Simultaneous Wireless Data and Power Transfer for a 1-Gb/s GaAs VCSEL and Photovoltaic Link

John Fakidis, *Member, IEEE*, Henning Helmers, and Harald Haas, *Fellow, IEEE*

***Abstract*— We study the trade-off between energy harvesting and data communication for a two-meter wireless gallium-arsenide vertical-cavity surface-emitting laser and photovoltaic link. The use of orthogonal frequency-division multiplexing with adaptive bit and power loading results in a peak data rate of 1041 Mb/s at a bit-error ratio (BER) of 2.2×10^{-3} under short-circuit conditions. The receiver is shown to provide power harvesting with an efficiency of 41.7% under the irradiance of 0.3 W/cm^2 and simultaneous data communication with a rate of 784 Mb/s at a BER of 2.8×10^{-3}. The experimental system is envisioned to become a paradigm for next-generation wireless backhaul communications and Internet-of-Things applications.**

***Index Terms*— Energy harvesting, gallium arsenide, Internet of Things, OFDM, photovoltaic cells, simultaneous lightwave information and power transfer, vertical-cavity surface-emitting lasers, 5G backhaul communications.**

I. Introduction

THE optical simultaneous wireless information and power transfer (SWIPT), also known as simultaneous lightwave information and power transfer (SLIPT) [1], is regarded to be a potential technological paradigm for unlocking the Internet-of-Things (IoT) era and fifth-generation (5G) and beyond backhaul communications [2]–[6]. For the first time, the concept of optical SWIPT is proved in the independent studies [2] and [3] by using off-the-shelf white light-emitting diodes (LEDs) and silicon (Si) solar panels. White LEDs typically consist of a blue-light-emitting chip and a yellow-phosphor coating. Part of the blue light is converted to red, green and yellow, whereas the rest is transmitted through the phosphor; thus, a broad power spectral distribution between 380 nm and 800 nm is achieved [7]. A *very low*[1] data rate of 3 kb/s is reported in [2] with a received optical and harvested electrical power of 16 mW and 1 mW, respectively at a link distance of 40 cm. In [3], a *low* data rate of 7 Mb/s and 136.5 mW and 2.1 mW of collected and harvested power, respectively are demonstrated using a multi-crystalline Si solar panel at a distance of 39 cm. This remarkable boost in data rate is attributed to the use of adaptive bit and power loaded orthogonal frequency-division multiplexing (OFDM); this technique leverages the communication channel optimally [3], [9]. Also, the solar panel used as a data detector in [3] consists of 36 cells connected in series that offer a total 3-dB bandwidth of 350 kHz; this value is 35 times larger than that achieved by the solar panel in [2] that is assumed to have only five or six inter-connected cells. As an advancement of these initial demonstrations, an alternating current-direct current (ac-dc) decoupling receiver is used for the first time in [5]. While the 3-dB bandwidth of the receiver is less than 100 kHz, a *high* data rate of 12 Mb/s is obtained. Also, the received optical power of the solar panel is estimated to be 1.42 W [5]. Organic solar cells are also shown to be capable of *high*-speed data detection in [4]. The developed 1-m wireless laser link is shown to achieve 34.2 Mb/s of data rate and 0.43 mW of harvested power. A red laser diode (LD) with a narrow bandwidth centered at 658 nm was used at the transmitter; the output dc power is reported to scale from 8.5 mW to 14.3 mW [4]. This improvement in data rate is attributed to the 3-dB bandwidth of 1.3 MHz for the organic cell as a result of its decreased active area (only 8 mm^2) and, thus, capacitance. The state-of-the-art data rate of SLIPT systems is further improved in [10] by using a triple-cation perovskite solar device at the receiver. In particular, 53-Mb/s data communication and power harvesting of 3.3 mW are shown to be attained using a 40-cm wireless link. The same LD with that in [4] was used and the received optical power from the perovskite solar cell is reported to be 50 mW [10].

