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Microwave and Millimeter-Wave MIMO Antenna Using Conductive ITO Film

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ABSTRACT This paper will present a novel design of optically transparent multiple-input multiple-output (MIMO) antenna made by indium tin oxide (ITO) films. The MIMO antenna involves patch and monopole antenna elements at 4.9 GHz and 26 GHz respectively. The upper and lower surface of the MIMO antenna are covered by a thin film of glass substrate with conductive ITO coatings, while top layer is radiating elements and the bottom layers is ground planes. Both patch and monopole antennas are fed by transparent 50Ω transmission lines. The prototypes were fabricated by an in-house photolithography process. Measurements are carried out to confirm the simulation. The characteristics showed that the proposed MIMO antenna can be considered as a potential antenna for 5G smartphone communications applications.

INDEX TERMS Multiple-input multiple-output, indium tin oxide, patch, monopole, glass, 5G, smartphone.

I. INTRODUCTION

While we are at the dawn of the fifth generation (5G) wireless communications, its higher data transmission speed and lower latency for real-time interaction open up new opportunities for users. This performance will not only provide new video formats like 360-degree video, but also enhance new technologies such as robotics, autonomous driving, augmented or virtual reality interaction, and a tactile internet applications ranging from industry automation and transport systems, while it may benefit emergency communication, healthcare, education and gaming in smart city. In order to provide wireless communication channels which is high speed, reliable and secure for mobile users, the antenna design for mobile phones have been a challenging topic to support the new 5G frequency bands. Two frequency ranges, sub-6GHz and millimeter-wave frequencies are the most concerned and recommended by related professionals enhanced mobile broadband. Multiple-input multiple-output (MIMO) antennas have been demonstrated [1]–[6] to achieve higher data rate for the sub-6 GHz operation. Over the past decade, conventional antennas are made by metal as a radiator, which are mounted on the printed circuit board (PCB) [1]–[12] substrate. Many designs have been demonstrated using substrates at lower relative permittivity [13]–[16]. Wider bandwidth and higher efficiency have been achieved at the expense of substrate thickness. In [17], [18], the use of magnetodielectric material for antenna substrate has been proposed. Complex electric properties, relative permittivity and permeability with the dielectric loss tangent and magnetic loss tangent are characterized. Slot in metal frame mobile phone antennas [19]–[21] have been investigated. The capacitive coupling between the internal antenna and slot in metal frame can generate multiband antenna in the complex and heavy structures.

Recently, some researchers [22]–[26] have studied optical transparent antennas using a metal mesh structure which is placed on the transparent acrylic or glass for wireless applications. Unfortunately, the visible metal mesh structure is not suitable for mobile phone antenna-on-display (AoD). Highly transparent conductive indium tin oxide (ITO) [27]–[29] are investigated for mobile phone antenna. An ITO film is printed on the glass panel of smartphone to become an optically invisible AoD with the advantage of saving PCB and the proposed AoD is shown in Fig. 1.

In this paper, the proposed ITO MIMO antenna printed on a glass substrate, which is mimicking the display panel of a smartphone will be demonstrated for microwave
(from 4.8 GHz to 5 GHz) and millimeter-wave band (from 24.25 GHz to 27.5 GHz) simultaneously. Measurements have been carried out to verify the design. This paper will be presented as follows. Section II will describe ITO and glass characteristics in microwave band. Section III will introduce the geometry and provides the results of ITO patch, monopole, and MIMO antennas in microwave band. Section IV will present the ring resonator which has been studied for glass characteristic at 26 GHz, and Section IV will propose and present the performance of the geometry of an ITO patch and monopole antennas in millimeter-wave band, and a MIMO antenna with elements working in microwave and millimeter-wave band. Finally, a conclusion is given in Section V.

