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A coupled model on energy conversion in laser power beaming

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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.

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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.

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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)*

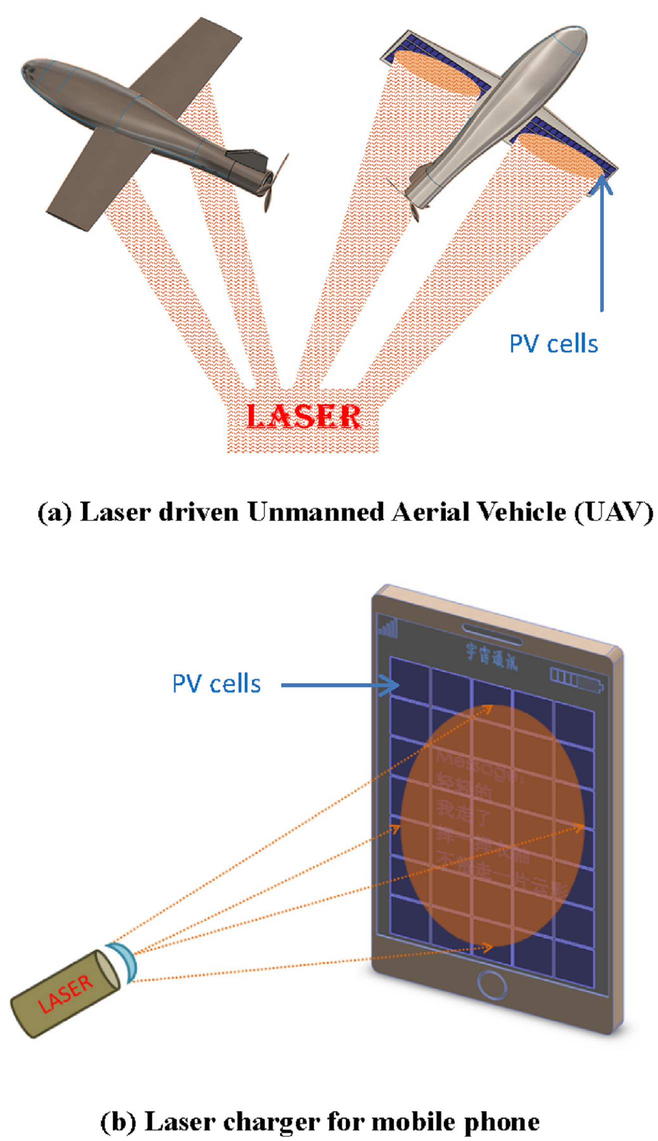

Fig. 1. (a) Conceptual applications of laser power beaming in remote/wireless power transmission - Laser driven Unmanned Aerial Vehicle (UAV). (b) Conceptual applications of laser power beaming in remote/wireless power transmission - Laser charger for mobile phone.

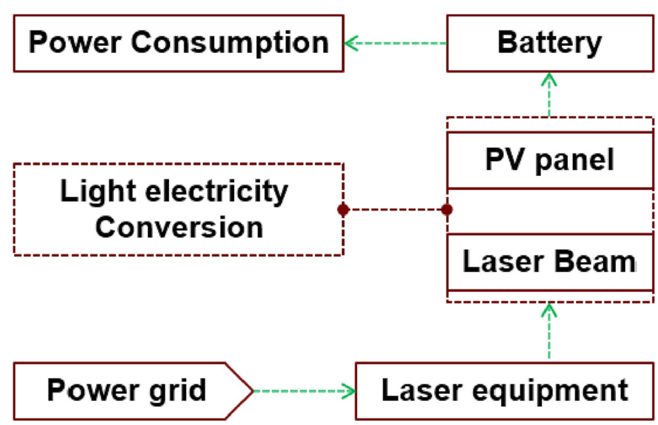

Fig. 2. Technique configuration of laser power beaming.

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]