

Review

Optically Transparent Antennas: A Review of the State-of-the-Art, Innovative Solutions and Future Trends

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Abstract: The requirement of mounting several access points and base stations is increasing tremendously due to recent advancements and the need for high-data-rate communication services of 5G and 6G wireless communication systems. In the near future, the enormous number of these access points might cause a mess. In such cases, an optically transparent antenna (OTA) is the best option for making the environment more appealing and pleasant. OTAs provide the possible solution as these maintain the device aesthetics to achieve transparency as well as fulfill the basic coverage and bandwidth requirements. Various attempts have been made to design OTAs to provide coverage for wireless communication, particularly for the dead zones. These antennas can be installed on building windows, car windscreens, towers, trees, and smart windows, which enables network access for vehicles and people passing by those locations. Several transparent materials and techniques are used for transparent antenna design. Thin-film and mesh-grid techniques are very popular to transform metallic parts of the antenna into a transparent material. In this article, a comprehensive review of both the techniques used for the design of OTAs is presented. The performance comparison of OTAs on the basis of bandwidth, gain, transparency, transmittance, and efficiency is also presented. An OTA is the best choice in these situations to improve the aesthetics and comfort of the surroundings with high antenna performance.

Keywords: optical antenna; optically transparent antenna; semi transparent antenna; transparent antenna; mesh grid; thin film; TCO; 5G



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1. Introduction

To fulfill the ever-increasing demands for high data rates in mobile devices enabling high-definition video streaming and other browsing aspects, the 5G and 6G technologies are emerging to provide higher data rates compared to the existing 4G technology. These technologies require several access points and base stations to accomplish the requirements of desired higher data rates. The antenna acts as a transducer that converts the electrical signal from the transmission line into electromagnetic waves to be transmitted in the free space and vice versa. Several types of antennas are mentioned in the literature, and may include microstrip patch, slot, dipole, bow tie, loop, spiral, PIFA, and fractal. The choice of the antenna depends on antenna application and design specifications. Design specifications include gain, bandwidth, polarization, impedance, resonant frequency, and half-power beamwidth. However, there is always a trade-off between antenna dimensions and antenna performance [1].

The basic components of a simple antenna are the radiating patch and ground, while the substrate is sandwiched between the patch and the ground. When feed is applied to the patch of the antenna, the patch receives a positive charge while the ground receives a negative charge, resulting in attractive forces between the ground and the patch. Hence,

the current is developed having maximum value at the center of the patch, while at the radiating edges, the electric field is maximum. The electrons in the current travel back and forth along the antenna path, thus creating electromagnetic radiations in the form of radio waves which travel at the speed of light from the transmitter to the medium.

The main concerning components of a transparent antenna are the transparent substrate, radiating patch, and ground [2]. Materials used for designing optical antennas are mentioned in Section 2, while Tables 1 and 2 show a list of suitable materials used in patch/ground for achieving transparency. The thickness of dielectric material has a direct relation with the bandwidth of the antenna. An increase in the thickness improves the antenna bandwidth. In addition, the choice of substrate material assists in achieving transparency at the cost of the conductivity of the antenna. Patch dimensions define the resonance frequency, radiation performance, and physical dimensions in terms of wavelengths and conduction losses. Higher conductivity results in fewer losses. Ground components help to mitigate the backside radiations while focusing the radiations in the intended direction.

The literature mentions metal meshing, conductive polymer, and thin film to convert an opaque antenna to a transparent antenna. For efficient antenna design, the electrical and optical properties of antennas must be taken into consideration. These properties of the antenna include the electrical dimensions of the antenna, polarization, permeability and permittivity of substrate material, conductance, resistivity, and transparency.

Antennas having thin structures, cheap cost, and high transparency are becoming more and more in demand for wireless applications, as discussed in [3]. A transparent antenna may help to reduce antenna size and aesthetics according to the size of mobile phones [4]. The 5G enabled antennas to have high attenuation due to higher frequency causing signal degradation. Therefore, several access points, signal repeaters, and base stations are needed to be deployed at closer distances on windows of buildings, streetlights, and other infrastructure to overcome this issue. This will help to maintain the aesthetics of the window as well as to meet the requirements for access points and base stations to provide network access to the vehicles and people passing by those buildings [5]. Moreover, transparent antennas may also be used in smart cities in which advanced wireless technology is needed to control the power, communication, and roads through data analysis and artificial intelligence.

Figure 1 illustrates the common techniques employed to disguise antennas from the general public and make them resemble camouflage patterns incorporated with tree, car screen, and cathedral cross while providing seemingly less 5G connectivity. Screen printed transparent antennas may also have various applications that include medical devices and electronic wearable devices [6].

Table 1. Summary of optical transparent antennas using thin film.

Ref.	Freq (GHz)	Substrate Material	Sub Thickness	Patch Material	Gain (dBi)	Bandwidth	Efficiency (%)	Transparency	Transmittance
[5]	5–18	PDMS	-	Fabric tissue (F)	3.2–4.2	0.1–25 GHz	66–90	-	-
[6]	23–30	Polyester fabric (F)	0.35 mm	Copper foil	4.2	24–28 GHz	-	-	-
[7]	10	Alumina	100 μ m	Polyaniline /copper	1.8, 4.69	9.6–9.9 GHz	56, 98	-	-
[8]	0.9	PET (F)	0.5 mm	Copper /CP (F)	3	0.8–0.95 GHz	-	-	-
[9]	2.4	Glass	-	AZO/AgNWs	-	2–3.5 GHz	-	-	80.28
[10]	45	Quartz	5 mm	AZO (F)	-	43–46.5 GHz	-	86	83
[11]	2.4	Silicon	-	AZO	4.9	-	−7.3 dBi	-	-

Table 1. Cont.

Ref.	Freq (GHz)	Substrate Material	Sub Thickness	Patch Material	Gain (dBi)	Bandwidth	Efficiency (%)	Transparency	Transmittance
[12]	2.53	Glass	2 mm	AgHT-4	9.8	2.49–2.58 GHz	-	-	75
[13]	28	Glass	2.54 mm	ITO, FTO, AgHT-4, AgHT-8	4.8, 4.2, 4.4, 4.2	26–36 GHz	81, 73, 75, 73	-	-
[14]	3.5	Glass	2.3 mm	AgHT-4	3.96	3.49–3.55 GHz	50	-	92
[15]	5.25	Polyimide	-	IZTO/Ag/IZTO	4.1–5.2	4.7–5.7 GHz	61–82	-	-
[16]	9.85	Quartz glass	1.5 mm	ITO	4.27	-	56	-	-
[17]	5.8	Glass	1 mm	ITO	6	5.7–6 GHz	-	-	-
[18]	0.1–1 THz	Polyimide	0.013 mm	Polymer	-	-	-	-	80
[19]	3, 5, 8, 13	Borosilicate glass	7 nm	Cu, ITO	−4, −2, 0.5, 2	3.1–10.6 GHz	27, 25, 20, 18	88	-
[20]	24.8	Pyrex glass	0.4 µm	ITO	11.5	17–30 GHz	92.30	-	-
[21]	2.45	Soda-lime glass	2 mm	MM		2–3 GHz	-		75
[22]	2	Corning glass	1.1 mm	AgGL	5.2	19.7%	60	51–70	-
[23]	1–8.5	Perspex	2 mm	AgHT-4	−2.5 to −33	1–10 GHz	-	-	-
[24]	2, 6	Corning glass	1.1 mm	AgGL	2–6	2.5–5.3 GHz	-	80	
[25]	750	Polyimide	20µm	ITO,TIO with MWCNT	4.5–5.8	723–780 GHz	47–61	-	-
[26]	23.92–43.8	Plexiglass	1.48 mm	-	2.8	23.92–43.8 GHz	90	-	-
[27]	2.4	Silica glass	1.4 µm	GZO	-	-	-	-	-
[28]	2.5, 5	Pyrex glass	4 mm	FTO	0.43, 3.63	-	72	-	74–84
[29]	2.45, 5.8	PET	0.175 mm	AgHT-8	−3.25, −4.53	1.6–2.95, 5.4–6.4		80	
[30]	4.9	Soda-lime glass	-	FTO	5.16	0.8 GHz	-	-	60
[31]	2.4	PET	0.05 mm	ITO	−1.36	2.2–3 GHz	20–52	96	

Table 2. Summary of optical transparent antennas using mesh grid.