II. MATERIAL CHARACTERISTICS

A highly transparent conductive ITO supplied from Luoyang Guluo Glass Co., Ltd., China, was used as a conductive material for the proposed antenna. It is well known that thicker ITO film results in smaller sheet resistance, but lower optical transparency. For our designs, the transparency is about 84%. The sheet resistance, $R_s$ and thickness, $t$ of ITO transparent conductive films are $6\Omega/$sq and 185 nm, respectively. The electrical conductivity, $\sigma \sim 9 \times 10^5 \text{ S/m}$, was calculated based on

$$\sigma = \frac{1}{R_s \times t}$$

An ITO film is coated on a 1.1 mm thick glass substrate with a relative permittivity, $\varepsilon_r$ of 5.5 and loss tangent, $\tan \delta$ of 0.001 in microwave band. The glass panel was also provided by Luoyang Guluo Glass Co., Ltd.

III. ITO ANTENNA IN MICROWAVE BAND

A. ITO PATCH ANTENNA

Fig. 2 (a) shows the perspective view of a transparent ITO patch antenna (Ant1). The resonant length of patch is $\sim \lambda_e/2$, where $\lambda_e$ is effective wavelength. The top and bottom layers are radiating square patch and ground plane (GND) with edge length of 12.8 mm and 30 mm, respectively. The patch is fed by a 50 $\Omega$ transmission line. Both conductive layers are realized by ITO transparent conductive films.

The radiation characteristics of Ant1 are simulated with High Frequency Structure Simulator (HFSS). The parameters of $\sigma = 9 \times 10^5 \text{ S/m}$, $\varepsilon_r = 5.5$, and $\tan \delta = 0.001$ are used in the simulation. To verify the simulation results, a prototype of Ant1 at 4.9 GHz was fabricated by an in-house photolithography process. The ITO glass is covered with photosist by spin coating. After baking, the photosist is exposed to a pattern of intense UV light using a mask aligner, from SUSS MicroTec MA/BA 6. The exposed photosist is then washed away by the developer solution, leaving windows of the bare underlying ITO film, which is then etched away by hydrochloric acid. Finally, the remaining photosist is removed by acetone and the ITO pattern is formed after the etching process. Shown in Fig. 2 (b), a 3.5 mm jack Sub-Miniature version A (SMA) connector is used for measurement. Its reflection coefficient was measured by an Agilent PNA E8361A, whereas its antenna gain and radiation pattern were measured with a compact range antenna measurement system. Fig. 3 shows the measured and simulated reflection coefficients. It can be seen that Ant1 has a measured and simulated bandwidth of 4.3% (with reflection coefficient $\leq -10 \text{ dB}$) from 4.798 GHz to 5.01 GHz. The measured and simulated gains are also shown in Fig. 3. The maximum measured and simulated gains are 2.3 dBi and 2.6 dBi at 4.9 GHz, respectively. Fig. 4 depicts the measured and simulated radiation patterns of Ant1 at 4.9 GHz. The radiation patterns have broadside, symmetrical, low cross-polarized level, and low back radiation in the $\phi = 0^\circ$ and $90^\circ$ planes within the entire operating band.
B. ITO MONOPOLE ANTENNA

Fig. 5 (a) shows the perspective view of a transparent ITO monopole antenna (Ant2). The resonant length of monopole is $\sim 0.4 \lambda_e$. The top and bottom layers are a radiating square monopole with an edge length of 10.4 mm and a 30 mm $\times$ 8 mm rectangular GND, respectively. The monopole is fed by a 50 $\Omega$ transmission line.

The performances of Ant2 are simulated with HFSS, a prototype was fabricated as shown in Fig. 5 (b). Fig. 6 shows the measured and simulated reflection coefficients of Ant2, it achieves a wide impedance bandwidth. The measured and simulated gains are also shown in Fig. 6, which have an average gain of 2.2 dBi at $\theta = 60^\circ$ over the entire bandwidth. Fig. 7 displays the measured and simulated radiation patterns of Ant2 at 4.9 GHz. The co-polarized fields in $\phi = 0^\circ$ and $90^\circ$ planes are bi-directional and omni-directional, respectively, which are also symmetrical. The cross-polarized field at $\phi = 90^\circ$ plane is a four-leaf clover shaped pattern and the difference between co-polarized and cross-polarized levels is larger than 15 dB.

