

Low Complexity Optical Inter-Satellite Communication Using Triple Junction Solar Cells

Ziheng Wang, Matthew Anderson, Mario Badás Aldecocea, Mohammad Dabiri, Hossein Safi, Harald Haas, and Iman Tavakkolnia

LiFi research and Development Centre, Electrical Engineering Division, University of Cambridge, Cambridge, United Kingdom

ABSTRACT

Pointing and acquisition remain major constraints in optical inter-satellite links. This work demonstrates a low-complexity auxiliary-reception concept that repurposes the spacecraft photovoltaic surface, already present for power generation, and adds a passive AC/DC (alternating-current/direct-current) separation path to detect the incoming optical modulation. A GaInP/GaAs/Ge triple-junction cell is integrated and tested at 980 nm using direct-current-biased optical orthogonal frequency-division multiplexing (DCO-OFDM). In darkness, irradiances of 14.1 and 5.64 W m⁻² yield Shannon capacity estimates of 6.32 and 2.44 Mbit/s, respectively. End-to-end transmissions using a BER threshold of 3×10^{-3} achieve data rates of 2.18 and 1.21 Mbit/s under the same conditions. Optical-power measurements and propagation analysis relate the experimental irradiances to transmitted optical power and link distance. The results establish an architecture in which spacecraft solar cells serve as secondary optical receivers.

Keywords: optical inter-satellite communication, photovoltaic receiver, triple-junction solar cell, optical communication, DCO-OFDM, experimental characterisation

1. INTRODUCTION

Establishing an optical inter-satellite link requires the pointing, acquisition, and tracking (PAT) system to place a narrow transmitted beam on the dedicated receive aperture. During acquisition, the beam may already illuminate the spacecraft body or photovoltaic surface while still missing the terminal, so optical power reaches the spacecraft but not the communication receiver. The photovoltaic surface provides a natural auxiliary capture area because it already presents a substantial exposed area for power generation. An alternating-current (AC) extraction path can route the modulated photocurrent to the acquisition electronics while maintaining a separate direct-current (DC) path for the cell's electrical output. Previous photovoltaic receivers establish the technical basis for this architecture. Wang *et al.* combined solar-energy harvesting with orthogonal frequency-division multiplexing (OFDM) reception;¹ Fakidis *et al.* demonstrated 0.5-Gb/s and 1.04-Gb/s laser links using single-junction GaAs photovoltaic receivers with adaptive bit and power loading;^{2,3} Younus *et al.* later achieved 3.8 Gb/s using multi-segment GaAs photonic power converters (PPCs);⁴ and Anderson *et al.* extended optical reception to large semitransparent CdTe panels and examined their tolerance to angular and lateral misalignment.⁵ Extending this receiving function to a spacecraft gallium indium phosphide/gallium arsenide/germanium (GaInP/GaAs/Ge) triple-junction cell requires the contact arrangement, mechanical support, illumination geometry, electrical loading, and signal extraction path to be integrated as a complete receiver.

This work implements that integration using a 27 cm² spacecraft cell secured in a custom 3D-printed holder, interfaced through a custom printed circuit board (PCB), and connected to an external AC extraction circuit. A square microlens forms a uniform 980 nm illumination footprint across the exposed photovoltaic surface. A direct-current-biased optical orthogonal frequency-division multiplexing (DCO-OFDM) waveform places equal-power quadrature phase-shift keying (QPSK) symbols on 255 independent subcarriers spanning 9.77 kHz to 2.49 MHz.

Corresponding author: Ziheng Wang, email: zw475@cam.ac.uk

The experimental characterisation follows the signal from optical delivery to capacity and data-rate measurements. Optical-power measurements at multiple positions in the illumination field provide aperture-averaged estimates of the incident irradiance, while propagation calculations relate transmitted optical power and link distance to the irradiance across the receiving cell. Under dark laboratory conditions, a signal-to-noise ratio (SNR) estimator characterises the frequency-dependent signal quality of the assembled optical and electrical path at two irradiance levels. Subcarriers with non-negative SNR are retained, and the cyclic extensions are included in the OFDM symbol duration when calculating the aggregate Shannon capacity. End-to-end DCO-OFDM transmission then measures the data rate achieved at a BER threshold of 3×10^{-3} .

