Design and Analysis of Rectangular Microstrip Patch Antenna Operating at TM_{03} mode with Single and Stacked Structure for Bandwidth Enhancement

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Abstract

The goal of this paper is to enhance the bandwidth of a Rectangular Patch Microstrip Antenna, RPMA, operating at higher order mode, TM_{03} mode, using three techniques: thick substrate, capacitive-feeding and stacked patches techniques. The constant of substrate, for all designs, is 9.8 with loss tangent 0.001, Alumina substrate. Four RPMA's operating at TM_{03} mode are designed: a conventional RPMA with two thicknesses, thin and thick substrate thickness, a capacitively-fed RPMA, and stacked capacitively-fed RPMA. The composite effect of integrating the three techniques is appeared in stacked capacitively-fed RPMA design. This design offer a wide bandwidth reach 65% with maximum gain 8.78dB. The performance of these designs(VSWR, the far field radiation pattern, and the current distribution) has been analyzed with the aid of Microwave Office software (MW-Office 2006,Version 7).

Keywords: Microstrip patch antenna, Bandwidth enhancement, Gain, Radiation pattern

I. Introduction

Micro strip Patch Antennas (MPA's) are increasing in popularity for use in wireless applications due to their low-profile structure. Therefore they are extremely compatible for embedded antennas in handheld wireless devices such as cellular phones, pagers etc... The telemetry and communication antennas on missiles need to be thin and conformal and are often microstrip patch antenna's (MPA's). Another area where they have been used successfully is in Satellite communication. Some of their principal advantages are:low cost, light weight, low fabrication cost, and low profile planar configuration. However, they suffer from the very narrow bandwidth, typically about 5% bandwidth with respect to the center frequency. This poses a design challenge for the microstrip antenna designer to meet the broadband techniques [1, 2, and 3].

There are numerous and well-known methods to increase the bandwidth of antennas, including increase of the substrate thickness, the use of a high dielectric substrate, the use of various impedance matching and feeding techniques, the use of multiple resonators [4], and the use of slot antenna geometry [4,5].

Design and analysis of rectangular patch micro strip antenna, RPMA, operating at TM_{03} mode are studied in [6]. This analysis include the calculation of radiation pattern theoretically by using cavity model and comparing it with that produced by using MW-office simulation program. The effect of dielectric constant and aspect ratio on the pattern, and also the effect of feed position on input impedance are studied.

From the analysis published in [6], see Figure 5and 6, one can see that the MPA operating at TM_{03} mode with ε_r=9.8 and aspect ratio W/L=2 has the advantages of rather high gain and no side lobes will appear at E_θ and E_φ components (h=0.16cm, f=2.15GHz).But the disadvantages of TM_{03} mode is low impedance bandwidth. Therefore enhancing the bandwidth is studied in this research. All the proposed antennas are simulated with Microwave Office (MWO) software

II. Single RPMA Cavity Model

Cavity model is used to analyze single RPMA. The parameters for the design of RPMA are:

- **Frequency of Operation**:

The wave number k inside a dielectric material is simply related to the wavelength according to [7]

$$k = \frac{2\pi}{\lambda_d} \qquad \dots (1)$$

Where λ_d is the wavelength inside the dielectric material and its related to the wavelength in free space by the following equation:

$$\lambda_d = \frac{\lambda_o}{\sqrt{\varepsilon_r}} \qquad \dots (2)$$

Where, ε_r is the dielectric constant of the substrate.The wave number for any n,m mode is

$$k_{mn} = \sqrt{\left(\frac{m\pi}{W}\right)^2 + \left(\frac{n\pi}{L}\right)^2} \qquad \dots (3)$$

where m, n= 0, 1, 2…,k_{mn}= wave number at m, n mode, W=width of the microstrip patch antenna, and L=length of the microstrip patch antenna

Then in terms of frequency and speed of light and using equations (2) and (3), equation (1) can be written as follows

$$f_{mn} = \frac{k_{mn}c}{2\pi\sqrt{\varepsilon_r}} \qquad \dots (4)$$

Where f_{mn} is the resonance frequency of m, n order mode c=speed of light. It's clear that the resonance frequency depends on the patch size and the filling dielectric constant so for TM_{03} mode k=3π/L then the initial value of the non-radiating edge, L, using equation (4) is

$$L = \frac{3c}{2f_{03}\sqrt{\varepsilon_r}} \qquad \dots (5)$$

The radiating edge W, patch width, is usually chosen such that it lies within the range L<W<2L, for efficient radiation. The ratio W/L=2 is chosen for all proposed designs.

