Analysis of Photoelectric Conversion Efficiency of Space Laser Energy Transfer Based on Temperature Rise Effect

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Abstract. Temperature is an important factor affecting the efficiency of laser energy transmission. In this paper, aiming at the application of laser energy transmission in space, the existing spatial laser energy transmission photoelectric conversion model is improved and the mathematical model of photocell temperature rise is established. The model is used to analyze the influence of photoelectric cell temperature change on photoelectric conversion efficiency. The model takes into account various factors such as temperature, photoelectric cell material, space thermal radiation, laser space transmission characteristics, and improves the accuracy of the current model. On this basis, the maximum photoelectric conversion efficiency under different conditions and the corresponding photoelectric cell temperature are calculated. The conclusion shows: when other conditions remain unchanged, the photoelectric conversion efficiency first increases and then decreases with the increase of temperature. In addition, the stability value of the temperature of the photocell is generally different from the corresponding temperature value under the maximum efficiency under different conditions. So it is necessary to adjust the temperature according to the specific situation. It provides a theoretical basis for the practical application and temperature control of laser energy transfer in space.

1. Introduction
Laser energy can be transmitted over long distances by laser to the recipient. On the receptor, the light energy is converted into electric energy through a photocell, providing necessary energy for the receptor. In this way, the energy transmission relationship between the space station and the microsatellite can be established in the future, which can effectively extend the working time of the spacecraft in the shadow area. Temperature is an important factor affecting photoelectric conversion efficiency and photocell life. The space environment is characterized by large temperature difference, strong radiation and single heat exchange mode. Under different energy transmission conditions, the temperature variation range of photocell is large, which has a great impact on the efficiency of photoelectric conversion. At the same time, too high temperature may cause irreversible damage to the photocell, so that the transmission work can not be carried out. While the effect of temperature on laser energy transfer focused on the damage mechanism of temperature on photocell in the past[1], the influence of temperature on energy transfer efficiency has not been study and the model precision is not enough. In order to study the influence of temperature on space laser energy transmission, it is necessary to establish photoelectric conversion efficiency model and temperature rise model of space photovoltaic cell. For the photoelectric conversion model, Shi Dele[2] gave the method of establishing the photoelectric conversion efficiency model by filling factor F.F. The model is mainly applicable to engineering application scenarios, and the calculation accuracy is low. Landis G A[3] gave the method
of solving the laser energy transmission efficiency by photoelectric conversion efficiency under solar irradiation, which improves the calculation accuracy to a certain extent, but there are still few factors to be considered. Li Beibei[4] established a circuit model for calculating the efficiency of laser energy transmission based on output power, but the parameters related to photovoltaic materials are still not considered, and there is room for improving the accuracy. Based on the above model, the model of photogenerated current and reverse saturated current in output power model is improved, and the reflectivity of material and the transmission characteristics of space laser are considered. At the same time, by introducing a more accurate gap width model to improve the accuracy, the maximum photoelectric conversion efficiency and the optimal photoelectric conversion temperature can be calculated. For the photovoltaic cell temperature rise model, Li Beibei[4] gave a method to build the model based on the heat conduction theory, but the accuracy of the solution model of the laser energy transfer efficiency in this model is poor, and it is not suitable for the space environment. According to the application characteristics of space environment and combined with the improved laser energy transfer efficiency model, the temperature rise model is improved, so a more accurate temperature rise model of space photovoltaic cell is obtained. Then combined with the improved photoelectric conversion model and temperature rise model, the influence of light temperature on photoelectric conversion efficiency is analyzed concretely, and the necessity of optimum photoelectric conversion temperature and battery temperature control is explored.

2. Mathematical model of conversion efficiency of space laser irradiated photocell

Laser is absorbed by the photovoltaic cell of the receptor and generates photogenerated current through photoelectric conversion, which provides energy for the loads connected by the receptor. In this section, on the basis of the output power-based photoelectric conversion model, the photogenerated current and reverse saturated current models are improved, and the space transmission characteristics of photovoltaic materials and lasers are taken into account to establish a more accurate photoelectric conversion efficiency model for space laser energy transmission.

The photoelectric conversion efficiency is equal to the ratio of the output power of the photocell to the incident power of the laser. Photoelectric conversion efficiency formula

\[ \eta_{\text{laser}} = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{I_{\text{op}}V_{\text{op}}}{\Phi_{\text{inc}}S} \quad (1) \]

In which \( I_{\text{op}} \) and \( V_{\text{op}} \) is the corresponding output power output current and output voltage, respectively. The commonly used photoelectric conversion model is derived from the following photoelectric conversion equivalent circuit diagram.

