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Design and Radiation Characterization of Rectangular Microstrip Patch Antenna for Millimeter-wave Communication

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ABSTRACT: *This paper presents the effect of dielectric constant and height of the substrate on radiation efficiency, directivity and gain, fringing field and radiation pattern, which are calculated and investigated with different parameters of the patch antenna for the millimeter-wave of 900 MHz and 1800 MHz frequencies. The fringing field created on patch antenna depends on the relative dielectric constant of the substrate. The desired radiation efficiency, directivity, beam width and gain can be achieved by selecting proper design parameters and substrate material of the patch antenna. For the height of 1.5 mm of polypropylene tape substrate, the estimated result of radiation efficiency is consistence with the previous report. Moreover, it is investigated that the electric field radiation pattern area is reduced with the increasing of dielectric constant of the substrate.*

KEYWORDS *rectangular patch antenna, polypropylene substrate, radiation efficiency, antenna directivity, radiation pattern.*

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I. INTRODUCTION

With the wide spread proliferation of wireless communication technology in recent years, the demand for compact, low profile and broadband antennas has increased significantly. To meet the requirement, the microstrip patch antenna has been a solution because of its low profile, light weight and low cost [1]. Microstrip patch antennas which are operating at millimeter-wave range are becoming more common to enter new niches of technologies in Bluetooth [2], Wi-Fi [3], WLAN [4] and many other wireless communication applications [5]. However, conventional microstrip patch antenna suffers from less radiation efficiency, narrow bandwidth, low directivity and gain due to surface wave loss and large and thicker substrate size configuration [2]. This poses a design challenge for the microstrip patch antenna designer to meet the broadband techniques [6].

Several techniques have been proposed to enhance the radiation efficiency in the state-of-the-art antenna research. The use of thick substrate, low dielectric substrate, multi-resonator stack configurations, impedance matching, slot antenna geometry and cutting a resonant slot inside the patch are the recently reported methods to increase the radiation efficiency and the directivity of patch antennas [7, 8]. There are many methods of microstrip antenna feeding have been demonstrated including co-axial feed, aperture coupling, proximity coupling. Among the methods, microstrip line feeding is an efficient feeding scheme because of its simple fabrication, easy connection to dielectric substrate and impedance matching property [9]. However, the thickness of the dielectric substrate deteriorates the antenna bandwidth efficiency by increasing surface wave and spurious feed radiation along with line feeding. Consequently, an undesired cross polarized radiation is led by feed radiation effects [10, 11]. Therefore, it is addressing from the wireless communication industry to optimizing the design of the microstrip patch antenna for achieving the maximum radiation efficiency.

In this paper, we have designed and investigated the radiation of a microstrip antenna with a rectangular patch. By using numerical analysis and MATLAB simulation tools, the effects of dielectric constant and height of substrate analyzed on the antenna radiation efficiency. Finally, a set of optimal design parameters has been proposed for reserving sufficient radiation efficiency.

II. GEOMETRY OF PROPOSED PATCH ANTENNA

Figure 1 shows the geometry of the proposed microstrip patch antenna. It consists of a conducting patch and ground plane with separating by a substrate that acts as a dielectric medium. The dimension of the patch, consequently microstrip patch antenna, as well as the antenna radiation performance depend on the resonant frequency and the dielectric constant of the substrate.

