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Design and Fabrication of Microstrip Circular and Rectangular Patch Antennas at 2.4 GHz

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Abstract: The microstrip circular and rectangular patch antennas are proposed in this design because it has low profile and easy to be fabricated on dielectric substrate and integrated with electronic circuits of transceiver which are printed on the same substrate. The dimensions and performances of the designed rectangular and circular antennas are optimized by using Computer Simulation Technology (CST) software. Using the optimized dimensions the designed circular and rectangular patch antennas are fabricated on FR-4 substrate with dielectric constant of 4.3 and thickness of 1.5 mm. The fabricated antennas are tested by using network analyzerwhich gives the practical measured results for both antennas interms of return results and impedance bandwidth.

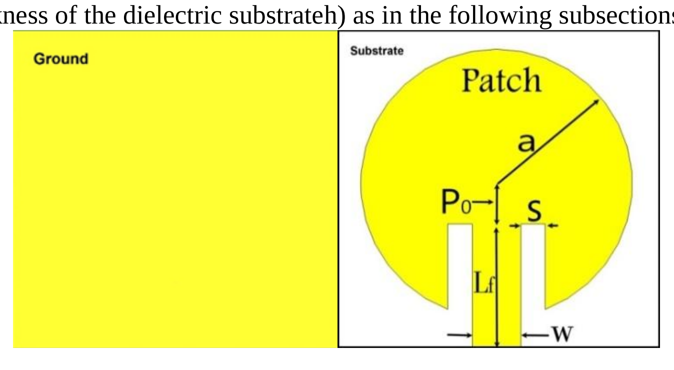
Keywords: bamd width – return loss – rectangular patch – CST - directivity

1- INTRODUCTION

The microstrip circular and rectangular patch antennas shown in Fig. 1 are proposed in this design because it has low profile and easy to be fabricated on dielectric substrate and integrated with electronic circuits of transceiver which are printed on the same substrate. The proposed microstrip circular patch antenna shown in Fig. 1(a), and rectangular patch antenna shown in Fig. 1(b) consists both of circular and rectangular conducting patch with thickness $\mathbf{t \ll \lambda}$ with placed on one side of dielectric substrate with thickness h within the range ($\mathbf{0.003\lambda \leq h \leq 0.05\lambda}$) while the ground placed on the other side of the substrate with thickness $\boldsymbol{t \ll \lambda}$ where $\boldsymbol{\lambda}$ is the operating wavelength. There are various substrates that can be used for the design of microstrip patch antenna and their dielectric constants are usually in the range $\mathbf{2 \leq \epsilon_r \leq 12}$[1]. The design of the antenna is achieved by using FR-4 substrate with dielectric constants of 4.3, thickness of 1.5mm and tangent loss 0.025. The dimensions and performances of the designed antenna are optimized by using Computer Simulation Technology (CST) software. A comparison between measured performances of the designed antennas has been done. The proposed circular and rectangular microstrip antennas in this project is chosen to operate at 2.4 GHz to support many application in Industrial, Scientific, wireless communication (such as Wi-Fi, Bluetooth), and Medical sectors(ISM)[2].

2- SINGLE CIRCULAR PATCH ANTENNA DESIGN

The top and the bottom views of single inset feed circular patch antenna shown in Fig. 1 are sketched as in Fig. 2. The patch and ground planes for the proposed antennas are assumed to be printed on the FR-4 dielectric substrate which has dielectric constant $\boldsymbol{\epsilon_r}$ **=4.3** The dimensions of antenna structural parameters such as patch radius, feeding point location $\mathbf{P_o}$, the width $\boldsymbol{w_f}$ and length $\mathbf{L_f}$ of inset feed microstrip transmission line shown in Fig. 2 should be calculated. To achieve the calculation of the previous patch dimensions three important parameters must be available are (the frequency of operation f, the dielectric constant of the substrate$\in_r$ and the thickness of the dielectric substrateh) as in the following subsections.