Ref	Freq (GHz)	Substrate Material	Sub Thickness	Patch Material (Mesh)	Gain (dBi)	Bandwidth	Efficiency (%)	Transparency	Transmittance
[32]	0.84	Glass	0.006 mm	Ag/Ti	-	-	85	81	-
[33]	2.4–2.5	Acrylic	1.2 mm	Metal mesh	4.14	2.48–2.52 GHz	56	82	-
[34]	18	Quartz	-	ITO/metal mesh	-	-	38, 41	-	73–95, 66–94

Table 2. Cont.

Ref	Freq (GHz)	Substrate Material	Sub Thickness	Patch Material (Mesh)	Gain (dBi)	Bandwidth	Efficiency (%)	Transparency	Transmittance
[35]	2.46–2.94	Fused silica	-	Tortuous MM	−3.4	2.82–3.0 GHz	81	-	30–45
[36]	3.45	PDMS	2–4 mm	EGaIn (liquid metal)		3.3–3.5 GHz	60	-	-
[37]	2.4–2.48, 5.15–5.8	Glass	1.09 mm	MMMC	0.74, 2.30	-	43, 46	-	75
[38]	2.43–2.48	Borosilicate glass	4, 3.5, 3, 2.5 mm	Meshed patch	4.4	2.39–2.58 GHz	-	74	-
[39]	2.3–3	PET/PMMA	4–5 mm	Metal mesh	6	2.4–2.9 GHz	90	70	-
[40]	2.33–2.53, 4.7–5.6	PDMS	3 mm	Mesh	2.2, 3.1	170–200 MHz, 700–900 MHz	37, 44	-	50–70
[41]	2.4–2.5	Acrylic	1 mm	Micromesh	4.75, −4.23, and 2.63	2.4–2.6 GHz	66.32, 7.76, and 42.69	80	-
[42]	60	Thick fused silica 7980 Corning	0.2 mm	Al-MM	3.20	53.55 GHz	-	78	-
[43]	2.4, 2.55	Quartz	2.25 mm	Silver epoxy mesh	4.94, 7.23	2.4–2.6 GHz	-	90	-
[44]	28	Glass	0.7 mm	Ag-alloy (diamond-shaped)	9.16	27.5–29.5 GHz	52	41	-
[45]	2–2.5	Plexiglass	2.03 mm	Meshed copper	7.32	-	78	70–95	-
[46]	27–35	Acrylic	2 mm	Cu micro-grids	-	27–35 GHz	-	-	-
[47]	0.5–20	PET	0.1 mm	Metal mesh	10.4	0.78–20 GHz	-	-	72
[48]	22–40	COPs	0.1 mm	Thin MM	1.12	24–29 GHz, 35.5–37.5 GHz	34–43	92–98	
[49]	6.63, 7.291, 7.29, 7.22	FR-4	1.62 mm	MWCNT	8.8	4.5–8.5 GHz	86	-	-

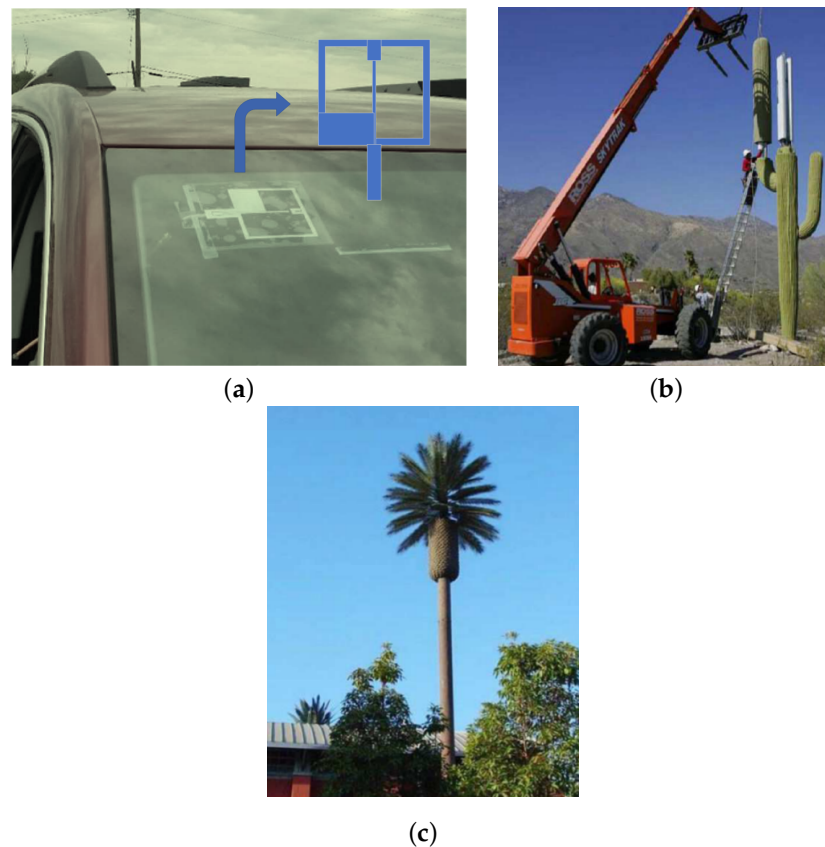


Figure 1. Examples of optically transparent antennas. (a) On car windscreen [50]. (b) On cactus camouflage platforms [51]. (c) On tree camouflage platforms [51].

In the urban environment, transparent antennas embedded into the glass of high-rise buildings may work as a camouflage antenna to provide connectivity in the dead zones. However, this may affect the gain, efficiency, and radiation pattern of the antenna adversely. The process used to convert an opaque to a transparent antenna causes the inefficiency of the antenna due to the meshing of the conducting part or material resistivity of thin films [52].

Gain and Bandwidth for Various Antenna Applications

Antennas are designed for several applications working at different frequency bands. The RF spectrum is shown in Figure 2, where the spectrum is differentiated based on different applications. Therefore, the bandwidth and gain requirement also depends on the type of antenna, choice of substrate, patch material, the electrical length of the antenna, and feeding techniques. Some applications require low gain and bandwidth, while others have higher requirements.

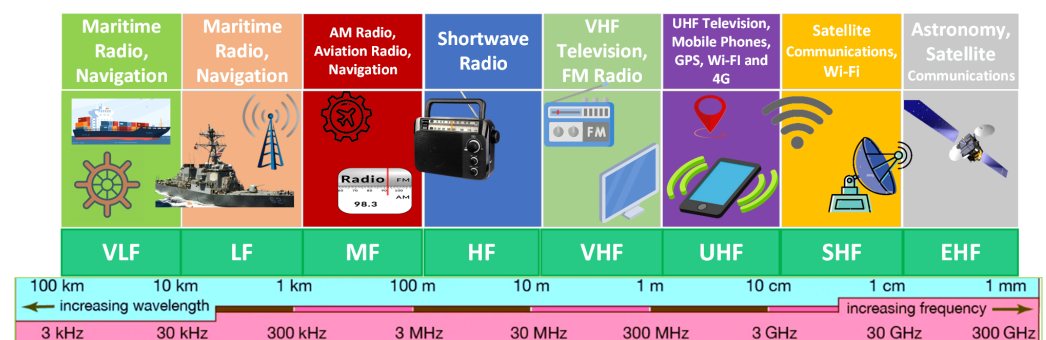


Figure 2. RF spectrum and its applications [53].

