An Optically Transparent Antenna Based on Transparent Conductive Oxides for Tera-Hertz Applications

S. Syed Feroze Hussain and D. Thiripurasundari

Abstract A U-shaped transparent patch antenna made up of indium tin oxide (ITO) and fluorine doped tin oxide (FTO) conductive material is designed on polyimide substrate proposed to resonate at 750 GHz. The substrate material has dielectric constant and loss tangent of 3.5 and 0.008, respectively. The ground plane is made out of conductive oxide material such as ITO and FTO. The thickness of patch is 0.4 µm. The gain, impedance bandwidth, return loss and VSWR are analysed, and results are plotted. The return loss of −30.30 dB, −30.84.50 dB and −16.65 dB are obtained for the U-shaped ITO, FTO and copper-based antenna, respectively. An impedance bandwidth of 9%, 14% and 5.23% and gain of 2.772 dB, 1.965 dB and 4.915 dB are obtained for ITO, FTO and copper-based antenna, respectively. The transparency of ITO and FTO are greater than 80%. The low density portions are identified and removed to form the shape of rake. This structure enhances the transparency of the antenna with very little compromise in performance. The rake-shaped antenna has gain of 2.117 dB and 1.1707 dB along with impedance bandwidth of 9.3% and 12.62% is obtained for indium tin oxide and fluorine doped tin oxide, respectively. The rake-based antenna has return loss of −30 dB and −37 dB for ITO and FTO, respectively. There is an increment in bandwidth over 0.3% for indium tin oxide, and increase in return loss over 10 dB for fluorine tin oxide antenna is obtained with rake structure. The co-cross polarization ratio for both the U-shaped transparent antenna as well as the rake-shaped antenna structure are more than 30 dB. These type of transparent antenna result in larger bandwidth, high data rates and are suitable for microscopic scanning, military applications and inter-satellite communications.

Keywords Transparent antenna · Indium tin oxide · Fluorine tin oxide

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1 Introduction

The invention of micro strip antennas by Sir Deschamps in 1953 has found its applications in mobile technologies because of its light weight, small structure and compactness. The mounting of antenna on objects such as glass panels on buildings, automobile windows, monitors etc. without deviating much from its transparency has provided path to the development of transparent antennas. The applications integrated with optical transparent antenna are optical LED [1], liquid crystal display [2, 3] solar cells [4, 5], energy harvesting, light, display devices such as monitors and wearable applications [6]. Various conductive films such as variant of tin oxide (ITO/FTO) [7–10], aluminium-doped zinc oxide (AZO) [11–13], fluorine-based tin oxide (FTO), gallium-doped zinc oxide (GZO) [13] and silver-coated polymer (AgHT) [14–16] films are used in design of transparent antenna to produce reasonable performance and transparency. The methods used for designing transparent antenna are transparent conductive oxide (TCO), mesh type, micro metal mesh conductive (MMMC), meta-material loading, rectangular and circular patch antenna which can be used to implement dual band, multiband and broadband characteristics. The terahertz antenna creates an easier and faster data transfer, high capacity, higher data rate and low latency, which will be demanded by end-user in future generation. A wide variety of transparent substrates can be opted to design a transparent micro strip antenna such as glass, polyimide, etc. These thin films are deposited using various deposition methods such as magnetron-based sputtering, spray-based techniques, sol–gel process and pulsed deposition technique [17–29]. The increase in film thickness causes conductivity of film to increase while the optical transparency decreases. The radiation efficiency increases as the conductivity increases, thereby resulting in compromise between optical transmission and radiation performances. The factors such as low resistivity, higher transparency, stability, growth temperature, sheet resistance, heat resistant and film thickness are considered for optimal radiation performances. By using thick substrates, both impedance bandwidth and antenna size increases. The radiation performance is reduced because of higher permittivity therefore results in reduction in size of antenna. However, transparent conductors have lesser conductivity and better optical transmittance than non-transparent conductors.