2. EXPERIMENTAL SETUP AND METHODS

2.1 Cell holder and interface PCB

The experimental receiver was built around a GaInP/GaAs/Ge triple-junction spacecraft photovoltaic cell manufactured by Lightricity with an area of 27 cm^2 . Integrating the cell into the optical bench required mechanical support that left the illuminated surface exposed and an electrical interface that converted its rear and edge contacts into a coaxial output. The resulting design combines a custom 3D-printed open-frame holder with a dedicated interface PCB, as shown in Figure 1. The holder follows the perimeter of the device and restrains the cell without covering the photovoltaic surface or obstructing its edge connections; four corner screws secure the complete assembly to the supporting board. The PCB accommodates the cell's contact arrangement through a broad contact region beneath the device and a series of smaller pads along one edge. Metal tabs bridge the cell contacts to these pads, and the PCB routes the generated photocurrent to a subminiature version A (SMA) coaxial connector linked to the external extraction circuit. With the cell secured above the board, the open front face admits the uniform illumination, while the SMA port connects the cell output to the receiver chain. The completed module serves as the receiving element in the optical and electrical bench described next.

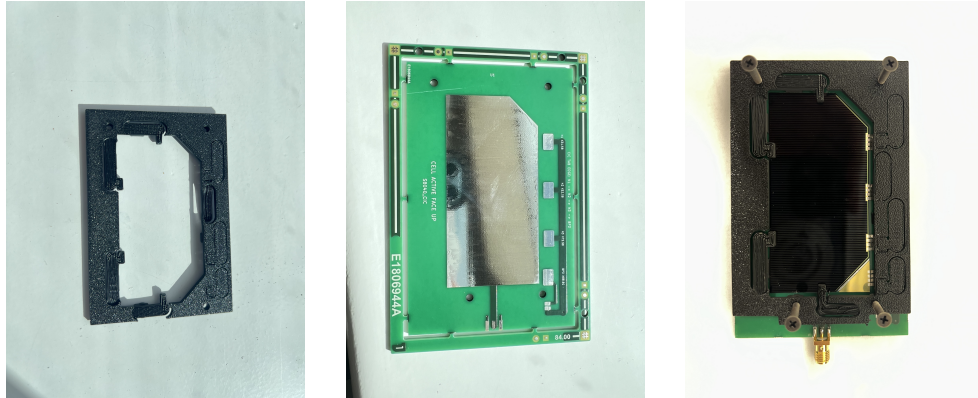


Figure 1. Receiver assembly and interface hardware: (left) custom 3D-printed open-frame holder; (middle) interface PCB showing the broad rear-contact region and edge pads; and (right) assembled photovoltaic receiver with the cell surface exposed and the SMA connector accessible.

2.2 Optical and electrical bench setup

Figures 2 and 3 present the experiment. The transmit chain begins with a Keysight 33600A-series arbitrary waveform generator (AWG), which applies the DCO-OFDM drive waveform to the radio-frequency (RF) port of a Mini-Circuits ZFBT-4R2GW+ bias tee. A separate DC supply establishes the laser operating bias through the DC port, and the combined output from the RF+DC port drives a 980 nm Thorlabs L980P100A laser diode.⁶ The emitted beam passes through a square microlens that forms a rectangular footprint over the exposed photovoltaic surface. Comparable square illumination profiles produced by microlens beam shaping are reported for photovoltaic reception by Anderson *et al.* and for a VCSEL-array optical wireless system by Safi *et al.*^{5,7} Independent mounts for the microlens and receiver allow the footprint to be positioned on the cell. The communication measurements were conducted in darkness using the DCO-OFDM configuration defined in Section 2.5. The modulated optical field generates AC and DC components in the photovoltaic cell output. A

second ZFBT-4R2GW+ bias tee receives this output at its RF+DC port, directs the AC waveform from its RF port to a Keysight MSOX4154A oscilloscope, and connects its DC port to a 50 Ω load. The paired bias tees therefore establish the electrical operating condition of the laser at the transmitter and separate the recovered modulation from the DC current path at the receiver. The receive bias tee is specified for operation from 0.1 to 4200 MHz in a nominal 50 Ω system.⁸ The measured subcarrier SNR consequently characterises the complete implemented chain. The oscilloscope digitizes the recovered waveform for offline OFDM processing, and the optical-power measurements described next provide the aperture-averaged irradiance estimate used to interpret the communication measurement.

