Analysis of the Influence of Atmospheric Turbulence on Laser Wireless Power Transmission

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Keywords: Atmosphere Turbulence, Laser Wireless Power Transmission, Adaptive Optics, Photovoltaic Array.

Abstract: Laser Wireless Power Transmission (LWPT) technology has significant applications in many fields, such as emergency rescue, remote power supply for aircraft, and space solar power stations. As the beam transmission distance increases, the effects of atmospheric turbulence become significant. However, this issue has not yet been specifically discussed. In this paper, theoretical analysis and numerical simulation experiments are carried out to study the effect of atmospheric turbulence on the performance of LWPT. The results show that the power transmission efficiency of LWPT is determined jointly by the mean and uniformity of the beam intensity. Under the influence of moderate atmospheric turbulence (with C_n^2 of $8.6\times10^{-16}m^{-2/3}$), the maximum power of the photovoltaic array will be seriously affected (from 100% to less than 0.5%), and simply compensating for the tilt aberration will not make a significant difference. The conclusion of this paper shows the importance of adaptive optics (AO) systems in future long-range LWPT links.

1 INTRODUCTION

Laser Wireless Power Transmission (LWPT) is a rapidly advancing technology in recent years. It enables the wireless transmission of electrical power through free space. Compared with traditional cable-based power transmission, LWPT technology does not need to consider cable laying and daily maintenance, and can dynamically adjust the direction of the radiated power. Therefore, LWPT has incomparable advantages in many special scenarios(Kawashima et al., 2007; Achtelik et al., 2011; Sprangle et al., 2015; Mohammadnia et al., 2021), such as nuclear power plants, oil wells, mines, remote power supplement of aircraft etc. In addition, compared with the common microwave or electromagnetic coupling wireless power transmission technology, the laser beam has the characteristics of short wavelength, good directivity, and good monochromaticity. Therefore, the equipment in the LWPT link is smaller and lighter, and the power transmission distance is longer (up to km level or above). For the above-mentioned reasons, LWPT technology has attracted extensive attention in recent years(Gou et al., 2023; Kim and Park, 2020; Javed et al., 2022).

In 2007, N. Kawashima demonstrated a laser-powered kite, which flew with an altitude of more than 50 m, and a long-time stable flight operation was successfully realized (more than 1 hour)(Kawashima et al., 2007). In 2010, a quadcopter drone called Pelican, developed by LaserMotive, took off at the Future of Flight Aviation Center in Washington. A 2.25 kW laser diode array, placed 18 m away, is used to power the drone. During the experiment, the drone flew for 12.5 hours (150 times its original endurance), making it the longest hovering record for a laser-powered aircraft at the time(Achtelik et al., 2011). In 2015, P. Sprangle reported a laser-powered twin propeller aerial vehicle. The experiment was carried out indoors, and the distance between the laser emitter and the drone was 40 m(Sprangle et al., 2015). In 2016, M. A. Vorontsov reported the LWPT experiment based on the coherent fiber array systems. The beam transmission distance was 7 km, and the coherent fiber array was used to compensate for the atmosphere turbulence to improve the performance of LWPT(Vorontsov and Weyrauch, 2016). In 2021, A. Mohammadnia analyzed the electric power received by laser-powered drones when using three commercial photovoltaic materials, and a two-phase

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Huang, G., Geng, C. and Li, X.
Analysis of the Influence of Atmospheric Turbulence on Laser Wireless Power Transmission.
DOI: 10.5220/0013167500003902

In *Proceedings of the 13th International Conference on Photonics, Optics and Laser Technology (PHOTOPTICS 2025)*, pages 41-48
ISBN: 978-989-758-736-8; ISSN: 2184-4364

cooling system was suggested for photovoltaic panels to reduce the temperature of the under radiate area(Mohammadnia et al., 2021).

In the LWPT system, the most important concern is power transmission efficiency, which is composed of three parts: electro-optical conversion efficiency of the laser source, beam's transmission efficiency in the free space, and photo-electric conversion efficiency of the photovoltaic array (PVA). It is well known that atmospheric turbulence will severely affect the wavefront of laser beams(Guo et al., 2022), so that the far-field intensity distribution of the laser beam changes constantly, mainly reflected in the beam dithering, beam spreading, and uneven beam intensity distribution.