In practice the fringing effect causes the effective distance between the radiating edges of the patch to be slightly greater than L therefore the dimensions of the patch along its length have been extended on each end by a distance *ΔL*, which is given empirically by[7]

$$\Delta L = 0.412h\frac{(\varepsilon_{eff}+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon_{eff}-0.258)\left(\frac{W}{h}+0.813\right)} \qquad \dots (6)$$

where

ΔL=line extension

h=dielectric substrate thickness

ε_{eff}=effective dielectric constant , and it is given by

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(\frac{1}{\sqrt{1+10h/W}}\right) \qquad \dots (7)$$

For a given resonance frequency f_r, and for TM_{03} mode the effective length is given as:

$$L_{eff} = \frac{3c}{2f_r\sqrt{\varepsilon_{eff}}} \qquad \dots (8)$$

The actual length of the patch is given by :

$$L = L_{eff} - 2\Delta L \qquad \dots (9)$$

- **Bandwidth(BW)**

The bandwidth of an antenna refers to the range of frequencies over which the antenna can operate correctly. The antenna's bandwidth is the number of Hz for which the antenna will exhibit an SWR (Standing Wave Ratio) less than 2:1. The bandwidth of the antenna depends on the patch shape, resonant frequency, dielectric constant and the thickness of the substrate. The bandwidth can also be described in terms of percentage of the center frequency of the band [8].

$$BW = \frac{F_H-F_L}{F_c}x100\% \qquad \dots (10)$$

Where F_H,F_L, and F_C are the highest, lowest, and center frequencies respectively for which VSWR≤2

- **Gain**

The gain of the antenna is the quantity which describes the performance of the antenna or the capability to concentrate energy through a direction to give a better picture of the radiation performance. This is expressed in dB, in a simple way we can say that this refers to the direction of the maximum radiation. An approximate relationship between the gain and the half power beam width of both principal planes is expressed as [9]

$$G = 10log\frac{A}{HPBW_E^O HPBW_H^O} \qquad \dots (11)$$

Where A is a unit less constant .A popular values for A used by many antenna engineers are 30,000, 26,000, and 35,000

$HPBW_E^o$ = half-power beam width in one E-plane

$HPBW_H^o$ = half-power beam width in H-plane at a right angle to the other

III. Design of TM_{03} RPMA and Bandwidth Enhancement

1. Design of Thin Substrate RPMA

A thin single rectangular patch microstrip antenna ,RPMA operating at TM_{03} mode at resonance frequency 2.15GHz is designed using equations (1-9). The radiating patch has dimensions (L x W) and is printed on a dielectric substrate of thickness h and relative permittivity ε_r. In this study, Alumina substrate (ε_r=9.8, loss tangent tanδ=0.001) is used. The patch dimensions are(6.63x13.37)cm^2.The thickness of the substrate, h= 0.16cm (≈0.035λ_d) which is considered thin substrate). The radiating patch is excited by coaxial feed probe at proper feed location (x_f=5.85cm,y_f=1.65cm). The dimensions of the ground plane are(26.52x53.47)cm^2. Figure (1) shows the geometric parameters for this design.

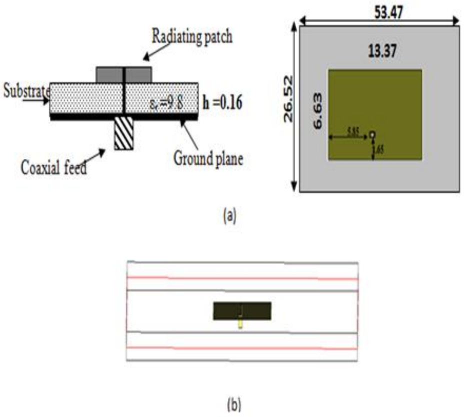


Figure 1: Thin substrate RPMA (a) side and Top view of geometric parameters(b) three dimension view of antenna configuration using MWO software (all dimensions in cm)

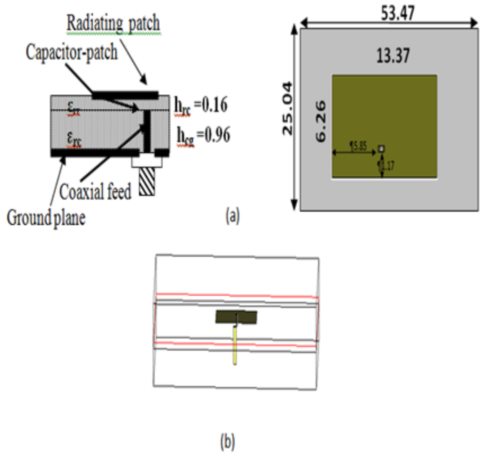


Figure 2: Capacitively-fed RPMA (a) side and Top view of geometric parameters (b) three dimension view of antenna configuration using MWO software. (all dimensions in cm)

2.Bandwidth Enhancement Techniques

The methods for increasing the BW of MPA's are continuously getting upgraded. There are various techniques for increasing the bandwidth of MPA's. In this research three techniques are used; thick substrate, capacitive-feed, and stacked configuration techniques. All designs are constructed with the same dielectric substrate material, Alumina with ε_r=9.8.The MPA's designed by applying these bandwidth enhancement techniques are discussed separately as follows:

2.1 Thick Substrate RPMA

The first bandwidth enhancement technique is that by increasing the thickness of thin substrate RPMA. This design consists of a rectangular patch with dimensions (6.26x13.37)cm^2, calculated using equations(1-9) ,printed on dielectric substrate with ε_r= 9.8 of thickness h=0.96cm (0.2λ_d). This value of thickness is the best one which is reached after many simulation trails. The patch is fed with direct coaxial feed probe at proper feed location (x_f=5.85cm,y_f=1.56cm).

2.2 Capacitively-Fed RPMA

In order to increase the bandwidth further a second technique is examined. This is done by replacing the direct feed technique of the pervious design in section 2.1 by a capacitive feed technique, as shown in Figure (2). In this design the RPMA consists of a radiating patch, a ground plane, and a small patch (capacitor patch) located between the ground plane and radiating patch.

