An On-Glass Optically Transparent Monopole Antenna with Ultrawide Bandwidth for Solar Energy Harvesting

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Abstract: An on-glass optically transparent monopole antenna with ultrawide bandwidth is presented in this work, and the proposed antenna is of ring shape and coplanar waveguide fed structure. Optically transparent indium tin oxide (ITO) thin film with a thickness of ~160 nm is used as the conductive layer, which is sputtered on an optically transparent glass substrate. An impedance bandwidth of 6 GHz from 1 to 7 GHz is achieved, with a return loss lower than $-10\,\text{dB}$, meaning a fractional bandwidth of 150%. The proposed antenna exhibits reasonable radiations of omni-directionality in the H plane and bi-directionality in the E plane. Like other transparent antennas discussed in literature, the antenna gain is relatively low ($-4\,\text{dBi}$ at 5 GHz). In order to optimize the antenna performance, multi-film approach is proposed to reduce its sheet resistance, and the result shows that the antenna gain at 4 GHz can be improved from $-8\,\text{dBi}$ to $5\,\text{dBi}$ when optimizing the sheet resistance from $10\,\Omega/\text{sq}$ to $0.01\,\Omega/\text{sq}$. The designed antenna possesses a high optical transparency, which makes it easy to integrate to the surface of windows or display panels, and it can be applied for solar energy harvesting and many other ultra-wideband applications, with little chance of detection.

Keywords: optically transparent antenna; indium tin oxide (ITO); solar energy harvesting; ultrawide bandwidth

1. Introduction

Conventional microwave circuits and components are usually made of non-transparent materials, including the non-transparent substrates such as Rogers, and non-transparent conductors such as copper (Cu) or gold (Au). However, there are some drawbacks to these designs. For instance, these devices are relatively thicker and heavier, and also they are not suitable for applications requiring optical transparency, such as windows, display panels, and solar cells. Therefore, in recent years the microwave components designed with transparent and conductive thin films printed on transparent substrates have obtained great interest from researchers [1–4].

One of the mainly important applications of optically transparent antennas is their integration with solar cells on cube satellites (CubeSats) or even smaller satellites, where a major challenge is to mount solar cells, antennas, and other instruments in limited space. Therefore, optically transparent antennas are of great significance in small satellite applications for space saving, as it could be directly integrated on the surface of solar cells and other instruments. Other possible applications incorporate the integration of these transparent antennas with windows, display panels and car windshields. Research scientists from National Aeronautics and Space Administration (NASA) first proposed the idea of making transparent antennas using transparent thin films in 1997, for the sake of integrating microwave components more conveniently into automobiles and satellites [5]. Another example of using optically transparent antennas in solar applications is described in [2], where a reflectarray is...
proposed by using transparent and conductive films (TCFs). The most commonly used TCFs include fluorine-doped tin oxide (FTO), silver-coated polymer (AgHT), graphene, and indium tin oxide (ITO) [1,4,6]. Optically transparent devices possess the merits of low thickness, light weight, high optical transparency, and aesthetic value. The realization of optically transparent devices will solve many issues in military and civilian areas including solar energy harvesting applications, and they have been applied in filters, absorbers, antennas, reflectarrays and so on [1–4,7].

Since the unlicensed ultra-wideband (UWB) frequency spectrum (3.1–10.6 GHz) was released by the USA Federal Communications Commission (FCC) in 2002, much research has been focused on UWB wireless communications [8]. Transparent film based antennas with ultrawide bandwidth have been less adequately investigated, and this may be due to the difficulty of device fabrication, lossy nature and low efficiency of transparent materials [4,9]. Monopole antennas have received a lot of attention due to their good characteristics, such as ultrawide bandwidth, simple structure, and ease of fabrication [10–18]. In this work, we present a new type of ITO and glass based optically transparent monopole antenna with an extremely large fractional bandwidth. Furthermore, a multi-film approach is proposed and investigated for alleviating the low-gain issue of this antenna, with the result indicating that the antenna gain at 4 GHz can be improved from −8 dBi to 5 dBi when optimizing the sheet resistance from 10 Ω/sq to 0.01 Ω/sq. Because of the existence of optically transparent and tunable dielectrics, such as liquid crystals which can be tuned under external electric or magnetic fields [19,20], this work could promote the realization of reconfigurable antennas with both optical transparency and tunable properties by combining liquid crystals and TCFs.