For the PVA in the LWPT link, the size and shape are specially designed according to the fixed beam intensity distribution. Turbulence will invalidate this optimized design, and then reduce the conversion efficiency of PVA. From the research in recent years, it can be find that most experiments are carried out indoors or outdoors at a short distance, so turbulence has a limited effect. In the long-range (7 km) LWPT experiment, the performance of the LWPT system was greatly improved when the turbulence effect was mitigated(Vorontsov and Weyrauch, 2016). Many papers have discussed the effect of static beam intensity distribution (such as Gaussian) on PVA efficiency(Zhou and Jin, 2017), but the effect of turbulence has not been analyzed yet. As the beam transmission distance of LWPT becomes longer in the future, it will be very valuable to study the effects of turbulence on LWPT.

In this paper, the basic principle of the LWPT system is briefly introduced, followed by the problems. Then the mathematical models, including the turbulence model and PVA model, are introduced, which can be used to generate varying far-field beam intensity distributions and observe the performance of PVA. In the end, simulation experiments are conducted to give qualitative conclusions. The experiment results show that the maximum power of PVA is determined jointly by the mean and uniformity of the beam intensity. In addition, the moderate turbulence (with C_n^2 of $8.6\times10^{-16}m^{-2/3}$) can cause a severe power drop of the PVA, and only realizing the tilt aberration compensation can not effectively alleviate this phenomenon.

The rest of this paper is organized as follows: the current situation and problems of LWPT are shown in section 2. In Section 3, the effects of the atmosphere turbulence are introduced in detail. In Section 4, simulation experiments based on turbulence with different levels and PVA with different cells are conducted.

2 CURRENT SITUATION AND PROBLEMS

Fig. 1 shows the structural scheme of the LWPT system. First, electric power is converted into optical power by the laser source. Then, the optical power is directed by the acquisition, tracking, and pointing (ATP) system, and emitted by the optical antenna. Laser beams reach the remoted photovoltaic array (PVA) after long-range atmospheric transmission. In the end, the optical power is converted into electric power by the PVA and then drives the load, such as a drone.

In the process of free space propagation, the intensity distribution of the laser beam varies randomly due to the turbulence. The left corner of Fig. 1 shows the PVA and the laser spot at the target plane in ideal condition and with turbulence. The intensity distribution of the spot is generally considered to be Gaussian distribution in ideal conditions, due to the diffraction in laser resonators. The shape of the PVA and the connection of the cells is usually optimized for this situation, in order to improve the photo-electric conversion efficiency. When the turbulence is considered, the spot will deviate from the surface of the PVA, and the intensity distribution becomes irregular, resulting in a mismatch with the PVA's design.

Here, the power transmission efficiency of the entire LWPT link is represented by η, and it can be determined by the following formula:

$$\begin{aligned}\eta &= \eta_{Tx-io}\cdot\eta_{Tx-oRx-i}\cdot\eta_{Rx-io}\\ &= \frac{P_{Tx-out}}{P_{Tx-in}}\cdot\frac{P_{Rx-in}}{P_{Tx-out}}\cdot\frac{P_{Rx-out}}{P_{Rx-in}}\end{aligned} \tag{1}$$

The parameter η consists of the following parts:

1)Electro-optical conversion efficiency η_{Tx-io}, which equals to the ratio of the emitted optical power P_{Tx-out} to the input electrical power P_{Tx-in}, and it is mainly determined by the type of the laser.

2)Beam's transmission efficiency in the free space $\eta_{Tx-oRx-i}$, which equals to the ratio of the received optical power P_{Rx-in} to the emitted optical power P_{Tx-out}, and it is mainly determined by the diffraction effect, atmospheric absorption, and the occlusion of obstacles.