(b) (a)

Fig 1. Proposed inset feed microstrip circular patch antenna (a) patch (top view) (b)ground plane (bottom view)

2.1 Substrate thickness selection

The thickness h of the substrate must be within the design condition ($\mathbf{0.003\lambda \le h \le 0.05\lambda}$)[3], therefore for $\boldsymbol{\lambda}$=125 mm at f=2.4 GHz, then the required thickness must be within 0.375≤ $\mathbf{h}$ ≤6.25 mm. In this work different thicknesses h=0.6, 1.5, 1.9 mm has been taken

2.2 Circular Patch Radius and Effective Radius

Since the dimension of the patch is considered a circular loop, the actual patch radius is given by [3].

$$a = \frac{F}{\left\{1+\frac{2h}{\pi \epsilon_r F}\left[\ln\left(\frac{\pi F}{2h}\right)+1.77726\right]\right\}^{\frac{1}{2}}} \quad (1)$$

Where $F = \frac{8.791\times10^9}{f_r\sqrt{\epsilon_r}}$. Eq (1) does not take into consideration the fringing effect. Since fringing makes the patch electrically larger, the effective radius a_e of patch is used and is given by [4].

$$a_e = a\left\{1+\frac{2h}{\pi \epsilon_r a}\left[\ln\left(\frac{\pi a}{2h}\right)+1.7726\right]\right\}^{\frac{1}{2}} \quad (2)$$

2.3.The width and length calculation of feed microstrip line.

The charcterstic impedance of microstrip line is given by the following equations [4]

$$Z_O = \begin{cases} \frac{120\pi}{\sqrt{\epsilon_{reff}}\left[\frac{w_f}{h}+1.393+0.667\, ln\left(\frac{w_f}{h}+1.444\right)\right]} & \frac{w_f}{h} > 1 \\ \frac{60}{\sqrt{\epsilon_{reff}}}\ Ln\left(\frac{8\,h}{w_f}+\frac{w_f}{4\,h}\right) & for\ \frac{w_f}{h} < 1 \end{cases} \quad (3)$$

The length L_f of inset feed line shown in Fig 2 is given by [4],

$$L_f = \frac{C}{4f\sqrt{\epsilon_r}} \quad (4)$$

2.4 Calculation of inset cut

Resonant frequency of patch antenna depends on inset cut (S). Expression which relates inset cut and resonant frequency is given by [5]

$$S = \frac{v_o}{\sqrt{2\epsilon_{reff}}}\frac{4.65\times10^{-12}}{f_{GHz}} \quad (5)$$

Where $v_O = 3 \times 10$^8

2.5. The conductance of circular microstrip patch

The total conductance G_{tot} is expressed as

$$G_{tot} = G_{rad} + G_c + G_d \quad (6)$$

Where G_c is the conductance due to conduction loss, G_d is the conductance due to dielectric loss, and G_{rad} is the conductance due to the radiated power across the gap between the patch and ground plane at $\varphi^- = 0$ is given as [5]

$$G_{rad} = \frac{(Ka_e)^2}{480}\int_0^{\pi/2}[\, J_{02}'^2 + \cos\theta^2\, J_{02}^2]\sin\theta\, d\theta \quad (7)$$

Where, $J_{02} = J_o(ka_e \sin\theta) + J_2(ka_e \sin\theta)$ (8)

& $J'_{02} = J_o(ka_e \sin\theta) - J_2(ka_e \sin\theta)$ (9)

Since G_c&G_d are very small with respect to G_{rad} therefor they can be neglected , hence $G_t = G_{rad}$

2.6. Resonant input resistance:

The input impedance of circular patch at resonance is real. Taking the reference of the feed point at $\acute{\rho} = a_e$ then the input resistance is given by

$$Rin(\acute{\rho} = a_e) = \frac{1}{G_{rad}} \tag{10}$$

Where G_{rad} is given by Eq (7).

2.7. The inset feeding point location

In this project inset feed line has been used as shown in Figure 1. The feeding point must be located at $\acute{\rho} = P_o < a_e$ from the centre of the circular patch so that the input resistance of circular patch given by Eq (10) will reduce to a value that must be equal to the characteristic impedance Z_0 of the inset feed microstrip line. Then the input resistance of circular patch with inset feed at any radial distance $\acute{\rho} = P_o$ is given by [6]

$$Rin(\acute{\rho} = P_o) = Rin(\acute{\rho} = ae)\frac{j_1^2(KP_o)}{j_1^2(Ka_e)} \tag{11}$$