The capacitor patch is fed by a coaxial feed probe. The radiating patch (6.26x13.37)cm^2 is printed on a substrate of ε_{rr}=9.8 with thickness h_{rc}(the spacing between the Radiating and the capacitor patches)=0.16cm. A small rectangular capacitor patch with dimensions 0.83cm x 0.39cm (the same dimensions of the coaxial probe feed) is printed on a substrate of ε_{rc}=9.8 with thickness h_{cg}(the spacing between the capacitor patch and the ground plane)=0.96cm. The radiating patch is fed by electromagnetic coupling from the capacitor patch. The feed position of coaxial feed probe with respect to the radiating patch is(x_f=5.85cm,y_f=1.17cm). The optimum geometric parameters gives the best result is achieved after many simulation trails.

2.3 Stacked Capacitively-Fed RPMA

Here we try to enhance the bandwidth more by using a third technique, multilayer configuration, add to the pervious design in section 2.2. The geometry of the proposed capacitively-fed stacked RPMA is shown in Figure (3). Its consist of a radiating patch on top of a feeding patch on top of a small capacitor patch on top of a ground plane with dielectric layers between; the radiating and the feeding patches, ε_{rr} ,between the feeding and the capacitor patches, ε_{rf} ,and between the capacitor patch and the ground plane, ε_{rc}. All these dielectric layers are of the same substrate material ε_{rr}=ε_{rf}=ε_{rc} =9.8, with their thicknesses named by h_{rf}, h_{fc}, and h_{cg} respectively. Their values are 0.16, 0.16, 0.96cm respectively. The capacitor-patch was fed by a coaxial feed probe at feed position (with respect to the feeding patch) (x_f=5.8cm,y_f=1.68cm). The dimensions of both the radiating (W_rxL_r) and the feeding (W_fxL_f) patches have the same values(6.68x13.39)cm^2. Two coupling are presented here, the first between the radiating and the feeding patches and the second between the feeding patch and the capacitor patch, therefore the bandwidth has been improved. A small variation in patch dimensions is done to get the maximum matching using the MWO software.

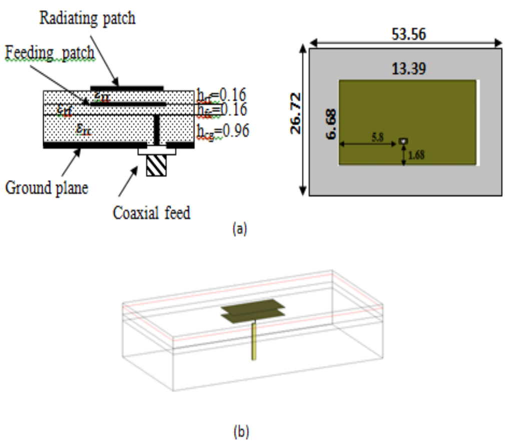


Figure3: Stacked capacitively –fed RPMA: (a) side and Top view of geometric parameters (b)Three dimension view of antenna configuration using MWO software. (all dimensions in cm)

IV. Result and Analysis of Microstrip Patch Antenna's

The proposed antennas have been designed and simulated using MW-Office 2006, Version 7 software. Each proposed antenna is discussed as follows:

1. Thin Substrate RPMA

A conventional thin substrate RPMA operating at TM_{03} mode was first designed as a reference. The frequency band produced is 9MHz centered at f=2.15GHz .The percentage impedance bandwidth is 0.4% calculated using equation (10), which is considered very low value. Figure (4-a,b,c) shows VSWR, Smith chart, and gain for the design, respectively. Since a microstrip patch antenna radiates normal to its patch surface, the elevation for E_θ at ϕ= 90° (H-plane) and E_ϕ at ϕ= 0° (E-plane) would be important. Figure (5-a,b) shows the radiation pattern at f=2.15. The gain produced at resonance frequency, f=2.15GHz, at 0dB, is 10.7 dB, as shown in Figure (5-a) .Normalized value of the radiation pattern for both principal planes gives the half-power beamwidth (HPBW) value. Figure (5-b) gives the HPBW's at -3dB for both principal planes at f=2.15GHz . It can be noticed that in the H-plane E_θ component and in the E-plane E_φ have symmetrical shapes with respect to the zenith ($\theta=0^o$).Current and electric field distributions at f=2.15GHz are shown in Figure. (6).

