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***Research Paper***

# Iterative Analysis of Dielectric Constant of Patch Antenna Substrate at UHF Band

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**Abstract**

This paper presents an investigation of effect of substrate material properties on the performance of antenna. The simulations are tested for 30 different dielectric materials on the basic RPA antenna model as well as on the most common U shape model using CST Microwave Studio. Two designs are proposed. On the basis of simulation results it has been concluded that for the first design the best material is which has a dielectric constant of 2.7 ($\varepsilon_r$ = 2.7) with bandwidth improvements of around 69.33% to 88.6% as compared to the most frequently used materials at present. For the second design the best result is obtained for the material that has dielectric constant in the range 2.0 to 2.7. For a material having dielectric constant of 2.1 ($\varepsilon_r$ = 2.1) bandwidth improvement of around 11.74% with respect to RT Duroid was observed. For the second design, radiations from all other materials were not available in the working frequency range of 1GHz to 6GHz.

***Keywords***: *Dielectric constant; FR4; RO4003; RT Duroid; TLC laminates.*

## 1. Introduction

The concept of microstrip antenna was first given by Deschamps in 1953 and a patent in 1955 [1]; but the concept gained attention after the development of printed circuit board (PCB), microwave technology and different kinds of low attenuation media materials which made microstrip antenna more practical. The microstrip patch antenna finds widespread applications in present days when the compatible devices are widely used in our day to day communication like cell phones, USB dongles, hotspot etc. Thus, physical size reduction and bandwidth enhancement along with high gain are major design considerations [1,2] for a practical antenna. The main focus of this paper is on substrate material of patch antenna, which generally has dielectric constant in the range of $2.2\leq\varepsilon_r\leq12$ [3,4]. The performance of MPA (Microstrip Patch Antenna) change by changing substrate material and its thickness. However, by increasing thickness, surface waves are introduced which degrade the pattern and polarization characteristics [1,2]. Hence, in order to design an appropriate antenna the effect of dielectric material must be analyzed. In this paper RPAs (Rectangular Patch Antenna) are designed with different materials with different dielectric constants in the lower range from $2\leq\varepsilon_r<5$ with 30 iterations of step size 0.1each. Higher $\varepsilon_r$ materials are not considered in this paper as it is known that thin substrate with higher dielectric constant are used for microwave circuitry because of its tightly bound fields; but, they are less efficient and have smaller bandwidth [4,5]. The working range of frequency is 1GHz to 6 GHz which cover our most of the day to day communication. The rest of the paper is organized in different sections, Section II explains different existing materials used as substrate for MPA along with their properties. Section III represents two sets of designs proposed for 30 different materials; first set is based on basic MPA that is the rectangular patch antenna (RPA) and the second set is one of the most common U slot RPA. Section IV illustrates the simulation results of the performance parameters for the proposed 30 iterations of $\varepsilon_r$ with step size of 0.1. Lastly, in Section V conclusion is made and future work is proposed.

## 2. Substrate Material

There are several material used as substrate for MPA one of the most commonly used material is polytetrafluoroethylene or Teflon fiber glass. The effective dielectric constant i.e $1\leq\varepsilon_{eff}\leq\varepsilon_r$ depends on the frequency of operation [1,2,3] by the following relationship.

$$f_c \cong \frac{1}{2L\sqrt{\varepsilon_0\mu_0\varepsilon_r}} \quad (1)$$

Where $f_c$ is the center frequency or critical frequency and other symbols are having these usual meaning. This relationship for different ranges of dielectric constant material is shown in Fig. 1 which supports our iteration range from $2\leq\varepsilon_r\leq5$ because for the lower range of dielectric constant the variation with frequency is very small. Some of the most commonly used substrate materials and their properties are presented in Table 1 and their short description is presented in this section.

*a) Bakelite*

Bakelite or polyoxybenzylmethylenglycolanhydride, is one of the most common form of plastic used in different industries. It has considerable mechanical strength [6] and insulating properties and hence is used as substrate of the microstrip patch antenna.

