

Article

# Analysis and Experiment of Laser Wireless Power Transmission Based on Photovoltaic Panel

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**Abstract:** A photovoltaic panels is a device used for converting solar and other energy into electrical energy. In laser wireless power transmission, there is a problem that the conversion efficiency of the photovoltaic panel is not as high as that of a single photovoltaic cell, and the output power is not as large as expected. This is not conducive to the popularization and use of wireless power transmission via laser. It is important to find out why the output power of the photovoltaic panel irradiated by lasers is not high. According to the laser intensity distribution equation, it is deduced that the laser in a very small area has an equivalent uniformity intensity distribution through the comparative calculation of the light intensity of two adjacent points. Then, the input non-uniform laser can be broken down into many equivalent uniform small lasers with different light intensity values. Based on this theory, the photovoltaic array model under laser was established, and it was simulated by MATLAB/Simulink. The simulation results reveal that the greater the difference between the light intensity values of these small spots, that is to say, the more non-uniform the laser, the lower the output power of the photovoltaic module illuminated by it. A multi-wavelength experimental platform was built, and comparative experiments of laser wireless power transmission were carried out using three kinds of lasers: 808, 532, and 1030 nm. The experimental result was in good agreement with the simulation result. The above results show that the deduced theory and the model based on it are correct.

**Keywords:** laser; output characteristics; illumination; photovoltaic panel; wireless power transmission; efficiency



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## 1. Introduction

Lasers can be used for long-distance wireless power transmission [1,2]. The authors of [3–6] point out that it has the capability to charge remote mobile devices such as unmanned aerial vehicles. In [7], laser wireless power transmission is used to replace wired transmission as indoor power transmission. The main processes are the lasers' emission by an optical source and subsequent absorption in a photovoltaic panel to transform the laser into electricity. As shown in [8–10], the system achieves the purpose of remote power transmission through the photoelectric conversion of laser and photovoltaic cells. It is reported in the literature [11–13] that under the condition of AM1.5, that is, 1000 W/m<sup>2</sup>, the conversion efficiency of lasers and photovoltaic cells is between 17% and 25%. In other words, 1 W laser can be converted into 0.17 to 0.25 W electricity of. The literature [14] uses an 808 nm laser when the laser power is 0.1 W, that is, the illuminance is 1000 W/m<sup>2</sup>, the conversion efficiency of crystalline silicon can reach 35.85%. This technology not only provides power for unmanned aerial vehicles and boats but also improves their endurance [15,16].

A laser emits a non-uniform beam with a Gaussian intensity profile. Each cell of a photovoltaic panel receives different power densities when illuminated by a laser. These cells then introduce a mismatch in the output of the photovoltaic panel because the output of each cell is influenced by the power density. This mismatch mainly refers to the relationship

between the incident laser’s power and the output electrical power of the photovoltaic cells array composed of multiple photovoltaic cells. Some cells in the array may consume electric power as a load. This mismatch not only reduces the output power of the photovoltaic panel but also presents security risks. For example, a cell with a low current will generate heat as a load and eventually cause a fire [17]. Therefore, performing a mismatch analysis and a simulation of photoelectric conversion when lasers are used to illuminate the photovoltaic panel can serve as the basis for improving the efficiency of wireless power transmission via lasers. Accordingly, such analysis and simulation are crucial to relevant technical research.

## 2. Output Characteristics of the Photovoltaic Panel

A photovoltaic cell is an optoelectronic device usually made of silicon. The equivalent circuit of a photovoltaic cell is shown in Figure 1.

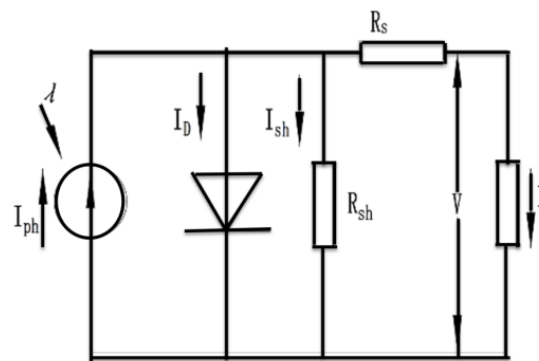


Figure 1. Equivalent circuit of a solar cell.

In Figure 1,  $I_{ph}$  is the cell photocurrent. The photocurrent source is connected in parallel with a reverse diode, the current of which is denoted by  $I_D$ . The intrinsic shunt resistance of the cell is denoted by  $R_{sh}$ .  $R_s$  denotes the series resistance of the cell.  $I$  is the output current and the corresponding output voltage is  $V$ . The relationship between the current  $I$  and voltage  $V$  in the equivalent circuit model can be determined as follows:

$$I = I_{ph} - I_0 \left[ \exp\left(\frac{V + I \times R_s}{A \times V_t}\right) - 1 \right] - \frac{V + I \times R_s}{R_{sh}}, \tag{1}$$

$$I_{ph} = [I_{sc} + K_i(T - T_r)] \times I_r / 1000, \tag{2}$$

$$V_t = \frac{K \times T}{q}, \tag{3}$$

where  $I_{SC}$  denotes the short circuit current (A),  $T$  denotes the operating temperature (K),  $T_r$  denotes the nominal temperature (298.15 K),  $K_i$  denotes the short circuit current temperature coefficient (A/K),  $I_r$  denotes the laser irradiation ( $W/m^2$ ),  $I_0$  denotes the reverse saturation current of photovoltaic cells (A),  $A$  denotes the diode quality factor,  $q$  denotes the electron charge (C, which generally takes a value of  $1.602 \times 10^{-19}$  C),  $K$  denotes the Boltzmann constant (J/K, which generally takes a value of  $1.381 \times 10^{-23}$  J/K), and  $V_t$  denotes the thermal voltage (V).

When multiple cells are connected in series or in parallel to form a photovoltaic array, this array is also known as a photoelectric panel. The equivalent circuit of the classical photoelectric panel is shown in Figure 2, where  $m$  and  $n$  denote the number of series and parallel connections in the photoelectric panel, respectively.