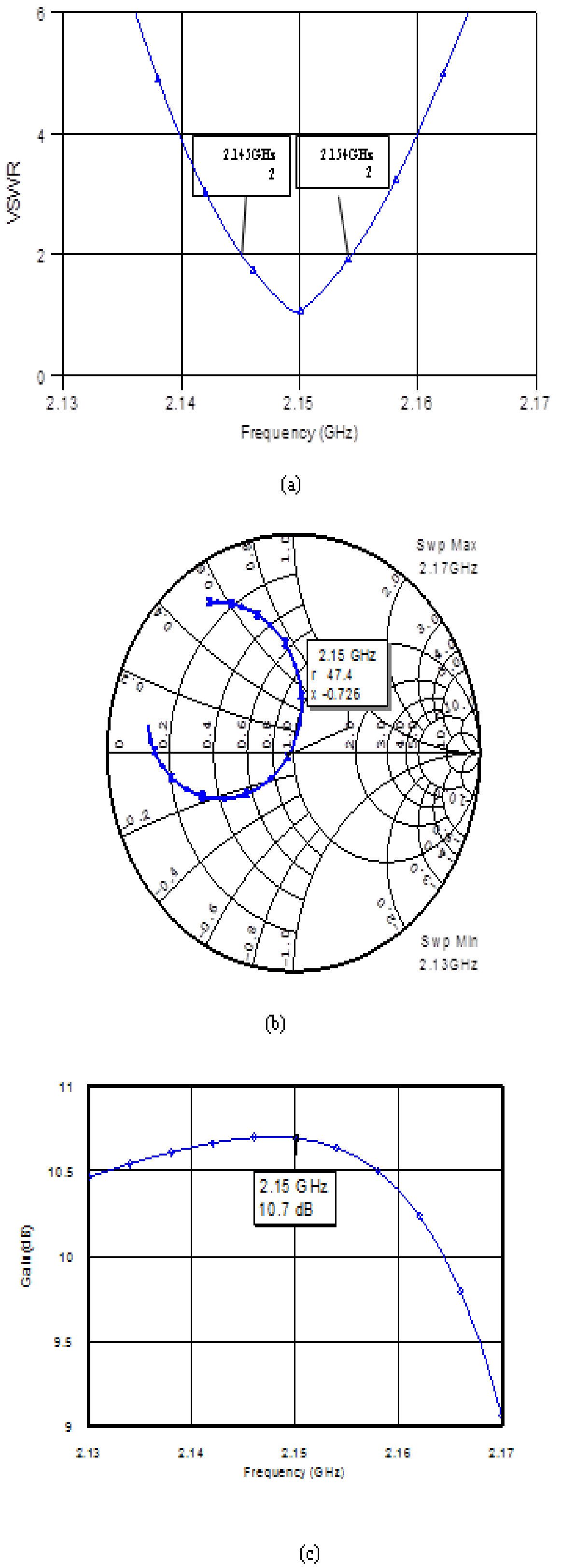


Figure4: The characteristics of a thin substrate RPMA(a) VSWR curve, (b) Smith chart, (c) gain curve

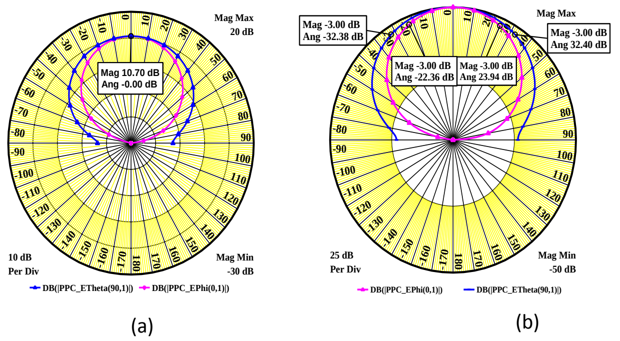


Figure 5: (a) Maximum radiation at 0dB and (b) HPBW at -3dB for both principal planes at f=2.15 GHz for thin substrate RPMA

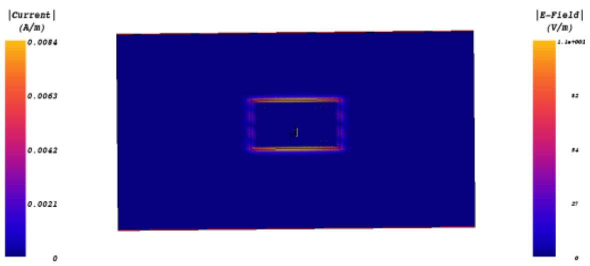


Figure 6: Current and Electric field distributions at f=2.15GHz for a thin substrate RPMA.

2. Thick Substrate RPMA

By applying thick substrate technique to the above design shown in section 1 ,the impedance bandwidth is improved. This is clearly shown in Figure (7-a). The bandwidth is nearly 12%. Impedance matching is shown in Figure (7-b). Maximum gain produce from this design are 8.89dB at 1.98GHz and 6.56dB at 2.12GHz as shown in Figure (7-c).

Figure (8) shows radiation pattern and HPBW for both E and H-planes at these values of frequencies. Figure (9) shows the current and electric field distributions at these two values of frequencies.

