

## Effect of Three Different Dielectric Substrates on the Performance of Rectangular Microstrip Antenna Designed for 2.4 GHz using CST

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### ABSTRACT

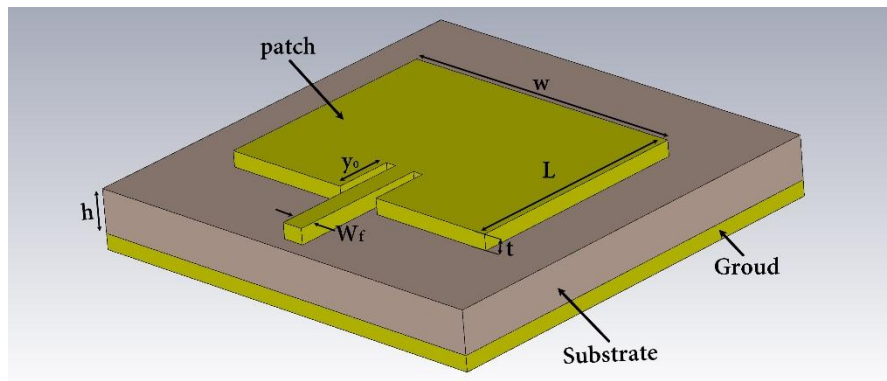
This paper presents a design of a low profile inset feed microstrip rectangular antenna working at 2.4 GHz to support application in industrial, scientific, and medical sectors. The design of the antenna is achieved by using three different substrates with dielectric constants of 2.2, 3.6, and 4.3, each with variable substrate thicknesses of 0.6, 1.5, 1.9mm in order to know the effect of substrate properties on the antenna performance such as gain, efficiency, return loss, and frequency bandwidth. The dimensions and performances of the designed antenna are optimized by using Computer Simulation Technology (CST) software hence a comparison has been performed among previous the antenna performances. The practical results for the antenna with the substrate of (dielectric constant of 4.3) and (thickness of 1.5mm) show that the return loss is (-33) dB which close to the simulation value, but there is a small difference (about ~30MHz) in the Impedance bandwidth. However, all other results were close.

**Keywords:** Microstrip, Antenna, return loss, Directivity, CST.

## INTRODUCTION

Microstrip rectangular patch antenna consists of a conducting patch of the ground plane between them is a dielectric medium called the substrate having a particular value of dielectric constant. The patch is made of conducting material such as copper or gold (Pozer and Schaubert, 1995). The patch can be of any profile such as rectangular, square, circular, elliptical, or triangular. Microstrip antennas have several advantages such as lightweight, small volume, and low-profile over conventional microwave antennas (Bhal and Bhartia, 1980), because of the low-profile characteristics of Microstrip antenna, it is most widely used in defense, aerospace, military, and satellite communication applications (Balanis, 2005). Microstrip antennas suffer from disadvantages such as narrow bandwidth, poor efficiency, low gain, and low power. Selection of dielectric constant is essential because it increases the bandwidth of the antenna may decrease (Jayanthi *et al.*, 2008) (Ahmed *et al.*, 2020). The proposed microstrip shown in Fig. (1), consists of a rectangular conducting patch with thickness with length  $L$  and width  $W$  is placed on side of the dielectric substrate with thickness  $h$  within the range  $(0.003\lambda \leq h \leq 0.05\lambda)$ . While the ground is placed on the other side of the substrate with thickness, where  $\lambda$  is the operating wavelength. In some cases, the circular and rectangular patch gives the same performances at a given frequency if the substrate is the same for both patches, (Mohammed and Al Taan, 2022). Various substrates can be used for the design of microstrip patch antenna and their dielectric constants are usually in the range of  $2 \leq \epsilon_r \leq 12$ . (Basilio *et al.*, 2001).

In this work, the proposed rectangular microstrip antennas, in this project are chosen to operate at 2.4GHz to support many applications, especially in wireless communication and the medical area.



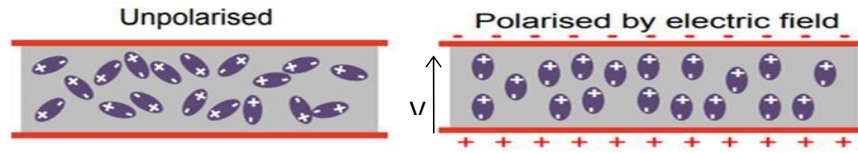
**Fig. 1: Geometry of microstrip rectangular patch antenna**

### Materials and properties of dielectric substrates

In general, the Printed Circuit Board (PCB) substrate shown in Fig. (1) consists of insulator material with thickness  $h$  (typically 1.5 mm) coated by a very thin copper conductor on both sides with thickness  $t$  (typically 0.01 mm). The PCB is used for printing patch antenna shown in Fig. (1) by using the etching process and its substrate materials meet two challenges are dielectric loss ( $\alpha_d$ ), and conductor loss ( $\alpha_c$ )

### Dielectric loss

The dielectric loss depends on the nature of the insulating material used in the PCB when the electric field  $E$  vol/m is applied across the PCB a polarization occurs and charges are displaced relative to the electric field producing displacement current as shown in Fig. (2), this will lead to a reduction in the magnitude of electric field hence dielectric loss occurrence.