The boundaries in optical wireless communication (OWC) using solar or photovoltaic (PV) cells as data detectors are significantly extended in [9]; a *high* data rate of 522 Mb/s is shown to be obtained for a 2-m infrared (IR) wireless communication link. This was achieved by using a gallium-arsenide (GaAs) vertical-cavity surface-emitting laser (VCSEL) with an operation wavelength of 850 nm, a GaAs PV cell with an active area of 0.8 mm^2 and adaptive bit and power-loaded dc-biased optical OFDM. As an example of a single-junction PV cell, the GaAs PV device is designed to offer maximum power efficiency under monochromatic illumination [11]; this is because transmission and thermalization losses are minimized by the suitable matching of the photons energy and the semiconductor bandgap. The receiver used in [9] includes a variable resistor connected to the output of the PV cell; it is shown not to be able to provide optimal values for the data

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[1]The categorization of the values of data rate γ to *very low*, *low*, *high* and *very high* is based on a taxonomy for optical wireless communication (OWC) given for the first time in [8]. In particular, the term *very low* is used for $\gamma < 1$ Mb/s; *low* for 1 Mb/s $\leq \gamma < 10$ Mb/s; *high* for 10 Mb/s $\leq \gamma < 1$ Gb/s; and *very high* for 1 Gb/s $\leq \gamma < 100$ Gb/s.

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rate and power at the same time. Hence a follow-up study is performed in [6] using an ac-dc separating receiver as that used in [5]. The GaAs PV receiver is shown to be capable of optical SWIPT with a data rate of 743 Mb/s and collected and harvested power of 3.2 mW and 1.3 mW, respectively. In this letter, we extend our investigation in [6] by improving the achievable data rate and the end-to-end dc power efficiency by 1.06 and 1.2 times, respectively. Also, we prove that the 2-m wireless IR laser link is eye-safe. The trade-off between energy harvesting and information transfer is studied by modifying the peak-to-peak (pp) amplitude of the OFDM signal over the $I-V$ curve of the PV cell. More importantly, we provide and analyze new data communication results with a *very high* rate of 1041 Mb/s. A comparison with the state of the art in SLIPT is given considering the data rates, harvested power and total link efficiency achieved so far.

The rest of the letter is organized as follows: the experimental setup is given in Sec. II; the results are discussed in Sec. III; and concluding remarks are provided in Sec. IV.

II. Experimental Setup

The experimental setup is given in Fig. 1. An arbitrary waveform generator (AWG) (Keysight, 81180A) is used for the creation of an analog OFDM signal. A power supply unit (PSU) (Tenma, 72-10480) is used to provide the dc bias to the 850-nm VCSEL (Optek, OPV300). The dc voltage V_{dc} and current I_{dc} from the PSU are read to be 2.01 V and 5 mA, respectively. These values are used to ensure that the LD is biased in the middle of its linear dynamic range. The dc electrical power consumed at the transmitter is calculated to be $P_{\mathrm{Tx,elec}} = 10.1$ mW by using $P_{\mathrm{Tx,elec}} = V_{\mathrm{dc}} I_{\mathrm{dc}}$. The values of 125 mV, 250 mV and 500 mV are applied to the input pp voltage u_g of the OFDM signal. The maximum input voltage of 500 mVpp ensures that negligible clipping is induced by the dynamic range of the LD to the ac signal. The incoming ac and dc signals are combined using a bias tee (Mini-circuits, ZFBT-4R2GW+). The superpositioned ac and dc signal is fed to the IR VCSEL from the bias tee. The LD converts the electrical signal to an optical one; the avg dc optical power is measured to be 2.63 mW by placing a power sensor (Thorlabs, S121C) at 1 mm from the transistor-outline (TO)-46 package of the LD. The divergent optical beam is collimated in free space by using a plano-convex lens (Edmund Optics, 86-921).