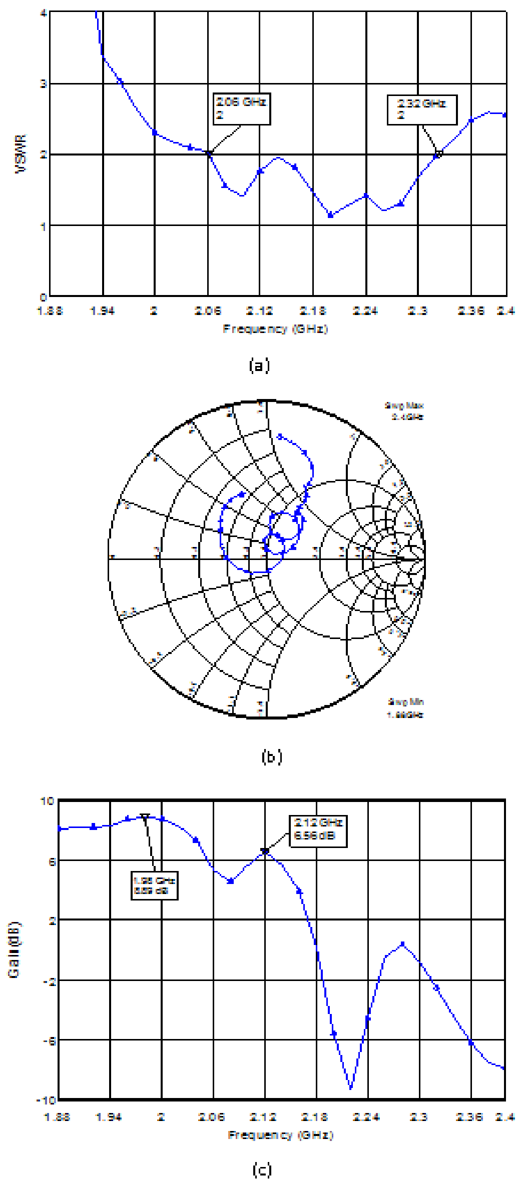
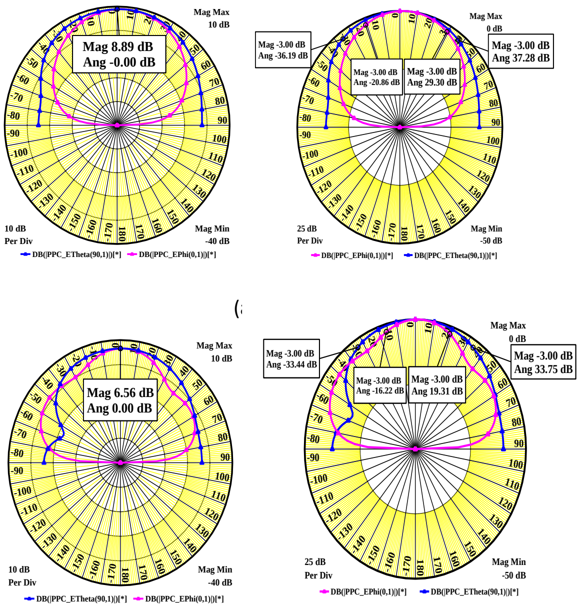


Figure7: The characteristics of a thick substrate RPMA (a) VSWR curve (b) Smith chart , and (c) gain curve



(b)

Figure8: Maximum radiation at 0dB(to the left) and HPBW(to the right) at -3dB for thick substrate RPMA for both principal planes at frequencies, f,: (a)1.98 and (b) 2.12GHz.

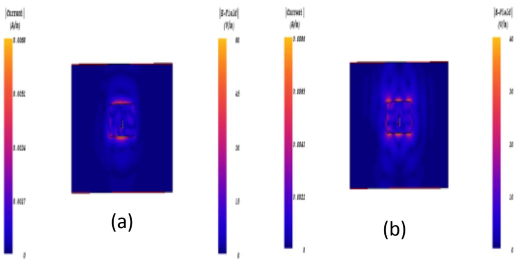
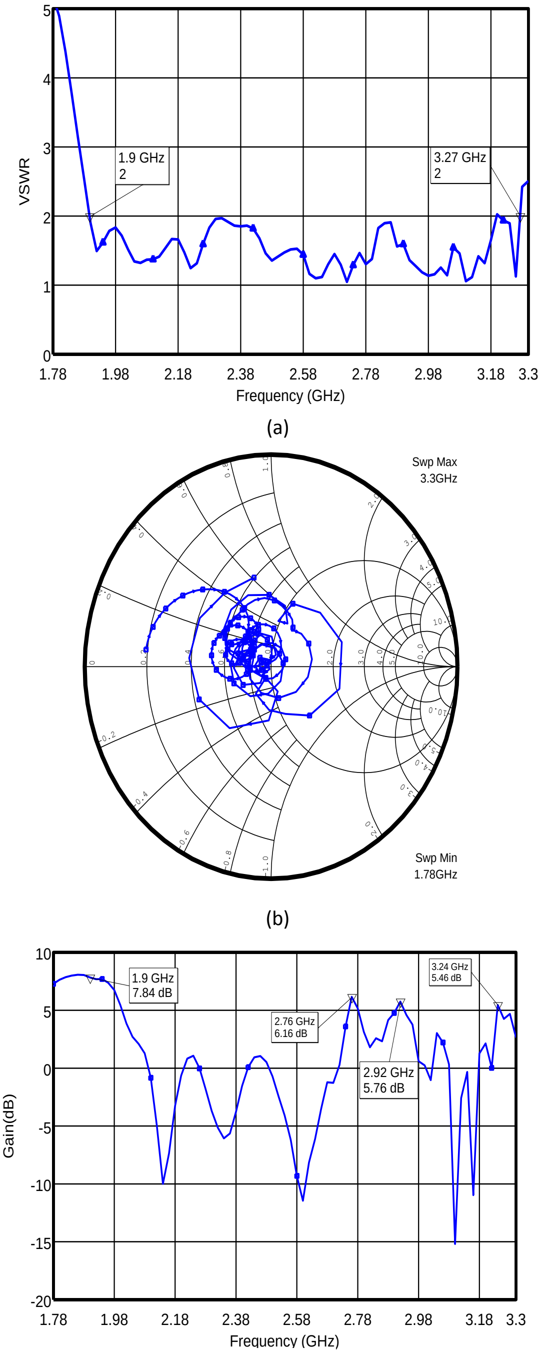


Figure9: Current and electric field distributions for thick substrate RPMA for frequencies: (a) 1.98,(b)2.12GHz

3. Capacitively-Sed RPMA

To enhance the bandwidth more, the direct feed for thick substrate RPMA is replaced by indirect capacitive feed technique. A very good result is achieved here. The impedance bandwidth can reach 53%as shown in Figure (10-a).