C. ITO MIMO ANTENNA

Parametric study is carried out for the separation between Ant1 and Ant2 using HFSS on a rectangular glass substrate with length 150 mm and width 70 mm which is the size of a typical smartphone display. Fig. 8 shows the top view of transparent ITO MIMO antenna (Ant1 and Ant2). The patch and monopole are on the top of the glass while the antenna GNDs are at the bottom of the glass.

The S-parameter and gains of transparent ITO MIMO antenna are studied in three cases. For Case 1, the position of Ant2 remains unchanged and the distance between Ant1 and Ant2, $d_1$ is varied along y direction and vice versa for Case 2. For Case 3, the positions of Ant1 and Ant2 are
changed simultaneously by reducing $d_1$. Ant1 and Ant2 are denoted as Port 1 and Port 2, respectively. Fig. 9 illustrates $S_{12}$ gain against $d_1/\lambda_0$. $S_{12}$ decreases from $-23$ dB to $-36$ dB and Ant2 gain increases from $-11.78$ dBi to $1.28$ dBi monotonically with $d_1$ for the three cases, respectively. The lowest $S_{12}$ and highest Ant2 gain are obtained when $d_1/\lambda_0 = 1.47$ at $f_0 = 4.9$ GHz and the structure is shown in Fig. 8. It is noted that $S_{11}$, $S_{22}$, and Ant1 gain are stable when moving Ant1 or/and Ant2 for the three cases and the results are omitted in Fig. 9.

A prototype of transparent ITO MIMO antenna with two antennas was fabricated as shown in Fig. 10. Fig. 11 shows the measured and simulated S-parameters of the transparent ITO MIMO antenna. Similar responses of $S_{11}$ and $S_{22}$ are obtained when comparing to each single element. It can be seen that Ant1 has a measured bandwidth of 5.6% (with $S_{11} \leq -10$ dB) from 4.776 GHz to 5.052 GHz. Ant2 also achieves a wide impedance bandwidth (with $S_{22} \leq -10$ dB) across the entire operating band. Good measured isolation between two ports below $S_{12} = -32$ dB is obtained. The measured and simulated gains are shown in Fig. 12, both Ant1 and Ant2 measured gains have 1 dBi for both ports at 4.9 GHz. Fig. 13 displays the measured and simulated radiation patterns of Ant1 and Ant2. The broadside and low back radiation are obtained in Fig. 13 (a) and co-polarized field in $\phi = 90^\circ$ plane has 1 dBi at $\theta = 60^\circ$ in Fig. 13 (b).

### FIGURE 9. Simulated $S_{12}$ and Ant2 gain against $d_1/\lambda_0$ of transparent ITO MIMO antenna.

![Simulated $S_{12}$ and Ant2 gain against $d_1/\lambda_0$ of transparent ITO MIMO antenna.](image)

### FIGURE 10. A prototype of transparent ITO MIMO antenna at 4.9 GHz.

![A prototype of transparent ITO MIMO antenna at 4.9 GHz.](image)

### FIGURE 11. Measured and simulated S-parameters of transparent ITO MIMO antenna.

![Measured and simulated S-parameters of transparent ITO MIMO antenna.](image)

### FIGURE 12. Measured and simulated gains of transparent ITO MIMO antenna.

![Measured and simulated gains of transparent ITO MIMO antenna.](image)

### FIGURE 13. Measured and simulated radiation patterns of transparent ITO MIMO antenna at 4.9 GHz (a) port 1 (b) port 2.

![Measured and simulated radiation patterns of transparent ITO MIMO antenna at 4.9 GHz (a) port 1 (b) port 2.](image)

## IV. ITO ANTENNA IN MICROWAVE AND MILLIMETER-WAVE BAND

In the previous section, it has been successfully demonstrated that applying ITO patch and monopole antennas
for MIMO operation at microwave band (from 4.8 GHz to 5GHz). In this section, the ITO MIMO antenna is applied in microwave (from 4.8 GHz to 5GHz) and millimeter-wave (from 24.25 GHz to 27.5 GHz) bands design.

