CHAPTER 3

Flexible Optically Transparent Antennas

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Abstract

Communication in today’s world has never been more connected than it is now, much of which is taking place wirelessly. Every device that communicates wirelessly does so by means of an antenna. Devices nowadays, especially cellular devices, often times have multiple antennas for different protocols. WiFi, GPS, GSM, and Bluetooth are typically well represented and have become standard features. We have seen the evolution of these antennas and the trend is clear: smaller, lighter, and more efficient. Today’s cellular devices include novel antennas that do not protrude from the device, which allow the device maker to focus more on the aesthetics. As the room for the antenna in these devices becomes more cramped, newer and more innovative solutions must be devised to keep up with demand. Antennas that can conform to different shapes clearly have an edge over their rigid counterparts, and many companies now are already developing devices that are completely flexible.

Wearable antennas that can provide connectivity between multiple devices in close proximity and then to the outside world are not out of the question. In the world of displays, this flexible technology is already in place. In fact, the Flexible Display Center at Arizona State University is providing many services related to the development of flexible and transparent thin film technologies. There are opportunities for component makers to dive into this market and that includes antenna designers. For the antenna designer, this presents unique challenges due to the fact that the antenna will need to be flexible while maintaining radiation characteristics, as well as robust enough to survive mechanical distortions. In this chapter, state-of-the-art designs and fabrication techniques of optically transparent antennas are surveyed. Moreover, a case study of a flexible transparent monopole antenna based on indium tin oxide and kapton polyimide substrate is presented.
1 Introduction

The transparent device market extends well beyond displays. There have been examples of fully transparent USB drives, LED displays, and even smart phone prototypes. This adds another dimension of complexity for the design engineer, as they will be required to match or exceed the same performance characteristics of rigid and opaque antennas using transparent materials. In this application, it is not possible to use the meshed configuration that will be presented later, so the design engineers will most likely be limited to transparent conductive oxides on a fully transparent substrate.

On a somewhat larger scale, communications have taken place wirelessly by means of large, and often unsightly, antennas. Images are conjured of the enormous satellite dishes that were used to receive television signals in areas where cable service was unavailable. Many companies have begun to take into account the visual impact that their stations are making upon the environment. For example, in the US, there are more than half a million cell towers and over 1.5 million other service antennas [1]. The companies who manufacture and install these antennas, whether through legislation, demand, or some combination, have grown more cognizant of the impact that they have on the environmental aesthetics of the installation areas. Towards this end, there has been considerable development in different ways of mitigating or enhancing the aesthetics of these devices. Cell towers have been integrated into existing buildings, such as church towers, flag poles, brick facades, and sculptural art, among others. They have been disguised as many different types of trees, cacti, and other naturally occurring features. This is a worldwide phenomenon, with disguised towers seen in South Africa, Portugal, Italy, and other places. The trouble with these is that in urban areas particularly, it is difficult to disguise these large antennas effectively using naturally occurring features. This presents an opportunity for thin, transparent, conformal antennas to be deployed. This type of device can be adhered to large windows of tall buildings where rooftop space is at a premium. For example, figures as high as US$3000/month are quoted for rooftop access in Manhattan. At the opposite end of the spectrum, larger format antennas that are deployed on the battlefield or in very remote locations need to be lightweight, compact, and portable. Space-based installations especially will benefit from an antenna that can be rolled up for transportation and unrolled once the destination is reached, whether it is a satellite, space station, or even another planet.

A thin, transparent antenna will also find applications where surface area is of critical importance. In the world of cube satellites or small form factor satellites, the majority of the surface area is designated for solar cells. A device of this nature placed over one of the exterior solar panels would give them additional flexibility without disrupting energy harvesting. The cube satellite deployment cost must take into account weight as a factor, which would be reduced by employing a thin film antenna on its exterior. They must also account for volume. The estimated cost for a 1U satellite launch can reach as high as US$100,000. Integration of the
antenna with the solar panel can help alleviate the designers from having to reserve space within the chassis and also limit losses from transmission behind the solar panels. Solar panel integration is also one of the major applications of a terrestrial nature, presenting the opportunity for dual-use installations. Both residential and commercial solar installation costs could be offset by leasing the surface area to communications companies.

