A Fractal Octagonal-Shaped Transparent Antenna for C-band Applications

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Abstract—This work describes the analysis, design, and fabrication of a transparent planar antenna for C-band applications. The bandwidth of the antenna, according to measurements of the reflection coefficient $S_{11}$, is 3-6 GHz, with a peak value of -26 dB. The measured radiation pattern for the antenna is omnidirectional, with an average gain of -6.9 dB.

Keywords—transparent antenna, ultra-wideband, ITO, Minkowski fractal, octagonal patch, CPW.

I. INTRODUCTION

The wireless communication systems have evolved rapidly in the last years. The requirements of the new technologies point to the optimized use of the electromagnetic spectrum. There are different alternatives to get better exploitation of different bands in the electromagnetic spectrum.

The C-band is one of the most used band because of the high data capacity and the links that do not require line of sight (LoS). The principal uses of the C-band are satellite communications, ISM applications. Although there are different assigned frequency bands in UHF, C-band, and K-band, the C-band is that offers the best relation between bandwidth and NLoS (no line of sight) links in 5G band mobile telephony systems [1]–[6].

The different frequencies of the C-band point to use a wideband to approach. The wideband antennas not only can be used to communicate systems but also are used in applications of radiofrequency energy harvesting. The massive use of the C-band for commercial communications systems increases the energy to be harvested in comparison with other bands [7], [8].

There is recent work related to the application of transparent conductive films to design transparent antennas. The fabrication of transparent antennas consists of the integration of a transparent conductive film over a transparent dielectric substrate [9]–[13]. The main objective of fabricating transparent antennas is to make an easily integrable antenna in a wide variety of scenarios, which include glasses for vehicles [14], implementation of discrete base-stations (BS), the connectivity of solar panels, and others.

There is a variety of literature that reports the results of transparent antennas. Hakimi et al. [9] present a CPW-fed transparent antenna that consists of a ring resonator and a reduced-size ground plane. They used conductive material is ITO, reinforced with a gold layer to increase the conductivity of the plate. The antenna has a wideband behavior, which operates in the frequencies between 2-20 GHz, with a peak reflection coefficient of -20 dB in 7 GHz. Awalludin et al. [10] show the simulation of a square patch transparent antenna that operates at the 2.4 GHz Industrial, Scientific, and Medic (ISM) band. The antenna is fabricated with AZO conductive film, with tests of glass and quartz substrates. The obtained reflection coefficient $S_{11}$ of the antenna is -16 dB.

Other works make an effort to get optimization in the behavior of the antenna. Song et al. [11] propose a method to improve the properties of an antenna by increasing the conductivity of an AgHT4 film with the addition of metallic particles in the borders of the antenna. The implemented antenna reaches a -15 dB of the reflection coefficient at the frequency of 2.4 GHz. Another example of the optimization of the design is the work of Li et al. [12] that consists of a transparent antenna made of Micro Metal Mesh Conductive (MMMC) film. The operation frequencies are 2.4 and 5.8 GHz, with a peak reflection coefficient of -22 dB. Finally, Eltresy et al. propose the design of a transparent multiband antenna that operates in both 2.4 and 3.7 GHz frequencies. They used conductive film is AgHT4 over a plexiglass substrate.

This work describes the analysis, design, and fabrication of a transparent planar antenna for every frequency contained in C-band. The design consists of a planar monopole octagonal patch antenna, which is expected that have a wideband behavior. The antenna was fabricated with a 1 mm glass substrate with a 150 nm ITO (Indium-Tin Oxide) transparent conductive film. The feedline of the antenna was designed using a CPW (Coplanar Waveguide) with a separation of 0.3 mm between the feedline and the ground plane. The designed octagonal patch was modified with a Minkowsky-Like fractal structure. The objective of including fractals in the design is to test the
improvement of the reflection coefficient and the increase of the electrical length without a significant increase in the physical length.

II. DESIGN

A. Initial design

The design points to make a reduced size transparent antenna in order to integrate in a mobile system. In order to use a single-metallization substrate, the main antenna design consists of a coplanar waveguide (CPW) line that feeds an octagonal patch. This design has a wide band behavior [15]–[17]. The considered CPW model must include the particular features of the ITO film, which has lower conductivity in comparison with a metallic film (about three magnitude orders) and is thinner than the metallic film [18].