A. MILLIMETER-WAVE CHARACTERIZATION OF GLASS SUBSTRATE

The dielectric characteristics of glass substrate are studied in millimeter-wave band. The most precise methods for determining characteristics of the substrate are the resonator-based methods, including parallel-plate resonators, microstrip ring resonators, and cavity resonators. The parallel-plate resonator method is usually applied in the microwave band. For millimeter-wave band, the microstrip ring resonator method is investigated for the dielectric characteristics of the glass substrate.

**FIGURE 14.** Prototype of transparent ITO ring resonator and measured $S_{21}$ of transparent ITO ring resonator.

Fig. 14 shows the prototype of a transparent ITO ring resonator. The top and bottom layers are an ITO ring with two microstrip lines and a square GND with each side 15 mm in length, respectively. Two pieces of 2.92 jack SMA connectors are used for the measurement which is performed using an Agilent PNA E8361A. The ring resonator produces $S_{21}$ with frequency resonance at 26 GHz and is shown in Fig. 14. A peak position and $-3$dB bandwidth at the resonant frequency from measured $S_{21}$ are used to calculate $\varepsilon_r$ and $\tan \delta$ from equations (2) to (8). $\varepsilon_r$ can be extracted from the effective relative permittivity, $\varepsilon_{\text{eff}}$ and the dimensions of the ring resonator [30] by using (2) below:

$$\varepsilon_r = \frac{2 \times \varepsilon_{\text{eff}} + M - 1}{M + 1}$$

$\varepsilon_{\text{eff}}$ is a function of the ITO ring radius, $r_m$, the resonant frequency $f_0$ obtained from measurement of the insertion loss, $L_A$, and the speed of light in vacuum, $c$. It is defined in (3) as:

$$\varepsilon_{\text{eff}} = \left( \frac{c}{2 \times \pi \times r_m \times f_0} \right)^2$$

$M$ in (2) is a function of the thicknesses of the glass, $h$ and that of the ITO ring, $t$, as shown in (4).

$$M = \left( 1 + \frac{12 \times h}{w_{\text{eff}}} \right)^2$$

**FIGURE 15.** Perspective view and prototype of Ant3.

**FIGURE 16.** Measured and simulated reflection coefficients and gains of Ant3.

**FIGURE 17.** Measured and simulated radiation patterns of Ant3 at 26 GHz.

$w_{\text{eff}}$ in (4) is the effective ITO ring width and is given as follows:

$$w_{\text{eff}} = w + \frac{1.25 \times t}{\pi} \left[ 1 + \ln \left( \frac{2h}{t} \right) \right]$$

where $w$ is the width of the ITO ring.

The loss tangent is computed using (6) as follows:

$$\tan \delta = \frac{\alpha \times \lambda_0 \times \sqrt{\varepsilon_{\text{eff}}} \left( \varepsilon_r - 1 \right)}{8.686 \times \pi \times \varepsilon_r \left( \varepsilon_{\text{eff}} - 1 \right)}$$
TABLE 1. Ring dimensions, measured parameters from $S_{21}$, and calculated dielectric characteristics at 26 GHz.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>$r_m$ (mm)</th>
<th>$w$ (mm)</th>
<th>$f_s$ (GHz)</th>
<th>BW $-3$dB (GHz)</th>
<th>$L_A$ (dBi)</th>
<th>$\varepsilon_r$</th>
<th>tan $\delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values</td>
<td>0.965</td>
<td>0.5</td>
<td>26</td>
<td>0.72</td>
<td>36.21</td>
<td>5.4</td>
<td>0.0035</td>
</tr>
</tbody>
</table>

where $\lambda_0$ is the free-space wavelength and the attenuation, $\alpha$ is obtained from its unloaded quality factor, $Q_0$ given in (7).

$$\alpha = \frac{\pi}{Q_0 \lambda_{\text{eff}}}$$ (7)

where $\lambda_{\text{eff}}$ is the effective wavelength and $Q_0$ is obtained from the insertion loss, $L_A$ and the $-3$dB bandwidth, $\text{BW}_{-3dB}$ measured at $f_0$ using (8) below:

$$Q_0 = \frac{f_0}{\text{BW}_{-3dB} \times \left(1 - 10^{-\frac{L_A}{20}}\right)}$$ (8)

Designed ring dimensions, measured parameters from $S_{21}$, and calculated dielectric characteristics are listed in Table 1.