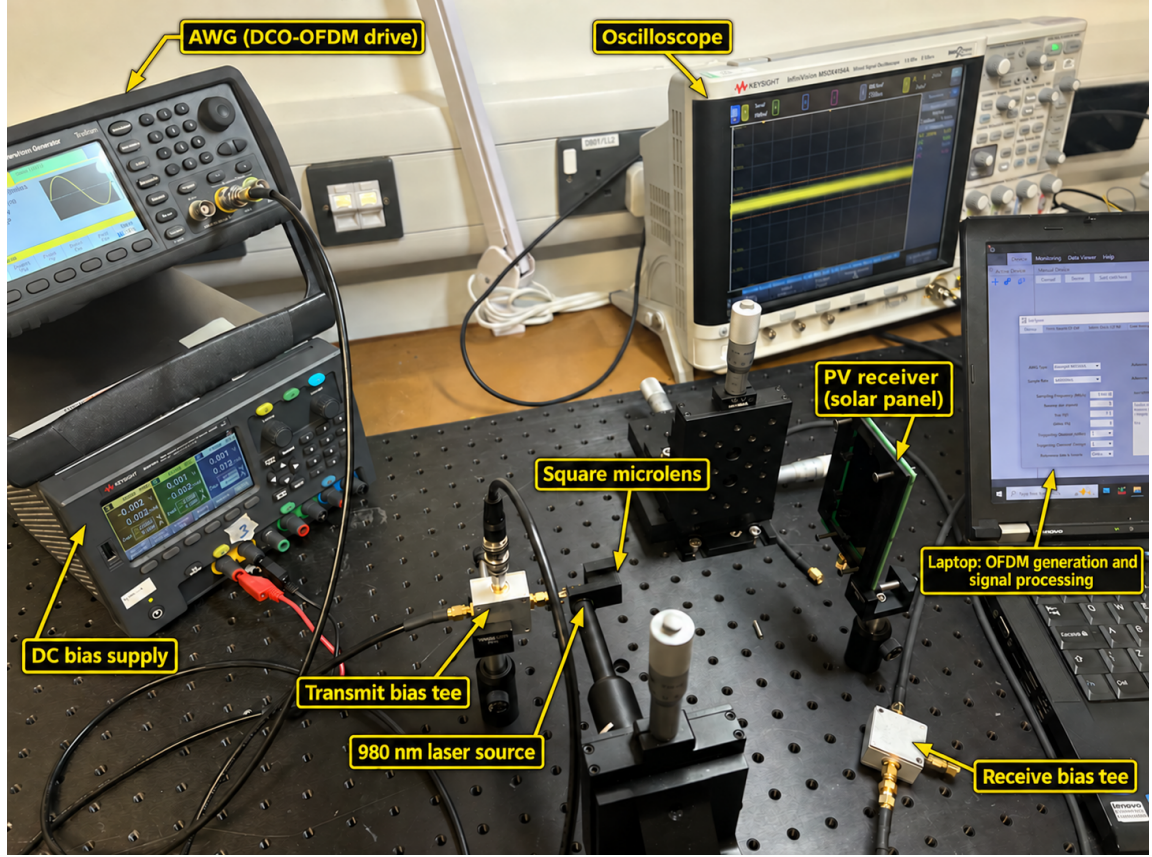


Figure 2. Experimental arrangement comprising DCO-OFDM waveform generation, laser biasing, the 980 nm optical source, square microlens, photovoltaic receiver, and oscilloscope.