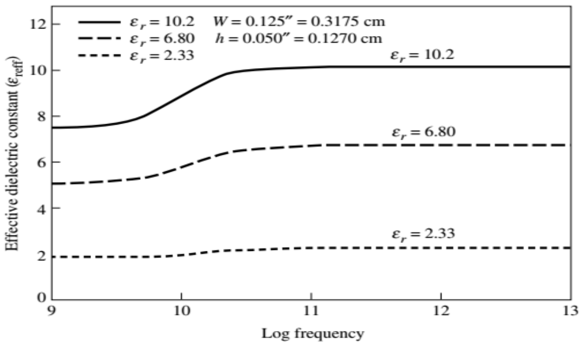


**Fig. 1:** Effective dielectric constant versus frequency for typical substrates.

*b) FR-4 or (FR4) Gloss Epoxy*

FR-4 or (FR4) materials are glass reinforced epoxy laminate which is a composite material [7]. FR-4 glass epoxy is a high-pressure laminate with good strength to weight ratio. With about 0.10% water absorption [7] with dielectric breakdown parallel to laminate is greater than even 60 KV with very good electrical insulating properties.

*c) RO4003*

RO4003® is a hydrocarbon ceramic laminate which is designed to present better frequency performance and economical circuit fabrication. The thermal coefficient of expansion (CTE) of RO4003®provides numerous key benefits to the circuit designer [8]. Its expansion coefficient is alike of copper which allows the material to exhibit excellent dimensional stability, a property needed for mixed dielectric multi-layer boards construction.

*d) Taconic TLC*

Taconic TLC substrates uses 7628 style fiberglass that provides excellent performance. They have excellent PIM values in PCBs, are low in cost, have excellent dimensional stability and high flexural strength. They are mostly used in LNBs, power amplifiers, PCS/PCN large format antennas and passive components[9].

*e) RT Duroid*

RT Duroid is Glass Microfiber that has the lowest electrical loss for Reinforced PTFE material with low moisture absorption and excellent chemical resistance [10]. Most common application of RT Duroid substrate is in commercial airline broadband antenna, microstrip and stripline circuits and missile guided system. It is easy for cutting, machining and is also environment friendly.

**Table 1:** Properties of different substrates

| Parameters | Bakelite | FR-4 | RO4003 | Taconic TLC | RT Duroid |
|---|---|---|---|---|---|
| Dielectric constant | 4.8 | 4.4 | 3.4 | 3.2 | 2.2 |
| Loss tangent | 0.03045 | 0.013 | 0.002 | 0.002 | 0.0004 |
| Tensile strength | 60 MPa | <310MPa | 441MPa | 241 MPa | 450MPa |
| Surface resistivity | 1 $\times 10^{10}\Omega$ | 1$\times$ $10^8$ MΩ | 4.2$\times$ $10^9$ MΩ | 1 $\times 10^7$MΩ | 3.0 $\times$ $10^7$ MΩ |

From the above discussion we can conclude the fact that for low frequencies the effective dielectric constant is essentially constant. At intermediate frequencies its value begins to monotonically increase and eventually approaches the value of the dielectric constant of the substrate. The initial values (at low frequencies) of the effective dielectric constant is referred to as the *static value*, and is given as,

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(1+\frac{12h}{w}\right)^{1/2} \quad (2)$$

Where, $\varepsilon_{eff}$: effective dielectric costant
$\varepsilon_r$: Dielectric constant of substrate
$h$: Height of dielectric substrate
$W$: Width of the patch

Therefore in the upcoming section, discussion on the different design and their results for different dielectric materials at lower range of dielectric constant ($2 \le \varepsilon_r < 5$) is carried out.

## 3. Design

In this section two designs of rectangular patch antenna are taken. One is the basic design and the other is the U shaped most widely used antenna. The iteration results by changing values of dielectric constant are examined for both designs.

a) Basic Model

The basic model of RPA, consist of a very thin metallic strip (patch) placed on small fraction of wavelength above the ground plane (usually 0.003λ0 ≤ h ≤ 0.05 λ0) [1,3], with patch length L= 24mm and width W =30mm.The strip (patch) and the ground plane are separated by a dielectric sheet of thickness of 4 mm (referred as the substrate), as shown in Fig. 2.

