

Article

Optically Transparent Honeycomb Mesh Antenna Integrated into OLED Light Source

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Abstract: The co-integration of antennas with lighting sources appears as an effective way to distribute broadband networks closer to users, lowering interference and transmitted power, as well as to reduce energy consumption in future lighting systems. We here present an original contribution to the implementation of transparent and invisible antennas with OLED light sources. To validate the proposed approach, the honeycomb mesh technique was used, and an optical transparency of 75.4% was reached. The transparent mesh antenna was compared with the non-transparent full-metal antenna in terms of radio-electrical parameters. Our prototype was designed using copper films deposited on a glass substrate. The simulation results of the S-parameters and the radiation patterns were validated against measurements performed in an anechoic chamber. The directivity and gain obtained were 6.67 dBi and 4.86 dBi at 5.16 GHz, respectively. To study the effect of antenna integration with OLEDs, optical and photometric characterizations with and without the antenna were measured, and the colorimetric parameters were then treated using the IES TM-30-18 standard.



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Keywords: antenna design; optically transparent antenna; mesh antenna; Organic Light-Emitting Diodes (OLEDs); WLAN

1. Introduction

Due to their excellent integration qualities, high energy efficiency, low luminance without glare, and potentially low manufacturing costs, Organic Light-Emitting Diodes (OLEDs) can be easily integrated into urban spaces for pedestrian lighting. Manufacturers are still reluctant to invest massively in this technology, despite its maturity, as long as the LED market is booming. Nevertheless, in recent years, OLEDs have rapidly progressed, and commercially available models are already used in internal and exterior lighting, displays, automotive applications, aerospace, wearable biomedical devices, etc. [1–4]. These developments are of great interest for manufacturers because it is obvious that this technology will be at the heart of the next generation of general lighting sources in smart cities [5]. Intelligence applications indeed require new wireless network infrastructures to support the increase in the volume of communication linked to new services. Furthermore, the installation of a connected network of smart city services needs a larger communication area. Therefore, it is necessary to install more antennas at the interfaces of all connected objects and to multiply the base stations in cities to achieve reliable communication [6]. Due to the miniaturization of these objects and the visual pollution caused by the installation of more base stations in cities, this requirement becomes difficult to fulfill [7]. For this reason, optically transparent antennas can be quite a promising solution to replacing non-transparent antennas. Because of their optical transparency, these antennas can be integrated into screens, glazing, bus stop indicators, OLED lamps, etc. More antennas

means improvement in network coverage without increasing the visual or spatial impacts linked to their presence [8,9].

With the expansion of the transparent device market, optically transparent antennas have great potential for newer wireless communication systems. The manufacturing process is based on the deposition of electrically conductive and transparent material on transparent substrates [10,11]. According to the literature, the transparent materials used in the manufacture of these antennas are indium tin oxide (ITO) [12–15], fluorine-doped tin oxide (FTO) [16], aluminum-doped zinc oxide (AZO) [17], AgHT-4 [18,19], AgHT-8 [20–23]), ultra-thin metal film [24], and mesh structures [25–31].

The development of mobile devices benefits from the integration of antennas and transparent and flexible screen displays. The antenna-on-display (AoD) solution has already been implemented in the literature on OLED displays and Liquid Crystal Displays (LCDs). The original concept of optically invisible AoDs has been studied and tested in high-resolution OLED touch displays for WiFi and Bluetooth applications in smartwatches [32,33]. Furthermore, in [34], the authors presented a detailed study of an optically invisible antenna integrated into OLEDs and LCDs for smartphones. This antenna operates in the millimeter-wave (mm-Wave) band for 5G cellular applications. The techniques of diamond mesh and identical dummy grids are used to achieve optical invisibility and transparency. Dummy-grid structures are diamond-shaped and encompass the designed antenna region to eliminate any difference in optical transmittance. Similarly, Ref. [35] also presented an AoD that can eventually be integrated into display panels for the sub-6 GHz band. In addition, a simulation study of optically transparent antennas that can be integrated into OLED light sources was presented in [7,36,37]. All these studies were carried out to understand the operation of an antenna integrated into OLEDs without taking into consideration the effect of this integration on the display's color appearance.

This paper presents the design and realization of a transparent and invisible antenna, designed using a honeycomb mesh for the 5 GHz WLAN band. This study focuses on two main challenges in order to examine the antenna integration effects on the OLED light source. The first is the transparent antenna design using the mesh technique. This analysis is based on a comparison between two antennas: a full-metal antenna and a honeycomb-meshed one. The honeycomb mesh technique is used to design the invisible and transparent antenna with high transparency and an acceptable sheet resistance value. The second one consists of antenna integration and its effects on the OLED panel's visual characteristics. For this purpose, this paper aims to study the colorimetric parameters of a warm white OLED after the integration of the transparent mesh antenna. It contains a physical realization of the concepts analyzed in [37], which presented a comparative study on the simulation results of transparent circular patch antennas integrated into OLEDs. It is important to note that the meshing technique to achieve optical transparency has been widely discussed in the literature [7,25–37]. However, this paper presents, for the first time, a complete study, which contains the antenna electrical parameters and the colorimetric parameters of the OLED before and after antenna integration.

The remainder of this article is organized as follows: Section 2 describes the material characteristics used in the design. To justify the choice of the transparent antenna, Section 3 describes a comparison between this antenna and a non-transparent one. The experimental results are discussed and compared with the simulation results in Section 4. The method for antenna integration into an OLED light source and the effect of this integration on the radio-electrical parameters of the antenna and on the OLED colorimetric parameters are studied in Section 5. Conclusions and perspectives are presented in Section 6.

2. Material Characteristic

This article proposes the study of a transparent antenna integrated into an OLED light source to provide better connectivity for wireless communications. The proposed antenna is designed using transparent materials deposited on a glass substrate. Firstly, the characteristics of the materials used in this design are studied. These characteristics are

the optical and dielectric parameters of the glass substrate and the sheet resistance and transparency of the ITO used in antenna manufacturing.

2.1. Substrate Characteristics

The main characteristics of interest are optical transparency (T_{sub}), dielectric permittivity (ϵ_r), and the tangent of the loss angle ($\tan(\delta)$). The dielectric parameters were measured using the Vector Network Analyzer combined with the 85,070 B dielectric probe kit with a tolerance of $\pm 5\%$ and $\pm 0.05\%$ on the dielectric permittivity and dielectric losses, respectively. The measurement results of ϵ_r and $\tan(\delta)$ are shown in Figure 1. According to this figure, the measured values at a frequency of 5.16 GHz are $\epsilon_r = 6.2$ and $\tan(\delta) = 0.05$.