3)Photo-electric conversion efficiency η_{Rx-io}, which equals to the ratio of the consumed electrical power P_{Rx-out} to the received optical power P_{Rx-in}. This parameter is determined by the PV materials, the connection mode of PV cells, the uniformity of the beam intensity, and the degree of matching between the shape of the spot and the shape of the PVA. Turbulence will distort the wavefront of the laser beam, which will lead to the beam dithering, beam spread-

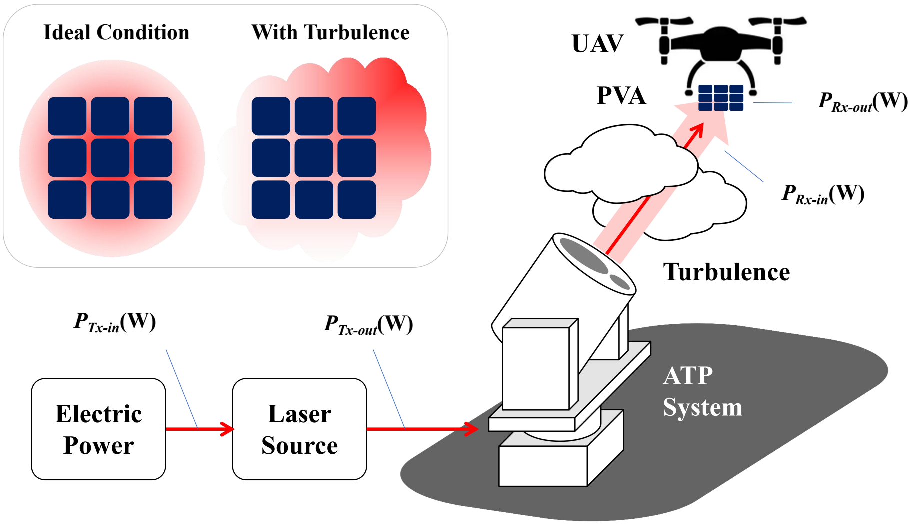

Figure 1: Structural of LWPT system for UAV power transmission.

ing, and uneven beam intensity distribution. These factors will reduce the photo-electric conversion efficiency η_{Rx-io} even though the material and the connection mode of PVA remain the same.

3 MATHEMATICAL MODEL

As shown in Section 2, atmosphere turbulence will have a serious impact on the photo-electric conversion efficiency of PVA. Obviously, the degree of influence is related to the intensity of the turbulence and the structure of PVA, and the corresponding mathematical models are shown below.

3.1 Turbulence Model

The distorted wavefront of the laser beam under turbulent atmosphere is always represented by the Zernike polynomial(Tyson, 2011), as shown in the following formula:

$$\phi(r,\theta) = a_0 + \sum_{k=1}^{N} a_k Z_k(r,\theta) \qquad (2)$$

Where $Z_k(r,\theta)$ is the k-th Zernike polynomial, and a_k is the coefficient. The first item in the Zernike polynomial a_0 is known as piston aberration, which has no effect on the efficiency of PVA. The second and third items (k=1 and k=2) are the tip/tilt aberrations in the x and y directions, which cause the beam dithering and then make the spot deviate from the PVA surface. The higher-order aberrations ($k \geq 3$) include defocus, astigmatism, coma, and so on, which causes the beam spreading and uneven beam intensity distribution.

The degree of the distorted wavefront can be characterized by generating the coefficient a_k which accords with specific statistical characteristics. According to Kolmogorov turbulence theory, the variance of Zernike coefficients of each order can be represented by(Tyson, 2011):

$$\langle a_j^2 \rangle = \frac{2.246(n+1)\Gamma(n-5/6)}{[\Gamma(17/6)]^2\Gamma(n+23/6)} \left(\frac{D}{r_0}\right)^{5/3} \qquad (3)$$

Where the operator $< \cdot >$ denotes ensemble average, and $\Gamma(\cdot)$ denotes Gamma function. The parameter D is the diameter of the laser beam, and r_0 is the atmospheric coherent length, which can be calculated by(Tyson, 2011):

$$r_0 = \left[0.423 k_0^2 sec(\beta) \int_0^L C_n^2(z)dz\right]^{-3/5} \qquad (4)$$

Where $k_0 = 2\pi/\lambda$ is the wavenumber, λ is the wavelength, β is the zenith angle, L is the beam propagation distance, and $C_n^2(z)$ is the well-known structural constant of atmospheric refractive index.