An important consideration must be made here for this and other applications by the design engineer that are often overlooked; the substrate. Selection of a substrate becomes a complicated balancing act for a transparent and flexible antenna. The ideal substrate has not only high transparency over the visible spectrum but also complimentary mechanical properties, chemical resistance, well-characterized electrical properties, cost, and availability. The environment and end user with which the device will be deployed will give the best guidance here, but a commonly used substrate mentioned in the literature is artificially made of polyamide films. These films have a very good blend of characteristics that make it well suited for deployment in a wide range of environments including direct sunlight, outer space, and harsh chemical environments. Traditional polyamide films are of an amber colour, and transparency is related to the thickness of the material. Recently, however, there has been some development of a fully transparent polyamide film, which should provide designers with a degree of freedom.

All of these reasons in addition to the substantial potential benefits from integrating transparent antennas within flexible and wearable electronics should serve to illustrate why research in this area could become a critical pathway for the advancement of technology across many sectors.
2 Fabrication Methods

With regard to the transparent antenna, what is meant by ‘optically transparent’ should be addressed. In this case, optical transparency means that the device is transparent over the visible range of the electromagnetic spectrum, typically with wavelengths ranging from 400 to 750 nm. Transparency itself can be interpreted in many ways. Fully transparent would imply that 100% of the incident light passes through without any reflection, absorption, or scattering. Materials and processes exist that can achieve performance close to that, but none so far have the electrical characteristics desirable for this application. Designers will find that what is most important to keep in mind when choosing a method for implementation is that there will be some trade-off between spectral and electrical performance, and careful consideration must be taken to choose the method that best fits the application.

2.1 Meshed antenna

There are two distinct methodologies for achieving optical transparency. The first is a so-called ‘gridded’ or ‘meshed’ method. This approach takes advantage of the fact that most of the antenna excitation happens at the edges or borders of the antenna due to the skin effect and can do away with conductive material in the middle of the planar device and still achieve good radiation characteristics, while at the same time enhancing transparency. The technique here is to adhere conductive metal film to the substrate, either in a pre-patterned fashion with an ink jet printer, or with a post-adhesion removal process utilizing photolithography. The main advantage of a grid or meshed antenna is that conductive materials can be used that are not themselves transparent. The meshed conductive features are clearly visible to the human eye and, therefore, would not be suitable for integration into transparent handheld devices; however, they would find themselves used in solar arrays, vehicle-to-vehicle communication, and opaque devices that require low-profile or conformal antennas.

2.1.1 Ink-jet application

It has been demonstrated that this method of antenna fabrication can be achieved by using an Ink-Jet printer. Yasin et al. showed an antenna fabricated using this method on a polyethylene terephthalate transparency using a silver conductive ink to be comparable to the performance of an antenna made of the same dimensions using copper [2]. One of the key features of this method is the ability to create patch antennas with very fine geometry using a commercial inkjet printer. Khaleel et al. showed in a similar research in which two antennas that were fabricated using the inkjet method, polyamide film, and conductive inks were characterized to show a very low susceptibility to performance degradation and resonance frequency shift due to bending/folding effects [3]. This suggests another of the benefits of this type of antenna: that it can be conformed to a variety of shapes after manufacture. This is a distinct advantage over traditional methods of conformal
antennas, which have to be tailored to their application during manufacture. The form factor demonstrated admits candidacy for wearable electronics. The small, highly flexible, and unobtrusive nature of these devices show great promise for integration in future technology. Examples of the inkjet method have also been shown in implementations of higher complexity. Subbaraman et al. fabricated a phased-array antenna around a similar polyamide film, and utilizing printed carbon nanotube thin-film transistors (CNT-TFTs) showed an insertion loss and power consumption of 8.17 dB and 11.2 mW, respectively [4]. This group was able to print multilayer devices on a single substrate, showing promise for use in airborne communication systems.