2. Antenna Design and Configuration

The three-dimensional geometry of the proposed optically transparent antenna is shown in Figure 1. In order to achieve a high transparency, two optically transparent materials, the ITO material and glass, were used as the conductive layer and substrate, respectively. The 1.1-mm-thick easy access glass possessed extremely high transparency (greater than 95%), and its dielectric constant and dissipation factor were 5.5 and 0.001 at the working frequency band, respectively. ITO is a heavily doped n-type semiconductor with a high optical transparency, and it has a bandgap of 4 eV. ITO materials have been widely used in the display industry as transparent electrodes. There is a tradeoff between its optical transparency and the sheet resistance [21]. The optical transparency $T$ of ITO thin films is usually approximated by [22]:

$$T \approx e^{\frac{-2t}{\delta}}$$

where $\delta$ is the skin depth for visible spectrum, and $t$ is the ITO film thickness. The skin depth $\delta$ can be roughly expressed by [6,23]:

$$\delta \approx \sqrt{\frac{2}{\omega \mu_0 \sigma}}$$

where $\omega$ is the angular frequency of visible spectrum, $\mu_0$ is the free space permeability, and $\sigma$ is the ITO film electrical conductivity. The sheet resistance $R_{\text{sheet}}$ can be written as [23]:

$$R_{\text{sheet}} = \frac{\rho}{t} = \frac{1}{\sigma t}$$

where $\rho$ is the resistivity of ITO films. Equations (1) and (3) show the tradeoff between optical transparency and sheet resistance, illustrating that thinner ITO film results in higher optical transparency, but larger sheet resistance. Therefore, thin films with a smaller sheet resistance are usually obtained at the expense of losing a certain transparency. The sputtering technique is widely used in the production of thin films, whose properties are strongly dependent on the sputtering conditions [24]. A sputtering machine was be used in this process with sputtering targets in the available deposition chamber, hence one layer or multi-layer film could be synthesized in a single run without breaking vacuum. For the initial design, only ITO film was produced and sputtered on the glass substrate, and in the presence of masks, antenna structures with specific shapes could be
created. The sheet resistance of the fabricated ITO thin film was \( \sim 10 \, \Omega/\text{sq} \), and the corresponding film thickness was \( \sim 160 \, \text{nm} \). The proposed antenna was designed symmetrically, and it applied an ungrounded coplanar waveguide (CPW) fed structure. The center line width \( S \) and gap \( G \) of the feeding structure were optimized to perform a 50\( \Omega \) impedance matching, and the values were 2.8 mm and 0.35 mm, respectively. As monopole antennas have the merits of providing broadband performance, it is easy to cover the UWB frequency range with a good reflection, and by the joint optimization of other sizes in an intelligent High Frequency Structure Simulator (HFSS), the reflection loss and radiation patterns could be slightly improved further. Ultimately, the determined lengths were \( L_1 = 18.7 \, \text{mm} \), \( L_2 = 19.7 \, \text{mm} \), the radiator’s external diameter was \( D_{\text{out}} = 24.5 \, \text{mm} \), and its internal diameter was \( D_{\text{in}} = 10.5 \, \text{mm} \). Other parameters are listed as follows: \( W_1 = 50 \, \text{mm} \), \( W_3 = 3 \, \text{mm} \), \( W_4 = 2 \, \text{mm} \).

![Figure 1. Three-dimensional geometry of the proposed optically transparent antenna.](image)

3. Results and Discussion

The proposed antenna was designed and fabricated, and its photograph is illustrated in Figure 2. A type of silver conductive epoxy was used to mount the 50\( \Omega \) SMA connector to the antenna. In order to show the transparency feature and its practical application feasibility from the sense of sight, the proposed antenna was placed in different backgrounds and situations (Figure 2). It seems that in all of the four situations the proposed antenna was hard to find at first glance, and only when the antenna was in and next to the white background (Figure 2c), the shadow of the ITO structure might be observed, but it was very weak. In all cases, the coin placed under the transparent antenna could be seen clearly.
Antenna performance can be investigated in terms of return loss, radiation pattern and gain. Return loss $S_{11}$ is used to examine the impedance matching, and the measured $S_{11}$ is shown in Figure 3. Based on this figure, it is noticeable that the measured fractional bandwidths for $S_{11} < -10 \text{ dB}$ and $S_{11} < -5 \text{ dB}$ are 150% (1 GHz to 7 GHz) and 175.8% (1 GHz to 15.5 GHz), respectively. In addition, the achieved return loss is lower than $-15 \text{ dB}$ between 2.5 GHz and 6.5 GHz, which corresponds to a fractional bandwidth of 88.9%, and the return loss of $-15 \text{ dB}$ means that only 3% of the total incident power is reflected in the frequency band.
The radiation pattern of the transparent antenna at the frequency of 5 GHz and 7 GHz are presented in Figure 4. It is shown from the figure that the E plane radiation pattern of the antenna is bidirectional whereas the H plane radiation pattern is omnidirectional. Slight discrepancies between the simulated and measured radiation patterns can be observed, and as the frequency increases, the radiation pattern is distorted. This is because of the high-loss characteristics of ITO materials, hence the signal is relatively weak and antenna gain is low. Hence, the effect of the noise from the chamber and SMA port becomes more prominent in the measurement. Due to the high-loss nature of transparent materials, the realized gains of many transparent antennas are relatively low [3,25]. Figure 5 illustrates the measured gain of the ITO antenna at various frequencies. The measured gains at 4 GHz and 5 GHz are −7 dBi and −4 dBi, respectively. It is also shown that all gains are negative in the frequency band, and from 6 GHz to 10 GHz the gains have a slight decrease, which might be due to the weak signal caused measurement error and impedance mismatching in this frequency band. In addition, the efficiency remains relatively stable in the frequency band of interest, ranging from 15% to 25%.
Figure 4. Simulated and measured radiation patterns for (a) the E plane of 5 GHz, (b) E plane of 7 GHz, (c) H plane of 5 GHz, and (d) H plane of 7 GHz.