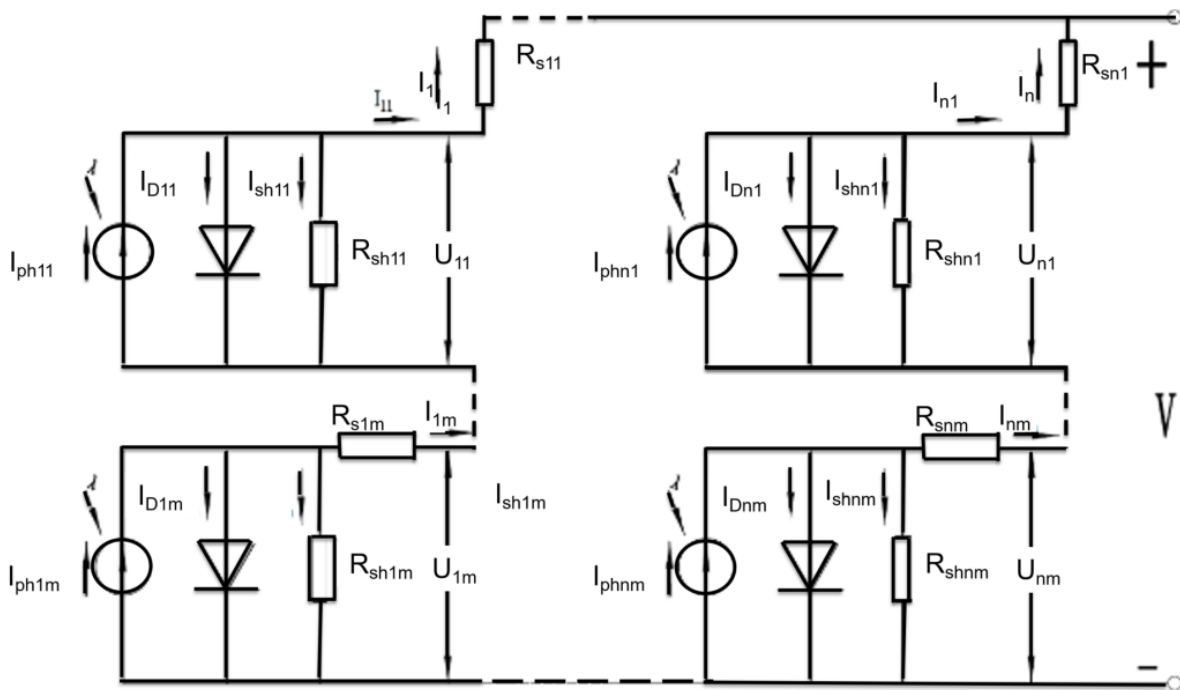


Figure 2. Equivalent circuit of the m series and n parallel connections in the photoelectric panels.

The current output of photoelectric panel  $I$  can be computed as:

$$I = n \times I_{ph} - n \times I_0 \times \left[ \exp\left(\frac{V + I \times \frac{R_s}{n}}{A \times V_t}\right) - 1 \right] - \frac{V \times \frac{n}{m} + I \times R_s}{R_{SH}}, \tag{4}$$

whereas the saturation current of photoelectric panel  $I_0$  changes along with the cell temperature. The relationship between these factors can be expressed as:

$$I_0 = I_{rs} \left[ \frac{T}{T_r} \right]^3 \exp\left[ \frac{q \times E_{g0}}{A \times K} \left( \frac{1}{T} - \frac{1}{T_r} \right) \right], \tag{5}$$

Meanwhile,  $I_{rs}$  represents the reverse saturation current of the photoelectric panel and is computed as [18–20]:

$$\frac{1}{2} I_{rs} = I_{sc} / [\exp(q \times V_{OC} / m \times K \times A \times T) - 1], \tag{6}$$

where  $I_{rs}$  denotes the photoelectric panel reverse saturation current (A),  $E_{g0}$  denotes the bandgap of semiconductor energy (which generally takes a value of 1 (eV)), and  $V_{OC}$  denotes the open circuit voltage (V).

According to Formula 6, a model of five photovoltaic cells connected in series is established by using MATLAB. The external interface form of the model is shown in Figure 3. The model has two input parameters: temperature and light. For example, the temperature of 25 °C and the illuminance of 300 W/m<sup>2</sup> are shown in Figure 3. The model shown in Figure 3 is expressed as 5 photovoltaic cells connected in series, which are irradiated by a laser with an illuminance value of 300 W/m<sup>2</sup> when the temperature is 25 °C. After photoelectric conversion, electric energy will be output through the positive and negative terminals of the model. The electric energy can be expressed in the form of current, voltage, or power. The format of the specific output will be determined by the measuring equipment connected to the model. When the model is connected to an ammeter, the current value will be displayed, and so on. Changing the input temperature and illuminance values will result in different electric energy output. Therefore, this

model can be used as a basic unit to build larger and more complex photovoltaic panels in subsequent simulation chapters.

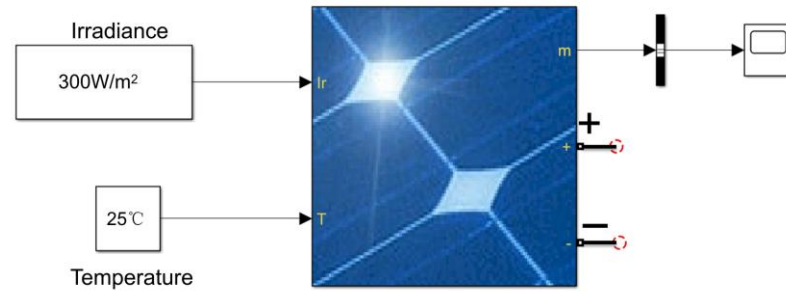


Figure 3. Photovoltaic module.

### 3. Laser Energy Distribution

For a photovoltaic cell, the conversion efficiency across the entire spectrum ranges between 20% and 25% [21]. Meanwhile, the band gap for the crystalline structure of silicon cells ranges from 1.125 to 1.2 eV. When the incident photon energy directly irradiates the band gap of silicon cells, the photovoltaic cells achieve their highest conversion efficiency.

