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Bandwidth Enhancement Analysis of Rectangular Microstrip Patch Antenna for Various Substrates

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Abstract

The goal of this research is to enhance the bandwidth of a rectangular patch microstrip antenna. The bandwidth of the antenna is tuned by analyzing the various dielectric substrate mat erials, height & width, coaxial feed line, input and output impedances with effective dielectric constant s, and effective length. The suggested rectangular microstrip patch antenna operates at a frequency of 4.4 GHz. As a function of various frequencies, the VSWR, S11 and efficiency are analyzed. This analysis emphasizes that a low dielectric constant with an appropriate height of the dielectric substrate material for a microstrip patch antenna is utterly important in terms of enhancing bandwidth as well as a surface wave. This analysis gives better results for the RT-Turoid and attains a bandwidth of 56.65% at 4.4 GHz of resonance frequency. This high bandwidth makes it useful in many wideband applications.

Keywords: Dielectric substrates; Rectangular patch; Bandwidth; Coaxial Feedline; S11 parameter; VSWR and Efficiency

Introduction

The ease of fabrication and integration with RF devices, low posture, light weight, and economy are the notorious aspects of microstrip patch antennas (MPAs) [1]. This is especially suitable for encapsulating antennas in tiny wireless devices. Antennas are an essential part of wireless and Wi- Fi communication. Communication systems make use of frequencies ranging from 1800 to 5600 MHz [2]. Despite this, the primary defect of a MPA is its intrinsically limited bandwidth, which reduces its wide utilization [3]. There are several acknowledged methods available to increase the bandwidth of this type of antenna. Increasing the thickness of the substrate and using a low-dielectric constant substrate material are the best ways to enhance the bandwidth. A thick substrate having a low dielectric constant is the most favorable to contribute greater efficiency, improved bandwidth, and larger radiation [4]. MPAs are commonly used in wireless devices. Therefore, the miniaturization of the patch antenna becomes an important issue in reducing the volume of an entire communication system.

The selection of the resonant frequency of the antenna must depend on a wide range of applications. Hence, the antenna designed should be able to operate at this frequency [5]. In this work, the contribution of various dielectric substrates and patch dimensions on the bandwidth enhancement of 4.4 GHz resonant frequency as well as the effect of coaxial-feed position coordinates, input impedance, and output impedance corresponding to VSWR, and S11 for various frequencies are studied.

Theory of Microstrip patch Antenna

Patch dimension is needed to design an antenna because it has an impact on the electrical performance as well as providing mechanical support to the antenna. The selection of an appropriate thick substrate with a low dielectric constant, the shape of the patch, and the thickness of the substrate significantly limit the problem of low efficiency, narrow bandwidth, and small gain. The fabrication of an antenna with compact size and low cost, a simple radiating element, good performance, and easy fabrication is the biggest challenge for designers, which is required by today's wireless systems. The resonant frequency (f_r), dielectric constant (ε_r) and thickness of the substrate (h) are the significant criteria for designing the patch antenna. Since some of the waves travel in the substrate and some in the air, the effective dielectric constant is given by [6].

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + \frac{1.8}{f_r\sqrt{\frac{\varepsilon_r + 1}{2}}}\right)^{-\frac{1}{2}} \quad \text{...............(1)}$$

Generally, the operating wavelength of the antenna is always greater than the height of the substrate h. But it should be taken into account that it should not become smaller than 0.025 of the operating wavelength. The equation below is used to find the height of the dielectric substrate as follows [7].

$$h = \frac{0.3c}{2\pi f_r\sqrt{\varepsilon_r}} \quad \text{........................(2)}$$

The bandwidth (BW) of an antenna indicates the range of frequencies over which the antenna can perform its function properly [8]. The patch shape, resonant frequency, dielectric constant, and thickness of the substrate cause the bandwidth enhancement of the antenna. The radiating edge, patch width, is usually chosen such that it lies within the range L<W<2L, for better radiation [9]. As the substrate thickness increases, the bandwidth also increases correspondingly. Also, the patch ordinarily finds it difficult to agree as the substrate thickness augments beyond a certain point (typically about 0.05 λ_0). The greater the width of the patch antenna, the greater the bandwidth and control over the antenna's radiation pattern. The width of the antenna patch can be calculated as given below [10].

$$W = \frac{c}{2f_r\sqrt{\frac{\varepsilon_r + 1}{2}}} \quad \text{............(3)}$$

