

On the Design of Slot Cut Circularly Polarized Circular Microstrip Antennas

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Abstract

Circularly polarized microstrip antenna is frequently realized by cutting the slot inside the patch and feeding it along the diagonal axis. In the reported literature, procedure to design them at any given frequency is not available. In proposed work, circularly polarized slot cut circular microstrip antenna at 900 MHz is discussed. By studying the surface current distributions at two orthogonal modes, formulations in their resonant length are proposed. The frequencies calculated using them closely agree with simulated results. Using proposed formulation, procedure to design circular polarized antennas at different frequencies is presented that gives circular polarized response. Thus, proposed work will be helpful to design similar circular polarized circular microstrip antenna at any desired frequency.

Keywords

Circular Microstrip Antenna, Circular Polarization, Rectangular Slot, Resonant Length Formulation

1. Introduction

The circular polarized (CP) microstrip antenna (MSA) is realized either by cutting narrow slot inside the coaxially fed MSA or by using dual feeds in conjunction with the power divider network, or by cutting asymmetrical U-slot or rectangular slot at an appropriate position inside the patch [1]-[11]. Amongst these techniques, U-slot or rectangular slot cut MSAs yields optimum response in terms of gain and axial ratio (AR) bandwidth (BW) [9]-[11]. However in these reported CP MSAs, formulation in resonant length at orthogonal modes and procedure to design them at any other frequency is not explained. Therefore, optimization process to design CP MSAs involves parametric study on different patch parameters using simulation software, followed by experimental validation. In this paper, first rectangular slot cut circular MSA (CMSA) to give CP response in 900 MHz fre-

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quency range, is discussed. On glass epoxy substrate ($\epsilon_r = 4.3$, $h = 0.16$ cm, $\tan\delta = 0.02$), it gives VSWR and AR BW of 20 and 7 MHz, respectively. To increase its gain, three layer suspended configuration is proposed which gives VSWR and AR BW of 32 and 9 MHz, respectively, with a gain of more than 3 dBi. Further by studying surface current distributions at orthogonal modes, formulation in their resonant length in terms of slot and patch dimensions for non-suspended and suspended MSAs, is proposed. The frequencies calculated using them closely agree with the simulated results. Using proposed formulations, procedure to design slot cut CP CMSA at any other frequency in non-suspended and suspended configuration is presented. It gives CP response with formation of small loop inside VSWR = 2 circle and with the broadside radiation pattern that shows co and cross polarization levels within 3 dB in E and H-planes. Thus, proposed formulations can be used to realize CP response at any desired frequency. All these MSAs were first designed and optimized using IE3D software [12]. For only the optimized and re-designed configurations, experiments were carried out to validate the simulated and proposed design procedure. The MSAs were fed using SMA panel type connector of 0.12 cm inner wire diameter. The impedance measurements were carried out using R & S vector network analyzer (ZVH-8). In simulations, infinite ground plane with infinite extent dielectric was assumed. This helps in realizing the simulation of MSA in reduced time. To realize this effect in measurements, size of substrate is taken to be more than six times the substrate thickness in all the direction with respect to patch periphery. The radiation pattern and the co-polar gain were measured using RF source (SMB 100A) and spectrum network analyzer (FSC6). The measurement was carried out in antenna lab wherein required minimum far field distance was kept between reference antenna and antenna under test.

2. Slot Cut CP CMSA

The rectangular slot cut CMSA is shown in **Figure 1(a)**. The units of the dimensions and frequencies referred in text and in figures are in cm and MHz, respectively. The CMSA radius “ a ” is calculated such that its TM_{11} mode frequency is 900 MHz [1]. To excite orthogonal modes, slot is cut in the patch center and coaxial feed is placed along the diagonal axis. The parametric study is carried out for length “ l ” = 0.6 ($0.02\lambda_0$) and for increasing slot width (w). For two orthogonal modes, their frequencies and ratio plots against respective VSWR and AR BWs at each of slot width (w) are shown in **Figure 1(b)**. The surface current distributions for “ l ” = 0.6 and $w = 1.5$ at two modes is shown in **Figure 2(a)** and **Figure 2(b)**. The slot has degenerated TM_{11} mode into two orthogonal modes. At each mode, one half wavelength variation in surface currents is present along x and y-axis. The reduction in the frequency of first mode (f_1) is higher as slot width is orthogonal to its surface currents. The variation in second mode (f_2) frequency is marginal. Thus “ f_2/f_1 ” ratio increases with increase in “ w ”. The optimum result is obtained for $w = 1.5$ cm to give simulated VSWR and AR BW of 29 and 8 MHz, respectively, as shown in **Figure 2(c)** and **Figure 2(d)**. The measured BW is 32 MHz. For $w > 1.5$ cm, f_2/f_1 ratio increases that do not maintain the required phase quadrature between two modes, which reduces AR BW.