Figure (10-b) shows a good impedance matching. Maximum gain produce from this design is located at different values of frequencies within the band of impedance matching as shown in Figure (10-c). Figure (10) shows the characteristics of a capacitively-fed RPMA. Figure (11) shows the Maximum radiation at 0dB, HPBW at -3dB, for different values of frequencies, where the gain is maximum, and Figure (12) shows the current and electric field distributions at these values of frequencies.



(c)

Figure10: The characteristics of a capacitively-fed RPMA (a) VSWR curve (b) Smith chart and (c) gain curve.

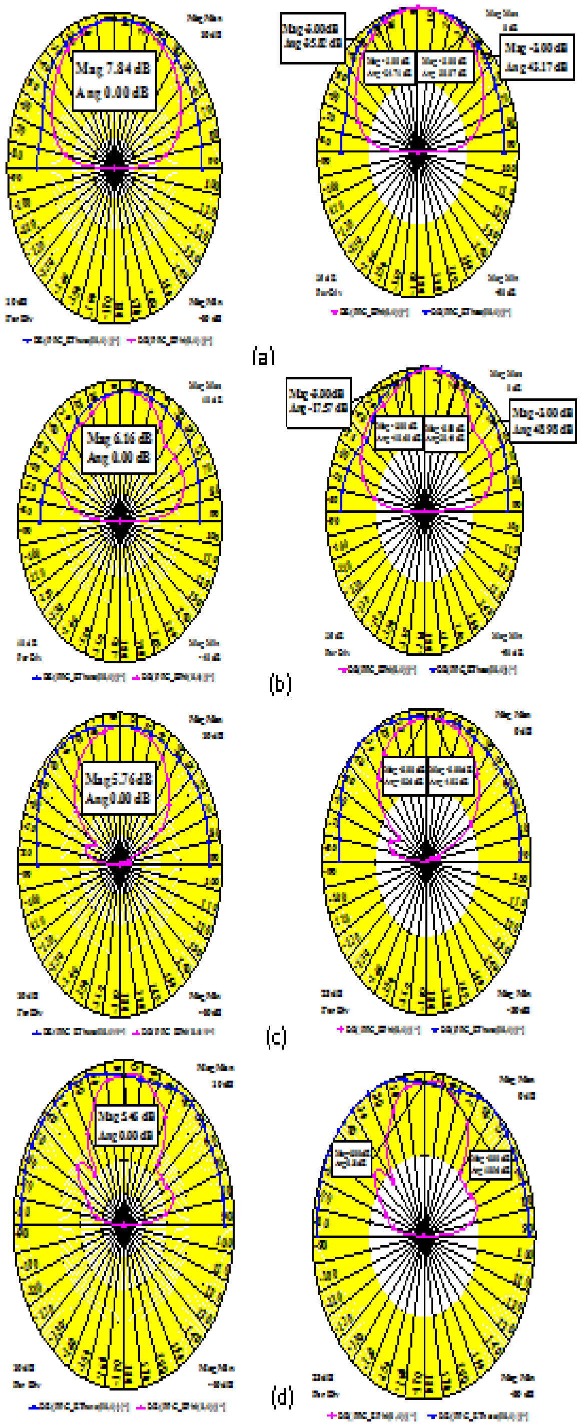


Figure11: Maximum radiation at 0dB(to the left) and HPBW at -3dB (to the right) for capacitively-fed RPMA for both principal planes at frequencies ,f,: (a)1.9, (b) 2.76,(c) 2.92,and (d) 3.24GHz.

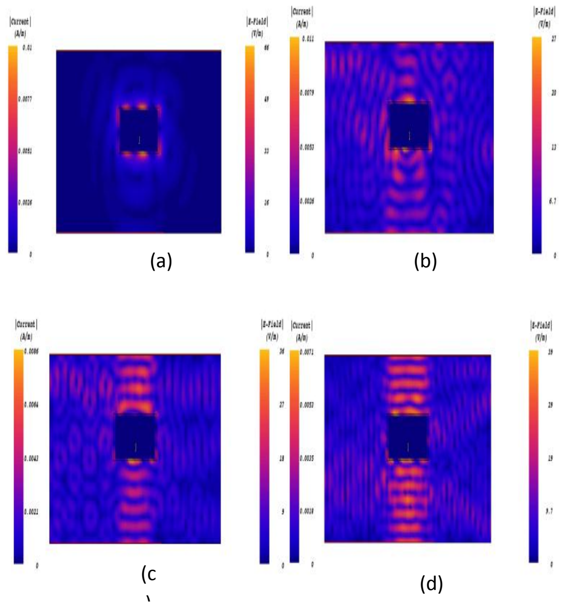


Figure 12: Current and electric field distribution for capacitively-fed RPMA at, frequencies, f, :(a)1.9,(b)2.76,(c)2.92and (d)3.24GHz

4. Stacked Capacitively-Fed RPMA

Finally by integrating three techniques together: thick substrate, indirect feed with stacked configuration a very wide bandwidth is achieved nearly 65% as shown in Figure (13-a). Figure (13-b) shows the very good impedance matching in which the frequency band is constrain in small area near the center of the Smith chart. The gain of the proposed design is shown in Figure (13-c). Figure (14) shows the radiation pattern and HPBW for different values of frequencies, in which the gain is maximum, with their current and electric field distributions shown in Figure (15). A conclusion for bandwidth enhancement designs is shown in Table (1).

