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Influence of Substrate Materials on the Performance of a Triple-Band Notched Frequency UWB Antenna

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ABSTRACT

In this paper, the influence of different substrate materials on the performance of a triple-band notched frequency of ultra-wide band (UWB) antenna is presented. The antenna has a rectangular shape with dimension 31 by 24 mm and operates at UWB frequency band of 3.1GHz to 10.6GHz. The antenna was simulated using HFSS software. The effect of eight different substrate materials with different dielectric constant was examined on the antenna. Under each substrate, the performance of the antenna was investigated based on the antenna gain, directivity, radiation pattern, voltage standing wave ratio (VSWR), impedance bandwidth and S-parameter. Through thorough analysis, the results gave strong indication that UWB antenna performance is greatly affected by the type of dielectric substrate material chosen for design. The paper demonstrates the effect dielectric substrate material has on the antenna performance measurement like radiation pattern, gain, directivity and VSWR.

Keywords: Dielectric Substrates, Patch Antenna, Return Loss, Triple-Band, UWB.

1 Introduction

Patch antenna nowadays is often employed in wireless systems due to its low cost, easy manufacture, lightweight, directive high-quality signal and versatility advantages [1]-[3] . The antenna consists of metal patch etched on dielectric substrate on one side while a ground plane is added to other side [4]. When excited by an electrical current from patch flowing across the dielectric substrate to the ground plane, the patch antennas develop maximum radiation along the broadside and nearly zero radiation along the edge [5]. The resonant frequency of patch antenna largely depends on the patch dimension. Likewise, the antenna characteristics mostly depend on the substrate permittivity and its thickness [6],[7]. The antenna mechanical strength depends on the substrate material which permits the propagation of surface waves [8]. The profile of such antenna depends on the permittivity. Thus, antenna with high permittivity substrate is smaller in size while the gain and bandwidth is traded [9]. A dielectric substrate has two prime parameters which are permittivity (the materials with high polarization) and its loss tangent (the dissipation of electromagnetic energy) [10]. The choice of substrate material is an important factor to consider during the design of patch antenna. Selecting a suitable substrate material is an effective way to improve low gain and restricted bandwidth inherent in patch antennas [10]-[13]. There are several substrate materials that can be used during patch antenna design. Practical wise, each substrate material will produce varying performance. The focus of several studies in patch antenna had always been on the radiators and ground plan while the substrate material had not been given adequate attention in the resent time [14]-[16]. Therefore adequate and good knowledge of responses and performance of each type of dielectric materials for patch antenna design would aid in design specification and choice of antenna substrate material for antenna designers. To this end, the influence of eight different substrate materials on the effectiveness of a triple-band notched frequency UWB antenna is investigated.

The antenna consists of a rectangular patch beveled in both lower corners for bandwidth improvement as in [13] with half ground plane modified by cutting of 0.5 mm directly at the back of the fed line. The antenna frequency notching was achieved with the use of hybridized method developed in [17],[18] to notch three frequencies (WLAN, Wi-MAX and ITU) from the operation of the antenna.

1.1 The Patch Antenna Design

The rectangular patch of dimension 31 by 24 mm board employed in [19] was also used for this study. In [19], a microstrip line-fed rectangular-shaped UWB antenna offering triple-band notch characteristics was developed. The notching was done primarily to provide rejection for Wi-Max (3.3-3.7 GHz), WLAN2 (5.15-5.825 GHz), and ITU (8.025-8.4 GHz) through the combination of slots and a modified electromagnetic band gap (M-EBG). The antenna consist of a rectangular patch beveled in both lower corners for bandwidth improvement with half ground plane modified by cutting of 0.5 mm directly at the back of the fed line. The feed lines and radiating elements are photo etched onto a dielectric substrate. The radiating patch was square-shaped and mounted on an FR4 substrate with dimensions of 31 by 24 mm. The patch antenna was developed using a copper material with a thickness of 0.038 mm placed on an FR4 substrate having a dielectric constant of 4.4. To further enhance the operation of the UWB antenna, a partial ground plane was used with a cut of 0.5 × 0.5 mm directly behind the fed line for better impedance matching. At lower both corners of the patch, a rectangular radiator was beveled to expand the impedance bandwidth beyond UWB operation. Several parameters of the antenna were estimated. These are based on the equation of patch antenna presented in [20],[21] as shown in the Eqs. (1) to (7). Also, a fed line of 50 Ω impedance was utilized.

