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ABSTRACT

Using photovoltaic cells as photovoltaic laser power converters (PLPCs) is a potential technology for long-range wireless power transfer. Intrinsic processes that limit the performance of PLPCs have not been fully investigated. Based on a thermodynamic model, we categorize and calculate the intrinsic losses in PLPCs. We use the experimental data of silicon and gallium arsenide to take into account the unavoidable Auger process. We find that the entropic loss generated during the absorption and emission of radiation is the major loss mechanism. Importantly, we show that in the presence of nonideal absorptivity and volumetric entropy production via Auger recombination, using lasers with photon energy equal to the bandgap of the PLPC can be impractical, e.g., comparable efficiencies can be achieved in much thinner silicon PLPCs illuminated by lasers with higher photon energies. We also investigate the methods of diminishing the intrinsic losses with respect to the Auger process: by intensifying the laser irradiance, the proportion of entropic loss in input power can be arbitrarily reduced; by using spectral and angular filters, the intrinsic losses can be diminished via absorption enhancement or emission restriction. Additionally, we discuss the practical efficiency limit of PLPCs accounting for the entropy production due to finite carrier mobilities. The results in this work estimate the potentials for efficiency improvements, which are fundamental to the design of PLPCs.

Laser power transfer (LPT) is a promising long-range and high-power-density wireless power transfer (WPT) technology whose full potential has yet to be unlocked. Traditional WPT technologies using inductive coupling or magnetic resonance coupling operate effectively only in short- and mid-range applications, facing the challenge of providing Watt-level power over meter-level distance for Internet of things (IoTs) and mobile devices.[1,2] Lasers, due to their coherence, can generate narrow and unidirectional beams with low divergence and high irradiance, whereby they become competitive candidates for long-range wireless power transmitters. At the receiver side, photovoltaic (PV) cells convert the laser into electricity, and thereby, they are also called photovoltaic laser power converters (PLPCs). Aside from powering consumer electronics and IoT devices,[2] LPT has been investigated for various applications, e.g., transdermal charging,[3] fiber-based charging and communication,[4] and extraterrestrial powering.[5] Some experimental evaluations of efficiencies of PLPCs have also been conducted. The efficiency of 45% has been reported for silicon (Si) PLPC,[6] and efficiency over 60% has been achieved by gallium arsenide (GaAs) heterostructures with multijunctions.[7] The efficiency of PLPCs plays a crucial role in the LPT system since the receiver-end environment is sensitive to the heat caused by inefficiency. While extrinsic losses due to reflection, contact shadowing, series resistance, incomplete collection of photogenerated carriers, and temperature rise restrict the performance of PLPCs, they can be diminished or even eliminated by better device designs.[8] However, intrinsic processes such as radiative recombination and Auger recombination are unavoidable. Taking only radiative recombination into account, the detailed balance efficiency of PLPCs has been calculated by Green, which can be arbitrarily close to 100% if the absorbed laser intensity is sufficiently large.[9] In this work, we extend the analysis by a thermodynamic model, accounting for both radiative and nonradiative recombination in real semiconductor materials. Using this model, intrinsic losses can be categorized and calculated. Efficiencies under the illumination of lasers with different wavelengths are compared, and the effect of spectral and angular filters on diminishing intrinsic losses with respect to the Auger process is investigated.

Figure 1 illustrates the schematic of a PLPC at ambient temperature of T.[10] While the PLPC absorbs an energy flux of $\dot{E}_L$ and an

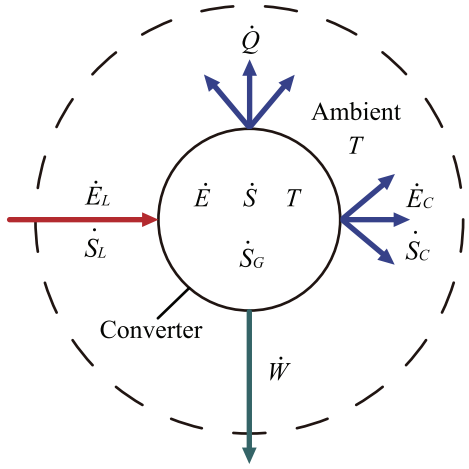

FIG. 1. Schematic of a thermodynamic model of the PLPC. The behavior of the PLPC is described by the energy/entropy fluxes, the energy/entropy changing rates, and the entropy generation rate.