**Fig. 2: Polarization of substrate electric charges due to the applied electric field**

The dielectric loss  $\alpha_d$  in dB per unit length is given by, (Basilio *et al.*, 2001):

$$\alpha_d = 27.3 \frac{\epsilon_r}{\sqrt{\epsilon_{reff}}} \frac{(\epsilon_{reff}-1)}{(\epsilon_r-1)} \frac{\tan\delta}{\lambda} \dots \dots (1)$$

As it could be seen from (1) that the dielectric loss in dB per unit length depends on the dielectric constant, the effective value of the dielectric constant and tangent loss factor denoted by  $\tan\delta$  and it is defined as the measure of signal loss due to the reduction in electric field energy in the substrate as mentioned above. The tangent of the phase angle can be calculated from the following, terms of substrate material are given, (Basilio *et al.*, 2001):

$$\tan\delta = \frac{\sigma}{2\pi f \epsilon_0 \epsilon_r} \dots \dots (2),$$

where  $\sigma$ ; the conductivity of the insulator material of the substrate,  $f$ ; the operating frequency,  $\epsilon_0$ ; the vacuum permittivity,  $\epsilon_r$ ; the dielectric constant of the insulator material of the substrate.

### Conduction loss

The conduction loss is caused by the ohmic surface resistance and skin effect of the copper strip coated on the two sides of the PCB. Skin effect is the tendency of an alternating electric current (AC) to become distributed within a conductor such that the current density is largest near the surface of the conductor and decreases exponentially with greater depths in the conductor it could be seen that the wave is a good conductor attenuates quickly, the distance over which they decay by a factor of  $1/e$  is called the skin depth  $\delta$ , then the definition of skin depth is  $\delta=1/\alpha$  where  $\alpha$  is the attenuation constant and in terms of fundamental parameters is given by the conductor loss  $\alpha_c$  in dB per unit length of the rectangular patch shown is given by, (Basilio *et al.*, 2001):

$$\alpha_c = 6.1 \times 10^{-5} \frac{R'_s z_0 \epsilon_{reff}}{h} \left[ \frac{w}{h} + \frac{0.667 \frac{w}{h}}{\frac{w}{h} + 1.444} \right] A \text{ for } \frac{w}{h} \geq 1 \dots \dots (3)$$

Where  $R'_s$  is the effective surface resistance of the patch conductor.

Three types of substrates with different important parameters such as dielectric constant  $\epsilon_r$ , tangent loss ( $\tan\delta$ ), and substrate thickness are proposed to be used in the design of rectangular patch antenna for the comparison between various antenna performances (return loss  $S_{11}$ , directivity  $D_o$ , efficiency  $\eta$ ) at resonance frequency 2.4 GHz; RT (duroid 5880), Rogers (RO3035) and FR-4 Epoxy. The (return loss) can also be called the ( $S_{11}$ ) factor, which was explained in the ref. (Al Taan *et al.*, 2020).

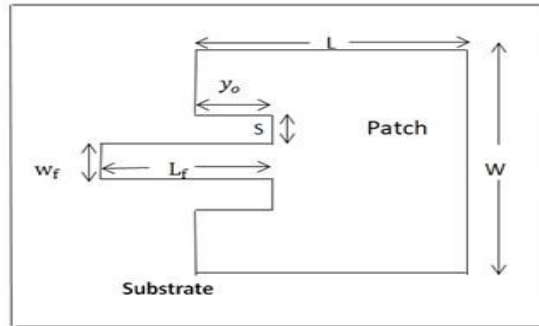
The properties of the above different substrates are listed in the (Table 1), (Basilio *et al.*, 2001) (Janina *et al.*, 2005) (Gonçalves *et al.*, 2016):

**Table 1: Properties of the different substrates and the patch**

Parameters	RT (Duroid 5880)	Rogers(R03035)	FR4 Epoxy
Dielectric constant	2.2.	3.6	4.3
Tangent loss ( $\tan\delta$ ) at $f = 2.4$ GHz	0.0009	0.0015	0.025
Surface resistivity	$2 \times 10^5$ Mohm.	$4.8 \times 10^9$ Mohm	$3 \times 10^7$ Mohm
Copper conductivity	$5.8 \times 10^7$ s/m	$5.8 \times 10^7$ s/m	$5.8 \times 10^7$ s/m

**Design of microstrip rectangular patch antenna:**

The top and the bottom views of the single inset feed rectangular patch antenna shown in Fig. (1) are sketched as in Fig. (6). The patch and ground planes for the proposed antennas are assumed to be printed on the different dielectric substrate which has dielectric constant = 2.2, 3.6, and 4.3 to see the effect of dielectric constant and substrate thickness on the antenna directivity, and the efficiency of the antenna. The dimensions of antenna structural parameters such as patch width  $w$ , length  $L$ , feeding point location  $y_0$ , the width  $w_f$  and length  $L_f$  of inset feed Microstrip transmission line shown in Fig. (1) 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  $\epsilon_r$  and the thickness of the dielectric substrate  $h$ ) as in the following:

