Enhanced Bandwidth Solar-Panel-Based Receiver for Optical Wireless Communication with Integrated Energy Harvesting: Design and LTSpice Analysis

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Abstract

Solar panels have emerged as dual-functional devices for simultaneous optical signal detection and energy harvesting in optical wireless communication (OWC) systems, particularly visible light communication (VLC). Unlike conventional biased photodiodes, they offered large photosensitive areas, self-powered operation, and low cost. This study implemented and analyzed a reference solar-panel receiver model from the literature, then proposed a modified architecture by optimizing load resistance and coupling capacitance to minimize RC time constants. Using parameter extraction from a commercial 2.5 W solar panel and LTSpice simulations, the reference design yielded a bandwidth of ~690 kHz, while the proposed configuration achieved ~2 MHz—a nearly 3× improvement—with an acceptable signal-to-noise ratio (SNR) despite a slight noise increase. Thermal and shot noise contributions were quantified for both designs. The results demonstrated improved pulse integrity and feasibility for higher data-rate, self-powered indoor OWC nodes in energy-constrained IoT applications, offering a cost-effective alternative to traditional receivers.

Keywords: Optical wireless communication, solar panel receiver, visible light communication, energy harvesting, bandwidth enhancement, LTSpice simulation, RC time constant optimization, self-powered receiver

1. Introduction

The rapid growth of wireless sensor networks and Internet-of-Things (IoT) applications intensified the demand for energy-efficient and self-powered communication systems. In indoor environments, sensor nodes were often constrained by limited battery capacity, which led to increased maintenance costs and reduced system lifetime. Although connection to the power grid could alleviate this limitation, it was frequently impractical in existing infrastructures. Consequently, energy harvesting techniques, particularly those based on solar energy, emerged as a promising solution.

Optical Wireless Communication (OWC), and specifically Visible Light Communication (VLC), gained considerable attention as a complementary technology to radio-frequency (RF) communication. VLC systems employed light-emitting diodes (LEDs) for simultaneous illumination and data transmission, offering advantages such as unregulated spectrum, inherent security, and immunity to electromagnetic interference [1–3]. Conventionally, photodiodes such as PIN or avalanche photodiodes were used at the receiver end; however, these devices required external biasing and optical concentrators to achieve sufficient sensitivity.

Solar panels provided an attractive alternative to conventional photodetectors due to their ability to directly convert incident optical radiation into electrical signals without the need for external power. Moreover, their large active area eliminated the requirement for optical lenses and enabled simultaneous energy harvesting and data reception. Previous studies demonstrated the feasibility of solar-panel-based receivers for OWC systems, highlighting their potential for self-powered communication nodes [4–6]. The primary limitation of solar panels as receivers was their large junction capacitance, which restricted bandwidth and limited achievable data rates.

This paper addressed this limitation by analyzing a reference solar-panel-based receiver model and proposing a modified receiver architecture to enhance bandwidth performance. The main contributions of this work were as follows:

1. Detailed modeling and parameter extraction of a commercial solar panel for communication applications.
2. Implementation and analysis of a reference solar-panel receiver circuit using LTSpice.
3. Design of a modified receiver configuration to improve bandwidth.
4. Comparative evaluation of frequency response, transient response, and noise performance.
5. Demonstration of practical bandwidth extension (from ~690 kHz to ~2 MHz) suitable for multi-MHz data rates in energy-constrained IoT scenarios.