B. MILLIMETER-WAVE ITO PATCH ANTENNA

Fig. 15 (a) shows the perspective view of a transparent ITO patch antenna (Ant3) at 26 GHz. The top and bottom layers of Ant3 are radiating square patch and GND with an edge length of 2.2 mm and 10 mm, respectively. The radiation characteristics of Ant3 are simulated with HFSS using $\varepsilon_r = 5.4$ and tan $\delta = 0.0035$ of glass substrate.

A prototype of Ant3, shown in Fig. 15 (b), was fabricated with a 2.92 mm jack SMA connector. Fig. 16 shows the measured and simulated reflection coefficients. It can be seen...
that Ant3 has measured and simulated bandwidths of 22% from 22.7 GHz to 28.3 GHz and 25% from 22.2 GHz to 28.55 GHz, respectively. The measured and simulated gains of Ant3 are 3.9 dBi and 4.4 dBi at 26 GHz, respectively, as shown in Fig. 16. Fig. 17 depicts the measured and simulated radiation patterns of Ant3 at 26 GHz. The broadside radiation patterns are obtained within the entire operating band.

C. MILLIMETER-WAVE ITO MONPOLE ANTENNA

Fig. 18 (a) shows the perspective view of a transparent ITO square monopole antenna (Ant4) at 26 GHz. The top and bottom layers of Ant4 are a radiating square monopole with an edge length of 1.9 mm and a 10 mm × 3.2 mm rectangular GND, respectively. The radiation characteristics of Ant4 are simulated with HFSS using $\varepsilon_r = 5.4$ and $\tan \delta = 0.0035$ of glass substrate.

A prototype of Ant4, shown in Fig. 18 (b), was fabricated with a 2.92 mm jack SMA connector. Fig. 19 shows the measured and simulated reflection coefficients of Ant4 and it achieves a wide impedance bandwidth. The measured and simulated gains of Ant4 are also shown in Fig. 19, which have measured and simulated gains of 3.7 dBi and 4.2 dBi at $\theta = 80^\circ$ and 26 GHz. Fig. 20 displays the measured and simulated radiation patterns of Ant4 at 26 GHz. The co-polarized fields in $\phi = 90^\circ$ plane is conical and symmetrical.

D. MICROWAVE AND MILLIMETER-WAVE ITO MIMO ANTENNA

Fig. 21 shows the top view of a transparent ITO MIMO antenna (Ant1, Ant2, Ant3, and Ant4). The patches

![Figure 23. A prototype of transparent ITO MIMO antenna at 4.9 and 26 GHz.]

![Figure 24. Measured and simulated S-parameters of transparent ITO MIMO antenna at 4.9 and 26 GHz.]

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operating at 4.9 GHz (Ant1), 26 GHz (Ant3) and monopoles operating at 4.9 GHz (Ant2), 26 GHz (Ant4) are on the top of the glass while the GNDs of the patch and monopole antennas are at the bottom of the glass. Parametric study is performed for the separation, $d_2$ between Ant3 and Ant4.

The S-parameters and gains of transparent ITO MIMO antenna are studied in three cases. For Case 1, the position of Ant4 remains unchanged and distance between Ant3 and Ant4, $d_2$ is varied along y direction and vice versa for Case 2. For Case 3, the positions of Ant3 and Ant4 are changed simultaneously by reducing $d_2$. The feeds of Ant1, Ant2, Ant3, and Ant4 are denoted as Ports 1, 2, 3, and 4, respectively. Fig. 22 demonstrates $S_{34}$ and Ant4 gain against $d_2/\lambda_0$.