**Fig. 3: Proposed inset feed microstrip rectangular patch antenna**

The width of the microstrip patch antenna is given as, (Kumar and Ray, 2003):

$$w = \frac{c}{2f} \sqrt{\frac{2}{\epsilon_r + 1}} \quad \dots \dots \dots (4)$$

where  $f$  is the resonant frequency of the patch antenna, and  $c$  is the free-space velocity of light. The effective dielectric constant  $\epsilon_{eff}$  is given, by as, (Kumar and Ray, 2003):

$$\epsilon_{reff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left[ 1 + 12 \frac{h}{w} \right]^{-1/2} \quad \dots \dots \dots (5)$$

The extended length of the patch is given by as, (Balanis, 1997).

$$\Delta L = 0.412h \frac{(\epsilon_{reff} + 0.3) \left( \frac{w}{h} + 0.264 \right)}{(\epsilon_{reff} - 0.258) \left( \frac{w}{h} + 0.8 \right)} \quad \dots \dots \dots (6)$$

The effective length of the patch is given by as, (Basilio *et al.*, 2001).

$$L_{eff} = \frac{c}{2f \sqrt{\epsilon_{reff}}} \quad \dots \dots \dots (7)$$

Then the actual length of the patch is given by, (Gonçalves *et al.*, 2016):

$$L = L_{eff} - 2\Delta L \quad \dots \dots \dots (8)$$

The characteristic impedance of the microstrip line is given by, (Basilio *et al.*, 2001):

$$Z_o = \left( \begin{array}{l} \frac{120\pi}{\sqrt{\epsilon_{reff}} \left[ \frac{w_f}{h} + 1.393 + 0.667 \ln \left( \frac{w_f}{h} + 1.444 \right) \right]} \quad \frac{w_f}{h} > 1 \\ \frac{60}{\sqrt{\epsilon_{reff}}} \ln \left( \frac{8h}{w_f} + \frac{w_f}{4h} \right) \quad \text{for } \frac{w_f}{h} < 1 \end{array} \right) \dots\dots\dots (9)$$

The width  $w_f$  is determined at  $Z_o=50\Omega$ . The length  $L_f$  of the inset feed line shown in Fig. (3) is given by, (Ziaur *et al.*, 2020):

$$L_f = \frac{c}{4f\sqrt{\epsilon_{reff}}} \dots\dots\dots (10)$$

The resonant frequency of the patch antenna depends on the inset cut (S). An expression that relates inset cut and the resonant frequency is given by, (Prabhakar *et al.*, 2016):

$$s = \frac{v_o}{\sqrt{2\epsilon_{reff}}} \frac{4.65 \times 10^{-12}}{f_{GHz}} \dots\dots\dots (11)$$

In this design inset feed line has been used as shown in Fig. 6. The feeding point must be located at the center of the edge of the rectangular patch so that the edge input resistance at  $y_o=0$  of a patch will reduce to a value that must match the characteristic impedance  $Z_o = 50\Omega$  of the inset feed microstrip line. The input resistance of a patch with inset feed at any distance from the edge of the patch is given by, (Basilio *et al.*, 2001):

$$y_o = \frac{L}{\pi} \cos^{-1} \sqrt{\frac{Z_o}{R_{in}}} \dots\dots\dots (12),$$

where  $Z_o$  is the characteristic impedance of the inset feed line,  $L$  is the patch length,  $R_{in}$  is the input edge impedance of the patch at  $y_o=0$  is given, (Basilio *et al.*, 2001):

$$R_{in} = \frac{1}{G_1 + G_{12}} \dots\dots\dots (13)$$

$G_1$ : The conductance of a single slot and  $G_{12}$ : is the mutual conductance between the slots of the patch. The physical dimensions that are required to design the proposed rectangular patch antenna are obtained and summarized for different dielectric constants and various substrate thicknesses as shown in the (Table 2).

**Table 2: The physical dimensions of the proposed antenna for different dielectric substrates and various substrate thicknesses at resonance frequency 2.4 GHz**

Parameter	Dielectric constant = 2.2			Dielectric constant = 3.6			Dielectric constant = 4.3		
	h = 0.6	h = 1.5	h = 1.9	h = 0.6	h = 1.5	h = 1.9	h = 0.6	h = 1.5	h = 1.6
Width of patch w(mm)	49.41	49.4	49.41	42.21	41.21	41.21	38.39	38.39	38.39
Length of patch L(mm)	42.12	41.38	42.06	32.92	32.5	41.21	30.14	29.87	30.13
Feeding point location $y_o$ (mm)	12.86	12.94	12.85	10.68	10.55	10.68	9.98	9.862	9.977
Width of the feed line $w_f$	1.864	4.661	5.9	4.241	3.348	4.241	4.241	2.94	3.724
Length of the feed line $L_f$ (mm)	21	21	21	16.5	16.5	16.5	15	15	15
Width of inset cut S(mm)	1.596	1.596	1.596	1.248	1.248	1.248	1.142	1.142	1.142