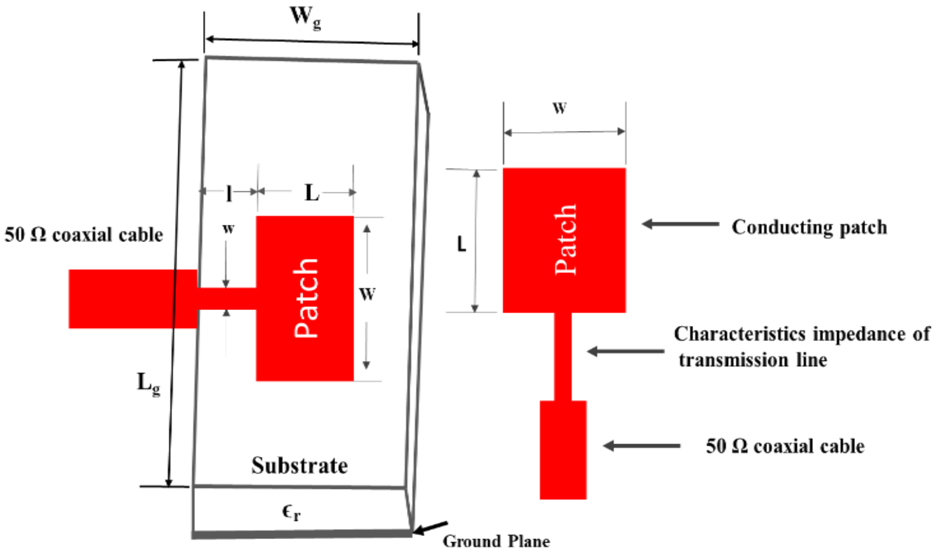

Fig. 1. Geometry of the proposed patch antenna.

III. DESIGN PRINCIPLES

After selection the desired resonant frequency (f_r), thickness (h) and dielectric constant (ϵ_r) of the substrate, the dimension of ground plane i.e., length (L_g) and width (W_g), and total impedance as well as radiation and beam pattern of the microstrip patch antenna can be obtained as [12, 13]:

i. Length and width calculation

The width of the Patch can be calculated by the formula:

$$W = \frac{1}{2f_r\sqrt{\mu_o\epsilon_o}}\sqrt{\frac{2}{\epsilon_r+1}} = \frac{v_o}{2f_r}\sqrt{\frac{2}{\epsilon_r+1}}$$

where v_0 = velocity of light = 3×10^8 m/s, and f_r = operating frequency in GHz.
The effective refractive index can be expressed as:

$$\epsilon_{eff} = \frac{\epsilon_r+1}{2} + \frac{\epsilon_r-1}{2}\left[1+12\frac{h}{W}\right]^{-1/2}$$

where, ϵ_r= relative dielectric constant of the base material, h = height of the substrate, W= width of the patch.
Effective length of the patch can be expressed as:

$$L_{eff} = \frac{1}{2f_r\sqrt{\mu_o\epsilon_o}\sqrt{\epsilon_{eff}}} = \frac{v_o}{2f_r\sqrt{\epsilon_{eff}}}$$

The extension of length of each side can be expressed as:

$$\Delta l = 0.412\frac{\epsilon_r + 0.300\left(\frac{W}{h}\right) + 0.262}{\epsilon_r - 0.258\left(\frac{W}{h}\right) - 0.813} \times h$$

The actual length of the patch can be expressed as:

$$L = L_{eff} - 2\Delta l$$

The thickness of the patch and transmission line is t << λ_0 [14], where λ_0 is the free space wavelength. Hence, the ground plane dimension, i.e., length (L_g) and width (W_g) for this design would be given as:

$$L_g = 6h+L$$
$$W_g = 6h+W$$

ii. Total input impedance

The total input impedance of the patch antenna is given by

$$Z_a = 90\,\frac{\varepsilon r^2}{\varepsilon r - 1}\left(\frac{L}{W}\right)^2$$

iii. Impedance matching

In practice, the characteristics impedance of the transmission line is usually real whereas that of the antenna element is complex. Also, the variation of each as a function of frequency is not the same. The efficient coupling-matching network must be designed which attempt to couple-match the characteristics of the two elements over the desired frequency range. There are coupling-matching networks, as shown in Fig. 2, that can be used to connect the transmission line to the antenna element of which quarter-wavelength transformer method is used in our design.

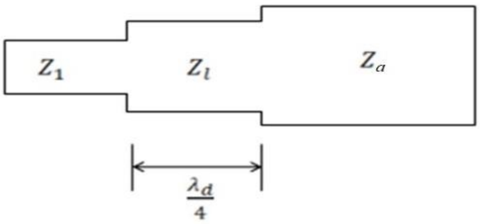

Fig. 2. Impedance matching of patch antenna

Characteristic impedance of the transmission line is

$$Z_l = \sqrt{Z_1 * Z_a}$$

where, Z_1 = probe impedance i.e., transmission line impedance.
Length of the transmission line is

$$\mathrm{TL} = \frac{\lambda_d}{4} = \frac{\lambda_o}{4\sqrt{\epsilon_r}}$$

Width of the transmission line can be expressed as:

$$TW = (5.98h\,\frac{1}{exp(\frac{Zl\sqrt{\varepsilon r+1.41}}{87})} - t)/0.8$$

iv. Radiation pattern

The radiation patterns of an antenna are of prime importance in determining most of its radiation characteristics, which include beam width, beam shape, directivity, and polarization and radiated power. The source of the radiation of the electric field at the gap of the edge of the microstrip element and the ground plane is the key factor to the accurate calculation of the pattern for the patch antenna. The radiated field equations are given as [15]:

