Analysis of Five Different Dielectric Substrates on Microstrip Patch Antenna

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ABSTRACT

The study of microstrip patch antennas has made great progress in recent years. Compared with conventional antennas, microstrip patch antennas have more advantages and better prospects. Different researchers have used different dielectric substrates to fabricate microstrip patch antenna. So a question arises that which dielectric substrate among the common substrates available gives better performance and what are the properties of the dielectric substrates which affects antenna performance. So a comparative study has been performed to know the dielectric properties of five different substrates which affect antenna performance. The aim is to design and fabricate five triangular microstrip patch antennas on five different substrates and analyze their radiation characteristics. The antenna is designed to work for X-band applications. The resonant frequency is taken 10 GHz and height of the dielectric substrate is kept constant i.e., 1.5mm for all the five antennas. The antenna is showing good results on 8 GHz frequency. This shift in the frequency is due to the fringing fields along the edges. This study will help for authors and researchers to get a fair idea of which substrate should be given preference and why to fabricate microstrip patch antenna.

KEYWORDS

Dielectric Substrate, Microstrip Patch Antenna, Triangular Patch, X-band, Radiation Characteristics.

1. INTRODUCTION

Microstrip patch antenna is one of the most preferred antenna structures due to their low profile and ease of fabrication. They are useful because they can be directly printed onto the circuit boards. They have many applications, especially in wireless communication and in satellite communication. For satellite communication, a very high microwave frequency is used. It is because the radio frequency gets reflected by the ionosphere. Five different triangular microstrip patch antennas have been designed for X-band applications. The resonant frequency is taken as 10 GHz. But it is seen that antenna is resonant at 8 GHz. This shift of frequency is due to the fringing field along the edges of the patch. The antenna dimensions must be trimmed by 2-4% for the antenna to be resonant at 10 GHz. For that to achieve, the effective dielectric constant and effective side of the equilateral triangle is to be calculated. However, we are only concerned about the analysis of radiation characteristics of the triangular patch antenna and not for the particular frequency on which it is resonant. So the effective side and effective dielectric constant is not taken into account while simulating the antenna structure. Also X-bands extends from 8 GHz to 12 GHz so it can work satisfactorily for satellite communication. For satellite communication, circular polarization is used. Since in satellite communication transmitting and receiving antennas are not stationary, therefore, there will be polarization mismatch which can be calculated by polarization loss factor; PLF. Polarization Loss Factor is given as-

$PLF = \cos^2 \phi$ .If one antenna is vertically polarized and other antenna is horizontally polarized than the angle between them is 90 degrees and no power is transferred. In circular polarization, waves propagate in all planes so there is no polarization mismatch. Suppose now that a linearly polarized antenna is trying to receive a circularly polarized wave or vice versa. Circular polarization is really two orthogonal linear polarized waves 90 degrees out of phase. Hence, a linearly polarized antenna will simply pick up the in-phase component of the circularly polarized wave. Circular polarizations also overcome from the interference caused by rain. Hence the reception of the antenna becomes strong. Axial ratio for circular polarization i.e., the ratio of major axis to the minor axis is unity unlike the linear polarization where it is infinite. Coaxial probe feed is used because it is easy to use and the input impedance of the coaxial cable in general is 50 ohm. There are several points on the patch which have 50 ohm impedance. We have to find out those points and match them with the input impedance. These points are found through a mathematical model. The dielectric substrates used are Bakelite, FR4 Glass Epoxy, RO4003, Taconic TLC and RT Duroid. The height of the substrates is constant i.e., 1.5 mm. Different parameters such as VSWR, Return Loss , Antenna Gain, Directivity, Antenna Efficiency and Bandwidth is analyzed.

2. PROPERTIES OF DIELECTRIC SUBSTRATES

2.1 Bakelite

Bakelite or polyoxybenzylmethylenglycolanhydride, is an early plastic. It is a thermosetting phenol formaldehyde resin, formed from an elimination reaction of phenol with formaldehyde. It is most commonly used as an electrical insulator possessing considerable mechanical strength.

2.2 FR-4 or (FR4) Gloss Epoxy

FR-4 or (FR4) is a grade designation assigned to glass-reinforced epoxy laminate sheets, tubes, rods and printed circuit boards (PCB). FR-4 is a composite material composed of woven fiberglass cloth with an epoxy resin binder that is flame resistant (*self-extinguishing*). FR-4 glass epoxy is a popular and versatile high-pressure thermo set plastic laminate grade with good strength to weight ratios. With near zero water absorption, FR-4 is most commonly used as an electrical insulator possessing considerable mechanical strength.