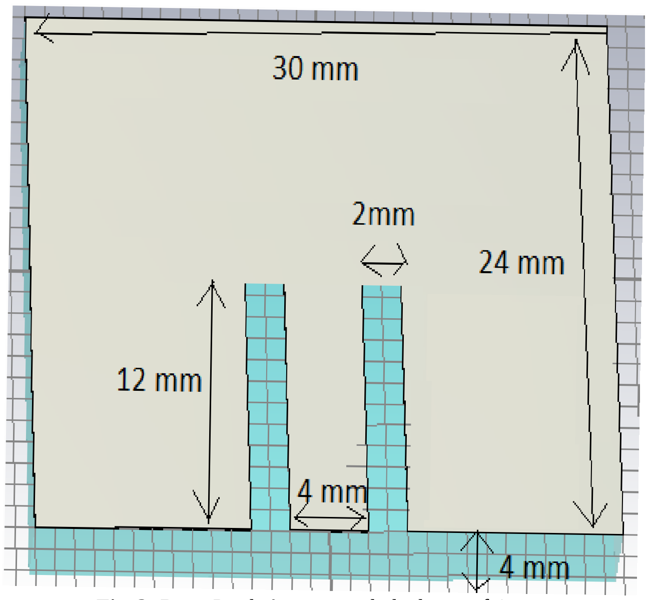


**Fig. 2:** Basic Patch Antenna with thickness of 4mm.

b) U Shape Model

One of the most common models in RPA is the U shape model in which the thickness of the substrate is 4 mm which is similar to the basic model chosen. The dimension of substrate is very close to the previous design here it is 30mm×30mm. In this model, a U shape slot is cut out from the patch to radiate the EM wave as shown in Fig. 3.

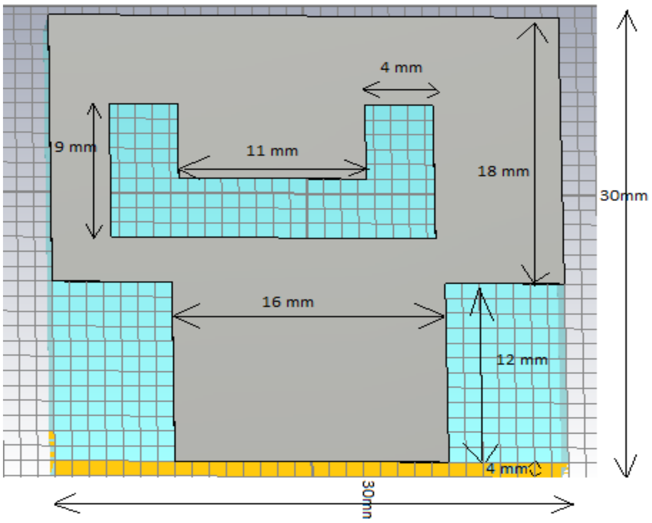


**Fig. 3:** U Shape Patch Antenna with thickness of 4mm.

## 4. Simulation Results

In this manuscript, the three performance parameters of antenna ($S_{11}$ Return Loss, Bandwidth and Gain) for the proposed 30 iterations of $\varepsilon_r$ with step size of 0.1 for both of the designs proposed in Section 3 has been analyzed. Fig. 4 illustrates the variation of $S_{11}$ with the change of dielectric constant or change of material. From the results it was observed that the patch antenna performed the best in the range of 2.4 to 3.4 ($2.4 \leq \varepsilon_r \leq 3.4$). For return loss, the findings are tabulated in Table 2.