For E-plane:

$$E_\theta = \frac{jke^{-jkr}}{2\pi r} E_0\, WhSin\,\theta \,.\frac{Sin(X)}{X}\,.\frac{Sin(Y)}{Y}$$

$$E_{\emptyset} = \frac{jke^{-jkr}}{2\pi r} E_0 \, WhCos\theta Cos\emptyset \, . \frac{Sin(X)}{X} \, . \frac{Sin(Y)}{Y}$$

For H-plane:

$$H_{\emptyset} = -\frac{E_{\Theta}}{\eta} = -\frac{jke^{-jkr}}{\eta 2\pi r} E_0 \, WhSin\theta \, . \frac{Sin(X)}{X} \, . \frac{Sin(Y)}{Y}$$
$$H_{\Theta} = -\frac{E_{\emptyset}}{\eta} = -\frac{jke^{-jkr}}{\eta 2\pi r} E_0 \, WhCos\theta Cos\emptyset \, . \frac{Sin(X)}{X} \, . \frac{Sin(Y)}{Y}$$

where, $X = k(\frac{W}{2} Sin\theta Cos\emptyset)$ and $Y = k(hSin\Theta Sin\emptyset)$.
The two radiating slots of one patch separated by the distance L_{eff}. The total field of the patch is given by

$$E_{\theta}^{T} = E_{\theta} . AF$$
$$E_{\emptyset}^{T} = E_{\emptyset} . AF$$
$$H_{\emptyset}^{T} = H_{\emptyset} . AF$$

where, array factor $AF = 2Cos(\frac{kLeff}{2} Cos\theta)$.

v. Beam width

The half power beam width of an antenna is equal to the angular width between directions where the radiated field reduces to half of the maximum value. Half power beam width for H and E planes are calculated respectively as:

For H-Plane: $$\theta_H = 2 \, sin^{-1}\{\frac{1}{2+k_0 W}\}^{1/2}$$

For E-Plane: $$\theta_E = 2 \, sin^{-1}\{\frac{7.03}{3k_0^2 L^2 + k_0^2 L^2}\}^{1/2}$$

where, $k_0 = w_0\sqrt{\mu\varepsilon} = 2\pi f_r \sqrt{\mu\varepsilon}$.

vi. Directivity and gain

The directivity is defined as the ratio of the maximum power density in the main beam direction to the average radiated power density. The directivity (*D*), and gain (*G*) of the patch antenna is expressed as:

$$D = \frac{4(k_0 W)^2}{\pi \eta_0 G_r}$$

and $$G = E_r * D$$

where, G_r $(=1/Z_a)$ is the radiation conductance of the patch and $\eta_0 = 120\pi$ ohm, E_r is the radiation efficiency of the antenna.

vii. Radiated power

The power radiated by an antenna can be obtained by the following equation:

$$P_r = 40k_0^2(k_0 h)^2\{1 - \frac{1}{\varepsilon_r} + \frac{2}{5\varepsilon_r^2}\}$$

viii. Surface wave power

The surface wave power is given by

$$P_{sur} = 30\pi k_0^2 \frac{\varepsilon_r(X_0^2 - 1)}{\varepsilon_r[\frac{1}{\sqrt{X_0^2-1}} + \frac{\sqrt{X_0^2-1}}{\varepsilon_r - X_0^2}] + k_0 h[1 + \frac{\varepsilon_r^2(X_0^2-1)}{\varepsilon_r - X_0^2}]}$$

where, $X_0 = \frac{\beta}{K_0} = 1 + \frac{1}{2}\{\frac{\varepsilon_r - 1}{\varepsilon_r} K_0 h\}^2$, and $\frac{\beta}{K_0} = 1 + \delta$.

v.Radiation efficiency

The radiation efficiency of the antenna can be calculated by the following equation:

$$Er = \frac{P_r}{P_r + P_{sur}}$$

IV. SIMULATION RESULT AND DISCUSSION

The Tables 1 and 2 show the variations of the radiation efficiency for different substrate materials and substrate height of polypropylene material, respectively for proposed design parameters. The different materials represent different radiation efficiency. The polypropylene tape shows the highest radiation efficiency, directivity and gain. The alumina represents the lowest radiation efficiency, directivity and gain. With the increasing substrate height, the radiation efficiency, directivity and gain decreases. For the particular height of 1.5 mm of polypropylene substrate, the radiation efficiency, directivity and gain are 99.0257, 8.6887 and 8.6040 respectively. With using of polypropylene thin-film tape as a substrate, the obtained result of radiation efficiency is consistence with the previous report [16].