2.3 RO4003

RO4003® Series High Frequency Circuit Materials are glass reinforced hydrocarbon/ceramic laminates (Not PTFE) designed for performance sensitive, high volume commercial applications. RO4000 laminates are designed to offer superior high frequency performance and low cost circuit fabrication. The result is a low loss material which can be fabricated using standard epoxy/glass (FR4) processes offered at competitive prices.

2.4 Taconic TLC

Taconic TLC substrates are specifically designed to meet the low cost objectives for newly emerging commercial RF/microwave applications. Taconic TLC substrates are manufactured in thickness .0145" (0.37 mm) with ε_r =2.70, and .020" (0.50 mm) with ε_r =3.0 and .031" (0.80 mm) and thicker with ε_r =3.30 and 3.20. Both materials exhibit excellent mechanical and thermal stability and cost less than traditional PTFE substrates.

2.5 RT Duroid

RT Duroid is Glass Microfiber Reinforced PTFE (polytetrafluoroethylene) composite produced by Roger Corporation. RT Duroid 5870 substrate has low loss tangent. They exhibit excellent chemical resistance, including solvent and reagents used in printing and plating, ease of fabrication – cutting, shearing, machining, environment friendly.

Properties of these substrates are given in tabular form.

Table 2.1 Properties of different substrates

Parameters	Bakelite	FR4 Glass Epoxy	RO4003	Taconic TLC	RT Duroid
Dielectric constant	4.78	4.36	3.4	3.2	2.2
Loss tangent	0.03045	0.013	0.002	0.002	0.0004
Water absorption	0.5-1.3%	$<$ 0.25%	0.06%	$<$ 0.02%	0.02%
Tensile strength	60 MPa	$<$ 310 MPa	141 MPa	-	450 MPa
Volume resistivity	3×10^{15} Mohm.cm	8×10^{7} Mohm.cm	1700×10^{7} Mohm.cm	1×10^{7} Mohm.cm	2×10^{7} Mohm.cm
Surface resistivity	5×10^{10} Mohm	2×10^{5} Mohm	4.2×10^{9} Mohm	1×10^{7} Mohm	3×10^{7} Mohm
Breakdown voltage	20-28 kV	55 kV	-	-	$>$ 60 kV
Peel strength	-	9 N/mm	1.05 N/mm	12 N/mm	5.5 N/mm
Density	1810kg/m^3	1850 kg/m^3	1790 kg/m^3	-	2200 kg/m^3

Dielectric constant of substrates affects antenna performance. The substrate which has a low dielectric constant will give better radiations than the substrate which has a high dielectric constant. Loss tangent or dissipation factor also plays a part in antenna performance. The high dielectric material allows for a reduction of space but at the cost of higher moisture absorption level.

Dielectric losses depend on the circuit configuration, dielectric constant, frequency and loss tangent. Dielectric constant and loss tangent vary with operating temperature changes and levels of humidity. Dielectric constant values usually vary between 0 and 0.05% over a 100 degree Celsius for most PTFE based laminates. Loss tangent or Dissipation factor can change significantly up to 200% with moisture absorption as little as 0.25% of dielectric weight. Thus moisture absorption should be as low as possible.

Dielectric materials cannot resist indefinite amount of voltage and with enough voltage applied, any insulating material can succumb to the electrical pressure and electron flow will occur. However, unlike the situation with conductors where the current is in a linear proportion to applied voltage (given a fixed resistance) current through an insulator is quite non-linear, for voltage below a certain threshold level, virtually no electrons will flow, but if the voltage exceeds that threshold, there will be a rush of current. Once current is forced through an insulating material, breakdown of that materials molecular structure has occurred. Hence volume resistivity and surface resistivity should be good. After breakdown, the material may or may not behave as an insulator any more, the molecular structure having been altered by the breach. There is usually a "puncture" of the insulating medium where the electrons flowed during breakdown. The breakdown voltage should be high. Thickness of an insulating material plays a role in determining its breakdown voltage, otherwise known as dielectric strength.

3. ANTENNA DESIGN

The resonant frequency is taken to be 10 GHz. The height of the antenna is 1.5mm.The resonant frequency corresponding to various modes can be given by-

$$f_r = \frac{ck_{mn}}{2\pi\sqrt{\varepsilon_r}} = \frac{2c}{3a\sqrt{\varepsilon_r}}\sqrt{m^2+mn+n^2}$$

Where c is velocity of light in free space and k_{mn} = wave number given by-

$$k_{mn} = \frac{4\pi}{3a}\sqrt{m^2+mn+n^2}$$

The expression for lowest order resonance frequency is given by-

$$f_r = \frac{2c}{3a\sqrt{\varepsilon_r}}$$

In this relation end effects of fringing fields are not considered. The resonant frequency may be determined with better accuracy if effective side and effective dielectric constant are calculated. The authors are only concerned to analyze antenna performance on different substrates under similar conditions so accuracy is not given much preference.