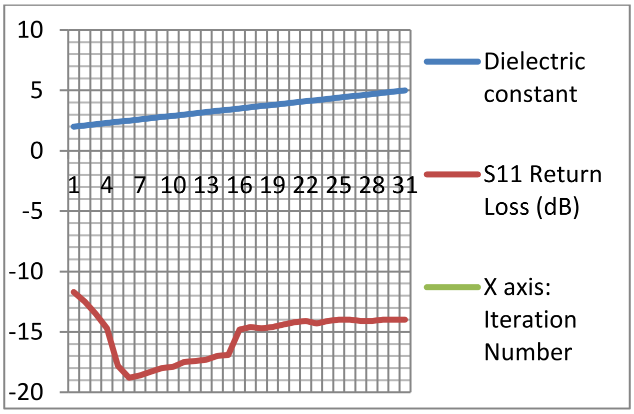


**Fig. 4:** $S_{11}$ of design 1 for 30 Iterations of dielectric constant.

**Table 2:** S11 of design 1 for different substrates

| $\varepsilon_r$ | $S_{11}$ (dB) | $\varepsilon_r$ | $S_{11}$ (dB) | $\varepsilon_r$ | $S_{11}$ (dB) | $\varepsilon_r$ | $S_{11}$ (dB) | $\varepsilon_r$ | $S_{11}$ (dB) |
|---|---|---|---|---|---|---|---|---|---|
| 2.0 | -11.7 | 2.6 | -18.6 | 3.2 | -17.3 | 3.8 | -14.6 | 4.4 | -14 |
| 2.1 | -12.5 | 2.7 | -18.3 | 3.3 | -17 | 3.9 | -14.4 | 4.5 | -14 |
| 2.2 | -13.5 | 2.8 | -18 | 3.4 | -16.9 | 4.0 | -14.2 | 4.6 | -14.1 |
| 2.3 | -14.7 | 2.9 | -17.9 | 3.5 | -14.8 | 4.1 | -14.1 | 4.7 | -14.1 |
| 2.4 | -17.8 | 3.0 | -17.5 | 3.6 | -14.6 | 4.2 | -14.3 | 4.8 | -14 |
| 2.5 | -18.8 | 3.1 | -17.4 | 3.7 | -14.7 | 4.3 | -14.1 | 4.9 | -14 |

Fig. 5 represents the variation of the Bandwidth with the change of dielectric constant or change of material. From the result it was observed that the patch antenna performed best in the range of 2.4 to 3.4 ($2.4 \leq \varepsilon_r \leq 3.4$) in terms of Bandwidth parameters and its findings are tabulated in Table 3.

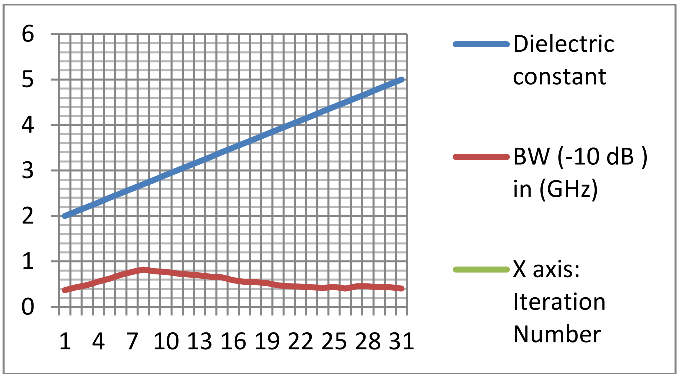


**Fig. 5:** Bandwidth of design 1 for 30 Iterations of dielectric constant.

**Table 3:** Bandwidth of design 1 for different substrates

| $\varepsilon_r$ | BW -10dB (GHz) | $\varepsilon_r$ | BW -10dB (GHz) | $\varepsilon_r$ | BW -10dB (GHz) | $\varepsilon_r$ | BW -10dB (GHz) | $\varepsilon_r$ | BW -10dB (GHz) |
|---|---|---|---|---|---|---|---|---|---|
| 2.0 | 0.3697 | 2.6 | 0.7726 | 3.2 | 0.6953 | 3.8 | 0.5243 | 4.4 | 0.4425 |
| 2.1 | 0.4359 | 2.7 | 0.8223 | 3.3 | 0.6677 | 3.9 | 0.4746 | 4.5 | 0.4084 |
| 2.2 | 0.4856 | 2.8 | 0.7837 | 3.4 | 0.6512 | 4.0 | 0.4581 | 4.6 | 0.4525 |
| 2.3 | 0.5574 | 2.9 | 0.7695 | 3.5 | 0.5849 | 4.1 | 0.4471 | 4.7 | 0.4525 |
| 2.4 | 0.6236 | 3.0 | 0.7395 | 3.6 | 0.5519 | 4.2 | 0.436 | 4.8 | 0.4359 |
| 2.5 | 0.7064 | 3.1 | 0.7119 | 3.7 | 0.5464 | 4.3 | 0.4194 | 4.9 | 0.436 |