As the slot cut CP CMSA is optimized on lossy substrate, the gain is less than 0 dBi. To improve the same, its three layer suspended configuration is proposed as shown in **Figure 3(a)** and **Figure 3(b)**. The two layers of glass substrate are separated by an air gap of thickness 0.16 cm, thereby giving total substrate thickness of 0.48 cm. The patch is fabricated on top glass epoxy layer whereas SMA connector is connected to the bottom glass epoxy layer which acts as a ground plane. In suspended configuration, effective dielectric constant (ϵ_{re}) reduces, that increases patch radius for $f_{TM_{11}} = 900$ MHz. The ϵ_{re} is calculated by using Equation (1) and further by using Equations (2) and (3), patch radius is calculated [1]. For 900 MHz, radius was found to be 6.5 cm. For suspended

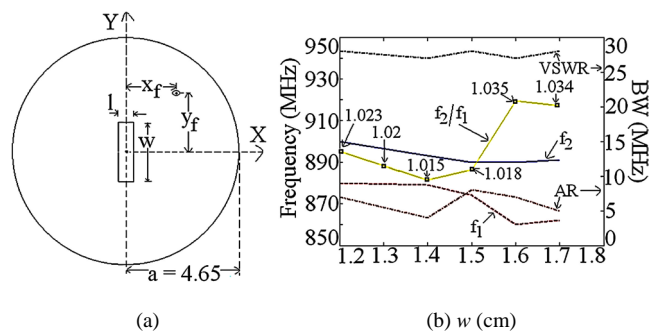


Figure 1. (a) Slot cut CP CMSA; its (b) dual frequency, ratio, AR and VSWR BW plots.

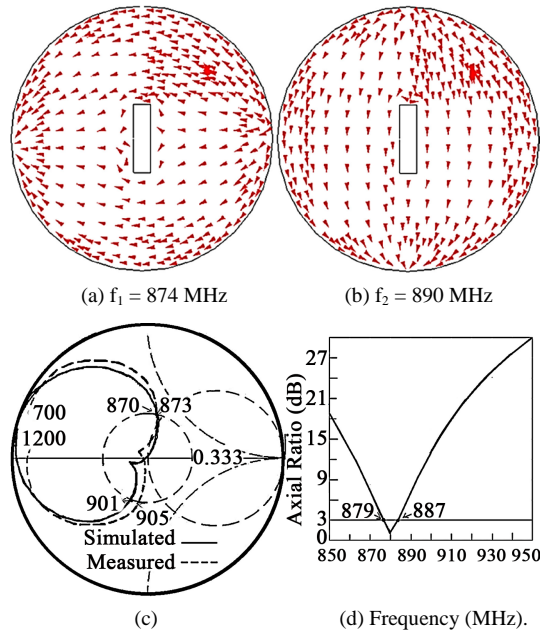


Figure 2. (a), (b) Surface current distribution at orthogonal modes and (c) input impedance and (b) simulated AR plots for slot cut CP CMSA.

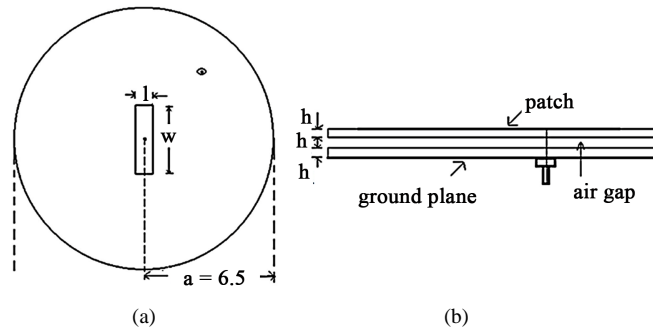


Figure 3. (a) Top and (b) side views of suspended slot cut CMSA.

slot cut CMSA, parametric study for variation in slot width is carried out and plots of orthogonal mode frequencies, their ratio, VSWR and AR BW's, are shown in **Figure 4**.

$$\epsilon_{re} = \frac{3\epsilon_r}{\epsilon_r + 2} \tag{1}$$

$$k = \frac{8.794}{f_r \sqrt{\epsilon_{re}}} \tag{2}$$

$$a = \frac{k}{\sqrt{1 + \frac{2h}{\pi\epsilon_{re}k} \left(\ln\left(\frac{\pi k}{2h}\right) + 1.7726 \right)}} \tag{3}$$

where,

h = glass epoxy substrate and air gap thickness, f_r = resonance frequency in GHz,

k = unit less number, a = patch radius in cm, ϵ_r = substrate dielectric constant, ϵ_{re} = effective dielectric constant.

The optimum AR BW is obtained for $w = 2.8$ and results for the same are shown in **Figure 5(a)** and **Figure 5(b)**. The simulated VSWR and AR BW's are 34 and 10 MHz, respectively. The suspended slot cut CP CMSA

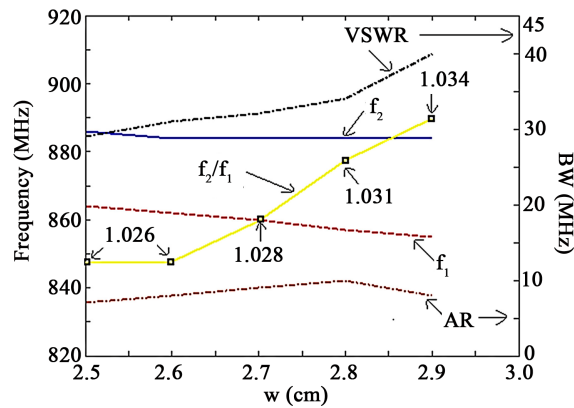


Figure 4. Dual frequencies, their ratio, VSWR and AR BW plots for suspended slot cut CP CMSA.