The effective dielectric constant ε_{eff} is derived from Eq. (1).

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

where ϵ_r is dielectric constant of the substrate and $\frac{w}{h} \gg 1$ denotes its width to height ratio while considering minimizing the fringing effect. The approximate expression for the normalized extended length of the antenna is obtained from;

$$\frac{\Delta L}{h} = 0.412\frac{(\epsilon_{eff} + 3)\left(\frac{W}{h} + 0.264\right)}{(\epsilon_{eff} - 0.258)\left(\frac{W}{h} + 0.8\right)} \tag{2}$$

Since the patch antenna length is expanded by ΔL, therefore, during dominant mode, the effective length L_{eff} of the antenna is expressed as

$$L_{eff} = L + 2\Delta L \tag{3}$$

The length and the speed of light determined the resonant frequency of the microstrip antenna as shown in Eq.(4).

$$f_r = \frac{1}{2L\sqrt{\mu_0\epsilon_0}\sqrt{\epsilon_r}} = \frac{v}{2L\sqrt{\epsilon_r}} \tag{4}$$

In Eq. (4), v denotes the speed of light, μ_0 is the permeability of free-space and ϵ_0 is the relative permittivity. The fringing effect is accounted for with modifications that include edge effects. Thus,

$$f_{rc} = q\frac{1}{2L\sqrt{\mu_0\epsilon_0}\sqrt{\epsilon_r}} = q\frac{v}{2L\sqrt{\epsilon_r}} \tag{5}$$

where the q factor f_{rc}/f_r is the fringe factor. Both length L and width W of the patch is estimated from Eq. (6) and (7). An increase in the substrate height increases the fringing effect. This causes a large gap between the radiating edges and the lower resonant frequencies as noticed in [10].

$$L = \frac{1}{2f_r\sqrt{\epsilon_{eff}}} - 2\Delta L \tag{6}$$

$$W = \frac{1}{2f_r\sqrt{\mu_0\epsilon_0}}\sqrt{\frac{2}{\epsilon_r + 1}} = \frac{v}{2f_r}\sqrt{\frac{2}{\epsilon_r + 1}} \tag{7}$$

The antenna dimension is given in Table 1 while Fig. 1 illustrates its configuration.

Table 1 Dimension of UWB antenna

Parameter	L	W	L_1	L_2	L_3	L_4	W_1	W_2
Dimension (mm)	31	24	17.7	0.5	11.5	1.5	10.25	3.3

The triple-band notched frequencies were achieved with the combination of two notching methods. Slot and modified electromagnetic band gap (MEBG) were used to notch three frequencies corresponding to Wi-Max (3.3-3.7 GHz), WLAN2 (5.15-5.825 GHz) and ITU (8.025-8.4 GHz).

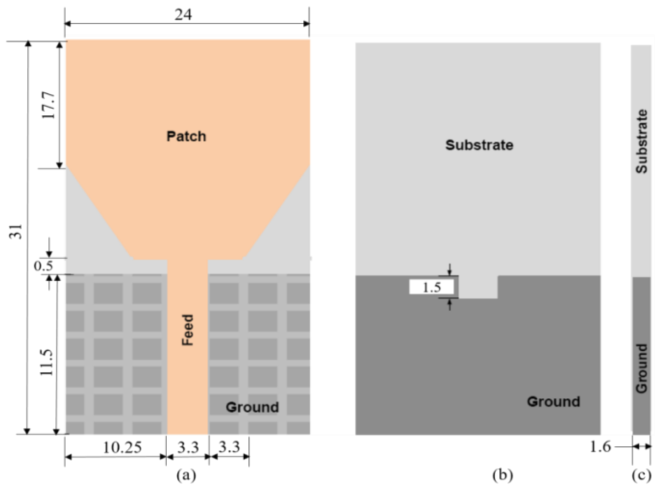

Fig. 1 Geometry of the rectangular patch antenna, (a) front view (b) side view (c) side view.

