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Flexible Transparent Antennas: Advancements, Challenges, and Prospects

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ABSTRACT Optically transparent electronic devices have attracted enormous interests in recent years. The development of transparent electronics emerges a lot of new industrial applications in variety of fields, such as displays, glasses, solar panels, satellite communications, terrestrial communications, integrated circuits, and sensors where optical transparency is required for unobtrusive placement of electronic devices on the surface. Over the last couple of years, there have been notable advancements in the development of transparent wireless electronics due to the emerge of new materials and fabrication technologies. Among transparent electronic devices, transparent antennas attract tremendous interests due to their widespread applications in healthcare industry, security sector, defence, sports, smart city, Internet of Things (IoTs) and many more. Many of these applications require antennas that are concurrently transparent and flexible. A transparent and flexible antenna can be easily integrated with displays, windows, solar cells and optoelectronic modules, thus, reducing the space in the integrated circuits. However, still the development of flexible-transparent electronics is associated with some challenges which continue to impede the progress of this emerging field. Among them are the contradictory relationship between the electrical conductivity and optical transparency of the transparent conductors, costly and complex processing of the transparent materials and unavailability of the appropriate materials. In this paper, we discuss current advancements in the development of flexible transparent antennas, including potential applications, various enabling materials and manufacturing approaches, technical hurdles, as well as prospects.

INDEX TERMS Antenna, composite, conductive-fabric, conductive-polymer, flexible, reconfigurable, transparent.

I. INTRODUCTION

OVER decades, transparent antennas are of use in lot of applications including display devices, energy harvesting and traditional communication networks [1], [2]. Optically transparent antennas have attracted tremendous interests due to their easy assembly with the existing infrastructure as a part of communication networks along with other transparent microwave devices to manipulate electromagnetic waves without jeopardizing the aesthetics of the environment for the growing 5G networks [3], [4], [5].

On the other hand, flexible antennas are gaining popularity in a substantial range of applications because of their easy integration with curved or non-planar surfaces. Especially, the fast-developing wearable technology [6] demands compact, flexible and low-cost antennas. Thus, the incorporation of optical transparency with flexible antennas offers a plethora of new opportunities because of their nearly invisible appearance and broader range of applications which was not imaginable before [7]. Flexible and transparent antennas have potential applications in unobtrusive

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wearable technology, terrestrial communications, vehicular communications, defence, satellite communications, lifestyle computing and many more. In comparison to traditional rigid and opaque antennas, the development of antennas that are simultaneously flexible and transparent imposes extra challenges. This has necessitated further advancements in the materials and manufacturing research.

This paper focuses on providing a comprehensive overview on the development strategies of flexible and optically transparent antennas, where using recently reported works in this area, we describe the key challenges associated with the realization of flexible-transparent antennas, optical, electrical and mechanical properties of the flexible-transparent materials, and fabrication challenges of flexible-transparent antennas. First, we introduce the properties of the current transparent materials, modifications introduced by the researchers to incorporate flexibility and enhance optical and electrical performance of the existing materials, and emergence of new materials; then overview has been implied on the fabrication methodologies of transparent antennas. Conclusions and future prospects on the development of flexible-transparent antennas are discussed in the final section. To the best of authors' knowledge, no other paper has comprehensively focused on the materials and methodologies towards the development of flexible-transparent antennas. Although some research articles [1], [3], [8], [9], [10] have reported the prospects and challenges of transparent antennas, there is still a lack of comprehensive review on flexible-transparent antennas encompassing a comprehensive highlights on the novel materials, processing and realization technologies. The realization of flexible and transparent antennas is associated with their unique potentials and challenges, which have arisen the need for a separate review article.

II. BACKGROUND: EMERGING APPLICATIONS OF OPTICALLY TRANSPARENT AND FLEXIBLE ANTENNAS

In the last century, engineers explored a novel initiative to replace the traditional hood-mounted monopole antennas of the auto-mobiles by windshield-embedded transparent antennas. The primary objective of this initiative was to incorporate wireless mobile network access points within the vehicles to receive radio broadcast signals without hampering aerodynamic performance and aesthetic appearance. In addition to providing aesthetically neutral communication access points on auto-mobile windshields, optically transparent antennas have gained significant popularity in recent years in a wide range of new applications, ranging from wearable technologies [11], solar panels [12], navigations to the emerging smart city projects [3].

One of the emerging applications of optically transparent antennas is solar cells integration in small satellites. The launch and operation process of satellites incorporate huge expenses. The volume and weight of a satellite are the major concerns for estimating the overall expenses of satellite installation. It is always a challenge for the engineers and scientists to reduce the volume and weight of the satellites to reduce the expenses. To keep the size and weight small, it is vitally important to efficiently utilize the surface area of a satellite to accommodate all of the power, transceivers and sensor circuits in minimal space. In particular, efficient use of the surface area is a great concern in small satellites. For instance, the popular 1U series cube satellites comprise a chassis of only $10 \times 10 \times 10$ cm^3, other small form factor satellites also comprise the limited surface area. In these small satellites, the majority of the chassis area is occupied by solar cells for energy harvesting. Integration of transparent antennas with the solar panels of these satellites not only saves space within the chassis but also mitigates the transmission losses associated with the solar panels.

Beyond the realm of incorporating network access points through solar panel integration, transparent antennas have many noteworthy application possibilities in communication networks. In recent years, the number of mobile devices has witnessed a sharp rise all over the world. To cope up with the high demand of communication networks and ensure satisfactory network quality for the overwhelming mobile devices, a large number of network components have been deployed. It is envisaged that the number of mobile devices will be increased in multifold in near future, which will certainly impose infrastructure challenges on the already overcrowded wireless networks. Moreover, modern communication technology is moving towards millimeter-wave frequency spectrum to meet the demands of high-speed communications, which in turn requires the installation of network components in close proximity to avoid communication dead zones [3]. Mounting a large number of network devices (antennas, filters, amplifiers, etc.) is evidently imposing a big challenge on the overall communication networks, especially in urban areas due to the limited availability of unoccupied spaces. There is no doubt that these overstretched network components have notorious visual impacts on the environment. Sometimes the impacts are so severe that property values are dropped because of the presence of cellular towers in close proximity to the property. In recent years, several innovative approaches have been exploited by network engineers to alleviate the visual impacts of the increasing number of network components. For example, disguised cellular towers are gaining popularity in many countries where cell towers' visual appearance are disguised by representing their appearance identical to ambient structures to blend in with their surroundings. For instance, cactus-like cell tower has been built in Arizona, USA, fir tree-like tower can be seen in Bedfordshire, U.K., concealed cell antenna identically matched with surrounding brick exterior is built in Sopot, Poland and flag pole-like cell tower can be witnessed in Texas, USA. Figure 1 illustrates some of these techniques of concealing cell towers' visual appearance. Although these approaches can be considered as effective camouflaging techniques of overwhelming cellular networks, these approaches could not be long-lasting solutions in overpopulated urban areas where it is challenging to find available spaces for installing a large number of camouflaging cellular towers.

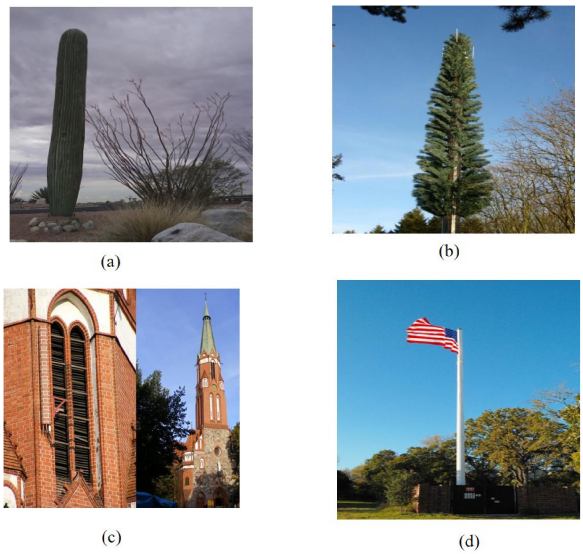


FIGURE 1. Disguised cell towers- (a) cactus-like cell tower in Arizona, USA (Photo source: Waymarking.com), (b) fir tree-like tower in Bedfordshire, U.K. (Photo source: Waymarking.com), (c) cell antenna concealed to match brick exterior in Sopot, Poland (Photograph by Pplecke), (d) flag pole-like cell tower in Texas, USA (Photo source: Waymarking.com).

Integration of conformal transparent antennas on the existing infrastructures, such as window glasses, automobile windshields, display devices, street lights and solar cells, can be an efficient alternative for incorporating network access points without compromising the aesthetics of the landscapes [3]. Moreover, the idea of integrating transparent antennas in solar cells will eventually create additional earning opportunities for solar-panel owners in the way of commercially leasing the surface areas of the solar panels to the owners of cellular towers [1]. Motivated by this economic impact, more people will come forward to install solar panels in their homes. Hence, this influential technology can play a vital role in economic prospects and clean energy technology.

Another promising application of conformal transparent antennas is wearable technology, both in medical and non-medical domains. Wearable technology has weaved itself into our daily life and becomes an indispensable part. It has revolutionized the standard of our lives in multiple aspects. Wearable technology has brought noteworthy advancements in modern healthcare and well-being facilities by offering innovative techniques of remote sensing, monitoring and transmitting patients' real-time health signs. Telehealthcare system can eventually lessen the involvement of manpower in the medicare system, thus, reducing the overall expenses of the healthcare industry. Telehealthcare facilities deal with the real-time monitoring of the patients' health through remote sensing, monitoring and providing real-time information, thus, facilitate instant remote intervention by experts in case of serious medical conditions, such as stroke, epilepsy, hypertension and cardiovascular diseases. Telehealthcare facilities are significantly beneficial for caring vulnerable people, e.g., elderly people and those suffering from chronic diseases as well as people living in isolated places where specialized medical facilities are instantly unavailable. Moreover, continuous monitoring of the vital physiological parameters, such as heart rate, respiratory parameters, blood pressure, blood oxygen saturation (SpO_2) level, calories and temperature can detect and screen the diseases at earlier periods, which provides the opportunity to get an earlier diagnosis before getting the condition life-threatening. In addition, telehealthcare facilities enable remote treatment of contagious diseases, like Coronavirus disease (COVID- 19), which enhances the safety of healthcare professionals by avoiding face-to-face contact [13]. So, it is evident that wearable technology is a driving force in modern healthcare system. The revolution of wearable technology and its surging demands have influenced the industry to develop new and more useful wearable devices. However, wearable devices should pose some particular characteristics for reliable operations near the human-body platform, which are not necessarily important for conventional antennas. Flexibility, robustness, wearers' complacency, lightweight, small size and low antenna-body coupling are the mandatory characteristics of wearable antennas. Besides these particular characteristics, unobtrusiveness is considered as one of the desired features of wearable electronics for aesthetic appearance and ensuring reliability in many applications. For instance, antennas and sensory types equipment integrated into the patient's body, suffering from mental illness, should be sight insensitive for the long-term continuous surveillance of accurate real-time health information pervasively. Patients suffering from mental illness often remove suspicious monitoring devices unconsciously. Unnoticeable monitoring devices can improve the reliability of the patients-care in these cases. Unobtrusive sensing technologies enable continuous remote surveillance of personal health status in home, hospital and public places without compromising daily activities and aesthetics. So, it is demonstrated that unobtrusive wearable technology can lead to significant improvement in the healthcare industry. Figure 2 illustrates some approaches towards unobtrusive sensory systems.

There are several approaches through which antennas' appearance can be made unnoticeable but all of them are not compatible with the wearable applications. For instance, embroidered antennas directly weaved into wearers' outfits is a viable approach to camouflage their appearance but they cannot perform consistently for long-term uses. After a few cycles of washing, the performance of the embroidered antennas deteriorates [20], [21]. Hiding a wearable antenna underneath the wearer's outfit is another method of achieving unobtrusiveness. But, the dielectric properties of the fabrics on top of the antenna affect its performance [22], [23]. Especially, humid and wet environments and wearer's sweat can increase the dielectric constant of the fabric which can severely affect the antenna resonance frequency, gain and efficiency. Apart from these approaches, optical transparency is considered as the most effective method of making wearable antennas' appearance visually imperceptible.

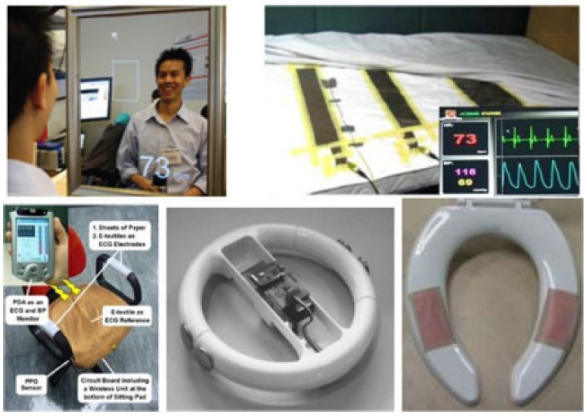


FIGURE 2. Unobtrusive sensing devices with sensors embedded in daily objects [14], such as mirror [15], sleeping bed [16], chair [17], steering wheel [18], and toilet seat [19]. (Figures are used with permission).