Where $Rin(\acute{\rho} = ae)$ is given by Eq (10), P_o is the distance between the inset feeding point and the centre of circular patch as in Fig 2, and k is the phase constant given by

$$k = \frac{2\pi}{\lambda} = \frac{2\pi f}{C} \tag{12}$$

2.8. Calculated result of physical dimension of the designed antenna

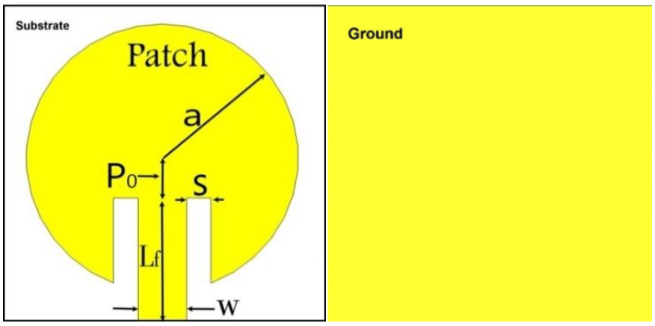
With the help of the previous formulae any using MATLAB code all the physical dimensions that are required to design the proposed circular patch antenna are obtained and summarized as shown in table. 1

Table 1: The calculated physical dimensions of the proposed antenna for dielectric constant ϵ_r = 4.3, for various substrate thickness h =1.5, and resonance frequency f = 2.4 GHz

Parameter	value
Dielectric constant ϵ_r	4.3
Radius of patch a (mm)	17
Effective radius of patch a_e(mm)	17.68
Feeding point location P_o (mm)	4.55
Width of feed line w_f	2.94
Length of the feed line L_f (mm)	17
Width of inset cut S (mm)	0.2

2.9 Simulation results

To optimize the dimenssions and performances of the designed inset feed microstrip circular patch antenna shown in Fig. 2, the CST program has been used to simulate such antenna as shown in Fig. 2 by using the physical calculated dimenssions shown in table. 1 .The simulation results of patch dimensions are shown as in table. 2.



(a) (b)

Fig. 2. Simulated circular microstrip patch antenna (a) the patch strip(top view) , (b) the ground(bottom view).

Table 2: The simulated physical dimensions of the proposed circular patch antenna for dielectric constant ϵ_r = 4.3, for various substrate thickness h =1.5, and resonance frequency f = 2.4 GHz

Parameter	value
Dielectric constant ϵ_r	4.3
Radius of patch a (mm)	17.78
Effective radius of patch a_e(mm)	17.68
Feeding point location P_o (mm)	5.85
Width of feed line w_f	2.94
Length of the feed line L_f (mm)	15
Width of inset cut S (mm)	1.47

2.10. Fabrication of the designed antenna

The designedmicrostrip circular patch antennahas been fabricated on the only available FR–4 Epoxy substrate with thickness h = 1.5 mm and dielectric constant ϵ_r $= 4.3$ after etching process the top view(patch) and bottom view(ground) of the fabricated antenna are shown as in Fig. 3. The dimensions of the fabricated antenna are those obtained by using CST program. Such dimensions are the patch radius a = 17.78 mm , feeding point location P_o = 5.85 mm, feeder line width w_{50} = 2.94 mm, and inset cut S = 1.47 mm.The network analyzer has been used used to test such fabricated antenna as shown in Fig. 3, which gives us practical return loss S_{11} results as shown in Fig. 4.

Fig. 3. The top view of the fabricated Microstrip circular patch antenna fixed with SMA connector

Fig. 4. Practical equipment set up using network analyzer for testing the fabricated circular patch antnna.

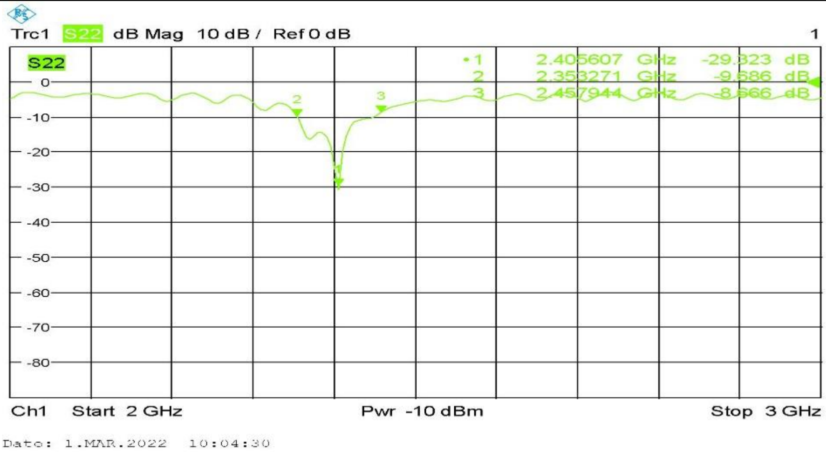


Fig. 5 Measured results of return loss for the designed circular microstrip antenna with dielectric constant $\in_r$ = 4.3 and substrate thickness h = 1.5 mm

2.11. Results and discusion

From measured results shown in Fig. 5 it is found that the patch antenna resonates at 2.4056 GHz with a return loss of – 29 dB, and the impedance bandwidth is BW = 105 MHz, and such results are summarized as in table. 3.