For 5G applications, authors in [54–57] designed antennas providing bandwidth of 34%, 28%, 11.7%, and 51%, respectively. The gain of these antennas mentioned are 2, 6.8, 15.1, and 12.4 dBi, respectively. In [58], an optimized Vivaldi antenna was designed for 5G communication, gain of 10.33 dBi, and 54% bandwidth was achieved.

Some other work discusses the 5G MIMO antenna design at mm-wave band. A gain of 11 dBi in [59] and 16 dBi in [60] was achieved; however, the antennas have large dimensions. For smaller antenna dimensions, antenna provide the gain of 15 dBi, as mentioned in [61]. Another work discusses 5G MIMO antenna for IoT applications in [62], in which FBW achieved at 2.5 GHz band was 11%, 17% at 3.5 GHz band, 20% at 5.5 GHz band, 18% at 7.5 GHz, and 29% at 28 GHz (mm-wave). Antennas having a bandwidth greater than 500 MHz fall under the category of ultra-wideband (UWB) antennas. Therefore, the research showing higher values of bandwidth is suitable for ultra-wideband applications. Moreover, higher gain reflects large antenna dimensions.

Optical antennas are suitable for satellite communication as they can hide the aesthetics of antennas while integrating with solar panels, commonly working at L, S, X, Ka, Ku, and W bands. For Earth observation, UHF and VHF bands are preferred, using monopole and dipole antennas providing gain less than 4 dBi, while phased array, helical, and Horn resulted in improved gain greater than 12 dBi at UHF, S, Ka, and X band, as discussed in [63]. Moreover, for gain, the available RF power budget and orbit determine that the gain and mission specifications will guide the bandwidth requirements for a particular antenna.

Implantable antennas used for biomedical purposes may also use optical antennas. In [64], a quad-band implantable antenna was designed where gain between -24 to -34 dBi was achieved. In [65], a compact conformal implantable antenna was designed where gain was realized between -18 to -30 dBi. An implantable slot antenna array was designed in [66], where the gain of -26 dBi was achieved. Hence, the literature suggests that the gain of implantable antennas is negative with smaller values. Here, the gain and bandwidth are determined based on the detection, monitoring, and treatment of a certain type of disease.

2. Optically Transparent Antennas

An optically transparent antenna acts similar to a normal conventional antenna, comprising ground, substrate, and radiating patch layers. Glass, quartz, acryl, sapphire, and Plexiglass are considered rigid substrate materials. Flexible includes PEN, PDMS, polyamide, PI, PET, and other materials, including water, Rogers 6002, PVC, and quarter glass, as mentioned in [67]. Top and bottom copper comprise either transparent conductive oxide material (TCOM) or metal mesh. Depending on the application, the substrate and radiating elements are chosen. These antennas are suitable for wireless communication, especially 5G, automotives, MIMO communication [68], and wireless access points, or may be combined with a satellite's solar panels [69] or in glass of a building for efficient 5G and IoT communication [27].

OTAs are designed using conductive films or metal meshing, as illustrated in Figure 3. The metal mesh allows the meshing of a radiating patch with mesh made up of copper, aluminum, gold, and silver having geometrical shapes of square, diamond, and hexagonal. Achieving transparency through conductive films requires the layering of conductive film materials. Moreover, the combination of the metal with conductive mesh also results in transparent antennas; details of such materials are mentioned in Figure 3.

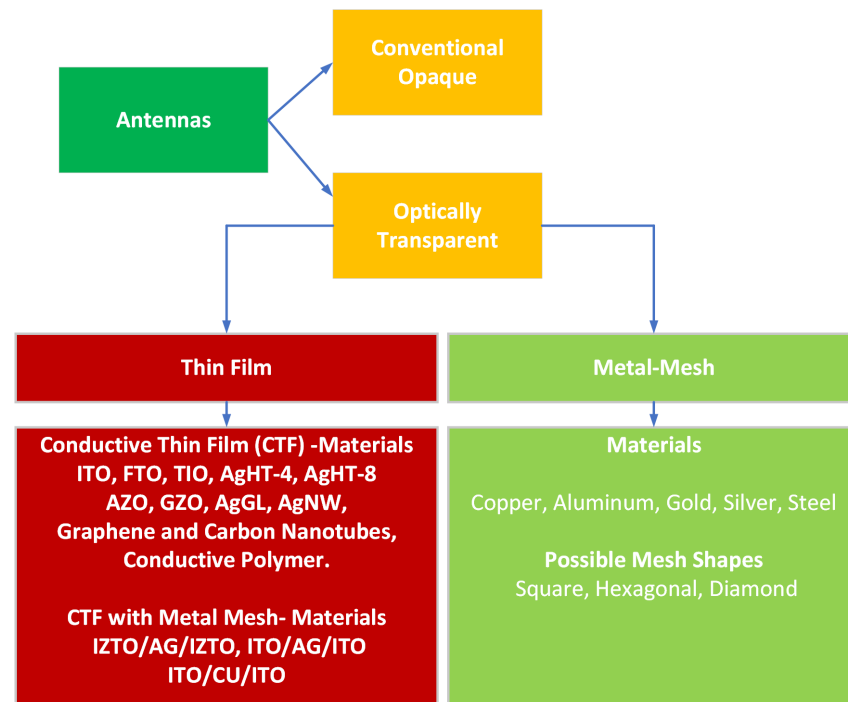


Figure 3. Classification of optically transparent antennas.

2.1. Transparent Antennas Using Thin Films

Antenna designed using thin films (ITO) provide advantages in terms of ease of availability, high conductivity, and high transmittance when they are integrated on the glass substrate. However, high cost is the major disadvantage. Zinc-based TCO materials and carbon nanotubes are considered appropriate in terms of performance with low cost. Optical antennas designed using IZTO/Ag/IZTO, in which metal mesh is sandwiched between thin-film layers, provide high transparency, low resistivity, and flexible structure; however, their fabrication process is complex as compared to the single-layer fabrication.

Transparent conducting oxide (TCO) material with gallium-doped zinc oxide (GZO) may be considered a good option for the design of a transparent antenna due to its high conductivity. Authors in [70] discussed several materials, including conductive polymers, TCOs, and conductive inks for these transparent antennas. Carbon nanotubes were suggested as a transparent radiating film in [71]. Several types of TCOs include fluorine-doped tin oxide (FTO), Al-doped ZnO (AZO), ITO, and Ga-doped ZnO (GZO). Other materials include ATO, FZO, IZO, and AIZO, as mentioned in [67].

The design of a conductive polymer microstrip fed patch antenna operating at 10 GHz was suggested in [7]. Polyaniline (Pani) was used as film material with electrical conductivity of 6×10^3 S/m with thickness of 100 μm . A gain of 2.08 dB was achieved. Figure 4 illustrates the design.

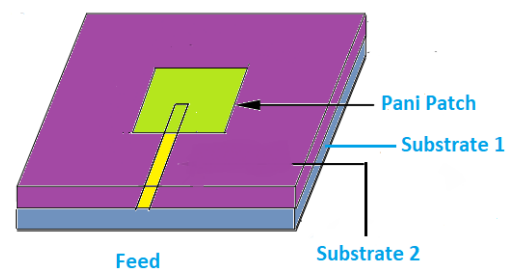


Figure 4. Conductive polymer microstrip fed patch antenna [7].

In [9], a transparent conducting film comprising AZO/silver nanowire (AgNW) on substrate of glass material was proposed through RF magnetron sputtering and spin-coating. The resistivity of AZO/AgWNs stacked films was $2.15 \times 10^4 \Omega\text{cm}$. Finally, from these stacked films, a wideband transparent antenna was designed at 2.4 GHz for Bluetooth communication. Therefore, TCOs are suitable for OTA fabrication due to their conductive nature within the RF range.