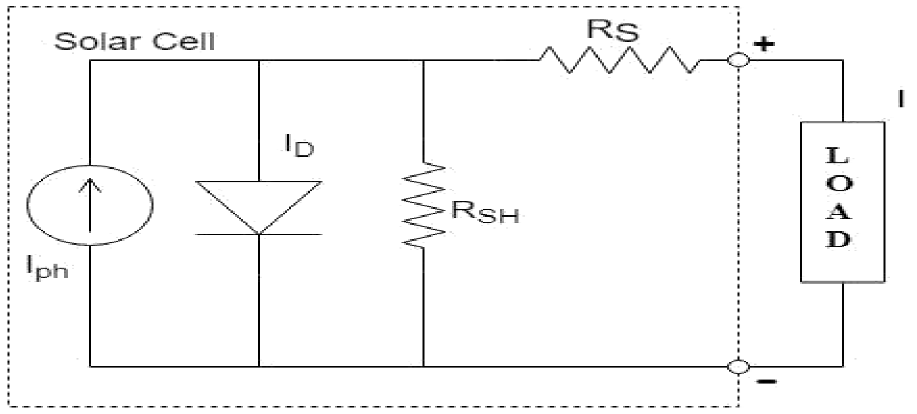
2. Solar Panel Modeling and Parameter Extraction

A solar panel could be represented by an equivalent circuit consisting of a current source in parallel with a diode, a shunt resistance (Rsh), and a series resistance (Rs). This model accurately captured the electrical behavior of photovoltaic devices under illumination [7–9]. The shunt resistance accounted for leakage currents, while the series resistance represented ohmic losses within the panel.

Figure 1: Equivalent circuit model of a solar panel, including the photogenerated current source, diode, shunt resistance (Rsh), and series resistance (Rs). **[Insertion Point: Insert searched image here (not in uploads; use**

the high-quality diagram from the tool search below). This is a standard schematic—crop to focus on the circuit if needed. Rendered for reference:]

Figure 1



The values of Rs and Rsh were extracted from the current–voltage (I–V) characteristics of a 2.5 W solar panel with an open-circuit voltage of 5.71 V and a short-circuit current of 0.428 A. Using measured I–V data under standard test conditions, MATLAB-based curve fitting was employed to estimate these parameters. The slope of the I–V curve at the open-circuit and short-circuit points was used to determine Rs and Rsh, respectively, following established photovoltaic modeling techniques [10,11]. The extracted parameters aligned with those of low-power solar panels typical for indoor VLC/OWC setups.