From Eq. 3, it can be seen that $(D/r_0)^{5/3}$ determines the variance of Zernike coefficients. In the practical LWPT link, the area of PVA is usually at the meter level, with the purpose of facilitating heat dissipation. In addition, the beam is usually transmitted near the Earth's surface with a large zenith angle, which also makes the value of r_0 small. At last, the wavelength of the laser beam in the LWPT link is usually short (810 nm or 980 nm), in order to match the quantum efficiency of the PV materials. As a result, the impact of atmospheric turbulence on the LWPT link is more serious than that of other laser transmission applications, such as directed energy and free space optical communication. In the following analysis, the RMS value is used to quantify the degree of wavefront distortion:

$$RMS = \sqrt{\frac{1}{D}\iint_D [\phi(x,y)^2]\,dxdy} \tag{5}$$

3.2 Photo-Voltaic Array Model

In practice, in order to achieve a specific voltage/current output, PVA is formed by multiple PV cells in series and parallel. The simplified model of the PV cell is shown in Fig. 2:

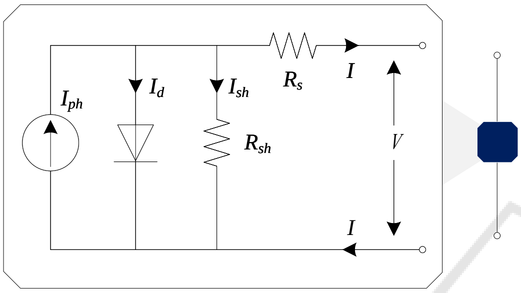

Figure 2: The simplified model of the PV cell.

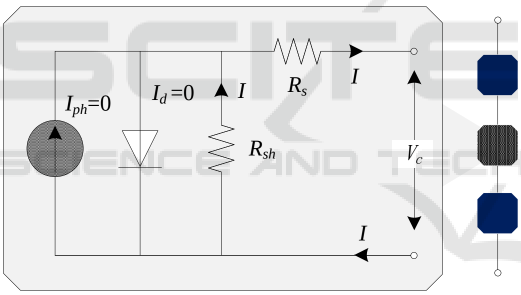

Figure 3: The simplified model of the three PV cells in series.

Where the parameters I and V are the output current and voltage of the PV cell. The three other current parameters I_{ph}, I_d, I_{sh} are the photo-generated current, dark current, and bypass current, respectively. The two resistance parameters R_{sh} and R_s are the bypass resistance and series equivalent resistance. Obviously, the output current I can be represented by:

$$I = I_{ph} - I_d - I_{sh} = I_{ph}(G) - I_d(T) - \frac{V + IR_s}{R_{sh}} \tag{6}$$

Where G (W/cm^2) is the irradiance of the laser beam, and T is the temperature. The photo-generated current I_{ph} is decided by the irradiance G and the receiving area of the PV cell. From Eq. 6, it can be find that the power of the PV cell is proportional to G when the temperature and the receiving area remain constant. When the cells are connected in series, the total power can be obtained by addition.

Fig. 3 shows the three PV cells in series, and the special is that irradiance G is not even. The middle cell receives an irradiance of $G = 0$. In this case, the photo-generated current I_{ph} is approximately equal to 0. In the series circuit, the current I is equal everywhere, so the output voltage of the middle cell can be calculated by:

$$V_c = -(R_{sh} + R_s)I \tag{7}$$

The minus sign in Eq. 7 means that the voltage V_c needs to be subtracted from the total voltage. In other words, the middle cell consumes the power P_c:

$$P_c = V_c I \tag{8}$$

In practice, the blocked PV cell will consume power in the form of heat, and the temperature will increase, producing "hot spot" effect, and even starting a fire. The common way to solve the "hot spot" effect is to attach a bypass diode to the PV cell, with the cost of reduced power. In summary, the output power of PVA depends on the mean and the spatial uniformity of the irradiance G. Therefore, when the turbulence is considered, the beam dithering, beam spreading, and varying beam intensity distribution will result in serious impacts.