An optical antenna using thin aluminum and zinc oxide layers was designed, as mentioned in [10]. These layers were co-sputtered onto Si and polycrystalline photovoltaic cells. Low-resistivity AZO was formed through the annealing process, as illustrated in Figure 5.

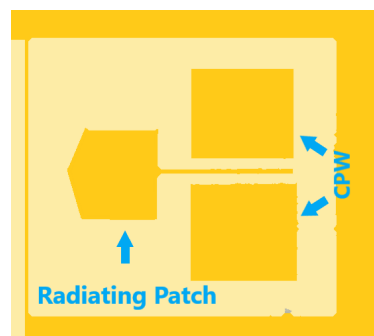


Figure 5. CPW antenna fabrication [10].

Another optical antenna with TCO and AZO combination was proposed in [11]. This material provides improved RF conductivity with high transmittance and provides a cost-efficient solution: an antenna array comprising two rectangular inset feed patch elements with dimensions $19 \text{ cm} \times 13 \text{ cm}$ operating at 2.4 GHz. Realized gain of 5 dB was obtained. RF properties of these materials allow the transparent antennas to integrate with the solar cells.

Authors in [72] proposed a transparent antenna working at 20 to 44 GHz frequency. Wide bandwidth was achieved through the rectangular-shaped branches that are attached to the infinite ground plane. Antenna size was taken as $10 \text{ mm} \times 12 \text{ mm} \times 1.48 \text{ mm}$. A return loss of 10 dB was achieved with a directional radiation pattern along with electrical tilt according to the required frequency. The authors in [12] discussed the transparent cone-top tapered slot antenna for UWB communication, designed to operate between 2.2 GHz to 12.1 GHz integrated onto solar panels along with harvesting EM waves that are converted to electrical energy.

A graphene nanoribbon-based terahertz patch antenna operating at 725–775 GHz band using polyimide substrate was designed in [73]. These types of antennas provide low transmit power with higher data rates while enhancing the security of wireless communication. This novel design resulted in 5.71 dBi gain and impedance bandwidth greater than 5%.

Authors in [13] used different TCOs, which included ITO, AgHT-4/8, and FTO, as conducting patch material. Figure 6 shows the design, comprising a silicon layer sandwiched between the anode and cathode layer. This solar patch transparent antenna was designed at 28 GHz for 5G communication. Their performance was tested with a nontransparent antenna. It was observed that the solar efficiency was reduced due to the shadow effect. This issue was resolved using the thin-film TCO as a radiating patch. The patch thickness of the transparent antenna was taken as four times thicker than the nontransparent one. It was also noticed that FTO gave the highest bandwidth while the return loss of ITO was -35 dB .

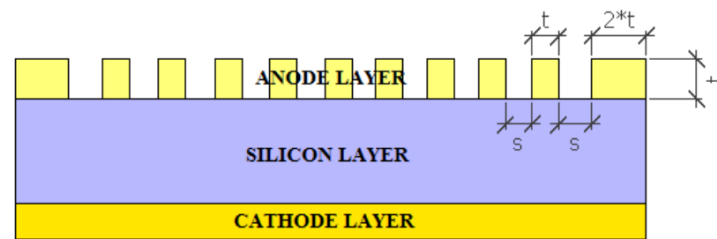


Figure 6. Solar patch transparent antenna [13].

In [14], an optically transmitted microstrip patched antenna mounted on the solar module surface was proposed, working at 3.4 to 3.8 GHz frequency. Polyester was used as a patch material having a conductive coating. The amorphous silicon solar cells worked for both the antenna ground plane and the photovoltaic generator. This topology resulted in a gain of 4 dBi at the resonant frequency.

In [15], silver was fabricated with an Ag monolayer while IZTO was fabricated at a multilayer, shown in Figure 7. These TCO materials were used for laptop computers at a frequency between 5.25 to 5.32 GHz. Results indicate the improved performance of Ag monolayer antennas as compared to the IZTO/Ag/IZTO multilayer. The efficiencies of multilayer antennas were 59–68% and 82–84%, respectively.

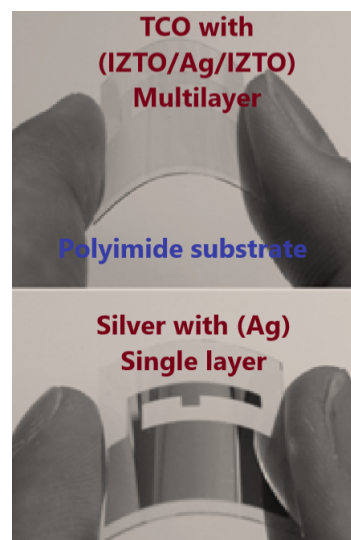


Figure 7. Antenna with Ag monolayer and multilayer of IZTO/Ag/IZTO [15].

Authors used ITO (indium tin oxide) for designing an optically transparent antenna in [16]. A thin sheet of the quartz glass substrate was used along with ITO film coatings, and the coaxial probe was used for feeding. This antenna resulted in the measured and simulated efficiency of 56.64% and 59.71%, respectively, with the gain of 4.27 dB and 4.52 dB, respectively. Optical antennas have applications for car network communication as well, which was proposed in [17]. This optical antenna worked at frequencies between 5.75 to 5.85 GHz. ITO material was used for the radiation patch which was placed on top of the glass substrate. FSS (frequency selective surface) acted as a ground for the microstrip antenna. As FSS has good transmittance of light, it helps to achieve directional radiation because it can reflect the electromagnetic waves received at the antenna.

For the feeding of the antenna, an SMA connector was used. The results demonstrated in this paper gave good radiation antenna parameters performance (S11 and gain).

In [18], a dual-band transparent antenna with two slotted circular rings (SRR) was suggested. AgHT-8 thin film was used as conducting patch for two circular SRRs and partial ground, providing transparency of 80%. Plexiglas material was used as substrate. The proposed antenna has dimensions 35 mm × 35 mm × 1.84 mm. Impedance bandwidth

of 13.27% at 2.4 GHz and 5.28% at 5.28 GHz was achieved. The resulting band is suitable for smart applications covering IEEE a/b/g and n frequency bands.

In [19], antenna efficiency was improved using transparent antenna. The antenna was designed to resonate between 3.1 GHz and 10.6 GHz and the patch was made of ITO film deposited on the borosilicate glass substrate, as shown in Figure 8. A bandwidth of 155% was achieved. The gain was improved by the homogeneous decomposition of the gold nanolayer, which in return reduced the ohmic loss.

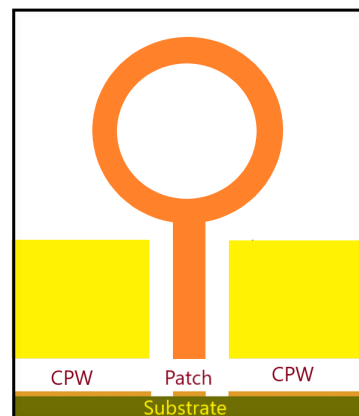


Figure 8. Transparent antenna using borosilicate glass substrate [19].

An optically transparent antenna producing high gain for k-band operating between 17.6 GHz and 30.5 GHz was proposed in [20]. This antenna was intended to work with satellite communication using ITO film and Pyrex glass as substrate material. The proposed antenna provided 12.3 dBi gain with 13.38 dBi directivity and 92% efficiency. An improved VSWR of 1.05, an enhanced bandwidth of 12.898 GHz, and an 11.52 dB realized gain at the center operating frequency of 24.8 GHz were achieved in this design.

A low-profile transparent microstrip patch antenna using conductive layers of FTO (fluorine doped in oxide) was proposed in [30]. The patch was electromagnetically excited using a coupled feeding technique, while cold soldering was used to feed the connector. The proposed antenna produced a gain of 5.61 dBi operating at 4.9 GHz of frequency. The reflection coefficient of -10 dB was achieved, and optical transmittance was found to be greater than 60%. The authors in [74] used doped ZnO thin films at 2.5 GHz frequency. Hourglass topology was used in the design. Multiarrays were proposed to solve the issues of low gain and antenna efficiency.