The maximum permissible exposure (MPE) [12] is calculated to be $\kappa' = 769.7\ \mu$W as shown in the Appendix. In order to ensure eye safety in free space, the optical power of the beam is measured using the power sensor with an iris of a 7-mm diameter. The maximum optical power on the transverse plane of the beam is measured to be 154.3 μW, 158.6 μW and 142.8 μW at the distances of 50 cm, 1 m and 1.5 m from the collimation lens, respectively. It is observed that the highest optical power is received in the middle of the wireless link and is 4.9 times lower than the MPE. The laser system will be considered for classification as Class 1 or 1M if the forward current of the LD is limited by a driver to such a value that allows a maximum optical power of $2.63\ \mathrm{mW} \times 4.9 = 12.89$ mW.

An aspheric condenser lens (Thorlabs, ACL50832U-B) is used at 2 m from the collimation lens to capture the laser beam. The condenser lens focuses the beam on the PV cell

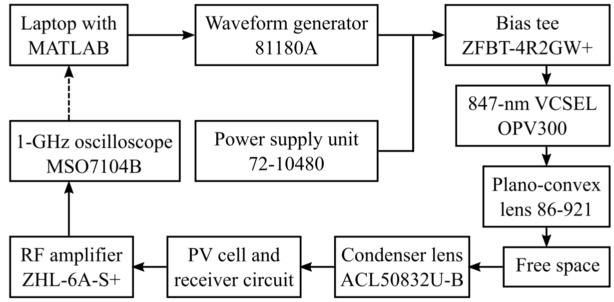

Fig. 1. Experimental setup. The arrow with the dotted line is used to show the final stage with the signal-to-noise ratio, data rate and bit-error ratio calculations.

that is placed at the back focal length of the lens, i.e. 17 mm. The PV cell is based on a positive-negative (p-n) GaAs homojunction capped with a 400-nm thick $Al_{0.5}Ga_{0.5}As$ window layer (doping concentration: $N_{\mathrm{A}} = 1 \times 10^{20}\ \mathrm{cm}^{-3}$) to facilitate lateral conduction [13]. The PV cell features a circular active area with diameter $D_{\mathrm{pv}} = 1$ mm and is mounted on a TO-46 socket. The optical power collected from the GaAs PV cell is measured to be $P_{\mathrm{Rx,opt}} = 2.35$ mW; this is 3.05 times higher than the MPE of 0.77 mW. However in a practical application scenario, the volume between the receiving lens and the PV cell attached to a printed-circuit board (PCB) would be enclosed in a metallic tube. The VCSEL-based PCB and the plano-convex lens would also be shielded at the transmitter within a metallic tube. Thus, human access to laser radiation classified as Class 3R or 3B would be ensured to be avoided. The irradiance on the cell is calculated to be $G = 299.2\ \mathrm{mW/cm}^2$ by using $G = 4P_{\mathrm{Rx,opt}}/(\pi D_{\mathrm{pv}}^2)$. The electrical circuit of the receiver consists of the PV cell and two branches as shown in Fig. 2. The first branch comprises an inductor with a value $L = 680\ \mu$H and a variable resistor R_{l} with a maximum value of 10 kΩ; this is used for dc energy harvesting. The variable resistor is modified and the load voltage V_{l} is measured to obtain the $I-V$ curve for the PV cell. Thus, the dc harvested power is determined by using $P_{\mathrm{Rx,elec}} = V_{\mathrm{l}}^2/R_{\mathrm{l}}$ and the total link or end-to-end dc power efficiency by using $\eta_{\mathrm{t}} = (P_{\mathrm{Rx,elec}}/P_{\mathrm{Tx,elec}}) \times 100\%$. The second branch consists of a capacitor with a value $C = 1$ nF and a variable resistor R_{c} with an upper limit of 500 Ω; this is used for capturing the ac communication signal. The variable resistance is set to $R_{\mathrm{c}} = 7.3\ \Omega$ because it has shown to maximize the achievable data rate in [9]. However by using the ac-dc decoupling receiver, the achievable data rate is jointly affected by the values of R_{c} and C as shown in [5]. The ac voltage signal $v(t)$ is fed to a radio-frequency (RF) amplifier (Mini-circuits, ZHL-6A-S+). The amplified ac voltage signal is captured and observed using a 1-GHz oscilloscope (Keysight, MSO7104A). The digital processing of the OFDM signal is performed in Matlab using a laptop. The laptop is connected to the AWG and the oscilloscope. Details of the creation and recovery of the digital OFDM signal along with the values of relevant parameters can be found in Sec. III-A in [9].