2 Antenna Design

A U-shaped transparent patch antenna made up of indium tin oxide (ITO) and fluorine tin oxide (FTO) conductive material is designed on polyimide substrate proposed to resonate at 750 GHz. The substrate material has a dielectric constant of 3.5 and loss tangent of 0.008. The ground plane is made out of conductive oxide material such as ITO and FTO. The antenna has a patch thickness of 0.4 µm, while the antenna made up of ITO and FTO have a finite conductivity [30, 31]. These transparent antenna

Table 1 Optimized dimension of transparent and copper based antenna

Parameter	ITO dimensions (μm)	FTO dimensions (μm)	Copper dimensions (μm)
Patch length (L × L1)	88.98 × 83.08	88.98 × 86.71	88.98 × 80
Patch width (*W* × W1 × W2)	133.2 × 39.5 × 45.3	133.2 × 46 × 42	133.2 × 35 × 38
Thickness of patch (*t*)	0.4	0.4	0.4
Substrate (*L* sub × *W* sub)	208.98 × 433.2	208.98 × 433.2	208.98 × 433.2
Substrate thickness (*h*)	20	20	20
Feed line length and width (L2 × W3)	60 × 13.9	60 × 15	60 × 12
Ground plane (L g × W g)	208.98 × 433.2	208.98 × 433.2	208.98 × 433.2

are compared with non-transparent material made of copper having conductivity of 5×10^6 S/m.

The overall size of the antenna is 208.98 × 433.2 μm. Table 1 illustrates the dimension of antenna. The design of antenna is suitable for applications such as microscopic imaging, inter-satellite communication and military applications.

The parameters L1, W1, W2 and feed strip width (W2) are adjusted to provide impedance matching of antenna. The L1 and W1 causes the changes in resonance frequency. *L* is the length of the patch, *W* is the width of the patch, W1 is the width of first arm, W2 is the width of second arm, L1 is the length of inner arm, W3 is the feed line width and L2 is the length of feed line. The resonant frequency and length and width dimensions are calculated using following equations:

$$fr = \frac{c}{2(L + 2\Delta L)\sqrt{\varepsilon_{\text{eff}}}} \tag{1}$$

where *fr* is frequency of operation, *L* is patch length, *c* is velocity of light propagation, ε_{eff} is effective dielectric constant, ΔL is patch extension length.

$$W = \frac{c}{2fr}\frac{1}{((\varepsilon_r + 1)/2)} \tag{2}$$

$$L = \frac{c}{2fr\sqrt{\varepsilon_{\text{eff}}}} - 2\Delta L \tag{3}$$

$$\Delta L = 0.412h \frac{(\varepsilon_{\text{eff}} + 0.3)\left(\left(\frac{w}{h}\right) + 0.264\right)}{(\varepsilon_{\text{eff}} - 0.258)\left(\left(\frac{w}{h}\right) + 0.8\right)} \tag{4}$$

$$\varepsilon_{\text{eff}} = \frac{(\varepsilon_r + 1)}{2} \frac{(\varepsilon_r - 1)}{2} \frac{1}{1 + 12\left(\frac{h}{w}\right)^{0.5}} \tag{5}$$

where ε_r, is dielectric constant of substrate material, h is the height of substrate and w is width of the patch.

2.1 RAKE Shaped Antenna

The antenna structure is modified to form RAKE-shaped structure in which the low-current regions are identified, and those regions are removed without changes in the resonant frequency of 750 GHz. The modified structure resembles the rake-shaped structure. This structure will enhance the transparency of the antenna and with very little compromise in performance. The gain, return loss, impedance bandwidth and VSWR are analysed, and results are plotted.

3 Results and Discussion

A U-shaped transparent patch antenna made up of ITO and FTO conductive material is designed on polyimide substrate proposed to resonate at 750 GHz as shown in Fig. 1. The transparent antenna is compared with copper-based antenna. Fig. 2 shows the −10db bandwidth for ITO ranges from 718 to 786 GHz with return loss of −30.30 dB. Figure 3 shows the simulated VSWR value of ITO is 1.063 which is in an acceptable limit (VSWR < 2). The antenna has a gain of 2.772 dB at 750 GHz. Figure 4a shows radiation pattern of ITO having co-cross polarization ratio more than 30 dB. Figure 5a shows the surface current density of antenna which

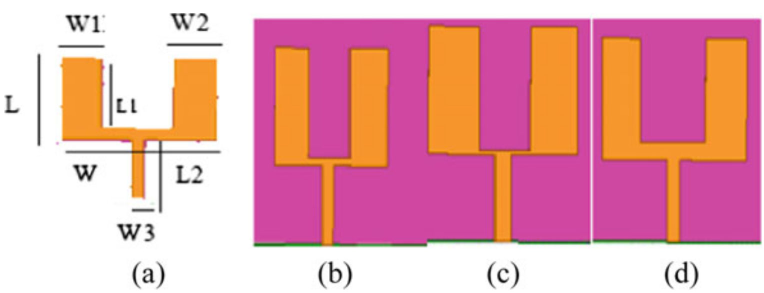


Fig. 1 Structure of transparent antenna **a** Antenna physical parameter **b** ITO **c** FTO **d** Copper