As resonant frequency is 10 GHz, the side of the antenna is given by-

$$a = \frac{2c}{3 f_r \sqrt{\varepsilon_r}}$$

Where, c = velocity of light

$$= 3 \times 10^{10} \ cm/s$$

a = Side of the equilateral triangle

3.1 Bakelite

Dielectric constant, $\varepsilon_r = 4 \cdot 78$

Loss tangent, $\tan\delta = 0.03045$

Height of the substrate $= 1.5 \ mm$

$$a = \frac{(2 \times 3 \times 10^{10})}{(3 \times 10 \times 10^{9} \times \sqrt{4.78})}$$

$$= 0.915 \ cm = 9.15 \ mm$$

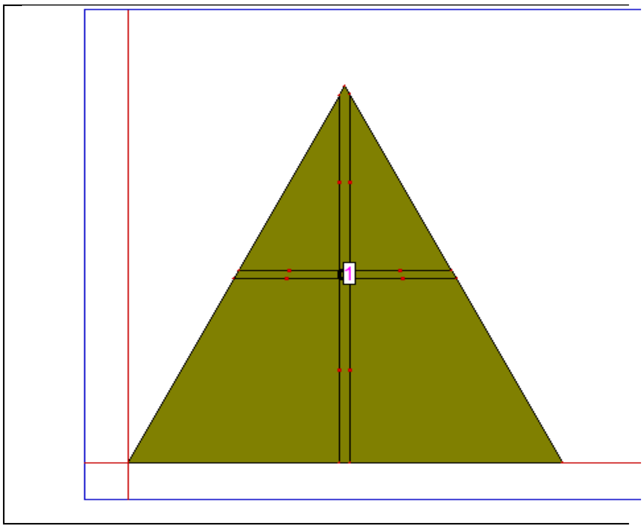

Fig.3. 1 Triangular patch on Bakelite

3.1 FR4 Glass epoxy

Dielectric constant, $\varepsilon_r = 4.36$

Loss tangent, $\tan\delta = 0.013$

Height of the substrate $= 1.5 \ mm$

$$a = \frac{(2 \times 3 \times 10^{10})}{(3 \times 10 \times 10^{9} \times \sqrt{4.36})}$$

$$= 0.9575 \ cm = 9.575 \ mm$$

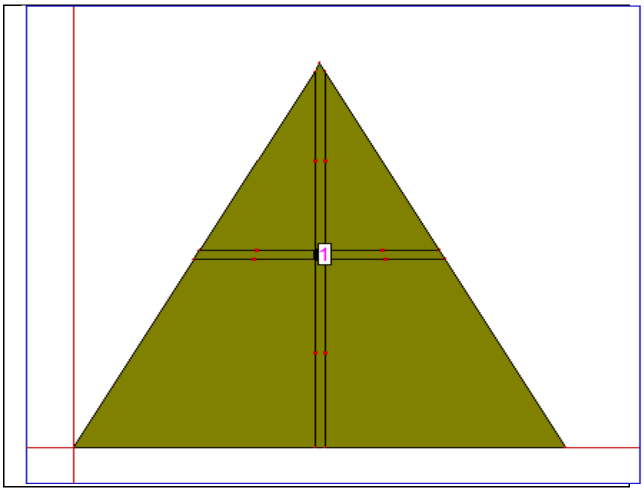

Fig.3.2 Triangular patch on FR4 Glass Epoxy

3.2 RO4003

Dielectric constant, $\varepsilon_r = 3.4$

Loss tangent, $\tan\delta = 0.002$

Height of the substrate $= 1.5 \ mm$

$$a = \frac{(2 \times 3 \times 10^{10})}{(3 \times 10 \times 10^{9} \times \sqrt{3.4})}$$

$$= 1.085 \ cm = 10.85 \ mm$$

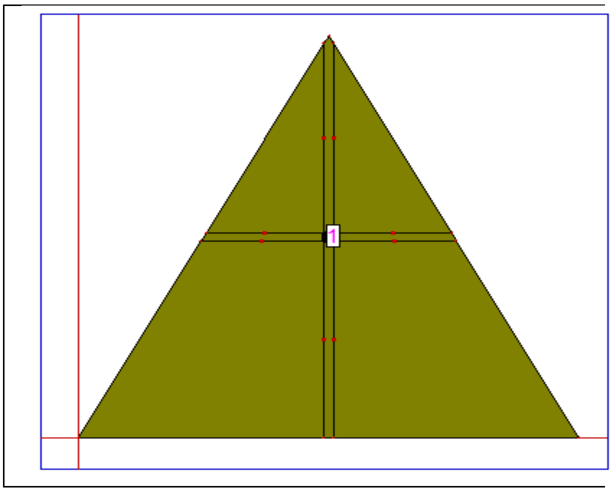

Fig.3.3 Triangular patch on RO4003

3.3 Taconic TLC

Dielectric constant, $\varepsilon_r = 3.2$

Loss tangent, $\tan\delta = 0.002$

Height of the substrate $= 1.5 \ mm$

$$a = \frac{(2 \times 3 \times 10^{10})}{(3 \times 10 \times 10^{9} \times \sqrt{3.2})}$$