Table. 3, performances practical results of the designed microstrip circular patch antenna

parameter	Measured results
Reasonance frequency	2.4056
Return loss (dB)	- 29.3
Impedance banwidth(MHz)	105

3- SINGLE RECTANGULAR PATCH ANTENNA DESIGN

The top and the bottom views of single inset feed rectangular patch antenna shown in Fig. 6 are sketched as in Fig. 6. The patch and ground planes for the proposed antennas are assumed to be printed on dielectric substrate which has dielectric constant $\boldsymbol{\epsilon_r}$ **=4.3** The dimensions of antenna structural parameters such as patch width w, length L, feeding point location $\mathbf{y_o}$, the width $\boldsymbol{w_f}$ and length $\mathbf{L_f}$ of inset feed microstrip transmission line shown in Fig. 6should be calculated. To achieve the calculation of the previous patch dimensions three important parameters must be available are (the frequency of operation f, the dielectric constant of the substrate$\in_r$ and the thickness of the dielectric substrateh) as in the following subsections.

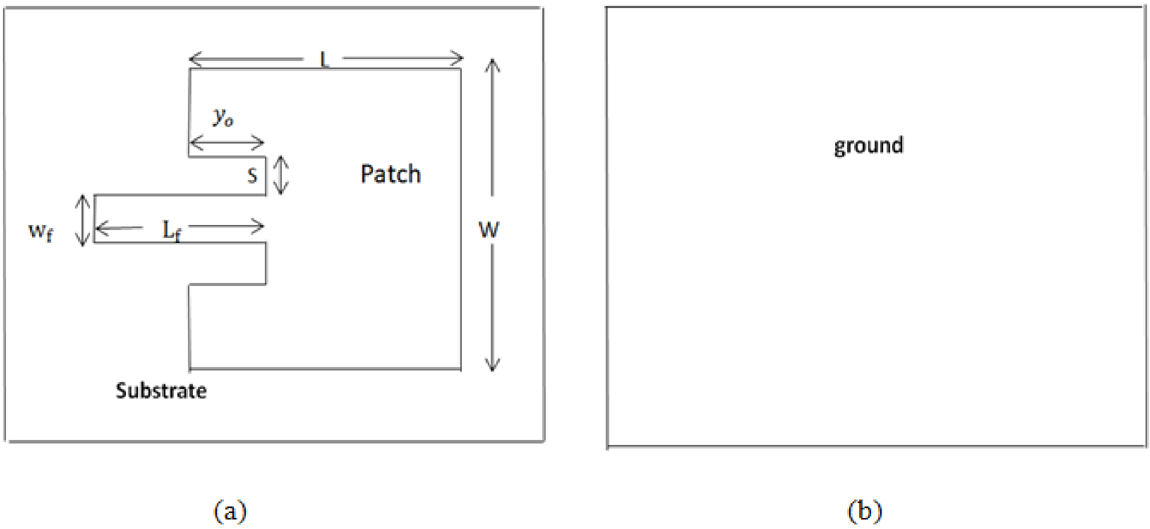


Fig 6. Proposed inset feed microstrip rectangular patch antenna (a) patch (top view) (b)ground plane (bottom view

3.1 Substrate thickness selection

The thickness h of the substrate must be within the design condition ($\mathbf{0.003\lambda \leq h \leq 0.05\lambda}$)[3], therefore for $\boldsymbol{\lambda}$=125 mm at f=2.4 GHz, then the required thickness must be within 0.375≤ **h** ≤6.25 mm. In this work thicknesses h=1.5 mm has been taken

3.2 width calculation of the patch

The width of the patch a is given by the following approximate expression [7].

$$w = \frac{c}{2f}\sqrt{\frac{2}{\epsilon_r+1}} \quad (13)$$

Where, f is the resonant frequency of the patch antenna, c is free-space velocity of light [8].

