Journal of Power Sources 393 (2018) 211–216

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

A coupled model on energy conversion in laser power beaming

Chen-Wu Wu[a,b,*], Jyhwen Wang[c], Chen-Guang Huang[a,d]

[a] Laboratory for Mechanics in Fluid Solid Coupling System, Institute of Mechanics, Chinese Academy of Sciences, Beijing, 100190, China
[b] Laboratory for Aerospace Science and Technology, Institute of Mechanics, Chinese Academy of Sciences, Beijing, 100190, China
[c] Department of Engineering Technology and Industrial Distribution, Texas A&M University, Texas, 77843, USA
[d] School of Engineering Science, University of Chinese Academy of Sciences, Beijing, 100049, China

HIGHLIGHTS

- Laser power beaming technology is demonstrated for unmanned aerial vehicle.
- A coupled model is established for energy conversion in laser power beaming.
- Interaction is revealed between electricity conversion and heat dissipation.
- Optimization point is determined for maximum electricity power output.

ARTICLE INFO

Keywords:
Laser
Electricity
Heat
Interaction
Equilibrium

ABSTRACT

The light-to-electricity conversion efficiency is of critical interest for the laser power beaming technology. The coupled interaction between electricity conversion and heat generation determines the actual light-to-electricity conversion efficiency. In this paper, a coupled model is established to describe such coupled interaction and the equilibrium point of laser illuminated Photovoltaic (PV) cells. A simplified equation is developed to solve the equilibrium temperature and the electricity conversion efficiency of a thin-film PV cell evenly illuminated by a laser. Numerical examples are provided for typical conversion conditions and a preliminary parametric study with sensitivity analysis is carried out for future system design.

1. Introduction

The laser power beaming technology has been conceived and experimented continuously for remote/wireless power transmission, due to its potential advantages over its microwave-based counterpart, as reported by Kare [1], Leopold [2], Landis [3] and Yuan [4]. The concept of laser driven Unmanned Aerial Vehicle (UAV), as shown in Fig. 1(a), has been extensively tested and validated by several research groups [5,6]. As depicted in Fig. 1 (a), the Photovoltaic (PV) panel attached to the bottom of the UAV is used to convert the incident laser energy into electrical energy. Similarly, laser power beaming technology could also be used to charge electric vehicles [7] or a mobile phone [8] coated with PV cells as shown in Fig. 1(b).

The typical technical configuration of laser power beaming is presented in Fig. 2, in which the light-to-electricity conversion takes place in the PV cells illuminated by a laser beam with a specific wavelength. The rechargeable battery is utilized to store the electricity generated by PV cells and supply the electricity for power consumptions. The laser equipment could be operated by power grid and could produce laser with different wavelengths to match the PV cells. Theoretically, the light-to-electricity conversion efficiency of the PV cells under laser irradiation could be much higher than Solar irradiation as long as the laser wavelength matches well with the band gap of the semiconductor of PV cells. It is also imaginable that the electrical power output from a PV panel would increase with increasing input laser power.

However, it is reported [5] that the ceiling of the maximum attainable power is an inevitable barrier when rapid recharge of the battery is pursued. In other words, the output electrical power would not be increased with increasing input laser power when the laser power approaches some threshold magnitude under specific condition. This phenomenon certainly limits the application of laser power beaming. But, why is there such a ceiling phenomenon, and how is the threshold determined for any system? Broadly speaking, it should, at least partially, be related to the temperature dependency of the light-to-electricity conversion efficiency of the PV cells. As extensively demonstrated in the work by Meneses-Rodriguez [9], O'Donnell [10], Singh [11], Theelen [12] and Wysocki [13], the temperature elevation always reduces the band gap and the lifespan of the carrier.

* Corresponding author. Institute of Mechanics, Chinese Academy of Sciences. No.15 Beisihuanxi Road, Haidian District, Beijing 100190, China.
E-mail addresses: chenwuwu@imech.ac.cn, c.w.wu@outlook.com (C.-W. Wu).

https://doi.org/10.1016/j.jpowsour.2018.05.010
Received 21 February 2018; Received in revised form 25 April 2018; Accepted 3 May 2018
0378-7753/

Nomenclatures

β	effective degradation coefficient t time
β_1	*temperature coefficient* β_2 *stress coefficient*
η	light-electricity conversion efficiency E_l (W/m^3) absorbed laser power density
η_0	value of η at $T = T_0$ $E_e = \eta E_l$ (W/m^3) Electrical power density
ρ	density $E_g = (1-\eta)E_l$(W/m^3) Heat generation density
C	*specific heat capacity*
$\nabla = \boldsymbol{i}\partial/\partial x + \boldsymbol{j}\partial/\partial y + \boldsymbol{k}\partial/\partial z$	Gradient operator
h_c	convective heat exchange coefficient
u	displacement
d	effective thickness of cell
n	unit normal vector
k	*thermal conductivity*
ε	*surface emissivity coefficient*
Q	*heat flux*
S_B	*Stefan-Boltzmann constant*
T	*temperature* α *thermal expansion coefficient*
T_0	reference temperature for calibration E Young's elastic modulus
T_{env}	*environmental temperature*
ν	*Poisson's ratio*
T_{ref}	*reference temperature for stress free state*
σ	*Stress*
ΔT	temperature elevation in relative to T_0 when η_0 is calibrated
$(\Delta T)_s$	temperature elevation in relative to T_{ref} corresponding to the assumed the stress-free state
x, y, z	the spatial coordinates with x, y being in plane of the cell and z normal to plane
$P_l = E_l \times d$ *(W/m^2)*	*absorbed laser power flux (density over surface)*