Fig. 6 represents the variation of the Gain at resonating frequency with the change of dielectric constant or change of material. From the result it has been observed that the Gain of antenna is best in the range of 2.0 to 2.2 ($2.0 \leq \varepsilon_r \leq 2.2$) and better in the range of 2.6 to 2.8 ($2.6 \leq \varepsilon_r \leq 2.8$) its findings are tabulated in Table 4.

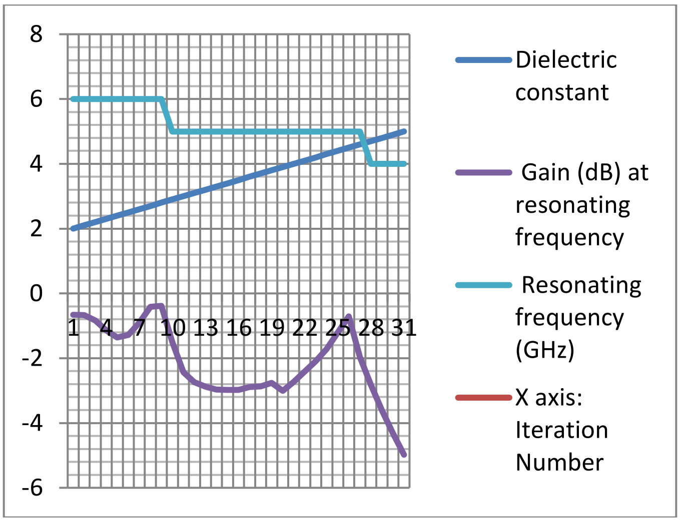


**Fig. 6:** Gain of design 1 for 30 iterations of dielectric constant.

**Table 4:** Gain of design 1 for different substrates

| $\varepsilon_r$ | Gain (dB) at $f_c$ | $\varepsilon_r$ | Gain (dB) at $f_c$ | $\varepsilon_r$ | Gain (dB) at $f_c$ | $\varepsilon_r$ | Gain (dB) at $f_c$ | $\varepsilon_r$ | Gain (dB) at $f_c$ |
|---|---|---|---|---|---|---|---|---|---|
| 2.0 | -0.66 | 2.6 | -0.90 | 3.2 | -2.88 | 3.8 | -2.76 | 4.4 | -1.2 |
| 2.1 | -0.67 | 2.7 | -0.41 | 3.3 | -2.97 | 3.9 | -3.01 | 4.5 | -0.71 |
| 2.2 | -0.83 | 2.8 | -0.38 | 3.4 | -2.98 | 4.0 | -2.73 | 4.6 | -1.97 |
| 2.3 | -1.14 | 2.9 | -1.5 | 3.5 | -2.98 | 4.1 | -2.41 | 4.7 | -2.82 |
| 2.4 | -1.36 | 3.0 | -2.44 | 3.6 | -2.89 | 4.2 | -2.09 | 4.8 | -3.62 |
| 2.5 | -1.28 | 3.1 | -2.74 | 3.7 | -2.87 | 4.3 | -1.72 | 4.9 | -4.32 |

Fig. 7, Fig. 8 and Fig. 9 illustrate the above parameters i.e $S_{11}$, Bandwidth and Gain respectively for design 2. Different iteration results are tabulated in Table 5, Table 6 and Table 7.