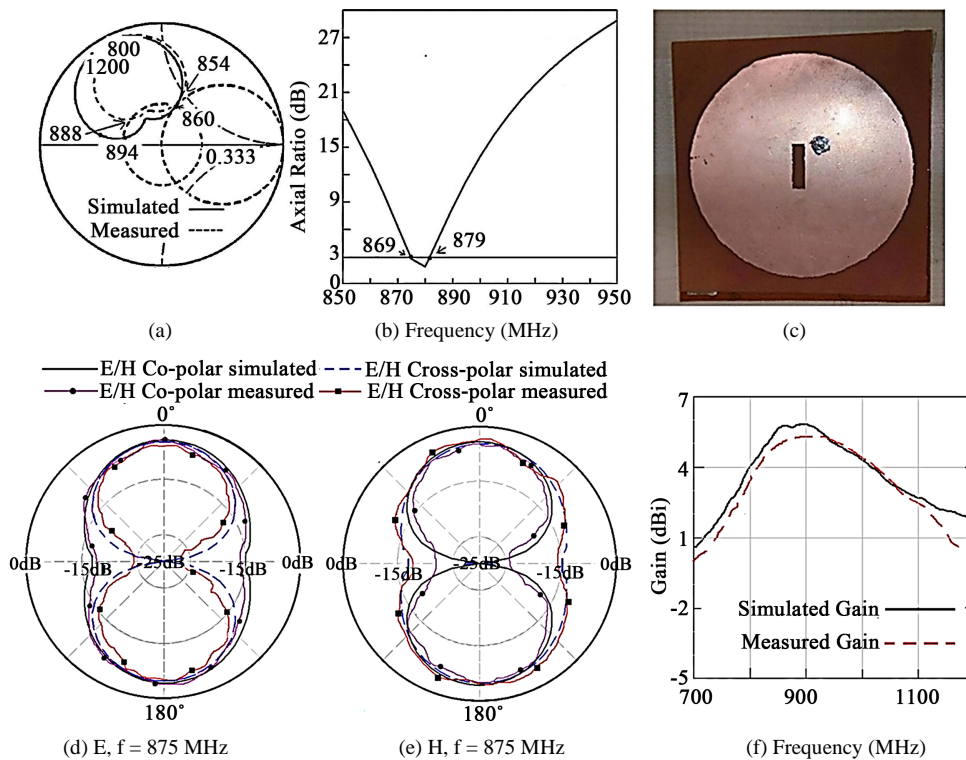


Figure 5. (a) Input impedance and (b) simulated AR plots, (c) fabricated prototype, (d), (e) radiation pattern and (f) gain variation over BW for suspended slot cut CP CMSA.

was fabricated and experiment was carried out. The measured BW is 32 MHz. The fabricated prototype of the configuration is shown in Figure 5(c). The surface current distribution at dual modes in suspended CMSA is similar to that present in non-suspended CMSA. The simulated and measured radiation pattern at center frequency of AR BW and gain variation over VSWR and AR BW's is shown in Figures 5(d)-(f). The co and cross polar levels are within 3 dB in the broadside direction which indicates the presence of CP. Due to use of suspended configuration antenna gain is more than 3 dBi. A good agreement is obtained between simulated and measured results. Although slot cut CP CMSAs discussed above are widely reported but the formulation to design them at any given frequency is not available. Hence most of the available work is based upon the parametric optimization. Here, by studying the surface current distributions, the formulation in resonant length at two orthogonal modes in slot cut CP CMSA is proposed. Further using proposed formulations, procedure to design slot cut CP CMSA at any other frequency is outlined.

3. Formulations for Slot Cut CP CMSAS

In slot cut CMSA, surface currents at two modes are circulating around the slot length. At first mode, they are perturbed in their length due to slot width whereas at second mode, current length is modified due to slot length. The formulation in resonant length on glass epoxy substrate is obtained by modifying patch radius in terms of slot width or length as given in Equations (4) & (5). The frequencies at two modes are calculated by using resonance frequency equation for TM_{11} mode as given in Equations (6) and (7). Using Equation (8), % error between calculated and simulated values is obtained. The frequencies and % error plots are shown in **Figure 6(a)**. At both the modes, closer agreement is obtained between simulated and calculated values. The formulation in resonant length for suspended CMSA as shown in **Figure 3(a)** and **Figure 3(b)**, is obtained by modifying patch radius in terms of slot dimensions as given in Equations (9) and (10). The frequencies and % error are calculated by using Equations (6)-(8) and they are plotted in **Figure 6(b)**. Over the entire range of slot dimension, closer agreement between simulated and calculated values is obtained.