4 SIMULATION EXPERIMENTS

In this section, numerical simulation experiments are conducted to quantify the influence of turbulence on LWPT. The structure of the simulation system is shown in Fig. 4, where the PVA is formed by the series-parallel connection of the PV cells. The intensity distribution of the laser beam is first spatially divided, and then fed into individual PV cells. A variable DC source is added to simulate the changing loads, and the output current I and the voltage V are recorded synchronously.

The size and position of the far-field laser spot and PVA are shown in Fig. 5. The laser beam is set to a Gaussian beam with diameter of D. The PVA is tangent to the Gaussian beam, and d is the side length. The parameter n is used to represent the number of PV cells in PVA. To simplify the model, gaps between different cells are not taken into account in the following experiments.

4.1 Influence of Single Wavefront Aberration

The influence of single wavefront aberration on the LWPT link is analyzed first. The RMS of the wave-

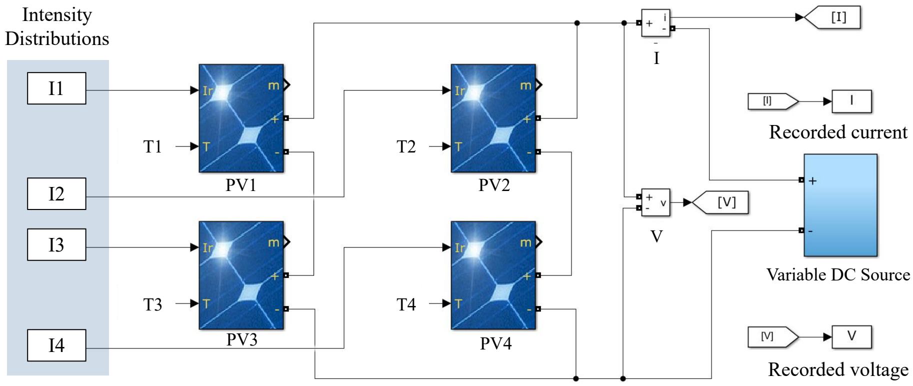

Figure 4: Structure of the simulation system.

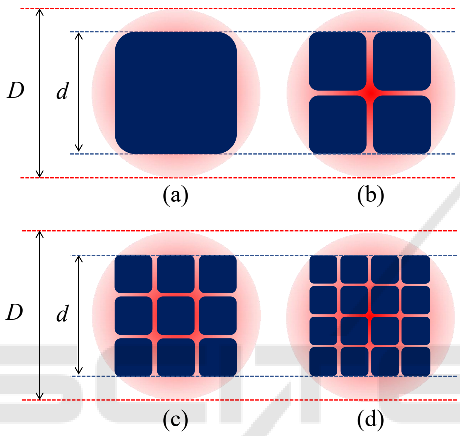

Figure 5: Laser spot and PVA with different cells. (a)n=1; (b)n=2; (c)n=3; (d)n=4.

front is set to range from 0 to 2. The maximum power of these four types of PVA is recorded, and the normalized results are shown in Fig. 6.

Fig. 6 (a) shows the simulation results of the PVA with only one cell. In this case, the PVA's maximum power is only determined by the mean of the beam intensity. The result shows that the tilt aberration has the least effect compared to the rest of the higher-order aberrations. This is mainly because the higher-order aberrations make the beam's intensity distribution flatter, which reduces the total optical power received by PVA.

Fig. 6 (b) to (d) shows the simulation results of the PVA with 4, 9, and 16 cells, and the results have made a big difference. In this case, the reduction of the maximum power is determined jointly by the mean and uniformity of the beam intensity. Therefore, the tilt aberration has the greatest effect on the PVA's maximum power for it disrupts the beam's uniformity to the greatest extent. Another interesting phenomenon is that as the number of PV cells increases, the effect of the astigmatism aberration gradually decreases. When the number of PV cells is 16 and the RMS is near 1, the astigmatism aberration even causes the maximum power of PVA to rise.