In addition to medical applications, flexible transparent wearable antennas have profound potential in a variety of noteworthy non-medical applications where visual imperceptibility, complacency and aesthetics are indispensable requirements of the systems. For instance, in the defence industry, there is a high demand for unnoticeable wearable devices that can be easily camouflaged. People working for security intelligence services need concealed communication devices integrated on their body for providing a secure communication network, which is vitally important for conducting their professional duties. For improving security against theft and counterfeiting in retail industries, factories and shops, visually imperceptible tracking devices are gaining popularity.

From the above discussion, it is explicit that optically transparent antennas have considerable potential in enormous applications. Many of these applications require reversibly deformable antenna structures to wrap on curved objects. Optically transparent antennas, which can conform to various shapes, certainly open a wide spectrum of applications over their rigid counterparts. In many applications, optically transparent antennas are frequently exposed to repeated physical deformations and harsh environmental impacts. So, in these applications, the antennas should have the robustness required to operate well under the extreme physical deformations, heat, chemical and humidity. Moreover, the wearable industry needs lightweight, biocompatible, small, low profile, conformal and unobtrusive antennas. However, despite having wide range of applications and significant economic impacts, there have been limited insights into flexible transparent antenna research. Lack of suitable materials and expensive fabrication processes are the major constraints that slow down the progress of the flexible transparent antenna development.

III. RESEARCH CHALLENGES

In literature, sparse research efforts have been focused on the development of transparent antennas that are simultaneously flexible, robust, efficient and can survive harsh environmental impacts. Limited availability of flexible transparent materials, poor electrical conductivity of transparent materials, high cost and manufacturing complexity are some of the major challenges in the development of such antennas.

One of the issues with the transparent conductors is related with the contradictory relationship between their sheet resistance and optical transparency, which leads to a compromise between RF and optical properties of the realized transparent antennas. The contradictory relationship between the electrical and optical properties of the transparent conductors is directly related to the skin depth. It can be noted that transparent conductors are imperfect conductors, whose electrical conductivities are significantly lower than traditional opaque conductors, i.e., copper, silver or gold. Due to the poor electrical conductivities, the skin depth of the transparent conductors are higher than conventional metals as indicated by the inverse relationship between the skin depth and electrical conductivity shown in Equation (1) [3], [9].

$$\delta = \left(\frac{\sigma\omega\mu}{2}\right)^{-\frac{1}{2}} \approx \frac{2m^*}{z_\infty q^2}\frac{\omega^2\tau}{N_e} \tag{1}$$

where,

δ = Skin depth
σ = Electrical conductivity
μ = Electron mobility
m^* = Effective electron mass
z_∞ = High frequency impedance
q = Electron charge
τ = Electron relaxation time
N_e = Electron density
ω = Angular frequency

At the desired frequency of operation, the conductor thickness should be higher than its skin depth for efficient antenna operation. As the conductivity of transparent conductors is lower than the traditional opaque conductors, their skin depth is higher than the traditional opaque conductors, so at a particular operating frequency, transparent conductors should be thicker than non-transparent conductors. A thicker conductor, however, incorporates a lower optical transparency. The optical transparency of a transparent conductor having a thickness of 't' is expressed by the following relationship [9]:

$$T(t) \cong e^{\left(\frac{2t}{\delta}\right)} \tag{2}$$

This relationship reveals that the optical transparency (T) decreases exponentially with the increase of the conductor thickness (t). As the conductor thickness should be kept more than its skin depth at a particular operating frequency, the high skin depth of transparent conductors incorporates a limit on the achievable highest optical transparency. It is, therefore, evident that it is quite challenging to achieve a high optical transparency without sacrificing the electrical conductivity. With the notoriously poor electrical conductivity of the transparent conductors, it

is very challenging to achieve high electromagnetic radiation from the antenna, due to the high level of associated Ohmic loss.

Moreover, when it is intended to impose flexibility and robustness on transparent antennas, the realization challenge is certain degree higher. The lack of appropriate conductors and dielectrics is the major obstacle in the development of reversibly deformable transparent antennas. Most of the materials that are used in transparent antenna development are not compatible with conformal operations. These materials need structural modifications to make them deformable. Researchers tried to incorporate structural modifications in the existing transparent materials to make them flexible and also tried to synthesize new transparent and concurrently flexible materials that are transparent and concurrently flexible. These efforts initiated by the researchers have been investigated in this paper. Although some flexible transparent dielectric materials, such as Kapton polyimide, polydimethylsiloxane (PDMS), polyethylene terephthalate, etc. are available, it is really a challenge to find transparent conductors that are reversibly deformable. Moreover, it is also challenging to maintain sturdy attachment between the conductors and dielectric materials in stressful operations. In general, the manufacturing process entails costly and complicated steps, and sometimes involves hazardous chemicals and toxic by-products. Some research efforts can be found that have developed more environmental friendly and cost-effective fabrication techniques. In this paper, these fabrications technologies are studied.

IV. TRANSPARENT MATERIALS FOR TRANSPARENT ANTENNA REALIZATION

Transparent antennas are ideally realized by combining transparent conductive materials used as the electromagnetic radiator and transparent dielectrics used as the substrate. In literature, most of the transparent antennas are developed from the dielectric materials corning glass, pyrex glass, synthetic quartz, polycarbonate, Kapton polyimide, PDMS, and polyethylene terephthalate. Among these materials, Kapton polyimide, PDMS, and polyethylene terephthalate are flexible. Although the dielectric loss of these materials is higher than the opaque rigid dielectrics, the major loss of transparent antennas arises from the conductive part which is responsible for the low antenna efficiency. It is highly challenging to find appropriate transparent conductors which have high electrical conductivity and good optical transparency. Moreover, most of the transparent conductors are not flexible. So, we have focused on the properties and challenges of transparent conductive materials in this review paper.

As explored in literature, transparent antennas are basically developed from transparent conducting oxides, transparent semiconducting oxides, transparent conductive polymers, metallic meshes, silver nanowires, monolayer molyb-denum disulfide, carbon nanotubes (CNTs), graphene films, MXene, mesh conductive fabric and water. These classes of transparent conductors have their own limitations that impose challenges on achieving good RF and optical performance as well as mechanical robustness. This section highlights the characteristics of these transparent conductive materials.

A. TRANSPARENT CONDUCTING OXIDES

Transparent conductive oxides (TCOs) [24] are the most often used transparent conductors. This class of material is well-known for facilitating Ohmic conduction. TCOs exhibit excellent free carrier concentration in the 10^{21} cm^{-3} range, and high optical transparency which make them a popular option for transparent antenna fabrication. The typical electrical conductivity of TCOs is nearly 10^5 S/m which is quite promising. However, the conductivity of TCOs is certain degree lower than copper (i.e., 5.8×10^7 S/m). This poor conductivity of TCOs leads to high antenna losses. From the previous section, it is demonstrated that there is an obvious trade-off between thin films' sheet resistance and optical transparency. In transparent conducting oxides, it is hard to achieve sheet resistance lower than 1Ω/sq while preserving a high level of optical transparency [25]. It needs to compromise between the achieved optical transparency and efficiency of the realized antennas with transparent conducting oxides.

However, transparent conducting oxides have manifold applications including touch screens and front contacts for displays or solar cells. Commonly used transparent conductive oxides (TCOs) are indium-tin-oxide (ITO) [26], fluorine-doped tin oxide (FTO) [27], aluminum-zinc-oxide [28] and gallium-doped zinc oxide (GZO) [9]. Numerous research approaches can be seen utilizing these metals in transparent antenna fabrication. Reference [26] reported a transparent antenna developed from ITO film. The sheet resistance and optical transparency of the ITO film were 8.6 Ω/Sq and 80%, respectively. The developed antenna had a gain of −4.1 dBi. Reference [27] reported a transparent antenna developed from FTO film. The sheet resistance and optical transparency of the FTO film were 7 Ω/Sq and 74.29%, respectively. The developed antenna had a gain of 0.43 dBi. Reference [28] reported a transparent antenna array developed from AZO film. The developed antenna array achieved a gain of 5 dBi. The characteristics of GZO film were investigated in [9]. The reported transparency of the GZO film was 98.0% for the film thickness of 0.1 μm, transparency reduced to 60.7% at 2.5 μm thickness. A patch antenna with GZO film was studied in this paper. The efficiency of this antenna was 40% for 0.1 μm film thickness, whereas, it increased to 70.06% for the 2.5 μm film thickness. In this paper, a planar dipole antenna operating at 2.4 GHz ISM band was also studied. This dipole antenna was etched from a 1.4 μm -thick GZO film on a 375 μm -thick c-plane sapphire substrate having a relative permittivity of 10.0. The conductivity of this GZO film was $3\times$ 10^5 S/m. This dipole antenna achieved a maximum gain of 2.1 dBi.

While transparent conductive oxides (TCOs) have been widely used in the transparent electronic industry, they have poor stability in mechanically stressful operations,

hence, are not appropriate candidates for the development of flexible transparent antennas. Some research efforts trying to address the above issue through nano engineering of TCOs have been reported [11]. The modifications in the nano regime has led to an improvement in structural flexibility as well as conductivity, thus providing a good solution for the realization of flexible-transparent antennas. Reference [29] reported transparent-flexible antennas fabricated with nano-engineered composite structures made with 8-nm Cu-doped Ag nanofilm (sheet resistance 12.5 Ω/sq) sandwiched between two 40-nm indium tin oxide (ITO) thin films, printed on flexible PDMS substrate. In this stacked structure, multiple optical resonances were induced between the ITO anti-reflection coatings, resulting in a destructive interference at the ITO-air interfaces (controlled by the ITO thickness), which enhanced the optical transparency. The achieved optical transparency of this nanocomposite film was nearly 96%. A high gain Fabry-Perot cavity antenna which employed an optically-transparent metasurface built from the above constructed TCO nanocomposites was reported in [29]. This metasurface antenna was successfully integrated with solar panels for energy harvesting. With the metasurface, the gain of the antenna was increased from 6.5 dBi to 13.6 dBi. Reference [26] reported an ITO/Cu/ITO nanocomposite film having a sheet resistance of 4.7 Ω/sq. The gain of the antenna made of the developed nanocomposite films was −1.96 dBi. However, this antenna was not flexible because of the rigidity of ITO film. Figure 3 illustrates the fabricated ITO film placed on a printed paper, the clear view of the letters demonstrates the high transparency of the ITO film. In [11], ITO film was structurally modified by mixing it with zinc (Zn) to enhance the flexibility. Moreover, the conductivity of this flexible Zn mixed ITO (IZTO) film was improved by fabricating multi-layered IZTO nanocomposite film, where silver (Ag) layer was sandwiched between two layers of IZTO films. The IZTO/Ag/IZTO (IAI) nanocomposite film was demonstrated as a good candidate for flexible transparent antenna fabrication. This multilayer IZTO/Ag/IZTO (IAI) film achieved 4.99 Ω/sq sheet resistance which was lower than other transparent conductive oxides (i.e., ITO, FTO, GZO). The fabricated monopole antenna in [11] achieved an average efficiency of 40% and 4-dBi peak gain at 2.4–2.5 GHz band, it was much robust physically that can withstand more than 500 times bending. Figure 4 shows the flexible IZTO/Ag/IZTO (IAI) nanocomposite film.



FIGURE 3. An ITO film on a printed paper demonstrating high transparency. (Reproduced from [26] with permission. Copyright © 2009 IET).



FIGURE 4. Flexible IZTO/Ag/IZTO nanocomposite film. (Reproduced from [11] with permission. Copyright © 2016 IEEE).

B. TRANSPARENT SEMICONDUCTING OXIDES

Transparent semiconducting oxides (TSOs), such as zinc-oxide (ZnO) [30], indium gallium zinc oxide (InGaZnO4) [31] have electrical conductivities between those of insulators and conductors. TSOs have also attracted popularity in the development of flexible-transparent electronic devices. TSOs typically have an intermediate free carrier concentration in the range $10^{14}-10^{18}$ cm^{-3} [31] which allows the formation of depletion layers. Due to the presence of the depletion layer, the free carrier concentration remains in the intermediate range, typically not more than multiple 10^{18} cm^{-3} controlled by the TSO thickness. In the TSOs, the free carrier concentration and the relevant Fermi level position can be controlled by controlling the concentration of native defects acting as donors. Transparent semiconducting oxides are used in transparent electronics industry as the transparent conductors. They can be good candidates in transparent antenna manufacturing. Some research approaches with TSOs in antenna fabrication can be witnessed in the literature. A ZnO thin films based nanoantenna for nonlinear frequency conversion was reported in [30]. In another research attempt, a capacitive antenna operating at 1–10 GHz made with ZnO film was reported in [32]. This capacitive antenna consisted of ZnO based pillars sandwiched between gold plates. The reported antenna achieved 0.701 dBi, 8.29 dBi and 10.2 dBi gains at the frequencies 0.8 GHz, 5.08 GHz and 9.89 GHz, respectively. A THz photoconductive antenna realized with single crystal ZnO was reported in [33]. However, like TCOs, the fabrication of TSOs with simultaneously good conductivity, flexibility, transparency, and robustness is highly challenging.

