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Article

Aerosol Jet Printed Transparent Wideband Antenna for Solar-Powered IoT Applications

Mustafa Ozcan ^{1,2} * and Yasemin Safak Asar ^{1,3}

¹ Gazi University, Graduate School of Natural and Applied Sciences, Department of Physics, 06500, Ankara, Türkiye

² Gazi University, Faculty of Science, Department of Physics, 06500, Ankara, Türkiye

³ Gazi University, Photonics Application and Research Center, 06500, Ankara, Türkiye

* Correspondence: mustafa.ozcan1@gazi.edu.tr

Abstract

The design, fabrication, and characterization of a highly transparent and flexible monopole antenna optimized for the 3–6 GHz frequency band is presented in this paper. In traditional Transparent Conductive Oxide (TCO) designs, there is always a trade-off between the RF efficiency and transparency. Therefore, an Aerosol Jet® 5X system was used to directly print a silver nanoparticle mesh over a 50-μm polyimide (PI) substrate. With this fabrication method, a durable structure was yield which works well both electrically and mechanically with 85% transparency and a gain of −2.5 dBi. In order to demonstrate how the antenna is flexible and compatible with other devices, it was bent over a cylindrical body and was integrated with a commercial solar panel. The results show that impedance matching and radiation characteristics of the antenna remain stable under bending conditions, and no critical decrease was observed in solar energy harvesting. Consequently, this design presents a suitable solution for energy-autonomous IoT systems, smart windows, and CubeSat applications.

Keywords: transparent antenna; metal mesh structure; energy harvesting; IoT applications; wideband antenna

1. Introduction

As communication devices become more compact and effective, they require aesthetically unobtrusive antennas [1,2]. Transparent and flexible designs are a well-suited solution to this problem, since their structure is naturally low-profile. Therefore, they can be a good alternative for IoT devices, wearables, smart surfaces, and space-constrained CubeSat platforms [3,4].

In order to find a balance between optical transparency and RF performance, new material studies are undoubtedly necessary. While researchers have investigated various conductive materials, including Transparent Conductive Oxides (TCOs), silver nanowires (AgNWs), graphene, and Indium Tin Oxide (ITO), each suffers from inherent limitations [5–7]. Advanced fabrication techniques, such as Aerosol Jet printing and screen printing, have recently unlocked more precise patterning on flexible substrates. This precision is now redefining the limits of optical transparency [8,9].

Recent studies demonstrate transparent antennas operating with acceptable performance in the 2.4 GHz to sub-6 GHz bands [10,11]. Mid-band capabilities of 3–6 GHz are realized through circularly polarized designs [12], wideband fractal slots [13], transparent MIMO configurations [14], and dual-band transparent structures for Wi-Fi 6E [15].

Moreover, comprehensive reviews of flexible antennas indicate that material selection, mechanical robustness, and real-world integration strategies are critical for sub-6 GHz 5G

applications [16–18]. Despite these advancements, it is still very challenging to achieve high transparency, flexibility, and reliable RF performance simultaneously in mid-band applications [19].

In order to bridge this gap, we present a transparent antenna designed for the 3-6 GHz range, fabricated using Aerosol Jet® 5X printing on a polyimide substrate. This method offers better mechanical flexibility and optical transparency compared to traditional approaches. Our experimental results show good agreement with simulations. Thus, the proposed design can be an ideal candidate for low-profile, surface-integrated communication systems.

The following is a summary of this study's contributions:

- **Innovative Fabrication:** Realizing a high-precision metal mesh with reliable RF performance and ~85% optical transparency through the use of Aerosol Jet® printing.
- **Conformal Robustness:** Verifying performance under bending conditions to demonstrate applicability for wearable applications.
- **System-Level Integration:** Demonstrating compatibility with self-powered IoT platforms, where the antenna shows negligible impact on the efficiency of commercial solar cells.

2. Antenna Configuration and Design Guidelines

To avoid the excessive simulation times associated with complex mesh geometries, we determined the antenna geometry (Figure 1) and design parameters (Table 1) using standard methodologies for fully metallic structures. A Coplanar Waveguide (CPW) feed was chosen to simplify the fabrication process, since the radiating element and ground plane are on the same substrate layer. Finally, a circular monopole configuration was selected to improve impedance bandwidth and ensure omnidirectional radiation.