### Directivity and radiation efficiency of the microstrip rectangular antenna

The total broadside directivity  $D$  for the two radiating slots, separated by the dominant  $TM_{010}$  mode field can also be written as, (Basilio *et al.*, 2001):

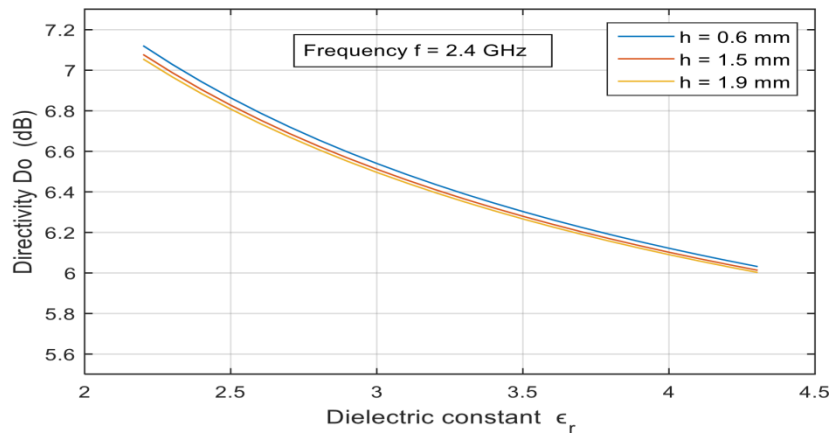
$$D = D_o D_{AF} = D_o \frac{2}{1 + g_{12}} \quad \dots \dots \dots (14),$$

where,  $D_o$ : directivity of a single slot of the patch, AF is the array factor given by

$AF = \left( \frac{1}{2} kL \sin\theta \sin\phi \right)$ , and  $g_{12}$  is the normalized mutual conductance given by, (Basilio *et al.*, 2001):

$$g_{12} = \frac{G_{12}}{G_1} \quad \dots \dots \dots (15)$$

The directivity of the designed proposed rectangular patch antenna is obtained and plotted as a function of dielectric constant different substrate thickness as shown in Fig. (4).



**Fig. 4: Theoretical calculation of the directivity for the designed antenna as a function of dielectric constant for different substrate thickness**

Radiation efficiency  $\eta$  of the antenna is defined as the power radiated  $P_{ad}$  over the input power  $P_{in}$  given by, (Jamal and Mudhaffer, 2006):

$$\delta = \frac{P_{rad(watt)}}{P_{in(watt)}} \quad \dots \dots \dots (16)$$

The total dielectric loss and conduction loss in dB of rectangular microstrip patch shown with length  $L$  is given by the following equations:

$$\alpha_{d tot} = \alpha_d \cdot L \quad \dots \dots \dots (17),$$

$$\alpha_{c tot} = \alpha_c \cdot L \quad \dots \dots \dots (18),$$

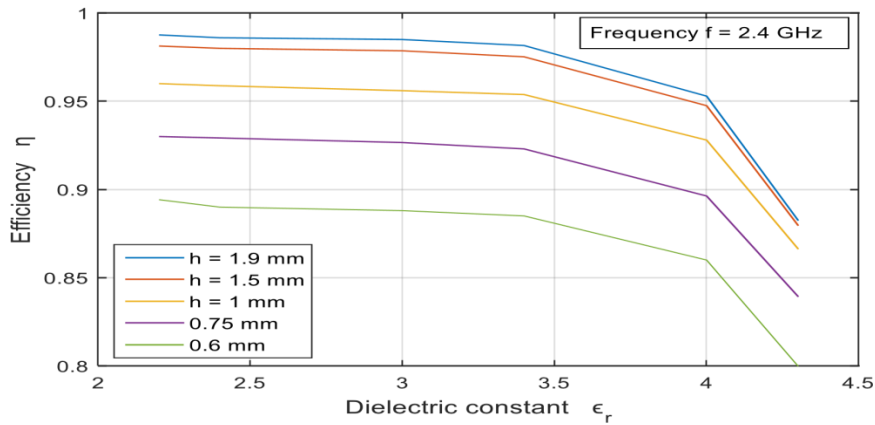
where  $\alpha_d$  and  $\alpha_c$  are given by (1) and (5) respectively.

Then according to (16), the efficiency becomes:

$$\delta = \frac{0.001 \cdot 10^{0.1 P_{rad dBm}}}{P_{in(watt)}} \quad \dots \dots \dots (19)$$

$$P_{rad(dB_m)} = P_{in(dB)} - \alpha_{c tot}(dB) \quad \dots (20)$$

With the help of the previous formulae, the radiation efficiency of the designed proposed rectangular patch antenna is obtained and plotted as a function of dielectric constant for as shown in Fig. (5).