C. TRANSPARENT CONDUCTIVE POLYMERS

Since the discovery of conducting polymers in the 1970s by Alan Heeger, Alan MacDiarmid, and Hideki Shirakawa (who later won the Nobel Prize in Chemistry in 2000 for

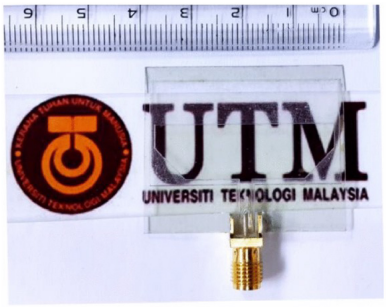


FIGURE 5. Antenna fabricated with AgHT-8 film. (Reproduced from [34] with permission. Copyright © 2015 IEEE).

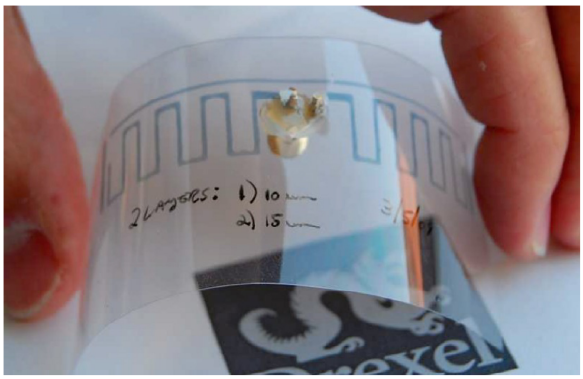


FIGURE 6. RFID Meandering dipole antenna realized with conductive polymer Clevios PH500 PEDOT-PSS. (Reproduced from [36] with permission. Copyright © 2009 IEEE).

this invention), they have attracted considerable attention in the development of solar panels, displays, electromagnetic shielding, electrostatic discharge protection, printed circuit-board technology, LEDs, photovoltaic devices and touch-panel controls. Transparent conductive polymers comprise some excellent features, such as lower surface mass, corrosion resistance, simple morphological modification process and optical transparency. For these promising features, they are becoming a popular alternative to the traditional metals, e.g., copper or gold in many applications, including the development of transparent antennas. Several examples of transparent conductive polymers employed for flexible transparent antennas are silver-coated polyester (AgHT-8) film [8], [34], polyaniline (Pani) film [35] and Clevios PH500 PEDOT-PSS [36].

A dual-band CPW-fed antenna fabricated with AgHT-8 thin film printed on polyethylene terephthalate (PET) substrate (thickness 0.175 mm) was demonstrated in [34]. AgHT-8 film has an electrical conductivity of 1.25×10^5 S/m and sheet resistance 8 Ω/sq. This dual band antenna operated at 2.45 and 5.8 GHz band with realized gains of −3.25 dBi and −4.53 dBi, respectively. Another transparent antenna made with AgHT-8 thin film and integrated with solar cell was reported in [37]. This UWB omnidirectional antenna operated at 3.1−10.6 GHz band with a maximum peak gain of −2 dBi and efficiency of 18%. Among transparent conductive polymers, AgHT-8 film is more popular in antenna manufacturing because of its good flexibility and transparency (over 80%), but AgHT-8 film comprises a sheet resistance of 8 Ω/sq [37], [38] [34], [39] which jeopardizes its compatibility in high efficiency applications. Figure 5 shows the prototype of an antenna realized with AgHT-8 film.

In [35], a patch antenna was designed with Pani having an electrical conductivity of 6000 S/m and thickness of 100 μm. The reported gain of the Pani-patch antenna was 3.42 dBi which was just 2.0 dBi lower than its copper counterpart, the efficiency of this Pani antenna was 56% whereas for copper antenna, it was 98%.

In [36], an RFID meandering dipole tag antenna, operating at 900 MHz, was realized with conductive polymer, Clevios PH500 PEDOT-PSS. Clevios PH500 EDOT-PSS has a conductivity of 300 S/m. To improve the conductivity, it was mixed with 10% Dimethyl sulfoxide (DMSO). The modified conductivity was 5×10^5S/m, which was much higher than the PEDOT-PSS and much closer to the conductivity of copper (5.9×10^7 S/m). The dipole antenna was deposited on polyethylene terephthalate (PET) substrate (dielectric constant of 3.8) having a thickness of 0.5 mm. The measured gain of this dipole antenna was −4 dBi. Figure 6 shows the prototype of the RFID Meandering dipole antenna made with conductive polymer Clevios PH500 PEDOT-PSS.

D. MESHED CONDUCTORS

Meshed conductors [40], [41], [42] are basically traditional metal-based conductors with a variety of pre-fashioned grids, pores or gaps throughout the surface for light transmission. Unlike thin film conductors, meshed transparent conductors are fabricated from traditional metals that are not transparent themselves. The meshed conductors leverage the opportunity of open spaces throughout their surfaces for light transmission while maintaining high levels of conductivity through the conductors. Copper (Cu) and silver (Ag) are mostly found in metal mesh films manufacturing. Due to the comparatively low price and more availability, Cu is mostly used in the metal mesh films. The sheet resistance of meshed conductors are lower than conductive oxides or conductive polymers thin films but their optical transparency are also lower than those films. Like thin films, compromise is required between the achievable optical and electrical properties of the meshed transparent conductors. Optical transparency of the meshed conductors depend on the percentage of free-space throughout the surface. Figure 7 shows the geometry of a mesh conductor integrated on PET [43]. To obtain more open area, it needs narrow width (w) of the grids and larger gaps (s) among them which drive to higher transparency but concurrently introduces higher sheet resistance. Thus, like other transparent conductors, e.g., thin films conductors, it needs to compromise between optical and RF performance of the antennas realized with meshed transparent conductors.

It can be noted that traditional Cu-, Au- and Ag-based meshed transparent conductors are not robust in repeated

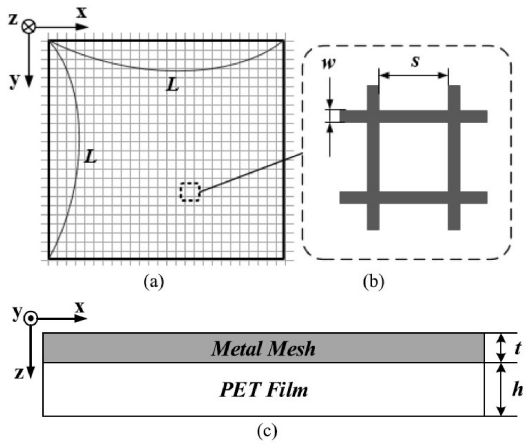


FIGURE 7. Geometry of a Cu-mesh deposited on PET. (Reproduced from [43] with permission. Copyright © 2020 IEEE).

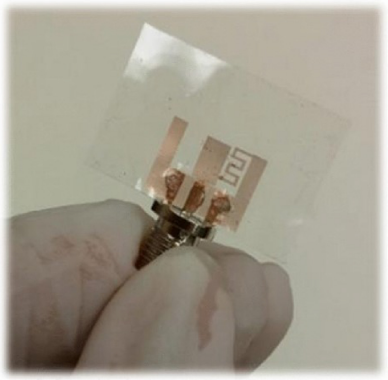


FIGURE 8. Flexible and transparent frequency reconfigurable mesh antenna. (Reproduced from [42] with permission. Copyright © 2017 IEEE).



FIGURE 9. Antenna fabricated with silver grid layers (AgGLs). (Reproduced from [45] with permission. Copyright © 2011 PIER).

bending or stretching and it needs special treatment in the manufacturing process to make them reversibly deformable. For instance, the Cu mesh structure exhibits weak integration to the substrates [44], particularly with flexible substrates. Due to the poor level of mesh-substrate integration, they fail to maintain stability when exposed to harsh physical deformations. Thus, traditional Cu mesh films deposited on flexible substrates cannot survive in mechanically stressful operations. In order to make Cu mesh film robust in repeated bending operations, a research investigation was endeavoured in [44]. In this analysis, RF sputtering method associated with a single-crystal Cu target was used to create high-quality Cu thin film with a high degree of homogeneity and crystallinity. Then, this developed honeycomb-shaped Cu micromesh structure was subsequently deposited on a flexible polyimide substrate by implementing UV lithography and wet etching processes. The developed mesh sheet, made out of this procedure, was remained stable after 1000 times of bending cycle. In another research approach [42], transparent antenna developed from tortuous copper micromesh achieved simultaneously good flexibility and radiation performance. So, it is demonstrated that metal mesh films can be good candidates for the realization of flexible transparent antennas but their robustness depends on the manufacturing techniques. Moreover, their transparency levels are to be compromised for achieving good electrical conductivity.

Reference [43] reported a transparent dipole antenna and a patch antennas for UHD TV applications utilizing copper mesh film as the transparent radiator of the antennas. The transparency of the copper mesh film was nearly 70% and the sheet resistance was 0.04 Ω/sq. The developed transparent dipole antenna achieved a peak gain of 2.4 dBi and an average efficiency of 72.1%. The transparent patch antenna achieved a peak gain of 6.2 dBi and an average efficiency of 83.8%.

In another approach, a new optically transparent, flexible, and mechanically reconfigurable zeroth-order resonant (ZOR) antenna using stretchable Cu-micromesh structure deposited on PDMS substrate was exhibited in [42]. The structure was able to undergo mechanical deformation such as stretching (up to 40%). However, the transparency levels of the mesh were to be compromised for achieving good electrical conductivity. The transparency of the demonstrated antenna in [42] was 32%, which was achieved with a sheet resistance of the conductor of 0.07 Ω/Sq. Upon stretching, the resonant frequency of the antenna was linearly tunable from 2.94 GHz to 2.46 GHz. At 2.92 GHz, the achievable gain was −0.2dBi. Prototype of this flexible mesh antenna is illustrated in Figure 8.

Reference [41] reported a gold grid layer (AuGL) transparent antenna. The transparency and sheet resistance corresponding to two different orientations of the meshes were 81% and 49%, and 0.22 and 0.073 Ω/sq, respectively. This millimeter-wave antenna array achieved a gain of 9.55 dBi at 56.3 GHz.

Reference [45] developed a transparent antenna with silver grid layers (AgGLs). Three transparent UWB antennas were developed from the AgGLs with various levels of transparency, i.e., 54.5%, 73.4% and 80.3% for the sheet resistances of 0.018 Ω/Sq, 0.022 Ω/Sq and 0.052 Ω/Sq, respectively. The maximum achieved gain was 6 dBi. Figure 9 shows the prototype of the AgGLs antenna [45].



FIGURE 10. Prototype of a AgNW antenna [46]. (Reproduced from [46] under a Creative Commons Attribution 4.0 International License (CC BY 4.0)).

E. SILVER NANOWIRE

Silver nanowires (AgNWs) or Silver nanofilms (AgNFs) are promising conductors for flexible and transparent electronics. AgNWs have excellent optical transparency, good electrical conductivity, and promising mechanical stability for conformal operations. In [46], a highly flexible and transparent fractal antenna for Wi-Fi (2.4 GHz), Bluetooth (2.4 GHz), and low-band 5G (3.5–4.2 GHz) applications have been developed with AgNW deposited on PET. The AgNW was manufactured with silver nano ink by screen printing associated with flash-light sintering (FLS) technology. AgNW patterns maintained low sheet resistance (1.1–9.2 Ω/Sq) with high level of optical transparency (75.2–92.6%). The developed fractal antenna maintained more than 1 dBi gain at the frequency range 2.3–4.1 GHz. The performance of the antenna remained stable after 100 cycle of bending tests upon 10 mm radius of bending. Figure 10 shows the prototype of the AgNW antenna.

Reference [47] developed a transparent and flexible silver nanowire (AgNW)-based bowtie antennas. AgNW was patterned by screen printing method on PET. The flexible and transparent AgNW film reported a low sheet resistance of 8.5 Ω/Sq and a high transparency of nearly 85%. This bowtie antenna achieved a radiation efficiency of 52%.