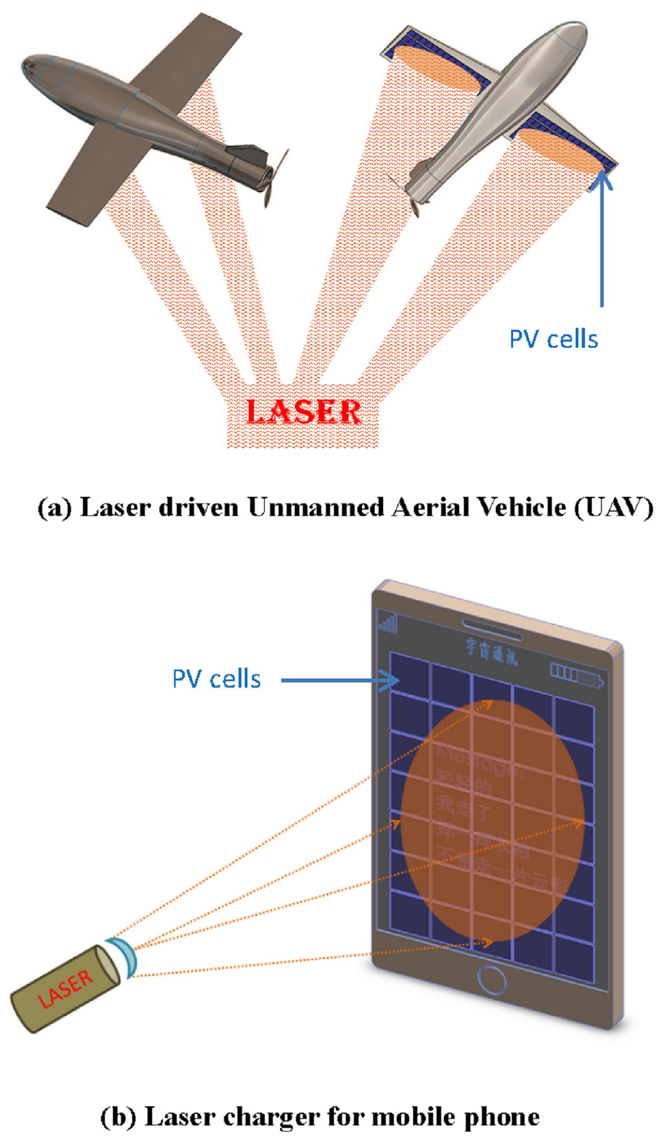

Fig. 1. (a) Conceptual applications of laser power beaming in remote/wireless power transmission - Laser driven Unmanned Aerial Vehicle (UAV). (b) Conceptual applications of laser power beaming in remote/wireless power transmission - Laser charger for mobile phone.

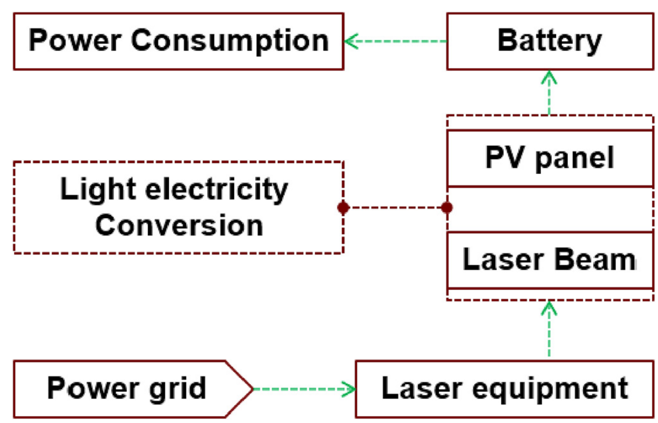

Fig. 2. Technique configuration of laser power beaming.

According to the law of energy conservation, the sum of the thermal/mechanical related energy from light-to-heat generation and the electrical energy from light-to-electricity conversion should basically equal to the absorbed laser energy. Herein, light-to-electricity conversion means the electricity produced from the absorbed laser energy by the PV cell, while the light-to-heat conversion means the direct heat generation in the PV cell from the absorbed laser energy. As such, the two energy forms of thermal/mechanical energy and electrical energy are intrinsically competing counterparts.

It is noteworthy that the thermal/mechanical related energy involves not only thermal energy but also mechanical deformation energy accompanied with temperature elevation of the PV cell, which is resulted from the heat dissipation of light energy as well as electrical energy. The latter is also commonly known as Joule heating due to electrical resistances in the PV panel. Of course, such effects could cause the laser power beaming system to fail if the PV cell temperature is excessively high when the intensity of the input laser is too high or the thermal diffusion is inadequate (i.e., the heat generated from the absorbed laser energy and accumulated in the PV cells cannot be adequately released to the environment).