Where

ε_r - Dielectric constant of the substrate,

C - Velocity of light,

f_r - Resonant frequency,

The length of the patch is given by [11].

$$L = L_{eff} - 2\Delta L \quad \text{........(4)}$$

$$\text{where} \quad L_{eff} = \frac{c}{2f_r\sqrt{\varepsilon_{eff}}} \quad \text{........(5)}$$

The length of the patch can be extended over each end by a distance ΔL according to the fringing effect, which is expressed by.

$$\Delta L = 0.412\frac{h(\varepsilon_{reff}+0.3)(\frac{w}{h}+0.264)}{(\varepsilon_{reff}-0.258)(\frac{w}{h}+0.8)} \quad \text{..................(6)}$$

Where

ε_{reff} - Effective dielectric constant.

f_r - Resonant frequency of antenna respectively.

The decreased resonant resistance is provided by the larger patch width which gives the increased power radiation, enhanced BW, and increased radiation efficiency. The selection of the patch width (W) should be greater than the patch length for proper excitation. The percentage bandwidth of the rectangular patch microstrip antenna can be calculated in terms of patch dimensions and substrate parameters as follows [12].

$$BW = \frac{Ah}{\lambda_0}\sqrt{\frac{W}{L}} \quad \text{................ (7)}$$

Where

$$\text{A=180 for } \frac{h}{\lambda_0\sqrt{\varepsilon_r}} \leq 0.045$$

$$\text{A=200 for } \frac{h}{\lambda_0\sqrt{\varepsilon_r}} \leq 0.075$$

$$\text{A=220 for } \frac{h}{\lambda_0\sqrt{\varepsilon_r}} \geq 0.075$$

An attempt has been made to enhance the bandwidth of an antenna by using a rectangular patch that has the significant aspects of feed line affability, beam scanning, and frequency acuteness [13]. The coaxial feed coordinates can be analyzed by [14].

$$X_f = \frac{L}{2\sqrt{\varepsilon_{reff}}} \quad \text{....... (8)}$$

$$Y_f = W/2 \quad \text{.......... (9}$$

The length and width of the ground plane is given by [15].

$$L_g = 6h + L \quad \text{......}$$

$$W_g = 6h + W \quad \text{...... (10)}$$

Suited input impedance matching of MPA plays a vital role in the enhancement of the bandwidth [16]. Thus, to improve the performance of the antenna, should have a low desired dielectric constant, which increases the bandwidth, efficiency, and gain of the microstrip antenna. The effective dielectric loading of a microstrip antenna influences both its radiation pattern and bandwidth.

Width and Length are the key factors of the input impedance of the antenna design. The input impedance of the MPA is calculated as follows [17].

$$Z_{in} = 90 \frac{\varepsilon_r^{\,2}}{\varepsilon_r - 1} \left(\frac{L}{W} \right)^2 \ldots\ldots(11)$$

The output impedance of MPA which is based on the strip line width and is given below.

$$\text{If} \left(\frac{W_f}{h} \right) < 1:$$

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left[\frac{1}{\sqrt{1 + 12 \left(\frac{h}{W_f} \right)}} + 0.04 \left(1 - \left(\frac{W_f}{h} \right) \right)^2 \right];$$

$$Z_0 = \frac{60}{\sqrt{\varepsilon_{reff}}} \ln \left(8 \left(\frac{h}{W_f} \right) + 0.25 \left(\frac{W_f}{h} \right) \right)$$

$$\text{If} \left(\frac{W_f}{h} \right) > 1:$$

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left[\frac{1}{\sqrt{1 + 12 \left(\frac{h}{W_f} \right)}} \right];$$

$$Z_0 = \frac{120\pi}{\sqrt{\varepsilon_{eff}} \left[\frac{W_f}{h} + 1.393 + \frac{2}{3} \ln \left(\frac{W_f}{h} + 1.444 \right) \right]} \ldots\ldots(12)$$

Where

W_f - Width of the feed line.

h - Dielectric thickness.

The voltage standing wave ratio (VSWR) indicates mostly a measure of the impedance mismatch between the transmitter and the antenna which is calculated by using the below equation:

$$VSWR = \frac{1 + |\Gamma|}{1 - |\Gamma|} \ldots\ldots(13)$$

$$\Gamma = \frac{Z_{in} - Z_0}{Z_{in} + Z_0} \ldots\ldots\ldots (14)$$

Where

Γ - Reflection Coefficient.