**Fig. 5: Theoretical calculation of efficiency for the designed antenna as a function of dielectric constant for different substrate thickness**

The calculated values of the directivity and efficiency of the designed microstrip rectangular patch antenna for different substrate thicknesses  $h = 0.6, 1.5$ , and  $1.9$  mm are summarized in the (Table 3).

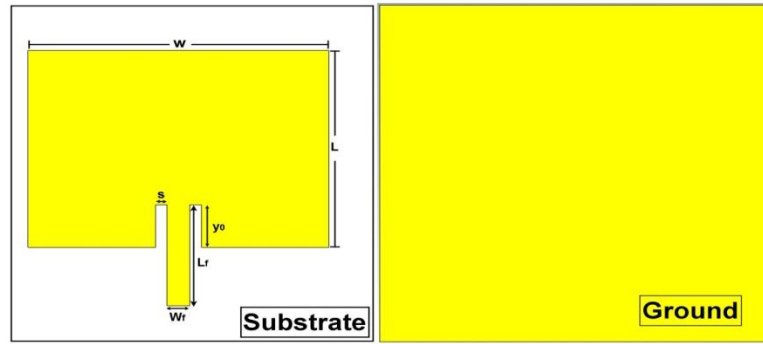
**Table 3: The calculated values of the directivity and efficiency of the designed patch antenna for different substrate thicknesses  $h = 0.6, 1.5$  and  $1.9$  mm**

Parameter	Dielectric constant $\epsilon_r = 2.2$			Dielectric constant $\epsilon_r = 3.6$			Dielectric constant $\epsilon_r = 4.3$		
	$h = 0.6$	$h = 1.5$	$h = 1.9$	$h = 0.6$	$h = 1.5$	$h = 1.9$	$h = 0.6$	$h = 1.5$	$h = 1.9$
Directivity D(dB)	7.121	7.077	7.055	6.263	6.24	6.227	6	6	6
Radiation efficiency $\eta$	0.8864	0.9778	0.9848	0.8756	0.9724	0.9799	0.8186	0.9117	

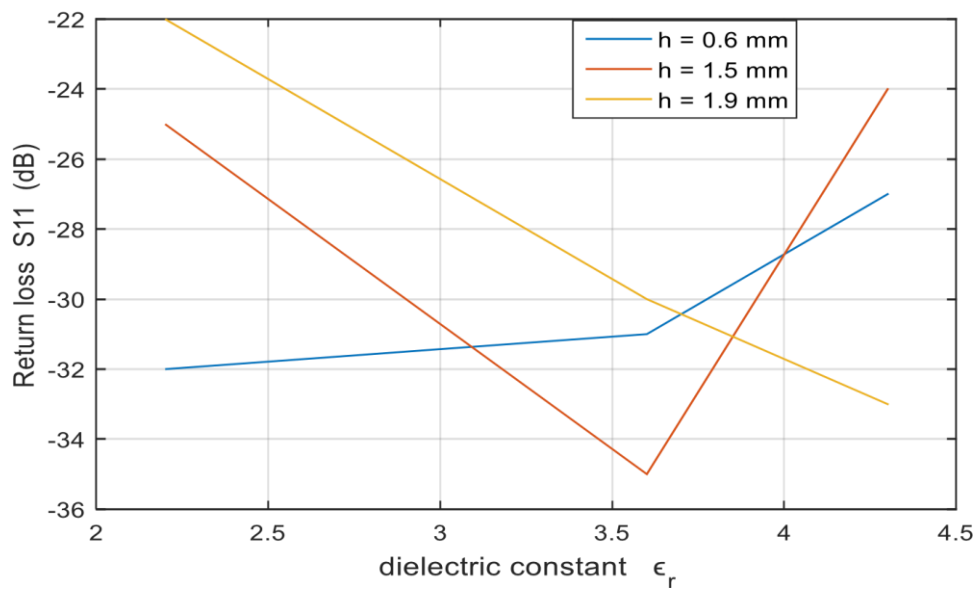
### Simulation Results and Discussion

To optimize the dimensions and performances of the designed inset feed Microstrip rectangular patch antenna shown in Fig. (3), the CST program has been used to simulate such an antenna by using the physical calculated dimensions at 2.4 GHz of the proposed single antenna shown in the (Table 2) and printed on three types of a substrate as shown in Fig. (6), with different dielectric constant and substrate thicknesses. The simulation results of the return loss  $S_{11}$  ( $20\log k_r$ ) in dB and impedance bandwidth (the frequency band at which the return loss  $\leq -10$  dB) in terms of dielectric constant  $\epsilon_r$  and for different substrate thickness  $h = 0.6, 1.5$  and  $1.9$  mm are shown as in Fig. (7), and Fig. (8). Where  $k_r$  is the voltage reflection coefficient.