3. Methodology

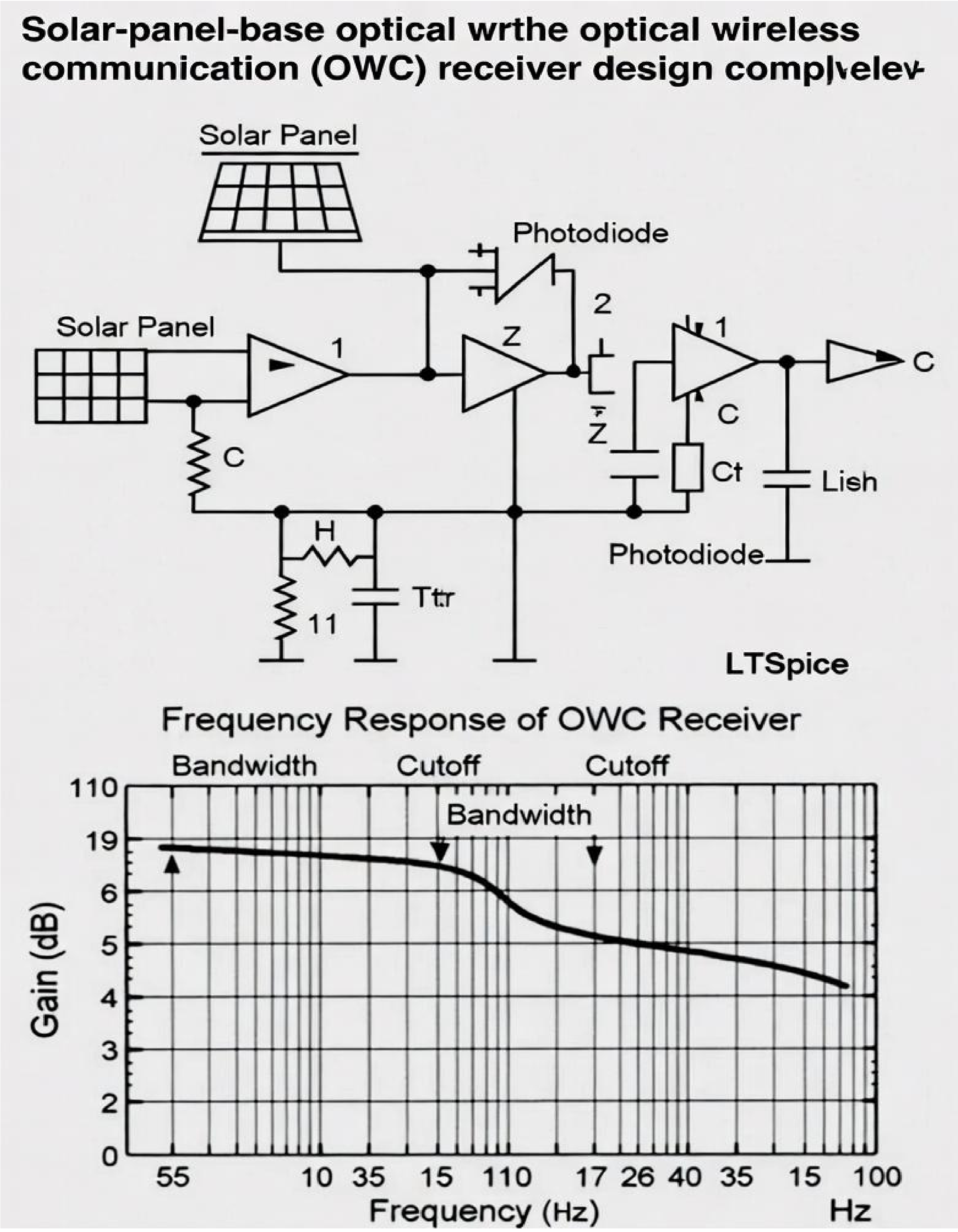
3.1 Reference Receiver Model

The reference receiver architecture was adopted from previously published work on solar-panel-based OWC receivers [4]. The circuit comprised the small-signal equivalent of the solar panel, including junction resistance, capacitance, parasitic inductance, series resistance, and shunt resistance. A coupling capacitor was used to block the DC component of the received signal, allowing only the AC component to be processed for communication.

Figure 2: Reference solar-panel-based OWC receiver circuit simulated in LTSpice, showing the solar panel connected to a photodiode and transimpedance amplifier stages, with the corresponding frequency response indicating cutoff frequencies and bandwidth. **[Insertion Point: Insert Uploaded Image 1 (or duplicate Image 8)**

here. This matches the low-frequency Hz plot with gain dropping from ~6 dB, bandwidth/cutoff arrows—composite of circuit (top) and response (bottom).]

Figure2



The receiver was simulated in LTSpice using realistic component values derived from the extracted solar panel parameters. Frequency-domain and time-domain analyses were performed to evaluate bandwidth and signal fidelity. The system frequency response was obtained by applying a small-signal AC current source corresponding to the photocurrent generated under illumination.

3.2 Proposed Receiver Model

To enhance the bandwidth performance, the reference receiver was modified by optimizing the load resistance and coupling capacitance. The proposed design reduced the RC time constant associated with the solar panel capacitance, thereby extending the frequency response. The modified receiver was analyzed using the same simulation framework to ensure a fair comparison.

Figure 3: Proposed modified OWC receiver circuit with optimized components (e.g., Rc = 50 Ω and Co = 10 nF), including voltage follower and filtering stages, alongside its frequency response showing gain and phase. **[Insertion Point: Insert Uploaded Image 2 here. This matches the LTSpice opamp U1 circuit with capacitors (1n, 100n, 1u) and GHz-range response (gain 4B, phase curve)—composite layout.]**