$$a_{e1} = a + \frac{w}{4} \tag{4}$$

$$a_{e2} = a + \frac{l}{4} \tag{5}$$

$$f_{r1} = \frac{1.84118c}{2a_{e1}\pi\sqrt{\epsilon_r}} \tag{6}$$

$$f_{r2} = \frac{1.84118c}{2a_{e2}\pi\sqrt{\epsilon_r}} \tag{7}$$

$$E = \left(\frac{f_{s1} - f_{r1}}{f_{s1}} \right) \times 100 \tag{8}$$

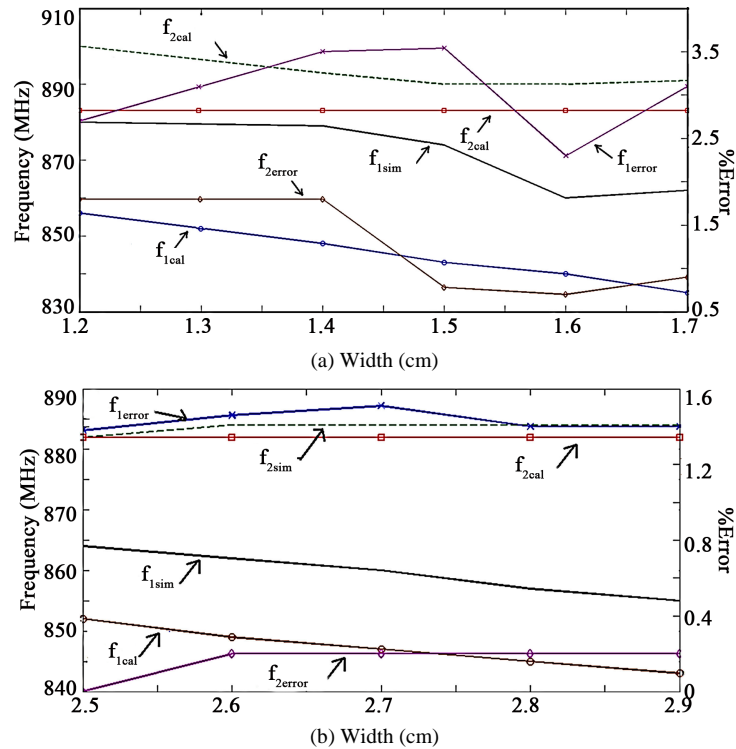


Figure 6. Dual frequency and % error plots for (a) non-suspended and (b) suspended slot cut CP CMSAs.

$$a_{e1} = a + \frac{w}{6} \quad (9)$$

$$a_{e2} = a + \frac{l}{6} \quad (10)$$

The substrate thickness at 900 MHz for non-suspended and suspended configuration is $0.005\lambda_0$ and $0.014\lambda_0$, respectively. Since difference in substrate thickness in two configurations is not larger, their resonant length formulations are nearly identical. As seen from **Figure 6(a)** and **Figure 6(b)**, calculated frequencies show 2% to 3% error with respect to simulated frequencies. As seen from **Figure 1(b)** and **Figure 4**, in optimized slot cut CP CMSAs, simulated f_2/f_1 ratio is 1.02 and 1.03 for non-suspended and suspended MSAs, respectively. The plots of simulated and calculated dual frequencies and their ratios are shown in **Figure 7(a)** and **Figure 7(b)**. For the optimized slot width, calculated f_2/f_1 ratio nearly equals 1.05 and 1.045 in non-suspended and suspended CMSAs, respectively. Using the proposed formulations, procedure to design slot cut CP CMSAs at different frequencies is presented below.

4. Design Procedure for Slot Cut CP CMSAS

In slot cut CP CMSAs at 900 MHz, slot length (l) is $0.02\lambda_0$ whereas feed point is placed along the diagonal axis, *i.e.* at $x_f = y_f = 0.06\lambda_0$. Using proposed formulations, design of slot cut CP CMSA is presented for equivalent patch TM_{11} mode frequency of 700, 1500, 2000 and 3000 MHz, on glass epoxy substrate. The patch radius is calculated by using equations (2) and (3) and at respective frequencies it is found to be, 6.0, 2.8, 2.05 and 1.33 cm. The plots of orthogonal mode frequencies and their ratio are generated by using proposed formulations for $l = 0.02\lambda_0$ and increasing slot width, and they are shown in **Figures 8(a)-(d)**. From these plots, value of slot width that gives f_2/f_1 of approximately 1.05, is selected. At 700, 1500, 2000 and 3000 MHz, slot width is found to be 2.0, 1.0, 0.7 and 0.6 cm, respectively.

At respective frequencies, slot of selected width and $0.02\lambda_0$ in length is cut in the patch center with feed is placed at $x_f = y_f = 0.06\lambda_0$, along the diagonal axis. The slot cut CMSAs are simulated and their input impedance plots are shown in **Figure 9(a)** and **Figure 9(b)** and **Figure 10(a)** and **Figure 10(b)**.