The return loss (S_{11}) is a parameter that presents the amount of power that is strayed to the load and is not put back as a reflection. Return loss is a function of how devices or lines are matched in a desirable manner. If the return loss is high, the match is good. The return loss of the circuit can be calculated as follows [18].

$$S_{11} = -20 \log \left[\frac{VSWR - 1}{VSWR + 1} \right] \ldots\ldots (15)$$

If an antenna is taken as a device that accepts power from a source and radiates it into space, the ratio of the power radiated into space to the power accepted from the source is the efficiency, which can be analyzed as given below [19].

$$\text{where} \quad P_r = 40k_0^{\,2}\left(k_0 h\right)^2\left\{1-\frac{1}{\varepsilon_r}+\frac{2}{5\varepsilon_r^{\,2}}\right\}$$

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

Results and Discussion

The bandwidth enhancement can be achieved by selecting proper design parameters and substrate material for the patch antenna. The methods for increasing the BW of MPA are continuously upgraded. Various techniques for increasing MPA bandwidth are theoretically analyzed using the above equations. In this research, the following methods are analyzed; patch dimension, frequency, choice of type of feeding, impedance matching, VSWR, and S_{11} parameter. The MPA is designed by applying these bandwidth enhancement techniques, which are discussed.

Frequency

The working frequency of the antenna must be reasonably chosen. The patch length has an influence on the resonant frequency. The suggested antenna must operate within the desired frequency band. The working frequency in our analysis is picked up to be 4.4 GHz for all the substrates that we have taken for bandwidth analysis of the antenna.

Shape of the Patch

MPA is composed ordinarily of a dielectric substrate concealed with two metallic sheets on both sides; one of them is the radiating patch, while the other is the ground. The radiating patch is composed of conducting materials such as copper and gold. Patches take various geometrical shapes, like rectangular, circular, triangular, square, etc. In our work, we take a rectangular shape for better results.

Dielectric Substrate

The overall performance of the antenna is controlled by the dielectric constant. The increased substrate thickness and the reduced dielectric constant are the basic criteria to improve the bandwidth. Generally, the range of the dielectric constant should be in the range ($2.2 \leq \varepsilon_r \leq 12$). To design an antenna, the selection of the substrate is crucial, and it must be a dielectric material. The material that has a low dielectric constant value is regarded as a better nonconductor because it can prevent the absorption of electrons into it, produces a low return loss, and has a higher bandwidth. Diverse types of substrates exist such as ceramic substrates, composite substrates, ferromagnetic substrates, synthetic substrates, semiconductor substrates, flexible substrates, low-loss substrates, low- cost substrates, etc. In this paper, the materials that are capable of being stretched, are considered the substrate material [20]. In this paper, eight substrates with different dielectric constants have been taken for analysis, which is given in Table 1.

Dielectric Materials	*Dielectric Constants*
RT-Duraid	2.2
Polypropylene	2.33
Taconic	3.2
RO 4003	3.4
FR4	4.36
Bakelite	4.78
Porcelain	6.80
Ceramic	10.2

Table 1

Thickness of the substrate

The antenna's performance can be enhanced by selecting an appropriate substrate that contains properties such as thickness, dielectric constant, loss tangent, flexibility, chemical stability, and weather- resistant, etc. If the height of the substrate augments the fringing field from the edge, this causes the extension of the length of the patch, leading to a decrease in resonant frequency. The dielectric substrate height of the rectangular patch should be generally between the range of $0.003\lambda_0 \leq h \geq 0.05\lambda_0$. The Patch is taken to be thin that is in range of $t << \lambda_0$ (where "t'' is the patch thickness) [21]. By keeping the resonance frequency as constant of 4.4GHz, the height, width, length and, effective dielectric constant, effective length and bandwidth of the antenna is calculated by using the equation (1), (2), (3), (4), (5) & (7) for the various dielectric substrates and tabulated as follows.