Fig. 2 shows the design of the triple-band notched UWB antenna. The estimation of the notch band frequency for the three notched frequencies, WiMAX, WLAN, and ITU, was calculated using Eq. (8) [16].

$$f_{notch(slot)} = \frac{V}{2 \times l_{slot} \times \sqrt{\epsilon_{eff}}} \tag{8}$$

where

$$\epsilon_{eff} = \frac{\epsilon_r + 1}{2} \tag{9}$$

In Eq. (8), l_{slot} stands for the overall length of the slot at the specified notch band centre frequency. Fig. 2 shows the geometry structure with dimensions (mm) of the three slots for notching WiMAX, WLAN, and ITU frequencies away from the UWB band.

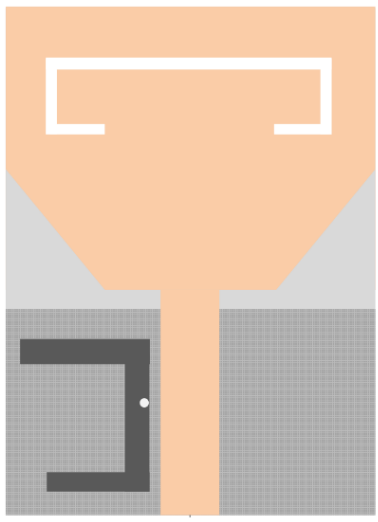

Fig. 2 Application of M-EBG and slots for multiple frequencies notching of the UWB antenna.

The antenna was modeled and simulated using HFSS and CST modeling tools on a dual-core computing system. The performance of the antenna was assessed using the S-parameter, as shown in Fig. 3.

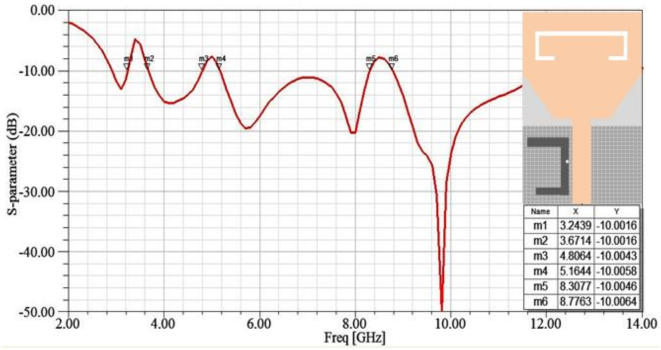

Fig. 3 S-parameter of triple-band notched antenna.

1.2 Effect of Dielectric Substrate

Several substrate materials can be used in design of UWB patch antenna. The substrates have different dielectric constant ranging from 2.2 to 12. Low dielectric constant consist of thick substrate and are mostly desirable for antenna performance in terms of efficiency and [22],[23], but are achieved at the cost of large element size, weight, dielectric loss, surface wave loss and extraneous radiation [24]. High dielectric constants consists of thin substrates and are mostly preferred due to tightly bound field that minimizes undesired radiation and coupling, thus given smaller sized antennas [25]. In patch antenna design, dielectric loss is a vital parameter to consider as it influences the performance of the antenna.

1.3 Dielectric loss

When an electric field is applied across the PCB, the charges in the substrate are displaced relative to the electric field that is producing the current. This leads to reduction in the magnitude of electric field given rise to dielectric loss as shown in Fig. 4.

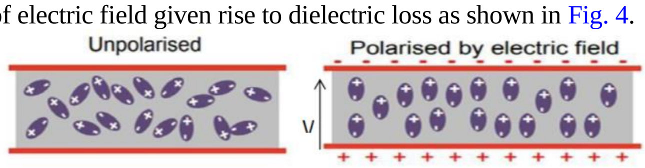

Fig. 4 Electric charge polarization of substrate when electric field is applied [23].