$$= 1.1175 \ cm = 11.175 \ mm$$

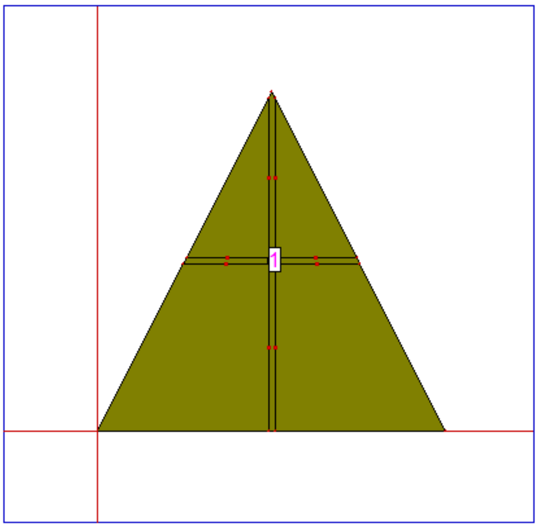

Fig.3.4 Triangular patch on Taconic TLC

3.4 RT Duroid

Dielectric constant, $\varepsilon_r = 3.2$

Loss tangent, $\tan\delta = 0.0004$

Height of the substrate $= 1.5\ mm$

$$a = \frac{(2\times3\times10^{10})}{(3\times10\times10^{9}\times\sqrt{2.2})}$$

$$= 1.3475\ cm = 13.475\ mm$$

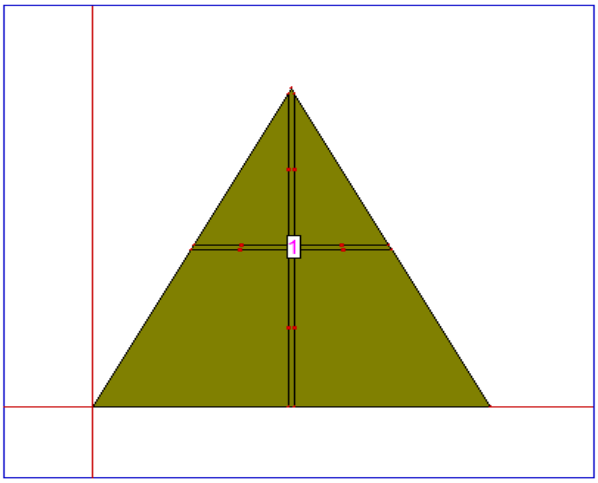

Fig.3.5 Triangular patch on RT Duroid

4 SIMULATION RESULTS

4.1 Return Loss vs. Frequency Graph

4.1.1 Bakelite

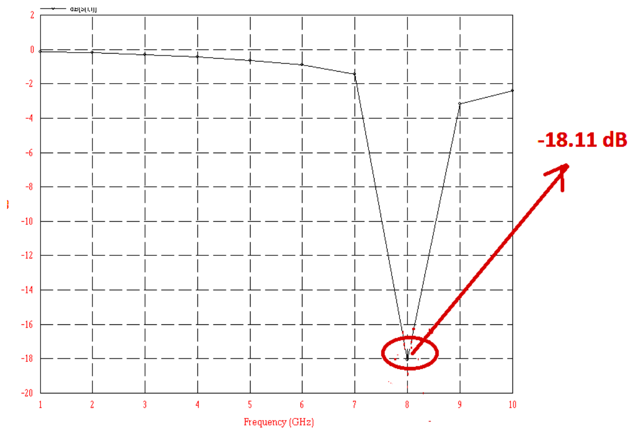

Fig.4.1.1 Return loss vs. frequency graph on Bakelite

Triangular patch antenna with Bakelite as a dielectric substrate when simulated on 10GHz frequency gives very low return losses of -18.11 dB on 8GHz frequency and its bandwidth is 12.50%.