The conversion efficiency of a cell increases as the energy of incident photons approaches the indirect band gap for silicon cells, which ranges from 1.125 to 1.2 eV depending on its crystalline structure. For a laser with a wavelength range of 800 to 1000 nm, the silicon cell theoretically achieves a conversion efficiency of 50% to 60% [22]. The non-uniformity of the laser will cause the current and voltage of each photovoltaic cell to be unequal, and the difference between each other is very large. The cells with low current or voltage will exist as resistors, and most of the current or voltage will be consumed by such a resistor. So, the main factor that restricts the conversion efficiency of laser-irradiated photovoltaic cells is the energy distribution state of the incident laser [14]. The intensity of the fundamental-mode Gaussian beam distribution can be expressed as follows (Equation (7)) [23,24]:

$$I = \kappa E^2 = \kappa \left\{ \frac{A_0}{W(z)} \exp\left[-\frac{r^2}{W^2(z)}\right] \right\}^2 = \kappa \frac{A_0^2}{W^2(z)} \exp\left[-\frac{2r^2}{W^2(z)}\right], \tag{7}$$

where  $K$  is the proportional coefficient,  $A_0/w(z)$  denotes the amplitude propagating along the  $z$ -axis at point  $(x = 0, y = 0)$ ,  $z$  denotes the distance from the spot to the focal point on the optical axis,  $\omega(z)$  denotes the spot radius of a Gaussian beam that intersects with the propagation axis at point  $z$ ,  $r$  denotes the curvature radius of the wave front, and  $E$  denotes the electric field at coordinate points  $(x, y, z)$ .

Assuming that at point  $Z$ , there are two adjacent points  $A$  and  $B$  in the laser spot, their coordinates are  $a(x_1, y_1, z)$  and  $b(x_1 + \Delta, y_1, z)$ , and  $\Delta$  tends to 0. Then, these two points can be considered as any two points within an extremely small area. The light intensity ratio of two points can be obtained from Equation (7):

$$\frac{I_a}{I_b} = \frac{k \frac{A_0^2}{w(z)} \exp\left(-\frac{2(x_1^2 + y_1^2)}{w^2(z)}\right)}{k \frac{A_0^2}{w(z)} \exp\left(-\frac{2(x_1 + \Delta)^2 + y_1^2}{w^2(z)}\right)} = \exp\left\{ \frac{2}{w^2(z)} \left[ -(x_1^2 + y_1^2)^2 + ((x_1^2 + 2\Delta x_1 + \Delta^2) + y_1^2)^2 \right] \right\} \tag{8}$$

Equation (9) can be obtained by calculation:

$$\exp\left\{ \frac{2}{w^2(z)} \left[ (2\Delta x_1 + \Delta^2)^2 + 2(x_1^2 + y_1^2)(2\Delta x_1 + \Delta^2) \right] \right\} \tag{9}$$

When  $\Delta \rightarrow 0$ , then:

$$\lim_{\Delta \rightarrow 0} \frac{I_a}{I_b} = \lim_{\Delta \rightarrow 0} \exp\left\{ \frac{2}{w^2(z)} \left[ (2\Delta x_1 + \Delta^2)^2 + 2(x_1^2 + y_1^2)(2\Delta x_1 + \Delta^2) \right] \right\} = 1 \tag{10}$$

Specifically,  $I_a \approx I_b$ . Equation (10) shows that the intensity of the laser spot at any point in an extremely small area is approximately equal. In other words, the light is equivalently uniform in a very small area.

If the radius of the clear aperture is  $\rho$ , then the light intensity can be expressed as:

$$I(\rho) = \kappa \frac{A_0^2}{W^2(z)} \int_0^\rho \exp\left[-\frac{2r^2}{W^2(z)}\right] (2\pi r) dr. \tag{11}$$

The light intensity in the clear aperture radius of  $\infty$  can be expressed as follows. If  $\rho$  approaches infinity, then the light intensity is expressed as:

$$I(\infty) = \kappa \frac{A_0^2}{W^2(z)} \int_0^\infty \exp\left[-\frac{2r^2}{W^2(z)}\right] (2\pi r) dr. \tag{12}$$

The ratio of intensity at distance  $\rho$  and  $\infty$  can be expressed as:

$$I(\rho) = \frac{I(\rho)}{I(\infty)} = \frac{\kappa \frac{A_0^2}{W^2(z)} \int_0^\rho \exp\left[-\frac{2r^2}{W^2(z)}\right] (2\pi r) dr}{\kappa \frac{A_0^2}{W^2(z)} \int_0^\infty \exp\left[-\frac{2r^2}{W^2(z)}\right] (2\pi r) dr} = 1 - \exp\left[-\frac{2\rho^2}{W^2(z)}\right]. \tag{13}$$

A ratio of 1 can be obtained from the above formula when the clear aperture approaches infinity. If the size of the clear aperture is 2.5 times that of the laser spot, then the ratio is equal to 0.99999 across all laser spot intensities. Therefore,  $I(\rho)$  is equal to 0.988, 0.977, and 0.864 when the value of the clear aperture is 2 times, 1.5 times, and 1 times larger than that of the laser spot, respectively.

The intensity distribution of the laser can be measured by using the photoelectric scanning method, where the solid-state laser acts as the laser source, the multi-hole aperture can yield different aperture diameters, and the photoelectric detector receives and converts the laser into electricity.

The photoelectric detector can be driven by a 2D mechanical device to scan the laser spot. The power distribution of the laser in the XOY plane is then recorded. Table 1 presents the data for the x-axis obtained from the experiment. The laser distribution intensity according to the experimental data is shown in Figure 4 [25,26].

**Table 1.** Laser power distribution intensity on the x-axis.

Location (mm)	Power (W)
0	0.014
1	0.136
2	0.501
3	1.046
4	1.512
5	1.802
6	1.899
7	1.854
8	1.702
9	1.346
10	0.733
11	0.222
12	0.029

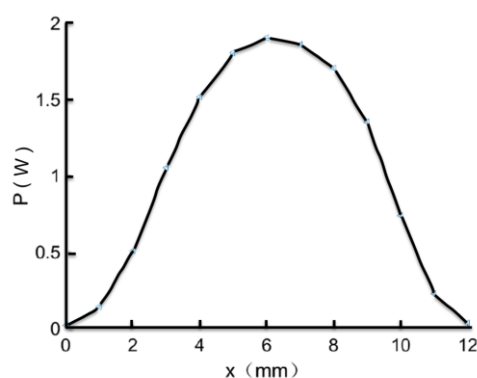


Figure 4. Gaussian distribution of the laser.