The two significant losses in patch antenna are the dielectric and conductor losses [27]. The attenuation constant of the antenna is calculated as using Eq. (10).

$$\alpha = \alpha_c + \alpha_d \tag{10}$$

where α_c and α_d denote the attenuation constant of the conductor and the dielectric respectively. The total attenuation constant is given by [27];

$$\alpha = \frac{8.687\pi}{Q_0 \times \lambda_g} \tag{11}$$

where Q_0 is the quality factor of the microstrip patch and λ_g is the guided wavelength. From Eqs. (10) and (11), the dielectric losses could be estimated as

$$\alpha_d = \frac{8.687\pi}{Q_0 \times \lambda_g} - \alpha_c \tag{12}$$

The conductor attenuation can be determined by calculation, simulation or measurement [28]. The strip coated on both side of the patch due to skin effect and the surface resistances are the cause of the conductor loss [29]. There is tendency that an alternating current becomes distributed within a conductor such that the current density becomes large at the conductor surface, while it decreases exponentially with depth within the conductor. The conduction losses α_c in dB is given Eq. (13) [19].

$$\alpha_c = 6.1 \times 10^{-5} \frac{R_s z_0 \varepsilon_{eff}}{h} \left[\frac{w}{h} + \frac{0.667 \frac{w}{h}}{\frac{w}{h} + 1.444} \right] A \; for \; \frac{w}{h} \geq 1 \tag{13}$$

where R_s is the effective surface resistance of the patch conductor, z_0 is the characteristics impedance of the microstrip and A is the patch area. Accounting for surface roughness of the patch, the conductor losses due to this, that is, $\alpha_{c,(rs)}$ is expressed as

$$\alpha_{c,(rs)} = \alpha_c \left[1 + \frac{2}{\pi} arctan \left(1.4 \left(\frac{\Delta}{\delta} \right)^2 \right) \right] \tag{14}$$

where Δ is the root means square (RMS) of the surface roughness and δ is the depth of penetration of the wave. When a dielectric material exposed to an alternating current, there could be absorption of electrical energy which causes dielectric loss. The loss may be as a result of a very small loss tangent δ. The dielectric loss α_d in dB per unit length is therefore expressed as

$$\alpha_d = 27.3 \frac{\varepsilon_r}{\sqrt{\epsilon_{eff}}} \frac{(\varepsilon_{eff} - 1)}{(\varepsilon_r - 1)} \frac{tan\delta}{A} \tag{15}$$

The loss tangent represents the quantitative dissipation of electrical energy due to the different physical phenomenal. It is expressed as

$$tan\delta = \frac{\sigma}{2\pi f \varepsilon_0 \varepsilon_r} \tag{16}$$

where σ is the conductivity of the substrate material, and f is the frequency of operation.

The choice of appropriate substrate material type as well as the thickness that fit the proposed application is one of the basic parameter to consider during the patch antenna design. Finding a suitable dielectric substrate and appropriate thickness for patched antenna that is capable of given high performance with acceptable charges at high frequency is one of the challenges faced by antenna designers [30],[31]. This study investigates eight different types of dielectric substrate materials used in patch antenna design. The effect of these materials on the performance of a triple-band notched UWB antenna was analysed based on the VSWR, S-parameter, impedance bandwidth, radiation pattern, gain and directivity. The designed and optimization was done on a core i5 computer system with HFSS and CST modeling. The simulation took about half an hour in processing the antenna.

2 Simulation Results and Discussions

2.1 Effect on the return loss

The result of the S-parameter and VSWR are shown in Fig. 5 and Fig. 6 while Table 2 shows the corresponding notch band frequencies of each of the substrate.

Apart from Gallium Arsenide (GaAs) with high dielectric constant that shows remarkable variation in the notch band of the antenna, all other dielectric substrates gives the same pattern of notch variation. The lower and upper limit of frequency of notch of each of the substrate deviate (increased) from the predefined band used in original design with FR-4. The same scenario is observed with the VSWR result at 2.0 marked value in Fig. 6.

As the dielectric constant of the substrate decreases, notch frequencies changes in upwards movement with little variation in notch bandwidth (BW).

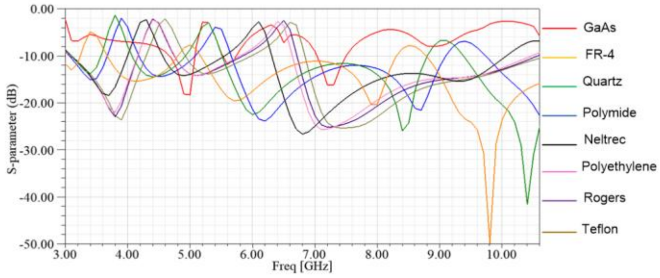

Fig. 5 S-parameter for the dielectric substrate materials.