Apart from the thermal failure, mechanical failure could also occur. As reported in the work by Siddiqui [14] and Turkovic [15], with temperature elevation, the thermal stress can develop from misfit thermal expansion of the structure and can lead to failure when the stress is higher than the material strength of the semiconductor devices.

Moreover, it is also revealed that the mechanical strain/thermal stress in the PV cell would influence its light-to-electricity conversion efficiency due to the change in the band gap of the semiconductors, as reported by Aissat [16], Jeon [17], Olsen [18], Prete [19], Reihlen [20] and Wu [21]. Obviously, the thermal stress within the PV cells is determined by its thermal expansion coefficients and the temperature gradient, while the temperature field of the PV panels is determined by the light-to-heat generation and the thermal environment surrounding them. In brief, the temperature field and the thermal stress in the PV panel are determined by the heat generation from the absorbed laser energy and the thermo-mechanical boundary conditions, which in turn instantaneously determine the light-to-electricity conversion efficiency.

Therefore, a detailed mathematical description of the light and thermo-mechanical response of a PV cell/panel illuminated by laser is necessary for the design and optimization of a laser power beaming system. This is not always the case for the common PV panels used for ground solar collection since the sunshine is not generally concentrated on the PV panels, as described by Feng [22], Evans [23], Dupré [24] and Cubas [25]. Thus, the existing research interest is mostly in sun-tracking [26] and sunshine-concentrating [27] where numerical simulations were used to study the thermal responses of the PV modules [28]. This partially explains why no thorough mathematical model depicting the laser-to-electricity conversion could be found on the present coupled physical problem.

The present work first demonstrates the physics governing the coupled interactions between the light-to-heat generation and light-to-electricity conversion in a PV cell illuminated by a laser. A mathematical model is established based on the law of energy conservation and thermo-elasticity theory. Then, a reduced form of the coupled model is proposed and formularized to solve the equilibrium temperature, thermal stress and the light-to-electricity conversion efficiency of the PV cell constrained by a rigid supporting frame. Based on the developed model, several numerical examples are presented. Finally, the dependency of the maximum attainable output electrical power on the system parameters is discussed and conclusions are drawn.

2. Coupled energy conversion model

The temperature dependency of the light-to-electricity conversion in a PV cell has been commonly known: the conversion efficiency would decrease with increased cell temperature. A large part of the absorbed laser energy would dissipate into heat, which means that the cell temperature would increase when it is subjected to laser illumination. In turn, the temperature field and its gradient field in the PV cell would change its light-to-electricity conversion efficiency, which leads to the so-called coupled interaction between the electrical energy conversion and thermal/mechanical related energy conversion as shown in Fig. 3.

In detail, Fig. 3 shows that the absorbed laser power density E_l consists of electrical power density E_e and heat generation power density E_g. The light-to-electricity conversion efficiency η determines the heat generation rate, which together with the thermo-mechanical boundary conditions in turn determines the conversion efficiency η. It is imaginable that a corresponding equilibrium of light-to-electricity conversion efficiency η exists for a specific combination of absorbed laser power and boundary condition. In the limiting case when the cell temperature is too high for any light-to-electricity conversion, the conversion efficiency η would be zero, which means that all of the absorbed laser power is dissipated into heat. In the ideal case when the initial heat generation is totally diffused into the surroundings immediately, the cell temperature is not changed and the light-to-electricity conversion efficiency η of the PV cell would be of its intrinsic designed value. Of course, the actual case should fall in between the limiting case and the ideal case. As the actual conversion efficiency of a PV cell is determined by the absorbed laser power, the boundary conditions and the cell parameters, a coupled model could be developed to describe the energy conversion and to optimize the laser power beaming system.

Mathematically, the actual light-electricity conversion efficiency η of the PV cell could be written by considering both the effects of temperature elevation and thermal stress, based on the work of O'Donnell [10], Singh [11], Olsen [18] and Evans [23]:

$$\eta = \eta_0[1 - \beta_1(\Delta T) + \beta_2\sigma] \quad (1)$$

where the temperature field is controlled by the heat conduction equation:

$$\rho C\frac{\partial T}{\partial t} = \nabla\cdot(k\nabla T) + E_g \quad (2)$$

and the thermal boundary condition:

$$k\frac{\partial T}{\partial n} = h_c(T - T_{env}) + \varepsilon S_B(T^4 - t_{env}^4) \quad (3)$$

If the state of plane stress is assumed [31–33], the first stress invariant for a film PV cell can be defined as:

$$\sigma = \sigma_{xx} + \sigma_{yy} \quad (4)$$

Such assumption of plane stress is accurate enough because the thickness of the thin-film PV cell is rather small in comparison to its in-plane dimension.