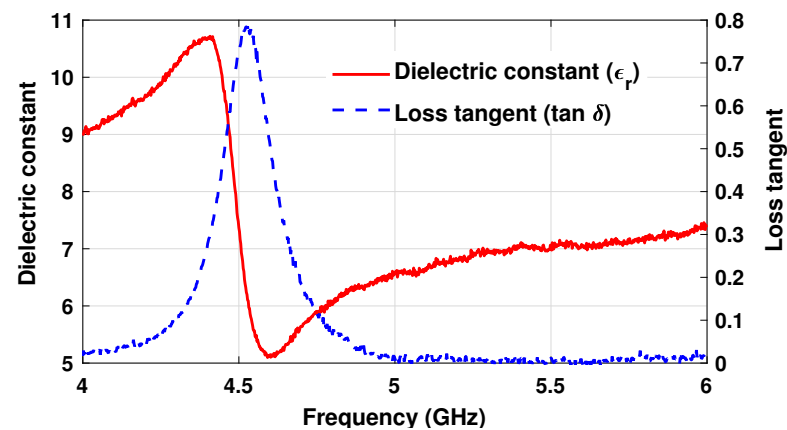


Figure 1. Dielectric permittivity and tangent of the loss angle.

The other parameter studied is optical transparency in the visible spectrum. This parameter was measured using an optical bench at room temperature and a MINOLTA-CS-1000 spectroradiometer. First, the luminance of the OLED was measured. Secondly, the glass substrate was inserted through a lens holder in front of the objective, in order to intercept the entire luminance. Transparency is the ratio of the latter luminance to the first result at the corresponding wavelength. Figure 2 illustrates this optical transparency; the median value is around 82.5%. Noise below 480 nm results from low emission in this band, leading to an increased noise level.

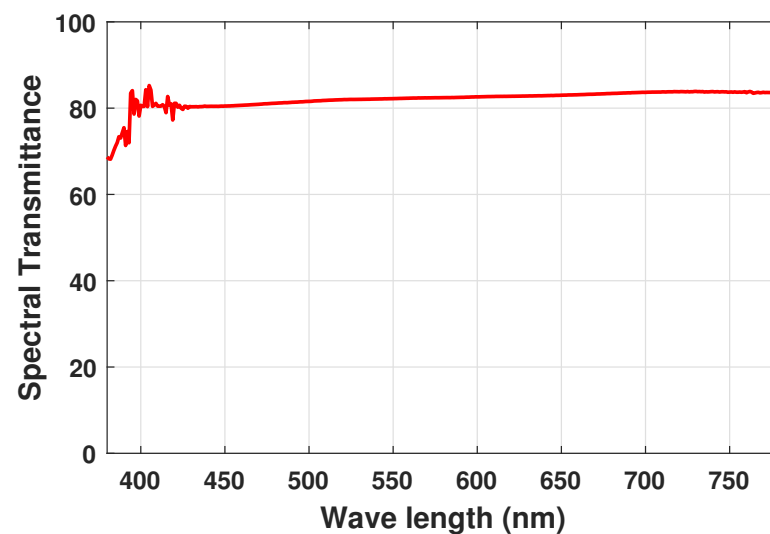


Figure 2. Optical transparency for glass substrate in the visible spectrum.

2.2. Sheet Resistance

The two popular types of transparent antennas are meshed and based on transparent conductive oxide (TCO)-type antennas. In this work, the ITO film and the mesh structure were studied and compared. The $R_s (\Omega/sq)$ resistance of the sheet and the transparency T (%) were compared to identify the most-suitable material of this design.

2.2.1. ITO Film

One of the TCOs widely used in the design of transparent antennas is ITO films. OLEDs use ITO as an electrode for its conductive and transparent properties allowing light to go out. Several researchers also use this material in the manufacture of optically transparent antennas [12,14,15]. Its high optical transparency makes it an ideal candidate, but its high sheet resistance remains a challenge for the realization of antennas. The sheet resistance is the electrical resistance of a square surface of a material of thickness “ t ” [9]. The sheet resistance of the ITO film is given by the following relation:

$$R_s = \frac{1}{\sigma \cdot t} \quad (1)$$

where σ is the conductivity and “ t ” is the thickness of the ITO film.

2.2.2. Mesh Structure

The structure of the metal mesh makes it possible to make optically transparent conductive films for antennas. The principle of the mesh technique is to create holes in a structure to let light pass. Transparency and sheet resistance change with the surface variation of these holes. Figure 3 represents the honeycomb structure chosen in this work. In general, the sheet resistance of the structure of the network is calculated by the equation [29]:

$$R_{s(mesh)} = \frac{q}{e} \times R_s \quad (2)$$

where $R_s = 0.047 \Omega/sq$ is the sheet resistance of the copper film (calculated by Equation (1) with $\sigma = 5.8 \times 10^7 \text{ S/m}$ and $t = 370 \text{ nm}$), q is the pitch value, and e is the metal strip.

Since the honeycomb structure was used, the leaf resistance was calculated in the OX and OY axes, compared to the direction of the current propagation in the meshed antenna. The resistors along each axis are given by the following relations:

$$R_{s(mesh)} = \frac{q_x}{e} \times R_s \text{ and } R_{s(mesh)} = \frac{q_y}{e} \times R_s \quad (3)$$

The values of the chosen parameters are: $q_x = 0.32 \text{ mm}$, $q_y = 0.5 \text{ mm}$, $e = 0.05 \text{ mm}$, and $R_s = 0.047 \Omega/sq$ (Equation (1)). Consequently, a value of approximately $R_s = 0.2 \Omega/sq$ was obtained for the mesh. Note that this value is greater than the resistance of the copper film, but the use of these techniques increases the transparency of the material [25,29].

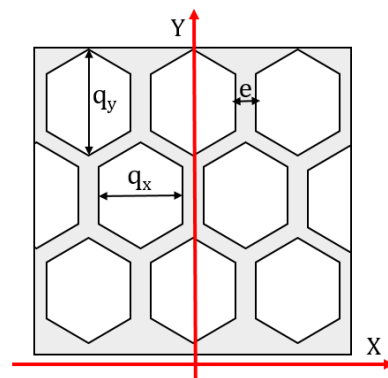


Figure 3. The geometry of the honeycomb mesh.

2.3. Optical Transparency

Optical transparency is another parameter that has been studied. Figure 4 illustrates a comparison between the optical transparency of the ITO film and the honeycomb structure from 380 to 780 nm. Although large mesh dimensions are needed to obtain high optical transparency, this also increases sheet resistance. From this figure, the mesh structure has excellent transparency compared to the ITO throughout the entire visible spectrum. The measured transparencies remain constant. The median transparency value of the network structure is around 75.4%, while that of the ITO film is 65.1%. Note that the measured transparencies are the sum of the transparencies of two layers of the ITO and meshed structure deposited on the glass substrate.