Table 1: Variation of radiation efficiency, directivity and gain with different substrate materials.

Material	Substrate height (mm)	Radiation efficiency (%)	Directivity (dB)	Gain
Polypropylene	1.5	99.0257	8.6887	8.6040
Duroid	2.32	96.2082	5.5110	4.9557
Rogers 6002	3	94.5452	4.4181	4.1771
FR-4	4.4	92.5013	3.8323	3.5450
Alumina	8.8	90.1152	3.3568	3.0250

Table 2: Variation of radiation efficiency directivity and gain with polypropylene tape-substrate height for 1.8 GHz frequency.

Substrate height (mm)	Radiation efficiency (%)	Directivity (dB)	Gain
1.5	99.0257	8.6887	8.6040
2.5	98.3684	8.4659	8.3277
3.5	97.7065	8.2368	8.0479
4.5	97.0414	8.0047	7.7679

Table 3: Comparison between two different design parameters.

Antenna characteristic	Design-1	Design-2
Operating frequency	0.9 GHz	1.8 GHz
Dielectric constant of the substrate	1.5 (polypropylene)	1.5 (polypropylene)
Height of the substrate	1.5 mm	1.5 mm
Width of patch	148.97 mm	74.48 mm
Length of patch	134.84 mm	66.81 mm
Length of the transmission line	68.04 mm	34.02 mm
Width of the transmission line	0.897 mm	0.918 mm
Thickness of the transmission line	0.035 mm	0.035 mm
Width of the ground plane	157.97 mm	83.48 mm
Length of the ground plane	143.84 mm	75.81 mm

The Tables 3 and 4 represent the two design parameters for the antenna with operating frequency 0.9 GHz and 1.8 GHz for the substrate of polypropylene at the height of 1.5 mm. The estimated radiation efficiency and the directivity of both the designs are around 99% and 8.7 respectively. However, the size dimension of the microstrip patch antenna for the design of 0.9 GHz frequency is almost twice than that of the antenna for the design of 1.8 GHZ.

Table 4: Comparison between two different designs.

Antenna characteristic	Design-1	Design-2
Operating frequency	0.9 GHz	1.8 GHz
Radiation efficiency	99.51%	99.02%
Directivity	8.85 dB	8.69 dB
Half power beam width of E-plane	82.83^0	63.47^0

It has been observed from the simulation results from Fig. 3 that the radiation efficiency is very low in the frequency range 1.5×10^{10} Hz. The maximum radiation efficiency has been obtained in the frequency range of 4×10^{10} to 5×10^{10} Hz. At the higher frequencies, above 5×10^{10} Hz, the radiation efficiency has been going to decrease slowly. Figures 4 and 5 depict that the radiation efficiency of the patch antenna decreases with increasing dielectric constant and substrate height. From the simulation results of Fig. 4 and 5, it might be predicted that the radiation efficiency would be theoretically about 1 at low dielectric constant of nearly 1, when the substrate height of the microstrip patch antenna will be less than 1 mm.

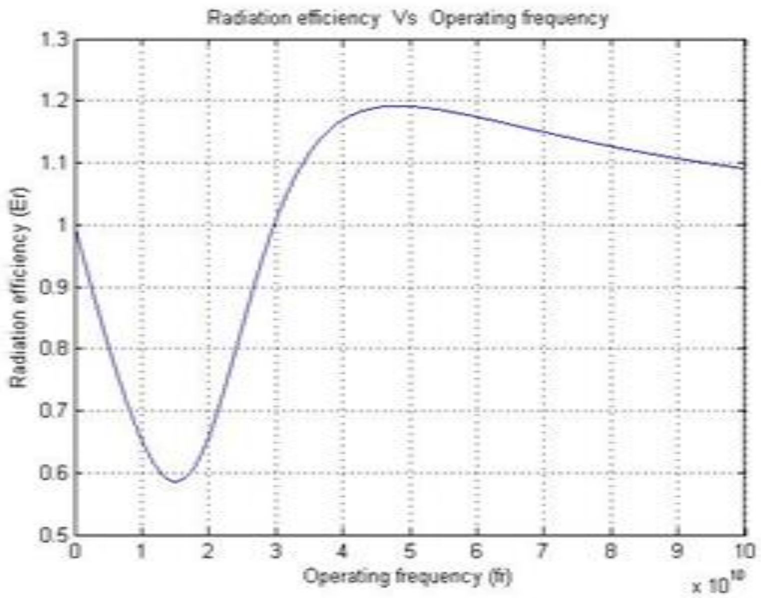

Fig. 3. Variation of radiation efficiency with operating frequency for the microstrip patch.