The two in-plane stress components are [31–33].

$$\sigma_{xx} = \frac{E}{(1-\nu^2)}[(\varepsilon_{xx} + \nu\varepsilon_{yy}) - \alpha(1+\nu)(\Delta T)_s] \quad (5)$$

$$\sigma_{yy} = \frac{E}{(1-\nu^2)}[(\varepsilon_{yy} + \nu\varepsilon_{xx}) - \alpha(1+\nu)(\Delta T)_s] \quad (6)$$

The strain-displacement relationship is [31–33].

$$\varepsilon_{xx} = \frac{\partial u_x}{\partial x} \equiv u_{xx} \quad (7)$$

$$\varepsilon_{yy} = \frac{\partial u_y}{\partial y} \equiv u_{yy} \quad (8)$$

Therefore, the first stress invariant is determined by the temperature gradient and the thermal expansion driven displacement field [31–33]:

$$\sigma = E\left(\frac{(u_{xx} + u_{yy})}{1-\nu} - \frac{\alpha(\Delta T)_s}{1-\nu}\right) \quad (9)$$

where the displacement field $\boldsymbol{u}$ could be calculated by solving the classic thermo-elasticity equation when the transient mechanical effects is insignificant for such thermal stress problem [31–33]:

$$\frac{3(1-\nu)}{1+\nu}\nabla(\nabla\cdot\mathbf{u}) - \frac{3(1-2\nu)}{2(1+\nu)}\nabla\times(\nabla\times\boldsymbol{u}) = \alpha(\nabla T) \quad (10)$$

This is the case where the continuous wave laser is utilized for power transmission, and the rate of temperature change and therefore the strain rate is insignificant [1,3,6]. As for the pulsed wave laser, only those of relative long pulse duration (> 1 ms) laser would be adopted, and the quasi-static assumption is still valid for thermo-elasticity analysis [2,4,7]. Of course, the transient mechanical effect would be significant only when the laser pulse duration is comparable to the elastic relaxation time. In such a condition, however, the instantaneous power intensity of the laser beam would be high enough to destroy the PV cell and therefore not suitable for power transmission. The detailed

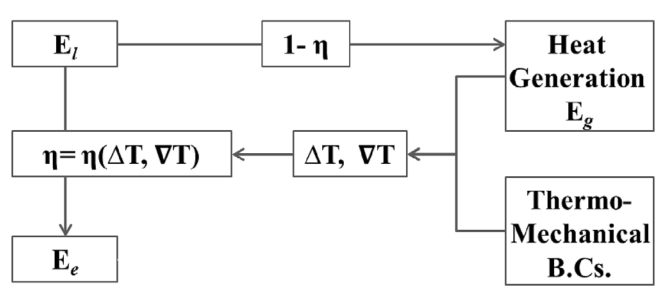

Fig. 3. Coupled interaction between electricity conversion and heat dissipation.

descriptions of thermo-elasticity formula could be found in the classic textbooks, like as those by Hetnarski [31], Timoshenko [32] and Landau [33].

Additional details of the thermo-elasticity theory on semiconductor devices could also be further referred to the work by Siddiqui [14], Turkovic [15] and Feng [22]. Basically, an iterative algorithm is necessary to solve the coupled Equations (1)–(10), although it would not be practical for the present work. Instead, the steady state case would be particularly analyzed herein to concentrate on the demonstration of the coupled physical problem.

Consider the general case that a film PV cell is evenly illuminated by a large laser spot. Ignoring the temperature gradient along the thickness ***d***, which is rather small in a multi-junction film PV cell according to Wu [29] and Yuan [30], the equation governing the steady state thermal behavior could be approximated as:

$$P_l(1-\eta_0[1-\beta_1\Delta T+\beta_2\sigma]) = h_c(\mathrm{T}-T_{env}) + \varepsilon S_B(T^4-T_{env}^4) \tag{11}$$

Equation (11) is actually an expression of the first law of thermodynamics that describes the conservation of energy, which represents herein the state of equilibrium between the heat generation from the absorbed laser energy and the heat diffusion into the environment.

Furthermore, if the PV panel is rigidly constrained by a relatively rigid supporting frame, one can ignore the deformation of the cell and obtain its thermal stress as

$$\sigma = \mathrm{E}\left(-\frac{\alpha(\Delta T)_s}{1-\nu}\right) \tag{12}$$

Hence, Equation (11) could be rewritten as:

$$P_l\left(1-\eta_0\left[1-\beta_1\Delta T-\beta_2\frac{E\alpha(\Delta T)_s}{1-\nu}\right]\right) = h_c(\mathrm{T}-T_{env}) + \varepsilon S_B(T^4-T_{env}^4) \tag{13}$$

which could be further simplified by letting the reference temperatures T_0 and $\mathrm{T}_{\mathrm{ref}}$ be identical and equal to some specific value, *e.g.* $\mathrm{T}_0 = \mathrm{T}_{\mathrm{ref}} = 270\,\mathrm{K}$, at which $\eta = \eta_0$ and the PV cell is assumed to be in a stress-free state. The linear superposition could be used in the computation of thermal stress when the residual stress is intentionally produced in a PV cell according to Feng [22]. This assumption is acceptable if the efficiency is calibrated at the initial state, and the temperature elevation induced nonlinearity in material elasticity is insignificant, which is the case for the PV cells presently considered for laser power beaming. Therefore, one can obtain the simplest equation governing the state of equilibrium of the PV cell as

$$P_l(1-\eta_0+\eta_0\beta(\mathrm{T}-T_{ref})) = h_c(\mathrm{T}-T_{env}) + \varepsilon S_B(T^4-T_{env}^4) \tag{14}$$

wherein

$$\beta = \beta_1 - \beta_2\left(\frac{\alpha \mathrm{E}}{1-\nu}\right) \tag{15}$$

