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A Transparent Proximity-Coupled-Fed Patch Antenna With Enhanced Bandwidth and Filtering Response

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ABSTRACT

This paper introduces a novel transparent proximity-coupled-fed patch antenna with enhanced impedance bandwidth and good filtering response. The proposed antenna consists of a ground plane, a specific feeding structure and a slotted patch. All the conducting surfaces are realized with metal meshes printed on glass substrates. Optical transparency of the antenna depends on the mesh density. The feed line of a traditional proximity-coupled-fed patch antenna is terminated with a driven stub etched with a half-wavelength U-shaped slot. This modification introduces an additional resonant mode but also a radiating null. By further etching a pair of quarter-wavelength open slots on the radiating patch, another resonant mode accompanied with an extra radiation null is generated. Finally, three resonant modes within the operating band along with two radiation nulls near the two edges of the passband are achieved. The proposed antenna is implemented to demonstrate an impedance bandwidth of 7.6\% from 3.41 to 3.68 GHz and a maximum gain of 4.6 dBi.

INDEX TERMS

Transparent antenna, filtering antenna, proximity-coupled-fed, bandwidth enhancement, metal mesh structure.

I. INTRODUCTION

In recent years, optical transparent antennas are gaining increasing attention in both the academia and industry due to their see-through characteristic. Since they can be seamlessly attached to automotive windshields, solar panels, display panels, building windows as well as indoor ceilings and walls, they present great potential for applications in satellite communications, mobile communications and indoor wireless communications.

One common approach to design transparent antenna is the use of the transparent conducting oxides (TCOs) such as indium tin oxide (ITO) \cite{1}, \cite{2} and silver-coated polyester (AgHT) films \cite{3}, \cite{4}. However, these films always suffer from high sheet resistance subject to their intrinsic characteristic. To further lower the sheet resistance, multilayered films (MLFs) combining TCO and metal are used. They include but not limited to Cu/ITO \cite{5}, ITO/Cu/ITO \cite{1}, \cite{6}, and IZTO/Ag/IZTO \cite{7}, (indium-zinc-tin oxide). Nevertheless, the aforesaid films usually exhibit thin thickness, which makes them basically inappropriate for design of microstrip antennas due to the large skin depth loss \cite{8}.

An alternative method is to use metal mesh structures \cite{9}–\cite{13}. It can achieve good balance between the transparency and conductivity by means of controlling the size of the meshes. By selecting appropriate thickness of the metal, skin depth loss can be greatly alleviated. However, these antennas still suffer limited bandwidth or high profile. On the other hand, research on the integration of antenna and filter is also gaining increasing popularity in recent years \cite{14}–\cite{19}. Such integration, coined the term filtering antenna, can make the RF (radio frequency) front end more compact and highly efficient as the filter together with the connection part can be removed.

In this paper, we propose and investigate a novel transparent proximity-coupled-fed antenna with enhanced bandwidth as well as good filtering response. To the authors’ best knowledge, it is the first time that a whole-structure-see-through
filtering antenna without cascading any filtering circuit has been presented. By utilizing well-designed feeding structure and slotted patch, three resonant modes along with two radiation nulls are obtained. Glass substrates and metal mesh structure are employed to realize good light transmittance. The proposed antenna features threefold advantage of enhanced impedance bandwidth, good filtering response and good optical transparency compared to the traditional proximity-coupled-fed patch antenna.

II. ANTENNA STRUCTURE AND WORKING MECHANISM

A. ANTENNA STRUCTURE

Although a few filtering antennas [14]–[19] have been reported in recent years, they either suffer from complicated structure or requirement of drilling and soldering. Note that for PCB (printed-circuit-board) technology, their fabrications may not be a problem. However, for transparent antenna especially designed on glass substrate, one hopes that the antenna structure should be as simple as possible. Besides, drilling and soldering should also be avoided due to the fragile characteristic of the glass as well as for aesthetic consideration. Featuring no requirement of drilling and intact ground plane, the transparent proximity-coupled-fed patch antenna is undoubtedly a good candidate to be attached to indoor ceilings and walls for indoor wireless communications or on windshields of vehicles for vehicle-to-vehicle communications. Our target is to realize a novel transparent proximity-coupled-fed patch antenna with improved bandwidth and good filtering response.