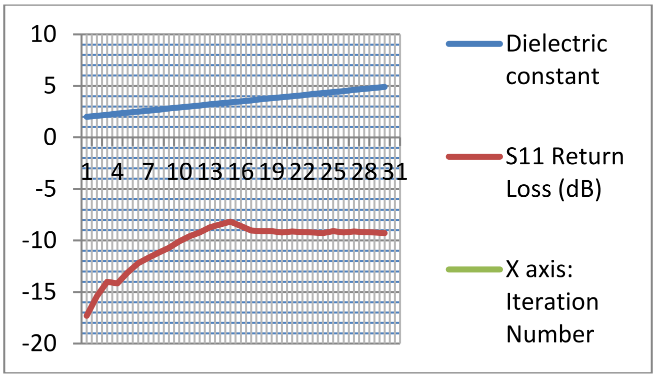


**Fig. 7:**.$S_{11}$ of design 2 for 30 iterations of dielectric constant.

**Table 5:** $S_{11}$ of design 2 for different substrates

| $\varepsilon_r$ | $S_{11}$ (dB) | $\varepsilon_r$ | $S_{11}$ (dB) | $\varepsilon_r$ | $S_{11}$ (dB) | $\varepsilon_r$ | $S_{11}$ (dB) | $\varepsilon_r$ | $S_{11}$ (dB) |
|---|---|---|---|---|---|---|---|---|---|
| 2.0 | -17.30 | 2.6 | -11.67 | 3.2 | -8.73 | 3.8 | -9.08 | 4.4 | -9.08 |
| 2.1 | -15.42 | 2.7 | -11.18 | 3.3 | -8.43 | 3.9 | -9.22 | 4.5 | -9.22 |
| 2.2 | -14.00 | 2.8 | -10.70 | 3.4 | -8.17 | 4.0 | -9.12 | 4.6 | -9.12 |
| 2.3 | -14.17 | 2.9 | -10.10 | 3.5 | -8.58 | 4.1 | -9.19 | 4.7 | -9.19 |
| 2.4 | -13.11 | 3.0 | -9.60 | 3.6 | -9.02 | 4.2 | -9.22 | 4.8 | -9.22 |
| 2.5 | -12.20 | 3.1 | -9.23 | 3.7 | -9.08 | 4.3 | -9.27 | 4.9 | -9.27 |

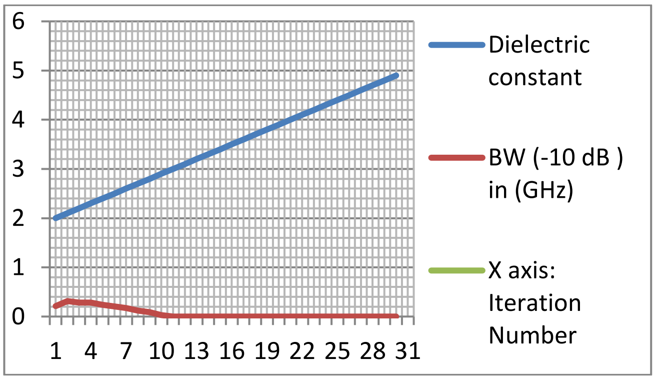


**Fig. 8**: Bandwidth of design 2 for 30 iterations of dielectric constant.

**Table 6:** Bandwidth of design 2 for different substrates

| $\varepsilon_r$ | BW -10dB (GHz) | $\varepsilon_r$ | BW -10dB (GHz) | $\varepsilon_r$ | BW -10dB (GHz) | $\varepsilon_r$ | BW -10dB (GHz) | $\varepsilon_r$ | BW -10dB (GHz) |
|---|---|---|---|---|---|---|---|---|---|
| 2.0 | 0.215 | 2.6 | 0.176 | 3.2 | 0 | 3.8 | 0 | 4.4 | 0 |
| 2.1 | 0.314 | 2.7 | 0.121 | 3.3 | 0 | 3.9 | 0 | 4.5 | 0 |
| 2.2 | 0.281 | 2.8 | 0.088 | 3.4 | 0 | 4.0 | 0 | 4.6 | 0 |
| 2.3 | 0.286 | 2.9 | 0.031 | 3.5 | 0 | 4.1 | 0 | 4.7 | 0 |
| 2.4 | 0.237 | 3.0 | 0 | 3.6 | 0 | 4.2 | 0 | 4.8 | 0 |
| 2.5 | 0.204 | 3.1 | 0 | 3.7 | 0 | 4.3 | 0 | 4.9 | 0 |