entropy flux of $\dot{S}_L$ from the laser, it simultaneously emits an energy flux of $\dot{E}_C$ and an entropy flux of $\dot{S}_C$ by luminescence. In addition, the PLPC transfers heat at a rate of $\dot{Q}$ to the ambient at temperature T. The entropy-free electrical work is delivered outward at a rate of $\dot{W}$. According to the first and second laws of thermodynamics, the equations of flux balance are given by

$$\dot{E} = \dot{E}_L - \dot{W} - \dot{Q} - \dot{E}_C, \tag{1}$$

$$\dot{S} = \dot{S}_L - \dot{Q}/T - \dot{S}_C + \dot{S}_G, \tag{2}$$

where $\dot{E}$, $\dot{S}$, and $\dot{S}_G$ are the energy changing rate, entropy changing rate, and entropy generation rate in the converter, respectively. In a steady state of $\dot{E} = \dot{S} = \dot{T} = 0$, the output power $\dot{W}$ can be calculated by eliminating $\dot{Q}$ between the balance equations as follows:

$$\dot{W} = \dot{E}_L(1 - T/T_{FL}) - \dot{E}_C - T(\dot{S}_G - \dot{S}_C), \tag{3}$$

where $T_{FL} \equiv \dot{E}_L/\dot{S}_L$ is the effective flux temperature[10] of the laser radiation. The first term on the right side of Eq. (3) involves a Carnot factor of $(1 - T/T_{FL})$,[10,11] which is the efficiency of the Carnot cycle between reservoirs of temperature T_{FL} and T, provided that the emission and the entropy generation in the converter are prevented. The second and third terms are the emission loss and the entropic loss, respectively.

In this Letter, we assume that the lasers are strictly monochromatic. The entropy flux $\dot{S}_L$ carried by the strictly monochromatic radiation or the strictly unidirectional radiation is equal to zero,[12] leading to an infinite effective flux temperature of the ideal laser radiation. In this case, the Carnot factor in Eq. (3) vanishes, and the remaining losses consist merely of the emission loss and the entropic loss. In a reversible heat engine, the entropy production during each operating cycle is zero. However, the entropy produced during the absorption and emission of radiation is unavoidable[13] and thereby has to be accounted for. The entropy generation rate during the absorption and emission of radiation consists of the entropy generation rate during absorption $\dot{S}_{Ga}$ and the entropy generation rate during emission $\dot{S}_{Ge}$,[14]

$$\dot{S}_{Ga} = (\dot{E}_L - \mu\dot{N}_L)/T, \tag{4}$$

$$\dot{S}_{Ge} = \dot{S}_C - (\dot{E}_C - \mu\dot{N}_C)/T, \tag{5}$$

where $\dot{N}_L$ is the absorbed particle flux from the laser radiation, $\dot{N}_C$ is the luminescent particle flux emitted by the converter, and μ is the chemical potential of the photons interacting with the carriers in the PLPC.[15] Since the emission process also carries away an entropy flux of $\dot{S}_C$, the net effect is a reduction of entropy inside the converter. To exclude extrinsic losses, infinite carrier mobilities and negligible contact loss are assumed. With the assumptions, the separation of the electron and hole quasi-Fermi levels is equal to qV,[14] where q is the elementary charge and V is the applied voltage. In addition, the separation is also equal to the aforementioned chemical potential,[15] so the relation $\mu = qV$ can be used for the calculation. In the absence of other entropy production processes (only radiative recombination is involved), the output power can be calculated by substituting Eq. (4) and (5) into Eq. (3) as follows:

$$\dot{W} = \mu(\dot{N}_L - \dot{N}_C). \tag{6}$$

This result is almost identical to the detailed balance equation of the output power,[16] as the introduction of the chemical potential of radiation is based on the spectral balance of absorption and emission.[15]