Therefore, the equilibrium temperature T and actual light-to-electricity conversion efficiency η could be calculated for any absorbed laser energy P_l via solving the algebraic Equation (14) with given material properties and environment heat diffusion properties.

3. Numerical example and discussion

The main parameters for numerical example are listed in Table 1, where the values are from public database for typical film PV cells, as also used by Meneses-Rodríguez [9], Singh [11], Siddiqui [14] and Dupré [24].

It is noteworthy that the convective heat transfer boundary condition is modeled with two parameters, $\mathrm{T}_{\mathrm{env}}$ and h_{c} to simplify the coupled model on the temperature change and the actual light-to-electricity efficiency of the PV cell.

The top surface of the PV cell is assumed to be uniformly irradiated by laser beam and simultaneously exchanges heat with the surroundings through radiation and convection. Of course, for a transient heat conduction problem, the exact thermal boundary conditions at the bottom surface of the panel and the supporting structure depend on the specific system configuration. However, the simplified boundary conditions combining both the radiation and convection are commonly accepted for a steady-state heat conduction problem as only the balance between the heat generation from the absorbed laser energy and the heat diffusion from the surfaces into the surrounding is under consideration. For the same reason, the material density, thermal capacity or thermal conductivity do not appear in the equation or listed herein, as these parameters would not introduce mathematical deviation in the outcome if only the thermal equilibrium state is considered.

Solving equation (14) with the parameters listed in Table 1, one can achieve the equilibrium temperature and equilibrium electrical power density of the PV cell. Therefore, the dependencies of the equilibrium temperature, thermal stress and electrical power density on input laser power density, ambient temperature as well as convective heat transfer coefficient can be obtained as shown in Figs. 4–7. It should be noted that the logarithmic power density over surface is adopted in these figures for convenience, and again considering the 2-dimensional characteristic of the thin-film PV cell whose thickness is rather small compared to its in-plane dimensions.

Fig. 4 shows the equilibrium temperatures and thermal stress of the PV cell vs. different absorbed laser power densities at different environment temperatures when the convective heat transfer coefficient is $200\,\mathrm{W\,m^{-2}K^{-1}}$. Herein, the three environment temperature levels are chosen mainly based on the potential surroundings of UAV flying in the relevant altitudes. Obviously, the increase in the environment temperature would directly raise the equilibrium temperature of the PV cell if the constant convective heat transfer coefficient is assumed.

It is noteworthy that the characteristic of thermal stress in the PV cell greatly resembles that of the temperature elevation according to the intrinsic linear relationship between them as described by equation (12). One can easily image that the dependency of thermal stress on the input laser power density should be similar to that of the equilibrium temperature with difference only in a negative constant coefficient $\left(-\frac{\alpha \mathrm{E}}{1-\nu}\right)$. In detail, the PV cell would be under compression due to its constrained thermal expansion and the absolute value of the compressive stress would increase with increasing input laser power density.

It is also shown that the equilibrium temperature of the PV cell always increases with increasing input laser power density P_l. The rate of increase in equilibrium temperature is gradual when the input laser energy is lower than $10\,\mathrm{kW/m^2}$ (Log $(\mathrm{P}_l/\mathrm{Wm^{-2}}) = 4$) and is abruptly increased after that. This indicates that there exists a relatively stable thermo-mechanical response of the PV cell to the irradiation of laser with a large range of input powers, although the critical magnitude of the input laser density should depend on the convective heat transfer coefficient.

Fig. 5 depicts the equilibrium electrical power density P_e produced

Table 1
Main parameters for numerical examples.

Parameter	Unit	Magnitude	Range
P_l	$[\mathrm{Wm^{-2}}]$	/	$(1.0\times10^3, 1.0\times10^5)$
η_0	[1]	5.0×10^{-1}	/
β_1	$[\mathrm{K^{-1}}]$	2.0×10^{-3}	/
β_2	$[\mathrm{Pa^{-1}}]$	1.0×10^{-10}	/
α	$[\mathrm{K^{-1}}]$	5×10^{-6}	/
E	[Pa]	4.5×10^{10}	/
ν	[1]	3.0×10^{-1}	/
h_{c}	$[\mathrm{Wm^{-2}K^{-1}}]$	20, 200, 500	/
ε	[1]	0.8	/
$\mathrm{T}_{\mathrm{env}}$	[K]	200, 270, 340	/
$\mathrm{T}_{\mathrm{ref}}$	[K]	270	/