The inkjet method does, however, suffer from some drawbacks. A commercial inkjet materials printer and other capital equipment can cost tens of thousands of dollars and have relatively low throughput. The printing itself often needs to be repeated to ensure ink thickness is mechanically robust and requires thermal annealing. These aspects of this method make it somewhat ill-suited for high volume manufacturing in the near term; however, these are not intractable problems. The market for metallic inks is projected to grow, and it currently represents a multi-billion dollar market comprising mostly photovoltaic applications. An alternative to inkjet printing may be to acquire preprocessed materials from large manufacturers who specialize in film coating. Although this would shift to a removal process rather than an additive one, the cost savings realized may offset the process change.

2.1.2 Removal process

The removal process does not have to be complex. Standard semiconductor manufacturing techniques are well established in foundries and fabs worldwide. Hautcoeur et al. used a removal method to produce a meshed monopole antenna [5]. They deposited gold on a piece of Corning glass substrate using a planar magnetron sputtering process, and then by utilizing a standard photolithographic wet etching process, transferred the pattern to the deposited film to achieve the grid design. Their research showed that at high frequencies in the 60 GHz ISM band, the meshed antenna and a solid reflective monopole of the same dimension showed very similar electrical properties. Their research suggests that at least for higher frequencies, the grid design is a promising method for highly efficient transparent antenna applications. The results here reflect well-established manufacturing methodology. Sputter deposition and other forms of physical vapour deposition have been around for many years. The range of materials that can be deposited is vast and the applications are many.

2.2 Transparent conductive oxides

One class of deposited material that lends itself to the transparent antenna topic is transparent conductive oxides. This class of metal oxides is typically deposited within a high vacuum chamber from either a sintered or metallic magnetron target
or by an electron beam evaporation process. These processes are well understood and can be deposited on a variety of substrates, including polyamide. The most popular in this group is indium tin oxide (ITO), although the oxides of zinc and tin have also been prepared. The combination of low sheet resistance and high optical transparency in the visible spectrum lend this material to applications in touch displays, EMI shielding, patterned electronics, and LED manufacture. Employing these materials in a transparent antenna requires a full understanding of the semiconductor physics involved.

### 2.2.1 Sheet resistance

The greatest challenge facing the use of transparent conductive oxides in this application is the relationship between sheet resistance and optical transparency. Having previously defined optical transparency, it is important to define sheet resistance as it is a critical measure for a transparent conductive oxide film. Sheet resistance is most often given in units of ohms per square and is a special case of resistivity for a uniform sheet thickness. Ohms per square is a convenient unit, due to the fact that a film conductor is three dimensional and resistance is defined as:

\[
\text{Resistance} = \text{resistivity} \times \frac{\text{length}}{(\text{width} \times \text{thickness})}
\]

Sheet resistance is then defined as resistivity divided by the thickness of the film, and letting length equal width, we have ohms per square. To avoid misinterpretation, it is typically written as ohms per square, or ‘\(\Omega/\square\)’. This is done to distinguish it from bulk resistivity, which is defined as sheet resistance multiplied by film thickness. It is obvious that low sheet resistance is critical to radiation efficiency; however, this is offset by losses in transparency due to increased film thickness. The measurement of sheet resistance is typically done with a device called a four-point probe. This device uses separate pairs of current carrying probes and voltage sensing probes, and is more accurate than a traditional multi-meter. The quality of the film is usually expressed in terms of a figure of merit defined as a ratio of percent transmission divided by sheet resistance.