One possible approach to improve antenna performance is applying multi-film theory [23]. The multi-film approach can be used to reduce sheet resistance of thin films, and multi-layer films are simplified as a combination of each film coupled in parallel. The overall sheet resistance $R_{\text{total}}$ can be approximated by:

$$\frac{1}{R_{\text{total}}} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_n}$$

where $R_1$, $R_2$, and $R_n$ are sheet resistance of each single layer deposited on substrates. A preliminary experiment was carried out to verify the multi-film approach by sputtering copper on an ITO sample through the described sputtering machine. Copper, instead of gold, was applied to decrease the sheet resistance to a greater extent due to its higher electrical conductivity (5.9 $\times$ 10$^7$ $S/m$). Because of the very short time of copper sputtering, the thickness of copper film was expected to be only a few nanometers, and the transparency of the ITO/copper composite film was slightly reduced. The sheet resistance of composite film was measured by using a digital four-probe tester shown in Figure 6, and it can be seen that the sheet resistance was reduced to 2.732 $\Omega$/sq. With the copper sputtering, a decrease in device transparency similar to [6] will be found, and a worse transparency is expected if a thicker copper layer is applied for a better sheet resistance. In the next step, the relationship between sputtering conditions and optical transparency/thickness of fabricated films will be studied, and a more precise preparing of multi-layer films will be carried out. The effect of the sheet resistance of the conductive layer on the performance of this antenna was also
investigated. As can be seen from the results shown in Figure 7, the antenna gain at 4 GHz can be improved from $-8$ dBi to $5$ dBi when optimizing the sheet resistance from $10\ \Omega/sq$ to $0.01\ \Omega/sq$. At the sheet resistances of $2\ \Omega/sq$ and $2.732\ \Omega/sq$, the obtained antenna gains are $-0.2$ dBi and $-1.2$ dBi, respectively. Table 1 presents the corresponding gains at various frequencies for these sheet resistances, which are made up of ITO and copper films with different proportions. We can see from the table that the gain decreases slightly at high frequencies, which is due to worse impedance matching and weak signals, while it is noticeable that the gain becomes better at all frequencies when the film sheet resistance is smaller. As the repeatability and accurate thickness control of multi-layer films are not yet optimized at this point, the comparison and analysis of measured results will be carried out in a deeper level after the optimization of thin film preparation in the near future.

Figure 6. Sheet resistance of the ITO/copper composite film measured by a digital four-probe tester.

Figure 7. The E plane and H plane radiation patterns of the proposed antenna at 4 GHz when optimizing the sheet resistance $R_s$ of conductive layer.
Table 1. Gains at different sheet resistances under various frequencies.

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>2 GHz</th>
<th>4 GHz</th>
<th>8 GHz</th>
<th>14 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain (dBi) for $R_0 = 0.01$ Ω/sq</td>
<td>2.4</td>
<td>5</td>
<td>3.8</td>
<td>3.2</td>
</tr>
<tr>
<td>Gain (dBi) for $R_0 = 2$ Ω/sq</td>
<td>$-2.5$</td>
<td>$-0.2$</td>
<td>$-2.9$</td>
<td>$-4.9$</td>
</tr>
<tr>
<td>Gain (dBi) for $R_0 = 2.732$ Ω/sq</td>
<td>$-3.4$</td>
<td>$-1.2$</td>
<td>$-4.8$</td>
<td>$-6.9$</td>
</tr>
<tr>
<td>Gain (dBi) for $R_0 = 10$ Ω/sq</td>
<td>$-9.8$</td>
<td>$-8$</td>
<td>$-13.5$</td>
<td>$-14.7$</td>
</tr>
</tbody>
</table>

4. Conclusions

In this paper, an optically transparent CPW fed ring monopole antenna based on ITO thin film is presented. The proposed antenna possesses a ultrawide bandwidth of 6 GHz (fractional bandwidth of 150%) from 1 to 7 GHz with a return loss lower than $-10$ dB. The obtained E plane radiation pattern is bidirectional and the H plane radiation pattern is omnidirectional. In order to alleviate the common issue of relatively low gains for conductive thin film based transparent antennas, a multi-film approach is proposed and investigated, and the result shows that the antenna gain can be improved from $-8$ dBi to $-1.2$ dBi when optimizing the sheet resistance from $10$ Ω/sq to $2.732$ Ω/sq. The optimization of thin film preparation and the corresponding results will be presented in the near future. The proposed transparent antenna is expected to be used in solar energy harvesting and other communication and navigation applications, such as building windows, car windshields, display panels and CubeSat-like small satellites.

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References


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