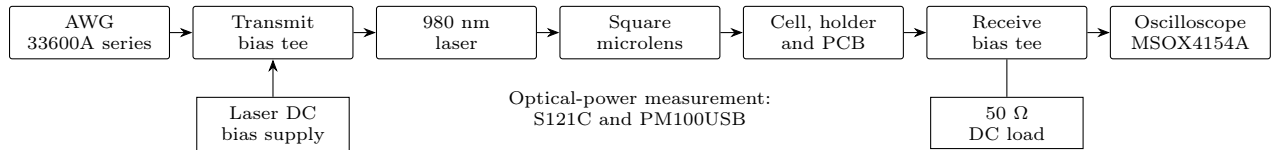


Figure 3. Experimental signal chain. The transmit bias tee combines the AWG waveform with the laser DC bias. The receive bias tee directs the recovered AC waveform to the oscilloscope and terminates the DC port with a 50 Ω load. The S121C sensor and PM100USB interface provide the optical-power measurement of the shaped field.

2.3 Optical power measurement

To relate the recovered electrical response to the illumination delivered by the microlens, the Thorlabs S121C silicon power sensor was translated to several positions within the shaped footprint and connected to a PM100USB interface.^{9,10} The multi-position mean was $\bar{P}_s = 1.0$ mW for the higher-irradiance experiment and 0.4 mW for

the lower-irradiance experiment. The 980 nm source lies within the sensor's 400–1100 nm operating range, for which the manufacturer specifies a measurement uncertainty of $\pm 3\%$ at 980 nm.⁹ The sensor remained in its original housing, where a circular entrance aperture of diameter $d_s = 9.5$ mm defines the optical collection area A_s . Each reading therefore represents the incident power integrated over A_s . Dividing each multi-position mean by this aperture area gives the mean sampled aperture-averaged irradiance,

$$E = \frac{\bar{P}_s}{A_s} = \frac{\bar{P}_s}{\pi(9.5 \times 10^{-3}/2)^2}. \quad (1)$$

Equation (1) gives $E = 14.1 \text{ W m}^{-2}$ and $E = 5.64 \text{ W m}^{-2}$ for the two experiments. The respective sensor uncertainties are ± 0.423 and $\pm 0.169 \text{ W m}^{-2}$. These irradiances define the conditions used for the subcarrier SNR analysis in Section 3 and the horizontal references in the propagation comparison of Section 2.4.

2.4 Transmitted power and incident irradiance

The aperture-averaged irradiances obtained from Equation (1) establish the illumination levels used for the two experimental SNR records. Figure 4 relates these bench conditions to an inter-satellite propagation geometry by mapping transmitted optical power to the incident signal irradiance averaged across the 27 cm^2 receiving cell at six propagation distances. The calculation adopts a circular transmitting aperture of diameter $D_{\text{tx}} = 8$ cm at $\lambda = 980$ nm. Its aperture field follows a truncated Gaussian profile with radius ratio $\alpha = a/w = 1.12$, where $a = D_{\text{tx}}/2$ is the aperture radius and w is the radial position at which the field amplitude falls to $1/e$ of its on-axis value. The truncated-Gaussian far-field treatment follows the circular-aperture model applied to intersatellite optical links by Badás *et al.*, based on the transmitting-antenna formulation of Klein and Degnan.^{11,12} The mean incident signal irradiance across the cell is

$$\bar{E}_{\text{sig}}(P_{\text{tx}}, z) = \frac{P_{\text{tx}}}{4\pi z^2 A_{\text{cell}}} \int_{A_{\text{cell}}} G_{\text{tx}}(\theta(x, y)) \, dA, \quad (2)$$

where P_{tx} is the optical power delivered to the transmitting aperture, z is the propagation distance, and $G_{\text{tx}}(\theta)$ is the dimensionless gain of the truncated Gaussian aperture, including the truncation imposed by α . With x and y measured from the beam-axis intercept on the receiver, the local off-axis angle is $\theta(x, y) \simeq \sqrt{x^2 + y^2}/z$. Equation (2) is evaluated over a square surface of area $A_{\text{cell}} = 27 \text{ cm}^2$, with the beam centred on the surface, zero pointing offset, and the receiver normal to the line of sight. For the centred, normal-incidence geometry, the calculated irradiance scales linearly with P_{tx} and decreases with distance as diffraction distributes the transmitted power over a wider field. The horizontal lines in Figure 4 mark $E = 14.1$ and 5.64 W m^{-2} ; the calculated curves report the irradiance averaged over the full cell area. Within the displayed range up to 5 W, the higher level intersects the 10, 20, and 30 km curves, while the lower level also intersects the 50 km curve. Section 2.5 next defines the DCO-OFDM waveform used to obtain the experimental SNR records.