Dielectric Constant ε_r	*Effective dielectric constant (ε_{reff})*	*Height (mm)*	*Width (mm)*	*Length (mm)*	*Effective length(mm)*	*Band width %*
2.2	2.03	2.19	26.95	21.71	23.9	56.65
2.33	2.14	2.13	26.40	21.11	23.3	55.51
3.2	2.89	1.82	23.52	18.29	20	37.24
3.4	3.07	1.76	22.98	17.79	19.4	35
4.36	3.9	1.56	20.82	15.83	17.2	27.64
4.78	4.27	1.48	20.05	15.05	16.5	25.12
6 .80	6.03	1.24	17.26	12.80	13.8	17.81
10.2	8.99	1.01	14.40	10.5	11.3	11.95

Table 2

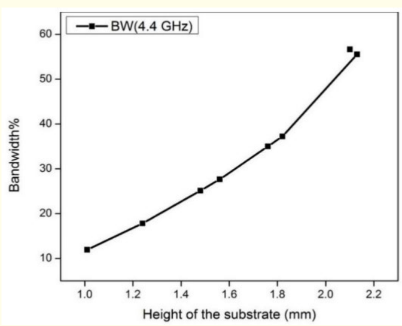

Figure 1: Bandwidth versus thickness of various substrate at 4.4 GHz.

The multifarious dielectric constants of the substrate will change the dimensions of the antenna deeply, which affects the bandwidth of the antenna. The analysis of bandwidth is carried out due to the change in substrate height for diverse dielectric substrate materials, as shown in Fig.1. By changing the height of the substrate, the bandwidth can also be changed. The change in height of the substrate from 1 mm to 2.2 mm along with the change in substrates, changes the bandwidth proportionally. At the height of the substrate h=2.19mm of RT-Duroid dielectric substrate, we obtained a bandwidth of 56.65%, which is the highest level at frequency 4.4GHz among all-dielectric substrate materials that we have selected for the tuning of bandwidth.

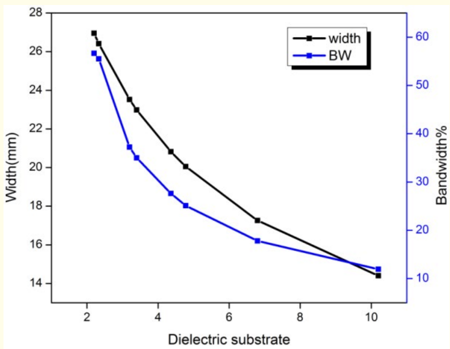

Figure 2: Bandwidth and Width for various dielectric substrate at f0= 4.4GHz.

The width of the patch has always been in accordance with the bandwidth. Bandwidth increases according to the width of the patch up to its limit, which describes the bandwidth enhancement techniques. Fig.2 confirms that if the width of the patch decreases bandwidth also decreases for the diverse dielectric substrate. An analysis of various dielectric substrate materials confirms that high dielectric constant materials reduce the width of the patch, which limits the bandwidth. As a function of a dielectric substrate material value of 2.2, the patch, which has a width of 28 mm provides bandwidth enhancement of 56.33%.

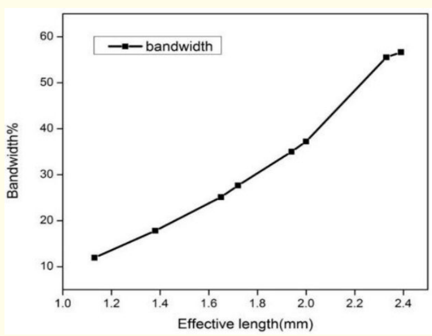

Figure 3: Bandwidth versus Effective length.

Fig. 3 shows the variation of the bandwidth with effective length. It can be observed from this analysis that the large effective length gives a better bandwidth. As the dielectric substrate constant increases, the effective length of the patch decreases, as well as the bandwidth. The dielectric substrate of RT-Turoid, with an effective length of 23.9 mm, provides a better bandwidth.

Choice of type of feeding

The choice of the best feed point location, which achieves the highest performance of the designed antenna in bandwidth enhancement. From the origin, the best feed point is tried and located at Xm, Yn direction. Among the various feed techniques, only the coaxial probe feed technique comprises of a central probe conductor that is directly connected with a patch antenna and supplies its feeding energy. The coax represents the outer connector around the probe, and it is connected with the ground plane by which the circuit becomes complete [22].

To further improve the bandwidth, a coaxially-fed patch is introduced to realize the enhancement of the radiation pattern. The coaxial cable feed is easy to implement, however, this type of power generates spurious radiation that affects the radiation pattern.

