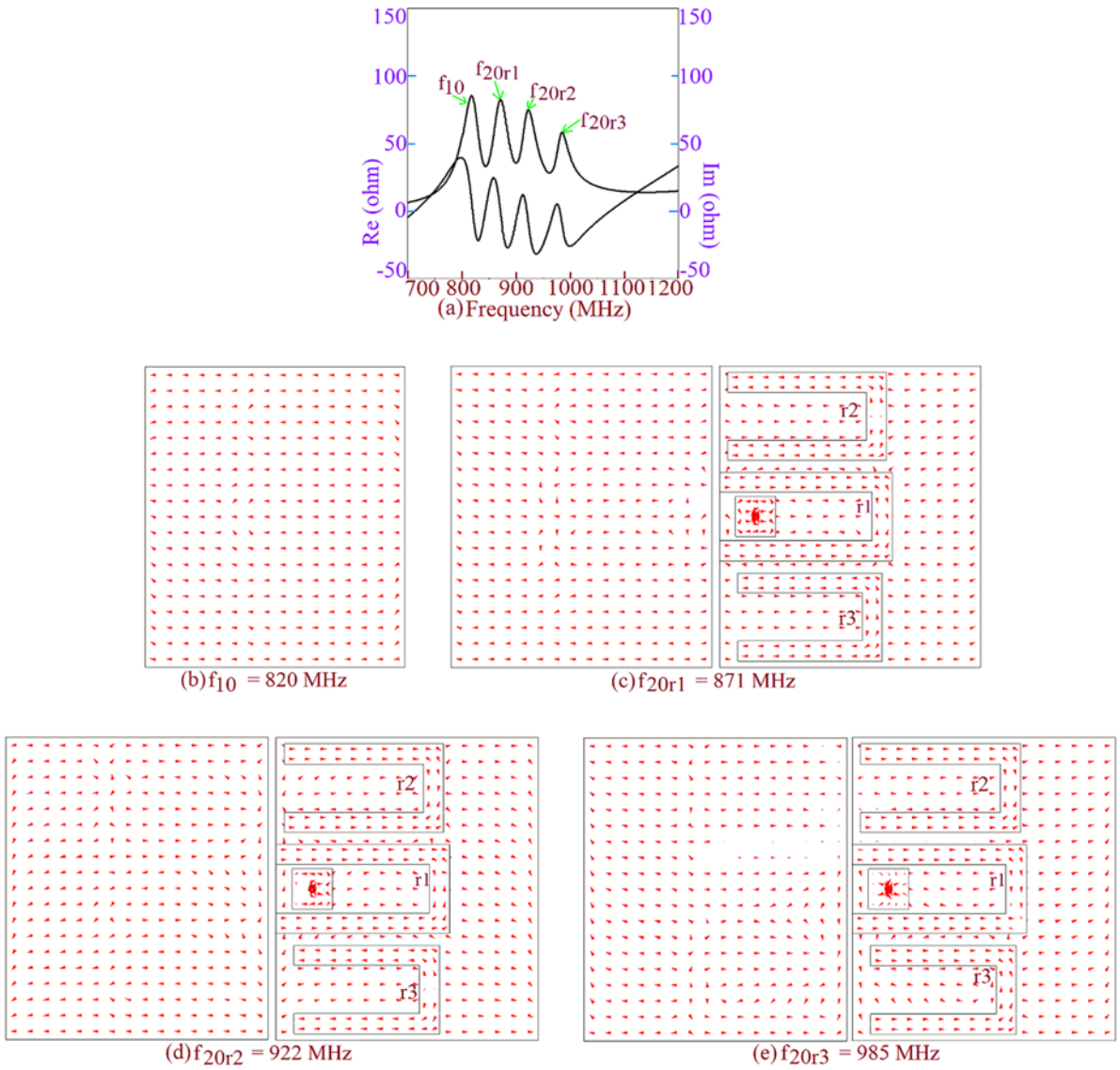


Figure 8. (a) Resonance curve plot and (b–e) surface current distribution at the observed resonant modes for proximity fed RMSA loaded with three C-shape resonators.

resonators is studied, and its resonance curve plot and modal current distributions at the observed resonant peaks are shown in Fig. 8.