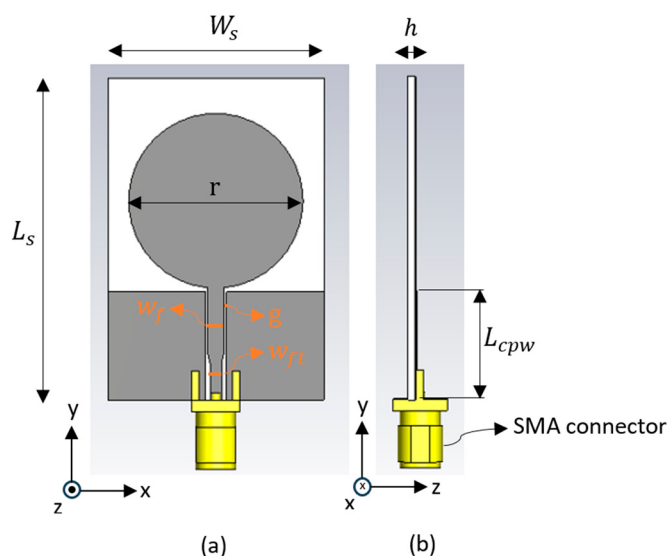


Figure 1. Designed antenna geometry (a) top view and (b) side view.

A polyimide ($\epsilon_r = 3.5$, $\tan \delta = 0.0027$) substrate was used due to its availability, optical transparency, and flexibility. To use it in wearable applications, a thin substrate thickness of $50 \mu\text{m}$ was selected. We set the gap (g) to 0.20 mm and the signal line width (w_f) to 2.20 mm for achieving an 50Ω impedance matching. An SMA connector was included in the simulation to improve the agreement between simulated and measured results.

Table 1. Design parameters of the proposed antenna.

Parameter	Dimension (mm)
W_s	30.00
L_s	45.00
h	0.05
r	25.00
g	0.20
w_f	2.20
w_{ft}	1.60
L_{cpw}	13.50

3. Fabrication Process via Aerosol Jet Printing

An Aerosol Jet® 5X system (Figure 2a), which precisely deposits atomized conductive inks (silver nanoparticles) onto the substrate, was used for fabrication. With this method, it is possible to fabricate mesh structures ranging from micrometers to millimeters.

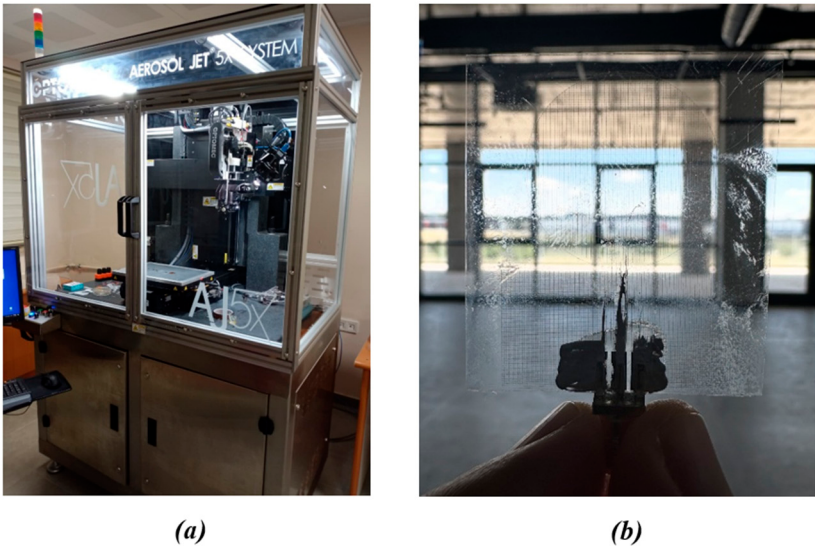


Figure 2. (a) Aerosol Jet® 5X printing machine, (b) fabricated antenna.