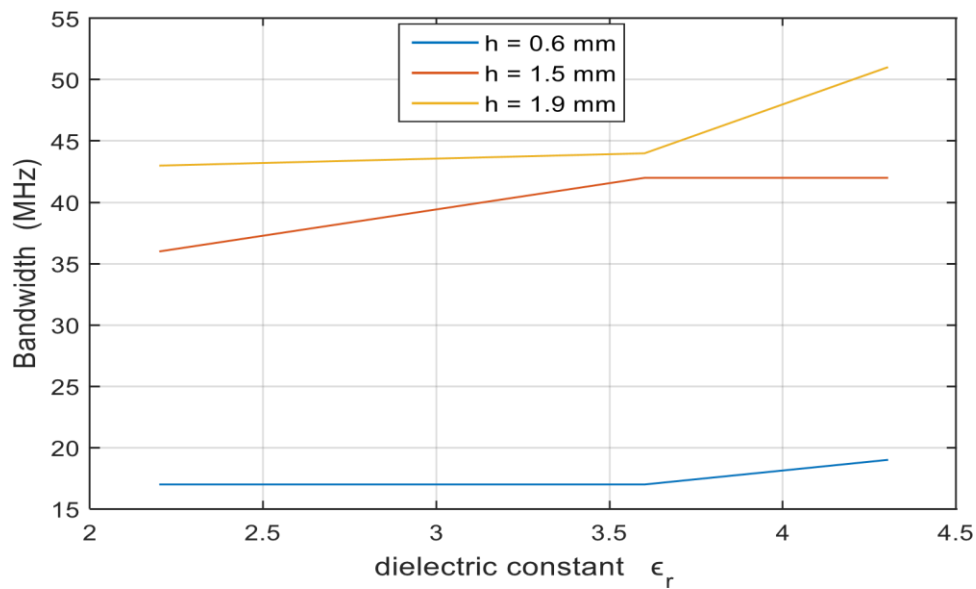




**Fig. 6: Simulated rectangular microstrip patch antenna (a) the patch strip (top view), (b) the ground (bottom view).**



**Fig. 7: The simulated results of return loss as a function of dielectric constant with different substrate thickness**

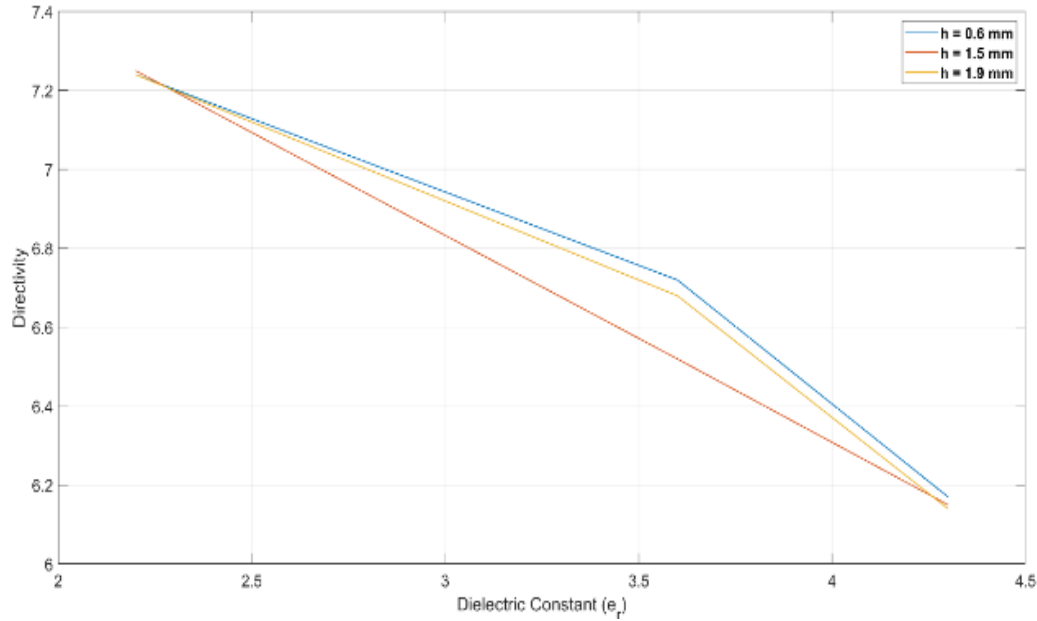


**Fig. 8: The simulated results of impedance bandwidth as a function of dielectric constant with different substrate thickness**