2.5 DCO-OFDM waveform and subcarrier SNR estimation

To characterise the frequency-selective response of the integrated photovoltaic receiver, the optical carrier was modulated using direct-current-biased optical orthogonal frequency-division multiplexing (DCO-OFDM). The available electrical bandwidth is divided into narrow orthogonal subchannels, allowing the measured signal quality to be resolved at every tone. The Hermitian symmetry supplies the corresponding negative-frequency components and produces a real-valued IFFT output; the DC and Nyquist bins carry no independent complex symbols. This construction leaves 255 independent positive-frequency subcarriers. As shown in Figure 3, the real-valued waveform forms the AC laser drive and is superimposed on the separately supplied DC bias, so that the multicarrier signal modulates the emitted optical intensity about the laser operating point.¹³

The subcarrier grid follows directly from the waveform sampling configuration. With an AWG waveform rate $f_w = 125$ mega-samples per second (MSa/s) and an upsampling factor $L = 25$, the IFFT sample rate f_s , subcarrier spacing Δf , and useful symbol duration T_u are

$$f_s = \frac{f_w}{L} = 5 \text{ MSa/s}, \quad \Delta f = \frac{f_s}{N} = 9.77 \text{ kHz}, \quad T_u = \frac{1}{\Delta f} = 102 \mu\text{s}. \quad (3)$$

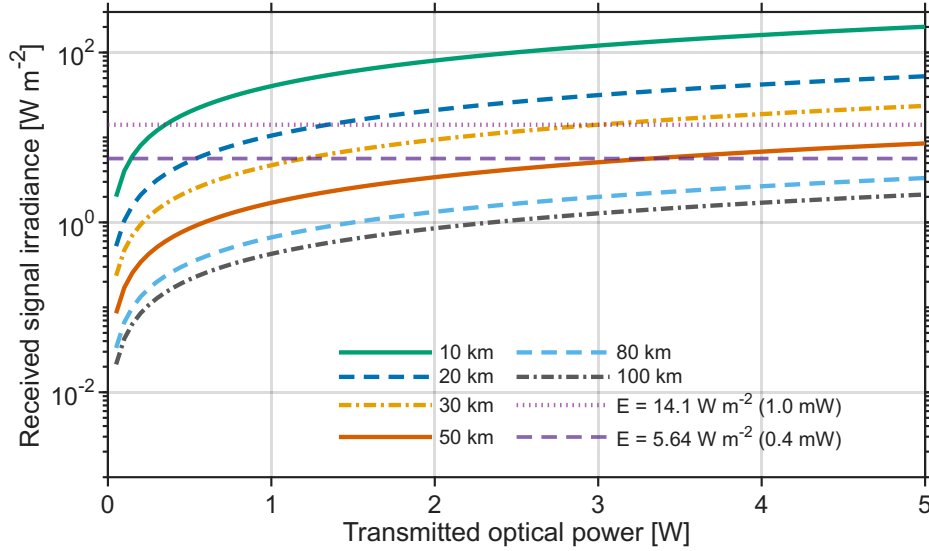


Figure 4. Calculated incident signal irradiance averaged across a centred 27 cm² square receiving surface versus transmitted optical power at propagation distances of 10, 20, 30, 50, 80, and 100 km. The calculation uses a 980 nm truncated-Gaussian beam, an 8 cm circular transmitting aperture, $\alpha = 1.12$, zero pointing offset, and a receiving surface normal to the line of sight. The horizontal lines mark the experimental levels, $E = 14.1$ and 5.64 W m⁻². Positive transmitted powers are displayed on the logarithmic irradiance axis.