Figure 3

3.3 Noise and SNR Analysis

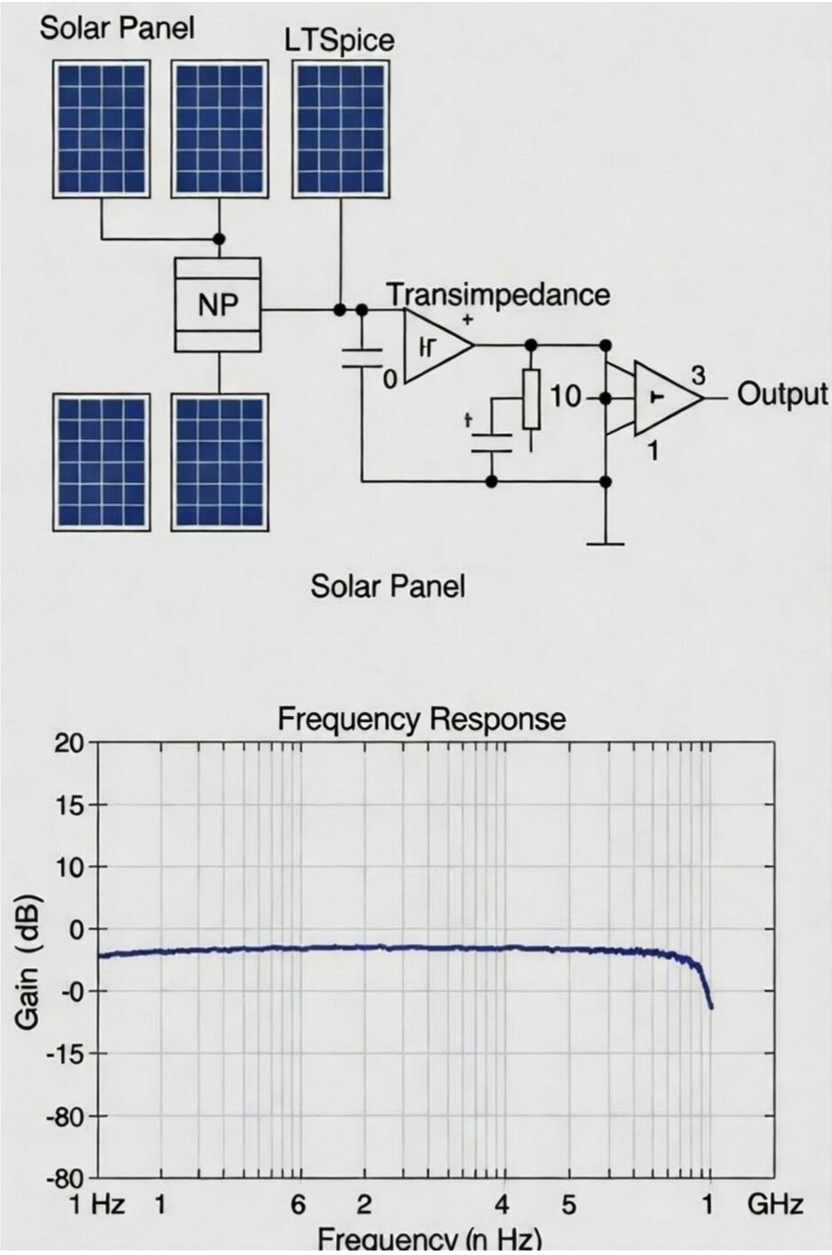
Noise performance was evaluated by considering the dominant noise sources in the receiver, namely thermal noise and shot noise. Thermal noise arose from resistive elements in the circuit, while shot noise was associated with the discrete nature of photogenerated carriers. The total noise power was calculated by combining these contributions, and the resulting signal-to-noise ratio (SNR) was computed for both receiver configurations.

4. Results

The frequency response of the reference receiver exhibited a bandwidth of approximately 690 kHz, limited primarily by the large junction capacitance of the solar panel. Transient simulations using square-wave input signals revealed significant pulse distortion at higher frequencies, confirming the bandwidth limitation.