Fig. 7 explains the slight increase of the curves when the astigmatism aberration is introduced in Fig. 6 (d), which shows the mean and MSE value of the beam intensity received by the 16 different PV cells. For the tilt aberration, with the increase of the RMS of the wavefront, the mean value of the intensity received by different PV cells decreases, whereas the MSE value does not change much (even increases briefly), which means that the beam's uniformity remains basically unchanged (uneven as always). For the astigmatism aberration, the mean value of the intensity decreases, whereas the MSE value also decreases, which means that the beam's uniformity is gradually improving (from uneven to uniform), so it has a positive impact on the maximum power of PVA.

Fig. 8 shows the diffraction pattern of the corresponding far-field spot, which is also consistent with the above interpretation. The astigmatism aberration reduces the mean of the beam intensity, but the shape of the far-field spot is closer to square, so the intensity received by different PV cells becomes more uniform.

4.2 Influence of Atmosphere Turbulence

In this section, the influence of atmosphere turbulence on the LWPT link is analyzed. The first 15 Zernike coefficients are used to generate the distorted wavefront. The beam diameter is D=0.3 m, the wavelength of the laser beam is λ=810 nm, the beam propagation distance is 5 km, and the beam is assumed to travel along the horizontal atmosphere. The atmosphere refractive index structure constant C_n^2 are set to 0, $5.8\times10^{-17}m^{-2/3}$, $1.9\times10^{-16}m^{-2/3}$, $3.7\times10^{-16}m^{-2/3}$, $5.9\times10^{-16}m^{-2/3}$, $8.6\times10^{-16}m^{-2/3}$. The corresponding r_0 ranges from ∞ to 6 cm, which causes the value of D/r_0 to change from 0 to 5. There are three kinds of cases in the following simulations:

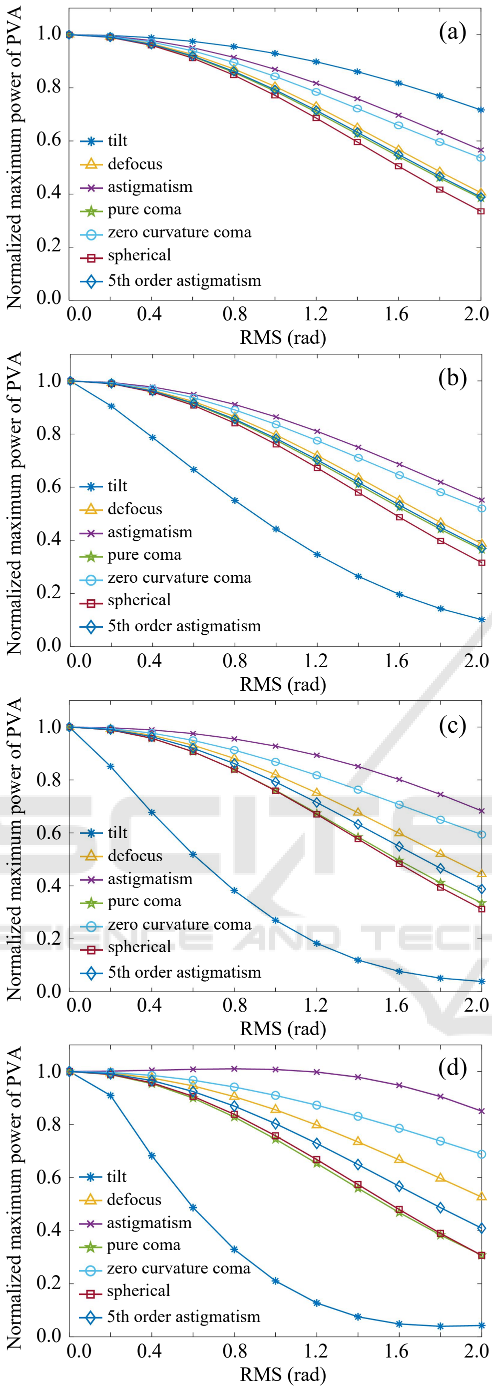

Figure 6: Relationship between the RMS of single wavefront aberration and the maximum power of PVA. (a)n=1; (b)n=2; (c)n=3; (d)n=4.

without turbulence, with turbulence, and with tilt correction. The experiments are repeated 20 times in each case.