Table 2 The notch band of different dielectric substrate

S/N	Name of Material	Dielectric Constant	WLAN (GHz)			Wi-MAX (GHz)			ITU (GHz)		
			Lower	Upper	BW	Lower	Upper	BW	Lower	Upper	BW
1	GaAs	12.90	5.08	5.52	0.44	5.74	7.03	1.29	7.50	10.76	3.26
2	FR-4	4.40	3.24	3.67	0.43	4.81	5.16	0.35	8.31	8.78	0.47
3	Quartz	3.78	3.58	4.07	0.49	4.93	5.51	0.58	8.80	9.37	0.57
4	Polymide	3.50	3.68	4.18	0.50	5.08	5.66	0.58	9.10	9s.73	0.63
5	Neltrec	2.60	4.00	4.56	0.56	5.55	6.30	0.75	10.06	11.01	0.95
6	Polyethylene	2.25	4.16	4.76	0.60	5.80	6.64	0.84	10.48	11.60	1.12
7	Rogers	2.17	4.17	4.75	0.58	5.85	6.71	0.86	10.58	11.73	1.15
8	Teflon	2.10	4.30	4.92	0.62	6.00	6.84	0.84	10.74	11.91	1.17

2.2 Effect on radiation pattern

The antenna's radiation pattern for the different substrate materials is shown in Fig. 7 for E-plane (Fig. 7 (a)) and H-plane (Fig. 7 (b)) respectively. The two planes formed an 8-shape. The closely related shape of the radiating pattern shows that there is no significant effect of different dielectric substrate on the radiation pattern of the antenna. To further analyze this, Fig. 8 relays a 3-D polar plot of far-field radiation patterns for each dielectric substrate material at UWB resonant frequency of 6.85GHz. Similar to Fig. 7, there is no significance difference in the results obtained for the radiation pattern considering the different substrates. However, for GaAs, FR-4, Quartz, Polymide, Neltrec, and Polyethylene substrates, the field strength is more concentrated along the x-axis than those present in Rogers and Teflon substrates. This indicates that both Rogers and Teflon substrates produces the least performance among the other substrate materials.

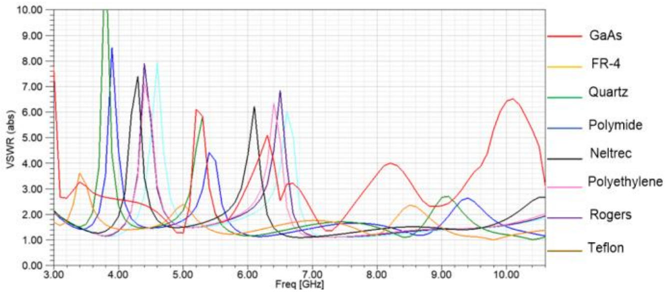

Fig. 6 VSWR for the dielectric substrate materials.

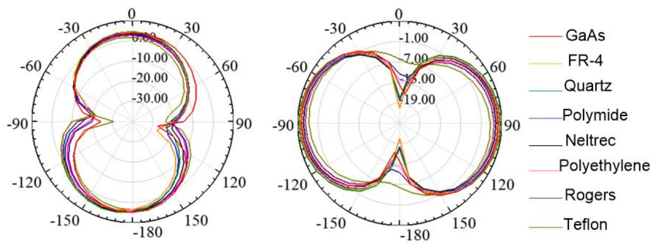

Fig. 7 Radiation pattern of the dielectric substrate materials (a) E-Plane, (b) H-Plane.