Each active tone is located at $f_k = k\Delta f$, $k \in \mathcal{K}$, and the generated measurement grid spans 9.77 kHz to 2.49 MHz. Each useful OFDM symbol is extended by a cyclic prefix (CP) of 15 IFFT samples and a cyclic suffix (CS) of 5 IFFT samples. The extended sequence is upsampled by $L = 25$, shaped by a root-raised-cosine (RRC) filter with roll-off factor 0.1 and a span of 64 symbols, and clipped at ± 3.2 in normalised sample amplitude before scaling to the AWG output range. These operations leave the tone spacing unchanged. The same frequency grid defines the experimental SNR spectra and the per-tone capacity calculation in Section 3.

Channel response measurement uses known, unit-power QPSK symbols on every active subcarrier. Let $X_{k,m}$ and $Y_{k,m}$ denote the transmitted and recovered complex symbols, respectively, for subcarrier k in estimation frame m , and let $M = 80$ be the number of statistically independent estimation frames. The channel coefficient is estimated by averaging the received-to-transmitted symbol ratio,

$$\hat{H}_k = \frac{1}{M} \sum_{m=1}^M \frac{Y_{k,m}}{X_{k,m}}. \quad (4)$$

Using $\hat{H}_k$ from Equation (4), the noise power and corresponding subcarrier SNR are calculated as

$$\hat{\sigma}_{e,k}^2 = \frac{1}{M} \sum_{m=1}^M \left| Y_{k,m} - \hat{H}_k X_{k,m} \right|^2, \quad \hat{\gamma}_k = \frac{|\hat{H}_k|^2}{\hat{\sigma}_{e,k}^2}, \quad (5)$$

Here, $\hat{\sigma}_{e,k}^2$ is the mean squared residual power on subcarrier k , $\hat{\gamma}_k$ is the corresponding linear SNR estimate, $|\cdot|^2$ denotes squared magnitude, and a hat denotes a quantity estimated from the recorded frames. The unit-power QPSK symbols satisfy $|X_{k,m}|^2 = 1$.

Table 1 lists the waveform-generation and channel-sounding parameters used in the experiment.

Offline processing of each oscilloscope record yields one SNR value for every active frequency bin, providing the experimental input to the frequency-resolved analysis in Section 3.

Table 1. Waveform-generation and channel-sounding settings for the DCO-OFDM experiment.

Parameter	Setting
IFFT size / independent positive-frequency tones	512 / 255
Waveform sample rate / upsampling factor	125 MSa/s / 25
QPSK estimation frames used for SNR	80
CP / CS length	15 / 5 IFFT samples
RRC roll-off factor / span	0.1 / 64 symbols
Normalised clipping levels	-3.2 / $+3.2$
Omitted subcarriers	0
Nonlinear equalisation	Disabled
BER threshold	3×10^{-3}
AWG amplitude / programmed offset	$7.5 V_{pp}$ / $0 V$

3. RESULTS AND DISCUSSION

The recorded subcarrier SNR provides a frequency-resolved measurement of the complete receiver chain under the 980 nm square-microlens illumination used in the experiments. Each exported value is obtained after laser modulation, optical delivery to the triple-junction cell, photovoltaic conversion, AC extraction, and oscilloscope acquisition. Figure 5 compares the positive-SNR responses measured at the two irradiance levels.