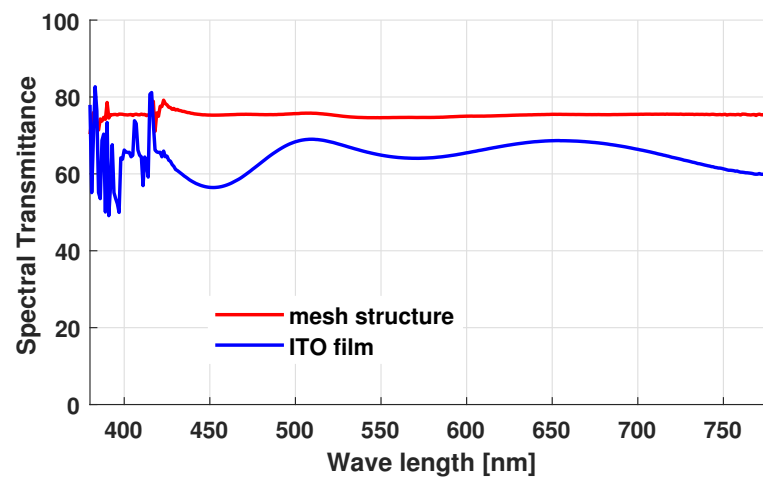


Figure 4. Comparison between the optical transparency for the ITO film and mesh structure in the visible spectrum.

Global transparency results from the sum of three layers: two mesh grids and the substrate. Assuming that the contributions of the grids are identical, we can determine the contribution of the mesh as:

$$T_{tot} = T_{mesh} \cdot T_{substr} \cdot T_{mesh} \quad (4)$$

$$T_{mesh} = \sqrt{\frac{T_{tot}}{T_{substr}}} \quad (5)$$

Inserting the previously measured transparency values in Equation (5), the transparency of the mesh can be evaluated as 95.5%. This suggests that if the OLED glass substrate and its anode can be used as the support and ground plane, respectively, the impact of a single mesh layer would be quite small. This argument goes in favor of the co-design and co-integration of the display and radiation functions.

2.4. Comparison between ITO and Mesh Technique

The comparison of the transparency and sheet resistance of the ITO film and mesh structure is given in Table 1. According to this table, the transparency of the mesh structure is 15.82% higher than that of the ITO film, while its sheet resistance is more than 20-times lower than that of the ITO. Therefore, the mesh structure obtains better performance compared to that of the ITO film. In this paper, the mesh structure was chosen to design the transparent antenna integrated into the OLED light source.

Table 1. Comparisons between the ITO film and mesh structure.

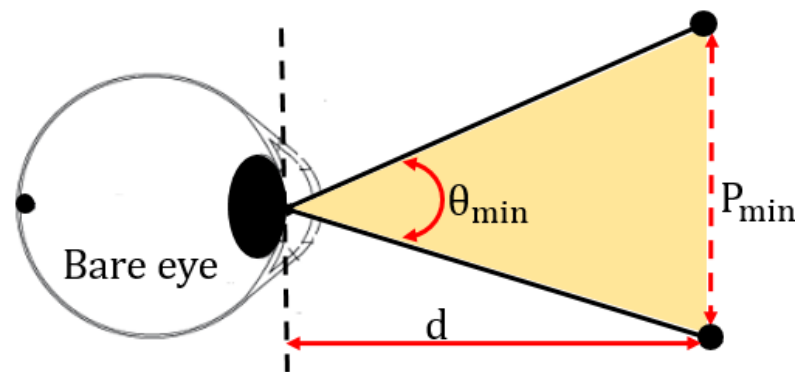
	ITO Film	Copper Film	Mesh Structure
Transparency (%)	65.1	opaque	75.4
Sheet resistance (Ω/sq)	4.51	0.047	0.2
Thickness (nm)	370	370	370

2.5. Invisibility to the Bare Eye

In order to integrate the mesh antenna into the OLED, the parameters of the honeycomb structure were optimized so that the human eye cannot distinguish the structure. The performance of the human eye was taken into account in this optimization. Therefore, the angular discrimination of the eye is $\theta_{min} = 4.9 \times 10^{-4}$ rad [38]. The distance between two distinct points can be expressed as follows:

$$p_{min} = d \cdot \tan \theta_{min} \approx d \cdot \theta_{min} \quad (6)$$

The distance d between the eye and the object depends on the intended application in which the mesh will be used (Figure 5). This distance is equal to the minimum value of the punctum proximum. Thus, a distance of 1 m was considered, which is quite sufficient for the antenna to be invisible in OLED light sources.

**Figure 5.** Diagram of the discrimination of two points observed with the bare eye [38].

The distance calculated using Equation (6) is approximately $p_{min} = 490 \mu m$. We can conclude that the mesh antenna using these parameters will be invisible to the bare eye at a minimum distance of 1 m.

3. Antenna Configurations

Two complementary case studies were implemented to investigate an antenna integrated into the OLED. The non-transparent antenna was designed with an all-copper film. The optically transparent and invisible antenna uses a honeycomb-shaped mesh structure. The all-metal version served as the reference standard for characterizing RF properties.

3.1. Non-Transparent Antennas

A reference non-transparent patch antenna was first designed using an entirely copper film. The geometry of the non-transparent antenna is shown in Figure 6. This antenna consists of a radiating element on one side of the glass substrate (thickness of $h_s = 1.1$ mm) and a ground plane on the other side.

The width ($W_f = 1.77$ mm) and the length ($L_f = 5.8$ mm) of the antennas' feedline were calculated to match the characteristic impedance of 50Ω . Both antennas occupy a volume of $25 \times 25 \times 1.1$ mm³. A copper film (conductivity of $\sigma = 5.8 \times 10^7$ S/m, thickness of $t = 370$ nm and sheet resistance of $R_s = 0.05 \Omega/sq$) was used to design the two antennas.

The dimensions were calculated using the equations in [39], so that the antenna operates in the 5.15 GHz WLAN band.

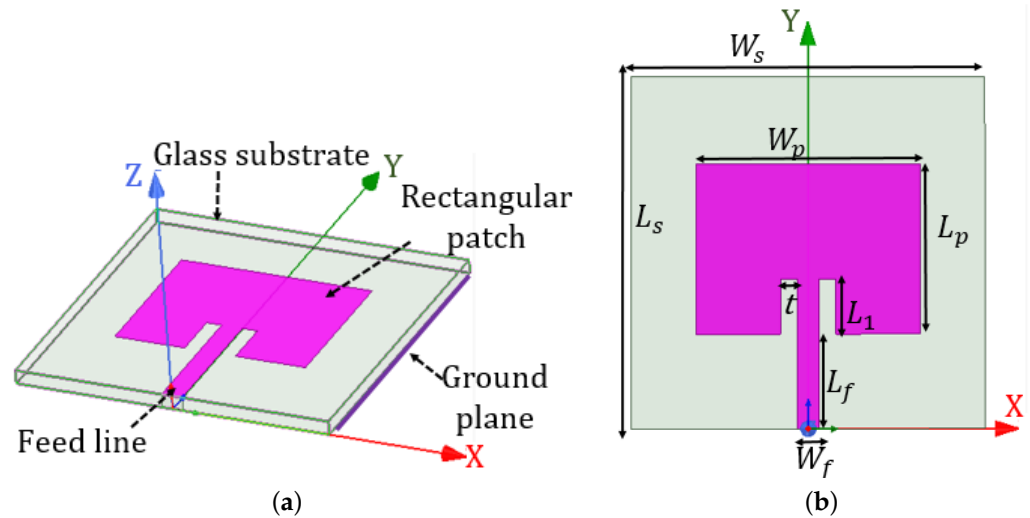


Figure 6. Rectangular patch antenna geometry: (a) 3D view, (b) top view. $W_s = 25$ mm, $L_s = 25$ mm, $L_p = 11.76$ mm, $W_p = 15.8$ mm, $t = 1$ mm, $L_1 = 5.4$ mm, $L_f = 5.8$ mm, and $W_f = 1.77$ mm.