The surface current distribution at C-shape resonator mode is shown over the patch as well as over the C-shape resonator, i.e. the back view of the geometry. With three C-shape resonators, four resonant modes are present in the optimum design, i.e. for RMSA TM_{10} mode and TM_{20r} mode in each C-shape resonator. At the resonance condition of TM_{10} mode, surface currents vary along the horizontal direction inside the rectangular patch, whereas at respective C-shape resonator mode, currents are showing two half wavelength variation along the C-shape length. This highlights a linear and horizontal variation of the modal currents over the antenna aperture across the resonant modes, which contribute to the S_{11} BW, and that achieves a broadside radiation pattern over the same. When the respective C-shape resonator mode is dominant then surface current over the rectangular patch is affected. This leads to some contribution of the vertical surface current components over the rectangular patch. These current components are the main source of variation in the broadside gain by around 1–1.5 dBi over the S_{11} BW, as observed in the above gain plots for the optimum designs.

Comparative analysis for the proposed design

To highlight the novelty in the proposed study, a comparative analysis of the proposed optimum design against the reported wideband configurations is presented in this section. Among the proposed designs, RMSA loaded with three C-shape resonators provides maximum S_{11} BW for a smaller substrate thickness. Hence, a comparison of the same against the reported wideband MSAs is tabulated in Table 1 and is discussed below. The comparison is presented for measured S_{11} BW and gain against the antenna thickness and patch area. The substrate thickness (h_t) mentioned in Table 1 is normalized with respect to the wavelength (λ_c), whereas patch area (A_p) is normalized with reference to the square of the wavelength (λ_c^2) at the center frequency of S_{11} BW (f_c). This

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Table 1. Comparison of the proposed optimum wideband design against the reported wideband MSAs

MSA shown in	Measured BW (MHz, %)	Peak gain (dBi)	Patch area (A_p/λ_c^2)	Substrate thickness (h_t/λ_c)
Figure 4(a), three C-shape resonators	220, 24.42	8.0	0.187	0.053
Ref [5]	408, 24.82	7.2	0.205	0.076
Ref [6]	880, 39.82	9.2	0.242	0.08
Ref [7]	3100, 12	6.8	>9	0.144
Ref [8]	620, 26.5	9.9	0.602	0.05
Ref [9]	1110, 29.4	9.9	1.836	0.079
Ref [10]	2040, 68	10	0.336	0.023
Ref [11]	528, 51	11	1.007	0.1035
Ref [12]	520, 44	9.0	0.667	0.7
Ref [13]	240, 26.4	6.1	0.122	0.04
Ref [14]	256, 27.58	6.1	0.14	0.04
Ref [15]	5760, 99	3.66	0.15	0.05
Ref [16]	7700, 110	4.5	0.587	0.06
Ref [17]	1960, 30.1	8.0	0.8	0.054
Ref [18]	80, 9	7	0.165	0.04
Ref [20]	969, 69.84	9	0.34	0.13
Ref [21]	1230, 30.1	12.8	1.418	0.133
Ref [22]	380, 15.6	7.7	>1	0.06
Ref [23]	2255, 38.8	13.0	1.49	0.135
Ref [24]	680, 13.15	10.1	0.163	0.069

normalization helps in comparing different configurations optimized in different frequency bands and substrate thickness, on a common platform.