The geometry of the proposed filtering antenna structure is depicted in Fig. 1, while its dimensions are listed in Table 1. The antenna is realized using two glass substrates with a thickness \( h = 1.1 \, \text{mm} \), dielectric constant \( \varepsilon_r = 5.5 \), and loss-tangent \( \delta = 0.005 \). Silver mesh with physical parameters of strip gap \( s = 120 \, \mu\text{m} \), strip width \( w = 20 \, \mu\text{m} \), and strip thickness \( t = 5.5 \, \mu\text{m} \) is utilized to implement the metal part of the antenna. This choice is a good tradeoff between optical transparency and antenna efficiency. The sheet resistance can be calculated as \( 0.02 \, \text{ohm/square} \) [13].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>( P_w )</th>
<th>( P_t )</th>
<th>( S_w )</th>
<th>( S_t )</th>
<th>( S_{w2} )</th>
<th>( T_w )</th>
<th>( T_t )</th>
<th>( U_{w1} )</th>
<th>( U_{w2} )</th>
<th>( U_{t2} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>20.46</td>
<td>16.82</td>
<td>0.82</td>
<td>8.07</td>
<td>11.22</td>
<td>5.34</td>
<td>10.94</td>
<td>0.54</td>
<td>0.96</td>
<td>8.39</td>
</tr>
<tr>
<td>Parameter</td>
<td>( U_{t2} )</td>
<td>( U_{t0} )</td>
<td>( M_w )</td>
<td>( M_t )</td>
<td>( M_{w2} )</td>
<td>( F_w )</td>
<td>( F_{w2} )</td>
<td>( F_t )</td>
<td>( G_w )</td>
<td>( G_t )</td>
</tr>
<tr>
<td>Value</td>
<td>3.06</td>
<td>1.42</td>
<td>0.86</td>
<td>2.94</td>
<td>3.06</td>
<td>1.76</td>
<td>0.58</td>
<td>9.8</td>
<td>10.56</td>
<td>4.9</td>
</tr>
</tbody>
</table>

Performances of the four designs are depicted in Fig. 3. As seen, for the glass substrates we use, the bandwidth of the traditional proximity-coupled patch antenna is limited as only one resonant mode is achieved with slow roll off of the antenna gain, showing little filtering response. After introducing the driven stub along with the U-shaped slot, an extra resonant mode together with a radiation null at the lower band \( (f_{L}, f_{\text{Null1}}) \) is brought in. Furthermore, by etching a pair of slots in the radiating patch, another resonant mode and radiation null at the higher band \( (f_{H}, f_{\text{Null2}}) \) are introduced. Finally, in Design IV, by adding a matching stub in the feeding line, better impedance matching is obtained.
1) ANALYSIS OF RESONANT MODES AND RADIATION NULLS

To gain more insight into the generation of extra resonant modes and radiation nulls, Designs I, II and III have been investigated from the input impedance’s point of view. Their input impedances ($Z_{in}$) are depicted in Fig. 4. Comparing Design I and Design II, it can be observed that a new peak at the lower band shows up. Consequently, an extra resonant mode shows up at frequency $f_L$, where the imaginary part of $Z_{in}$ is zero, while the real part roughly equals to 50 $\Omega$. At frequency $f_{Null\,1}$, $Z_{in}$ approaches to zero, thus generating a radiation null. For Design III, an extra peak appears at the higher band. Similarly, this not only introduces a radiation null at frequency $f_{Null\,2}$, where $Z_{in}$ approaches to infinity, but also adds an additional resonant mode at frequency $f_H$. As seen, the generation principles of the radiation nulls are actually quite different. However, they are in common that large impedance mismatch is caused, leading to little radiation.

Current distributions have also been explored to have intuitive sense of the working mechanism. Fig. 5 depicts the current distribution on the feeding stub and radiating patch of the final design (Design IV) at three resonant frequencies. It can be concluded that these three resonant modes are respectively produced by the driven stub, the fundamental mode and higher-order mode of the patch. Although the length of the driven stub is short, due to the U-shaped slot etched on the stub, its effective length is far longer than the physical length. In other word, it can be regarded as a meandering stub. From Fig. 5(a), we observe that the driven stub works in half wavelength. The fundamental mode of the patch is TM$_{10}$ mode, while the higher-order mode can be regarded as modified TM$_{12}$ mode. Normally, TM$_{12}$ mode cannot well radiate because of the transverse ($y$-direction) opposite currents. However, in the proposed antenna, these currents can be cut off by the slot as shown in Fig. 5(c). Note that despite a small part of currents are still reversely oriented on the patch, most of the currents travel along the...
same direction, giving rise to good radiation. Fig. 6 presents the current distributions on the feeding stub and radiating patch at two radiation null frequencies. As seen, at lower radiation null frequency \((f_{\text{Null} 1})\), the energy concentrates between the patch and stub, and the induced currents have reversed directions. While for the upper radiation null case \((f_{\text{Null} 2})\), the energy is attracted to the vicinity of the open slots. Similarly, the induced currents are oppositely oriented. Consequently, at these two frequencies, the radiations due to the induced currents would counteract each other, resulting in two radiation nulls.