4.1.2 FR4 Glass epoxy

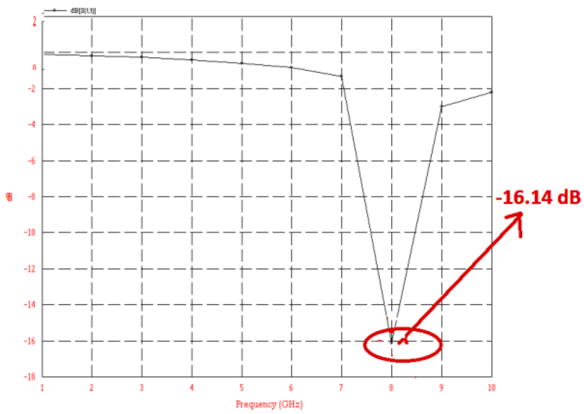

Fig. 4.1.2 Return loss vs. frequency on FR4 Glass Epoxy

Triangular patch antenna with FR4 Glass Epoxy as a dielectric substrate when simulated on 10 GHz frequency gives a return loss of -16.14dB on 8GHz frequency and its bandwidth is 10.12%.

4.1.3 RO4003

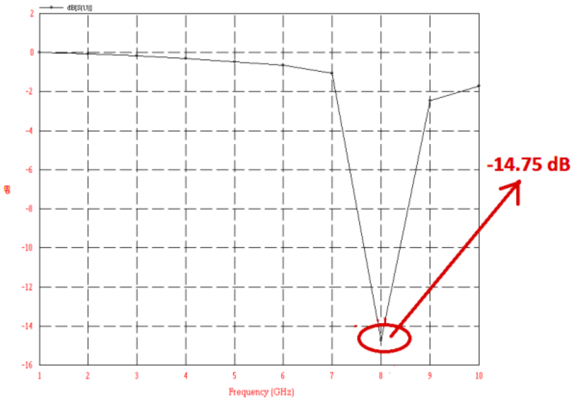

Fig. 4.1.3 Return loss vs. frequency graph on RO4003

Triangular patch antenna with RO4003 as a dielectric substrate when simulated on 10 GHz frequency gives a return loss of -14.75dB on 8GHz frequency and its bandwidth is 7.59%.

4.1.4 Taconic TLC

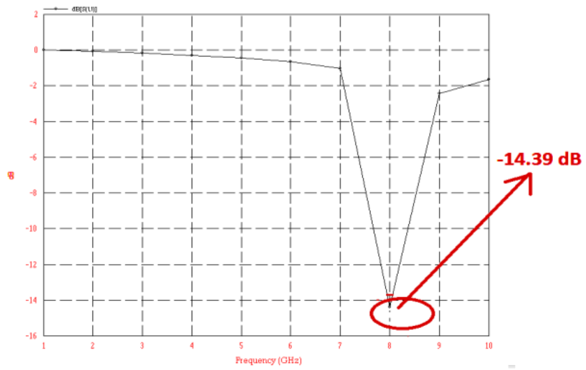

Fig.4.1.4 Return loss vs. frequency graph on Taconic TLC

Triangular patch antenna with Taconic TLC as a dielectric substrate when simulated on 10 GHz frequency gives a return loss of -14.39dB on 8GHz frequency and its bandwidth is 8.80%.. It can be seen that the difference of the dielectric constant of RO4003 and Taconic TLC is just 0.2 but there is increase in bandwidth of the Taconic TLC.

4.1.5 RT Duroid

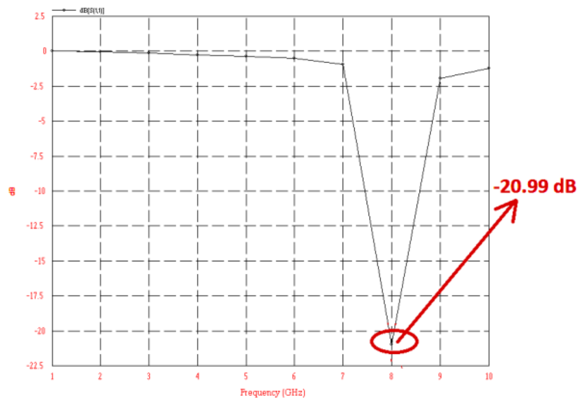

Fig.4.1.5 Return loss vs. frequency graph on RT Duroid

Triangular patch antenna with RT Duroid as a dielectric substrate when simulated on 10 GHz frequency gives an excellent low return loss of -20.99dB on 8GHz frequency and its bandwidth is 15%. It can be seen that the dielectric constant of this substrate is very low but it gives best performance in terms of return loss and bandwidth. Return losses should be as low as possible so that all the input power should be radiated into space when the antenna is transmitting electromagnetic waves and all the incoming power should be efficiently received by the antenna when the antenna is receiving the electromagnetic waves.