In [37], an MIMO antenna for WLAN applications was proposed, operating between 2.4 to 2.48 GHz and 5.15 to 5.8 GHz. The antenna used MMMC (micro metal mesh conductive) films. Using SANTE self-assembling nanoparticle technology, these films were constructed. A high transmittance above 75% and low resistance was achieved, along with efficiency greater than 40%.

The design of a BLC (branch line coupler) using nanotechnology-based micro metal (MM) conductive film was suggested for a transparent antenna in [21]. The final design, shown in Figure 9, shows high transparency with good conductivity.

A micro metal (MM) conductive film-based branch line coupler (BLC) operating at 2.5 GHz was proposed in [21], as illustrated in Figure 9. The proposed design promises high transparency and good conductivity. This proposed transparent antenna design provided a bandwidth of 38%. They can easily be mounted on a building's glass surface, hence providing a basic solution for 5G communication while the major application of the BLC lies in the intelligent transport system for inter-/intravehicle communication.

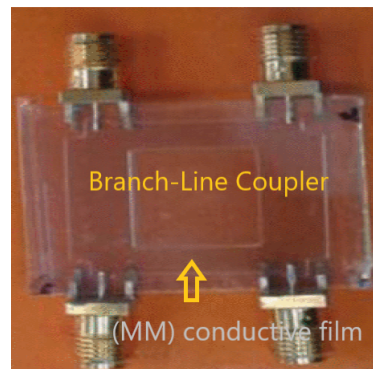


Figure 9. Branch line coupler based on micro metal (MM) conductive film [21].

An H-shaped slot antenna for transparent antennas was fabricated using the AgGL material suitable for urban cellular communication, as suggested by the authors of [22]. Ohmic losses were restricted through transparent and conductive AgGL coating. The results obtained were 5 dBi of gain and bandwidth of around 20% operating at 2 GHz frequency. This scheme is considered suitable for multilayer array designing for cellular networks in urban areas. They proposed a transparent antenna for urban cellular communication for broadband applications with a size of 300 mm $\times$ 300 mm.

Several authors proposed various optically transparent antennas operating at 800 MHz in [32,75], 1–8.5 GHz as suggested by [23,24,76], and 19.5 GHz as recommended by [77]. The antenna size in these studies was taken below 80mm $\times$ 80 mm. The conductive coating of single transparent conductive material printed on the substrate on one side was used. The paper [78] discusses the transparent 1D electromagnetic band gap antenna using thin-film alloy working at millimeter-wave frequencies. At 30 GHz frequency, the attenuation of less than 0.3 db/mm was observed. The antenna can be used for AoD application with radiation of 3.4 dBi.

Authors in [25] suggested optically transparent antennas working at 750 GHz frequency using multi-walled carbon nanotube (MWCNT)-based transparent conducting oxide materials (TCOMs). Transparent antennas were designed through ITO and tin oxide (TIO) materials. The performance of the transparent antenna was improved using the shorting technique. Using this technique, a return loss of around -40 dB was achieved at the resonance frequency. Furthermore, poor radiation, narrow bandwidth, and the low gain of the conventional transparent antennas can be overcome using MWCNT-based antennas.

In [26], AgHT-8 conducting material was used as ground and radiating patch with Plexiglass substrate of size 10 mm $\times$ 12 mm $\times$ 1.48 mm, as demonstrated in Figure 10. The rectangular-shaped branch helps to provide the wideband feature of the antenna. The antenna operates in a 23.92 to 43.8 GHz range. The proposed scheme provided a bandwidth of 58.71%. This scheme proved to be the most suitable for 5G communication.

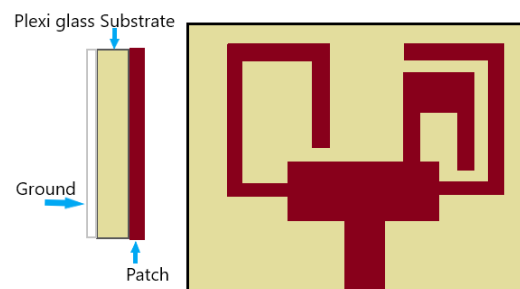


Figure 10. Transparent wideband antenna with radiation patch using AgHT-8 [26].

A reflect optical transparent antenna using ITO was proposed in [79]. This design reduces the conduction losses during the operation of reflect array, producing 272° of phase change through a subwavelength rectangular patch. The authors also suggested several

techniques that can reduce the loss in the reflect array antenna design. A 26 GHz design frequency was chosen, resulting in a peak gain of 22.2 dBi; moreover, good efficiency and better reflect array performance were observed in this design.

ITO is the most widely used material for antenna transparency. Due to the shortage of this material along with high prices, this material was replaced by zinc oxide heavily doped with gallium (GZO), as proposed by authors in [27]. Material conductivity can be compared to that of ITO as they are produced in the form of thin films. A planar dipole was fabricated to investigate the efficiency of this system at 2.4 GHz frequency.

In [29], authors presented the dual-band CPW (coplanar waveguide) optical transparent antenna working at 2.45 GHz and 5.8 GHz with AghT-8 material. The antenna had a size of 36 mm × 39 mm × 0.175 mm printed on 2 mm thick glass, as shown in Figure 11. This material has above 80% transmittance with $\sigma = 1.25 \times 10^5$ S/m, of electrical conductivity, which is high compared to other TCOs or nanowires. The results show return loss of less than −10 dB along with good antenna performance.

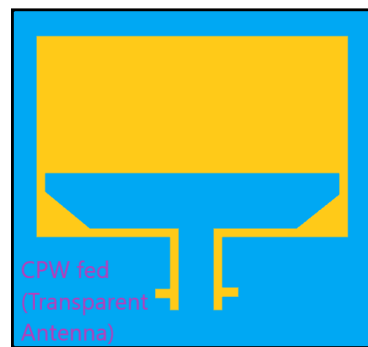


Figure 11. CPW-fed dual-band transparent antenna [29].

An alternate representation of ITO as indium zinc tin oxide was proposed in [31,80] to overcome ITO weakness, operating at 2.45 GHz (Wi-Fi frequency band). The sheet resistance was kept around 2.52 Ω /sq, having 80% optical transmittance. Acrylic substrate with 100 nm thickness was used in the design. The efficiency of this antenna was 7.7% with a peak gain of around −4.3 dBi.

2.2. Transparent Antennas Using Mesh Grid

Antenna design using the mesh-grid technique provides several advantages in terms of ease of fabrication, low cost, and high conductivity; however, reducing grid size may improve the conductivity at the cost of low optical transparency of the antenna. Figure 12 illustrates the advantages and disadvantages of various techniques implemented to design optically transparent antenna.

Optically transparent antenna designs using mesh grid for radiating surface are classified to metal mesh, millimeter metal mesh, and grating mesh. Figure 13 shows the pros and cons of these techniques. Metal mesh provides improved conductivity; however, due to increased mesh, optical transparency is compromised. In case of metal mesh, the size of mesh is taken as very small, in micrometers, and it provides normal conductivity but with improved optical transparency. The grating mesh contains nonuniform meshing, providing improved optical transparency.

A transparent antenna using metal mesh was presented in [33]. It can be integrated with smart widows, IoT, and mobile devices. The operating frequency was chosen for WLAN (802.11b) at 2.4–2.5 GHz. The conductive material was designed using the square structure of lattice using wired metal mesh between 0.2 to 0.5 nm thickness. The proposed antenna provided 3.4 dBi gain using simulation software, while the measured gain was 5.2 dBi. In this scheme, radiation efficiency greater than 50% was achieved. It was noticed that wired and micro metal meshes were considered to have low resistance and high

conductivity in contrast to transparent antennas. The authors in [34,81] suggested these metal meshes for the shielding of electromagnetic interfaces.