F. MONOLAYER MOLYBDENUM DISULFIDE

Molybdenum disulfide (MoS_2) is a conformal 2-D semi-conductor, which is atomically thin [48]. MoS_2 has robust mechanical configuration, good electrical conductivity and excellent optical properties. Due to its amazing features, it is becoming a potential material for nano-scale integrated flexible electronic device manufacturing industry. Reference [48] reported the wafer-scale fabrication of transparent MoS_2 electronics on polyethylene terephthalate (PET) substrates through modified chemical vapor deposition (CVD) technique. Figure 11 illustrates some approaches towards the realization of flexible electronics utilizing (MoS_2). Reference [49] reported an atomically thin and flexible ultra-fast battery-free electromagnetic energy harvester at Wi-Fi-band realized

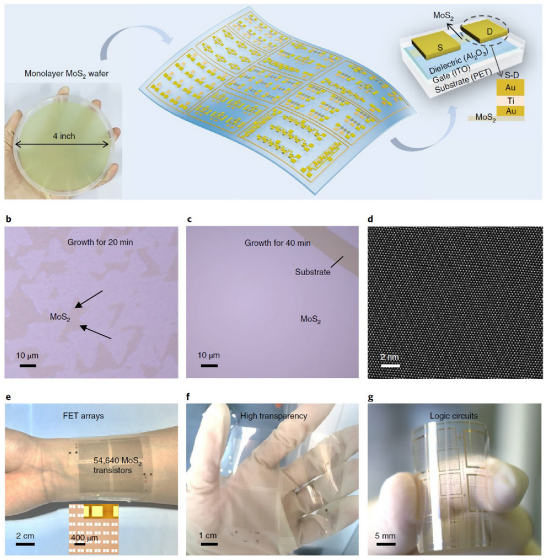


FIGURE 11. Development of flexible and transparent transistors realized with MoS_2 printed on PET film. (a) Schematic diagram of flexible transistor arrays in an integrated circuit. Left inset: a 4-inch monolayer MoS_2 wafer grown by epitaxy techniques. Right inset: geometry of the flexible FETs made with MoS_2. (b) Image of the MoS_2 film grown on a 4-inch sapphire substrate for 20 min. (c) Photo of a continuous monolayer MoS_2 film grown for 40 min. (d) HRTEM image of the as-grown monolayer MoS_2. (e) Photograph of a flexible MoS_2 transistor array wrapped on a human wrist. (f) Prototype of the flexible MoS_2 transistor arrays. (g) Prototype of flexible transparent integrated multi-stage circuits consisting inverters, NOR gates, NAND gates, SRAMs, AND gates and five-stage ring oscillators [48]. (Reproduced from [48] with permission. Copyright © 2020, The Author(s), under exclusive licence to Springer Nature Limited).

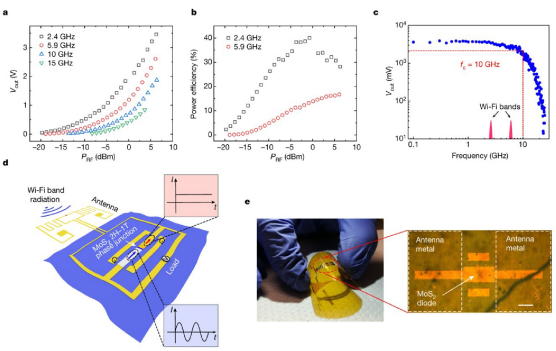


FIGURE 12. An RF energy harvester realized with MoS_2 based rectenna. (a) Output voltage vs input RF power for the frequencies 2.4 GHz, 5.9 GHz, 10 GHz and 15 GHz. (b) Power efficiency vs input power. (c) Output voltage as a function of frequency of the input signal for the applied RF power $P_{RF} = 5$ mW. (d) Prototype of the flexible rectifier. (Reproduced from [49] with permission. Copyright © 2019, The Author(s), under exclusive licence to Springer Nature Limited).

with MoS_2. This MoS_2 energy harvester also functioned as a flexible mixer, converting frequency beyond 10 GHz. This energy harvester could be a promising solution for seamless wireless charging of wearable and implantable sensors. Figure 12 illustrates the MoS_2 energy harvester. Reference [50] reported a hybrid MoS_2-graphene based antenna operating at the ISM band. The feasibility of the hybrid MoS_2-graphene structure and the effect of laser power on the sheet resistance was studied in this work. The achieved sheet resistance was 8.5 Ω/Sq for 4.5 W implied laser power. The designed antenna was a CPW polygon monopole

antenna operating at 5.8 GHz band. Glass (dielectric constant 4.5, loss tangent 0.002) was used as the substrate of this antenna. The reported gain of the antenna was 2.21 dBi, this result showed better performance than the similar antenna realized with only graphene (1.72 dBi gain for graphene antenna).

G. CARBON NANOTUBES (CNTS)

Carbon nanotubes (CNTs) are becoming popular in the electronic industry. The promising features of CNTs are their high conductivity, lightweight, elasticity, stability against environmental impacts, ease of handling, and low processing cost. These features are rendering their popularity in electronic device manufacturing industry. CNTs are widely used in the manufacturing of RF and microwave devices, such as amplifiers, filters, rectifiers and antennas. The first developed antenna with CNT was a dipole antenna which was developed by Burke *et al.* in 2006 [51]. Since then, variety of antennas have been developed utilizing CNTs, where researchers exploited the advantageous features of CNTs to develop compact, flexible, lightweight, and cost-effective antennas. It should be noted that the conductivity of CNTs is lower than the conductivity of the traditional conductors, i.e., copper or silver; so different methods have been explored to improve the conductivity of CNTs. Some of the conductivity increment techniques of CNTs are depositing dopants and threading/ bundling of multiple CNT tubes. According to morphology, CNTs are either single walled CNTs (SWCNTs) or multi walled CNTs (MWCNTs) referring the number of concentrically interlinked nanotube layers [52]. Both SWCNTs and MWCNTs have been utilized in antenna manufacturing. In [53], a high frequency semi-transparent antenna has been reported which was manufactured with SWCNTs coated Indium Tin Oxide (ITO). This antenna operated at 0.76 THz exhibiting a gain of 4.9 dBi and 21% fractional bandwidth. Reference [54] presented a comprehensive study on the electromagnetic characterization of multi-wall carbon nanotube–doped fluorine tin oxide (FTO) film for the development of transparent antennas. They studied the characteristics of CNT-FTO deposited on a Pyrex substrate by the spray pyrolysis technique. The analysis revealed that mixing with carbon nanotubes notably boosted the surface conductivity of the FTO thin film. It was found that high level of optical transmittance (about 77%) was achieved at the sheet resistance of 5 Ω/sq.

Reference [55] reported an optically transparent antenna realized from silver-carbon nanotube hybrid conductive coating on polycarbonate. The sheet resistance of the hybrid conductor was 13 Ω/sq and the transparency was 89.3%. The monopole antenna operated at 2.9 GHz with a gain of −3.23 dBi and efficiency of 50%.

H. GRAPHENE FILM

Graphene is a popular conductor in electronics industry, which falls in the group of two-dimensional nanomaterial. Graphene comprises some attractive features, such as high electrical conductivity, good light transmittance, promising mechanical robustness and high flexibility [56], [57]. Graphene is the thinnest two-dimensional conductive material whose electrical conductivity can be modified by simply carrier doping, this process does not jeopardize the optical transparency of the graphene film. Graphene is a popular metal for the development of electronic devices, such as antennas, filters, resonators, and absorbers. A number of research attempts can be found which reported the development of thin conformal antennas using graphene films [58], [59], [60]. A monolayer CVD graphene film comprises nearly 97.7% optical transmittance; however, the reported sheet resistance of the monolayer CVD graphene film is 750 Ω/Sq [61] which is notoriously high and severely affects antenna performance. To solve the high sheet resistance issue of the graphene film, researchers utilized the topology of doped multi-layer stacked graphene film. In [62], a doped six-layer stacked graphene film was reported which had a sheet resistance of 18 Ω/sq and optical transparency of nearly 85%. Reference [56] reported a doped three-layer stacked graphene film which had a sheet resistance of 80 Ω/sq and optical transparency of nearly 90%. In this work, carrier doping was implied with bis (trifluoromethanesulfonyl) amine (TFSA).

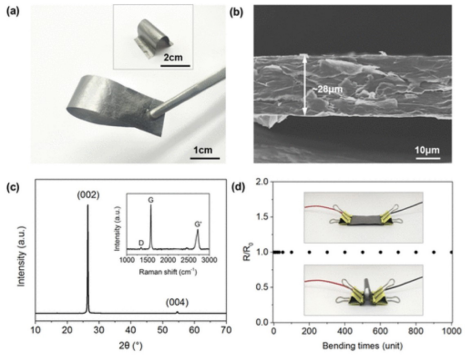


FIGURE 13. Characterization approaches of GAF. (a) Photo of GAF demonstrating high flexibility. (b) Scanning electron microscopy (SEM) image of the cross-sectional view of GAF having a thickness of 28 μm. (c) X-ray diffraction pattern and Raman spectrum of GAF. (d) Testing the mechanical stability of GAF. (Reproduced from [63] with permission. Copyright © 2020 ACS Publications).

An efficient flexible wearable antenna realized with flexible graphene-assembled film (GAF) was reported in [63]. The demonstrated antenna was a coplanar wave-guide (CPW) antenna operating at 3.5 GHz and performed as an wearable strain sensor. The realized antenna was very thin and occupied small area (50 mm × 50 mm). The utilized GAF film achieved an electrical conductivity of 10^6 S/m with a thickness of 28 μm, the film was manufactured through high-temperature heat treatment followed by rolling compression process. The characteristics of the GAF film is illustrated in Figure 13. The film was deposited on polyethylene terephthalate) (PET) substrate having a thickness of 0.06 mm. This ultra-thin antenna demonstrated high elasticity functioning as an effective flexible sensor. Figure 14 depicts the antenna prototype working as an wearable strain sensor.

A dual-band wearable conformal antenna realized with highly conductive graphene film was reported in [64]. The

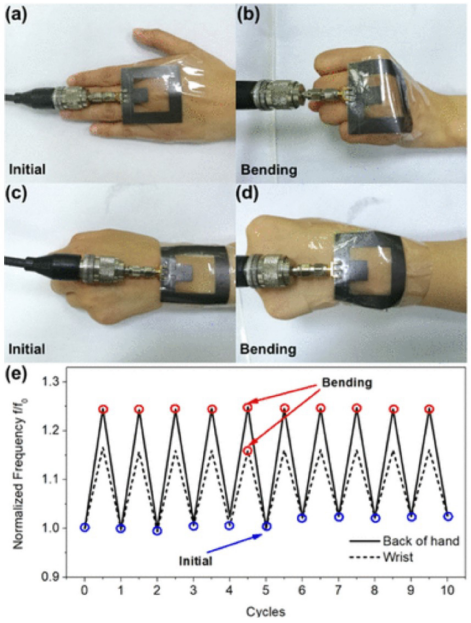


FIGURE 14. Semitransparent and flexible antenna sensor system for human motion detection. (a) Flexible antenna sensor attached to the back of the hand in the unbent (initial) state, (b) antenna sensor wrapped on hand exhibiting bent state. (c) Antenna sensor on the wrist in unbent (initial) state. (d) Antenna sensor wrapped on wrist in bent state. (e) Response of normalized frequency in initial and bending states. (Reproduced from [63] with permission. Copyright © 2020 ACS Publications).

operating frequency of the flexible GAF antenna covered the Wi-Fi band, 2.4–2.45 GHz and 5.15–7.1 GHz. The reported GAF film had a high conductivity of 1.13×10^6 S/m. The maximum realized gain was 6.85 dBi at 6.12 GHz.

Grapehne-conductive nanowire hybrid structure has improved electrical conductivity, physical stability and transparency. For example, graphene-silver nanowire (AgNW) hybrid film has excellent stretchability, transparency, and electrical conductivity [7]. Thus, this hybrid graphene film is a prominent candidate for flexible and transparent electronics industry. In [7], a stretchable transparent antenna made from the graphene-AgNW hybrid structure was demonstrated. This demonstrated antenna worked with a glucose sensor for wireless monitoring the glucose level of diabetic patients. This antenna and sensor system was transparent, stretchable, hydrophilic, biocompatible and integrated with soft contact lens. In this intraocular sensor system, graphene-AgNW hybrid film was deposited on ultra-thin parylene substrate (thickness 500 nm). Parylene demonstrated excellent transparency, stretchability and biocompatibility [65], thus, became a superior substrate for intraocular electronics. Figure 15 illustrates the intraocular sesnsor system realized with graphene-AgNW hybrid film.

I. MXENE

In the group of 2D materials, MXene is becoming a popular candidate, especially in the field of conformal electronics. Chemically, MXene is a member of the family of 2D transition metal carbides and nitrides comprising a chemical formula of $M_{n+1}X_n$, where M is an early transition metal

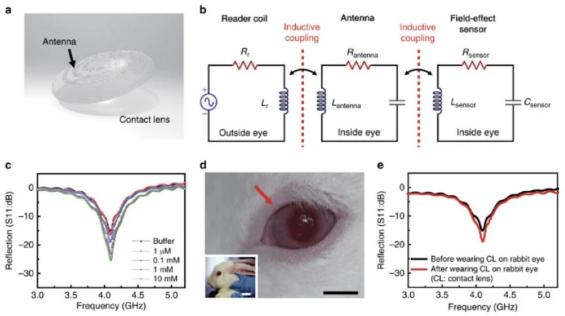


FIGURE 15. (a) Geometry of the transparent glucose sensor on contact lens. (b) Equivalent circuit for wireless sensing on contact lens. (c) Wireless monitoring of glucose concentrations from 1 μm to 10 mm. (d) Wireless sensor integrated on the eyes of a live rabbit. (e) Reflection-coefficient results before and after integrating contact lens on an eye of live rabbit. (Reproduced from [7] under a Creative Commons Attribution 4.0 International License (CC BY 4.0)).