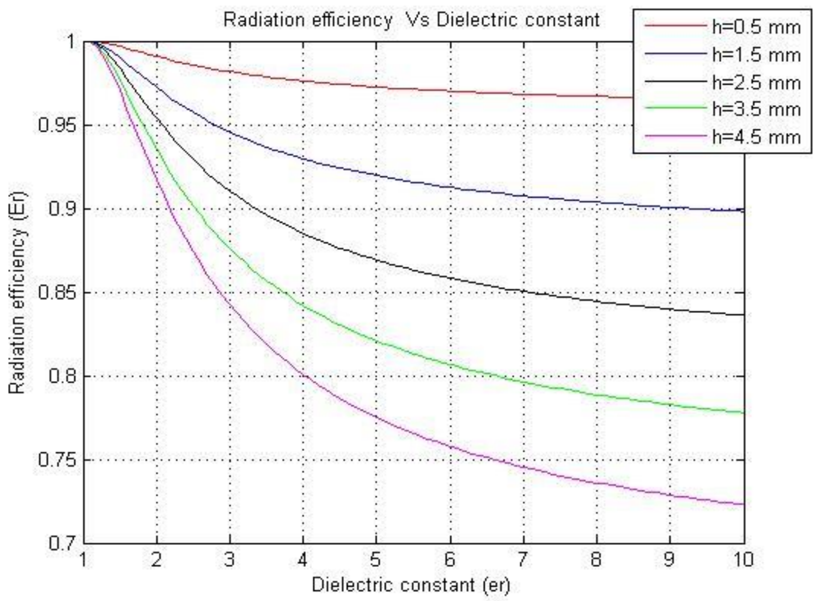

Fig. 4. Variation of radiation efficiency with dielectric constant for the microstrip patch.

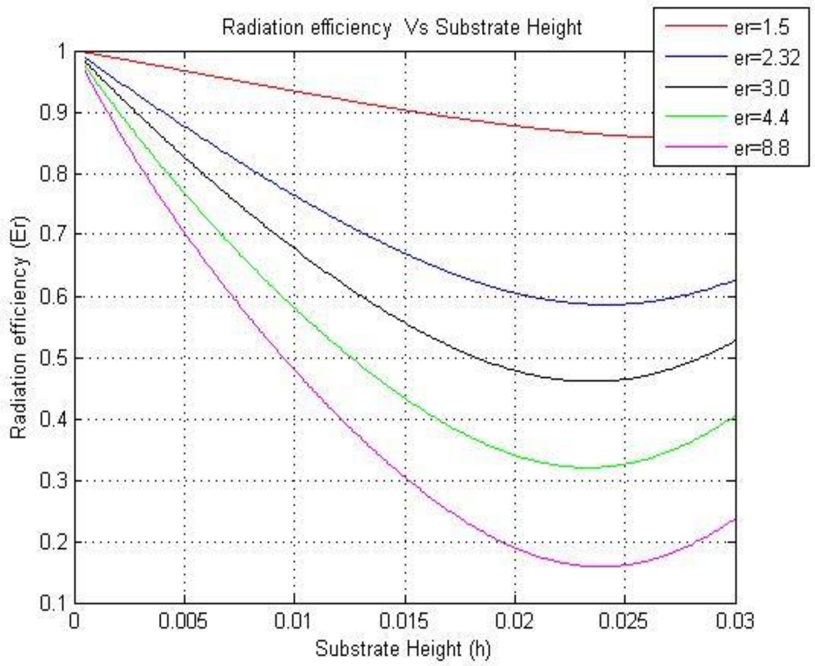

Fig. 5. Variation of radiation efficiency with substrate height for the microstrip patch.

The electric field radiation patterns are shown in Figs. 6 and 7 for the angle of theta and phi, respectively. With the increase of the dielectric constant value, the radiation pattern area reduces for both cases.