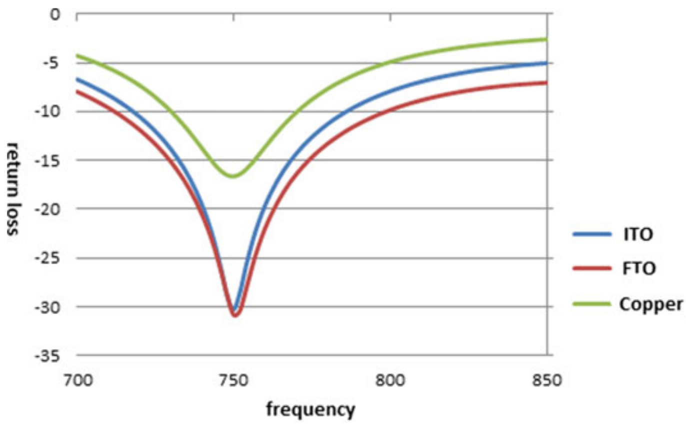


Fig. 2 Return loss versus frequency plot **a** ITO **b** FTO **c** Copper

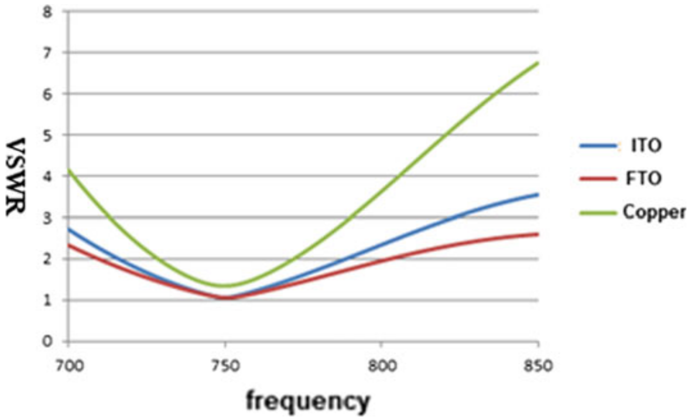


Fig. 3 VSWR versus frequency **a** ITO **b** FTO **c** Copper

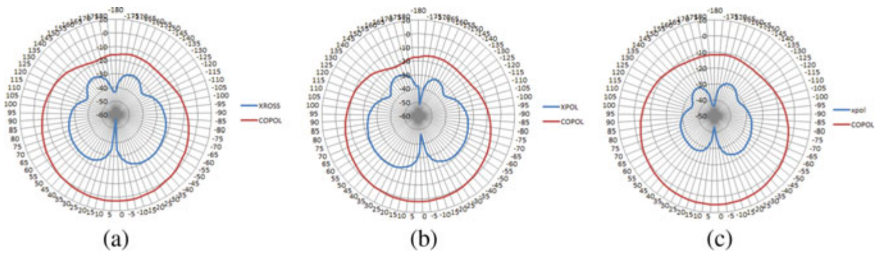


Fig. 4 Antenna radiation pattern **a** ITO **b** FTO **c** Copper

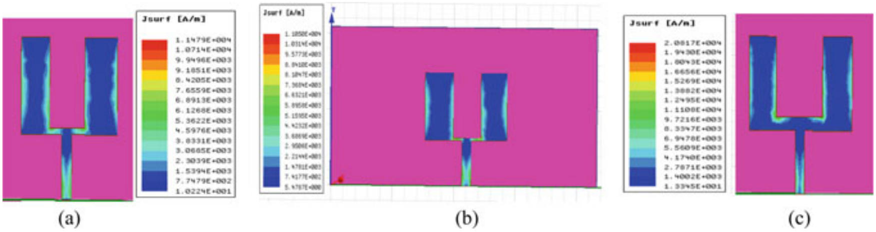


Fig. 5 Surface current density plot **a** ITO **b** FTO **c** Copper

is 1.141e^4[A/M]. The current density is more at edges of the U-shaped arm patch and also along the feed line.