In general, $S_{34}$ decreases from $-20$ dB to $-46$ dB and Ant4 gain increases from $-10.2$ dBi to $2.4$ dBi with $d_2/\lambda_0$ for the three cases, respectively. The lowest $S_{34}$ and the highest Ant4 gain are obtained when $d_2/\lambda_0 = 11.27$ at $f_0 = 26$ GHz and the structure is shown in Fig. 21. It is noted that other S-parameters and gains are stable when moving the Ant3 or/and Ant4 for the three cases and the results are omitted in the Fig. 22.

A prototype of the transparent ITO MIMO antenna with four antennas was fabricated. Two pieces of 3.5 jack and two pieces of 2.92 jack SMA connectors are used for measurement and are shown in Fig. 23. Fig. 24 shows the measured and simulated S-parameters of transparent ITO MIMO antenna with four antennas. Similar responses of $S_{11}$, $S_{22}$, $S_{33}$, and $S_{44}$ are obtained when comparing to the responses of each single element. From Fig. 24 (a) and (c), Ant1 and Ant3 have a measured bandwidth of 5.1% from 4.788 GHz to 5.038 GHz and 22% from 22.59 GHz to 28.32 GHz, respectively. Shown in Fig. 24 (b) and (d), Ant2 and Ant4 also achieve a wide impedance bandwidth across the entire operating band. $S_{12}$ and $S_{34}$ are equal to $S_{21}$ in Fig. 24 (a) and $S_{13}$ in Fig. 24 (c), respectively, and $S_{12}$ and $S_{34}$ are omitted in Fig. 24 (b) and 24 (d), respectively. Measured isolation between all ports are below $-35$ dB. The measured and simulated gains for four antennas are shown in Fig. 25, the measured antenna gains at 4.9 GHz in Fig. 25 (a) and 26 GHz in Fig. 25 (b) are around 1 dBi and 2 dBi, respectively. Fig. 26 displays the measured and simulated radiation patterns of Ant1, Ant2, Ant3, and Ant4. Broadside and low back radiation patterns are obtained in Fig. 26 (a) and (c). The co-polarized field in $\phi = 90^\circ$ plane of Fig. 26 (b) and (d) are 1 dBi and 2 dBi at $\theta = 60^\circ$ and 80$^\circ$, respectively. Finally, Table 2 lists the radiation characteristics of proposed and referenced [27] and [28] antennas reported ITO antennas.
TABLE 2. Comparison between the antenna and referenced antenna.

<table>
<thead>
<tr>
<th>Antenna</th>
<th>Type(s)</th>
<th>Pattern</th>
<th>Gain (dBi)</th>
<th>Frequency (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>This paper</td>
<td>Patch &amp;</td>
<td>Broadside &amp; conical</td>
<td>2</td>
<td>4.9 &amp; 26</td>
</tr>
<tr>
<td></td>
<td>monopole</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[27]</td>
<td>Patch</td>
<td>Broadside</td>
<td>7</td>
<td>28</td>
</tr>
<tr>
<td>[28]</td>
<td>Patch</td>
<td>Broadside</td>
<td>6</td>
<td>28 &amp; 39</td>
</tr>
</tbody>
</table>

This paper has studied the patch and monopole locating on the display, and then the broadside and conical radiation patterns can be obtained. References [27] and [28] are fed by probe with Rogers RT5880 and fed by microstrip line with stack patch, respectively. Although the gain is only 2 dBi, a simple structure with stripline feed method in the proposed one. It is noted that this is the first paper for demonstrating in ITO antenna at the microwave and millimeter-wave bands.

V. CONCLUSION

A novel design of optically transparent MIMO antenna made of conductive ITO films for microwave and millimeter-wave band is proposed. The single element of ITO patch and monopole antennas at 4.9 and 26 GHz are studied. The ITO MIMO antenna with two (4.9 GHz) and four elements (4.9 and 26 GHz) printed on the 150 mm × 70 mm rectangular glass substrate is investigated. The prototypes were fabricated by an in-house photolithography process. Measured results agree with the simulated results very well. The proposed MIMO antenna has potential applications in 5G smartphone.

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