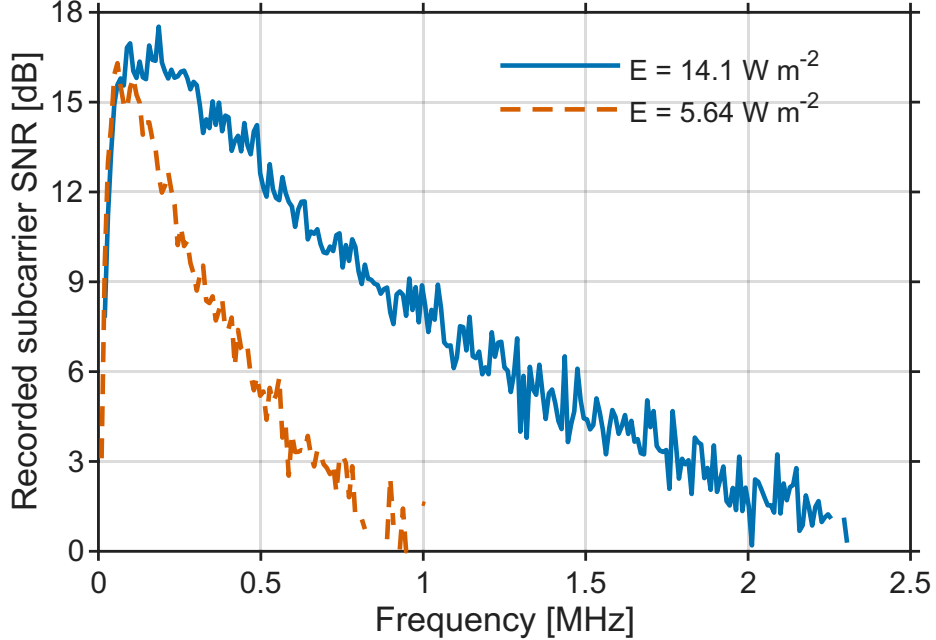


Figure 5. Recorded positive-SNR subcarrier responses at $E = 14.1$ and 5.64 W m^{-2} in darkness. Higher irradiance extends the response across a wider frequency range.

The capacity calculation retains subcarriers with a linear signal-to-noise power ratio of at least unity and includes the cyclic-prefix and cyclic-suffix intervals in the OFDM symbol duration. Let s_k denote the SNR of subcarrier k in decibels, γ_k its linear value, and $\mathcal{K}_+$ the set of retained subcarriers. The corresponding Shannon capacity estimate is¹⁴

$$\gamma_k = 10^{s_k/10}, \quad \mathcal{K}_+ = \{k \in \mathcal{K} : \gamma_k \geq 1\}, \quad C = R_{\text{OFDM}} \sum_{k \in \mathcal{K}_+} \log_2(1 + \gamma_k), \quad (6)$$

where $\mathcal{K}$ contains the 255 independent measured tones and $R_{\text{OFDM}} = f_w/[L(N + N_{\text{CP}} + N_{\text{CS}})] = 9.40 \text{ ksymbol/s}$ is the OFDM symbol rate after the cyclic extensions. Here, $N_{\text{CP}} = 15$ and $N_{\text{CS}} = 5$ are the cyclic-prefix and

cyclic-suffix lengths listed in Table 1. The measured SNR already contains the effect of the ± 3.2 waveform clipping applied before transmission, so no additional clipping correction is introduced in Equation (6).

At $E = 14.1 \text{ W m}^{-2}$, the response first crosses 0 dB at 2.26 MHz and 234 measured subcarriers satisfy $s_k \geq 0$ dB. At $E = 5.64 \text{ W m}^{-2}$, the first crossing occurs at 0.825 MHz and 100 subcarriers satisfy the same condition. Applying Equation (6) gives capacity estimates of 6.32 and 2.44 Mbit/s, respectively.

The end-to-end DCO-OFDM transmission tests used a BER threshold of 3×10^{-3} . The successfully transmitted and recovered data rates were 2.18 Mbit/s at $E = 14.1 \text{ W m}^{-2}$ and 1.21 Mbit/s at $E = 5.64 \text{ W m}^{-2}$. The measured data rates follow the irradiance-dependent change in the positive-SNR bandwidth and remain below the corresponding Shannon capacity estimates.

4. CONCLUSION

This work demonstrates how a spacecraft GaInP/GaAs/Ge triple-junction solar cell can provide optical signal reception within an inter-satellite link. A custom mechanical and electrical interface, combined with passive AC/DC separation, recovers the modulated photocurrent while retaining a distinct DC output path. Laboratory measurements verified multicarrier reception and end-to-end DCO-OFDM transmission, achieving a data rate of up to 2.18 Mbit/s. Optical-power measurements and propagation analysis further related the experimental illumination conditions to transmitted optical power and link distance. By extending a photovoltaic surface already present for power generation into a large-area optical capture aperture, the proposed architecture provides a practical low-complexity route to secondary optical reception during link acquisition.