The original E-shape MSA design reported in [5] offers comparable BW but requires thicker substrate. The multiple slots cut design discussed in [6] offers large BW on thicker substrate. However, it displays variation in the broadside gain by more than 3 dBi across the S_{11} BW. This is attributed to the asymmetric placement of slots with respect to the patch center. The double U-slot cut design discussed in [7] offers lower BW for substrate thickness in excess of $0.1\lambda_c$. The wideband design discussed in [8] offers equivalent value of the BW for the antenna volume but the design consists of modified patch shape, slots, shorting post, and the differential feed. These design features increase the design complexity. Wideband antenna presented in [9] requires large antenna volume. The dual U-slot cut design presented in [10] does offer wider BW on thinner substrate. But it requires differential feeding and dual feeds. The gap-coupled array designs employing proximity feed yield BW of around 50% [11, 12], but it requires large antenna size and thicker substrate. The modified ground plane design offers equivalent BW on thinner substrate but they have lower peak gain; attributed to the increased back-lobe radiation [13, 14]. The modified ground plane designs discussed in [15, 16] offer very large BW or those discussed in [17] provide comparable values of BW and gain against the proposed design. However, in these designs, an explanation about the resonant modes in the structure, which leads to a wider BW is not presented. Also, these designs employ modifications in the patch as well as ground plane thereby increasing the design complexity. Based on a similar technique as discussed in the proposed work, coaxially fed wideband design on thinner substrate is reported in [18] that employs printed circuit element positioned below the patch. This design offers lower BW against the proposed configuration. The proximity fed design discussed in [20] requires higher antenna thickness and employs multiple resonators placed around the fed patch. Against this proposed configuration is single resonator design optimized on a thinner substrate. The configuration discussed [21] employs array of four patches with a differential feeding. It offers higher BW and gain against the proposed design, but requires much higher antenna size. The multi-layer design discussed in [22] employs gap-coupled design involving half U-slot cut rectangular patch fed using the aperture coupled technique. This design requires larger patch size and offers lower BW against the proposed configuration. The antenna discussed in [23] employs fed E-shape patch electromagnetically coupled with four rectangular resonators. This antenna offers higher BW and gain but overall antenna dimensions are very large. The design discussed in [24] employs cavity backed configuration and offers higher broadside gain against the proposed design. Here, selection of cavity-backed design increases the antenna volume.

A gap-coupled multi-resonator technique is the simplest method among all the wideband techniques in MSA, since it just involves the placement of parasitic resonator in the immediate vicinity of the fed patch. Furthermore, proximity feeding is a simpler method to increase the MSA BW on thicker substrate and is widely reported in the literature. However, the proximity feeding has the limitation on thinner substrate due to a higher capacitive impedance offered by the feeding strip. In the reported papers, no techniques are discussed that consider the BW improvement on a thinner substrate while using the non-contact proximity feed. This paper presents a novel technique that provides BW increment

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on substrate thickness of around $0.05\lambda_c$, while using a proximity strip. The proposed method works on a similar concept of multi-resonator gap-coupled design and thus is simpler in implementation and design, against the reported wideband techniques. In comparison to the reported work, the proposed study presents a novel technique using the proximity strip and coupled resonators that provides BW of 24% with a broadside radiation characteristics and a peak gain of 8 dBi, on a substrate thickness of $0.053\lambda_c$. The addition of printed resonators does not increase the patch size and maintains a single patch wideband configuration. Against the reported configurations, the proposed design offers improved results in terms of S_{11} BW, gain, and substrate thickness, considered together. These are all the novelties in the proposed work against the reported configurations.

Conclusions

The proximity feeding is a widely reported and simplest technique to be used to enhance the MSA BW, but on a thicker substrate. But this method has limitations on a thinner substrates due to the higher capacitive impedance offered by the feeding strip. This paper puts forward a technique to increase the BW on thinner substrate, while using the proximity feeding and the rectangular patch. The parasitic Ring shape or C-shape resonators are placed below the patch, and thus they do not increase the antenna size. Among all the proposed configurations, the design employing three C-shape resonators offers the optimum result. It gives S_{11} BW of 24%, peak broadside gain of 8 dBi, but on substrate thickness of $0.053\lambda_c$. With the obtained antenna characteristics, the proposed antenna can find applications in GSM 800–1000 MHz frequency band.

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