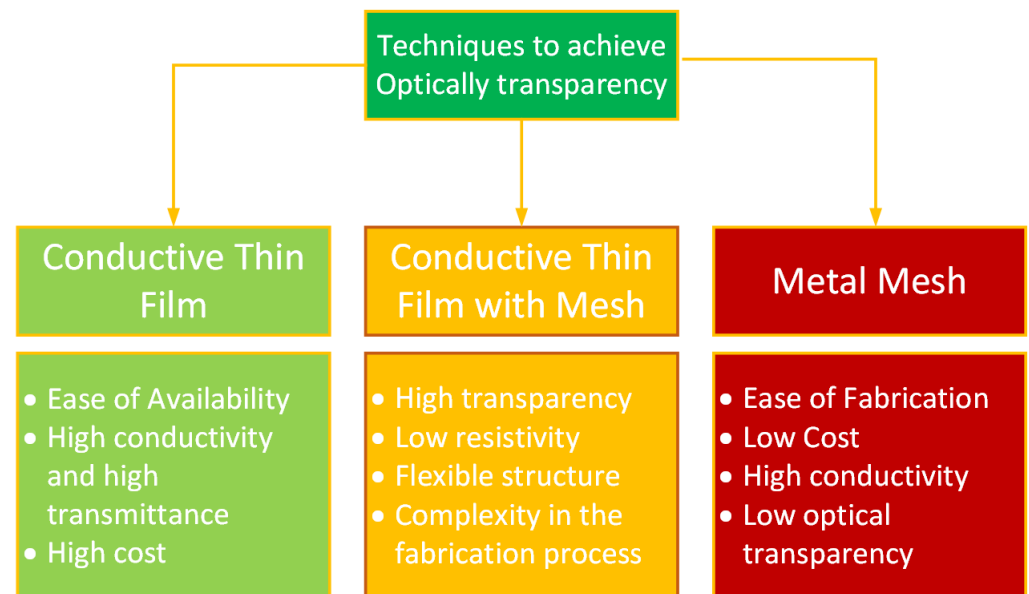


Figure 12. Techniques to achieve optical transparency.

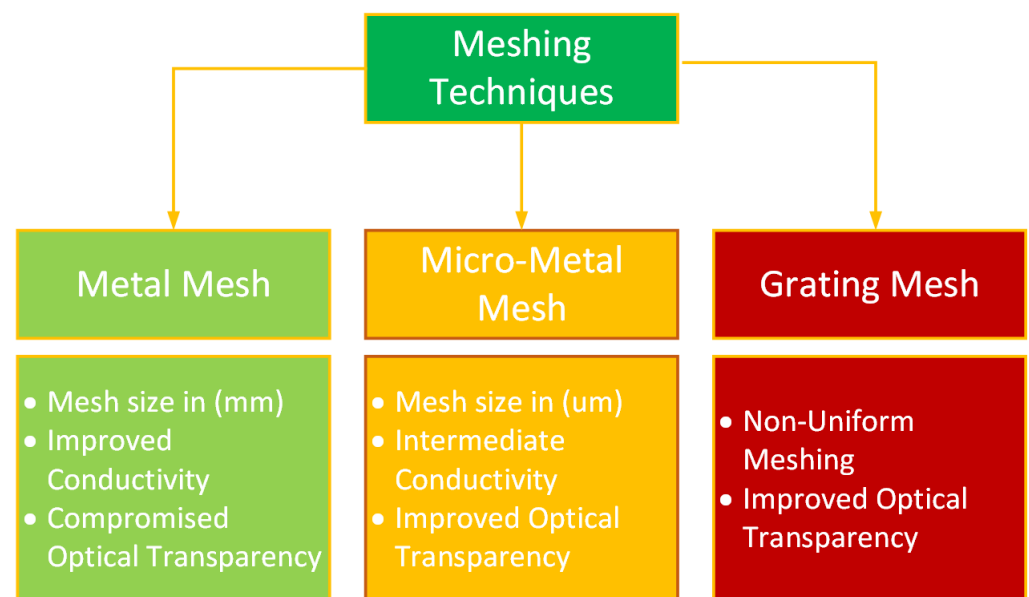


Figure 13. Meshing techniques for optical antenna.

A novel zeroth-order resonant (ZOR)-based micromesh optical antenna structure was discussed in [35]. This antenna was implemented using a mechanical reconfigurable model. ZOR helps in reducing the size while the tortuous micromesh was used as patch material. This structure can undergo deformation by stretching, twisting, and folding without any breakage. This design can operate at 2.94 to 2.46 GHz. The size of the material chosen was $8.32\text{mm} \times 11.6\text{mm} \times 0.4\text{mm}$. A gain of -0.02 dB was achieved in this configuration. Similar work was discussed in [36,82,83], where metal materials/substrate were taken as tortuous, while the Cu mesh replaced previous works of EGaIn/PDMS, E-textile/fabrics, and AgNWs/PDMS. A -2.4 dBi gain was achieved at 3.45 GHz, while it was 12.8 dBi at 2.1 GHz. Similarly, at 2.92 GHz, the gain of 0.37 dBi was noted.

A circularly polarized antenna using meshed patch was investigated in [38], where different mesh configurations were proposed. The opto-radio electrical performance was compared. The proximity coupling technique was altered to feed the mesh patch, hence providing improved optical transparency. Different ground plane antennas were fabricated, one with copper and the other with solar cell ground plane. Results gave 2.79 and 3.27 bandwidth at the frequency of 2.43 GHz operational frequency, with a gain of 4.9 and 4.4 dBi, respectively.

Authors in [39] proposed a wideband dual-polarized patch antenna with transparency. Conductive films were printed with metal meshes replacing the metal plates. The sheet resistance of 0.5/sq was taken through the material of polyethylene terephthalate. Layers of the planar conductor were separated by poly methyl methacrylate plates used as substrate. Using the stacked round microstrip patches, wide bandwidth was achieved. Results showed 19% antenna bandwidth while radiation efficiency of around 75% was achieved. The antenna transparency of 70% was noticed, and the radiation pattern was also very stable, with a very small back radiation level across the 2.4–2.9 GHz frequency.

In [40], transparent wearable antennas using conductive mesh were proposed. This method is a cost-effective method providing more robust bending than other transparent antennas. The antenna operated at the dual-band of 2.33–2.53 GHz and 4.7–5.6 GHz. The prototype was fabricated and tested. The given frequencies can be used for WLAN along with instrument, scientific, and management (ISM) bands. Two layers of conductors were implemented to improve the antenna performance, the gain, and efficiency of the antenna as a trade-off with the transparency of the antenna.

In [84], an optical transparent antenna was designed at 5–6 GHz frequency band using mesh wire of high conductivity on top of Lexan substrate. The arrays showed a peak gain of 6.5 dBi, which is less than the traditional antenna of 7.8 dBi but still acceptable for the transparent antenna. A coplanar waveguide transparent bandpass filter was proposed in [85], comprising an aluminum thin-film structure of the micromesh. The filter was designed through the dc sputtering; thus, high performance was achieved using the thin-film micromesh structure with the resistivity of 10^{-8} Ω -cm and optical transparency of 78%. The antenna works at 2.4 GHz with a reflection coefficient of 25 dB, along with 5% bandwidth and minimum insertion loss.

Authors in [33] (already mentioned above) used 2.45 GHz to design the optical transparent antennas. Several materials were used in their study, noted as metal mesh, multilayer ITO, and conductive grids. Conductive grids provided maximum transparency of 90% as compared to other materials. The conductivity was 1.5×10^6 S/m, 2.8×10^6 S/m, and 1.5×10^6 S/m, respectively. The substrate material in the case of a conductive grid has a minimum dimension of $0.2\text{mm} \times 0.36\text{mm} \times 0.003\text{mm}$. Radiation efficiency was 56% in the case of metal mesh, along with a higher gain of 4.14 dBi, higher than the other two materials. Similar work to that described above was carried out in [41–43] at frequencies of 60 GHz, 1.25 GHz, and 28 GHz using materials of gold grid, silver epoxy mesh, and Ag-alloy, respectively.