ACKNOWLEDGMENTS

The authors acknowledge support by the UK Space Agency and European Space Agency (ESA) (contract no. 4000150161) “Development of a High Speed Optical Inter Satellite Link (OISL) Terminal Based on a Low Complexity Platform” under the General Support Technology Program.

REFERENCES

- [1] Wang, Z., Tsonev, D., Videv, S., and Haas, H., “On the design of a solar-panel receiver for optical wireless communications with simultaneous energy harvesting,” *IEEE Journal on Selected Areas in Communications* **33**(8), 1612–1623 (2015).
- [2] Fakidis, J., Videv, S., Helmers, H., and Haas, H., “0.5-Gb/s OFDM-based laser data and power transfer using a GaAs photovoltaic cell,” *IEEE Photonics Technology Letters* **30**(9), 841–844 (2018).
- [3] Fakidis, J., Helmers, H., and Haas, H., “Simultaneous wireless data and power transfer for a 1-Gb/s GaAs VCSEL and photovoltaic link,” *IEEE Photonics Technology Letters* **32**(19), 1277–1280 (2020).
- [4] Younus, O., Majleseini, B., Nacke, R., Osahon, I. N. O., Pellegrino, C., Babadi, S., Tavakkolnia, I., Helmers, H., and Haas, H., “Multi-segment photonic power converters for energy harvesting and high-speed optical wireless communication,” *Journal of Lightwave Technology* **44**(8), 2974–2985 (2026).
- [5] Anderson, M. P. J., Osahon, I. N. O., Rush, M., Haas, H., and Tavakkolnia, I., “Semi-transparent CdTe solar panels for optical wireless communications,” in [*Optical Fiber Communication Conference (OFC) 2026*], *Technical Digest Series*, Tu2H.6, Optica Publishing Group (2026).
- [6] Thorlabs, *L980P100A 980 nm Multimode Laser Diode*. 100 mW, 5.6 mm package. https://www.thorlabs.com/NewGroupPage9_PF.cfm?Category_ID=220&Guide=10&ObjectGroup_ID=4737.
- [7] Safi, H., Babadi, S., Osahon, I. N. O., Sparks, A., Kostakis, I., Powell, D., Meredith, W., Missous, M., Missous, M., Tavakkolnia, I., and Haas, H., “Chip-scale beam-shaped optical wireless system for high-speed and energy-efficient connectivity,” *Advanced Photonics Nexus* **5**(2), 026018 (2026).
- [8] Mini-Circuits, *ZFBT-4R2GW+ Coaxial Bias-Tee* (2025). Rev. C. <https://www.minicircuits.com/pdfs/ZFBT-4R2GW+.pdf>.
- [9] Thorlabs, *S121C Standard Photodiode Power Sensor*. Detector, aperture, and measurement-uncertainty specifications. https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=3328&partnumber=CAL-PD.

- [10] Thorlabs, *Power and Energy Meter Interfaces with External Readout*. <https://www.thorlabs.com/power-and-energy-meter-interfaces-with-external-readout>. Accessed: Sep. 9, 2026.
- [11] Aldecocea, M. B., Piron, P., Bouwmeester, J., Saathof, R., and Loicq, J., “Seidel optical aberrations and optimum truncated gaussian beams on intersatellite free-space optical communications,” *Optics Express* **33**(16), 33686–33703 (2025).
- [12] Klein, B. J. and Degnan, J. J., “Optical antenna gain. I: Transmitting antennas,” *Applied Optics* **13**(9), 2134–2141 (1974).
- [13] Islim, M. S. and Haas, H., “Modulation techniques for Li-Fi,” *ZTE Communications* **14**(2), 29–40 (2016).
- [14] Shannon, C. E., “A mathematical theory of communication,” *Bell System Technical Journal* **27**(4), 623–656 (1948).