4.2 VSWR vs. Frequency Graph

4.2.1 Bakelite

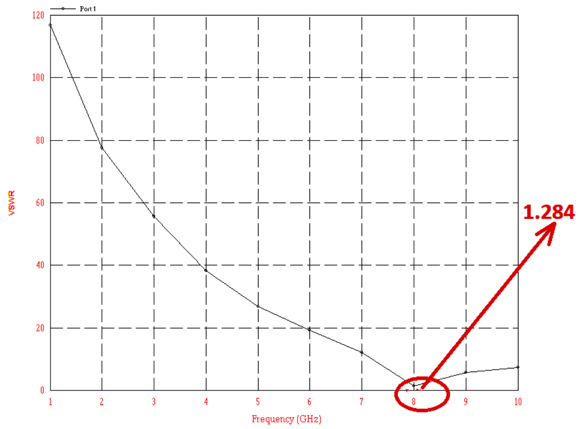

Fig.4.2.1 VSWR vs. frequency graph on Bakelite

Triangular microstrip patch antenna with Bakelite as a dielectric substrate gives a voltage standing wave ratio of 1.284 at 8GHz frequency which is close to acceptable value of 1.

4.2.2 FR4 Glass epoxy

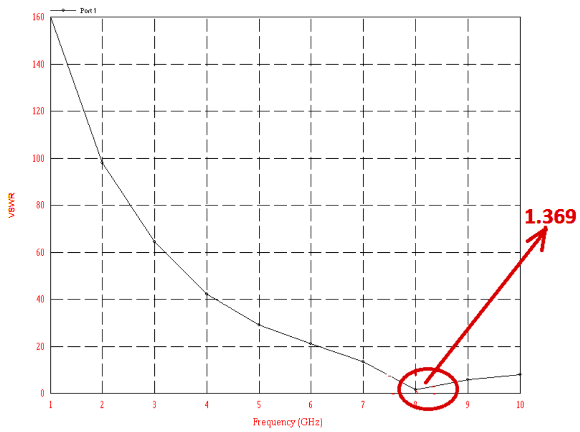

Fig.4.2.2 VSWR vs. frequency graph on FR4 Glass Epoxy

Triangular microstrip patch antenna with FR4 Glass epoxy as a dielectric substrate gives a voltage standing wave ratio of 1.369 at 8GHz frequency which is slightly more than the Bakelite which has higher dielectric constant than FR4 substrate.

4.2.3 RO4003

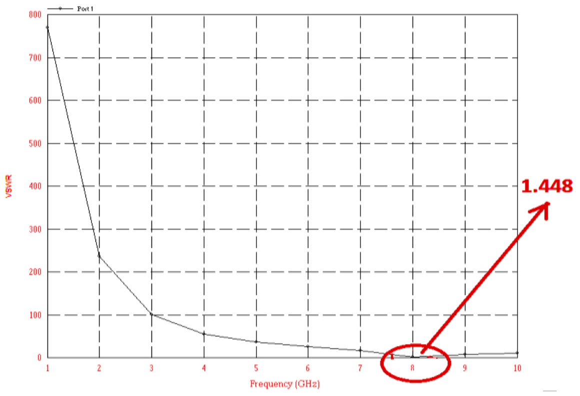

Fig.4.2.3 VSWR vs. frequency graph on RO4003

Triangular microstrip patch antenna with RO4003 as a dielectric substrate gives a voltage standing wave ratio of 1.448 which is slightly more than FR4 Glass epoxy. It is to be noticed that as the value of dielectric constant is decreasing, the value of VSWR is increasing.

4.2.4 Taconic TLC

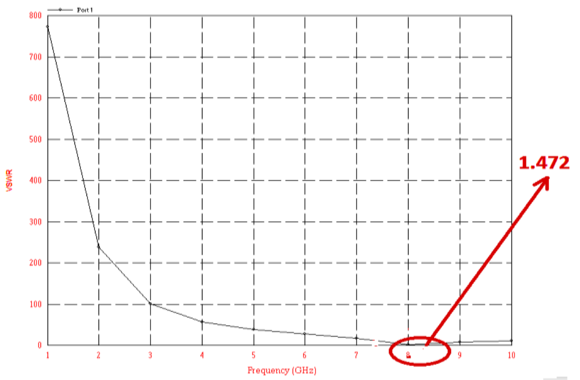

Fig.4.2.4 VSWR vs. frequency graph on Taconic TLC

Triangular microstrip patch antenna with Taconic TLC as a dielectric substrate gives a VSWR value of 1.472 at 8GHz which is close to 1.5. There is a difference of 0.2 in the dielectric constant of Taconic TLC and RO4003, but VSWR increases by 0.024.