#### 4. Simulation and Analysis

The divergence angle of a laser is usually small [27]. In the transmission process, the energy can be concentrated, and the corresponding dissipation loss is small. Therefore, lasers are ideal sources of light for wireless power transmission. The initial research direction in this area was to build a device for converting beam energy into thermal energy. However, this conversion does not work well. The main reason is that heat is converted into electricity and a generator is needed in the middle, which will increase the intermediate loss. Additionally, although the laser peak power is high, which can make the temperature of the spot reach a very high temperature quickly, these areas are not enough for power generation. There is no such low-temperature generator currently. Later studies used photovoltaic cells to receive light energy for photoelectric conversion and achieve wireless power transmission.

Photovoltaic cells are usually made in series or in parallel, which is appropriate for uniform beam irradiation. In order to solve the problem, bypass diodes are usually added at both ends of the photovoltaic cell to prevent current reversal between the branches. However, a laser is a Gaussian beam, that is, the light intensity is strong in the middle but weak in others. In addition, when the laser is weak, the output current is low, thereby reducing the output of the whole photovoltaic panel. Such a photovoltaic panel cannot work at maximum efficiency.

The aforementioned problems limit the overall performance of lasers. Therefore, the intrinsic relationship between the voltage, current, and power of the photovoltaic panel and the intensity of the laser must be analyzed to increase the output current or voltage of the photovoltaic panel to overcome the drawbacks of wireless power transmission via lasers and to solve the non-uniform illumination problems encountered with laser irradiation.

Taking the photovoltaic model shown in Figure 3 as the basic unit, the model of the photoelectric receiver under laser irradiation was built using MATLAB/Simulink software, as shown in Figure 5. The photoelectric receiver comprised the 12 basic units shown in Figure 3. Each unit has input parameters of temperature and illuminance, respectively. Because the temperature is not the focus of this research, the temperature of each unit is input as 25 °C. Equation (10) has proved that the intensity distribution of the laser spot is equivalently uniform in a small area. So, the laser spot can be divided into many small equivalent uniform areas with different intensity distributions. In the photovoltaic receiver model under laser irradiation shown in Figure 5, it is assumed that the illuminance values of each unit are equal. Specifically, the five cells in each unit have the same irradiance and they are in the a small laser spot with an equivalent uniform distribution of intensity. It is assumed that the illuminance value corresponding to the maximum power in Table 1 is 1000 W/m<sup>2</sup>. The other illuminance value can be calculated according to the proportions presented in Table 1. The calculation results are listed in Table 2. The illuminance parameter of the unit in the seventh row and second column of the model is 1000 W/m<sup>2</sup>. In other words, it is at the center of the laser and has the maximum illumination. With it as the center, the input illuminance of the units on both sides decreases in turn. In order to better

compare the simulation results, different illuminance values in Table 2 are input as light intensity parameters to the model of the photoelectric receiver under laser irradiation. It is used to analyze the output power of the photovoltaic panel under different uniform light irradiation.

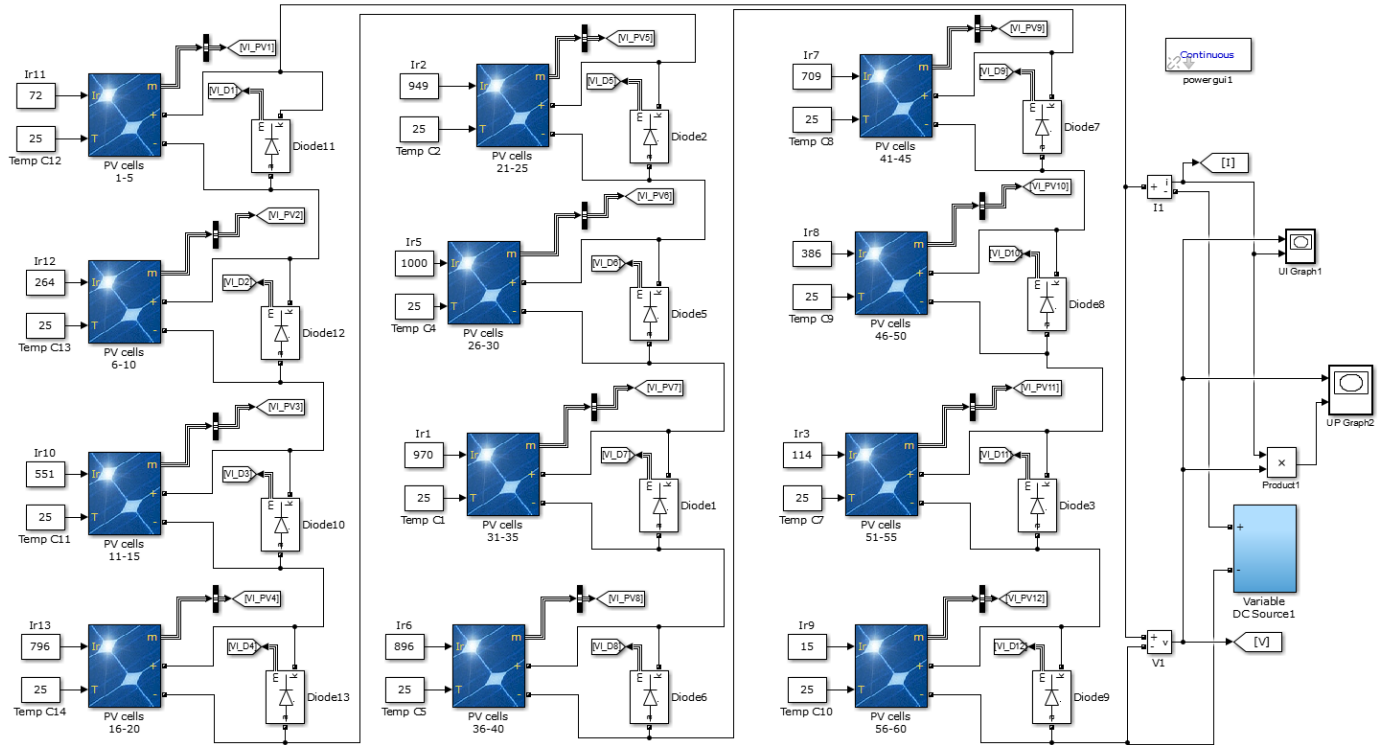
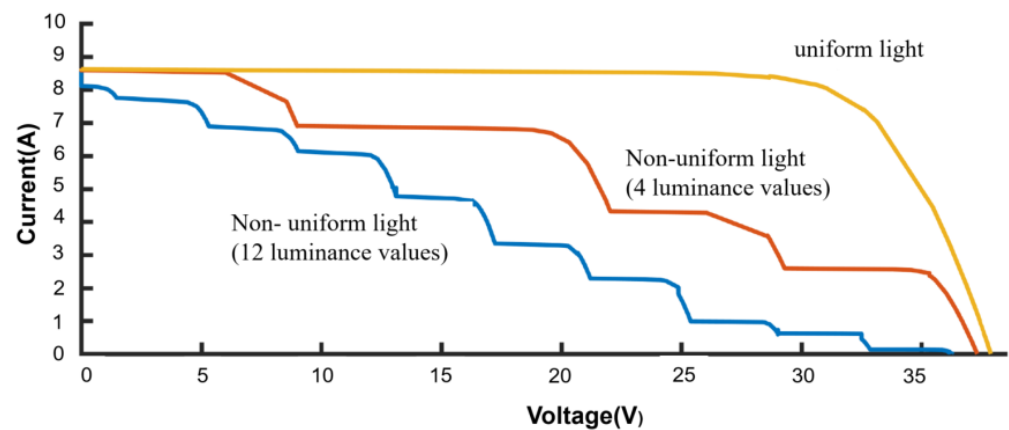