2) PARAMETERS STUDY
Study on some key parameters has been carried out to gain deeper understanding of the working principle of the proposed filtering antenna. The performance of Design IV with different lengths of U-shaped slot and driven stub is illustrated in Fig. 7. It can be observed that as the lengths of U-shaped slot and driven stub increase, the lower resonant mode along with the radiation null will move toward the lower frequencies. Thus, one can know that the driven stub etched with a U-shaped slot plays an important role in controlling the frequency of the lower resonant mode and radiation null. The influence of the length and position of the open slot in the radiating patch is also investigated as shown in Fig. 8. We can see that the upper resonant mode and radiation null are dominated by the length of the open slot, while the position has minor effect on them. Another key parameter of the proposed antenna is the length of the radiating patch, and its effect is shown in Fig. 9. As seen, it mainly controls the middle resonant mode as well as the suppression level at stopband.

3) DESIGN GUIDELINE
According to the analysis above, a design guideline for the proposed transparent filtering antenna is recommended as follows:

1) Design a traditional proximity-coupled-fed patch antenna on the glass substrates.
2) Modify the end of feeding line as a driven stub etched with a half-wavelength U-shaped slot at the desired frequency.
3) Etch a pair of quarter-wavelength open slots on the radiating patch at another desired frequency.

4) Add a matching stub in the feeding line and have a minor tuning of the key physical parameters to obtain excellent impedance matching and good filtering response.

III. EXPERIMENTS

A. FABRICATION PROCESS
In this work, standard photolithography and lift-off process are employed to fabricate the designed transparent filtering antenna. The fabrication process shown in Fig. 10 is described as follows: Firstly, photoresist \(\text{AZ-R@nLOF 2070}\) is spin-coated onto the glass substrate and cured on a hot-plate at 110° C. Then antenna pattern window is fabricated on the photoresist by photolithography followed by standard developing process. Prior to the silver deposition, a \(\sim 10\)-nm Nickel layer was deposited to improve the adhesion of silver to the glass substrate. Then a \(\sim 5.5\)-um silver is deposited on the sample by thermal evaporation. Finally, the antenna structure is achieved by a lift-off procedure, and the two-glass substrates were aligned under a microscope and bonded by an UV-curable adhesive.

B. EXPERIMENTAL RESULTS AND DISCUSSION
The fabrication prototype of the proposed transparent filtering antenna placed on top of a piece of writing is
FIGURE 8. Performance of the proposed filtering antenna (Design IV) with different combination of length and position of the open slot. (a) Input impedance. (b) Reflection coefficient and realized gain.

FIGURE 9. Performance of the proposed filtering antenna (Design IV) versus different length of the radiating patch. (a) Input impedance. (b) Reflection coefficient and realized gain.

FIGURE 10. Fabrication process of the proposed transparent filtering antenna.


FIGURE 11. As shown, the writing can be read clearly. Silver paste for electric connection and adhesive for fixation were utilized to combine the antenna and SMA connector. The S-parameters were acquired by using an Agilent E8361A Network Analyzer, while the radiation performance was measured by a SATIMO system. Fig. 12 depicts the reflection coefficient as well as the gain of the proposed antenna. The measured \(-10\)-dB impedance bandwidth is 7.6%, covering 3.41 GHz to 3.68 GHz, compared to the simulated one, 8.5% (3.36 GHz to 3.66 GHz). The measured maximum antenna gain is 4.6 dBi, while the simulated one is 5.4 dBi. In addition, the proposed antenna experiences sharp roll-off outside the operating band. A suppression level of above 10 dB is achieved at two sides of the passband. The discrepancy between the simulation and measurement is attributed to the fabrication error as well as the assembly error of minor air gap inevitably existing between the two glass substrates. The radiation patterns of the antenna are presented in Fig. 13. It exhibits low cross-polarization level in addition to good front-to-back ratio.

The antenna efficiencies of the proposed filtering antenna realized with PEC (Perfect Electric Conductor), metal mesh and CTO with sheet resistance of 1 ohm/square are shown in Fig. 14. As seen, in the simulation, only around 5% drop is recorded between the mesh case and PEC case. For the CTO case, the efficiency is considerably low, indicating that normal CTO suffers limited applications. The measured efficiency for the proposed transparent filtering antenna at 3.55 GHz reaches 70%.

The optical transparency of the ground region of the proposed antenna was measured with a UV 1800 from Shimadzu Schweiz GmbH. 60% of optical transparency is obtained over
FIGURE 11. Fabricated prototype of the proposed transparent filtering antenna.

FIGURE 12. Measured and simulated performances of the proposed transparent filtering antenna. (a) Reflection coefficient. (b) Realized gain.

FIGURE 13. Measured and simulated radiation patterns of the proposed transparent filtering antenna at center frequency (3.55 GHz).

FIGURE 14. Measured and simulated antenna efficiencies of the proposed transparent filtering antenna realized with different conductive films.