Feed Point Location

The feeding probe point location could be positioned at the point (Xf, Yf) in the x-y direction. The stationed points are disposed of by equations (9) and (10). The centre of the patch was taken at its origin. The feed point location is given by the coordinates (x, y) from the origin. The feeding point ought to be positioned at that point on the patch, which provides the best performance of the antenna, where Xf and Yf are the desired input feed points on the x and y axes, respectively. In this design, the impedance of the feeding point for the microstrip patch antenna can be controlled by changing the location of the feed point. The correct selection of the feeding point location decreases the input impedance and raises the return loss, gain, efficiency, directivity, and bandwidth. The feeding coordinates can be calculated for the various substrates by using equations (8) and (9) and are given in Table. 3.

Dielectric constant (ε_r)	*Width(mm)*	*X_f (mm*	*Y_f (mm)*
2.2	26.95	13.47	7.62
2.33	26.41	13.20	7.21
3.2	23.52	11.76	5.37
3.4	22.98	11.49	5.07
4.36	20.82	10.41	4
4.78	20.05	10.02	3.66
6.80	17.26	8.63	2.6
10.2	14.40	7.2	1.7

Table 3

Impedance matching

Impedance matching of the circuit is the basic criteria in an antenna, which provides better radiation and a large bandwidth for wide application in communication. Impedance matching is the practice of designing the input impedance of an electrical load or the output impedance of its corresponding signal source to maximize the power transfer or minimize signal reflection from the load. The frequency for which the impedance magnitude is maximum, or equivalently the reactance is zero, is often defined as the resonant frequency.

In the high-frequency domain, impedance matching is one of the most important parameters that is used to improve the performance of the system. The aim is to ensure maximum power transfer and avoid reflected waves. Many approaches have been used to enhance the bandwidth of patch antennas, such as by obtaining a good impedance match between the feeding line and the radiating element [23]. The input and output impedance, which result in better bandwidth and higher efficiency of the antenna, are calculated by using equations (11) and (12) for various dielectric materials, and the calculated values are tabulated as follows.

Dielectric constant (ε_r)	***Effective dielectric constant (ε_e)***	***Input Impedance (Ω)***	***Output Impedance (Ω)***
2.2	2.03	235.99	165.3
2.33	2.14	234.93	165.7
3.2	2.89	253.3	137.8
3.4	3.07	259.7	132.5
4.36	3.9	294.3	115.4
4.78	4.27	311.0	108.9
6.80	6.03	394.5	89.6
10.2	8.99	541.0	71.9

Table 4

From Table. 4 above, we know that low dielectric constant materials cause impedance matching in the circuit, which leads to an enhancement of the bandwidth. Instead, as the dielectric constant increases, the difference between the input and output impedance increases, which causes mismatching in the circuit and provides a narrow bandwidth.

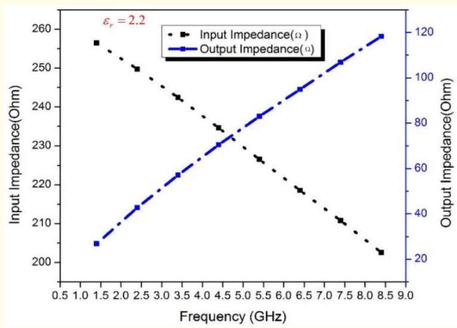

Figure 4: Input and Output Impedance versus Frequency.

It can be noted from Fig.4, which is calibrated as a function of frequency change with an impedance of RT-Turoid. Input and output impedance versus change in frequency emphasizes the good impedance matching in which the input and output impedance values intersect at the frequency of 4.4 GHz that is selected as a resonant frequency, which causes better results in VSWR, S_{11} and, efficiency of an antenna.

S_{11} parameter, VSWR & Antenna Efficiency.

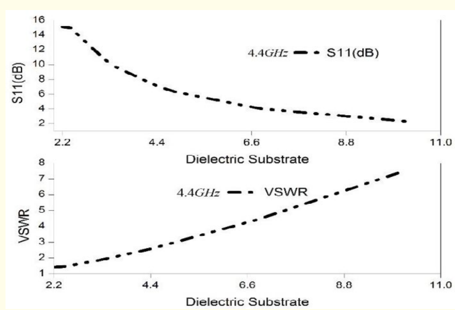

Figure 5: S_{11} &VSWR versus various dielectric substrate at 4.4 GHz.

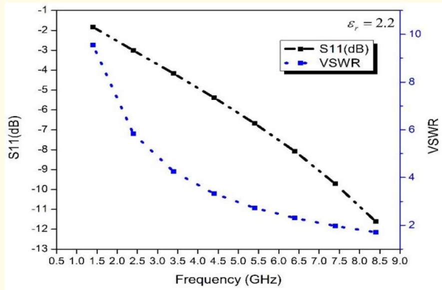

Figure 6: S_{11} &VSWR versus Frequency.