(such as Ti, V, Nb, and Mo) and X is carbon or nitrogen. MXenes consist of odd number of layers where carbon or nitrogen (X) layers are sandwiched by metals (M) [66]. MXene films are promising candidates for transparent and flexible antenna realization because of their high electrical conductivity, low sheet thickness and ease of fabrication methods. 2D titanium carbide MXene films can achieve electrical conductivities up to 5000 to 10,000 S/cm, which is higher than other solution-processed 2D materials. 2D titanium carbide material is stronger than traditional metals and can be processed with very thin layer. The thickness can be hundred thousand times lower than a human hair and can be deposited on arbitrary surfaces, thus, they can be used in ultra-thin antenna fabrication. The electromagnetic interference (EMI) shielding characteristics of the thin film of Ti_3C_2 was demonstrated in [67] where it showed comparable performance to metals and better performance than other nano materials of similar thicknesses. They reported a flexible dipole antenna for the first time with varying the MXene sheet thicknesses from 62 nm to 8 mm. The reported antenna operated in the Wi-Fi and Bluetooth frequency bands.

The most attractive characteristics of MXene is that conductive ink of MXene can be made by simply dissolving MXene titanium carbide in water. The high conductivity of the MXene permits the propagation of radio waves in a very thin printed layer. In [68], a group of researchers from the Drexel university explored the realization of a flexible-transparent MXene antenna by utilizing novel spay-on technology. They prepared MXene aqueous colloidal solution (conductive MXene ink) by dissolving MXene to water and then sprayed this ink on polyethylene terephthalate (PET) sheets (plain surface) and cellulose paper (rough surface) by using air spray gun. Two types of surfaces were selected to examine MXene's deposition capability on broad range of substrates. The detail investigation of MXene coating on the substrate is illustrated in Figure 16.

Drexel researchers also compared their antenna performance with other printed nano sheet antennas made from graphene, silver ink and carbon nanotubes [68].

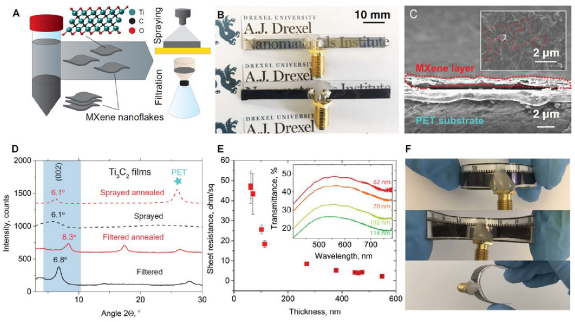


FIGURE 16. Development of Ti_3C_2 MXene antennas. (A) 2D Ti_3C_2 MXene solution. (B) Prototypes of MXene dipole antennas (top antenna is 62-nm-thick and bottom antenna is 1.4-mm-thick). (C) SEM image of the sprayed MXene. Individual Ti_3C_2 flakes are highlighted with red dotted lines. (D) X-ray diffraction (XRD) patterns of MXene films prepared by vacuum-assisted filtration (black solid line) and thermal treatment at 150°C (red solid line). Thermal treatment of the MXene film shifts the (002) MXene peak position from 6.8° to 8.3°. The same comparison was made with the sprayed 1.4-mm-thick MXene film on PET, as-sprayed MXene film (black dashed line), and the film was heated at 150°C (red dashed line). Annealing changed the (002) peak position from 5° to 6.1° and increased its intensity. The peak around 23° is attributed to the PET substrate. (E) Sheet resistance versus thickness of the sprayed MXene films. (F) Sprayed MXene dipole antennas under bending at different curvature radius demonstrating its stability in conformal operations. (Reproduced from [68] under a Creative Commons Attribution 4.0 International License (CC BY 4.0)).

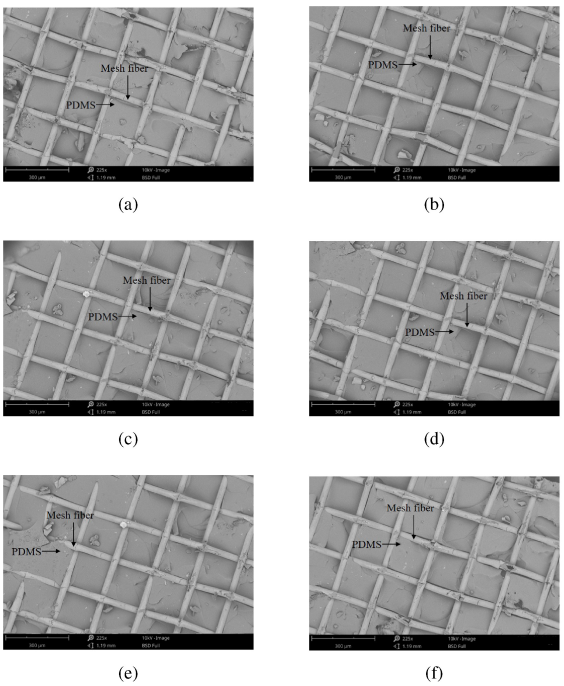


FIGURE 17. SEM images of the composite-(a) no bent, (b) after 10× bending cycle, (c) after 20× bending cycle, (d) after 30× bending cycle, (e) after 40× bending cycle, (f) after 50× bending cycle. (Reproduced from [73] with permission. Copyright © 2020 IOP).

It was found that MXene antennas outperformed graphene and silver ink antennas, demonstrating MXene's superiority in thin antenna realization.

A reconfigurable dipole antenna made from MXene is reported in [67] where the contraction strains (achieved up to 65.5%) of MXene springs was utilized to tune the antenna properties. This antenna was developed to remotely monitor heat sources.

So, it is explicit that MXene can be a potential candidate in the world of flexible transparent electronics.

J. MESH CONDUCTIVE FABRIC

E-textiles have become a precious materials in flexible electronic industry. E-textiles offer a lot of promising characteristics, such as excellent flexibility, stretchability, ease of handling and low cost. These characteristics are indispensable in flexible electronic devices. It is needless to say that e-textiles are the most popular conductors in flexible device manufacturing industry. A lot of different types of flexible antennas have been developed from e-textiles. The most advantageous feature of e-textiles is their convenient and cost-effective processing; e-textiles can be integrated with flexible dielectrics by gluing, sewing, embroidering or heat curing. E-textile is also an attractive conductor in transparent-flexible antenna fabrication. Mesh style conductive fabric, e.g., VeilShield developed by Less EMF Inc. USA, has good optical transparency (nearly 72%) and flexibility [69], [70], [71], [72], [73]. Due to the mesh structured geometry, VeilShield forms a strong attachment with transparent polymer PDMS. VeilShield-PDMS composite comprises excellent transparency, flexibility and robustness [73]. Figure 17 shows the SEM image of the fabricated composite under different bending cycles, which illustrates the robustness of the composite under bending [73]. The measured transparency of the composite under different bending cycles was also studied in this paper [73] and showed stable optical transparency under repeated bending. A variety of transparent-flexible antennas have been developed from VeilShield-PDMS composite. Reference [69] reported an optically transparent and flexible UWB antenna using VeilShield attached on PDMS. Reference [70] reported a dual band transparent, flexible and robust wearable antenna using VeilShield-PDMS composite. This antenna was completely encapsulated inside PDMS cover, thus protected from external dust, liquid and shock. This wearable antenna operated at 2.4 and 5 GHz ISM band with promising RF performance on human-body environment. Figure 18 shows the prototype of the flexible-transparent dual band antenna. Reference [70] also introduced the utilization of double layers of fabric to enhance the RF performance of the antenna. Although the double layer fabrics decreased transparency, the RF performance of the antennas was significantly improved. Figure 18 shows the prototype of the flexible-transparent dual band antenna and Figure 19 shows the prototype of the flexible-transparent dual band antenna using double layer of fabrics. In [71], a compact flexible-transparent wearable antenna was developed from VeilShield-PDMS composite. This antenna utilized optimized defected ground plane to enhance the optical transparency without significantly increasing the back radiation. Reference [72] reported a flexible-transparent CP RFID antenna realized with VeilShield-PDMS composite. Figure 20 shows the prototype of the flexible-transparent RFID antenna. This antenna was

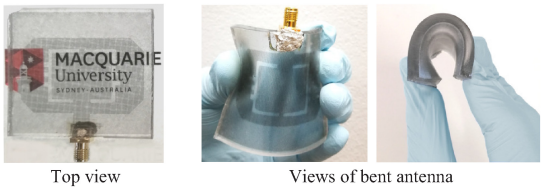


FIGURE 18. Photo of the fabricated prototype of the flexible and transparent dual band antenna developed from VeilShield-PDMS composite. (Reproduced from [70] with permission. Copyright © 2019 IEEE).

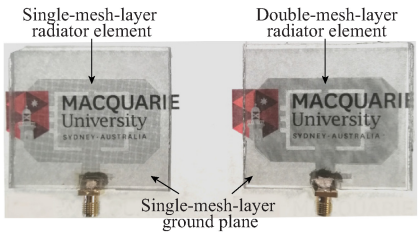


FIGURE 19. Photo of the fabricated prototype of the flexible and transparent dual band antenna developed from double layer VeilShield and PDMS composite. (Reproduced from [70] with permission. Copyright © 2019 IEEE).



FIGURE 20. Photographs of the fabricated prototype of the RFID antenna made with VeilShield-PDMS composite: (a) unbent state, (b) bent state. (Reproduced from [72] with permission. Copyright © 2020 IEEE).

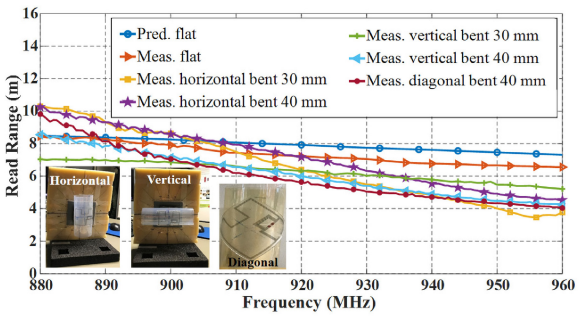


FIGURE 21. Read range of the CP tag antenna in flat state and various bending configurations. The inset shows the bending test set-up. (Reproduced from [72] with permission. Copyright © 2020 IEEE).

tested in both flat and bent axis and showed promising performance as shown in Figure 21 which demonstrates the robust connection of the IC to the antenna.

K. WATER

Water is an attractive material for flexible-transparent electronic device manufacturing. Water has the excellent properties of easy availability, low cost, excellent transparency, liquidity, easy handling, high dielectric constant and good electrical conductivity. Pure water provides almost 100% optical transparency within the visible light spectrum [74] and behaves as a dielectric material with high permittivity and high dielectric loss [75]. Although pure water has limited conductivity, after mixing with salt, conductivity is boosted significantly. In the literature, significant research efforts can be found on water-filled antennas where either pure water [75], [76], [77] or salt water [78], [79], [80], [81] was used. Moreover, some research efforts used both [82] for improved performance and some efforts investigated water-based reconfigurable antennas [83], [84]. Moreover, a new type of water-based antenna was introduced in [12], whose operating principle was described as a dense dielectric patch antenna (DDPA). Later, another water-based patch antenna was introduced in [85] where both the patch and ground were realized from water enclosed inside transparent plexiglass. The antenna was highly transparent except the small central disk-loaded feeding probe. This antenna operated at 2.4 GHz band with omnidirectional conical beam radiation patterns and demonstrated 35% impedance bandwidth. Its measured gain and efficiency varied from 1.5 to 4 dBi and 57% to 82%, respectively, over the operating band. The diameter of the antenna was 306 mm ($\sim$2.45 λ_0) and height was 37.6 mm ($\sim$0.3 λ_0). Although these water-based antennas provided good RF performance and transparency, their occupied size were quite large and they were not flexible due to the use of rigid transparent materials in water holders. Later, research efforts [86], [87] focused on the development of water based flexible, robust and transparent antennas. In these efforts, water was enclosed inside transparent flexible cavity made with PDMS polymer. These reported antennas were highly flexible, robust, transparent, compact and provided good RF performance. In [86], a flexible-transparent wearable antenna was reported, the reported peak gain of 3.2 dBi was achieved and the achieved efficiency was 51%. Reference [87] reported a similar antenna having frequency tuning capability with varactor diode. The operating frequency of this antenna was tunable from 2.38 GHz to 2.67 GHz, the peak gain varied between 2.28 dBi to 3.27 dBi and efficiency varied between 44.1% to 50.4% in this tuning range. Figure 22 shows the prototype of the flexible-transparent water antenna. These research explorations demonstrate that water is a potential candidate for the development of robust, transparent and flexible antennas.