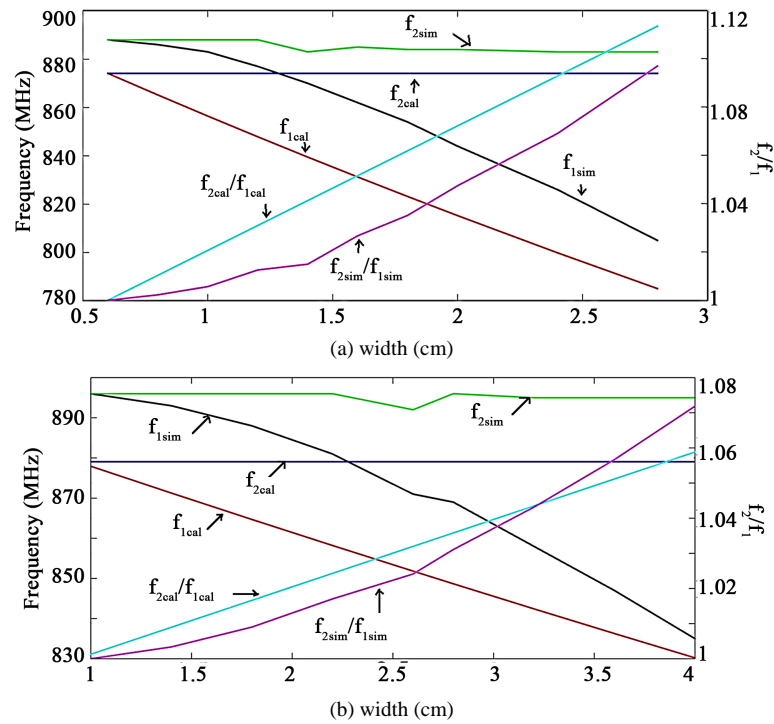


Figure 7. Simulated and calculated dual frequencies and ratio plots for (a) non-suspended and (b) suspended CP CMSAs.

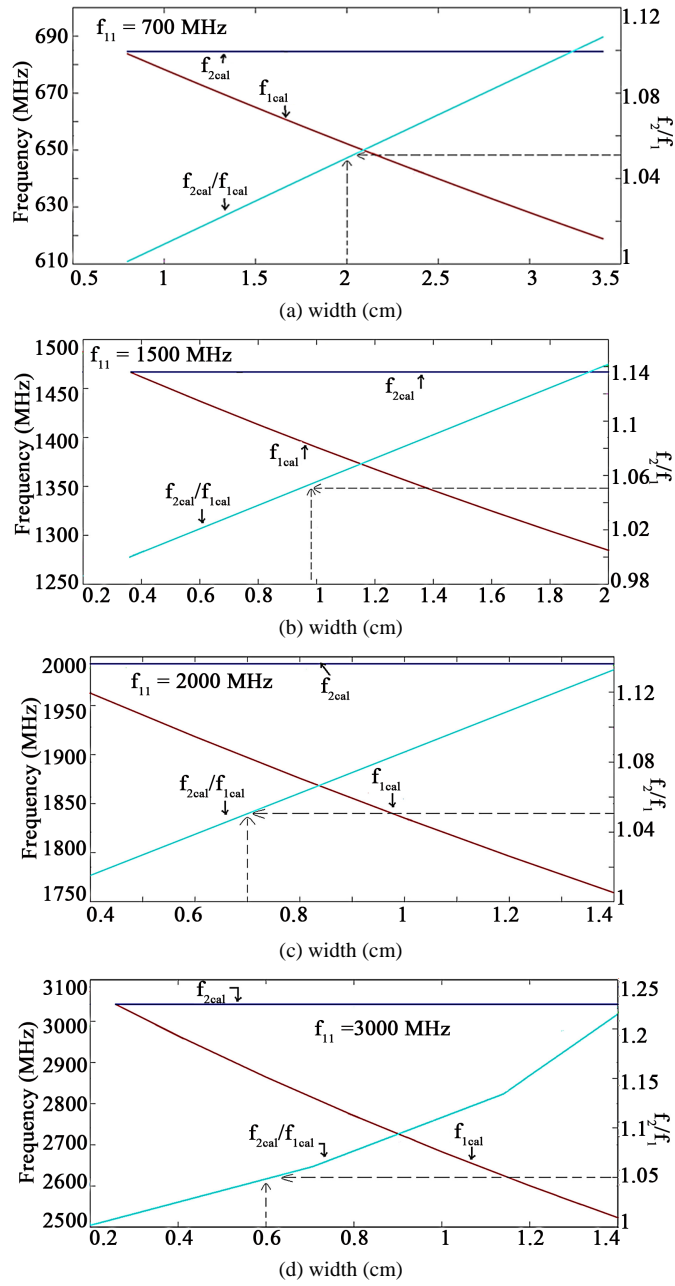


Figure 8. (a)-(d) Dual frequencies and their ratio plots for slot cut CMSA at different frequencies.

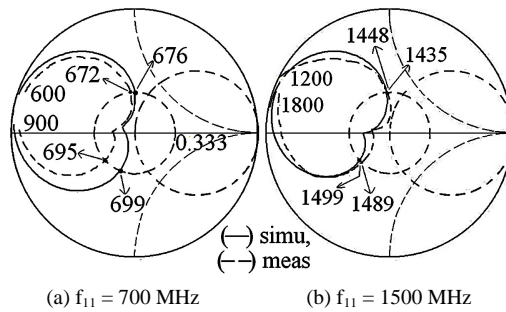


Figure 9. Input impedance plots at (a) 700 and (b) 1500 MHz for slot cut CP CMSA.