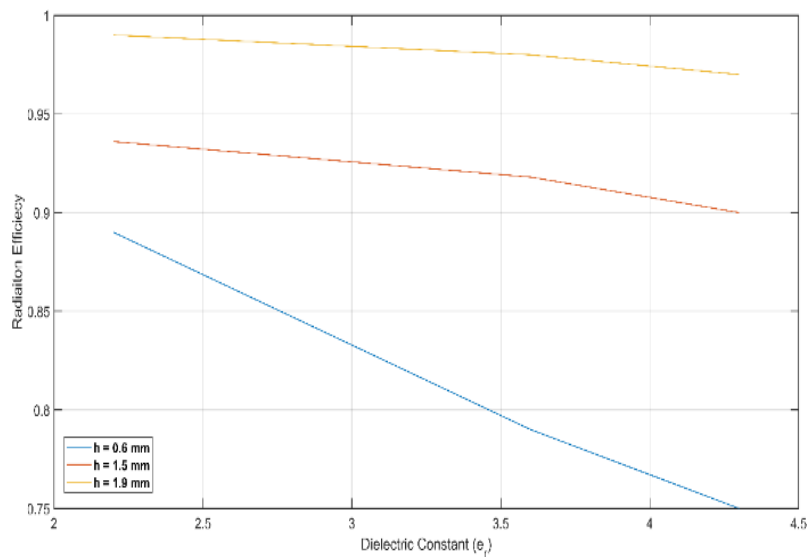


It is observed from Fig. (7), that the best value for S11 was at  $h = 1.5\text{mm}$  and  $\epsilon_r \sim 3.5$ , because; a large value of  $\epsilon_r$  gives good polarization, and the return loss will be reduced, so the incident wave is not distorted. In such a design, one can be obtained a good bandwidth in these values as in Fig. (8).

Also, the simulated and calculated results of the patch directivity and efficiency are plotted in Fig. (9), and Fig. (10).



**Fig. 9: The simulated results of directivity for the rectangular patch as a function of dielectric constant with different substrate thickness**



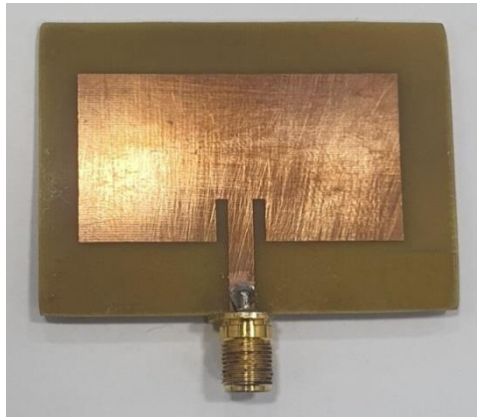
**Fig. 10: The simulated results of efficiency for the rectangular patch as a function of dielectric constant with different substrate thickness**

From Fig. (9 and 10), it is noted that a better efficiency value could be obtained for the higher values of thickness and  $\epsilon_r$ , but less directivity was given for the antenna.

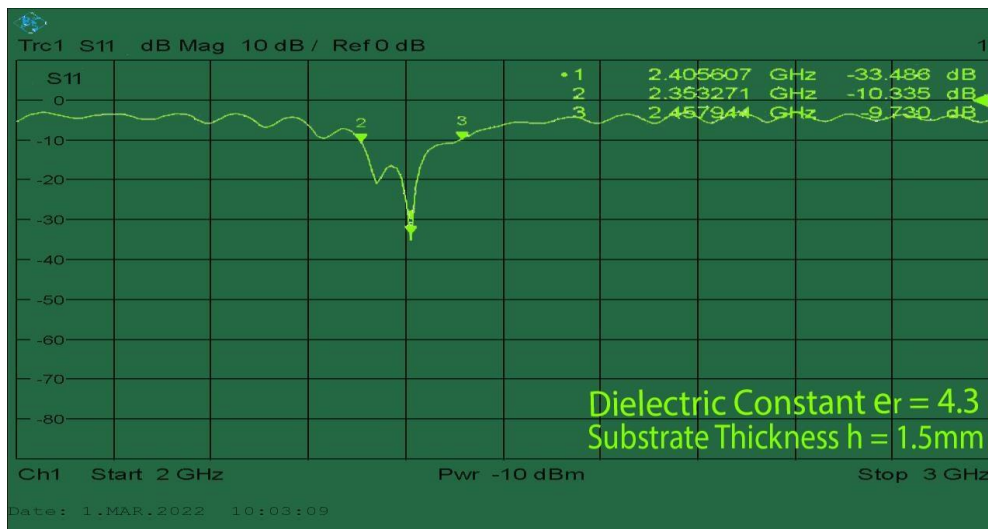
The reason for this is that for a fixed substrate thickness  $h$ , the resonant length and directivity increase with a decrease in the dielectric constant. The high dielectric substrate has the highest strength and breakdown voltage due to which it does not succumb to the electrical pressure easily. From the above, it is inferred that the working frequency of the antenna depends on the height of the substrate  $h$  and the dielectric constant. This agrees with (Khan and Nema, 2012; Ashish *et al.*, 2021).

### Fabrication of the Designed Antenna

To fabricate our antenna, the available substrate selected was FR-4 Epoxy ( $\epsilon_r = 4.3$ ) with thickness  $h = 1.5$  mm after the etching process the top view (patch) of the fabricated antenna is shown in Fig. (11). The dimensions of the fabricated antenna are those obtained by using the CST program. Such dimensions are the patch length  $L = 29$  mm, width  $w = 38$  mm, feeding point location  $y_0 = 7.4$  mm, feeder line width  $w_{50} = 2.94$  mm, and inset cut  $S = 1.47$  mm. The network analyzer has been used to test such fabricated antenna, which gives us practical return loss  $S_{11}$  results as shown in Fig. (12).