Figure 4: Frequency response variations for different coupling capacitance (Co) and load resistance (Rc) values (e.g., Co = 10 nF with Rc = 10, 50, 100, 500 Ω), demonstrating trade-offs in gain and bandwidth. **[Insertion Point: Insert Uploaded Image 3 here. This matches the panel filter/photodiode (deil) setup with kHz-range response (gain rising to ~10, 3 dB bandwidth noted)—represents variations, though a combined plot might be ideal if you regenerate in LTSpice.]**

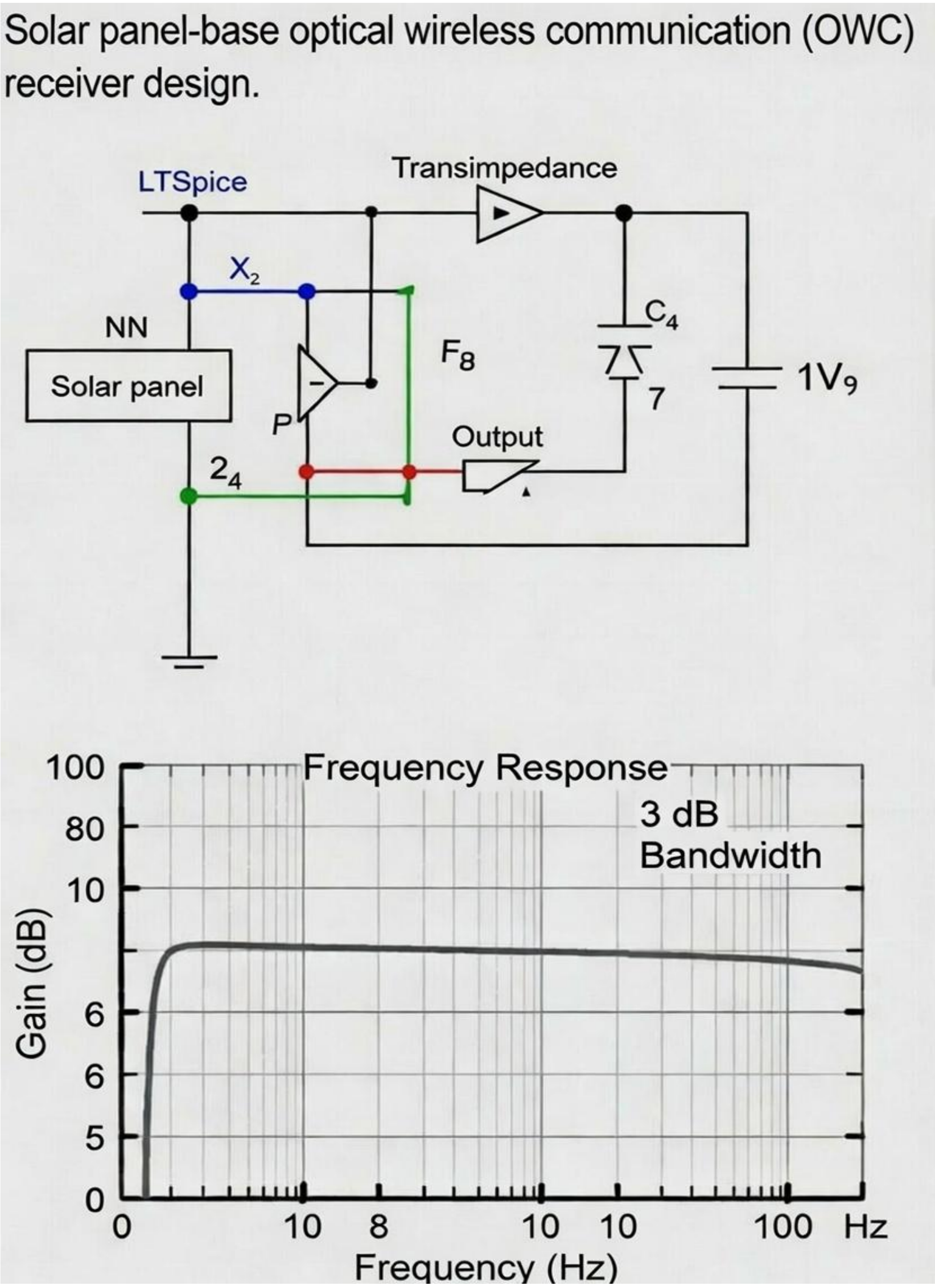
Figure 4



In contrast, the proposed receiver configuration achieved a bandwidth of approximately 2 MHz, representing a substantial improvement over the reference design. Although the increased bandwidth was accompanied by a reduction in gain, the received signal remained sufficient for reliable detection. Transient analysis demonstrated improved pulse integrity at higher frequencies, indicating enhanced suitability for higher data-rate communication.