The antenna made of FTO has −10 dB bandwidth ranges from 712 to 820 GHz which is highest among the other materials. The return loss of FTO is –30.84 dB as shown in Fig. 2. Figure 3 shows the simulated VSWR value of FTO which is 1.3449. The antenna has a gain of 1.965 dB at 750 GHz. Figure 4b shows the radiation pattern of FTO with co-cross polarization ratio is greater than 30 dB. Figure 5b shows the surface current density of antenna which is 1.105e^4[A/M]. The current density is more at the borders of the patch and at the centre of the feed line and decreases at the inner patch of the arms.

The non-transparent antenna made of copper has bandwidth of 5.3% (730–770 GHz) which is lowest compared to transparent antenna. While the return loss of copper-based antenna is −16.65 dB as shown in Fig. 2. Figure 3 shows the simulated VSWR value of 1.35 (copper). Figure 4c shows the radiation pattern of copper antenna having co-cross polarization ratio more than 30 dB. The antenna has a peak gain of 4.915 dB at 750 GHz. Figure 5c shows the surface current density of antenna which is 2.08e^4[A/M]. The current density is more at the edges of the patch and at the feed line while it reduces at the centre of the U-shaped arms.

Table 2 shows the comparative analysis of the radiation performances between transparent oxide-based antenna and copper-based antenna. The RAKE-shaped structure has been developed by identifying the low-current regions, and those regions

Table 2 Performance comparison of transparent and copper-based antenna

Parameters	Indium Tin Oxide	Fluorine doped Tin Oxide	Copper
Return loss	−30.30 dB	−30.84 dB	−16.64 dB
Operation band	718–786 GHz	712–820	730–770
Impedance bandwidth	9%	14%	5.3%
VSWR	1.063	1.3449	1.35
Gain	2.772 dB	1.965 dB	4.915 dB
Surface current density	1.141e^4	1.105e^4	2.08e^4

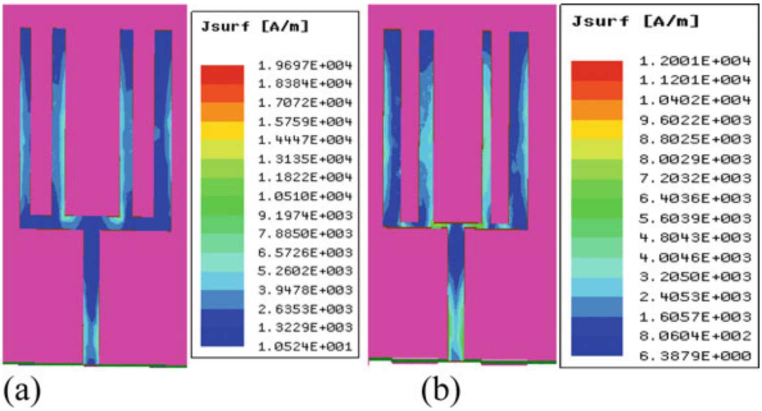
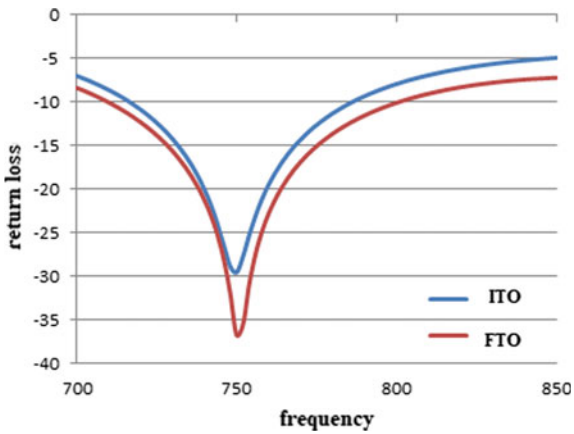


Fig. 6 Surface charge density plot **a** RAKE shaped ITO, **b** RAKE-shaped FTO

are removed without changes in the resonant frequency of 750 GHz. Figure 6a and b shows that the current density is more at the border of the inner rakes and at the bottom of the feed line for ITO. In FTO it is more at the edges of the inner rakes, borders of outer rakes, top portion and the central part of feed line. Figure 7 shows that the reflection coefficient of −30 dB and −37 dB is obtained for indium and fluorine oxide, respectively. Figure 8 shows the VSWR plot of rake-shaped structure which is 1.069 and 1.029 for ITO and FTO-based antenna, respectively. Figure 9a and b shows the radiation pattern for rake-shaped antenna with co-cross polarization ratio is more than 30 dB. Table 3 illustrates the gain of the antenna for ITO and FTO-based antenna are 2.117 dB and 1.1707 dB, respectively. The impedance bandwidth for rake-shaped transparent antenna is 9.3 and 12.62% with surface charge density 1.969eˆ4[A/M] and 1.200eˆ4 [A/M] is obtained for indium and fluorine-based antenna. This structure will enhance the transparency of the antenna and with very little compromise in