4.2.5 RT Duroid

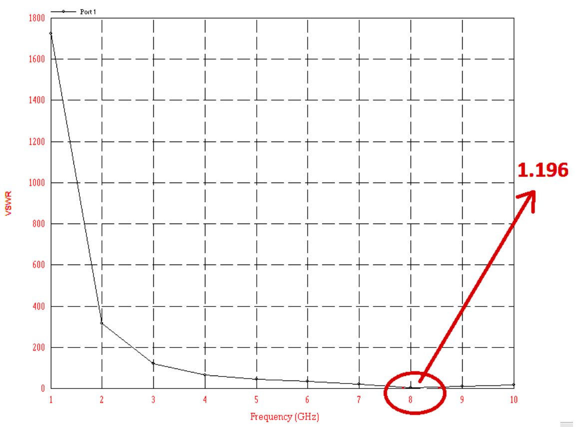

Fig.4.2.5 VSWR vs. frequency graph on RT Duroid

RT Duroid has the minimum dielectric constant among the five substrates considered thus gives the lowest voltage standing wave ratio of 1.196.

4.3 ANTENNA 3D GAIN PATTERN WITH DIFFERENT SUBSTRATES

4.3.1 Bakelite

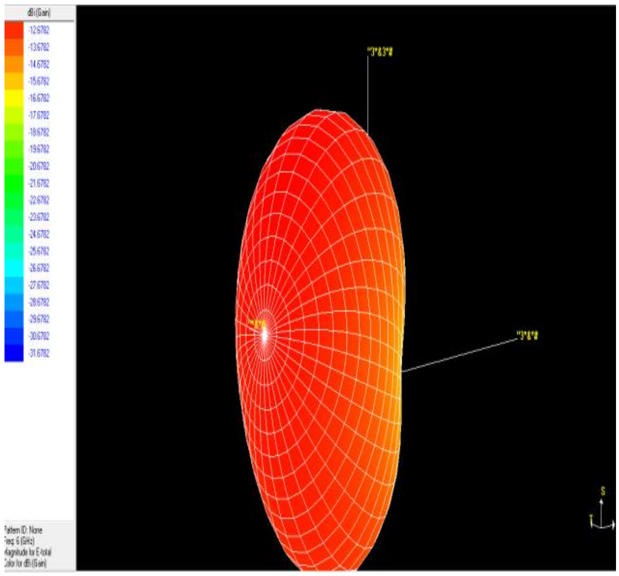

Fig.4.3.1 Antenna 3D radiation pattern on Bakelite

4.3.2 FR4 Glass epoxy

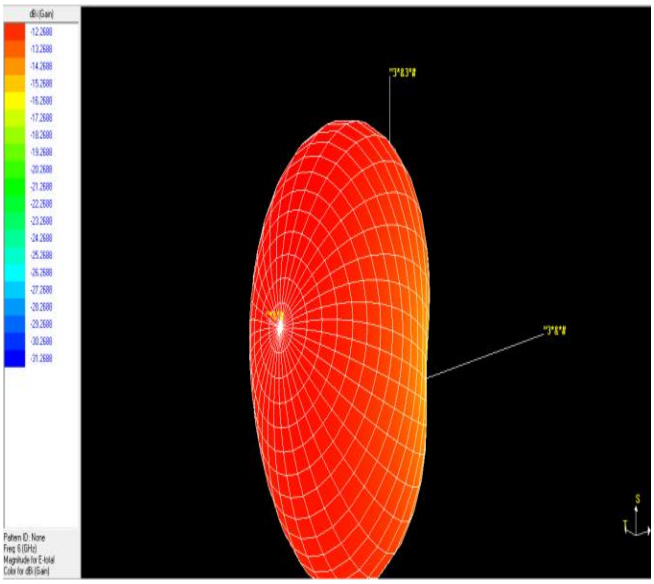

Fig.4.3.2 Antenna 3D radiation pattern on FR4 Glass Epoxy

4.3.3 RO4003

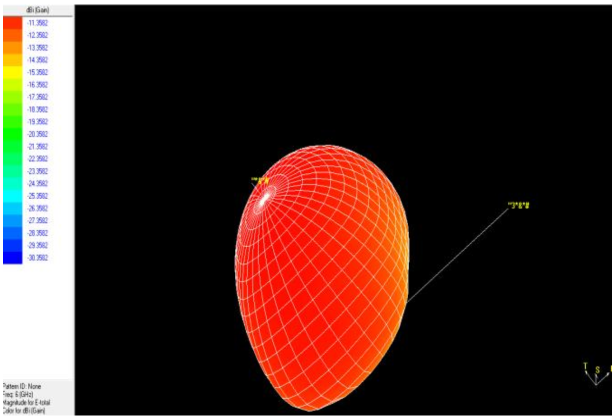

Fig.4.3.3 Antenna 3D radiation pattern on RO4003

4.3.4 Taconic TLC

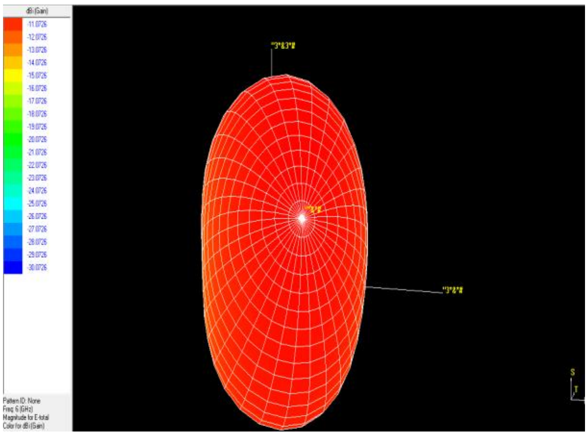

Fig.4.3.4 Antenna 3D radiation pattern on Taconic TLC

4.3.5 RT Duroid

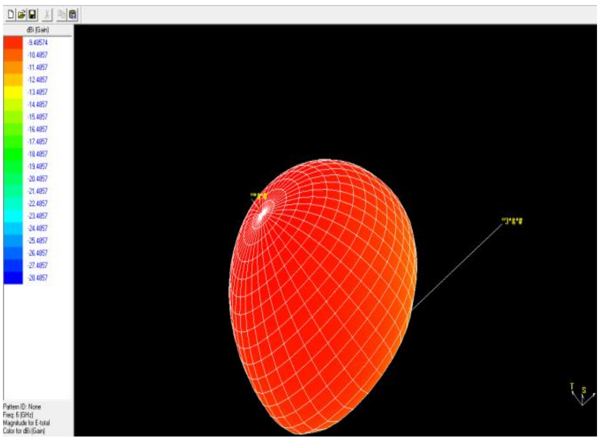

Fig.4.3.5 Antenna 3D radiation pattern on RT Duroid

5. FINAL TABLE

The final table is given below in which values for different parameters are given for all the substrates considered indicating the performance analysis of the substrates.

Table2. Final Table

Parameters	**Substrates**				
	Bakelite	**FR4 Glass epoxy**	**RO4003**	**Taconic TLC**	**RT Duroid**
Resonant frequency	10 GHz	10 GHz	10 GHz	10 GHz	10 GHz
side	9.15 mm	9.575 mm	10.85 mm	11.175 mm	13.475 mm
Frequency	8 GHz	8 GHz	8 GHz	8 GHz	8 GHz
Return Loss	-18.11 dB	-16.14 dB	-14.75 dB	-14.39 dB	-20.99 dB
VSWR	1.284	1.369	1.448	1.472	1.196
Gain	3 dBi	4 dBi	5 dBi	5.5 dBi	6.5 dBi
Directivity	6.5 dBi	6.5 dBi	7 dBi	7 dBi	7.5 dBi
Bandwidth	12.50 %	10.12 %	7.59 %	8.80 %	15 %
Antenna efficiency	42-45 %	50 %	67.5 %	70 %	80 %
Radiating efficiency	42-45 %	50 %	70 %	67.5 %	80

6. CONCLUSION