3.2. Transparent Antenna

The transparent antenna designed using the honeycomb-shaped mesh structure can be integrated into an OLED light source structure with minimal impact on the luminous efficiency. The proposed antenna was designed to cover the WLAN band, but it can be operated on other bands by optimizing the mesh parameters. Figure 7 shows the geometry of the mesh antenna with the dimensions of the honeycomb mesh. For the ease of comparison, the non-transparent and mesh antennas have the same dimensions

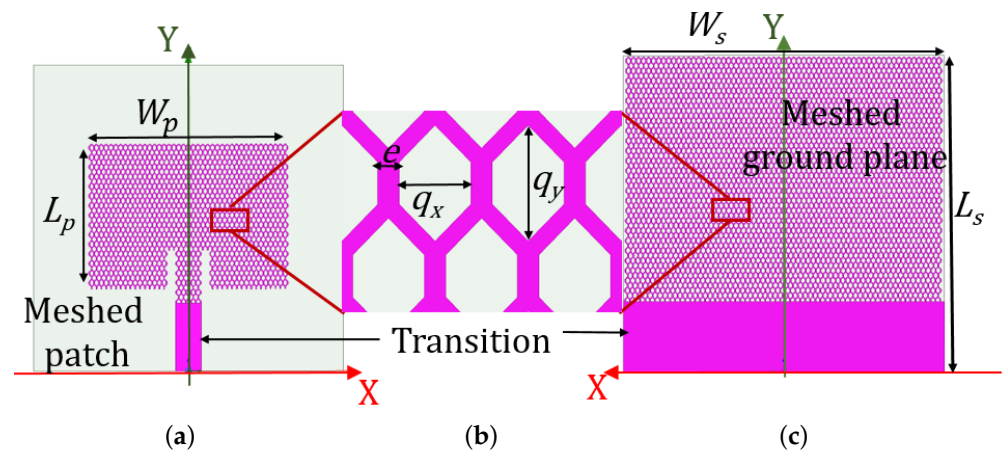


Figure 7. Transparent antenna geometry: (a) meshed radiating patch, (b) mesh cells, and (c) meshed ground plane. $W_s = 25$ mm, $L_s = 25$ mm, $L_p = 11.76$ mm, $W_p = 15.8$ mm, $e = 50$ μ m, $q_x = 320$ μ m, and $q_y = 500$ μ m.

3.3. Comparison between the Non-Transparent and Transparent Antennas

Both designs were simulated and analyzed using an electromagnetic solver software, Ansys Electronics Desktop V.13.0.2. The electrical and radiation parameters of the antennas were compared. Figure 8 shows the comparison between the return losses for the compared antennas. For both candidates, the antenna impedance's were well matched to 50Ω at the resonance frequency of 5.15 GHz, because the return losses were less than -10 dB. The bandwidth defined by ($S_{11} \leq -10$ dB) was 130 MHz (5.19–5.32 GHz) for the non-transparent antenna and 110 MHz (5.09–5.2 GHz) for the transparent antenna. It should be

noted that the compared antennas had the same size; however, the disagreement observed between the resonance frequencies is justified by the resistance values for each structure (solid metal layer versus mesh metallic layer).

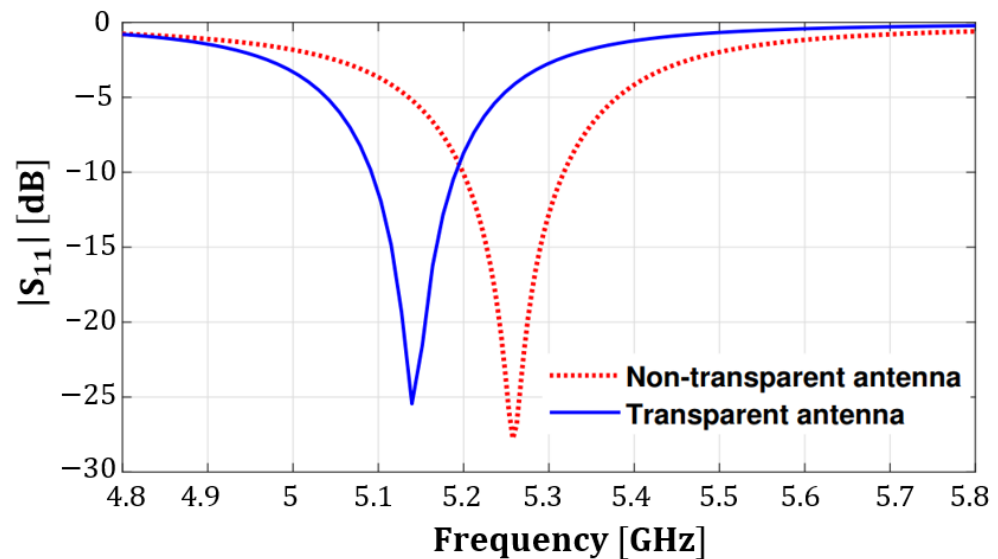


Figure 8. Comparison between the return losses of the compared antennas (non-transparent and transparent).

The radiation patterns for the two antennas are also compared in Figure 9. These diagrams are obtained for the resonance frequencies of each antenna and for the two planes: the XZ-plane (Figure 9a) and YZ-plane (Figure 9b). These results are in acceptable agreement because the antennas' sizes are equivalent. The maximum gains were 6.23 dBi and 5.5 dBi for the non-transparent and transparent antennas, respectively. Both antennas achieved good gain in the operating band for WLAN applications. Therefore, increasing the resistance value of the sheet deteriorated the gain of the mesh antenna. This can be compensated by using meta-materials and applying array antenna techniques [40].