III. Results and Discussion

In Fig. 3, the data rate γ and generated current I_{l} are given as a function of the load voltage V_{l}. The maximum-power point (MPP) is shown to be achieved for the current

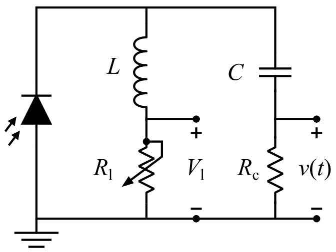

Fig. 2. Electrical circuit of the photovoltaic-cell-based receiver [6].

and voltage values $I_{\mathrm{mpp}} = 1.11$ mA and $V_{\mathrm{mpp}} = 0.88$ V, respectively. The maximum harvested power is, therefore, calculated to be $P_{\mathrm{m}} = I_{\mathrm{mpp}} V_{\mathrm{mpp}} = 0.98$ mW. Thus, the maximum total link efficiency and power conversion efficiency of the PV cell are calculated to be 9.8% and 41.7%, respectively; the maximum power efficiency of the cell is determined using $\eta_{\mathrm{pv,m}} = (P_{\mathrm{m}}/P_{\mathrm{Rx,opt}}) \times 100\%$. For voltages above V_{mpp}, the generated current drops rapidly towards zero; this corresponds to a dc voltage of 1.04 V that approximates the open-circuit condition. Note that electronic circuits often require higher supply voltages such as 3.3 V or 5 V. This can be achieved by the connection of PV cells in series, most elegantly realized in an integrated fashion on chip level, i.e. by vertical stacking (multiple junctions) or lateral segmentation (multiple segments) [13].

The increase in the generated dc voltage across R_l causes a decrease in the data rate. This is because of the corresponding decrease in the voltage of the junction that results in a lower mean pp voltage of the OFDM signal and, thus, a reduced signal-to-noise ratio (SNR). As the input mean pp voltage of the OFDM signal increases, the achieved data rates are shown to increase. This is because the relevant SNR increases; note that significant signal clipping is induced for $u_g = 750$ mV and the achievable data rates are comparable to the respective ones for $u_g = 250$ mV. For input pp voltage values of 125 mV, 250 mV and 500 mV, the maximum data rates of 478.7 Mb/s, 730.8 Mb/s and 1041.3 Mb/s, respectively are obtained at the short-circuit point; the relevant bit-error ratio (BER) values are 1.5×10^{-3}, 1.6×10^{-3} and 2.2×10^{-3}, respectively. While maximum data rates are attained under the short-circuit condition, energy harvesting is negligible at the same point due to the extremely low dc voltage of 7.5 mV. At the MPP, the electrical receiver circuit is shown to provide data rates of 347.3 Mb/s, 530.4 Mb/s and 783.8 Mb/s with BER values of 2×10^{-3}, 1.7×10^{-3} and 2.8×10^{-3}, respectively. In Fig. 4, the estimated and power loaded SNR and the number of loaded bits are given as a function of frequency for $R_l = 7.3\ \Omega$ and $u_g = 0.5$ V. This measurement results in the *very high* data rate of 1041.3 Mb/s; to the best of the authors' knowledge, this is a world-record value reported in the literature of OWC using PV cells as data receivers. The frequency profile of SNR is shown to be in accordance with that of a band-pass filter; the central frequency is calculated to be 31.1 MHz and the 3-dB bandwidth is determined to be 40.8 MHz. The attenuation of SNR in frequencies below 20 MHz is attributed to the ac-coupling capacitor in the receiver circuit; an increase in capacitance C is expected to reduce the dc-wander effect [5]. It is observed that bit and power loading is complete at 237.2 MHz, whereas the estimated SNR keeps rolling off from