In the microwave network, the parameter S_{11} represents the input side reflection coefficient, which quantifies the amount of RF or microwave energy coming back to the port for the signal transmission. When a signal is transmitted through a transmission line, some of the signal power is always reflected or returned to the source due to discontinuities in the transmission line. The measure of this reflected power is called S_{11}. Generally, the range of values for return losses from -10 dB to -12 dB is acceptable. VSWR is the ratio of the maximum to the minimum of this undesired signal wave. It is a measure of how efficiently radio-frequency power is transferred from a power source to a load. In the case of an MPA, the input impedance versus the output impedance, which is utilized as a transitional criterion for determining the S_{11} parameter (a measure of the reflection coefficient Γ), VSWR are analyzed. The return loss is expressed in dB in terms of S_{11} as a function of various frequencies. Taking antenna parameters into account, VSWR is affected by the dielectric substrate and frequency.

By using equations (13), (15), and (16), the important parameters such as reflection coefficient, VSWR, S_{11}, efficiency are evaluated. The dielectric substrate and frequency dependence magnitudes of the S_{11} parameter and VSWR are shown in Figs (5) and (6). The Fig.5 shows that as the dielectric constant of the substrate increases, the S_{11} parameter decreases and attains -11.61 dB, but the VSWR increases and attains 7.2 at the frequency of 4.4 GHz, which means that 90% of the power is delivered to the antenna as an input, which enhances the bandwidth of the antenna.

The reflection coefficient, VSWR, S11 and efficiency are evaluated and tabulated for the material of RT- Turoid, which yields the best results among the selected dielectric materials as follows.

Frequency (GHz)	*Refection Coefficient*	*VSWR*	*S11(dB)*	*Efficiency (%)*
1.4	0.810576	9.55	-1.824	77
2.4	0.707585	5.84	-3.004	82
3.4	0.618723	4.24	-4.17	86
4.4	0.538174	3.33	-5.382	89
5.4	0.463750	2.73	-6.674	91
6.4	0.394416	2.3	-8.081	92
7.4	0.326995	1.97	-9.709	93
8.4	0.26258	1.71	-11.61	93

Table 5

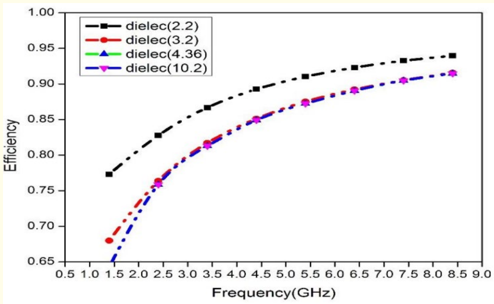

Figure 7: Antenna Efficiency versus Frequency.

The variation in antenna efficiency with frequency is studied for the various dielectric substrates with dielectric constant values of 2.2, 3.2, 4.36, and 10.2, which are shown in Fig.7. From the figure, we come to know that as the frequency increases, efficiency also increases. At the same time, it is found that efficiency decreases as the dielectric constant increases. The dielectric constant of 2.2 attains maximum efficiency among all substrates, which is selected for further analysis.

Conclusion

We have analyzed the implementation of different parameters, such as length, height, and width of the patch, coaxial feeding coordinates, input, and output impedance for different dielectric substrate materials at the desired frequency of 4.4 GHz, on the execution of microstrip patch antennas for better bandwidth enhancement. The feed point locations Xf and Yf which are the desired input feed points on the x- and y-axes, respectively are analyzed to provide the best performance of the antenna. Impedance matching between the feeding line and the radiating element is carried out. The input and output impedances that result in greater bandwidth and higher antenna efficiency are investigated. The important parameters, such as the reflection coefficient, VSWR, S_{11}, and hence the efficiency are evaluated and for the low dielectric material of RT- Turoid (2.2) which yields better results. Here we attained 56.65% of bandwidth, -9.709 dB of S_{11}, 1.97 of VSWR at a frequency of 7.4 GHz which means that 90% power is delivered to the antenna as an input which enhances the bandwidth of the RT- Turoid antenna. So by tuning the above parameters with their limitations, a large bandwidth can be achieved, which is beneficial for communication systems where more bandwidth is required. The resulting output is the directional pointer of a rectangular microstrip patch antenna, which will help future researchers get a clear idea of it.

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