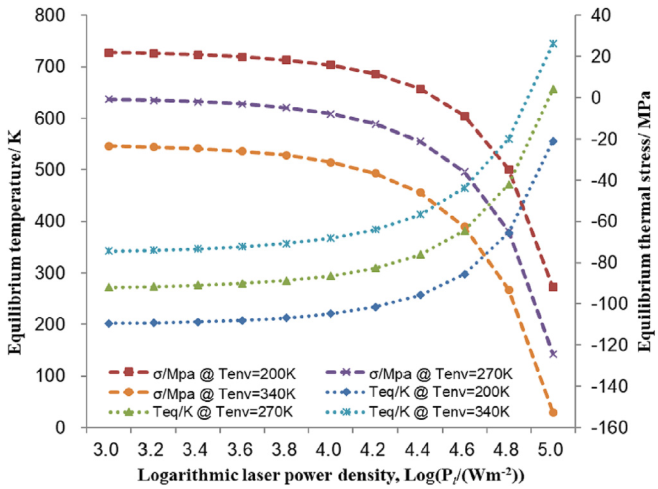

Fig. 4. Equilibrium temperature and thermal stress vs. input laser power density at different environment temperatures for the cases with h_c = 200 $Wm^{-2}K^{-1}$..

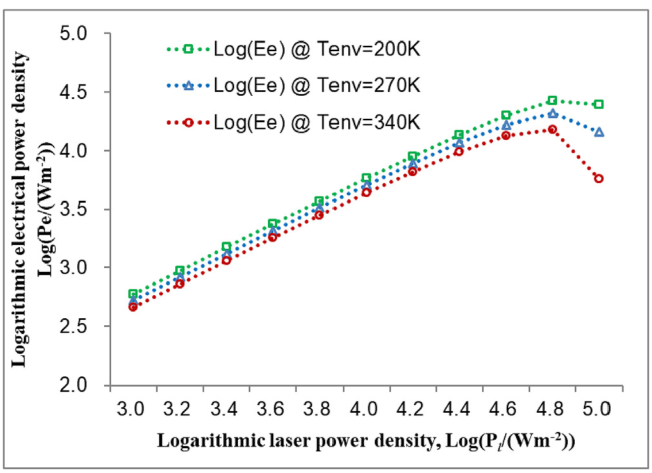

Fig. 5. Equilibrium output electrical power density vs. input laser power density at different environment temperatures for the cases with h_c = 200 $Wm^{-2}K^{-1}$..

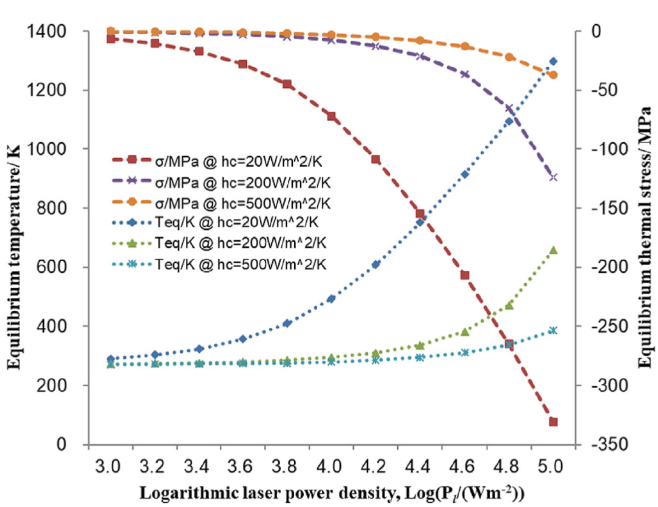

Fig. 6. Equilibrium temperature and thermal stress vs. input laser power density with different convective heat transfer coefficients for the cases with T_{env} = 270 K

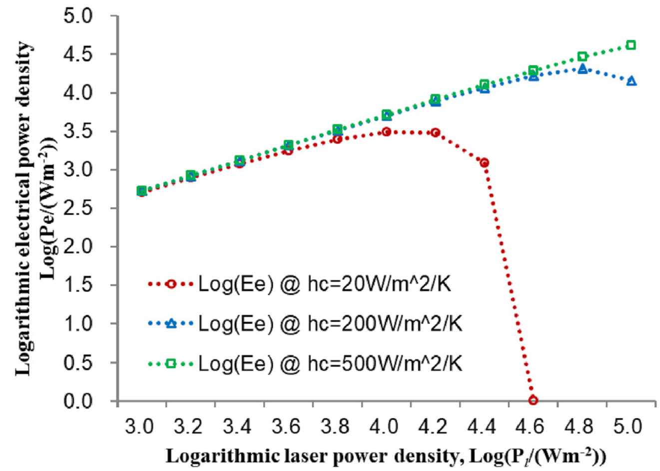

Fig. 7. Equilibrium output electrical power density vs. input power density at different convective heat transfer coefficients for the cases with T_{env} = 270 K

by the PV cell vs. different input laser power density at three different environment temperatures when the convective heat transfer coefficient is 200 $Wm^{-2}K^{-1}$. It is understandable that the output electrical power density P_e decreases with increased environment temperature as indicated by the three data curves in Fig. 5. It can be noted that the relatively low output electrical power density corresponds to the relatively high equilibrium temperature of the PV cell as shown in Fig. 4.