![Figure 1. Equivalent circuit diagram of photoelectric conversion](image)

According to Kirchhoff's law, the following current relation is obtained:

\[ I_{\text{op}} = I_{\text{ph}} - I_{\text{sh}} \quad (2) \]
In which $I_{ph}$ is photo-generated current, $I_d$ is P-N junction current, $I_{as}$ is P-N the leakage current due to junction defects.

Lasers emitted from space stations decay during long-distance transportation. The energy of the acceptor is inversely proportional to the square of the transmission distance. Photovoltaic cells absorb photons and produce electron-hole pairs, which generate photo-generated current. When the laser is transmitted from the ground to a long-distance space target, Zhang Haifeng[5] gave the number of photons received by the target end:

$$N_p = \frac{4\phi_{\text{laser}} S A_K Q E T R_a}{\pi R^2 \theta_i^2} \beta \alpha$$

(3)

Among them, $\phi_{\text{laser}}$ is the incident laser power, $A_p$ is the effective area of the photovoltaic cell, $K$ is the efficiency of the ground emission system, $Q E T$ is the internal quantum efficiency, $\beta$ is the atmospheric transmittance, $\alpha$ is the energy attenuation factor caused by atmospheric jitter, $R$ is the distance from the space station to the center of the acceptor photovoltaic cell, and $\theta_i$ is the divergence angle of the beam caused by the laser emission telescope.

$S$ is the number of photons with 1 joule energy:

$$S = \frac{1}{h \nu} = \frac{\lambda}{1024 \times e}$$

(4)

In which, $\lambda$ is the wavelength of the incident laser, $e$ is a unit charge.

In the case of vertical incidence, the standard reflectivity formula is:

$$R_{\text{panel}} = \frac{(n_1 - n_2)^2}{(n_1 + n_2)^2}$$

(5)

In which $n_1$ and $n_2$ represents the refractive index of vacuum and photocell to vacuum, respectively. Absolute index of refraction $n = C/\nu$, Thus the vacuum refractive index is obtained: $n_i = 1$, therefore,

$$R_{\text{panel}} = \frac{(1 - n_1)^2}{(1 + n_2)^2}$$

(6)

In this paper, the laser is emitted from the space station without the effect of atmospheric attenuation. The effective area of the photovoltaic cell is equal to the product of the area of the photovoltaic cell and the cosine value of the incident angle of the laser. $Q E T$ is mainly affected by temperature. So the coefficient $K_T$ is introduced to correct the laser. Therefore, the laser is transmitted to the acceptor over a long distance in space. The current produced by the receptor is:

$$I_{ph} = N_p \times \frac{e \phi_{\text{laser}} A \cos(\theta_{\text{norm}}) Q E T_0 [1 + K_T (T - T_0)][1 - (1 - n_1)^2 / (1 + n_2)^2]}{1024 \pi R^2 \theta_i^2 / \lambda}$$

(7)

In which $A$ is the surface area of the photocell, $\theta_{\text{norm}}$ is the angle between the incident laser and the photocell normal, $\lambda$ is the wavelength of the incident laser, $K_T$ is the temperature correction coefficient. Reference temperature $T_0 = 298 K$.

Suganya J[6] expressed P-N junction current as:

$$I_d = I_{as} \exp \left( \frac{-e V_j}{n k T} - 1 \right)$$

(8)

In which $I_{as}$ is the reverse saturation current, which is a measure of leakage (or compound) phenomenon occurring when minority carriers cross p-n junction under reverse bias. While the minority carriers are generated by thermal excitation, so the reverse saturation current is greatly affected by temperature. Hiroshi M[7] gave the expression of the reverse saturation current of a single Si battery:
In which $D = 1.5 \times 10^8 \text{ m}^2/\text{cm}^2$, $E_g(T)$ is the forbidden band width of the photocell, which is mainly affected by temperature. Yi Mingguang[8] fitted with actual observation data and gave the expression of the gap width of the improved silicon cell changing with temperature:

$$E_g(T) = E_g(0) - A \frac{T}{T_c} [1 + B \ln\left(\frac{T}{T_c}\right)]$$  \tag{10}

The fitting parameters are as follows:

$$E_g(0) = 1.17323$$

$$A = 0.049V$$

$$B = 0.567$$

According to the circuit relations

$$I_{ph} = \frac{IR_s + V}{R_{sh}}$$ \tag{11}

Therefore, the mathematical model of photoelectric conversion efficiency of laser irradiation is:

$$I_{op} = \frac{4\phi_{laser} A \cos(\theta_{laser}) QE(T_0) [1 + K_f (T - T_0)] [1 - (1 - n_s)^2]}{1024 \pi R^2 \theta_l^2 / \lambda} \frac{-D \exp(-\frac{eT E_g(0) - eA T [1 + B \ln(T) - B \ln(T_c)]}{K'TT}) (\exp(\frac{e(V_{op} + I_{op} R_s)}{nkT} - 1))}{(1 + n_s)^2}$$

$$\text{Therefore, the mathematical model of photoelectric conversion efficiency of laser irradiation is:}$$

$$\frac{I_{op} R_s + V_{op}}{R_{sh}}$$

$$\eta_{laser} = \frac{I_{op} V_{op}}{\phi_{laser} S}$$ \tag{12}

3. Space photovoltaic cell temperature rise model

In this section, on the basis of the traditional heat conduction equation, considering the application characteristics of laser energy transmission in space environment and combining with the photoelectric conversion efficiency model of space laser energy transmission, the temperature rise model of photovoltaic cell based on space thermal radiation is established.