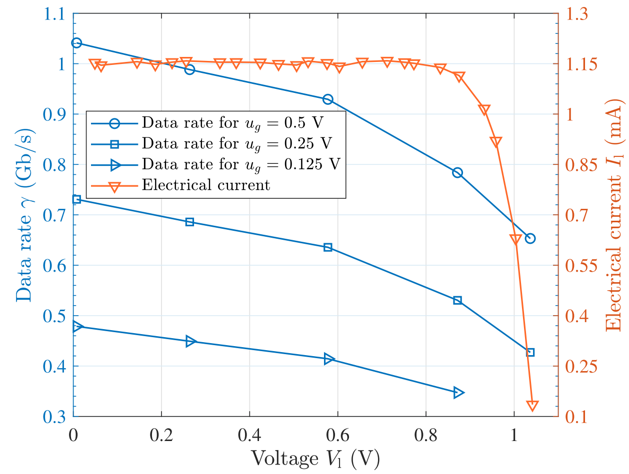

Fig. 3. Data rate and dc electrical current as a function of load voltage. The data rates achieved correspond to bit-error ratio values that belong to the range $[1.2 \times 10^{-3}, 1.9 \times 10^{-2}]$.

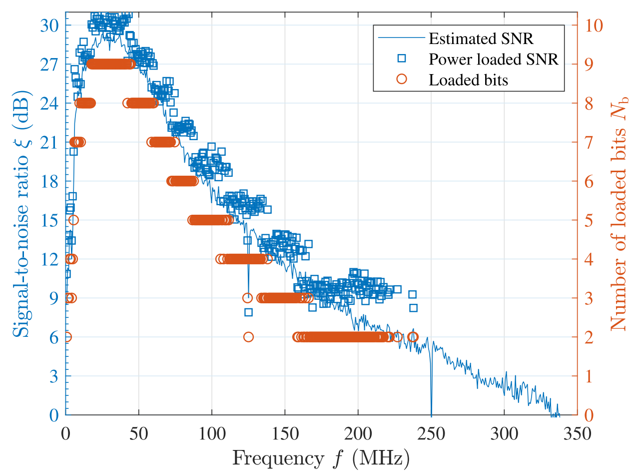

Fig. 4. Estimated and power loaded signal-to-noise ratio (SNR) and number of loaded bits as a function of frequency for the load resistance $R_l = 7.3\ \Omega$ and $u_g = 0.5$ V.

6 dB to 0 dB at the frequency of 337.7 MHz. This means there is still margin to transmit subcarriers of a single bit of information in the estimated SNR region between 3 dB and 6 dB thus increasing the achievable data rate.

In Table I, key features and findings of state-of-the-art studies in SLIPT are summarized. The data rate is shown to be massively increased by 21.9 and 13.3 times for the GaAs VCSEL and PV link in [6] compared with the organic and perovskite solar cell based links, respectively. This is attributed to the very large 3-dB bandwidth of 24.5 MHz of the GaAs PV cell measured in [9] compared to the relevant values of 1.3 MHz [4] and 289 kHz [10] measured for the organic and perovskite solar cell, respectively. A remarkable boost of 6.2 and 6.6 times in the end-to-end dc power efficiency is shown to be achieved for the GaAs laser and PV link developed in [6] compared with the 1-m link using an organic solar cell and the 0.4-m link based on a perovskite solar cell, respectively. This is mostly due to the high power conversion efficiency of the GaAs PV cell, i.e. 42.4% in [6], compared to those of 7% and 6.5% for an organic and a perovskite solar cell measured in [4] and [10], respectively. All of the experimental studies given in Table I report harvested power levels of