Fig. 9 (a) shows the simulation results of the PVA with only one cell. It can be found that when the turbulence is considered, the maximum power of PVA decreases rapidly (from 1 to 0.005) with the increase of D/r_0. Fig. 9 (b) to (d) show the simulation results of the PVA with 4, 9, and 16 cells, and it can be found that as the number of cells increases, the effects of atmospheric turbulence become more severe, and the maximum power of PVA decreases to 0.0035, 0.0027, and 0.0023, respectively. In addition, compensating tilt aberration can only have an obvious effect when D/r_0 is less than 3. This is because when D/r_0 is larger, the higher-order aberrations in wavefront distortion start to increase, which makes the beam's intensity distribution flatter, and reduces the total power received by PVA.

Fig. 10 shows the diffraction patterns of the corresponding far-field spot, where the tilt aberration is removed. With the increase of D/r_0, it can be found that the spot flattens out. Therefore, even if the tilt aberration is well corrected, the maximum power of PVA cannot be significantly increased.

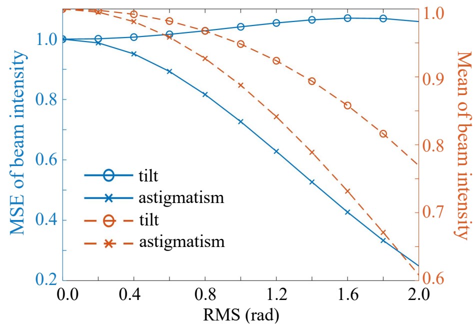

Figure 7: Statistical characteristics of the beam intensity distribution when the number of PVA cell is 16.

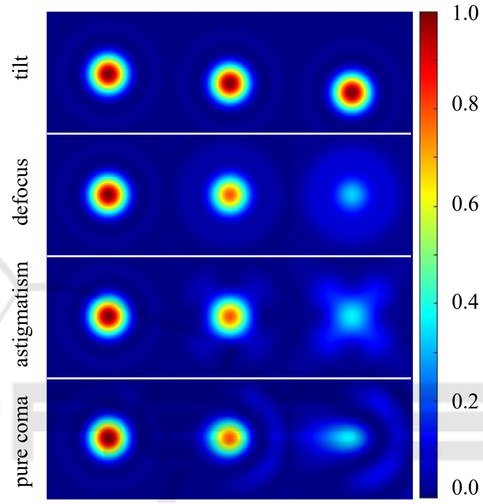

Figure 8: Diffraction patterns of the far-field spots with different single wavefront aberrations.