### 2.2.2 Implementation

There are several examples of transparent antennas fabricated from transparent conductive oxides. Guan et al. specifically showed two different transparent conductive oxides, ITO and fluorine-doped tin oxide [6]. Although this group’s antenna was fabricated on a piece of glass, the optical and electrical characteristics are especially interesting. Several film thicknesses were produced, between 19.8 and 1.3 \(\Omega/\square\). The 19.8 \(\Omega/\square\) had the highest transmission at 550 nm of >95%, whereas the 1.3 \(\Omega/\square\) had just >70%. With the efficiency values among the various film thicknesses determined, an empirical formula for the rate of gain lowering at 2.4 GHz was estimated to be 0.20 dB/\(\Omega/\square\) and the rate of efficiency lowering is 2.7%/\(\Omega/\square\). The results here suggest that it is feasible to use these types of antennas in transparent devices. It is, however, unclear what method of manufacture was used to produce the films used in this study. There are many factors that are present...
when producing a TCO, including deposition technique, doping concentrations, substrate preparation, plasma enhancement, film stress, and many more. The film quality across the entire sector varies greatly; therefore, design engineers must carefully choose a thin film manufacturer and clearly and completely specify optical, mechanical, and electrical requirements. Yasin et al. describe some of the critical parameters to be considered when designing an antenna with ITO [7]. Their group discusses the importance of electron mobility in the ITO film and how it relates to both transparency and conductivity. It was shown that as electron mobility increased, they were able to increase the thickness at which 90% transparency was achieved, and also increase the radiation efficiency. As was mentioned earlier, having a deep understanding of the semiconductor physics involved here shifted the relationship between transmission and conductivity. Yasin and his team further discussed the efficiency dependence upon frequency. Based on their experimental results, efficiency increased linearly with increasing resonance frequency. This is because at higher frequencies the ratio of film thickness to skin depth is increased, which results in a higher conductivity.

2.2.3 Prefabricated substrate
Also on the market today are prepared substrates that include conductive films. AgHT, copper clad polyimide, and more obscure variants such as ITO clad polyimide and polyamide. This family of substrates is preprocessed in large quantities, which makes it more suitable for high volume manufacturing than the inkjet printing method for the manufacture of grid or mesh style antennas. As before, careful consideration for material properties must be taken to ensure good performance characteristics. While these AgHT films are readily available commercially, they do suffer performance degradation when compared with an ITO film. Yasin et al. in a different study showed that for a comparable surface resistance, the AgHT film had 15% lower transmission in the visible spectrum [8]. This sacrifice suggests that at comparable levels of transparency, the antenna constructed from AgHT will be around 20% less efficient than one constructed using ITO. It is important, however, to note that this may be acceptable for some applications. The design engineer should always consider limiting factors and in this case a device constructed from AgHT may represent a significant cost savings if the performance characteristics fall within the requirements.

3 Substrate Selection
In addition to the considerations given to the conducting media and geometric layout of the device, the substrate also plays a critical role in the performance of a transparent antenna. In selecting a substrate that is suitable for this application, other factors in addition to transparency should be considered, the first of which is durability. Questions that are important for the design engineer to consider with regard to durability are: What are the environmental conditions like? Will the device be exposed to solar radiation? Large temperature swings? Wet or humid
conditions? Repeated flexing and bending? Exposure to chemicals? The second question has to do with the electrical properties of a potential substrate, relative permittivity, and dielectric strength. The gain and efficiency of a patch antenna can be increased by selecting a substrate with a lower permittivity, preferably as close to 1 as possible. A more often used measure of dielectric strength is the loss tangent. This measures the angle in the complex plane of real and complex losses (ohmic losses and reactive losses). It must be noted, however, that loss tangent is a function of frequency as well. Therefore, the resonance frequency loss tangent for a given substrate should be specified. It is not unrealistic to expect the selection of substrates to expand in the near-term, especially as the market demands thinner, lighter, and more robust devices for the end user.