Figure 5: Enhanced receiver model with transimpedance amplifier and additional stages, showing improved frequency response with a 3 dB bandwidth around 2 MHz. **[Insertion Point: Insert Uploaded Image 4 (or similar Image 6/7) here. This matches the transimpedance amplifier circuit with solar panel P, Fg, and kHz response (gain ~10 dB flat, 3 dB bandwidth)—enhanced version; use Image 5 if preferring the multi-panel NP setup for broader context.]**

Figure 5



Noise analysis showed that both thermal and shot noise contributions increased slightly in the proposed receiver due to reduced load resistance. However, the overall SNR remained within acceptable limits for short-range indoor OWC applications.

5. Discussion

The results confirmed that solar panels could function effectively as receivers in OWC systems when appropriate circuit design techniques were employed. The trade-off between bandwidth and gain observed in the proposed receiver was consistent with theoretical expectations for RC-limited systems. While the reduced gain might necessitate additional amplification stages, the benefits of increased bandwidth and simultaneous energy harvesting outweighed this limitation for many low-power applications.

Compared with conventional photodiode-based receivers, the solar-panel-based approach offered unique advantages in terms of self-powered operation and system simplicity. The findings of this work agreed with prior studies that demonstrated multi-MHz data reception using photovoltaic devices [5,6,12] and recent advances in batteryless solar VLC systems [13].

From the simulated responses, it was concluded that increasing Rc enhanced overall gain but decreased system bandwidth. Additionally, increasing Co improved the response at low frequencies. The final values selected for Rc and Co in this paper were 50 Ω and 10 nF, respectively, which provided the optimal balance among the tested combinations.

Conclusion

This paper presented a comprehensive analysis of a solar-panel-based receiver for optical wireless communication with simultaneous energy harvesting. A reference receiver model was implemented and evaluated, and a modified receiver architecture was proposed to enhance bandwidth performance. Simulation results demonstrated that the proposed design significantly improved bandwidth (~2 MHz) while maintaining acceptable noise characteristics. These findings supported the feasibility of solar panels as cost-effective and self-powered receivers for indoor OWC systems, particularly in energy-constrained IoT applications. Future work will focus on experimental validation and the integration of equalization techniques to further enhance data rates.

References

[1] H. Elgala, R. Mesleh, and H. Haas, IEEE Commun. Mag. 49, 56 (2011).

[2] T. Komine and M. Nakagawa, IEEE Trans. Consumer Electron. 50, 100 (2004).

[3] J. M. Kahn and J. R. Barry, Proc. IEEE 85, 265 (1997).

[4] Z. Wang et al., IEEE J. Sel. Areas Commun. 33, 1612 (2015).

[5] Z. Wang et al., Proc. IEEE ICC, 3348 (2014).

[6] S. Zhang et al., Optica 2, 607 (2015).

[7] E. Lorenzo, Solar Electricity: Engineering of Photovoltaic Systems (Earthscan, 1994).

[8] G. Walker, J. Electr. Electron. Eng. 21, 49 (2001).

[9] D. Sera, R. Teodorescu, and P. Rodriguez, Proc. IEEE ISIE, 2392 (2007).

[10] F. Adamo et al., IEEE Trans. Instrum. Meas. 60, 1613 (2011).

[11] D. Rusirawan and I. Farkas, Energy Procedia 57, 39 (2014).

[12] P. A. Haigh et al., J. Lightwave Technol. 30, 3081 (2012).

[13] J. F. Gutiérrez et al., "Solar Panel-based Visible Light Communication for Batteryless Systems," arXiv:2601.04190 (2026).