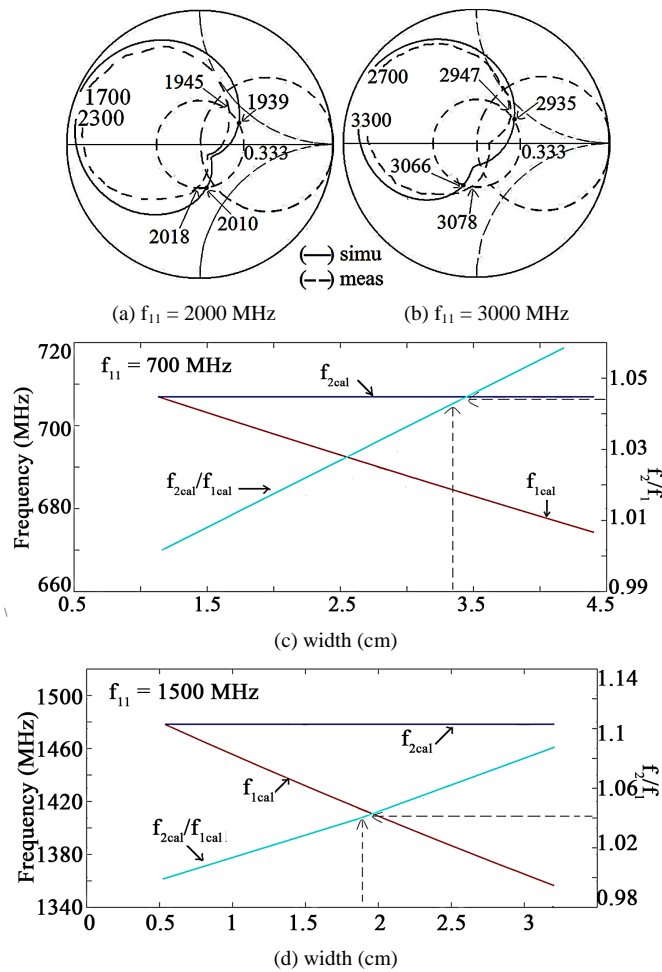


Figure 10. (a), (b) Input impedance plots at two frequencies for slot cut CP CMSA and (c), (d) calculated dual frequencies and ratio plots for suspended slot cut CP CMSAs.

At all the frequencies CP response with formation of small loop (kink) inside $VSWR = 2$ circle is obtained. The simulated VSWR and AR BW at 700 and 1500 MHz are, 23 and 6 MHz and 54 and 13 MHz, respectively. The simulated VSWR and AR BW's at 2000 and 3000 MHz are, 71 and 18 MHz and 131 and 26 MHz, respectively. The simulated VSWR and AR BW's at 2000 and 3000 MHz are, 71 and 18 MHz and 131 and 26 MHz, respectively. The measured BW at 700, 1500, 2000 and 3000 MHz are, 23, 51, 73 and 131 MHz, respectively. At each of the frequencies, simulated and measured radiation pattern, in the broadside direction shows co and cross polarization levels within 3 dB, which indicates the presence of CP. Further suspended slot cut CP CMSAs are designed. To realize impedance matching for coaxially fed suspended MSAs, at each of the frequencies, the effective substrate thickness is selected to be $\leq 0.03\lambda_0$. Thus at 700, 1500 and 2500 MHz, three layer suspended configuration with an air gap of 0.16 cm between two glass epoxy layer is selected. At 3000 MHz, two layer suspended configuration in which glass epoxy layer suspended above the ground plane is used. The patch radius is calculated by using Equations (1)-(3) and it is found to be, 8.3, 3.6, 2.6 and 1.9 cm at 700, 1500, 2000 and 3000 MHz, respectively. Using proposed formulations for suspended CP CMSAs, plots of orthogonal frequencies and their ratio are generated for $l = 0.02\lambda_0$ and increasing slot width. At each of the frequencies they are shown in **Figure 10(c)** and **Figure 10(d)** and **Figure 11(a)** and **Figure 11(b)**.

The value of slot width that gives f_2/f_1 of nearly 1.045 is selected as shown in their respective plots. At 700, 1500, 2000 and 3000 MHz, slot width was found to be, 3.4, 1.8, 1.6 and 1.1 cm, respectively. The slot of $0.02\lambda_0$ in length (l) and selected slot width is cut inside suspended CMSAs. The simulated and measured input impedance plots for slot cut CMSAs are shown in **Figures 12(a)-(d)**. At all the frequencies, small loop is observed inside $VSWR = 2$ circle in the smith chart. The simulated VSWR and AR BW at 700 and 1500 MHz are, 21 and 8