3.3 Length calculation of the patch

The effective length of patch after taking into fringing effect can be calculated by

$$\mathbf{L = \frac{c}{2f\sqrt{\epsilon_{reff}}} - 2\Delta L} \quad (14)$$

The effective dielectric constant ϵ_{reff} for the case of (w/h > 1) is given by[9].

$$\epsilon_{reff} = \frac{\epsilon_r+1}{2} + \frac{\epsilon_r-1}{2}\left[1 + 12\frac{h}{w}\right]^{-1/2} \quad (15)$$

The extension ΔL of patch length due to fringing effects can be determined by[10].

$$\Delta L = 0.412h\frac{(\epsilon_{reff}+0.3)\left(\frac{w}{h}+0.6\right)}{(\epsilon_{reff}-0.258)\left(\frac{w}{h}+0.8\right)} \quad (16)$$

3.4.The width and length calculation of feed microstrip line.

The charcterstic impedance of microstrip line is given by the following equations[11].

$$Z_O = \begin{cases} \dfrac{120\pi}{\sqrt{\epsilon_{reff}}\left[\frac{w_f}{h}+1.393+0.667\ ln\left(\frac{w_f}{h}+1.444\right)\right]} & \dfrac{w_f}{h} > 1 \\ \dfrac{60}{\sqrt{\epsilon_{reff}}}\ Ln\left(\dfrac{8\,h}{w_f}+\dfrac{w_f}{4\,h}\right) & for\ \dfrac{w_f}{h} < 1 \end{cases} \quad (17)$$

Where w_f is feed line width, It is difficult to find the width w_f in terms of characteristic impedance Z_o from (17) then a MATLAB program has been used to plot Z_o as a function of the width w_f for dielectric constant ϵ_r= 4.3 , substrate thicknesses h = 1.5 mm, then width w_f is determined at Z_o = 50Ω

The length L_f of inset feed line shown in Fig 10 is given by [12],

$$L_f = \frac{c}{4f\sqrt{\epsilon_r}} \quad (18)$$

3.5 Calculation of inset cut

Resonant frequency of patch antenna depends on inset cut (S). Expression which relates inset cut and resonant frequency is given by [13]

$$S = \frac{v_o}{\sqrt{2\epsilon_{reff}}}\frac{4.65\times10^{-12}}{f_{GHz}} \quad (19)$$

Where $v_O = 3 \times 10$^8

3.6. Calculation of inset feed point location $\mathbf{y_o}$

In this design inset feed line has been used as shown in Fig. 7. The feeding point must be located at y_o from the edge of the rectangular patch so that the edge input resistance of the patch at $y_o = 0$ will reduce to a value that must match the characteristic impedance Z_0 of the inset feed microstrip line. The inset feed at any distance y_o as a function of the characteristic impedance of the inset feed line is given by [14]

$$y_o = \frac{L}{\pi}\cos^{-1}\sqrt{\frac{Z_o}{R_{in}}} \quad (20)$$

Where Z_o is the characteristic impedance of the inset feed line, L is the patch length, R_{in} is the edge input impedance of the patch at $y_o = 0$ is given by [15]

$$R_{in} = \frac{1}{G_1+G_{12}} \quad (21)$$

G_1: The conductance of single slot and is given by[16].

$$G_1 = \frac{1}{120\pi^2}\int_0^{\pi}\left[\frac{\sin\frac{1}{2}kwcos\theta}{cos\theta}\right]^2 sin^3\theta\ d\theta \quad (21)$$

G_{12} : is the mutual conductance between the slots of the patch and is given by [17].

$$G_1 = \frac{1}{120\pi^2}\int_0^{\pi}\left[\frac{\sin\frac{1}{2}kwcos\theta}{cos\theta}\right]^2 J_o(kLsin\theta)sin^3\theta\ d\theta \quad (22)$$

3.6. Summary of the calculated result

With the help of the previous formulae all the physical dimensions that are required to design the proposed rectangular patch antenna are obtained and summarized as shown in table. 4

Table 4: The calculated physical dimensions of the proposed rectangular antenna for dielectric constant ϵ_r = 4.3, substrate thicknesses h =1.5 mm, and resonance frequency f = 2.4 GHz

parameter	Calculated value
Width of patch w (mm)	38.39
Length of patch L (mm)	29.87
Feeding point location y_o (mm)	9.862
Width of feed line w_f	2.94
Length of the feed line L_f (mm)	15
Width of inset cut S (mm)	1.142