From Fig. 5, it is observed that the logarithmic output electrical powder density is directly proportional to the logarithmic input laser power density when the latter, Log (P_l) is less than 4.4. And thereafter, the increase of output electrical power density is clearly reduced. More importantly, the output electrical power density is inversely proportional to the input laser power density after Log (P_l) reaches 4.8 as indicated by the inflexion points of the curves in Fig. 5.

Fig. 6 shows the equilibrium temperatures and thermal stress of the PV cell vs. input laser power density with different convective heat transfer coefficients when the environment temperature is at 270 K. Again, the curves of the thermal stress and temperature elevation for any same case show a mirror symmetry.

As presented earlier, there is a positive correlation between the equilibrium temperature of the PV cell and the input laser power density. The ability of the PV cell to diffuse heat into the environment, which is mainly characterized by the convective heat transfer coefficient, influences greatly the rate of the equilibrium temperature increase. A lower convective heat transfer would lead a rapid increase in equilibrium temperature. For instance, the cell temperature would approach to an unacceptable level if only natural convection is taken into account, which gives a convective heat transfer coefficient of 20 $Wm^{-2}K^{-1}$, as represented by the curve denoted with small diamonds in Fig. 6. It also implies that the contribution of the surface radiation heat transfer to the total thermal diffusion is insignificant at the present temperature level of the PV cell.

Fig. 7 depicts the equilibrium output electrical power density produced by the PV cell vs. input laser power density at different convective heat transfer coefficients when the environment temperature is at 270 K.

The linear proportional increase of the output electrical power density with increasing input laser power density as well as the inflexion characteristics are demonstrated again. The physics underlining of such a phenomenon could be understood through the following elaborations: 1) The light-to-electricity conversion efficiency is basically negatively correlated with the PV cell temperature, that is $\eta = f_1(T)$, in which the thermal strain effect should also be included. 2) The equilibrium temperature of the PV cell would increase with the increase of input laser power, i.e. T= $f_2(P_i)$, where the laser power considered is over a unit area as W/m^2 in the paper. Therefore, 3) The light-to-electricity conversion efficiency is a complex function of the input laser power density, i.e. $\eta = f_1(f_2(P_i))$ and always decreases with increased input laser power density. Thus, the output electrical power would decrease with further increase of the input laser power when the increasing rate of power generation is less (due to degradation of conversion efficiency) than the rate of input power increase.

As shown in Fig. 7, the higher the convective heat transfer coefficient, the more electrical power would be obtained. Moreover, the output electrical power could be cut off when input laser power is too high or the convective heat transfer coefficient is too small, which could lead to permanent thermo-mechanical failure of the PV cell.

It should be noted that the present model is focused on the physics underlining of the energy conversion in laser power beaming technology based on a simplified form, and it does not involve any specific geometrical characteristic of the PV cell/panel. Moreover, the transient thermal/mechanical responses of the structure have not been taken into account. The current treatments could underestimate some localized thermal/mechanical behaviors spatially or temporally, which might be important factors affecting the reliability of the devices and should be particularly investigated for detailed design of a practical laser power beaming system.

4. Conclusions

The coupled interaction between electricity conversion and heat generation is modeled for light-to-electricity conversion in laser power beaming technology. For the first time, the coupled model on energy conversion of PV cell irradiated by monochromatic light laser is established to include both effects of temperature and thermal stress. The coupled problem is simplified for a thin-film PV cell evenly illuminated by a laser, and equilibrium solutions are obtained for typical cases. The equilibrium temperature, thermal stress and output electrical power density can be analytically predicted for a laser power beaming system in a specific surrounding.

Based on the present work, it is revealed that a relative low environment temperature and high thermal diffusion would decrease the equilibrium temperature and therefore increase the output electrical power density. Furthermore, it is shown that there is always a maximum output electrical power density versus the input laser power density. That is, the output electrical power would decrease with increasing input laser power once the latter reaches some threshold magnitude. It means that an optimization point of input laser power exists for a specific system, which can be found through the present coupled model.

Acknowledgement

Authors Chen-Wu Wu and Cheng-Guang Huang would like to acknowledge the support from the National Natural Science Foundation of China (Grant No. 11572327 and No. 11332011).