It was observed that the conductivity of Ag-alloy was high, 2.5×10^7 S/m, in contrast to other materials, providing an efficiency 41 dB higher than other materials. In addition, the gain was 9.1 dBi, the highest among the materials used. This scheme provided a scanning angle of -60° to 60° . The drawback of this scheme is the higher width of the substrate. Moving towards the concept of an antenna on display, the author in [44] proposed an antenna using photolithography that can be integrated into the display panels of OLED and LCD, thus making a novel optical invisible antenna. This technology was termed “antenna on display” (AoD). It gives promising direction toward the millimeter-wave 5G cellular devices. A high optical transparency of 88 percent was achieved with an antenna working on 28 GHz. The authors designed a multilayer schematic to achieve the phased array configuration. A gain of 6.6 dBi was achieved. The dummy grids were introduced to improve the transparency which degrades the gain. Hence, immaturity of

the anisotropic conductive film needs to be improved for achieving reasonable antenna gain while maintaining transparency.

Conductors with meshed design along with a plane of solid ground were proposed by the authors in [45]. They used circular and rectangular patches in their designs, and the meshing technique provided transparency to the antennas. The authors discussed the trade-off between the optical transparency and antenna efficiency relation in this paper. They further proposed refined meshing for achieving a good level of optical transparency along with optimized antenna parameters, but the reduction in meshing can help in achieving higher transparency with little issues with antenna performance. The fabrication process also provides the limitations of meshing. These antennas operate between 2.2–2.5 GHz, as shown in Figure 14. They are suitable for integration over solar cells.

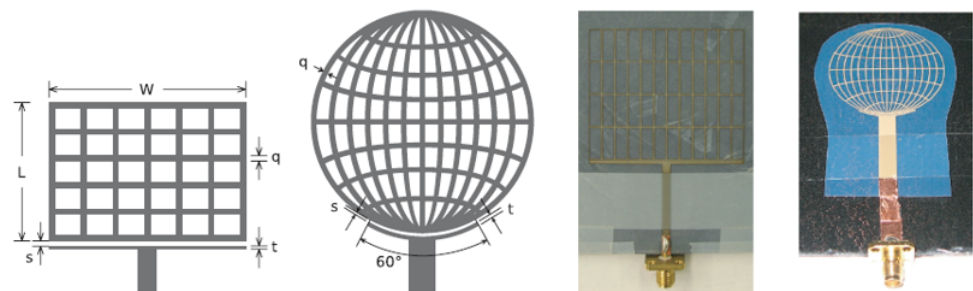


Figure 14. Meshing using rectangular and circular patch [45].

Some authors also proposed transparent antennas in the mm-wave band. In [46], they achieved high transparency using fabrics of select textiles. To achieve transparency, very fine mesh was used, operating between 27 and 35 GHz. Low-cost acrylic was used as substrate material. This scheme seems to be a strong option for 5G applications that may be used in autonomous vehicles. Figure 15 shows its basic topology. A transparency level of above 70% for veil shield was achieved, but it was less than 50% for radio screens. Good simulation results were achieved, showing a bandwidth of around 8 GHz.

Authors in [86] presented the copper honeycomb mesh operating at an 80 GHz frequency band. This topology promises to give better results that are similar to a solid structure. Likewise, in [87], a 60 GHz antenna was designed using silver (Ag) mesh from which 12 dBi gain was achieved along with optical transparency of 75%. The results show that increasing the density of the mesh will decrease the antenna transparency, but on the other hand, the transmission line losses are also decreased. The antenna designs are shown in Figure 16a,b.

A novel double-sided micromesh metal layer 4×2 optical transparent antenna was presented in [88], working at 60 GHz frequency. This scheme provided transparency above 80%. A reasonable gain of 13.6 dBi was achieved at the operating frequency. Later, this antenna was compared with an opaque antenna with copper radiating patch at 59.7 GHz, providing 15.6 dBi gain, as shown in Figure 17.

An optically transparent water patch wideband antenna producing the pattern of broadside radiations was presented in [89]. The ground plane and the patch were enclosed in a Plexiglass transparent container containing distilled water. High optical transparency was achieved using air as substrate material, providing a low-cost solution. The water patch was excited using an L-shaped metallic probe in the air substrate. The impedance of 34.9% was achieved at operating frequency between 1.61 GHz–2.29 GHz and SWR < 2. Using this scheme, a maximum efficiency of up to 75% can be achieved with a maximum gain of 6.6 dBi.

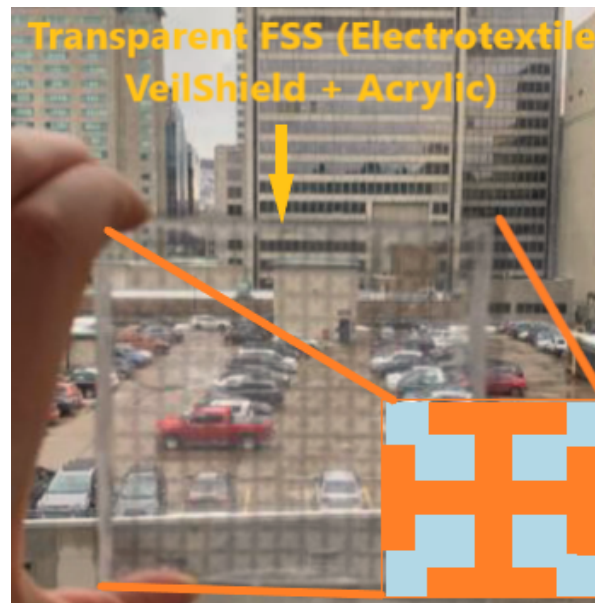


Figure 15. Transparent frequency selective surface (FSS) antennas in the mm-wave band [46].

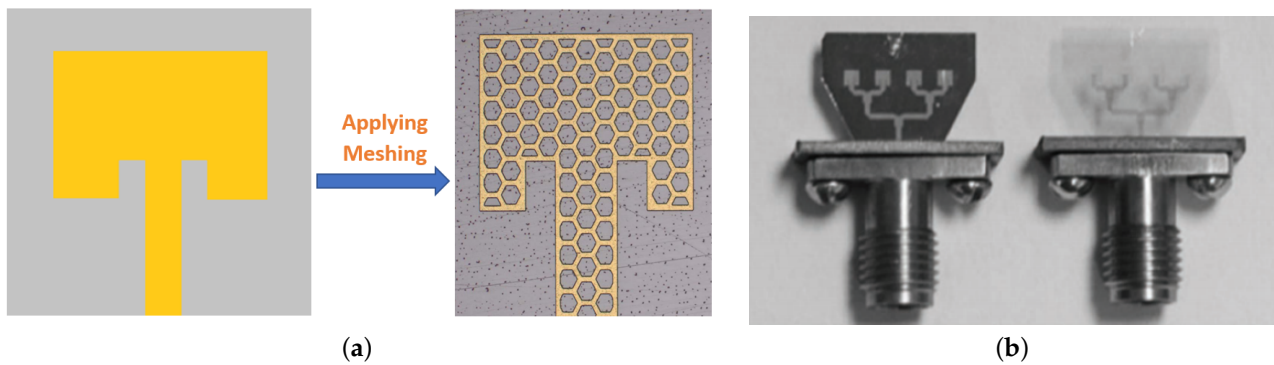


Figure 16. Examples of optical transparent antennas. (a) Honeycomb mesh [86]. (b) Silver meshing [87].