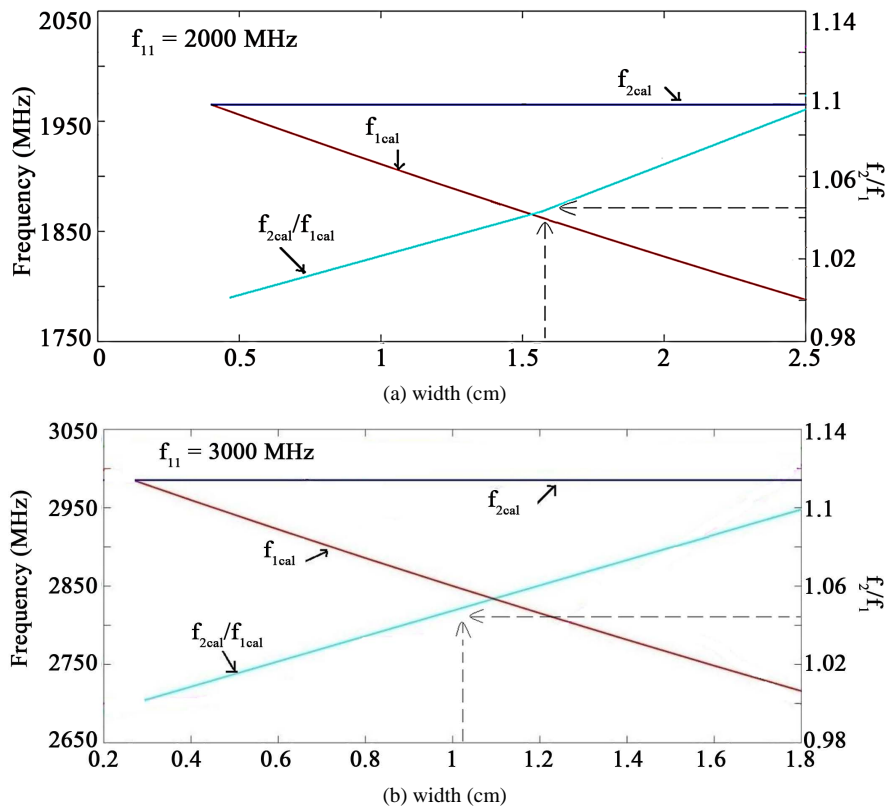


Figure 11. (a), (b) Calculated dual frequencies and their ratio plots for suspended slot cut CP CMSAs at different TM₁₁ mode frequencies.

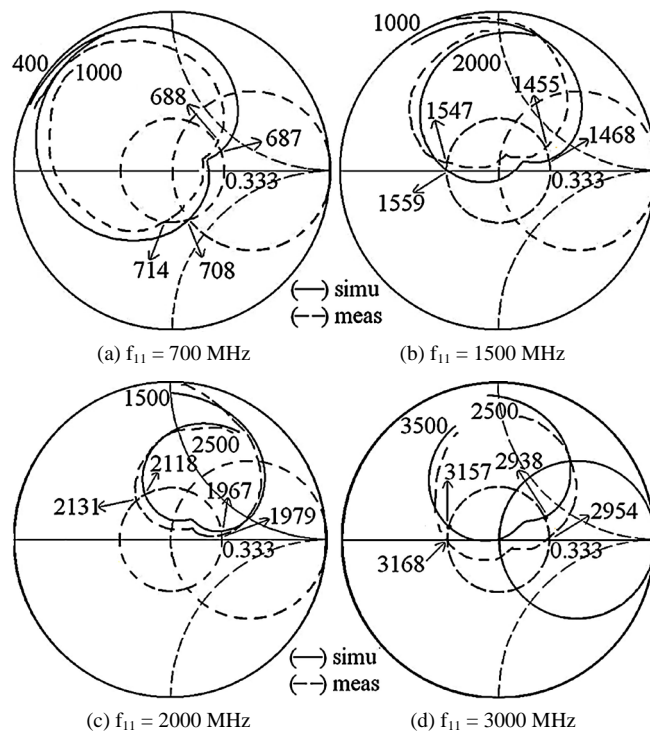


Figure 12. (a)-(d) Input impedance plots for suspended slot cut CP CMSAs at different TM₁₁ mode frequencies.

MHz and 91 and 17 MHz, respectively. The simulated VSWR and AR BW's at 2000 and 3000 MHz are, 151 and 18 MHz and 219 and 26 MHz, respectively. The measured BW at 700, 1500, 2000 and 3000 MHz are, 26, 92, 152 and 214 MHz, respectively. The simulated and measured pattern plots at center frequency of AR BW for suspended CP CMSAs at 1500 and 3000 MHz is shown in **Figures 13 (a)-(d)**. The pattern shows co and cross levels within 3 dB, which indicates the presence of CP. For $f_{TM_{11}} = 900$ MHz, using the proposed formulations slot cut CP CMSA is also designed on RT-duroid substrate ($\epsilon_r = 2.33$, $h = 0.16$ cm, $\tan\delta = 0.001$). The patch radius for non-suspended and suspended configurations was calculated to be 6.5 and 7.5 cm, respectively. Using proposed formulations, plots for dual frequencies and their ratio are generated as shown in **Figure 14(a)** and **Figure 14(b)**. For frequency ratio of 1.05 and 1.045 for non-suspended and suspended CMSAs, slot width was found to be 1.5 and 2.4 cm, respectively. The slot of $0.02\lambda_0$ in length and selected slot width is cut inside the circular patch. The simulated and measured input impedance plots are shown in **Figure 15(a)** and **Figure 15(b)**.

For non-suspended CMSA, simulated VSWR and AR BWs are, 13 and 5 MHz, respectively. The measured BW is 12 MHz. For suspended CMSAs simulated values are, 26 and 4 MHz, respectively whereas measured BW is 24 MHz. The pattern shows difference between co and cross polarization levels to be less than 3 dB in the broadside direction. Thus proposed work will be useful for designing slot cut CP CMSAs at any desired frequency and on different substrates.