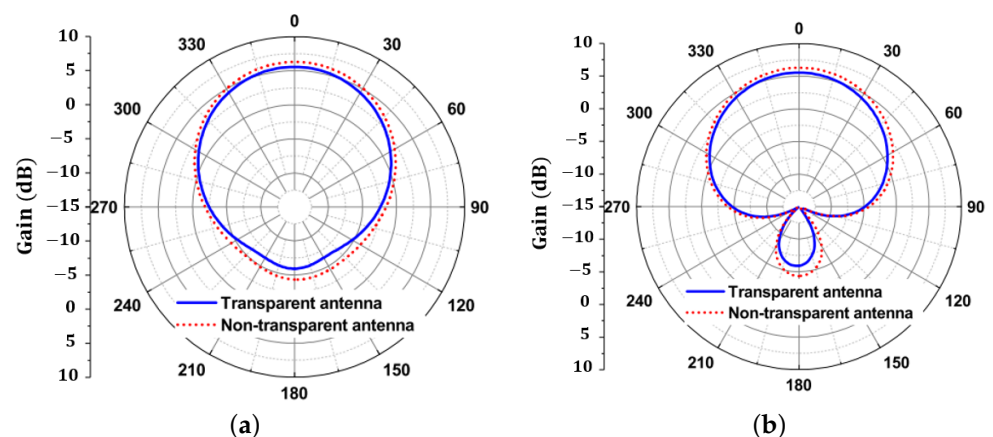


Figure 9. Comparison between the radiation patterns of the compared antennas: (a) XZ-plane and (b) YZ-plane.

4. Experimental Results

The antennas were optimized using electromagnetic solver Ansys Electronics Desktop software and were manufactured by the photolithography process to validate the results obtained in the simulation. Figure 10a shows photographs of the fabricated antennas. Their reflection coefficients and radiation patterns were measured. The first was evaluated using

the Vector Network Analyzer. The latter was measured inside an anechoic chamber, as shown in Figure 10b.

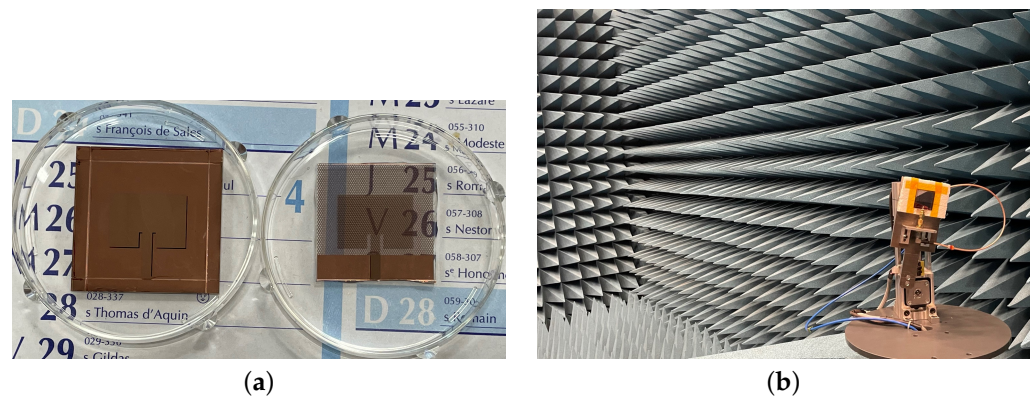


Figure 10. Manufactured antennas: (a) non-transparent and transparent antennas; (b) antenna measurement chamber setup.

4.1. Reflection Coefficient Comparison

The simulated and measured reflection coefficient of the non-transparent and transparent antennas are shown in Figure 11. The impedance matching of the manufactured transparent antenna was not well matched; this may be justified among other things by the process inaccuracies in the manufacturing of the mesh antenna, the electrical losses of the glass substrate, and the increase in the resistance value of the sheet through the use of the mesh technique. Additionally, the metal thickness $t = 370$ nm was so thin that it was comparable to the skin depth value of $0.9 \mu\text{m}$ (calculated using the skin depth equation [24]); high loss was present, which reduced the performance of the antenna.

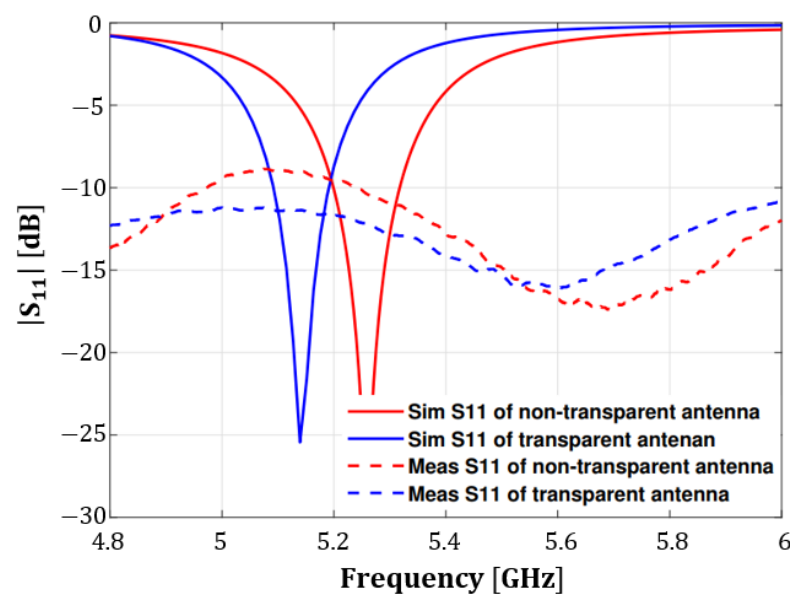


Figure 11. Measured and simulated return loss of the transparent and non-transparent antennas.

To minimize the losses due to the skin depth, a metal thickness greater than $3 \times 0.9 = 2.7 \mu\text{m}$ should be used. However, the metal deposition technique used does not make it possible to obtain this thickness. However, the proposed antennas still exhibited acceptable impedance matching over the WLAN frequency band.

4.2. Radiation Patterns Comparison

The far-field radiation patterns of the non-transparent antenna at 5.27 GHz are shown in Figure 12. Figure 13 shows the far-field radiation patterns of the transparent antenna at 5.16 GHz. In general, the simulated results matched the measured results. The observed deviations were attributed to the manufacturing problems and losses related to the electrical characteristics of the substrate. It was also observed that the antenna had an essentially unidirectional radiation pattern. The measured back radiation could not be evaluated due to the measurement configuration of the anechoic chamber.