The manufactured prototype antenna is shown in Figure 2b, where the mesh line width is about 30 μm and the unit cell spacing is 250 μm. To ensure alignment and prevent short circuits on the slippery polyimide surface, the connector was bonded using silver adhesive and a custom mold. The gap between the signal line and ground planes was kept clear of silver adhesive to prevent impedance mismatch.

4. Experimental Validation and Discussion

4.1. Reflection Coefficient and Radiation Patterns

The reflection coefficient (S_{11}) of the antenna was obtained using a VNA, and the radiation pattern was measured in an anechoic chamber (Figure. 3). The maximum realized gain of the antenna was -2.5 dBi.

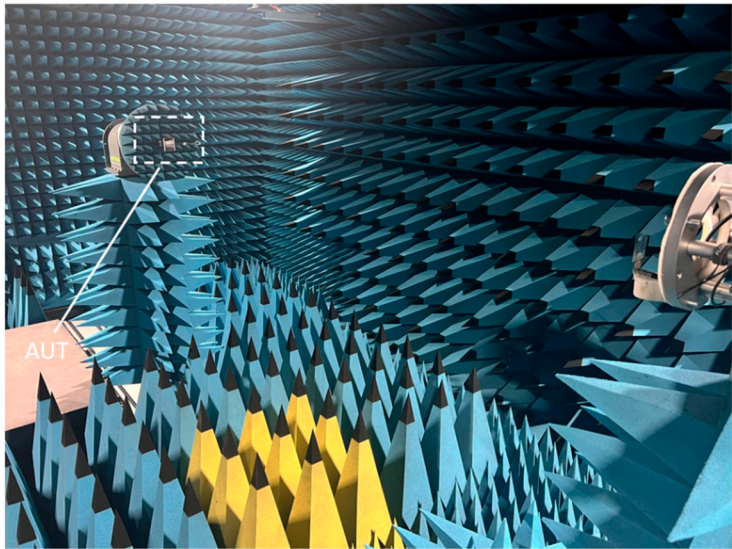


Figure 3. Measurement setup inside the anechoic chamber.

Although the measurement and simulation results for S_{11} agreed well (Figure 4), small deviations in the radiation pattern, specifically in the null regions at $\theta = 90^\circ$ and $\theta = 270^\circ$ (Figure 5a), were observed.

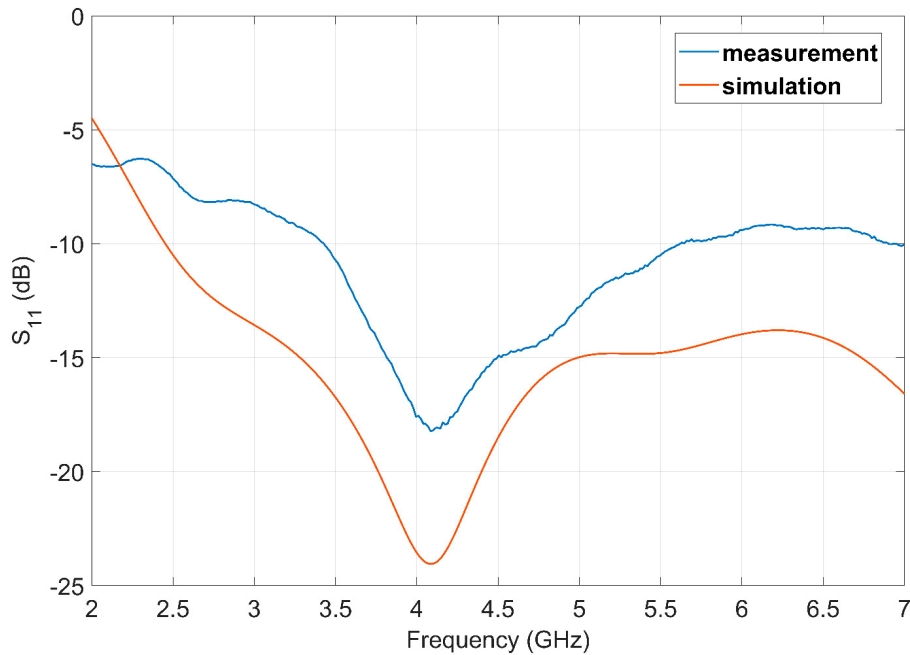


Figure 4. Measured and simulated results of the antenna reflection coefficient.