3.7 Simulation results

To optimize the dimenssions and performances of the designed inset feed microstrip rectangular patch antenna shown in Fig. 6, the CST program has been used to simulate such antenna by using the physical calculated dimenssions shown in table. 4.The simulation results of patch dimensions are shown as in table. 5

Table 5: The simulated physical dimensions of the proposed rectangular patch antenna for dielectrc constant ϵ_r = 4.3, for substrate thickness h =1.5, and resonance frequency f = 2.4 GHz

Parameter	value
Width of the patch w (mm)	38.39
Length of the patch L (mm)	29.39
Feeding point location y_o (mm)	7.4
Inset cut S (mm)	1.47
Width of inset feed line w_{50} (mm)	2.94

***3.8.* Fabrication of the designed antenna**

The designedmicrostrip rectangular patch antennahas been fabricated on the only available FR–4 Epoxy substrate with thickness h = 1.5 mm and dielectric constant $\epsilon_r = 4.3$ after etching process the top view(patch) and bottom view(ground) of the fabricated antenna are shown as in Fig. 7. The dimensions of the fabricated antenna are those obtained by using CST program. Such dimensions are the patch length= 29 mm , width 38 mm feeding point location y_o = 7.4 mm , and feeder line width w_{50} = 2.94 mm, and inset cut S = 1.47 mm.The network analyzer has been used used to test such fabricated antenna as shown in Fig. 11, which gives us the following practical return loss S_{11} results as shown in Fig. 8.

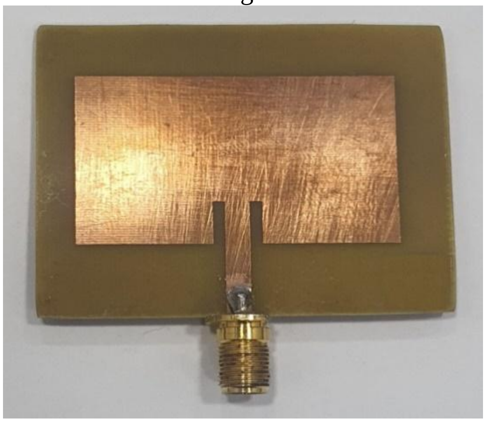


Fig.7: The top view of the fabricated Microstrip rectangular patch antenna fixed with SMA connector

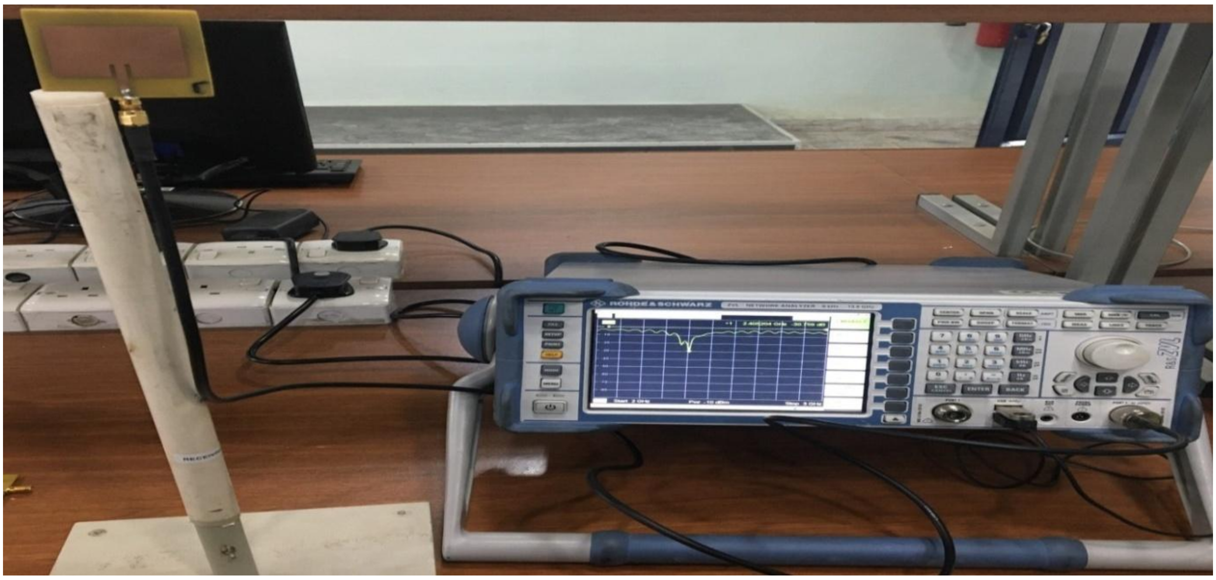


Fig. 8: Practical equipment set up using network analyzer for testing the fabricated rectangular patch antenna.