In the following analysis, planar PLPCs with perfect antireflection coating and perfect rear reflection mirror are assumed. The luminescent particle flux $\dot{N}_C$ and energy flux $\dot{E}_C$ emitted by the PLPC are given by the generalized Planck law as follows:[14,15]

$$\dot{N}_C(\mu, A) = \frac{2\pi A}{h^3c^2}\int_0^\infty \frac{a(E)E^2dE}{\exp[(E-\mu)/kT] - 1}, \tag{7}$$

$$\dot{E}_C(\mu, A) = \frac{2\pi A}{h^3c^2}\int_0^\infty \frac{a(E)E^3dE}{\exp[(E-\mu)/kT] - 1}, \tag{8}$$

where A is the surface area of the PLPC, c is the speed of light in free space, h is Planck's constant, and k is Boltzmann's constant. Following Shockley and Queisser,[16] the absorptivity $a(E)$ is assumed to be unity for photon energies equal to or larger than the bandgap energy E_g of the PLPC and zero for other photon energies. To minimize the thermalization loss, the incident laser is assumed to have photon energy equal to E_g. To specify the incident power of the laser, we define the incident irradiance P_L as the total laser power incident on the surface of the PLPC divided by the surface area A, which is applicable irrespective of the spatial uniformity of the laser. Thus, the absorbed energy flux $\dot{E}_L$ and the absorbed particle flux $\dot{N}_L$ are

$$\dot{E}_L = a(E_g)AP_L = AP_L, \tag{9}$$

$$\dot{N}_L = \dot{E}_L/E_g = AP_L/E_g. \tag{10}$$

The conversion efficiency from incident laser power to output power is defined as

$$\eta \equiv \dot{W}/AP_L. \tag{11}$$

With Eqs. (6)–(11), the conversion efficiency can be evaluated for varying incident laser irradiances and bandgap energies.

For each incident irradiance and bandgap energy, the maximum power point (MPP) can be found by

$$\frac{d\dot{W}}{dV} = 0, \tag{12}$$

where the relation $\mu = qV$ is used. For brevity, we use efficiency to denote the MPP efficiency. In Fig. 2, efficiencies $\eta(P_L, E_g)$ are given for incident irradiances from 0.01 W/cm^2 to 10 W/cm^2 and bandgap energies from 1 eV to 2 eV as a contour plot at a temperature of 300 K. It can be derived from Eq. (11) that the efficiency increases almost logarithmically with the incident irradiance, provided that $E_g - qV \gg kT$ (see supplementary material),

$$\eta(P_L, E_g) = \eta(P_{L0}, E_g) + \frac{kT}{E_g} \ln\left(\frac{P_L}{P_{L0}}\right). \tag{13}$$

Therefore, efficiencies in a wide range of incident irradiances can be estimated with the efficiency at a specific irradiance P_{L0} for each bandgap energy.

Figure 3 shows the MPP output power and loss curves as fractions of input power AP_L. It is evident that the entropic loss produced during the absorption and emission of radiation $T(\dot{S}_{Ga} + \dot{S}_{Ge} - \dot{S}_C)$ is the major loss mechanism for all bandgap energies. At a fixed incident irradiance, devices with larger bandgap energies will have higher efficiencies, largely due to the reduction in the proportion of entropic loss. Moreover, under higher incident irradiances, the fraction of input power via emission loss is almost constant, while the proportion of entropic loss diminishes logarithmically, as shown in Fig. 3(b).

The efficiency can be arbitrarily close to 100% if the incident irradiance is sufficiently large.[9] At a fixed incident irradiance, the efficiency can be improved by applying a spectral filter or an angular filter to limit the emission flux.[9] Photon fluxes with frequencies or angles in the forbidden band of the filter will be recycled and eventually contribute to the output power. For nonideal lasers, the filters designed with bandwidths and emission angles in accordance with the laser profiles can optimally boost the efficiency. By such design, the expansion of photon modes during absorption and emission processes is minimized, whereby the entropic loss is greatly diminished.

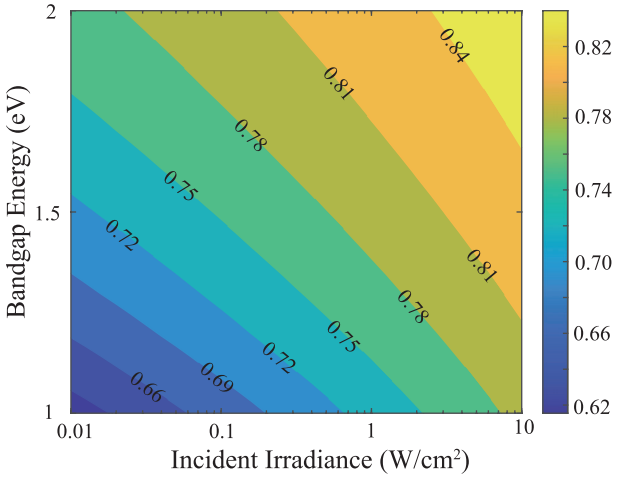

FIG. 2. Contour plot of efficiency as a function of incident irradiance and bandgap energy at 300 K.