V. FABRICATION TECHNOLOGIES OF TRANSPARENT ANTENNAS

The widely used fabrication technologies of transparent antennas include Physical vapor deposition [11], Chemical vapor deposition [61], Photo-lithography [42], [45], RF sputtering [26], Spray pyrolysis [27], Inkjet printing [88], Coat-and-print [89], Electrospining [90] and Layer-by-layer polymer-textile assembly technology [70].

The overview of these methods are briefly described in the following subsections:

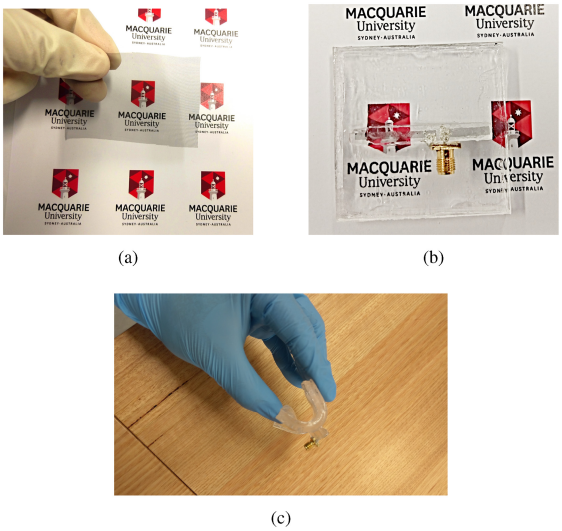


FIGURE 22. (a) A VeilShield sample demonstrating its transparency, (b) The antenna prototype made with VeilShield, PDMS and water, (c) Antenna bent to a very low radius. (Reproduced from [86] with permission. Copyright © 2020 IEEE).

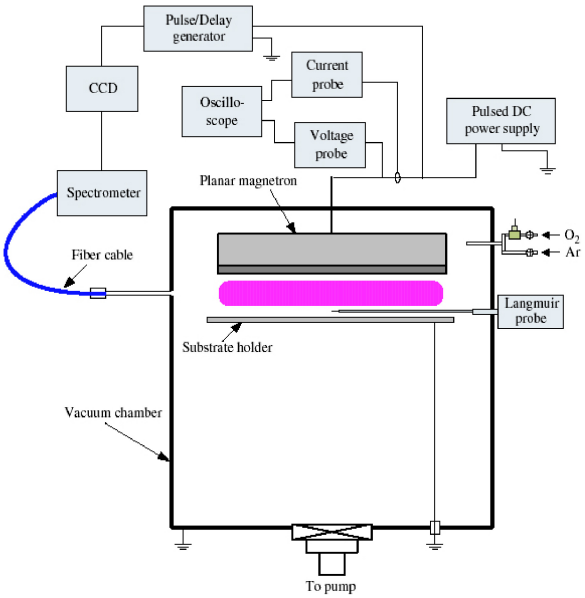


FIGURE 23. Schematic diagram of the mechanism of a pulsed DC magnetron sputtering system. (Reproduced from [92] under a Creative Commons Attribution 4.0 International License (CC BY 4.0)).

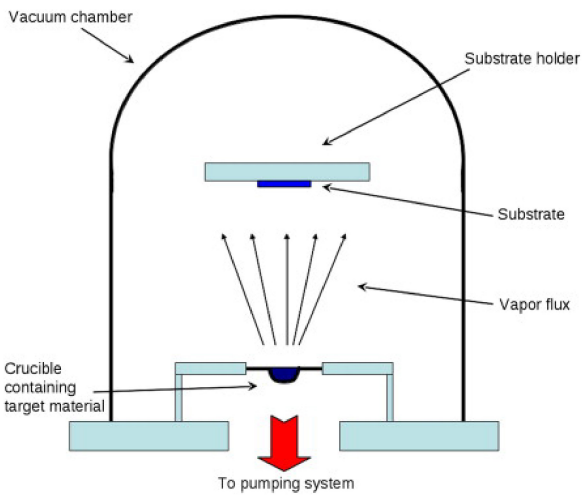


FIGURE 24. Schematic diagram of a typical thermal or electron beam evaporation system. (Reproduced from [91] with permission. Copyright © 2013 Elsevier Inc).

A. PHYSICAL VAPOR DEPOSITION

Physical vapor deposition (PVD) is the most utilized manufacturing technology of thin film transparent antennas. Vacuum environment is created in this method where a solid material is vaporized to deposit on the surface of a substrate. Thin films fabricated through physical vapor deposition are highly durable and have good resistivity to scratching, corrosion and high temperatures. Different deposition techniques are used in this method, such as conventional direct current (DC) magnetron sputtering system [11], pulsed direct current (DC) magnetron sputtering system [11], electron beam evaporation and thermal evaporation systems [91]. Figure 23 and Figure 24 represent the schematic diagrams of the mechanisms of a pulsed DC magnetron sputtering [92] and evaporation procedure [91], respectively. The applications of PVD can be found in the manufacturing of antennas, solar cells, eyeglasses, insulating coatings, OLEDs and a variety of other semiconductor devices. However, PVD involves complex and costly fabrication method which makes it inappropriate for low-cost manufacturing of electronic devices in larger scale.

Reference [11] reported a wearable glass antenna which was fabricated using physical vapor deposition (PVD) technique. This antenna utilized IZTO/Ag/IZTO multilayer transparent-flexible film deposited on polyimide substrate. In this fabrication method, a ceramic sputter, using pulsed direct current (DC) magnetron sputtering system, was used to deposit IZTO, and a metal sputter, using conventional DC magnetron sputtering system, was used to deposit silver (Ag). The average transparency of the antenna was 81.1% and this antenna achieved high mechanical robustness.

B. CHEMICAL VAPOR DEPOSITION (CVD)

Chemical vapor deposition (CVD) is a popular deposition method of solid metals on substrates. Most of the CVD methods work under vacuum environment where chemical reactions happen between organometallic or halide compounds which are actually deposited and the other gases to produce non-volatile solid thin films on substrates. CVD is a multi-directional deposition method, whereas PVD is a line-of-sight impingement deposition technique, this is the most significant difference between CVD and PVD [93]. Figure 25 shows the typical CVD technique [93]. CVD is a widely used deposition technique in semiconductor manufacturing industry to fabricate precise and high-quality electronic devices.

Reference [61] reported a monolayer graphene antenna. In this work, graphene layers were grown on Cu foils by low pressure CVD in a conventional quartz tube furnace using

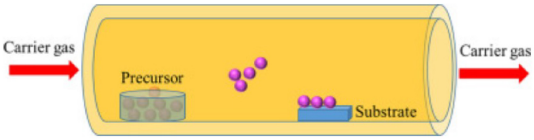


FIGURE 25. Schematic diagram of a typical CVD process. (Reproduced from [93] with permission. Copyright © 2021 Elsevier Inc).

CH_4 and H_2 gases. The CVD growth was carried out for 30 min with a CH_4 (2 sccm) and H_2 (20 sccm) flow at 1000°C under a total pressure of 1500 Pa. The CVD-grown graphene layer was transferred onto 1-mm-thick synthetic quartz substrates (20×20 mm^2) by a transfer technique using polymethyl-methacrylate (PMMA) supporting layers. Similar procedure was followed in [56] and [62] to manufacture graphene-based antennas using CVD technology.

C. PHOTO-LITHOGRAPHY

Photo-lithography process is another popular technology, which has been widely used in semiconductor manufacturing industry since 1960. Typical photo-lithography process comprises the steps of wafer cleaning, composition of barrier layer, photoresist implementation, soft baking, levelling of mask, exposure to light and hard-baking. Figure 26 illustrates the set-up of a typical mask-based photo-lithography procedure [94]. There are two types of photoresist: positive and negative. In positive resists, the resist is strategically exposed to UV light which subsequently alters the chemical composition of that particular portions of the exposed resist to make it more soluble in the developer. In this way, pre-fashioned patterns of the resist are etched away. After removing the exposed resist by the developer solution, an exact layout of the pattern remains on the wafer. In negative resists, exposure to UV light polymerizes the chemical structure of the photoresist and makes it insoluble to the developer. This procedure is exactly the opposite of positive photoresist. After UV exposure on negative resist, the mask comprises an inverse pattern of the original. Negative photoresist often incorporates poor accuracy due to edge-swelling. For this reason, positive photoresist is more popular in antenna manufacturing. It is demonstrated that photolithography process requires complex fabrication technique, it is expensive, needs hazardous chemicals and emits by-products. However, photo-lithography is still one of the most popular fabrication methods of transparent antennas. Enormous number of antennas can be found in literature that are fabricated with photo-lithography technology.

In [42], a flexible and transparent antenna using Cu-micromesh and PDMS substrate was fabricated by using photolithography process. With this process, 4.7 μm thick stretchable tortuous Cu mesh pattern was manufactured. The fabricated antenna achieved 32-44% transparency and upto 40% stretchability.

Reference [9] reported a zinc oxide heavily doped with gallium (GZO) film based planar-dipole antenna fabricated with Photo-lithography process. GZO thin films were grown on double side polished sapphire substrates

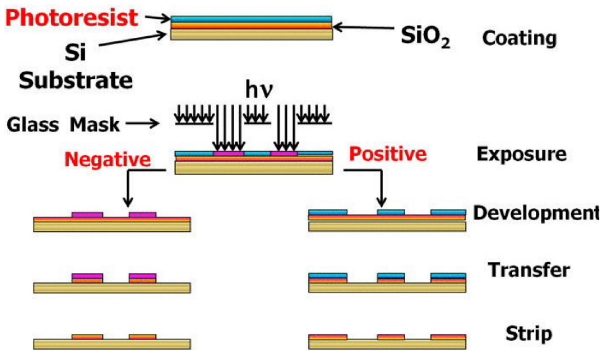


FIGURE 26. Typical photo-lithography process. (Reproduced from [94] with permission. Copyright © 2013 AIP Publishing).

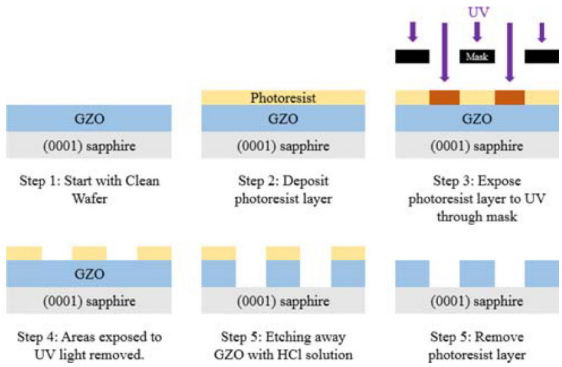


FIGURE 27. Photolithography process for GZO antenna. (Reproduced from [9] with permission. Copyright © 2017 Wiley Periodicals, Inc).

using plasma assisted molecular beam epitaxy with an RF plasma oxygen source and the Knudsen cells for Zn and Ga. Here, 1.4 μm-thick GZO film was deposited on a 375-μm thick c-plane sapphire substrate. The achieved transparency for this deposition was nearly 75%. Figure 27 shows the fabrication process of the GZO antenna and the fabricated prototype is shown in Figure 28. In [95], silver nanofibres (AgNFs) and fine silver nanowires (AgNWs) hybrid structure was photolithographycally patterned to form a transparent antenna integrated with soft contact lens for sensing operation.

D. RF SPUTTERING

RF sputtering is used to deposit thin film metals on substrate. This sputtering technique is used in thin film based transparent antenna manufacturing industry. For example, [26] used RF sputtering machine to fabricate an ITO -based antenna. Figure 29 illustrates the schematic diagram of the RF sputtering deposition machine. The sputtering machine was Plassys MP 450S. In this process, the deposition chamber contains two sputtering targets (75 mm diameter): one for ITO deposition: an indium oxide (In_2O_3)-tin oxide (SnO_2) ceramic disc (10% SnO_2 by weight and 99.999% purity), the other for metal deposition: a copper disc (99.995% purity). This configuration made it possible to synthesise single layer or multilayer in a single run without breaking vacuum. Targets



FIGURE 28. Fabricated transparent GZO dipole antenna. (Reproduced from [9] with permission. Copyright © 2017 Wiley Periodicals, Inc).