The selected design frequency for the antenna elements is 4 GHz, which is expanded due to the nature of the design. A 50 Ω impedance was considered for the design. This impedance was selected in the CPW feedline, considering a 0.3 mm of separation between the line and the ground plane. The analysis of the CPW feedline was made using the model described by Simmons [19], with the respective considerations studied by Shu et al. [20], related to the impact of the low-conductivity film in the dimensions of the CPW. The impedance $Z_0$ of the CPW is calculated using (1):

$$Z_0 = \frac{30\pi}{\sqrt{\varepsilon_{\text{eff},d}}} \frac{K(k'_1)}{K(k_1)}$$  \hspace{1cm} (1)

Where the parameter $\varepsilon_{\text{eff},d}$ is the effective dielectric permittivity due to the substrate thickness and the separation between the line and the ground plane, meanwhile the function $K$ refers to the capacitance per unit length formed between the line and the ground plane. This parameter is evaluated through an approximation of the quotient $K(k)/K'(k)$, as shown in (2):

$$K(k) = \left\{ \begin{array}{ll}
\frac{\pi}{\ln \left( \frac{1 + \sqrt{k}}{1 - \sqrt{k}} \right)} & 0 \leq k \leq 1 \\
\frac{\pi}{\ln \left( \frac{1 + \sqrt{k}}{1 - \sqrt{k}} \right)} & 1 < k \leq \frac{\sqrt{2}}{2} \\
\frac{\pi}{\ln \left( \frac{1 + \sqrt{k}}{1 - \sqrt{k}} \right)} & \frac{\sqrt{2}}{2} \leq k \leq 1
\end{array} \right\}$$  \hspace{1cm} (2)

The initial frequency ($f$) for the octagonal patch design is described by (3) [7], [21], [22]:

$$f = \frac{7.2}{(l + r + p)k}$$  \hspace{1cm} (3)
In the antenna design, we are taking two sides of the octagon as the replicated structure. The effective length is two times each side. It describes the initial length in terms of the radius, \( r \), of the next nest octagon. An illustration of the process is shown in Figure 1.

The shown structure was replicated three times. Considering the division of the initial segment in two parts; and the initial geometry composed of four segments, the fractal dimension is calculated evaluating (5):

\[
h = r \left( \frac{2}{4} \right)^3 = \frac{1}{8} r
\]

(6)

On the other hand, the effective length is calculated evaluating (4):

\[
D = \frac{\log(2)}{\log(4)} = \frac{1}{2}
\]

(7)

Using fractal structures decreases the resonance frequency, according to (6) and (7) because of the increase of the electrical length. The advantage of the use of fractal structures is that the increase of the electrical length is possible without a significant increase in physical lengths.

Then, the proposed fractal antenna is shown in Figure 2. The geometric dimensions of the antenna are represented by the parameters a, b, c, d, e, f, g, h, i, j, k, l, m and n, which values are listed in Table I. The selected substrate is 1.1 mm thick glass, with a relative dielectric permittivity \( \varepsilon_r = 5 \).

The selected conductive film is ITO (Indium-Tin Oxide) whit a thickness of 100 nm (Adafruit Technologies) due to its wide use and its conductive properties. The design of the antenna was made using the software HFSS v13 (Ansys), considering the conductive material as a thin film with a sheet resistance of 10 S/m.