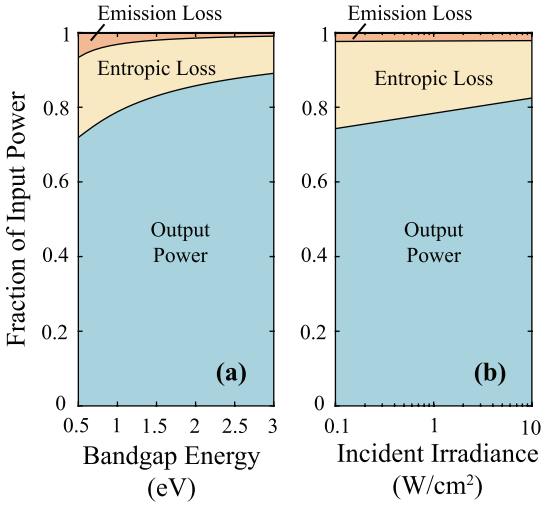

FIG. 3. Intrinsic losses and output power as fractions of input power. (a) The incident irradiance for calculation is 10 W/cm^2. (b) The bandgap energy for calculation is 1.42 eV. The entropic loss is solely contributed by the entropy produced during the absorption and emission of radiation.

The above analysis only involves radiative recombination. In the following analysis, two widely investigated PV materials, Si and GaAs, are analyzed accounting for nonradiative limitations in addition to radiative recombination. In real semiconductor materials, the free-carrier absorption and Auger recombination are also unavoidable. Since the free-carrier absorption is a minor effect in Si and GaAs devices, it can be neglected in the calculation.[17,18] However, Auger recombination can be comparable with radiative recombination even in thin-film materials and thereby is regarded as the sole intrinsic nonradiative recombination in the calculation. We consider the case where the semiconductor material is intrinsic or highly excited.[17,18] Finite Auger recombination rates will result in a volumetric entropy generation term that determines the entropy generation rate via Auger recombination as follows (see supplementary material):

$$\begin{aligned}\dot{S}_{GAug}(\mu, A, L) &= \frac{1}{T}\int \mu C_{\text{eff}} n_i^3 \exp\left(\frac{3\mu}{2kT}\right) dv \\ &= \frac{AL}{T}\mu C_{\text{eff}} n_i^3 \exp\left(\frac{3\mu}{2kT}\right),\end{aligned} \tag{14}$$

where L is the thickness of the planar PLPC, n_i is the intrinsic carrier concentration of the semiconductor material, and dv is the volume element. The effective Auger coefficients C_{eff} at room temperature are 3.79×10^{-31} cm^6 s^{-1} for Si and 7×10^{-30} cm^6 s^{-1} for GaAs.[19,20] The output power incorporating this volumetric entropy production term turns into

$$\dot{W} = \mu(\dot{N}_L - \dot{N}_C) - T\dot{S}_{GAug}. \tag{15}$$

Since the absorptivity that affects the absorbed particle fluxes is also thickness-dependent, an optimal thickness will emerge for achieving the highest efficiencies. The absorption coefficients $\alpha(E)$ of Si and GaAs are given in the literature.[21,22] To account for light trapping, we assume that the surfaces of the PLPC are randomly textured. With

randomly textured surfaces, photons incident upon the PLPC are diffracted away from the angles of incidence and thereby trapped inside the material via total internal reflection.[17,23] In the weakly absorbing limit ($\alpha L \ll 1$), the absorptivity of the textured PLPC with refractive index n is given by

$$a(E) = \frac{4n^2\alpha(E)L}{1 + 4n^2\alpha(E)L}, \tag{16}$$

which is very close to unity for large αL and can be applied as an approximate expression for all thicknesses.[17,23] Consequently, the absorbed energy and particle fluxes need to be modified with respect to the absorptivity: $\dot{E}_L = a(E_\lambda)AP_L$ and $\dot{N}_L = \dot{E}_L/E_\lambda$, where E_λ is the photon energy of the laser.