Five different substrates Bakelite, FR4 Glass epoxy, RO4003, Taconic TLC and RT Duroid, which are used for the fabrication of microstrip patch antenna, has been studied. Results are found to be best in the case of RT Duroid as it gives 80% efficiency with a bandwidth of 15%. The reason for increase in bandwidth is due to the increase in size of the RT Duroid based antenna geometry compared to the other substrate based geometry as bandwidth is directly proportional to antenna dimensions or antenna size. Also, RT Duroid has lowest dielectric constant among the five substrates which also increases the bandwidth because bandwidth is inversely proportional to dielectric constant or permittivity. RT Duroid gives a Gain of 6.5 dBi as compared to second best Gain of 5.5 dBi of Taconic TLC, thus a increase of 18.18%. Also, the Directivity is 7.5 dBi, 7.14% more than Taconic TLC. The reason for this is that for a fixed substrate thickness h, the resonant length and directivity increase with decrease in dielectric constant. RT Duroid gives maximum radiation due to its low dielectric constant. The return loss of RT Duroid is much better (-20.99 dB) as compared to other four substrates for the same resonant frequency. It decreases the Return losses to 45% better than Taconic TLC and 16% better than Bakelite. . Also, RT Duroid has highest tensile strength and breakdown voltage due to which it does not succumb to the electrical pressure easily. So it does not lose its insulating property. Water absorption changes dissipation factor or loss tangent of the dielectric substrate. As its water absorption is very low so its loss tangent remains constant. Bandwidth and radiation pattern depends on loss tangent also, so RT Duroid is good dielectric substrate for microstrip patch antenna. Thus, it is suggested that RT Duroid can be given preference over other four substrates which are considered.

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