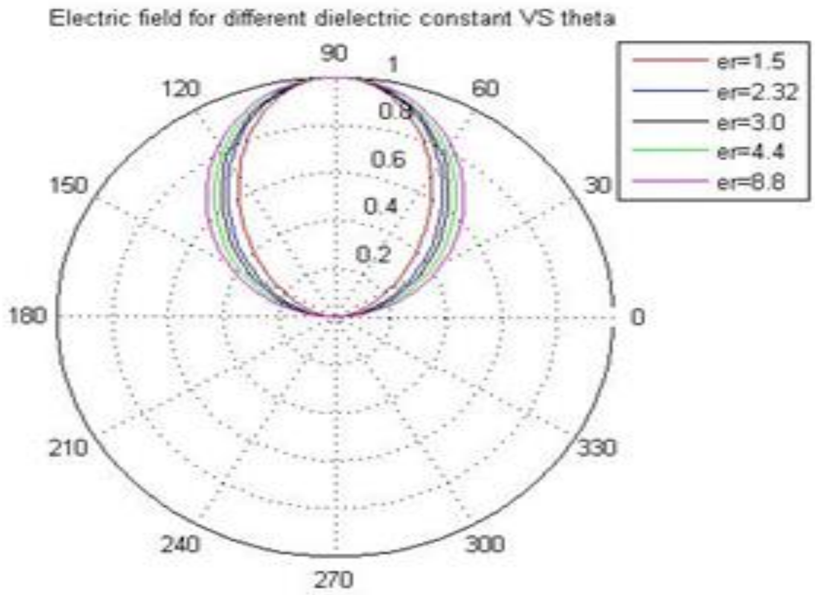

Fig. 6. Variation of electric field for different dielectric constant VS theta.

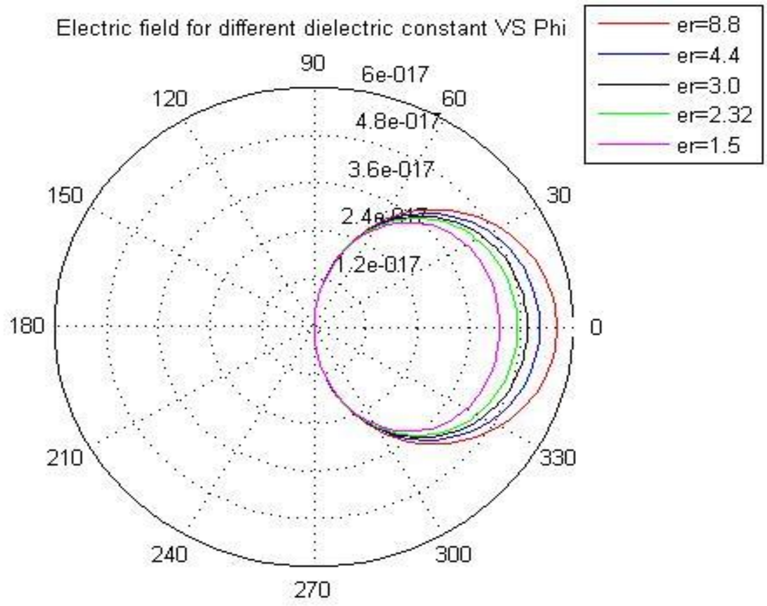

Fig. 7. Variation of electric field for different dielectric constant at angle phi

V. CONCLUSION

Patch antennas are extremely versatile antennas which can be utilized for many applications due to how simple it is to create different geometries. Their versatility is expanding as new designs, which are created and modeled using MATLAB simulation software. Patch which exists as free-form antenna shapes in cell phones or as multi-layer PCBs that utilize switching functionality built into the antenna. These complicated geometries create extremely small, smart antennas offering high directivity for desired channels and utilizing deconstructive interference effects to cancel out unwanted interference. The aim of this project is to design a rectangular patch microstrip antenna and to study the responses and the radiation properties of the same. In this project, an antenna has been designed with two different design parameters. Taking all results into consideration, we can say that there are many aspects that affect the performance of the antenna. Dimensions, selection of the substrate, and the operating frequency can take their position in effecting the performances. A rigorous advance analysis of the problems is essential with the application of the equivalence principle that introduces the unknown electric and magnetic surface current densities on the dielectric surface, where the formulation of the radiation problems will be based on the numerical solution of the combined field integral equations.

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