TABLE I
STATE OF THE ART IN OPTICAL SIMULTANEOUS WIRELESS INFORMATION AND POWER TRANSFER (SWIPT)

References	Transmitter technology	Receiver technology	Link distance d (m)	Data rate γ (Mb/s)	Harvested power P_l (mW)	End-to-end dc power efficiency η_t (%)
This work	850-nm GaAs VCSEL	GaAs PV cell	2.0	784	1.0	9.8
[6]	850-nm GaAs VCSEL	GaAs PV cell	2.0	743	1.3	8.0
[10]	660-nm AlGaInP laser	Perovskite solar cell	0.4	56	3.3	1.2
[4]	660-nm AlGaInP laser	Organic solar cell	1.0	34	0.4	1.3

a few mW that are considered to be sufficient for ultra-low-power IoT sensors such as RF identification transponder chips [14]. Also, these power levels are able to partially charge batteries during short bursts in higher-power IoT systems such as narrow-band cellular IoT mobile stations [15]. Ambient light will enable trickle charging, i.e. charging a fully charged battery at the same rate with its self-discharge rate. To the best of our knowledge, this work gives the highest data rate and total power link efficiency in the literature of optical SWIPT. The slightly improved data rate in this study compared to that reported in [6] is explained by the removal of the low-pass filter (Mini-circuits, SLP-250+) used in [6]; this allows the extension of the communication bandwidth by 40.3 MHz. The slightly lower harvested power in this work compared with that in [6] originates from a lower collected optical power from the GaAs PV cell by 1.37 times that results in a slightly lower PV efficiency. Also, the total link in this work is more efficient in terms of power than that in [6] because of the use of a more stable and efficient PSU.

IV. CONCLUSION

In this letter, the trade-off between energy harvesting and data communication was investigated for a 2-m eye-safe IR wireless link using a GaAs VCSEL and PV cell. The developed ac-dc separating receiver was shown to be capable of SLIPT offering a world-record data rate of 784 Mb/s and a harvested power of 1 mW. A potential application scenario is the provision of wireless power and data to IoT devices. During periods that the IoT device required very-high-speed communication exclusively, the receiver would be tuned to the short-circuit point; this was shown to offer a maximum data rate of 1041 Mb/s but with diminished electrical dc power. If the IoT sensor required maximum power, the receiver could be configured to operate close to the MPP by using a digital potentiometer. The use of multiple VCSELs and PV cells of high efficiency and bandwidth is envisioned to enable energy-autonomous 5G and beyond backhaul communications.

APPENDIX

According to Table A.1 in [12], the MPE κ for an 850-nm laser point source ($C_6 = 1$) expressed as irradiance is given by $\kappa = 10\, C_4 C_7$ (W/m^2). Parameters C_4 and C_7 represent correction factors for MPE evaluations and are calculated to be 2 and 1, respectively from Table 9 in [12]. In particular, C_4 is calculated by using $C_4 = 10^{0.002(\lambda - 700)}$, where $\lambda = 850$ nm. Therefore, the MPE is calculated to be $\kappa = 10 \times 2 \times 1 = 20$ W/m^2 $= 2$ mW/cm^2. This value is considered to be a conservative limit; this is because the VCSEL and the lens form an extended source ($C_6 > 1$) so long as the angular subtense, i.e. angle subtended by an apparent source as observed from a point in space, is higher than 1.5 mrad [12]. The MPE refers to the maximum collected power by the dilated pupil with a diameter $D_{\mathrm{ap}} = 7$ mm. Therefore, it can be expressed in terms of power as $\kappa' = \kappa\pi D_{\mathrm{ap}}^2/4$ that yields $\kappa' = 769.7$ μW.

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