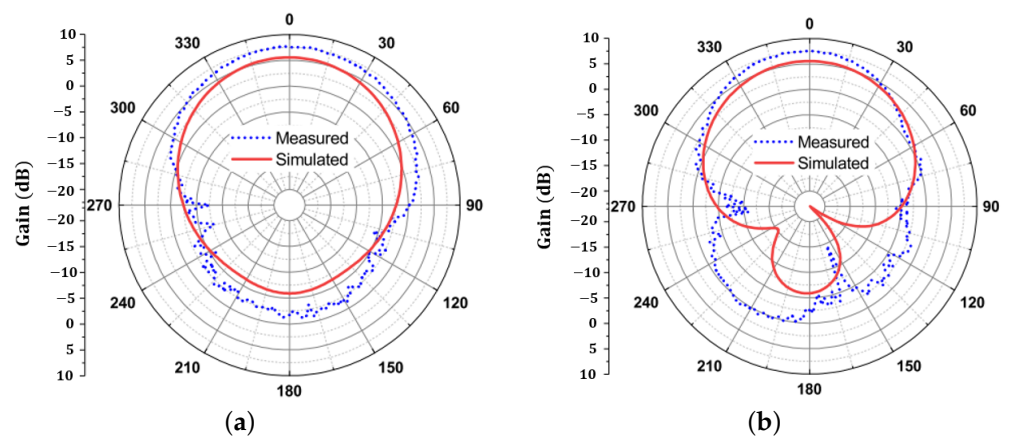


Figure 12. Measured and simulated radiation patterns of the non-transparent antenna: (a) in the XZ-plane and (b) in the YZ-plane.

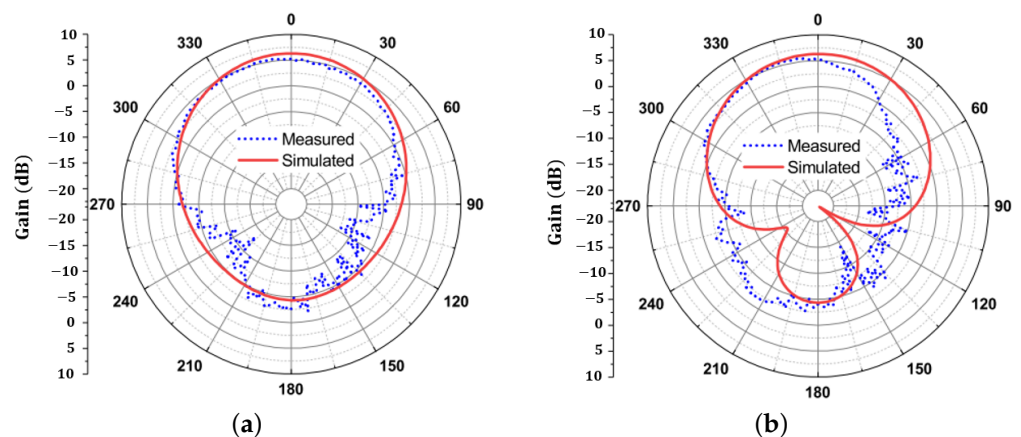


Figure 13. Measured and simulated radiation patterns of the transparent mesh antenna: (a) in the XZ-plane and (b) in the YZ-plane.

5. Antenna Integration into OLED

OLEDs will become the most-suitable technology in future display and lighting systems, thanks to their many benefits, such as the high quality of light and images with excellent color rendering, low power consumption, controllability in terms of color temperature, and the possibility to realize them on transparent or flexible substrates with lower manufacturing costs. The integration of antennas in this technology can provide a solution in terms of the implementation of future lighting systems and the coverage area in wireless communication. In [34], the authors discussed the use of transparent antennas for future cities to improve network capacity, reduce visual pollution, and expand infrastructure in 5G wireless communication. These antennas will also be a good candidate for future 6G systems, in which all possible communication scenarios will be found, such as terrestrial wireless communication networks, satellite communication, intelligent transport, and the massive Internet of Things (IoT) [41]. Therefore, this work aimed to study the antennas'

integration into OLED technology to contribute to scientific research into the development of lighting systems. How to integrate a transparent antenna into OLED technology will be discussed in this section. The parameters of the OLED model used in this study are the same as those of the commercialized device [42].

Generally speaking, an OLED is made up of several organic layers located between two electrodes. Each layer plays a specific role in the light-emission process. Figure 14 shows the OLED's structure, including the antenna location. Figure 14a illustrates the different components of the OLED. Layer 1 is the 0.7 mm-thick OLED glass substrate. To achieve proper OLED operation, the anode material must provide the balance between high transparency, good electrical conductivity, and good chemical stability. Additionally, the materials and thicknesses of the organic layers are crucial in the manufacturing of the OLED. The choice of materials and thicknesses of these layers, therefore, depends on the requirements and performance of the desired application. According to the literature, the most-used material is Alq3 (tris (8-hydroxyquinoline) aluminum) [43]. In the simulation model, Layer 2 is the ITO anode, whose thickness is 150 nm. Layer 3 contains the Hole Transport Layer (HTL), Electron Transport Layer (ETL), and Emissive Layer (EML) with a thickness of 270 nm. Layer 4 is the metal cathode made of aluminum and with a thickness of 120 nm. In order to protect the organic layers against oxidation, an encapsulation layer (Layer 5) is placed at the back of the cathode. After encapsulation, the metal Layer 6 is fixed for heat dissipation. Figure 14b shows the overall size of the proposed OLED model. The antenna is replaced on the front of the OLED to minimize the effect of the metal layer on its radiation, as shown in Figure 14c. The yellowish appearance is the result of the camera settings because the white balance was not set correctly.