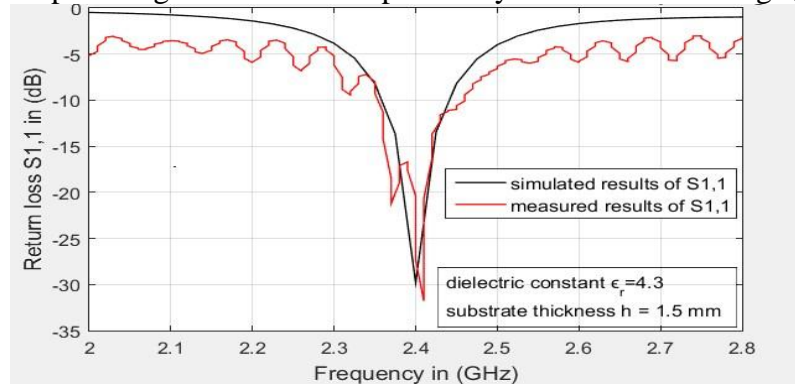


**Fig. 11: The top view of the fabricated microstrip rectangular patch antenna fixed with SMA connector**



**Fig. 12: Measured results of return loss for the designed rectangular microstrip antenna with dielectric constant  $\epsilon_r = 4.3$  and substrate thickness  $h = 1.5$  mm**

From measured results shown in Fig. (12), it is found that the patch antenna resonates at 2.4056GHz with a return loss of -33dB, and the impedance bandwidth is BW=100MHz. the return loss at designed resonance frequency  $f=2.4$ GHz is  $S_{1,1} = -27$  dB while from Fig. (13) the simulated value of return loss is  $S_{1,1} = -29$  dB. The simulated and practical measured performance results of the designed microstrip rectangular antenna are plotted by MATLAB as in Fig. (13).



**Fig. 13: Comparison of Simulated and measured results of return loss  $S_{1,1}$  for rectangular patch antenna**

Table 4, shows the comparison between the simulated and practical measured performance results of the designed Microstrip rectangular antenna which are obtained from Fig. (18).

**Table 4: Performances comparison between optimized and practical results of the designed microstrip**

Parameter	Optimized results	Measured results
Resonance frequency	2.4	2.4056
Return loss (dB)	-29	- 33
Impedance bandwidth (MHz)	79	100

## CONCLUSION

The paper presents a design of a low profile inset feed microstrip rectangular antenna working at 2.4 GHz. Three different substrates were studied using CST, with variable thicknesses of 0.6, 1.5, and 1.9mm. The simulation result of return loss  $S_{11}$  was less than -20dB *i.e.*, with reflection coefficient is less than 0.01 and this will lead to good performances due to very small reflected power. The designed patch antenna has narrow frequency bandwidth between (15-79MHz) depending on the thickness of the substrate also the bandwidth enhances as the substrate thickness increases and this may be useful in any application required to decrease the effect of radio frequency interferences. This simulation shows that the directivity and efficiency of the designed antenna decrease as the dielectric constant of the substrate increases for the same substrate thickness due to the increment in dielectric and conductor losses while the directivity decreased as the substrate thickness increases, and the efficiency increased as the thickness of substrate increases for the same value of dielectric constant. This is due to the total dielectric and conduction loss being decreased. Also, the results for directivity and efficiency were very close. The practical results show that the return loss (-33) dB is close to the simulation value, but there is a small difference (about ~30MHz) in the Impedance bandwidth. However, all other results were close.

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## تأثير ثلاث ركائز عازلة مختلفة على أداء الهوائي الرقيق المستطيل المصمم لـ 2.4 جيجا هرتز باستخدام CST

### الملخص

تقدم هذه الورقة تصميمًا لهوائي مستطيل الشكل منخفض النطاق يعمل بتردد 2.4 جيجا هرتز لدعم التطبيقات في القطاعات الصناعية والعلمية والطبية. يتم تصميم الهوائي باستخدام ثلاث ركائز مختلفة مع ثوابت عازلة تبلغ 2.2 و 3.6 و 4.3، ولكل منها سماكة ركيزة متغيرة تبلغ 0.6، 1.5، 1.9 ملم من أجل معرفة تأثير خصائص الركيزة على أداء الهوائي مثل الكسب والكفاءة وخسارة العودة وعرض النطاق الترددي. تم تحسين أبعاد وأداء الهوائي المصمم باستخدام برنامج تكنولوجيا محاكاة الكمبيوتر (CST) ومن ثم تم إجراء مقارنة بين أداء الهوائي السابق. تظهر النتائج العملية للهوائي مع الركيزة (ثابت العزل 4.3) و (سمك 1.5 مم) أن خسارة العودة هي (-31) ديسيبل وهي قريبة من قيمة المحاكاة، ولكن هناك فرق بسيط (حوالي ~ 30 ميغا هرتز) في عرض النطاق الترددي للمقاومة. ومع ذلك، كانت جميع النتائج الأخرى قريبة.

**الكلمات الدالة:** Microstrip، الهوائي، خسارة العودة، الحركية، CST.