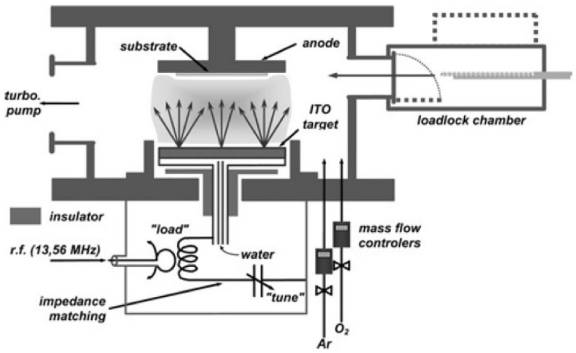


FIGURE 29. Schematic diagram of the RF sputtering deposition method. (Reproduced from [26] with permission. Copyright © 2009 IET).

were supplied with RF power (at 13.56 MHz) through an automatic matching network tuned for a minimum reflected power (1W). During ITO deposition, reactive gas flows (argon oxygen mixture) were adjusted for minimum film resistivity and bled into the sputtering chamber. Whereas, during copper deposition, only argon gas was fed into the chamber. Substrate (50 mm × mm Corning 1737 glass, 0.7 mm thick), clamped on a sample holder, was introduced in the deposition chamber via a loadlock chamber. The sample holder was revolved around a central axis, which allowed the positioning of the substrate in front of the selected target. Sputtering speed was calibrated for each target, thus, the thickness of each layer was controlled through the sputtering time.

E. SPRAY PYROLYSIS

Spray pyrolysis is another deposition technique of thin film metals on substrates. In this process, thin conductive film is deposited on the substrate by spraying a solution on a heated surface, where chemical compound is formed from the reaction of the constituents. Spray pyrolysis has been utilized in transparent antenna manufacturing industry for decades.

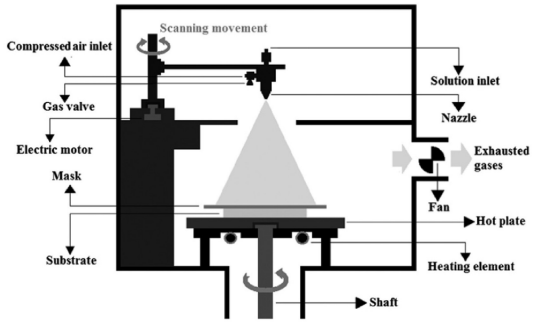


FIGURE 30. Schematic diagram of the spray pyrolysis deposition technique. (Reproduced from [96] with permission. Copyright © 2015 Taylor & Francis).

In [27], fluorine-doped tin oxide (FTO) was deposited on pyrex glass substrate by using spray pyrolysis. In the demonstrated method, substrate was cleaned with hydrochloric acid (HCl) and double distilled water and then placed on the hot plate at the temperature of 480°C. For the deposition of FTO (SnO_2:F) on substrate, stannic chloride ($SnCl_4$:$5H_2O$) and ammonium fluoride (NH_4F) were dissolved in ethanol (C_2H_5OH) and double distilled water and then pyrolytically sprayed on the pyrex glass surface by maintaining 35 cm distance from the nozzle tip to substrate. The deposited FTO layer achieved a transparency of about 74.29% with a sheet resistance of 7 Ω/Sq for 30 cc volume solution of FTO. The developed microstrip patch antenna operated at 5 GHz with 3.63 dBi maximum gain and 66.91% efficiency.

Another microstrip patch antenna made with FTO film deposited by spray pyrolysis was demonstrated in [96]. Figure 30 illustrates the schematic diagram of the spray pyrolysis deposition technique. The main elements of the deposition apparatus were the spray chamber, hot plate, heating element, spray nozzle, and gas valve. Borosilicate glass was used as the substrate for this deposition. The borosilicate glass was cleaned with hydrochloric acid (HCl) and double distilled water and then placed on the hot plate. A steel sheet of 0.3 mm thickness was used as the deposition mask. FTO solution was pyrolytically sprayed with the scanning nozzle onto this assembly, which was placed on the hot plate (without rotation). For preventing rapid reduction of the hot plate temperature, spraying was done in short intervals; hot plate temperature and the distance from the nozzle to substrate were approximately 500°C and 35 cm, respectively. The fabricated antenna with this method achieved nearly 1.72 dBi gain and 33.27% radiation efficiency in the operating band. Photographs of the fabricated FTO-based transparent microstrip antenna is shown in Figure 31.

Spray pyrolysis technique involves costly manufacturing procedure and requires well-maintained fabrication environment.

F. INKJET PRINTING

Commercial inkjet printers are becoming popular in antenna and RF device manufacturing industry. Antennas having fine and compact geometries can be fabricated by using inkjet

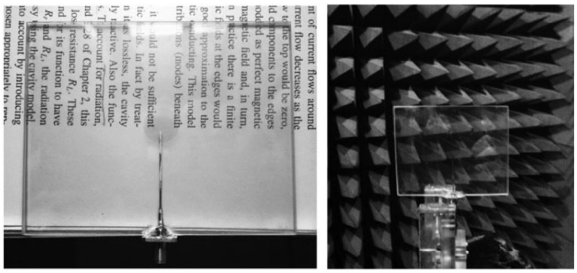


FIGURE 31. Photographs of the fabricated FTO transparent microstrip antenna. (Reproduced from [96] with permission. Copyright © 2015 Taylor & Francis).

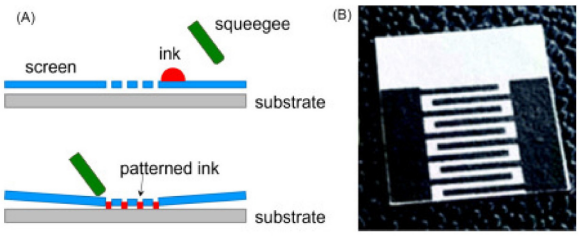


FIGURE 32. Block diagram of screen printing technique. (Reproduced from [46] under a Creative Commons Attribution 4.0 International License (CC BY 4.0)).

printing technology. Moreover, inkjet-printing technology is much faster and cleaner than conventional wet-etching techniques. Because of the speed and ease of prototyping process, inkjet printing can be a promising manufacturing technology for the next-generation flexible and cognitive electronics industry [97]. In [97], a flexible RFID antenna was fabricated through ink-jet printing of silver nano-ink on paper substrate. Flexible antennas realized in inkjet printers show good stability in bending operations and the fabricated prototypes show good performance [88], these features evidently demonstrate inkjet printing as an influential technology. In [88], an antenna was fabricated in inkjet printer by printing silver conductive ink on transparent substrate, polyethylene terephthalate. It was revealed that the performance of this antenna was comparable to an antenna made from copper, which demonstrated the significance of this technology in transparent RF device manufacturing. However, inkjet printing technology is associated with some limitations, such as high installation cost and fabrication tolerance. Structural irregularity of ink thickness sometimes impacts accuracy of fabrication and often repeated cycles of printing are required to achieve robust ink thickness on the substrate [1].

Reference [98] used inkjet printing technology to print CNT on paper substrate to realize a conformal RFID antenna. Reference [99] also used inkjet printing technology to print CNT on paper to realize a conformal monopole antenna. These antennas maintained good stability in conformal operations.

G. SCREEN PRINTING

Screen printing is a deposition technique of patterning conductive ink onto a substrate. This printing method uses a plate (screen mask) that uses a screen mesh for patterning. Screen printing is a type of "stencil printing" where viscous paste is forced to pass through the aperture of a stencil screen to create the pattern of any shape. Screen printing can be used to print on wide variety of substrates. Figure 32 illustrates the block diagram of the screen printing method to pattern an antenna.

Recently, screen printing has attracted great attention in the fabrication of transparent antennas. With the advancement of modern printing technology, fine printing is possible with screen printing. In [46], a highly flexible and transparent fractal antenna was fabricated with screen printing method by patterning AgNW on PET substrate. AgNWs-based screen-printable ink was made by mixing the washed AgNWs with polyvinyl pyrrolidone (PVP) solution. At the initial stage of manufacturing, 3g of PVP (K120, Mw $= 2 \times 10^6 - 3 \times 10^6$ gmol^{-1}) was dissolved in a solvent mixture containing of propylene glycol, isopropanol and 2-butoxyethanol with a ratio of 8:1:1. Then, AgNWs were mixed with PVP solution and agitated thoroughly using a propeller stirrer at a speed of 1500 rpm for 20 min to obtain the AgNW ink. The AgNWs patterns and antennas were printed on clean PET substrates using a screen stencil with a mesh count of 325, a wire diameter of 20 μm, and an emulsion thickness of 10 μm. Next, the printed samples were dried at 80°C for 10 min in an oven to evaporate the solvents. Then, the AgNW samples were immersed in warm water (60°C) or ethanol for 5 min to remove most of the PVP (k120), while remaining the AgNWs at the original position. the fabricated antenna achieved good transparency and flexibility. In a similar approach, [47] developed a transparent and flexible silver nanowire (AgNW)-based bowtie antenna by screen printing method on PET substrate.

H. COAT-AND-PRINT PATTERNING

Coat-and-print patterning is a novel fabrication technique of flexible electronics that combines the advantages of both mask based and printing technologies. This novel technology was originated from realizing silver nanowire (AgNW) based antenna with high precision, and excellent optical and RF performance [89].

The mask-based patterning technologies, such as photolithography or stencil screening can produce highly transparent patterns. But, the mask-based patterning technologies are complex, costly and suffer from poor patterning efficiency. On the other hand, direct printing technology is cost-effective, less complicated, fast and provides efficient patterning. However, direct printing technology only performs efficiently with high-concentration inks or short AgNWs (i.e., NWs with aspect ratios of less than 50). As a result, printed AgNW suffers from poor optical transparency. In [89], a new method was introduced which optimized the challenges of mask-based and printing technologies. In this technique, AgNWs were not directly printed, rather a polymer-based ink was patterned on the spin-coated AgNW films by inkjet printing technique. This protective

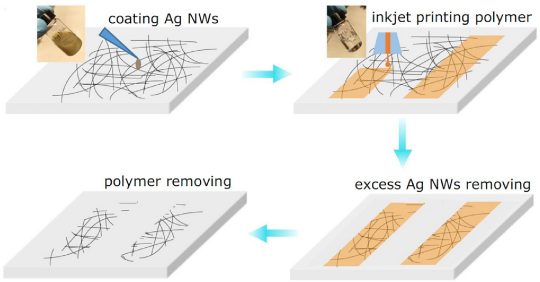


FIGURE 33. Coating and printing method of AgNW. (Reproduced from [89] under a Creative Commons Attribution 4.0 International License (CC BY 4.0)).

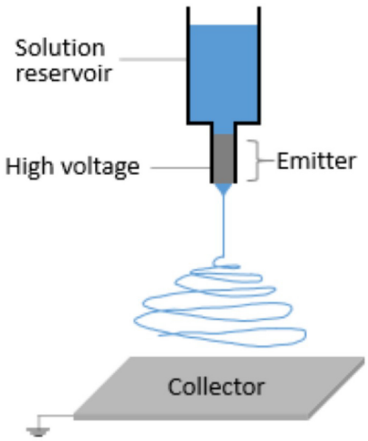


FIGURE 34. Typical electro-spinning process [90]. (Source: www.nanoscience.com).

polymeric layer had an impact on removing the excess AgNWs from the substrate and dissolving in an organic solvent. In this work, the average diameter of AgNWs was 27 ± 9 nm, and the length was 31 ± 7 μm. In this study, the electrical and optical properties of the coated and printed AgNW films were investigated by varying the properties of AgNW, which were controlled by varying the coating cycles (one to five cycles) and AgNW concentration (0.5–1.5 mg/mL). The transmittance of the Ag NW films was varied between 84.2 to 95.6% with a varying sheet resistance from 7.1 to 36 Ω/Sq. In this work, a flexible monopole antenna was realized by patterning the AgNW on flexible substrate. The AgNW antenna achieved a gain of −1.7 to 1.2 dBi in the frequency band 18 to 40 GHz. This flexible antenna reported satisfactory performance after 1000 cycles of bending, which demonstrated the effectiveness of this fabrication method in flexible device manufacturing industry. Figure 33 illustrates the coating and printing method of AgNW film.

I. ELECTROSPINNING

Electrospinning is a voltage-driven deposition process governed by the electrohydrodynamic phenomena where fibers and particles are made from a polymer solution. The most basic set up for this technique involves a solution contained in a reservoir (typically a syringe) and tipped with a blunt needle (for needle-based electrospraying), a pump, a high voltage power source and a collector. Figure 34 shows a typical elctrospinning process.

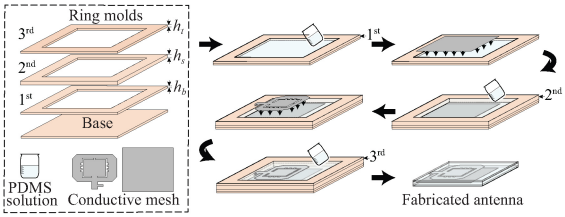


FIGURE 35. Fabrication technique of layer-by-layer polymer-textile assembly technology. (Reproduced from [70] with permission. Copyright © 2019 IEEE).