The size of Si photocell to be used is 20*20*0.2mm, since there is only radiation heat transfer in space under natural conditions, the photocell is regarded as a pure semiconductor, which is equivalent to the heat conduction model under the internal heat source, and the absorbed radiant heat energy is equivalent to the internal heat source.

Taking the center of single Si battery as the origin, the following model is established:

Figure 2. Two-dimensional model diagram of photocell
In which, the direction $x$ refers to the direction parallel to the outer edge of the photovoltaic surface, the direction $y$ refers to the normal direction of the photovoltaic cell receiving surface, $a$ represents the laser spot radius.

Therefore, the two-dimensional heat conduction equation of the photovoltaic cell is:

\[
\rho \mathcal{C}_p \frac{\partial T(x, y, t)}{\partial t} = \frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} \right) + \dot{Q}
\]

\[
\dot{Q} = \dot{Q}_{\text{laser}} + \dot{Q}_{\text{sun}} + \dot{Q}_{\text{earth}} + \dot{Q}_{\text{albedo}} + \dot{Q}_{\text{out}}
\]

(13)

Where $\dot{Q}$ is the heat source term, it includes laser radiation energy $\dot{Q}_{\text{laser}}$, solar radiation energy $\dot{Q}_{\text{sun}}$, earth infrared radiation $\dot{Q}_{\text{earth}}$, earth reflection radiation $\dot{Q}_{\text{albedo}}$, cosmic background radiation $\dot{Q}_{\text{space}}$, and external radiation of the photovoltaic $\dot{Q}_{\text{out}}$. In which $\dot{Q}_{\text{space}}$ is negligible relative to other radiation.

The energy of laser radiation used for heat generation needs to be removed from the reflected energy of the photovoltaic cell and the energy used for photoelectric conversion, which can be obtained by the following expression:

\[
\dot{Q}_{\text{laser}} = \alpha(1-\eta_{\text{out}})(1-R_{\text{panel}})\eta_\alpha \exp\left(-\frac{2}{\alpha}\right)\exp(-\alpha y)\cos\theta_{\text{out}}
\]

(14)

In which, $\eta_{\text{out}}$ is derived from the photoelectric conversion efficiency model in the previous section.

The expressions of the earth's infrared radiation, earth's reflection radiation and solar radiation are shown as follows, respectively. $\dot{Q}_{\text{earth}}$ and $\dot{Q}_{\text{out}}$ is obtained according to Stephen Boltzmann's law of Non-Blackbody total diffusion[9]:

\[
\dot{Q}_{\text{earth}} = \varepsilon_{\text{earth}} \sigma T^4 \cos \lambda_e
\]

(15)

\[
\dot{Q}_{\text{out}} = -2 \varepsilon_{\text{panel}} \sigma (T_{\text{panel}} - T_0) - \dot{Q}_r
\]

(16)

\[
\dot{Q}_{\text{albedo}} = (1-\eta_{\text{solar}}) \alpha_Q \phi_{\text{sun}} (h, \lambda, \theta)(\frac{A_b}{0.34})(\frac{\phi_{\text{sun}}}{1395})
\]

(17)

\[
\dot{Q}_{\text{sun}} = (1-\eta_{\text{solar}}) \alpha_Q \phi_{\text{sun}} \cos \theta
\]

(18)

In which, $\varepsilon_{\text{earth}}$ and $\varepsilon_{\text{panel}}$ are the infrared emissivity of the earth and the photovoltaic, respectively.

The Boltzmann constant $\sigma = 5.6704 \times 10^{-8} \ W/(m^2 \cdot K^4)$, $\lambda_e$ is the angle between the center of the earth and the center of the photovoltaic and the normal direction of the photovoltaic, $T_{\text{earth}}$ and $T_{\text{panel}}$ are the temperature of the earth and the photovoltaic, respectively.

The energy density of the earth's albedo radiation $\dot{Q}_{\text{albedo}}(h, \lambda, \theta)$ is obtained from the NANATN-1842[10] curve.