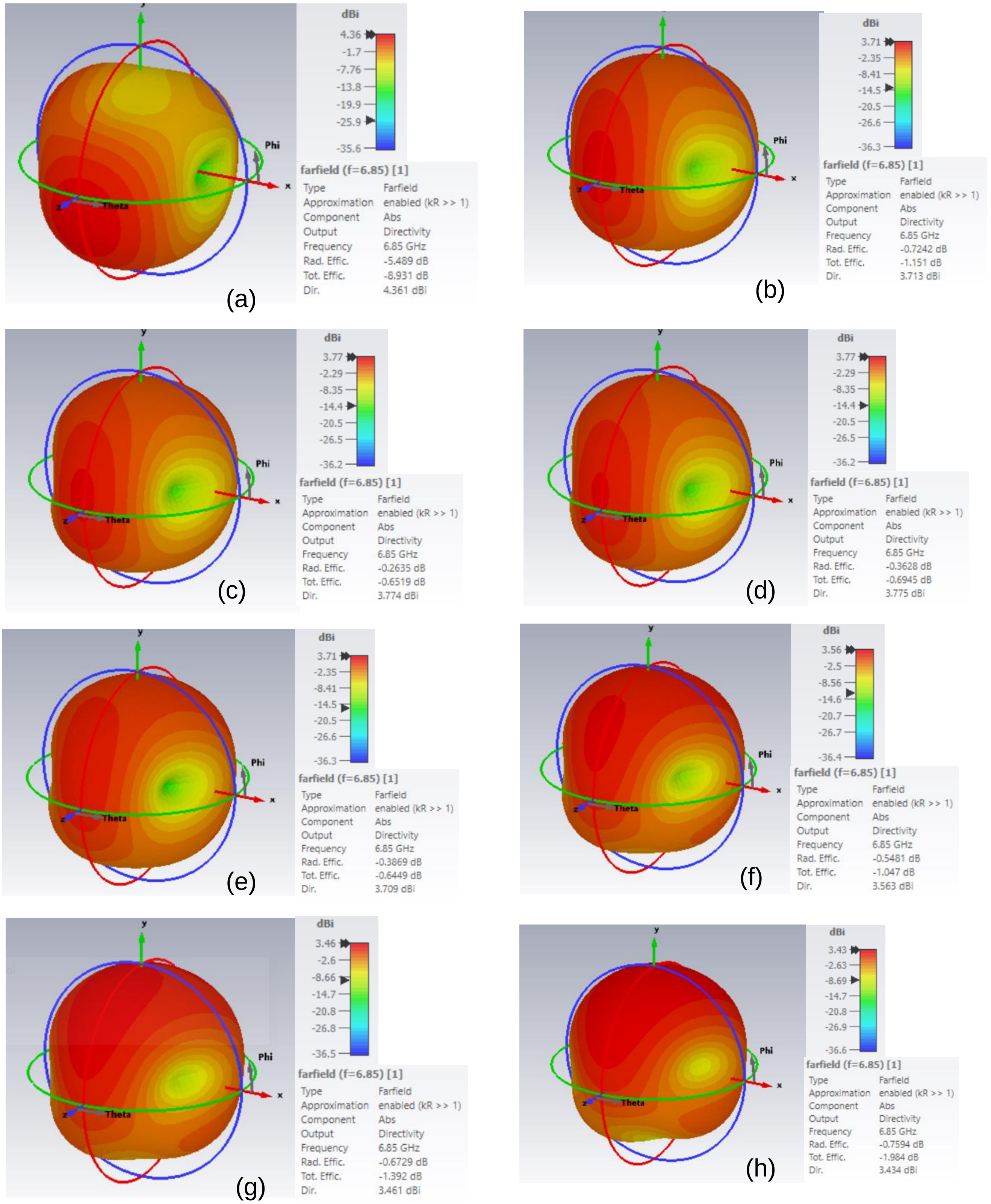

Fig. 8 Radiation pattern of the dielectric substrate material in 3-D view for (a) GaAs (b) FR-4 (c) Quartz (d) Polymide (e) Neltrec (f) Polyethylene (g) Rogers (h) Teflon.

2.3 Effect on directivity and gain

Table 3 shows that both Quartz and FR4 substrates gives better antenna gain while Teflon and Rogers produces the least performance in terms of gain and directivity. GaAs is observed to produce the best directivity value among the dielectric substrates investigated. In Fig. 9, the effect of varying dielectric constant on the gain and directivity value of the triple-band notched UWB antenna is presented. It can be observed that increase in dielectric constant from 2 to 4.5 values gives drastic increase in the antenna gain. A further increase in the dielectric constant beyond 4.5 to 12 did not produce a notable increase in the antenna gain. At these points, the antenna gain slightly reduces. However, a significant increase in the directivity was observed beyond 4.5.