Figure 5. Photovoltaic (PV) receiver model under laser irradiation.

Table 2. Irradiance distribution of the laser.

Location (mm)	Irradiance (W/m <sup>2</sup> )
0	0
1	72
2	264
3	551
4	796
5	949
6	1000
7	970
8	896
9	709
10	386
11	114
12	15

The electrical performance of the system was analyzed, and the photovoltaic panel characteristics were estimated by using the established model. The V–I curves of the photovoltaic panel under laser irradiation are shown in Figure 6.



**Figure 6.** V–I curve under laser irradiation.

Figure 6 presents the V–I curve of the photovoltaic panel when the irradiance changes and the temperature remains constant. The figure presents three V–I curves corresponding to three different illuminations. The top line shows the curve for irradiance uniformity, where the value of irradiance is  $1000 \text{ W/m}^2$  and the photovoltaic panel functions as a constant current source.

The two other curves illustrate the characteristics of the photovoltaic panel under laser irradiation. When the photoelectric panel is irradiated by non-uniform light, the relationship between the voltage and current is presented as the bottom curve. In these cases, light shows 12 values of irradiance: 15, 72, 114, 264, 386, 551, 709, 796, 896, 949, 970, and  $1000 \text{ W/m}^2$ . The photovoltaic panel outputs 12 current values, with each value corresponding to a certain voltage range and an equal voltage difference. The current decreases along with the increasing voltage. The maximum and minimum values are the current at irradiance of  $1000$  and  $15 \text{ W/m}^2$ , respectively. A spot that contains four values of irradiance ( $300$ ,  $500$ ,  $800$ , and  $1000 \text{ W/m}^2$ ) is presented as the middle curve and acts as a current source with four current values. The maximum and minimum values are the current at  $1000$  and  $300 \text{ W/m}^2$  illumination, respectively.

The area surrounded by the V–I curve and the axes reflects the output power of the photovoltaic panel. In Figure 6, the top curve has the largest area while the bottom curve has the smallest area. In other words, under irradiance uniformity, the output power of the photovoltaic panel reaches its maximum. The output power is the smallest when the spot contains 12 values of illumination that irradiate the cell. As shown in the figure, more non-uniform light corresponds to lower output power. Therefore, the low output power of the photovoltaic panel under laser irradiation can be ascribed to the non-uniformity of the laser. The degree of uniformity at the receiving end is hence a key factor in improving the conversion efficiency.

To further understand the effect of temperature on the photovoltaic panel under laser radiation, the output characteristics of the photovoltaic panel irradiated by a laser composed of 12 illuminance values at a temperature of  $100 \text{ }^\circ\text{C}$  were simulated and compared with Figure 6 at a temperature of  $25 \text{ }^\circ\text{C}$ , as shown in Figure 7. As can be seen from Figure 7, as the temperature increases, the output current and voltage gradually become lower. The area formed by the V–I curve and coordinates also becomes smaller, that is, the output power decreases. This is the same as the temperature characteristics of photovoltaic panels under uniform light irradiation. This shows that the temperature characteristics of the photovoltaic panel will not change with the uniformity of light, so this study was not carried out.



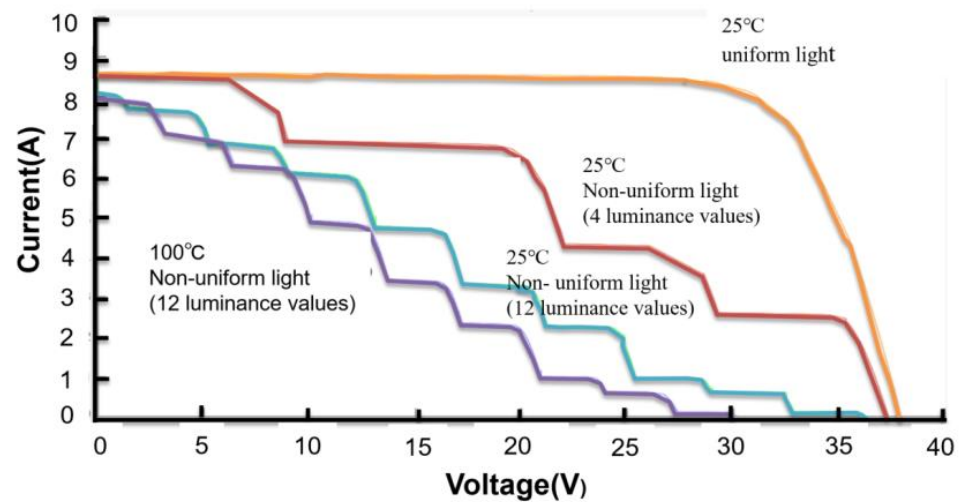


Figure 7. V–I curve at different temperatures.