Meanwhile, boundary conditions are determined:

The initial temperature is the cosmic background temperature:

\[
T\big|_{t=0} = 4K
\]

Photovoltaic cells are insulated in the direction of vertical thickness, therefore, the radial boundary:

\[
\frac{\partial T}{\partial x}\big|_{x=b} = 0
\]

There is only radiation heat transfer on the surface of the photovoltaic, the vertical boundary:

\[
k \frac{\partial T}{\partial y}\big|_{y=0} = (\varepsilon_f + \varepsilon_i) \sigma (T_0^4 - T(x, 0, t))
\]

4. Simulation and analysis

After establishing the model, we planned the energy transmission task, established relevant parameters, calculated the energy transmission efficiency under different temperatures and loads.
4.1. Parameter determination
Assuming that the distance between the laser source and the center of the photovoltaic cell remains unchanged during the energy supply period. The The simulation scenario is set as the micro-satellite sailing to the shadow area. \( Q_{\text{radar}} = Q_{\text{allzard}} = 0 \), A laser fired from the space station powers a tiny satellite's photovoltaic cell, extending its working time.

The laser irradiation power density: \( \phi_{\text{laser}} = 2000 \text{w/m}^2 \), the angle between the center of the earth and the center of the cell and the normal of the cell \( \lambda = 0^\circ \), the optical maser wavelength \( \lambda \) is set as 980nm, the absorptivity of the Si battery on 980nm laser is 0.95, the temperature coefficient of photocell \( K = -0.0025 \), the infrared emitting ability \( \varepsilon_{\text{panel}} = 0.85 \).

4.2. Simulation and result analysis
From the above model, it can be seen that the temperature and photoelectric conversion efficiency of photovoltaic cells are interacted, and it is relatively complex to find the law directly. So this paper establishes the Simulink model through MATLAB software, and makes the following simulation:

![Photoelectric Conversion Efficiency Simulation Flow](image)

The simulation mainly simulates the change of photoelectric conversion efficiency with temperature under different loads, and calculates the corresponding maximum photoelectric conversion efficiency and the optimal photoelectric conversion temperature.

The simulation results are as follows:

![Relation between photoelectric conversion efficiency and temperature under different loads](image)
As can be seen from figure 4, when the power density of laser irradiation is constant, the overall trend of laser energy transfer efficiency with the change of temperature first goes up and then goes down. Because with the increase of temperature, the quantum efficiency in the photocell increases continuously. When the temperature is too high, the photocell will suffer damage, which leads to the decrease of efficiency. The maximum conversion efficiency is different under different loads. When the load of photocell is 5\(\Omega\) and the temperature is about 130K, the maximum output power reaches 45%. As the load increases, the temperature required to achieve the maximum efficiency decreases, and the maximum efficiency increases. When the load reaches 10\(\Omega\) or above, the photoelectric conversion efficiency decreases with the increase of temperature.

Figure 5. Temperature rise model simulation flow of photovoltaic cells based on space thermal radiation

The simulation mainly simulates the changing trend of temperature and photoelectric conversion efficiency of photovoltaic cell after laser is absorbed by photovoltaic cell at the initial temperature of 30K. The stable temperature of photovoltaic cell under different loads is determined. The results are as follows:

Figure 6. Variation trend of photocell temperature with time under different loads
Figure 7. Variation trend of photoelectric conversion efficiency with time under different loads

As shown in figure 6 and figure 7, in the set simulation environment, the final temperature of the photocell is basically stable within the temperature range of 290-328K under different loads. When the load is only 1.5Ω, the photocell temperature happens to be stable around 290K, and the photoelectric conversion efficiency reaches the maximum value. However, for other loads, the photoelectric conversion efficiency does not reach the maximum value under the corresponding load within this temperature range. Combined with the above simulation of photoelectric conversion efficiency changing with temperature, we can conclude: For the small load, we need to heat up the photocell to achieve the maximum photoelectric conversion efficiency. For the large load, we need to heat the photocell. Therefore, we need to improve the energy transmission efficiency by controlling the temperature.

5. Summary

In this paper, the effect of temperature rise of photovoltaic cell on photoelectric conversion efficiency is studied for the application of laser energy transmission in space. By improving the photogenerated current model and reverse saturated current model, and combining the characteristics of laser space transmission, an accurate photoelectric conversion efficiency model of laser energy transmission is established. Based on the traditional two-dimensional heat conduction model and considering the space thermal radiation, the temperature rise model of photovoltaic cell for laser energy transmission in space environment is established. On the basis of the above model, the change of photoelectric conversion efficiency with the temperature of photovoltaic cell and the optimum photoelectric conversion temperature are successfully solved, and the temperature change trend of photovoltaic cell in the process of space laser energy transmission is simulated, which proves the necessity of space temperature control to improve energy transmission efficiency. However, due to the complexity of the space environment, it is still possible to obtain more accurate models by refining the parameters. It can also improve the photoelectric conversion efficiency of laser energy transmission from the aspects of the material structure of photovoltaic cells and the quality of laser light source, which will be continuously improved in the follow-up research.

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