Table 3 Gain and Directivity of dielectric substrate

Name of Material	Dielectric Constant	Gain	Directivity
GaAs	12.90	2.397526	4.361000
FR-4	4.40	2.522809	3.713000
Quartz	3.78	2.611300	3.774000
Polymide	3.50	2.436124	3.775000
Neltrec	2.60	2.161801	3.709000
Polyethylene	2.25	2.016758	3.563000
Rogers	2.17	1.980494	3.461000
Teflon	2.10	1.831039	3.434000

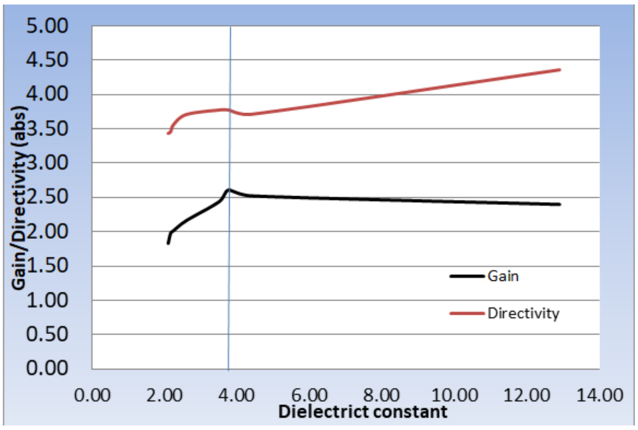

Fig. 9 Varying directivity and gain at resonant frequency 6.85GHz due to changes in dielectric.

2.4 Effect of different substrates on centre frequency

Table 4 illustrates the variation in the centre frequency and the impedance bandwidth as the dielectric constant changes. It can be observed that between dielectric substrate value of 2 and 4, the centre frequency reduces slightly, though, the variation can be considered insignificant. Above 4.5, there is a sharp reduction in the centre frequency as the dielectric constant increases. Thus, as the value of dielectric constant increases beyond 4.5, the resonance frequency and the impedance bandwidth of the triple-band UWB antenna decrease. This implies that using a substrate material with lower dielectric constant for the design of microstrip antenna will produce an antenna with wide bandwidth, though at the expense of gain and directivity.

Table 4 Dielectric constant and antenna impedance bandwidth

Name of material	Dielectric constant	Lower limit (GHz)	Upper limit (GHz)	Impedance bandwidth (GHz)	Centre frequency (GHz)
GaAs	12.90	4.67	7.50	2.83	6.09
FR-4	4.40	2.91	12.20	9.29	7.56
Quartz	3.78	3.10	12.40	9.30	7.75
Polymide	3.50	3.06	13.09	10.03	8.08
Neltrec	2.60	3.10	12.90	9.80	8.00
Polyethylene	2.25	3.10	13.05	9.95	8.08
Rogers	2.17	3.07	13.20	10.13	8.14
Teflon	2.10	3.07	13.16	10.09	8.12

3 Conclusion

Dielectric substrate material plays a significant role in the design of patch antenna. The choice of the substrate strongly influences the performance of such antenna. In this study, eight different substrate materials are simulated separately for the design of a triple-band notched UWB antenna. The effect of each of these substrates on the antenna performance was analysed. The results show that the antenna performance is greatly influenced by substrate material to a large extent. The performance of the FR4, and Quartz substrates is superb in terms of the antenna bandwidth, gain and directivity. High dielectric constant tends to favour applications that required high gain and directivity but with reduced impendent bandwidth as seen in the case of GaAs. However, both Rogers and Teflon substrates produces the least performance among the other substrate materials. It could inferred that for a wideband patch antenna design, a lower dielectric value is most suitable for better antenna performance that covers a wide range of operating frequencies. Therefore, for wideband application, a lower value of dielectric constant is most suitable for such application. Nevertheless when gain is been considered, dielectric constant between 3 and 4 will give suitable directivity and gain.

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