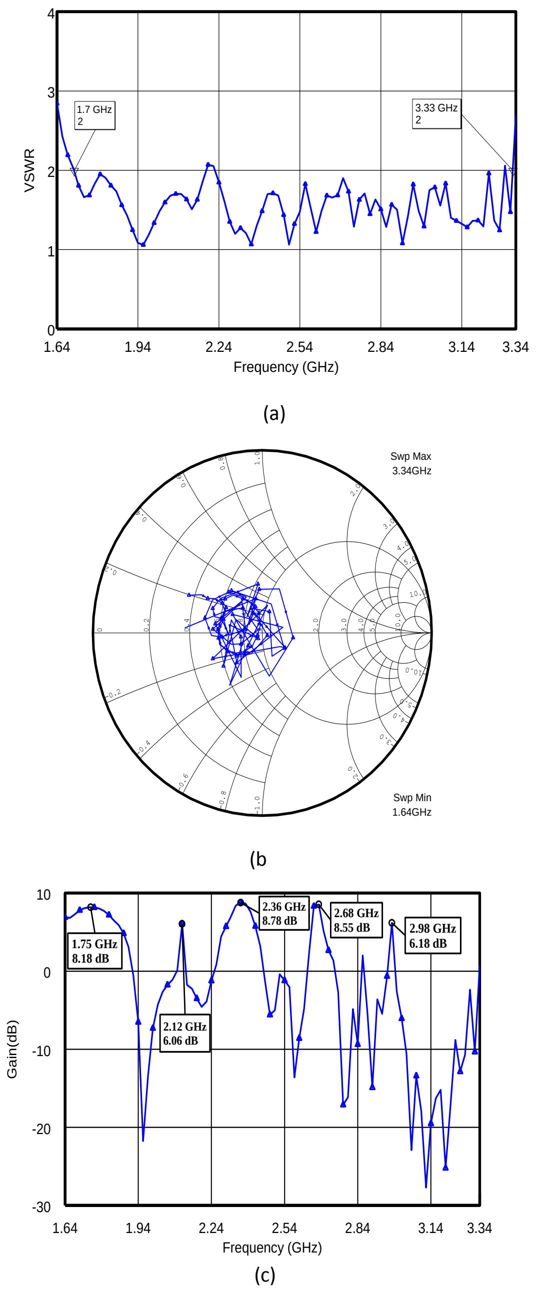


Figure 13: The characteristics of a stacked capacitively-fed RPMA (a) VSWR curve (b) Smith chart, (c) Gain curve.