It is believed that these differences stem from the experimental setup. The metallic rotator and the relatively large SMA connector (compared to the 50 μm substrate) acted as reflectors and scattered the waves.

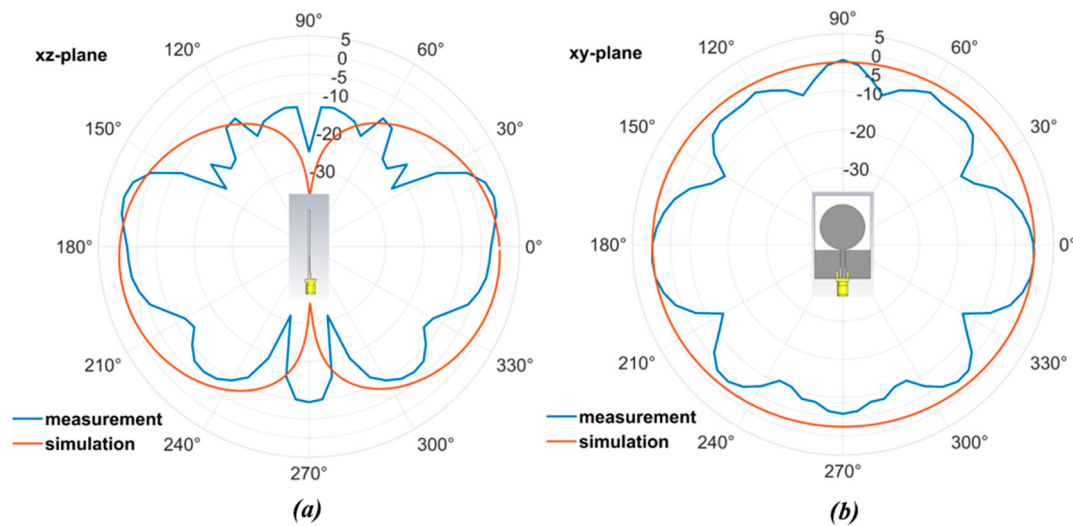


Figure 5. Measured and simulated co-polarized radiation patterns of the antenna at 4.5 GHz (a) xz-plane, (b) xy-plane.

The overall radiation characteristics in both planes closely match theoretical predictions in spite of these artifacts.

5. Optical Transparency Analysis

The sparse metallic mesh structure of the antenna provides transparency. The geometric aperture ratio of the grid structure can be used to theoretically estimate the effective optical transmittance (T_{opt}) of the antenna region due to the high transparency of the polyimide substrate. The transparency of a square mesh lattice is defined as [5]:

$$T_{opt} = \left(\frac{p - w}{p} \right)^2, \quad (1)$$

where w is the width of the printed conductive lines and p is the pitch (unit cell periodicity), defined as the sum of the line width and the spacing between lines ($p = w + s$).

It was used an optical microscopy to measure the geometric dimensions of the printed mesh to verify the fabrication precision (Figure 6). The inter-line spacing (s) and the average conductor width (w) were found to be 279 μm and approximately 21 μm , respectively. This corresponds to a periodicity (p) of 300 μm . From Eq. (1), the geometric optical transparency is calculated as 86.5% using the measured dimensions. In order to validate the theoretical estimation, optical transmittance was also measured at a wavelength of 550 nm. The result was found to be approximately 85%, which shows excellent agreement with the theoretical calculation.

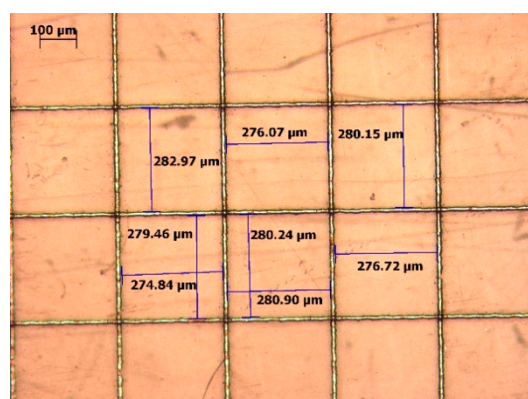


Figure 6. Measured and simulated co-polarized radiation.