The MPPs, again, are found by $d\dot{W}/dV = 0$ with respect to the device thickness and incident irradiance. It is shown in Fig. 4 that for lasers with photon energy equal to the Si bandgap, the highest efficiency is obtained for the ~3000 μm thick Si PLPC. However, for lasers with a wavelength of 1020 nm, the highest efficiency is comparable, but only 1/15 the material is required. Therefore, in the presence of volumetric entropy production and nonideal absorptivity, using lasers with photon energy equal to the bandgap of the PLPC can be impractical. Lasers with photon energies higher than the bandgap will excite hot carriers in PLPCs, and the excess energy will be transferred to the lattice in picoseconds via phonon emission.[24] This process accounts for the thermalization loss,[25] which in the calculation is incorporated in the entropic loss produced during the absorption and emission of radiation. For GaAs PLPCs, the optimal laser photon energy is identical to the bandgap of the material owing to the high absorption coefficient at the bandgap. For almost every device thickness, any discrepancy in laser photon energy will diminish the efficiency, while the optimal thickness is unchanged. Illuminated by lasers with photon energy equal to the bandgap, the optimal thickness is ~5 μm, and 79.5% efficiency can be achieved at 10 W/cm^2.

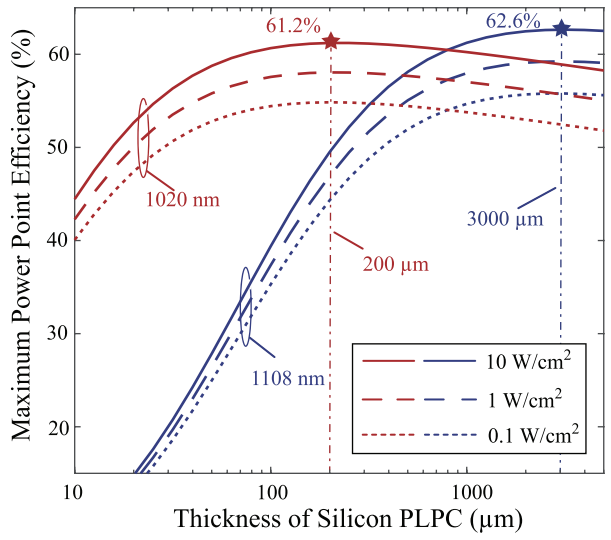

FIG. 4. Efficiencies of Si PLPCs illuminated by lasers with different wavelengths. Auger recombination is accounted for in the calculation. The optimal thickness for a specified laser wavelength is unaffected by the incident irradiance.

For the optimal thickness of Si PLPCs illuminated by the 1020 nm laser, a graphical illustration of intrinsic losses and output power is shown in Fig. 5(a). As in the radiative case, the major loss mechanism is the entropic loss produced during the absorption and emission of radiation, but the emission loss $\dot{E}_C$ is less than 0.3% and is, thus, negligible compared to the entropic loss via the Auger process $T\dot{S}_{GAug}$ (Auger loss). With such low emission loss, spectral or angular filters can barely diminish the proportion of emission loss in input power. However, using well-engineered spectral and angular filters in addition to the textured surfaces, the absorptivity given by Eq. (16) can be exceeded for the laser wavelength.[26,27] The enhanced light absorption is equivalent to increasing the incident irradiance, and thereby, higher efficiencies can be achieved. In Fig. 5(b), intrinsic losses in 5 μm GaAs PLPCs illuminated by lasers with photon energy equal to the bandgap are illustrated, which are almost identical to the curves in Fig. 3(b) due to the larger emission loss compared to the Auger loss. By means of spectral or angular filters, the emission flux can be reduced, and the efficiency can be further improved in GaAs PLPCs, nontrivially. As shown in the supplementary material, the efficiency improvement is guaranteed by both the high absorption coefficient at the bandgap and the low Auger recombination rate of the thin device. Therefore, to achieve higher monochromatic efficiencies, well-engineered spectral and angular filters can be incorporated into the design of PLPCs, which are beneficial to all kinds of PV technologies. In addition, we include a table that summarizes the effect of optical designs and provides brief design guidelines for different PV materials in the supplementary material.