References

[1] J.T. Kare, F. Mitlitsky, A. Weisberg, Preliminary demonstration of power beaming with non-coherent laser diode arrays, Space Technology and Applications International Forum (STAIF-99), in AIP Conference Proceedings, 1999 (AIP).
[2] Summerer Leopold, Oisin Purcell, Concepts for Wireless Energy Transmission via Laser, (2009) Europeans Space Agency(ESA)-Advanced Concepts Team.
[3] G.A. Landis, Photovoltaic receivers for laser beamed power in space, J. Propul. Power 9 (1) (1999) 105–112.
[4] Y.C. Yuan, et al., Responses of thin film photovoltaic cell to irradiation under double laser beams of different wavelength, Mater. Sci. Forum 743–744 (2013) 937–942.
[5] X.-Z. Gao, et al., Reviews of methods to extract and store energy for solar-powered aircraft, Renew. Sustain. Energy Rev. 44 (2015) 96–108.
[6] R. Mason, Feasibility of laser power transmission to a high-altitude unmanned aerial vehicle, Technical Report Rand Project Air Force Santa Monica CA, RAND, 2011 UG1242.D7.M35.
[7] Z. Bi, et al., A review of wireless power transfer for electric vehicles: prospects to enhance sustainable mobility, Appl. Energy 179 (2016) 413–425.
[8] V. Iyer, et al., Charging a smartphone across a room using lasers, Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies 1 (4) (2018) 1–21 143.
[9] D. Meneses-Rodríguez, et al., Photovoltaic solar cells performance at elevated temperatures, Sol. Energy 78 (2) (2005) 243–250.
[10] K.P. O'Donnell, X. Chen, Temperature dependence of semiconductor band gaps, Appl. Phys. Lett. 58 (25) (1991) 2924–2926.
[11] P. Singh, N.M. Ravindra, Temperature dependence of solar cell performance—an analysis, Sol. Energy Mater. Sol. Cell. 101 (2012) 36–45.
[12] M. Theelen, et al., Determination of the temperature dependency of the electrical parameters of CIGS solar cells, J. Renew. Sustain. Energy 9 (2) (2017) 021205.
[13] J.J. Wysocki, P. Rappaport, Effect of temperature on photovoltaic solar energy conversion, J. Appl. Phys. 31 (3) (1960) 571–578.
[14] M.U. Siddiqui, A.F.M. Arif, Electrical, thermal and structural performance of a cooled PV module: transient analysis using a multiphysics model, Appl. Energy 112 (2013) 300–312.
[15] V. Turkovic, et al., Multiple stress degradation analysis of the active layer in organic photovoltaics, Solar Energy Mater. Solar Cell. 120 (2014) 654–668.
[16] A. Aissat, et al., Enhanced efficiency by the effect of strain on the structure of a solar cell, Energy Procedia 50 (2014) 817–823.
[17] H.C. Jeon, et al., Effect of lattice mismatch and thermal expansion on the strain of CdTerGaAs heterostructures, Appl. Surf. Sci. 156 (2000) 110–114.
[18] G.H. Olsen, et al., The effect of elastic strain on energy band gap and lattice parameter in III-V compounds, J. Appl. Phys. 49 (11) (1978) 5523–5529.
[19] P. Prete, et al., Thermal strain effects on the excitonic states in GaAs/AlxGa1 − xAs multiple quantum wells, J. Appl. Phys. 75 (9) (1994) 4750.
[20] E.H. Reihlen, et al., Measurement of the fundamental band gaps of a strained GaInAs layer, J. Appl. Phys. 68 (4) (1990) 1750–1756.
[21] Y. Wu, et al., Strain effects on the work function of an organic semiconductor, Nat. Commun. 7 (2016) 10270.
[22] Z.c Feng, H. d. Liu, Generalized formula for curvature radius and layer stresses caused by thermal strain in semiconductor multilayer structures, J. Appl. Phys. 54 (1) (1983) 83–85.
[23] D. Evans, Simplified method for predicting PV array output, Sol. Energy 27 (1981) 555–560.
[24] O. Dupré, R. Vaillon, M. Green, Physics of the temperature coefficients of solar cells, Sol. Energy Mater. Sol. Cell. 140 (2015) 92–100.
[25] J. Cubas, S. Pindado, M. Victoria, On the analytical approach for modeling photovoltaic systems behavior, J. Power Sources 247 (2014) 467–474.
[26] H. Mousazadeh, et al., A review of principle and sun-tracking methods for maximizing solar systems output, Renew. Sustain. Energy Rev. 13 (8) (2009) 1800–1818.
[27] H. Baig, et al., Conceptual design and performance evaluation of a hybrid concentrating photovoltaic system in preparation for energy, Energy 147 (2018) 547–560.
[28] J. Zhou, et al., Temperature distribution of photovoltaic module based on finite element simulation, Sol. Energy 111 (2015) 97–103.
[29] C.-W. Wu, Q. Peng, C.-G. Huang, Thermal analysis on multijunction photovoltaic cell under oblique incident Laser irradiation, Energy 134 (2017) 248–255.
[30] Y.-C. Yuan, C.-W. Wu, Thermal analysis of film photovoltaic cell subjected to dual Laser beam irradiation, Appl. Therm. Eng. 88 (2015) 410–417.
[31] R.B. Hetnarski, M.R. Eslami, Thermal Stresses –Advanced Theory and Applications, Springer Science + Business Media, B.V, 2009.
[32] S.P. Timoshenko, J.N. Goodier, Theory of Elasticity, third ed., McGraw-Hill Education (Asia) Co, 2004.
[33] L.D. Landau, E.M. Lifshitz, Course of Theoretical Physics- Theory of Elasticity, third ed., Butterworth-Heinemann, 1999.