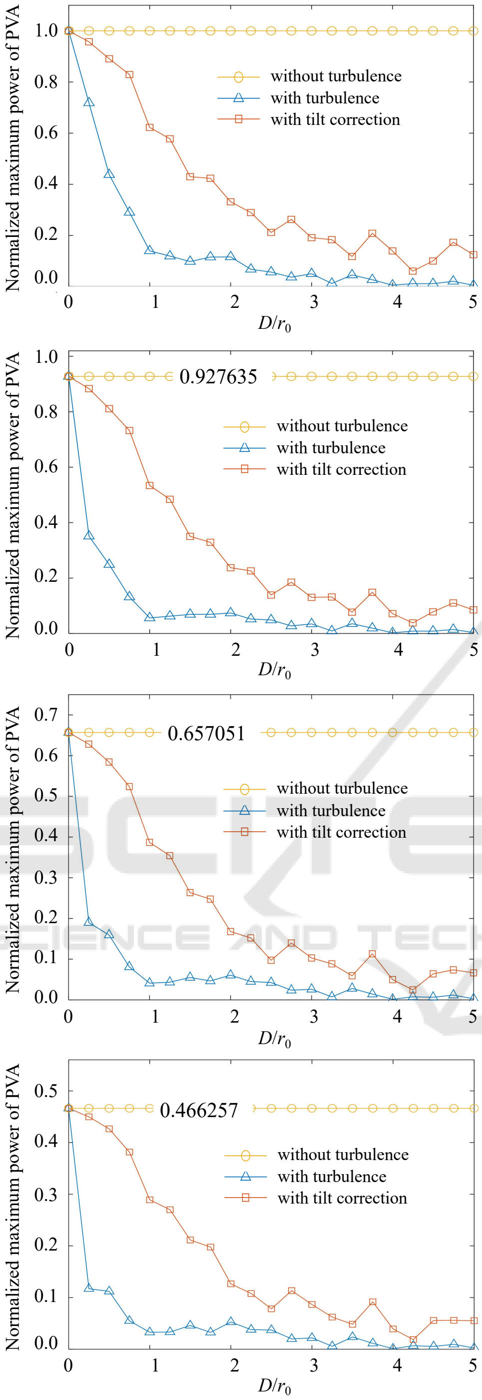

Figure 9: Relationship between the intensity of turbulence D/r_0 and the maximum power of PVA.

5 CONCLUSIONS

In this paper, the influence of atmosphere turbulence on the LWPT link is analyzed. Turbulence will distort the wavefront of the laser beam, which will lead to the beam dithering, beam spreading, and uneven beam intensity distribution. These factors will reduce the power transmission efficiency of the LWPT link. Simulation experiments show that the maximum power of PVA is determined jointly by the mean and uniformity of the beam intensity, and the influence of uneven beam intensity will be strengthened with the increase of the number of PV cells. In some special cases, the introduction of astigmatism aberration even increases the maximum power of PVA. In addition, simulation experiments also show that the moderate turbulence (with C_n^2 of $8.6 \times 10^{-16} m^{-2/3}$, r_0 of 6 cm) can cause a severe power drop of the PVA, this is partly due to the large beam diameter (D=0.3 m) and the short wavelength (λ=810 nm), for the purpose of heat dissipation and quantum efficiency matching. At last, the results show that with the increase of PV cells, the effects of turbulence become stronger, and the benefits of merely compensating the tilt aberration are also diminishing.

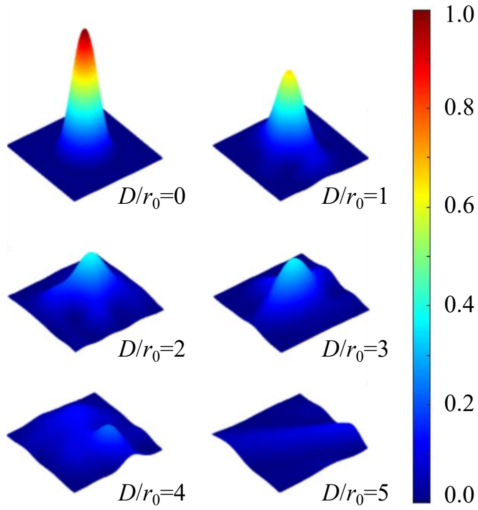

Figure 10: Diffraction patterns of the far-field spots with different intensity of turbulence D/r_0.

In conclusion, the simulation results indicate that in the turbulent atmosphere, it is not enough to achieve stable PVA tracking. The compensation of higher-order aberrations is also very important, especially in the case of PVA with more cells. In the future, adaptive optics(Guo et al., 2022) or fiber laser phased array can provide a solution to this problem. In addition, in future experiments, the liquid crystal spatial light modulator can be used to apply a controllable phase distribution to the beam to further verify the simulation results presented in the paper.

ACKNOWLEDGEMENTS

This work was supported by the Natural Science Basic Research Program of Shaanxi (Program No. 2023-JC-QN-0716) and the National Natural Science Foundation of China (Program No. 62405247) and the Fund of National Laboratory on Adaptive Optics, China.

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