For reference, the efficiencies of Si and GaAs PLPCs with optimal thicknesses are given for specified incident irradiances in Table. I. The Si PLPC is illuminated by the 1020 nm laser, and the GaAs PLPC is illuminated by the laser with photon energy equal to the bandgap of GaAs. Based on the numerical results at 0.1 W/cm^2, the efficiencies

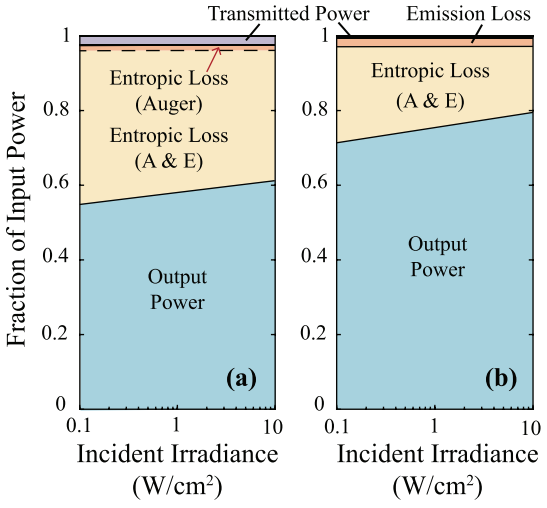

FIG. 5. Intrinsic losses and transmitted/output power as fractions of input power. (a) The results are given for the Si PLPC with 200 μm thickness illuminated by the 1020 nm laser. (b) The results are given for the GaAs PLPC with 5 μm thickness illuminated by the laser with photon energy equal to the bandgap. For brevity, the entropic loss produced during the absorption and emission of radiation is denoted by "A & E."

TABLE I. Efficiencies of PLPCs under various incident irradiances. The efficiencies are given both numerically and analytically. The analytical results are based on Eq. (13) and its extended form (see supplementary material) with the numerical results at 0.1 W/cm^2 chosen as the reference points.

	Si (200 μm)			GaAs (5 μm)		
Laser irradiance (W/cm^2)	0.1	1	10	0.1	1	10
Efficiency_numerical (%)	54.85	58.05	61.22	71.37	75.44	79.52
Efficiency_analytical (%)	54.85	58.39	61.93	71.37	75.56	79.75

estimated using Eq. (13) and its extended form (see supplementary material) are also listed. The absolute errors are less than 1%, which are mainly introduced by the change in MPP voltages.

In solar cells, Auger recombination is associated with Auger generation[28,29] (also called optically induced impact ionization). However, in PLPCs, the excess energy of the excited carrier $E_\lambda - E_g$ is negligible compared to E_g since the photon energy of the laser is close to E_g for achieving the highest efficiencies. In this case, the excess energy cannot excite new carrier pairs,[30] and thereby, Auger generation can be neglected.

In the presence of Auger recombination, the efficiency can still approach 100% if the laser irradiance is sufficiently large and the absorption is complete. In practice, finite carrier mobilities also produce volumetric entropy.[14,31] This volumetric entropy production demands a more compact design of the PLPC. Taking nonideal absorptivity into account, the optimal laser photon energy is larger than the bandgap of the PLPC. In this case, even higher efficiencies can be expected compared to PLPCs illuminated by lasers with photon energy equal to the bandgap. However, the efficiency is no longer a monotonic function of incident irradiance and will eventually be impeded by the resistive effects.

In conclusion, intrinsic losses in PLPCs are categorized and analyzed based on a thermodynamic model. The entropic loss generated during the absorption and emission of radiation is identified as the major loss mechanism. For Si and GaAs PLPCs, efficiencies are calculated considering Auger recombination, which estimate the potentials for engineering improvements well. In the presence of nonideal absorptivity and volumetric entropy production via Auger recombination, using lasers with photon energy equal to the bandgap of the PLPC can be impractical. The methods of improving the efficiencies with respect to the nonradiative losses are analyzed. In the absence of resistive effects, the efficiency can be close to 100% by intensifying the incident irradiance. By means of spectral and angular filters, the efficiencies of both Si and GaAs PLPCs can be improved accounting for the Auger loss. In practice, the entropy production due to finite carrier mobilities impedes the efficiency from approaching 100%.

See the supplementary material for the derivation of Eqs. (13) and (14) and the effect of spectral filters on improving the efficiency of GaAs PLPCs.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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