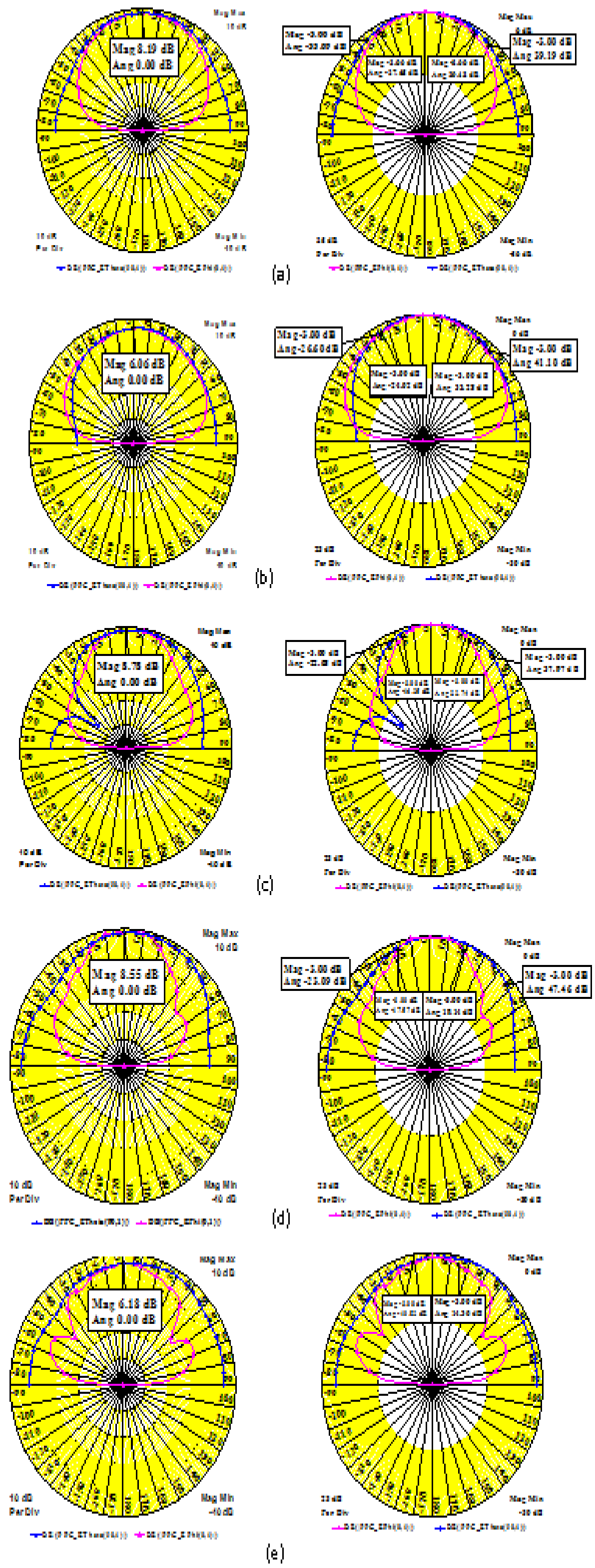


Figure 14: Maximum radiation at 0dB(to the left) and HPBW at -3dB (to the right) for stacked capacitively-fed RPMA for both principal planes at frequencies ,f,: (a) 1.76,(b) 2.12,(c) 2.36,(d)2.68,and(e)2.98GHz.

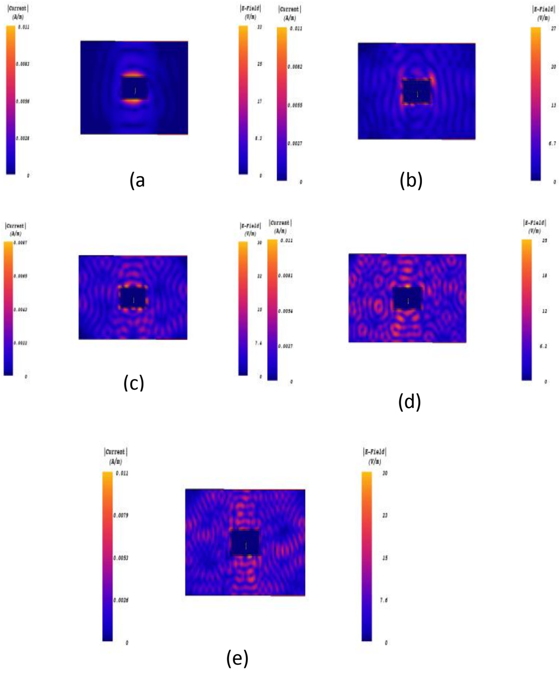


Figure15: Current distribution for stacked capacitively-fed RPMA at frequencies (a) 1.76,(b) 2.12,(c) 2.36,(d)2.68,(e)2.98GHz

Table 1: Frequency band, BW, and maximum gain for each design

	RPMA	Thick substrate RPMA	Capacitively –fed RPMA	Stacked Capacitively –fed RPMA
Frequency band(GHz)	2.154-2.145= 0.009	2.32-2.06= 0.26	3.27-1.9= 1.37	3.33-1.7= 1.6
f_c(GHz)	2.15	2.19	2.585	2.515
BW%	0.4	11.8	53	64.8
Maximum gain within frequency band(dB)	10.7	8.89	7.84	8.78

V. Conclusion

Four rectangular microstrip patch antennas operating at TM_{03} mode has been designed. Three techniques for bandwidth enhancement has been integrated, thick substrate, capacitvely-fed and stacked configuration. The simulation results indicate that bandwidth with rather high gain can improve by using capacitive –feed technique with single and stacked configurations RPMAs. The proposed two designs achieve a bandwidth of 53% (1.9 to3.27) GHz with 7.8dB gain for capacitively-fed RPMA and 64.8 %(1.7 to 3.33) GHz with 8.78dB gain for stacked capacitively-fed RPMA.

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تصميم وتحليل هوائي شريطي مستطيل الرقعة يعمل عند النمط TM_{03} بهيكلية مفردة ومتراصة لغرض تحسين عرض الحزمة الترددية

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الخلاصة:

الهدف من هذا البحث هو تحسين عرض الحزمة الترددية للهوائي الشريطي ذي الرقعة المستطيلة والذي يعمل في نمط عالي TM_{03} باستخدام ثلاث تقنيات: العازل السميك , التغذية السعوية, وتقنية الرقع المتراصة. ثابت عزل المادة العازلة ولكل التصاميم هو 9.8 بفقد 0.001 (الومينا). تم تصميم اربع هوائيات تعمل عند النمط TM_{03} : الهوائي الشريطي مستطيل الرقعة التقليدي بسمك قليل واخر سميك, هوائي شريطي مستطيل الرقعة بتغذية سعوية, واخيرا هوائي شريطي ذي رقعتين متراصتين فوق بعضها و بتغذية سعوية. جمع ثلاث تقنيات مع بعضها يظهر في التصميم الاخير والذي يعطي عرض حزمة ترددية واسعة تصل الى 65% مع تحصيل 8.78. تم تصميم وتحليل جميع التصاميم (نسبة فولطية الموجة الواقفة, هيكلية اشعاع المجال البعيد, وتوزيع التيار) باستخدام برنامج MW-Office 2006