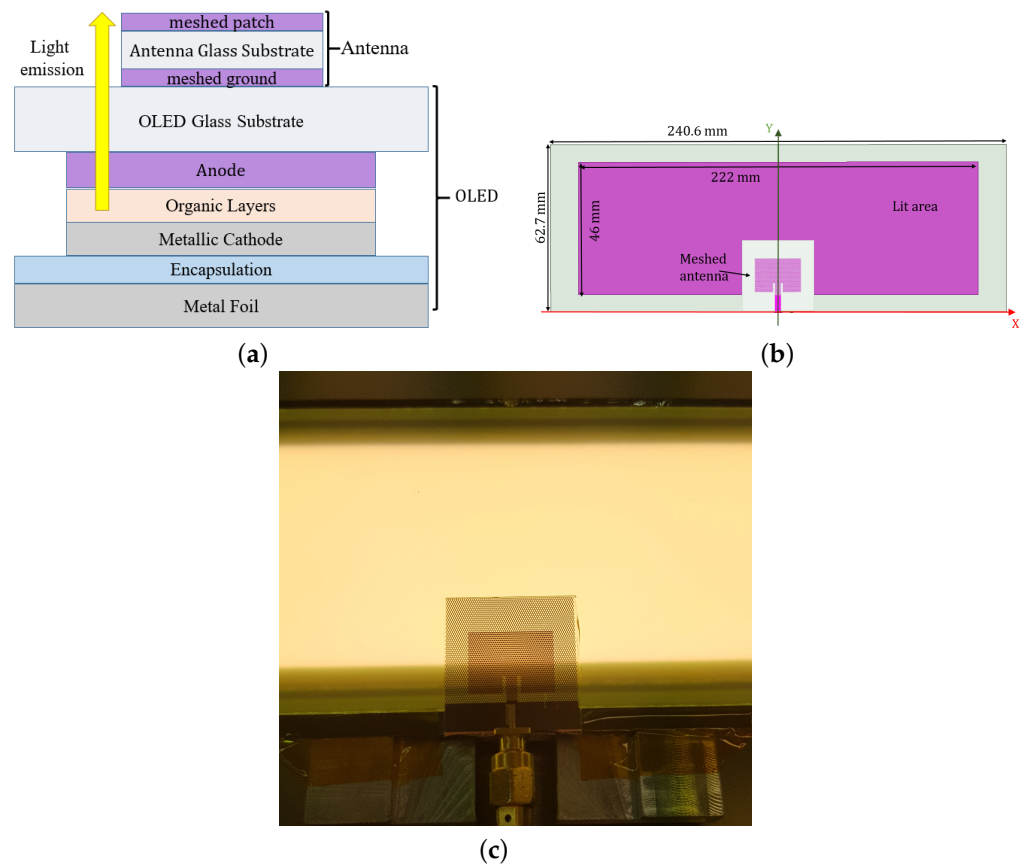


Figure 14. Antenna integration into the OLED structure; (a) cross-sectional view, (b) top view, and (c) in the measurement step.

5.1. OLED Effects on the Antenna Performances

The comparison between the measured and simulated reflection coefficient of the antenna with and without the OLED is shown in Figure 15. From this figure, it can be observed that an acceptable agreement between the results was obtained and the bandwidth can well cover the desired WLAN frequency band. The transparent antenna return loss is affected by the OLED. The layers of the OLED also affect the antenna impedance, and it is less adapted at 50Ω . The resonance frequency of the proposed antenna shifts to low frequencies with a narrow bandwidth.

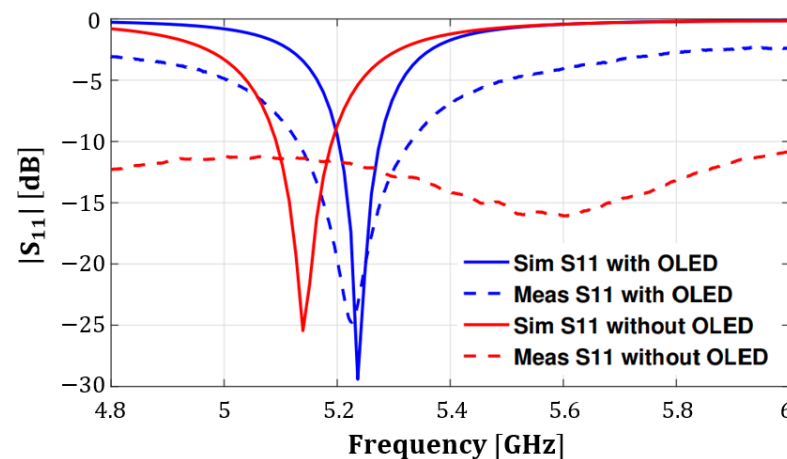


Figure 15. Comparison between measured and simulated return loss and with/without OLED.

Figure 16 shows the comparison between the radiation patterns of the mesh antenna, with and without the OLED: Figure 16a in the XZ-plane, Figure 16b in the YZ-plane, and Figure 16c with the OLED in 3D view. These diagrams are oriented in the direction of the light emission from the OLED. The obtained directivity and gain of the antenna with the OLEDs are 6.67 dBi and 4.86 dBi, respectively, at 5.22 GHz. These values were improved after the integration of the OLED; this can be explained by the effect of the OLED layers, which are considered as the ground plane reflecting the antenna radiation.

However, the materials used in the layers of the OLED light source are extremely critical for their efficiency and lifetime. The OLED panels contain ITO and aluminum electrodes and a metal foil layer, which serves as a reference ground for the antenna. The slight differences between the two results with and without the OLED can be interpreted by the effect of these layers on the antenna radiation. Since, the size of the layers is much larger than the size of the integrated antenna, these layers act as a large ground plane. This ground plane allows electromagnetic waves from the surface to be confined within the OLED panel, rather than radiating outwards. Therefore, these fields affect the electrical and radiation performance of the antenna.

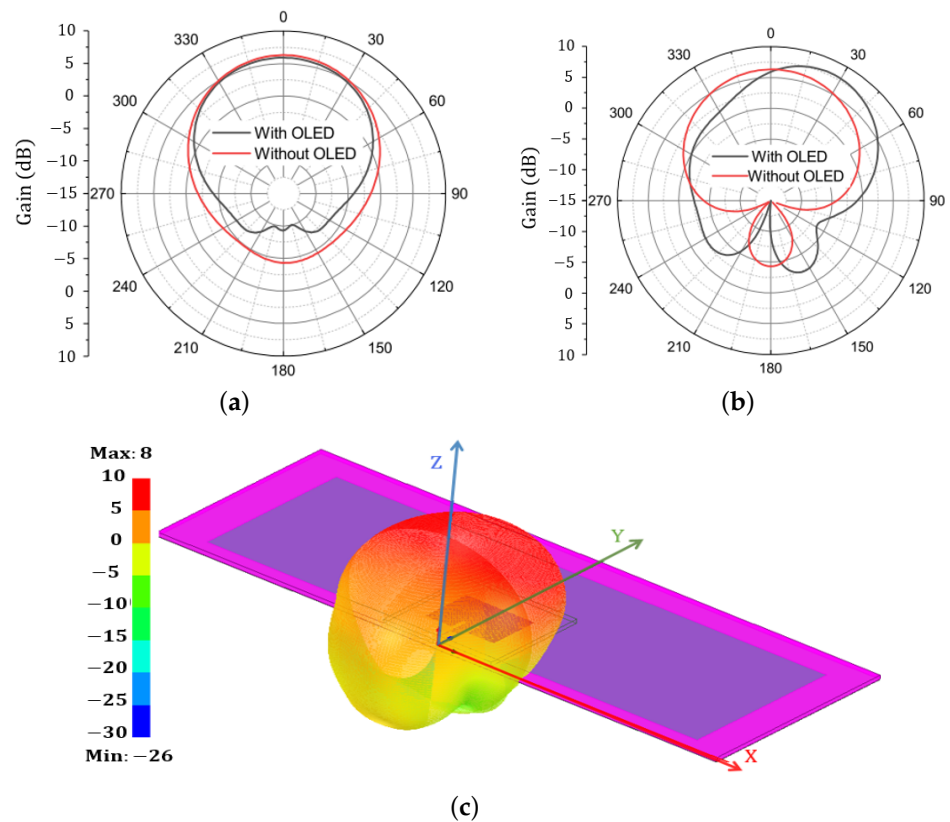


Figure 16. Radiation patterns of the transparent antenna with and without OLED; (a) in the XZ-plane, (b) in the YZ-plane, and (c) with OLED in 3D view.