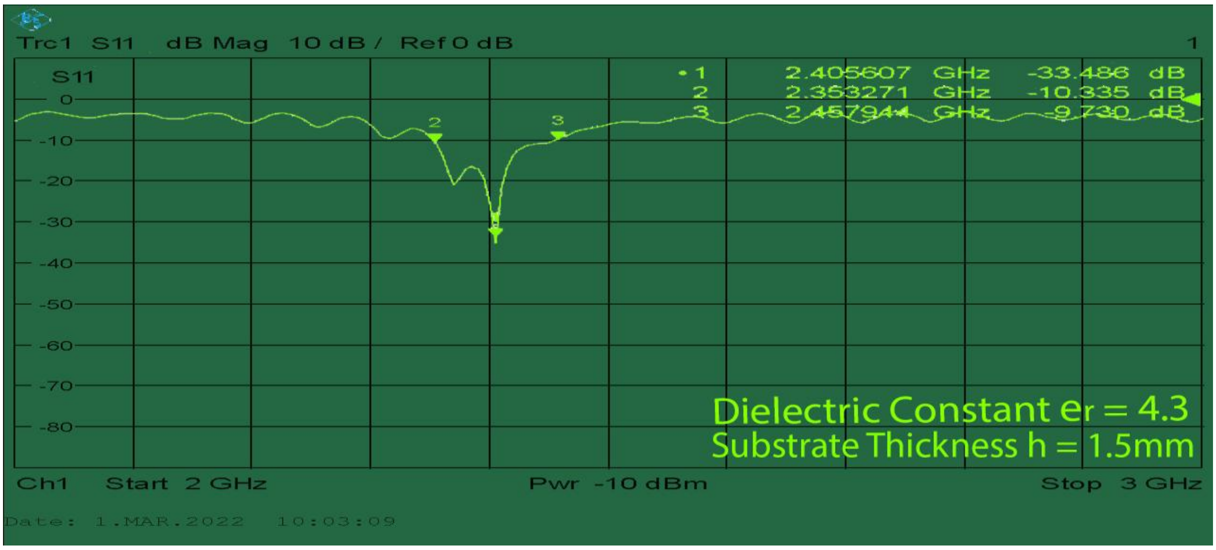


Fig. 9 Measured results of return loss for the designed rectangular microstrip antenna with dielectric constant ϵ_r = 4.3 and substrate thickness h = 1.5 mm

3.9. Results and discussion

From the measured results it is found that the patch antenna resonates at 2.4056 GHz with a return loss of -33.4 dB, and the impedance bandwidth is BW = 105 MHz. Table 6 . show the practical results of the designed microstrip rectangular antenna.

Table. 6 measured results of the designed microstrip rectanglar antenna.

parameter	Measured results
Reasonance frequency	2.4056
Return loss (dB)	- 33.4
Impedance banwidth (MHz)	104

4- CONCLUSION

A comparison between measurd performances of the designed circular and rectangular patchesboth working at 2,4 GHz and printed on FR-4 dielectric substrate with thickness h=1.5 mm, dielectric constant $\epsilon_r = 4.3$, and tangent loss tan $\delta = 0.025$ is shown as in table. 7. It could be seen from table. 7 that the measured results of the antenna performance are very close each to other.

The values of return losses for both patches shown in table. 7 are sufficiently low which tends to a very good antenna performance due to very low reflection coefficient which about 0.001.

Table. 7. A comparison between measurd performances of the designed circular and rectangular patches

parameter	Measure rectangular	Measured circular
Reasonance frequency	2.4056	2.4056
Return loss (dB)	-33	-29
Impedance banwidth (MHz)	105	105

It could be seen from table. 7 that that thereasonance frequency and impedance banwidth are the same for both rectangular and circular patches, while the return loss of rectangular patch is better than that of circular patch. Finally we can say that the performances of both patches are almost the same.

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