### 5. Experiment and Results Analysis

To verify the simulation results, a multi-wavelength experimental platform was built. In this platform, 36 polycrystalline silicon cells of 70 mm × 70 mm × 3 mm were used, which were spliced into a photovoltaic panel of 420 mm × 420 mm to receive laser light. The photovoltaic panel area is 0.1764 m<sup>2</sup>, as shown in Figure 8.

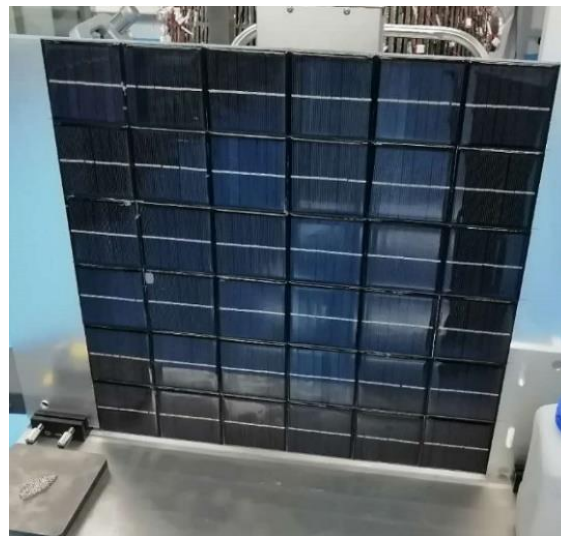
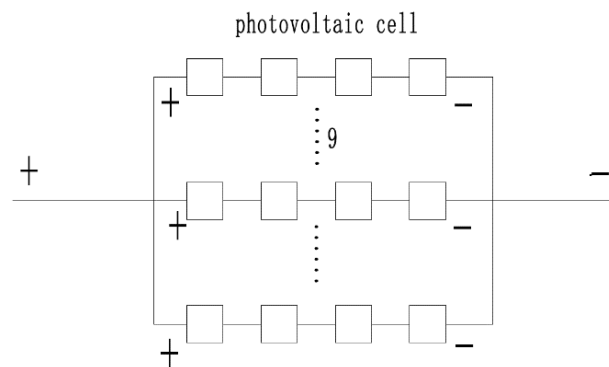


Figure 8. The spliced photovoltaic panels.

The open circuit voltage of each cell in the photovoltaic panel shown in Figure 8 is 0.6 V and the short circuit current is 120 mA (1000 W/m<sup>2</sup> standard light intensity). The 36 photovoltaic cells of the photovoltaic panel are divided into 9 branches. They are connected in parallel to form the total output of the whole photovoltaic panel. Each branch is composed of four photovoltaic cells in series. The circuit diagram is shown in Figure 9. When the above circuit connections are changed, the output voltage and current of the photovoltaic panel will be changed. However, since the comparison experiment only needs to be carried out under the same circuit connection, the relationship between the circuit connection and output will not be discussed in detail.



**Figure 9.** The circuit of photovoltaic panels.

A multi-wavelength experimental platform was built, and the comparative experiments of wireless power transmission via laser were carried out using three kinds of lasers: 808, 532, and 1030 nm. The laser is shown in Figure 10. The uniformity of the three lasers gradually decreases.



**(a)** 808 nm laser



**(b)** 532 nm laser



**(c)** 1030 nm laser

**Figure 10.** The laser in the experiment.

In the experiment, the laser output by the laser is directly irradiated on the photovoltaic panel after being transmitted through the air. The divergence angles of the three lasers are 126.38, 3.45, and 1.43 mrad, respectively. The divergence angle of 808 nm is the largest, that is, the quality of the 808 nm laser beam is the worst. The less obvious the Gaussian distribution, the more uniform the light intensity distribution and the closer the transmission distance. In the experiment, the power of the 5 W 808 nm laser is only 0.2 W after 0.5 m transmission while the power of the 5 W 532 and 1030 nm lasers is 1.1 and 2 W after transmission of 8.7 m. The divergence angle of the 1030 nm laser is the smallest with only 1.43 mrad, its light intensity is a typical Gaussian distribution, and the light uniformity is the worst, followed by the 532 nm laser.

In order to ensure the comparability of the experiment, the three lasers used in the experiment have basically the same output power, which is 5, 4.5, and 5 W, respectively. Considering that the divergence angle of the 808 laser is too large, the spot will be larger than the photovoltaic panel when the transmission distance is more than 1.2 m, so in the experiment, the 808 nm laser only measured the output parameters of the photovoltaic panel after 1.2 m of transmission. The other two lasers have a small divergence angle, and the transmission distance is 7.5 m; otherwise, the laser spot can only illuminate a few photovoltaic cells in the middle of the photovoltaic panel. In the experiment, the voltage and current of each photovoltaic cell irradiated by three kinds of laser, the voltage and current of each branch irradiated by three kinds of laser, and the total output voltage and current of photovoltaic panel irradiated by three kinds of laser were measured.

The voltages of the photovoltaic cells irradiated by the 808 nm laser are shown in Table 3. The voltages at the middle in Table 3 are higher than the voltages at the edge. The highest voltage is 4.27 V and the lowest voltage is 2.5 V, which means that the light intensity in the middle of the photovoltaic panel is strong and weak at the edge. However, there are not many photovoltaic cells with high voltage, and the difference between the maximum voltage and the minimum voltage is only 1.77 V, which is not too large. This is because

the intensity of the laser spot is strong in the middle and weak at the edge, and there is a logarithmic relationship between the voltage and the illuminance.