5.2. Antenna Effects on the OLED Colorimetric Parameters

After the study of the effects of the OLED on the radio-electrical parameters of the antenna, it is very important to investigate the influence of this integration on the color appearance of the OLED. Therefore, the optical and photometric characterizations of the OLED were carried out before and after the antenna integration. Figure 17 shows a photograph of the optical and photonic measurements of the OLED. These measurements were carried out on an optical bench at room temperature with the MINOLTA CS-1000 spectroradiometer. This measuring device was placed 1 m from the OLED, allowing the measurement of the optical and colorimetric parameters in the visible field (380–780 nm) in steps [44]. The measurements were carried out in both with and without the antenna and were repeated 21 times to ensure the accuracy of the measured values.

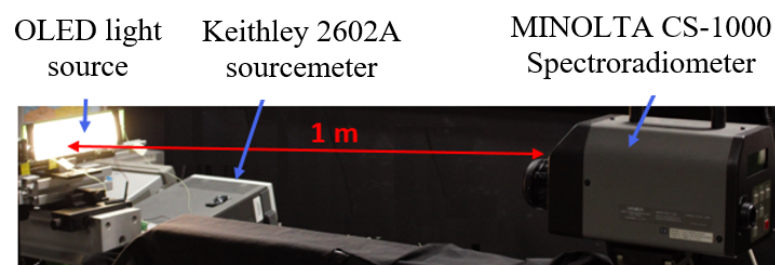


Figure 17. Measuring bench for the optical characterizations.

Then, the colorimetric parameters were calculated using the IES TM-30-18 color-rendering method [45]. Using this method is more appropriate for LED and OLED light sources, because it generates better colorimetric analysis than the CIE fidelity index method. This involves calculating the mean fidelity index (Rf) by the light source rendering test

from 99 Color Evaluation Samples (CES) compared to the International Commission on Illumination (CIE) standard [46], which only considers 8 Test Color Samples (TCS) to calculate Ra (Ra: color rendering index calculated according to the CIE 1995 CRI method). Colorimetric parameters such as the Spectral Power Distribution (SPD), Correlated Color Temperature (CCT), chromaticity coordinates (x, y) and (u', v'), the Duv value (the distance between the chromaticity coordinates (u', v') of the OLED and the Planckian locus on the CIE 1976 color space), Rf (fidelity index), and Rg (Gamut index) were calculated to understand the change in the color appearance of the OLED after the integration of the antenna.

Figure 18 illustrates a comparison between the SPD of a warm white OLED (CCT = 3000 K) and the SPD of the OLED measured with the integrated antenna. It was noticed that the SPD changed after the integration of the antenna. A variation in the SPD generally results in changes in the colorimetric parameters.

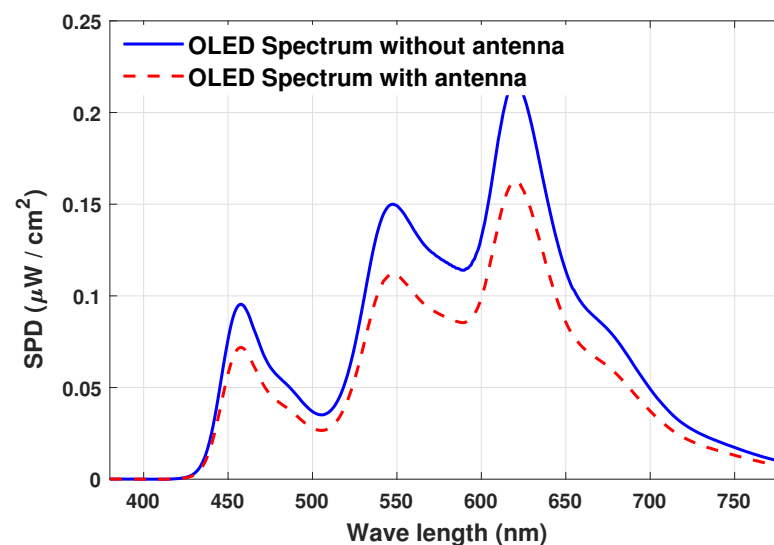


Figure 18. The SPD of the OLED with and without the mesh transparent antenna.

The average CCT, chromaticity coordinates (x, y) and (u', v'), Duv value, Rf, and Rg are shown in Table 2 for both the cases with and without the antenna. According to the MacAdam ellipse, the slight differences observed in these parameters are not detectable by users. The measurements, therefore, showed no significant difference between these parameters with and without the antenna. However, the luminance value decreased by 25% after the antenna was integrated, so this alteration will cause the lamp brightness to be non-uniform.

Table 2. Measured colorimetric parameters of the OLED before and after antenna integration.

Colorimetric Parameters	Without Antenna	With Antenna
Luminance (cd m^{-2})	8654 ± 12.3	6481 ± 8.3
CCT [K]	3037 ± 3.6	3033 ± 0.3
(x, y)	(0.4331, 0.4006)	(0.4330, 0.3998)
(u', v')	(0.2496, 0.5194)	(0.2498, 0.5191)
Duv	−0.0009	−0.0011
(Rf, Rg)	(86, 99)	(86, 99)

6. Conclusions and Perspectives

To the authors' knowledge, this paper has proposed for the first time an original contribution with the experiment tests to integrate a transparent antenna into an OLED light source and can serve as a reference. The discussed method involved first designing a honeycomb mesh that achieved optical transparency. With the chosen mesh parameters,

this transparency was approximately 75.4 %, while the antenna was not visible to the bare eye. This antenna was fabricated using a photolithography process and compared with its non-transparent counterpart in terms of the S-parameters and radiation patterns measured inside an anechoic chamber.

In addition, optical and photometric characterizations were carried out with and without an antenna. The luminance, spectral power distributions, correlated color temperature, CIE 1931 (x,y), CIE 1976 (u',v'), Duv value, fidelity, and gamut indexes were calculated using the IES TM-30-18 color-rendering method. It was assessed that integrating the three-layer antenna degraded the luminance of the OLED by 25 % due to the chosen substrate and mesh dimensions.

Optically transparent antennas will make it possible to replace conventional antennas in future devices. With the development of connected and intelligent objects, present in all sectors such as smart cities, smart lighting, transport, wearables, industry, smart hospitals, etc., these antennas will be crucial in future 6G applications. Therefore, future work will aim to improve the co-integration mechanism using some OLED layers as both a supporting and radiating element as an antenna. On the one hand, this will optimize the manufacturing cost by reducing the number of additional layers added. On the other hand, by minimizing the number of interfaces, it will reduce the transmission losses due to refractive index mismatches, thereby maximizing luminous efficiency. Furthermore, this approach to antenna/OLED co-integration could introduce new solutions for emerging technologies, such as transparent and flexible displays, wearable biomedical devices, and automotive lighting devices.

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