6. Integration with Photovoltaic Solar Cells

To understand the integration effects on the return loss, a test with a commercial solar cell was performed and the results are shown in Figure 7. As seen from the results, this integration caused an approximately 600 MHz downward frequency shift. The glass cover of the solar cell and the silicon layers inside result in such a shift. The antenna still operates within the 3-6 GHz range, despite this expected change. Furthermore, the effect of the antenna on the energy harvesting efficiency of the solar cell was also investigated. The solar cell open-circuit voltage (V_{oc}) was approximately 1.5 V under ambient sunlight. It was observed that this voltage remained virtually unchanged when the antenna was placed over the cell. This result confirms that the metallic mesh structure has high optical transmittance, and the solar cell continues to maintain its power generation under negligible shadowing conditions.

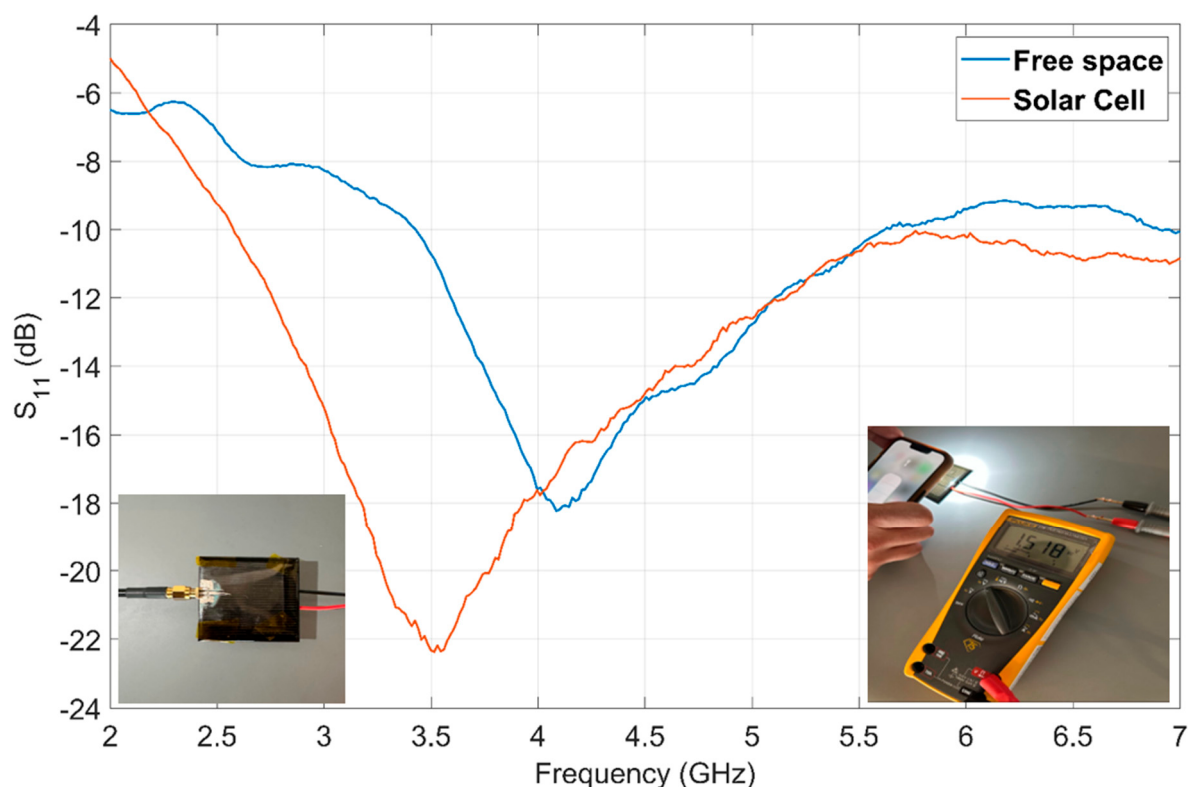


Figure 7. Measurement setup for the transparent antenna integrated with a photovoltaic solar cell and measured reflection coefficient (S_{11}) comparing the free-space and solar-cell-integrated configurations.