**Table 3.** The voltages of the photovoltaic cells irradiated by the 808 nm laser.

		1	2	3	4	5	6
Row \ Column		Voltage (V)					
1		2.75	3.67	4	3.87	3.7	3.85
2		3.07	4.03	4.19	4.16	4.08	3.92
3		3.96	4.19	4.27	4.27	4.17	4
4		3.97	4.13	3.18	4.25	4.21	4.02
5		3.36	4.06	4.15	4.18	4.07	3.97
6		2.5	3.47	3.6	3.83	3.63	3.62

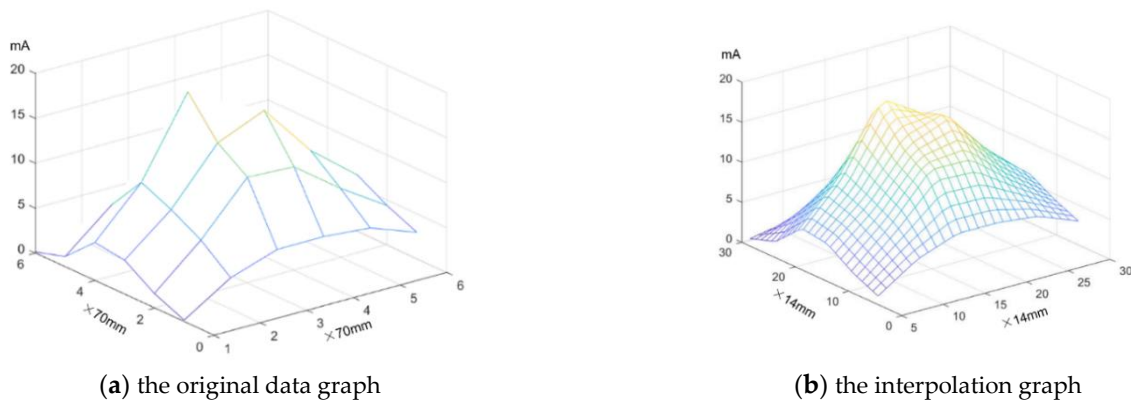
The currents of the photovoltaic cells irradiated by the 808 nm laser are shown in Table 4. The maximum current is 18.2 mA, located in the fourth row and third column, which is the center of the photovoltaic panel. The minimum value is 0.14 mA, located in the first column of the sixth row, which is the furthest edge position of the photovoltaic panel. There are 2 current values less than 1 mA and 28 current values of 1–11 mA. These values are located at or near the edge of the photovoltaic panel. There are 6 current values greater than 11 mA, located in the 3rd, 4th, and 5th columns of the 2nd, 3rd, and 4th row, which is the middle of the photovoltaic panel. Thus, the current of the photovoltaic cell irradiated by the 808 nm laser is also high in the middle and low at the edge.

**Table 4.** The currents of the photovoltaic cells irradiated by the 808 nm laser.

		1	2	3	4	5	6
Row \ Column		Current (mA)					
1		0.18	3.49	5.23	5.26	4.81	2.92
2		1.62	6.15	11.75	11.49	7.69	4.37
3		3.8	8.02	14.03	16.25	10.37	6.25
4		4.24	9.52	18.2	14.78	10.75	4.21
5		1.14	5.48	9.13	9.01	7.12	4.4
6		0.14	1.1	2.28	3.28	3.41	2.2

It can be seen from Equations (1) and (2) that the relationship between current and light intensity is proportional. The distribution of the current value reflects the light intensity distribution irradiated on the photovoltaic panel, that is, the light intensity distribution of the 808 nm laser. In Table 4, there are relatively few particularly low current values less than 1 mA, and the difference between the median value and the maximum value is only an order of magnitude. This shows that although the intensity of the 808 nm laser is still a Gaussian distribution, the energy distribution in the spot is relatively uniform.

Based on the data in Table 4, the distribution of the current, that is, the intensity distribution of the 808 nm laser, was fitted in MATLAB, as shown in Figure 11, where Figure 11a is the original data graph, and Figure 11b is the corresponding interpolation graph. It can be seen from Figure 11 that although the intensity of the 808 nm laser is still strong in the middle and weak at the edge, the difference between the maximum value and the minimum value is not particularly large, that is, the light uniformity is relatively better.



**Figure 11.** The distribution of current irradiated by the 808 nm laser.

In the experiment, the voltage and current of four photovoltaic cells connected in series were also measured, that is, the voltage and current of each branch, as shown in Table 5. The voltage of each branch in Table 5 is slightly higher than the sum of the voltages of the four photovoltaic cells connected in series in Table 4. However, the difference between the two is relatively small, indicating that the total voltage of the photovoltaic cells connected in series is equal to the sum of the voltages of the photovoltaic cells. Although the current of each branch in Table 5 is slightly higher than the smallest current of the four photovoltaic cells connected in series in Table 4, it is still less than the second smallest current value and far less than the maximum current in Table 4. This indicates that the total current of the photovoltaic cells connected in series is equal to the smallest value of all cells.

**Table 5.** The voltages and currents of the branch irradiated by the 808 nm laser.

Column \ Row	1	2	3	1	2	3
	Voltage (V)			Current t(mA)		
1	14.18	16.31	15.6	0.78	5.46	3.44
2	16.27	16.02	16.44	4.31	14.48	6.79
3	13.51	15.82	15.37	0.48	3.1	2.99

In the same way, the total output voltage and current of photovoltaic panel by the 532 and 1030 nm laser were measured, and the corresponding power values were calculated. Taking into account the loss caused by the distance, the voltage and current of the 808 nm laser at 1.2 and 7.5 m were measured, respectively, as shown in Table 6. The corresponding comparison figure is shown in Figure 12.