Fig. 7 Return loss versus frequency plot



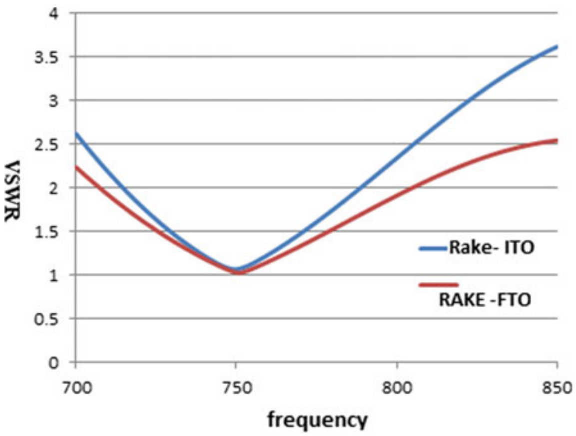
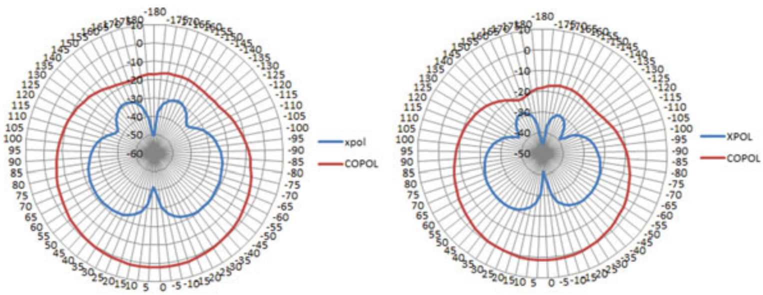


Fig. 8 VSWR versus frequency plot



(a) (b)

Fig. 9 Radiation plot **a** RAKE shaped ITO **b** RAKE-shaped FTO

Table 3 Comparison of RAKE-based transparent antenna

Parameters	ITO	FTO
Return loss	−30 dB	−37 dB
Operation band	716–786 GHz	705–800 GHz
Impedance bandwidth	9.3%	12.62%
VSWR	1.069	1.029
Gain	2.117 dB	1.1707 dB
Surface current density	1.969e^4	1.200e^4

radiation performance. The antenna overcomes the drawbacks of narrow impedance bandwidth (less than 5%) and low gain (less than 2 dB). Hence, the antenna is more suitable for high-frequency applications.

4 Conclusion

A U-shaped transparent patch antenna made up of ITO and FTO conductive material is designed on polyimide substrate proposed to resonate at 750 GHz. The antenna is compared to copper-based antenna which is non-transparent. The return loss of −30.30 dB, −30.84 dB and −16.65 dB are obtained for ITO, FTO and copper-based antenna, respectively. An impedance bandwidth of 9%, 14% and 5.23% and gain of 2.772 dB, 1.965 dB and 4.915 dB are obtained for ITO, FTO and copper-based antenna, respectively. The transparency of ITO and FTO are greater than 80%. The low-density portion are identified and removed without changing in resonance resulting in shape of rake structure. This structure enhances the transparency of the antenna with little compromise in radiation performance. The rake structure has reflection coefficient of −30 dB and −37 dB along with impedance bandwidth of 9.3% and 12.62% is obtained for indium and fluorine oxide-based antenna, respectively. The RAKE-based antenna has a gain of 2.117 dB and 1.1707 dB for indium tin oxide and fluorine tin oxide antenna, respectively. The antenna has broad impedance bandwidth and reasonable gain. The difference between co and cross polarization ratio is more than 30 dB for both U-shaped transparent and rake-based antenna. There is an increment in bandwidth over 0.3% for indium tin oxide and increase in return loss over 10 dB for fluorine tin oxide-based antenna. This antenna can be suitable for high data rate and secured communications due to its wider bandwidth. The antenna can be incorporated on glasses in buildings, windows of automobile, laptop screen and transparent surface to get rid of excess spacing condition and can be used along with integration with solar cell structure for photovoltaic applications.

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