4 Case Study

A compact, low profile, optically transparent, and flexible printed monopole antenna is presented in this chapter as a case study. The antenna resonates at 2.45 GHz, which is suitable for WLAN and Bluetooth applications. The proposed antenna is based on a Kapton polyimide substrate, which is known for its flexibility, robustness, and thermal endurance. Printed monopole antennas are preferred over other antenna topologies due to their wide impedance bandwidth, fabrication simplicity, and omni-directional radiation pattern, which is highly desired in WLAN and Bluetooth technologies. To comply with wearable and flexible technologies, integrated structures must be highly flexible and mechanically robust; they also have to tolerate high levels in terms of bending and thermal endurance. Polyimide kapton was selected as the antenna’s substrate since it exhibits an excellent balance of physical, chemical, and electrical properties with a low loss tangent over a wide frequency range. Moreover, kapton is available with low thicknesses yet has a good tensile strength (165 MPa at 73°F), a dielectric strength of 3500–7000 volts/mil, and a thermal rating of 65 to 150°C [9] (Fig. 1).

4.1 Antenna design and fabrication

As depicted in Fig. 2, the antenna design consists of a U-shaped monopole. This type of winding promotes a compact antenna size without significant degradation of the efficiency or disturbance to the radiation pattern. It is worth noting that the same design but based on conductive nano-silver particles and fabricated using inkjet material printer was presented by the authors of this chapter in [3]. Dimensions of the monopole antenna in millimetre are provided in Table 1.

The separation between the arms is optimized as 6 mm, which achieves the best return loss. It should be noted that smaller separations lead to increased capacitive coupling between the arms, which leads to increased impedance mismatch [3]. The U-shaped monopole is fed by a 50 Ω microstrip line with a width of 1.5 mm. The antenna and microstrip line structure are printed on the same side of a 26.5 mm × 25 mm polyimide substrate. On the other side of the substrate, a
12.5 mm × 25 mm flexible copper ground plane is positioned below the microstrip line with a 1-mm separation distance, which is essential for achieving the required impedance. It should be noted that the electrical length of the U-shaped monopole in addition to the ground plane size controls the resonance frequency of the antenna.

This substrate (a 50.8-µm kapton with a dielectric constant of 3.4 and a loss tangent of 0.002) was applied with a single layer of ITO by means of a magnetron sputtering process. The sputtered film’s properties consisted of: a thickness of approximately 460 nm, a sheet resistivity of 10.4 Ω/□, and an average transmission in the visible range (400–750 nm) of 80.9%. Using a standard photolithography process, the pattern was transferred onto the coated kapton using a photosensitive film and etched in a solution of HCl, HNO₃, and DI water (Fig. 3).
Design and analysis of the transparent monopole antenna have been carried out using the full-wave simulation software CST Microwave Studio, which is based on the finite integration technique [10]. The antenna’s reflection coefficient is obtained using an Agilent FieldFox (N9923A) Vector Network Analyser with 2 MHz to 6 GHz frequency range. The simulated and measured return loss versus frequency for the monopole antenna is presented in Fig. 4. The simulated return loss for the antenna is 17 dB at 2.4 GHz, with a 10 dB bandwidth at 139 MHz. The measured return loss is 23.5 dB at 2.485 GHz with a 10 dB bandwidth at 123 MHz. The slight
shift in the resonance frequency can be attributed to fabrication discrepancies and effects of the SMA feed. However, the amount of shift is only 3% which has no tangible impact on the performance of the antenna since the intended impedance bandwidth (2.4–2.85 GHz) required for the Industrial, Scientific, Medical (ISM) band is achieved. E-plane and H-plane far-field radiation patterns in the polar form are shown in Fig. 5. It can be inferred from the graph that the total radiation power is omni-directional with a slight tilt and a gain of 1.72 dB at 2.45 GHz.

5 Conclusions

Overall, the transparent antenna field is growing. The number of applications is increasing and the technology used to implement the designs is advancing. Antennas are the foundational technology for anything wireless, and as the world moves in that direction it follows that design engineers must keep up with advancements. This represents research opportunities across many fields, including, chemistry, materials sciences, and engineering. Each of the methods of fabricating transparent antennas presented in this chapter shows promise in one or more of the fields of application. The future in this field looks exciting.

References