**Table 6.** The total output voltage, current, and power.

Laser	Voltage of Measured (v)	Current of Measured (mA)	Output Power (mW) (Voltage × Current)	Input Power of the Laser (W)	Loss Rate of Power
808 nm (1.2 m)	15.92	41.66	663.227	5.0	86.74%
808 nm (7.5 m)	11.52	4.30	49.536	5.0	99.01%
532 nm (7.5 m)	8.19	1.11	9.009	4.5	99.80%
1030 nm (7.5 m)	8.38	0.72	6.034	5.0	99.88%

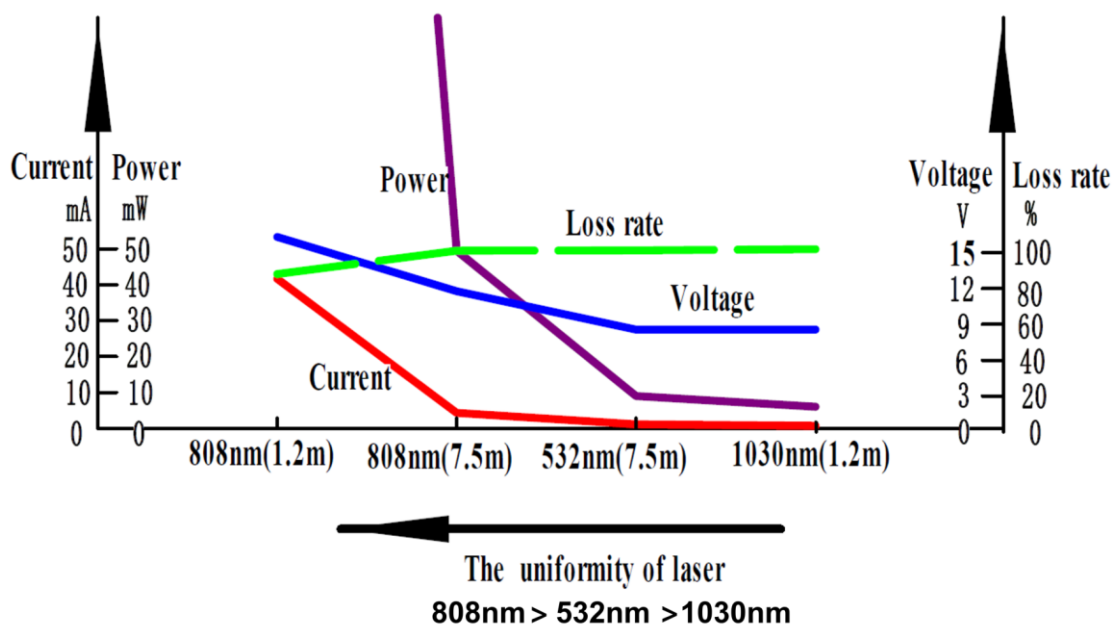


Figure 12. Comparison of results under different wavelengths of laser irradiation.

Since the spot at 1.2 m filled the entire photovoltaic panel, the spot size at 7.5 m exceeded the size of the photovoltaic panel. Compared with the loss at 1.2 m, 2 new losses are added at 7.5 m. One is the transmission loss due to divergence. The second is the collection loss. The reason is that the size of the photovoltaic panel is smaller than the spot size and the photovoltaic panel cannot completely absorb all laser light. As can be seen from Table 6, when the 808 nm distance increases from 1.2 to 7.5 m, the loss rate increases from 86.76% to 99.01%, which means that the two new losses are 12.27%. Since the spot size of 532 and 1030 nm is smaller than the size of the photovoltaic panel, there is no problem of collection loss. Moreover, the divergence angle of these two wavelengths is much smaller than 808 nm, so the loss caused by its divergence is also smaller than 808 nm, even if it is assumed that the transmission loss is equal to two new losses, that is, 12.27%. Since the losses of 532 and 1030 nm are 99.80% and 99.88%, respectively, the loss caused by un-uniform light is more than 87%, that is to say, the loss caused by non-uniform light is the main loss. It can also be seen from Table 6 that the power under 808 nm laser irradiation at 1.2 m is much greater than the power under 532 and 1030 nm laser irradiation at 7.5 m. The power under 808 nm laser irradiation at 1.2 m is 73.61 times that under 532 nm at 7.5 m and 109.91 times that under 1030 nm at 7.5 m. When the transmission distance becomes 7.5 m, part of the energy is lost due to the laser spot being larger than the size of the photovoltaic panel, and the other part is lost due to transmission. The power under 808 nm laser irradiation is still 5–8 times that under 532 and 1030 nm. It can also be seen from Table 6 that the power under 532 nm laser irradiation at 7.5 m is 1.49 times the power under 1030 nm laser irradiation at 7.5 m. Specifically, the order of the total output power in the experiment is: 808 nm > 532 nm > 1030 nm. The experimental results show that the output power of the photovoltaic panel increases with the uniformity of the laser, which is consistent with the above simulation results. The above results show that laser has an equivalent uniform intensity in a very small area and the photovoltaic module under laser irradiation based on it is correct. A laser spot composed of many small equivalent uniform spots with different light intensity values can be used as an important research method for related research. In addition, the rise in temperature of the photovoltaic panels is caused by laser irradiation. This leads to problems such as heat loss, low external quantum efficiency, and low conversion efficiency, which is also the reason for the low output power of photovoltaic panels.

## 6. Conclusions

In order to improve the output power of the photovoltaic panel, the light intensity of two adjacent laser points in a very small area was compared. The calculation results show that the laser has an equivalent uniform intensity distribution in a very small area. So, a non-uniform laser can be decomposed into many small equivalent uniform spots with different light intensity values. Based on this theory, the photovoltaic module under laser irradiation was established in MATLAB/Simulink. The simulation results reveal that the input laser, which is composed of many equivalent uniform small light spots with different light intensity values, is more non-uniform and corresponds to lower power output of the photovoltaic panel.

In order to verify the simulation results, a multi-wavelength wireless power transmission via laser platform was built. In the experiment, 808, 532, and 1030 nm lasers were used to irradiate the photovoltaic panel, respectively, and the corresponding voltage and current values were measured. The output power obtained by the measurement was 49.536, 9.009, and 6.034 mW, respectively, that is 808 nm > 532 nm > 1030 nm, which was in good agreement with the simulation result.

Therefore, improving the light uniformity at the receiving end is important for improving the conversion efficiency of photovoltaic panels in wireless power transmission via lasers. Furthermore, the power output of wireless power transmission via lasers is improved, which means it can be more widely used.

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