7. Mechanical Flexibility and Performance on Curved Surfaces

To show that the antenna can be easily wrapped around different surfaces without operational issues, the reflection coefficient was measured when mounted on a cylindrical body (Figure 8). A distinct resonance shift was observed when the antenna was put on the body, which changes the effective dielectric constant (ϵ_{eff}). However, it was observed that the bending itself had only minor effects on the antenna's reflection coefficient. Conformal bending caused an additional downward frequency shift in comparison to the cylindrical backing case, as expected. The antenna's effective length increased when it was wrapped around the cylinder, which caused an extra shift. Despite these frequency shifts, the antenna successfully maintained its wideband impedance matching characteristics.

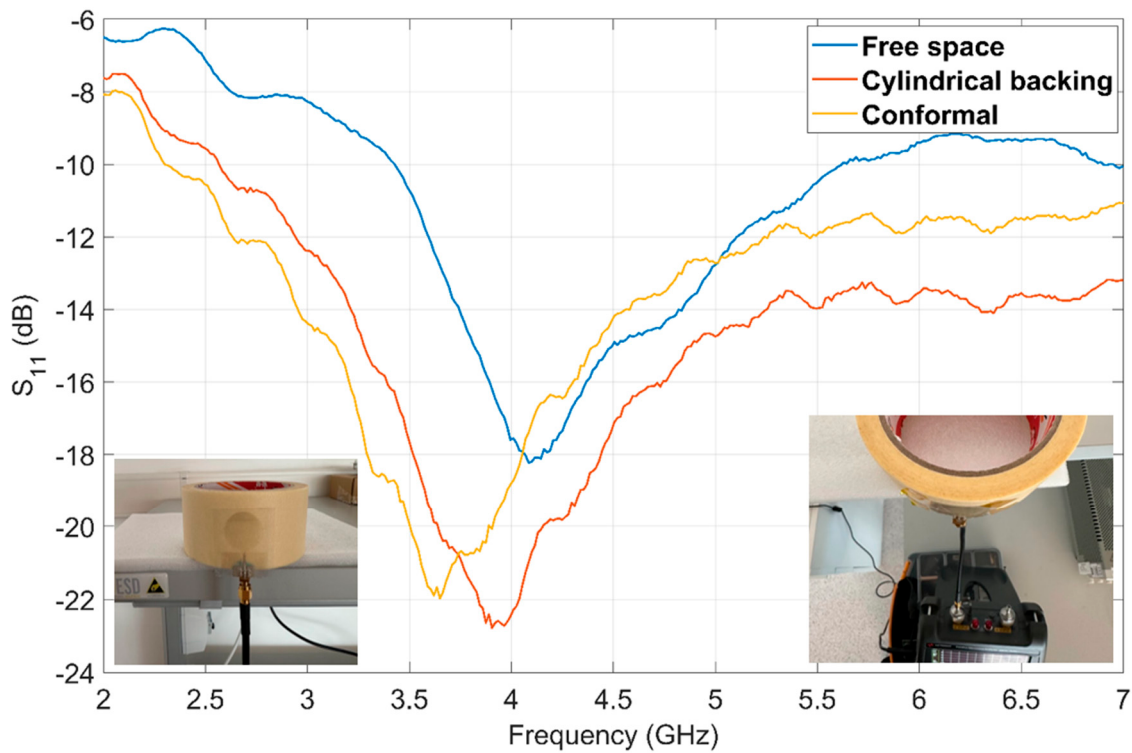


Figure 8. Measurement setup of the conformal antenna under bending conditions on a cylindrical support and measured reflection coefficient (S_{11}) for free space, cylindrical backing, and conformal bending configurations.

8. Comparison of the Proposed Antenna with Reported Transparent Antennas

A comparison between recent studies and our work is provided in Table 2. Transparent antennas reported in the literature are mostly designed using Transparent Conductive Oxides (TCOs) or metal meshes/nanowires, each exhibiting distinct advantages and disadvantages.

For instance, antennas utilizing TCO materials such as AgHT-4 or AgHT-8 [10,21] can obtain wide impedance bandwidths; however, they usually have low optical transparency (less than 75%) and a brownish tinge due to material properties. While ITO-based designs can be more transparent, they often require hard glass substrates, making them unsuitable for conformal and wearable applications [13].