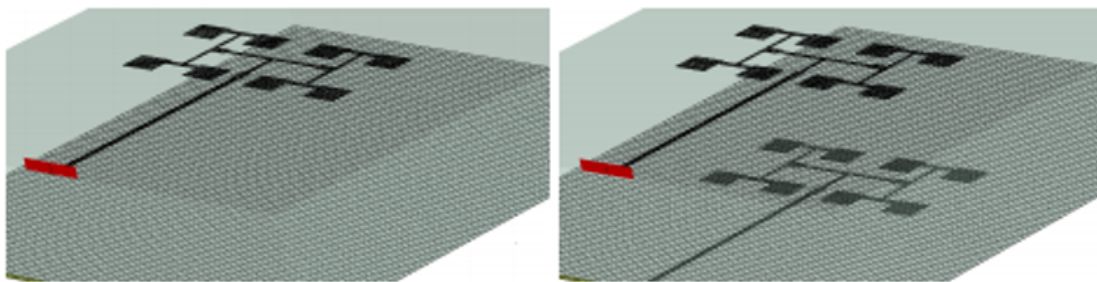


Figure 17. 4×2 multilayer optical transparent antenna [88].

The paper [90] discussed the design of external transparent patch and dipole antennas working at 470 MHz to 772 MHz for ultrahigh-definition (UHD) television applications. Optical transparency of around 70% was achieved using metal mesh topology having a sheet resistance of $0.04 \Omega/\text{sq}$. The average efficiency capacities fed transparent feed was 83% with a peak gain of 6.2 dBi, whereas, in the case of a transparent dipole, the peak gain was 2.4 dBi and efficiency was 72%. Therefore, the results were satisfactory as compared to the nontransparent antennas, providing good scope for their use in UHD TV applications.

A summary of the optical transparent antennas made using thin-film materials and mesh-grid technologies is given in Tables 1 and 2 respectively, where optical transparent

antennas operating at different frequencies, using various technologies and substrate materials, are discussed. Antenna gain, bandwidth, efficiency, transparency, and transmittance are recorded in Tables 1 and 2.

3. Discussion

The design of an optical antenna requires careful selection of radiating patch and substrate material. Table 1 exhibits a possible list of substrate and patch materials along with the antenna performance in terms of gain (dBi), bandwidth, efficiency, transparency, and transmittance. Antenna performance parameters aid in the careful choice of appropriate materials for optical antenna, depending on the antenna application.

Several substrate materials were tested in the literature; they include PDMS, PET, glass (quartz, Pyrex, soda-lime, borosilicate), and silicon, while AgHT-4/8, ITO, FTO, AZO, GZO, and TIO are possible patch materials used. The maximum gain of 11.5 dBi was achieved with Pyrex glass substrate with ITO patch, as mentioned in [20], followed by 9.8 dBi for glass substrate along with AgHT-4 patch material. An improved efficiency of 92% was achieved with an ITO patch on top of Pyrex glass substrate.

There is always a trade-off between efficiency and optical transparency. Most of the authors did not mention the transparency of the antenna where good efficiency of the optical antenna was achieved. For achieving higher efficiency, authors suggested Pyrex glass with ITO, and Plexiglass with FTO. Table 1 indicates reasonable efficiency for optical antenna designs achieving 92% (Plexiglass substrate with ITO conducting material), 90% (Plexiglass substrate), and 82% (polyimide substrate and IZTO/Ag/IZTO conducting material). Some applications require ultra-wideband optical antenna. Referring to Table 1, tissue fabric with PDMS substrate provides high bandwidth; similarly, multiband antenna designed using borosilicate glass combined with ITO provides 7 GHz bandwidth, while 10 GHz ultra-wideband is achieved using perspex substrate with AgHT-4.

For mesh-grid analysis, referring to Table 2, several mesh materials for the patch are suggested, which include metal mesh, aluminum mesh, micromesh, tortuous, and millimeter mesh. The bandwidths of 90%, 86%, and 81% were achieved using glass substrate with Ag/Ti, FR-4 with MWCNT, and fused silica with tortuous MM, while transparency up to 98% was achieved using thin MM with CoPs, as mentioned in [48]. Similarly, using metal mesh as radiating patch and PET as substrate material, 10.4 dBi gain was achieved. Moreover, diamond-shaped Ag-alloy with glass substrate provided 9 dBi gain, as indicated in [44,47].

Gallium-doped zinc oxide (GZO) can be considered a good option for the design of a transparent antenna due to its high conductivity.

The shadow effect reduces solar efficiency [13]. Silver integrated with Ag monolayer performed better for laptop applications, as compared to IZTO multilayer [15]. AZO offers high transmittance in the visible spectrum and strong RF conductivity at low cost, as mentioned in [11], while providing ease of integration with solar cells. A graphene-nanoribbon-based terahertz patch antenna provides low transmit power with higher data rates while enhancing the security of wireless communication [73]. AZO/AgNWs provide weak shielding against backside electromagnetic fields. However, increasing the stacked films thickness may improve the shielding against backside radiations. TCO materials are capable of providing transparency at optical frequency along with conductivity at RF frequency range. Therefore, these materials are suitable for OTA fabrication.

By using AZO/AgNWs stacked films, a wideband transparent antenna was achieved, as mentioned in [9]. Moreover, the advantages and disadvantages of thin film and metal mesh were discussed in the literature. Metal mesh provides low cost and ease of fabrication along with high conductivity, but increasing the meshing network will decrease the optical transparency of antenna; hence, a trade-off between the conductivity and transparency is required. On the other hand, thin films are expensive. ITO provides higher conductivity along with transmittance when integrated with glass, while in terms of ease of availability, ITO materials are a good choice. Metal mesh integrated with thin film, especially

IZTO/Ag/IZTO, provides low resistance, flexibility, and high transparency at the cost of a complex fabrication process.

4. Conclusions

The future 5G and 6G technologies require the installation of several base stations and access points at closer distances to achieve the required higher data rates. The transparent antenna is a possible solution that can be installed in windows of buildings and car windscreens to provide seamless wireless connectivity. This review paper presented a comparison of thin-film and mesh-grid technologies that enables the transformation from an opaque antenna to a transparent antenna. The performance parameters of both technologies are compared in terms of gain, bandwidth, efficiency, transparency, and transmittance for different applications and frequency bands.

The efficiency results of Tables 1 and 2 indicate that optical transparent antennas designed from thin-film material show better efficiency as compared to mesh grids. The conductive fabric tissue using polydimethylsiloxane (PDMS) substrate provided 90% efficiency; in addition, the antennas designed using ITO, FTO material with glass substrate had an efficiency of 86%, and the ITO thin film with Pyrex glass showed 92% efficiency.

In terms of transparency, the ITO thin-film technology provided the highest transparency of 90%. The mesh grid using quartz substrate showed a transparency of 95%. Therefore, mesh-grid technology performs a little better in terms of transparency, with a low-cost and simple fabrication technique.

Future directions include the addition of a metasurface-based Fourier lens to achieve wide-angle beam steering, which will be useful for future wireless communication, and a holographic three-dimensional display. Moreover, improvement of directivity and efficiency in a nanoantenna system may be considered. Losses in metal structures need to be reduced. Improved optical antennas may be designed for the detection of certain diseases inside the human body.

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Abbreviations

The following abbreviations are used in this manuscript:

OTA	Optical transparent antenna
CP	Conductive polymer
AgNWs	Silver nanowire
AZO	Aluminum zinc oxide
Cu	Copper
MMMC	Micro metal mesh conductive
MM	Micro metal mesh
MWCNTs	Multiwall carbon nanotubes
AgGL	Silver grid layer

TIO	Titanium-doped tin oxide
GZO	Zinc oxide heavily doped with gallium
FTO	Fluorine-doped tin oxide
IZTO	Indium zinc tin oxide
EGaIn	Eutectic gallium
Ag/Ti	Silver/titanium
PMMA	Polymethyl methacrylate
COPS	Cyclic olefin polymers
PDMS	Poly dimethyl siloxine
FSS	Frequency selective surface
FBW	Fractional bandwidth

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