### TABLE I. ANTENNA DIMENSIONS

<table>
<thead>
<tr>
<th>Label</th>
<th>Dimension (mm)</th>
<th>Label</th>
<th>Dimension (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>25</td>
<td>h</td>
<td>8</td>
</tr>
<tr>
<td>b</td>
<td>11</td>
<td>i</td>
<td>3.4</td>
</tr>
<tr>
<td>c</td>
<td>12.5</td>
<td>j</td>
<td>3.04</td>
</tr>
<tr>
<td>d</td>
<td>8.5</td>
<td>k</td>
<td>1.39</td>
</tr>
<tr>
<td>e</td>
<td>2.4</td>
<td>l</td>
<td>1.13</td>
</tr>
<tr>
<td>f</td>
<td>4</td>
<td>m</td>
<td>0.44</td>
</tr>
<tr>
<td>g</td>
<td>0.3</td>
<td>n</td>
<td>0.15</td>
</tr>
</tbody>
</table>

In order to appreciate changes in the reflection coefficient due to the application of the fractal structure, the antenna was simulated for \( N \) different applied fractal structures. The value for \( N=3 \) was selected, considering it is the maximum value possible due to the tolerances of the fabrication process of the antenna. Figure 3 shows the comparison of the reflection coefficient of the antenna.

A test of the reflection coefficient with different values of sheet resistance was made to demonstrate the impact of the low conductivity film in the bandwidth of the antenna. The results of the test are shown in Figure 4.
The final design was obtained after the simulation process. The antenna was fabricated. Figure 5 shows the fabricated antenna. Besides, in Table II, a comparison of respect to the antenna size against other works is presented.

The experimental characterization of the antenna was performed, comparing the results with the data obtained in the simulation. The characterization includes measurements of the reflection coefficient and the gain of the antenna. The measurements of the reflection coefficient were made with a Vector Network Analyzer (VNA) inside a Faraday cage. The connection between the antenna and the VNA was made using an SMA plug, which was soldered with Indium. The union was reinforced with liquid conductive paint. The reflection coefficient $S_{11}$ was measured and compared in Figure 6.

A 3D radiation pattern is shown in Figure 7. Radiation patterns for the E and H planes are shown in Figures 8 and 9, respectively. The radiation patterns point to an omnidirectional operation, with a peak gain in -6.9 dB. This gain is lower than the typical observed results in wideband planar antennas that use cooper opaque substrates. However, the perceived gain is in concordance to the results observed for other transparent antennas. Moreover, the designed antenna in this work reached the size of the antenna in comparison with other works, which in terms of area, is between 60% [12] and 90% [10] smaller than the antennas proposed by other authors. A comparison of dimensions of the antennas is shown in Table II.
TABLE II. COMPARISON OF TRANSPARENT ANTENNAS

<table>
<thead>
<tr>
<th>Author</th>
<th>Material</th>
<th>Freq. Range (GHz)</th>
<th>S11 peak (dB)</th>
<th>Dim. (mm)</th>
<th>Gain (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[9]</td>
<td>ITO+Au</td>
<td>2-20</td>
<td>-20</td>
<td>45x30</td>
<td>-4.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>@2GHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[10]</td>
<td>AZO</td>
<td>2.4</td>
<td>-16</td>
<td>60x50</td>
<td>ND</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>@2.4 GHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[11]</td>
<td>AgHTi</td>
<td>2.2</td>
<td>-15</td>
<td>120x60</td>
<td>-5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>@2.4 GHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[12]</td>
<td>MMMC</td>
<td>2.4, 5.8</td>
<td>-22</td>
<td>40x20</td>
<td>-5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>@2.4 GHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[13]</td>
<td>AgHTi</td>
<td>2.4, 3.7</td>
<td>-30</td>
<td>50x50</td>
<td>-1.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>@3.7 GHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>This work</td>
<td>ITO</td>
<td>3-6</td>
<td>-26</td>
<td>25x12.5</td>
<td>-6.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>@3.95 GHz</td>
<td></td>
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</tr>
</tbody>
</table>

N.D. No data

IV. CONCLUSIONS

A transparent ITO antenna was presented. The application of a Minkowsky like fractal structure decreases lightly the resonance frequency and improves marginally the reflection coefficient in the desire operation bandwidth. The bandwidth of the antenna is between 3 and 6 GHz, with a peak value in the $S_{11}$ reflection coefficient of -26 dB. The bandwidth of the antenna is longer than the expected and covers all the frequency range for the C-band. The antenna gets a reduction in dimensions in comparison with other transparent antennas without a significative change in the gain. The radiation patterns were measured to show an omnidirectional behavior for the antenna.

REFERENCES