On the other hand, recent studies [14,20] demonstrate that metal mesh and nanowire-based antennas yield superior optical transparency (>83%) and efficiency. Yet, due to their resonant characteristics, these designs often exhibit relatively narrow bandwidths (e.g., 4.4–5.0 GHz), unlike the broad bandwidth (3–6 GHz) achieved in this work. Furthermore, other flexible approaches fabricated with silver wires [6] and conductive inks [9] have been reported to suffer from lower realized gain and single-resonant-frequency operation.

The proposed antenna presents a superior balance between these parameters. It combines the broad bandwidth features of TCO antennas and the high optical transparency (~85%) of metal mesh designs into a single structure with high mechanical flexibility. Furthermore, its compatibility with commercial solar cells and conformal energy-autonomous IoT devices is demonstrated with negligible shadowing effects.

Table 2. Comparison of the proposed antenna with recently reported antennas.

Reference	Frequency (GHz)	Conductor Type / Structure	O.T. (%)	Peak Gain (dBi)	Flexibility
This study	3–6	Aerosol Jet® 5X (Metal Mesh)	85%	-2.5	High
[6]	2.45	Ag NWs / Screen Printing	85%	N/A	Yes
[9]	2.45	PEDOT: PSS /Aerosol Jet	~80%	-3.6	Limited
[10]	3.15–32	AgHT-8 / Laser Cutting	>75%	-4.8 (Avg)	Yes
[13]	2.99–6.82	ITO-PET / Manual Cutting	<87%	1.3	No
[14]	4.41–4.56	Wired Metal Mesh	83%	3.2	Yes
[20]	4.4–5	Ni-Metallic Mesh / Electrodeposition	91%	3.8	Yes
[21]	2.21–6	AgHT-4 / Manual Cutting	70%	0.53	Yes

9. Conclusions

In this study, the design, fabrication, and measurement of an optically transparent flexible monopole antenna operating between 3 and 6 GHz are presented. A metallic mesh structure was printed on a 50 μm thick polyimide (PI) substrate using a high-precision Aerosol Jet® 5X machine.

Return loss and optical transparency measurements exhibit strong agreement with the simulation, while some discrepancies are observed in the far-field patterns, particularly in the *xz*-plane. This discrepancy is thought to stem from the metallic casing of the antenna rotator and the large SMA connector inducing scattering effects relative to the thin substrate. To our knowledge, that presented type aerosol printing approach has not been documented yet in the literature to achieve such high optical transparency (~85%) and -2.5 dBi realized gain. Antenna designs that exhibit increased gain and transparency typically possess either a limited operational bandwidth or require complicated fabrication techniques, such as thin-film deposition. The presented antenna, despite having lower gain, offers production simplicity and a broader bandwidth, making it comparable to conventional ITO and metal-mesh-based designs.

In addition, the flexible structure and platform compatibility of the antenna were studied in this research. Firstly, the antenna was wrapped around a simple masking tape roll (radius = 100 mm) to understand its flexibility. Separately, it was placed over a commercial solar cell. The return loss of the antenna was measured during these experiments. Results show that the antenna maintains its wideband property, although the resonance points shift. Furthermore, the open-circuit voltage (V_{oc}) remains the same, which demonstrates that the antenna's shadowing effect is negligible while the antenna is placed over the solar cell. As a result, the proposed antenna offers a promising solution for "invisible" wireless communication systems such as next-generation smart cities, autonomous vehicles, and aesthetic-critical CubeSat platforms, since it can easily integrate with the platforms and has simple fabrication steps

Author Contributions: Conceptualization, M.O. and Y.S.A.; methodology, M.O. and Y.S.A.; software, M.O.; validation, M.O. and Y.S.A., formal analysis, Y.S.A.; investigation, M.O.; resources, Y.S.A.; data curation, M.O. and Y.S.A.; writing—original draft preparation, M.O.; writing—review and editing, Y.S.A.; visualization, M.O.;

supervision, Y.S.A.; project administration, Y.S.A. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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Conflicts of Interest: The authors declare no conflicts of interest.

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