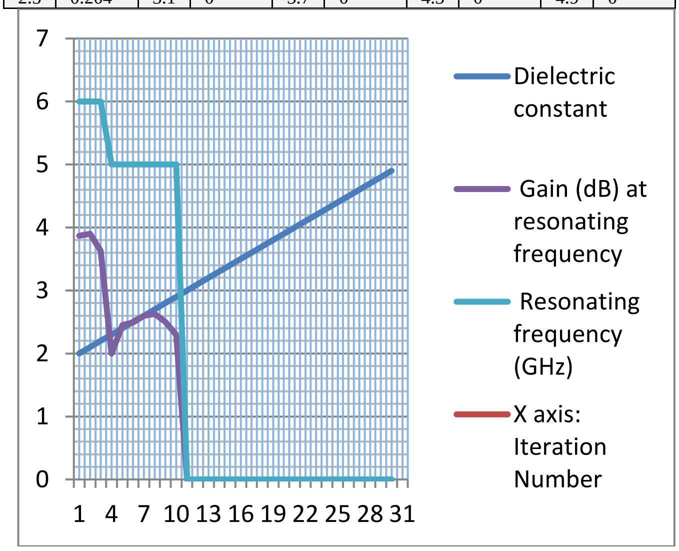


**Fig. 9:** Gain of design 2 for 30 iterations of dielectric constant.

**Table 7:** Gain of design 2 for different substrates

| $\varepsilon_r$ | Gain (dB) at $f_c$ | $\varepsilon_r$ | Gain (dB) at $f_c$ | $\varepsilon_r$ | Gain (dB) at $f_c$ | $\varepsilon_r$ | Gain (dB) at $f_c$ | $\varepsilon_r$ | Gain (dB) at $f_c$ |
|---|---|---|---|---|---|---|---|---|---|
| 2.0 | 3.87 | 2.6 | 2.6 | 3.2 | 0 | 3.8 | 0 | 4.4 | 0 |
| 2.1 | 3.9 | 2.7 | 2.63 | 3.3 | 0 | 3.9 | 0 | 4.5 | 0 |
| 2.2 | 3.63 | 2.8 | 2.5 | 3.4 | 0 | 4.0 | 0 | 4.6 | 0 |
| 2.3 | 2 | 2.9 | 2.3 | 3.5 | 0 | 4.1 | 0 | 4.7 | 0 |
| 2.4 | 2.45 | 3.0 | 0 | 3.6 | 0 | 4.2 | 0 | 4.8 | 0 |
| 2.5 | 2.49 | 3.1 | 0 | 3.7 | 0 | 4.3 | 0 | 4.9 | 0 |

From the above results it can be observed that the best performance is given by the material with dielectric constant in the range of 2 to 2.7 ($2\leq\varepsilon_r\leq2.7$).

## 5. Conclusion and future work

The simulations of two set of patch antenna with 30 different dielectric materials are investigated in this work. The first set is the basic model and the second set is the most common U shape model. From the result it can be concluded that for the first design the bandwidth of the best material with dielectric constant 2.7 ($\varepsilon_r$ =2.7) is around 88.6% better as compared to Bakelite and 85.5% better than FR4. On the other hand the proposed material's bandwidth is improved by 69.33% and 26.27% as compared to RT Duroid and RO4003 respectively. For the second design the best results are obtained for the material with dielectric constant 2.0 to 2.7 ($2\leq\varepsilon_r\leq2.7$). We observed the material is with, dielectric constant 2.1 ($\varepsilon_r$ = 2.1) has a bandwidth improvement of around 11.74% with respect to RT Duroid. If we consider the Gain of both design we find the best results in the range of 2.0 to 2.2 ($2.0\leq\varepsilon_r\leq2.2$) and better in the range of 2.6 to 2.8 ($2.6\leq\varepsilon_r\leq2.8$). In Presently available materials, RT Duroid furnishes these requirements in first group, but it is very expensive. FR4 is very cost effective but its performance is very much deprived for the frequency range of 1GHz to 6GHz. On the other hand material with dielectric constant in the range of 2.6 to 2.8 ($2.6\leq\varepsilon_r\leq2.8$) is a better choice for proposed substrate. Hence, further research can be done for development of material with $\varepsilon_r$ = 2.7 with sustainable mechanical and chemical properties.

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