TABLE 2. Comparison among reported and proposed transparent/filtering patch antenna.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Feed Type</th>
<th>Filtering Response</th>
<th>OT</th>
<th>Freq. (GHz)</th>
<th>Imp. BW</th>
<th>Profile ((\phi_c))</th>
<th>FOM</th>
</tr>
</thead>
<tbody>
<tr>
<td>[9]</td>
<td>Proximity coupled</td>
<td>No</td>
<td>Yes</td>
<td>2.45</td>
<td>2.66%</td>
<td>0.012</td>
<td>2.22</td>
</tr>
<tr>
<td>[10]</td>
<td>Direct</td>
<td>No</td>
<td>Yes</td>
<td>2.4</td>
<td>~30%</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>[11]</td>
<td>Direct</td>
<td>No</td>
<td>Yes</td>
<td>2.45</td>
<td>N.A.</td>
<td>0.01</td>
<td>N.A.</td>
</tr>
<tr>
<td>[12]</td>
<td>Direct</td>
<td>No</td>
<td>Yes</td>
<td>27</td>
<td>2.34%</td>
<td>0.076</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>27.5</td>
<td>11.4%</td>
<td>0.077</td>
<td>1.48</td>
</tr>
<tr>
<td>[13]</td>
<td>Probe</td>
<td>No</td>
<td>Yes</td>
<td>0.62</td>
<td>54.5%</td>
<td>0.133</td>
<td>4.10</td>
</tr>
<tr>
<td>[14]</td>
<td>Probe</td>
<td>Yes</td>
<td>No</td>
<td>2.5</td>
<td>19.6%</td>
<td>0.09</td>
<td>2.18</td>
</tr>
<tr>
<td>[15]</td>
<td>Probe</td>
<td>Yes</td>
<td>No</td>
<td>5.24</td>
<td>7%</td>
<td>0.03</td>
<td>2.33</td>
</tr>
<tr>
<td>[16]</td>
<td>Probe</td>
<td>Yes</td>
<td>No</td>
<td>3.4</td>
<td>23.5%</td>
<td>0.096</td>
<td>2.45</td>
</tr>
<tr>
<td>[17]</td>
<td>Probe</td>
<td>Yes</td>
<td>No</td>
<td>2.31</td>
<td>21.3%</td>
<td>0.1</td>
<td>2.13</td>
</tr>
<tr>
<td>[18]</td>
<td>Probe</td>
<td>Yes</td>
<td>No</td>
<td>5.44</td>
<td>22.6%</td>
<td>0.098</td>
<td>2.31</td>
</tr>
<tr>
<td>[19]</td>
<td>Probe</td>
<td>Yes</td>
<td>No</td>
<td>2</td>
<td>7%</td>
<td>0.03</td>
<td>2.33</td>
</tr>
<tr>
<td>Pro.</td>
<td>Proximity coupled</td>
<td>Yes</td>
<td>Yes</td>
<td>3.55</td>
<td>7.6%</td>
<td>0.026</td>
<td>2.92</td>
</tr>
</tbody>
</table>

\(\phi_c\): Free space wavelength at center frequency; OT: Optically transparent; \(^*\): -6-dB impedance matching level.

FOM = Imp. BW / Profile

the entire visible light spectrum. For a single layer of such silver mesh structure, the calculated value is 73.5% [13]. Considering the additional Fresnel loss due to the glass substrate as well as the test error, the measured value makes sense. To further improve the optical transparency, one can reduce the metal density. However, that would be at the cost of getting larger loss.

A comparison among reported and proposed transparent/filtering patch antennas is illustrated in Table 2. As seen, compared with the reported transparent antennas, the proposed one features compact structure, enhanced bandwidth as well as good filtering response, while in comparison with the filtering antennas in the literature, it shows the advantages of low profile, no requirement of drilling as well as see-through characteristic.

IV. CONCLUSION

This paper has introduced an optically transparent proximity-coupled-fed patch antenna with enhanced impedance bandwidth and good filtering response. The antenna structure as well as its working mechanism have been fully described and investigated. Employing the standard photolithography and lift-off process, the designed antenna has been fabricated and measured. Experimental results show that the proposed antenna has an enhanced impedance bandwidth of 7.6% (3.41 GHz – 3.68 GHz) compared to the traditional one of 3.5%. The optical transparency for the ground region reaches 60%. A gain of 4.6 dBi accompanied with
above 10-dB out-of-band suppression level is achieved for the antenna. The proposed antenna features enhanced impedance bandwidth, good filtering response as well as transparent characteristic simultaneously. Without any drilling, the proposed antenna with intact ground plane is a promising candidate in applications of vehicle-to-vehicle communications and wireless indoor communications when aesthetic is also considered.

REFERENCES


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