5. Conclusion

The design of narrow slot cut CP CMSA at 900 MHz is discussed. The slot degenerates patch TM_{11} mode into two orthogonal modes, to realize CP response. To improve the gain, three layer suspended design of slot cut CP CMSA is also proposed which gives gain of more than 3 dBi. In the reported literature on slot cut CP CMSAs, design guidelines to realize similar CP antennas at any given frequency are not available. Therefore by studying the surface current distributions at two orthogonal modes, formulation in resonant length in terms of slot and patch dimensions for non-suspended and suspended configurations, is proposed. The frequencies calculated using them closely agree with the simulated results. Further using proposed formulations, procedure to design similar slot cut CP CMSAs at different frequencies and on different substrates, is presented. At respective frequencies, it gives CP response with formation of small loop inside VSWR = 2 circle. Thus, proposed formulation

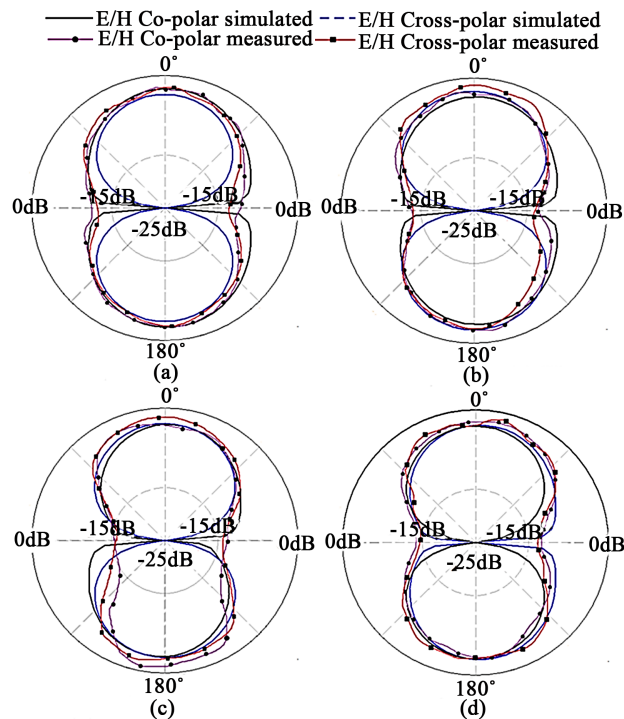


Figure 13. Radiation pattern at center frequency of AR BW at ((a), (b)) 1500 and ((c), (d)) 3000 MHz for suspended slot cut CP CMSAs. (a) (b) E, $f = 1500$ MHz, (c) (d) E, $f = 3000$ MHz.

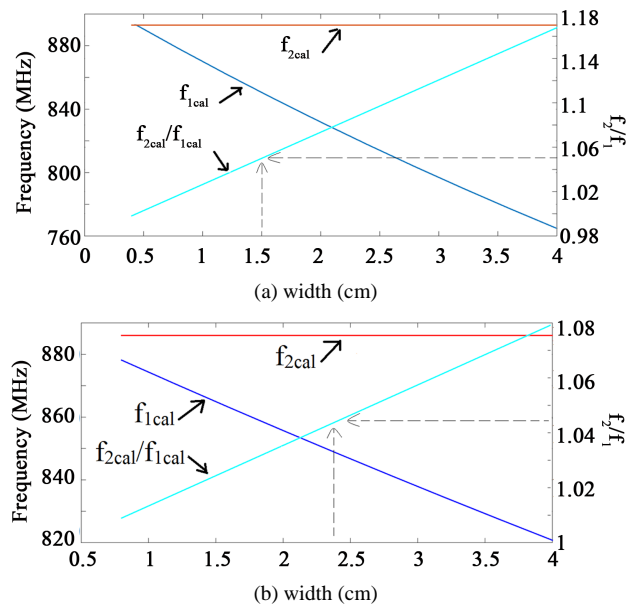


Figure 14. Dual frequencies and their ratio plots for (a) non-suspended and (b) suspended CMSAs on RT-duroid substrate for $f_{TM11} = 900$ MHz.

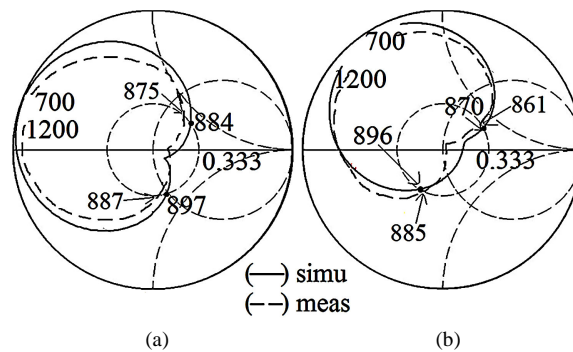


Figure 15. Input impedance plots for (a) non-suspended and (b) suspended CMSAs on RT-duroid substrate for $f_{TM11} = 900$ MHz.

and design procedure will be helpful for designing similar slot cut CP patch antennas. The proposed work can also provide some guideline to realize similar design procedure for other slot cut variations of CMSAs, rectangular MSA, equilateral triangular MSA and other modified patch shapes.

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