The spinning process is started when the solution is pumped at a constant flow rate and a specific voltage was applied to form an electric field between the needle tip and the collector. A charge is accumulated at the liquid surface. When the electrostatic repulsion is higher than the surface tension, the liquid meniscus is conically deformed.

Once the Taylor cone is formed, the charged liquid jet is ejected towards the collector. Collectors can be either stationary flat plates, rotating drums, mandrels, or disks. Depending on the solution viscosity, solid fibers are created as the solvent evaporating from the whipping motion that occurs during its flight time from the Taylor cone to the collector. The result is a non-woven fiber mat that is deposited on the collector.

Reference [95] developed a transparent antenna with hybrid nanostructure based on ultralong silver nanofibre (AgNFs) and fine silver nanowires (AgNWs) for intraocular presusre monitoring. This hybrid structure was fabricated by electrispinning of AgNFs for 10 seconds with successive spraying of AgNWs for 60 seconds. Twenty antenna samples were prepared in this study. The average sheet resistance was 0.3 ± 0.05 Ω/sq and the transparency was 73 ± 2.2%. This antenna was integrated with soft contact lens.

J. LAYER-BY-LAYER POLYMER-TEXTILE ASSEMBLY TECHNOLOGY

Some research approaches have been devoted to demonstrate simple, straightforward and low cost fabrication technology of flexible-transparent antennas. Reference [70] utilized flexible-transparent-conductive-mesh sheet, VeilShield from Less EMF Inc., USA, as the conductive parts of the antennas and flexible-transparent-polymer, PDMS, used as the substrates and protective encapsulations. The explored fabrication process was a simple layer-by-layer curing process, where VeilShield was integrated to PDMS by full curing method in oven. VeilShield is an e-textile which is easy to handle and can maintain structural regularity in the fabrication process. It can be easily cut to arbitrary shape by simply using cutting machine. The schematic diagram of this explored mold-based heat curing fabrication method is illustrated in Figure 35. This technique used some customized molds to give shape of the substrate and protective cover. The conductive parts were simply attached to the substrate by using small amount of uncured PDMS which was later cured in oven.

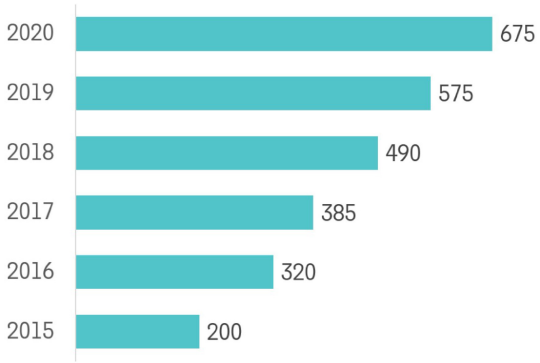


FIGURE 36. Global shipment of smartphones (in millions) from 2015 to 2020 with transparent AMOLED display panels (Source: Consumer Technology Association) [100]. (Source: www.mordorintelligence.com).

It is pertinent to mention here that the selected materials and realization process of this technology have some notable advantages that demonstrate its feasibility in the development of flexible transparent antennas in inexpensive, and non-complicated method. The utilized conductor VeilShield itself is not very robust in nature, but after integrating with PDMS, it transforms into a unique composite having the excellent features of high optical transparency, extreme flexibility and the ability to withstand harsh environmental impacts. The selected transparent conductor, VeilShield and transparent substrate, PDMS are easily available, inexpensive and do not require complex processing. VeilShield is actually a type of e-textile, which is quite easier to handle, has structural regularity and is less prone to fabrication inaccuracy than the existing metal deposition techniques. The selected substrate PDMS's properties are less sensitive to the change of environmental factors and manufacturing technique. PDMS's optical transparency is insensitive to its thickness, which makes it unique. Transparency of many other transparent dielectrics (e.g., polyimide) depend on their thickness. So, working with PDMS gives more freedom to antenna designers. Thickness and shape of PDMS can be easily customized, which provides more flexibility in antenna design. The demonstrated fabrication process is simple and inexpensive than the existing fabrication processes of screen printing, physical vapor deposition, and photolithography. The demonstrated method is potentially reproducible and can be implemented in the low-cost industrial production of flexible transparent antennas and other electronic devices. The proposed method does not need any hazardous chemical and does not exit by-products, which demonstrate its less impacts on the environment.

VI. PROSPECTS OF FLEXIBLE AND TRANSPARENT ANTENNAS

The global transparent electronics industry is witnessing a continuing proliferation and diversification. The consumer market of transparent electronics is forecast to elevate to 3800.39 million USD by 2026, which was 996.25 million USD in 2020, the compound annual growth rate (CAGR) of transparent electronics market is 25% for the forecast period 2021-2026 [100]. Figure 36 shows the number of global smartphones shipment (in millions) with transparent AMOLED display panels for the period 2015-2020. The report shows the rising demand of transparent displays. The cutting edge technologies of multi-touch flexible displays and see-through devices have attracted great attentions from global consumers. The global giant manufacturers are structuring their business roadmap considering this revolutionised customer demand. Hyundai recently announced to install transparent solar panels on the roof of the future electric vehicles (EVs) [101]. In April 2019, LG registered a patent for foldable display whose major portion was transparent. On June 2019, LG launched the razor-thin see-through OLED digital signage display. On September 2019, Huawei got license for a smartphone where camera, flash, LED indicator, light emitter, and sensor were located under the display. This smartphone consisted of a semi-transparent display portion stretching across the width of the device underneath the selfie camera. The users can adjust the transparency of the screen by simply touching the screen. On May 2019, Tianma Micro-electronics Co. launched a new OLED display demonstrating upto 50% transparency and high brightness. It can be noted that transparent displays have some peculiar features and advantages over the conventional displays, which attract consumers' attention. Conventional displays need backlights which consume power, so they are not energy efficient. In contrary, transparent displays utilize ambient backlight, thus they are more energy efficient. Moreover, traffic signs and billboards made with transparent displays would appear as floating signs and letters in the air, this appearance would improve the aesthetics. Similarly, windows can be made with transparent displays integrated with transparent electronics to perform multiple functions.

Antenna is an essential component in wireless communication. All of the modern smart electronic devices require antenna for data transmission and reception. The performance of these devices mostly depend on the efficiency of the integrated antennas. So, transparent and flexible antennas will occupy a vast majority application areas of the transparent electronics, especially in the upcoming high-speed wireless communications. Due to the attractive features of optical transparency and flexibility, there will be new application platforms for these antennas where optical transparency is of critically important. Transparent and flexible antennas will play a vital role in setting up unobtrusive communication links in the forms of penetrating with auto-mobile wind shields, windows, solar cells and displays. These forms of cutting-edge unobtrusive communication technologies will have applications in road traffic safety control, medical technologies, satellite communications, energy harvesting and many more. To satisfy these demands, new materials and manufacturing technologies have been explored by the researchers. This paper enlightens the novel approaches towards the development of flexible and transparent antennas.

TABLE 1. State-of-the-arts approaches towards the development of transparent antennas.

Conductor	Group	R_s (Ω/sq)	T (%)	Antenna	Frequency (GHz)	Gain (dBi)	Efficiency	Substrate	Flexibility	Fabrication	Dimension ($\lambda_g{}^3$)
ITO [26]	TCO	8.6	86	Monopole	0.8	-4.1	NA	Corning glass	No	RF sputtering	0.94×0.94×44
ITO/Cu/ITO [26]	TCO	4.7	61	Monopole	0.8	-1.96	NA	Corning glass	No	RF sputtering	0.94×0.94×0.44
IZTO/Ag/IZTO [11]	TCO	4.99	81.1	Monopole	2.45	4	40	Polyimide	Yes	PVD	0.69×0.47×0.03
ITO/Ag-Cu/ITO [29]	TCO	12.5	96	Dipole	2.95	0.8	NA	PDMS	Yes	RF sputtering	0.61×0.21×0.03
AZO [28]	TCO	38	NA	Patch array	2.4	4.9	43	Silicone	No	RF sputtering	NA
FTO [27]	TCO	4.81	69.2	Patch	5	3.63	74.05	Pyrex glass	No	Spray pyrolysis	NA
GZO [9]	TCO	2.38	75	Dipole	2.4	2.1	43.03	Sapphire	No	Photolithography	1.53×0.26×0.009
AgHT-8 [34]	TCP	8	80	CPW	2.45, 5.8	-3.25, -4.53	NA	PET	Yes	NA	0.54×0.58×0.003
Pani [35]	TCP	1.67	NA	Patch	NA	3.42	56	NA	Yes	NA	2.6×2.6×0.06
MoS_2-graphene [50]	2-D	8.5	NA	Monopole	5.8	2.21	NA	Glass	No	Laser writing	1.03×1.23×0.05
Monolayer graphene [61]	2-D	750	97.7	Dipole	21.6	6.2	NA	Synthetic quartz	No	CVD	1.4×1.8×0.14
3-layer graphene [56]	2-D	80	90.1	Monopole	9.8	0.3	52.5	Synthetic quartz	No	CVD	0.8×0.8×0.05
6-layer graphene [62]	2-D	18	85	CPW	4	-2	0.21	Corning glass	No	CVD	NA
MXene [68]	2-D	0.77	49	Dipole	2.4	-7	NA	PET	Yes	Spray	0.93×0.3×0.001
CNT-AgNW [55]	Mesh	13	89.3	Monopole	2.9	-3.23	50	Polycarbonate	Yes	NA	0.5×0.3×0.03
Cu micromesh [42]	Mesh	0.07	32	CPW	2.46-2.94	-0.02	NA	PDMS	Yes	Photolithography	0.1×0.14×0.006
AgGL [45]	Mesh	0.018	54.5	Monopole	2-6	6	NA	Corning glass	No	RF sputtering	1.6×1.6×0.04
AgNW [47]	Nanowire	8.5	85	Bowtie	2.45	NA	52	PET	Yes	Screen-Printing	0.28×0.64×0.002
Cu-mesh [43]	Mesh	0.04	70	Patch	0.55	6.2	83.8	PET	NA	NA	0.55×0.34×0.004
Cu-mesh [43]	Mesh	0.04	70	Dipole	0.6	2.4	72.1	PET	NA	NA	0.32×0.13×0.004
Mesh fabric [70]	Mesh	0.1	72	Patch	2.4, 5	2.2, 3.02	37, 44	PDMS	Yes	Heat-curing	0.67×0.77×0.06
Mesh fabric [71]	Mesh	0.1	72	Ring Patch	5.8	3.32	66	PDMS	Yes	Heat-curing	0.58×0.59×0.1
AuGL [41]	Mesh	0.22	74.6	Patch array	60	10	NA	Fused silica	No	Photolithography	2.7×4.2×0.08
Mesh fabric [86]	Mesh	0.1	94	Unidirectional	2.45	3.2	51	Water	Yes	Heat Curing	0.49×0.49×0.11
Mesh fabric [87]	Mesh	0.1	94	Unidirectional	2.38-2.67	2.28-3.27	44.1-50.4	Water	Yes	Heat Curing	0.78×0.78×0.16

VII. CONCLUSION

In this review paper, we have briefly over-viewed the background, prospects and challenges towards the development of flexible and transparent antennas. It is ascertained that flexible-transparent antennas have enormous demands in the Internet of Things (IoT), smart city projects, healthcare technologies, and satellite communications, to name a few. The most fascinating feature of flexible and transparent antennas is their light transmission capability and aesthetically neutral appearance. These features are highly advantageous for the overstretched communication networks and for wearable technology. But, the realization challenges have hindered the progress of this highly demanding technology.

This paper highlights the emerging materials and manufacturing technologies illuminating the recent progress of this promising technology. It is explicit that significant successful approaches have been incorporated towards the development of novel materials for the realization of robust, flexible and transparent antennas. It can be noted that there is contradictory relationship between the optical transparency and electrical conductivities of these conductors, but good number of transparent conductors have been reported in the literature that were successfully utilized in realizing antennas with excellent RF performance and optical properties. However, still it requires to explore new approaches to overcome the limitations of the existing transparent conductors for efficient antenna operations. It can be mentioned that this paper presents the characteristics of some novel transparent materials which have not been used in antenna manufacturing yet but used in other flexible-transparent electronics, e.g., sensors; these materials can be potential candidates for flexible-transparent antenna manufacturing. It is demonstrated that most of the fabrication techniques of transparent antennas require well-controlled fabrication environments, like clean room and also involve complex methods of antenna fabrication. Maintaining fabrication accuracy is often complicated in these fabrication processes. Moreover, these methods are not often cost-effective. For many applications that require less expensive, transparent, flexible, durable and more robust antennas, new designs and realization methods are still in need. Some state-of-the-arts research approaches towards the development of transparent antennas are summarized in Table 1.

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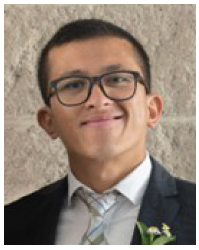
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