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Experimental demonstration of single-mode fiber coupling over relatively strong turbulence with adaptive optics

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High-speed free-space optical communication systems using fiber-optic components can greatly improve the stability of the system and simplify the structure. However, propagation through atmospheric turbulence degrades the spatial coherence of the signal beam and limits the single-mode fiber (SMF) coupling efficiency. In this paper, we analyze the influence of the atmospheric turbulence on the SMF coupling efficiency over various turbulences. The results show that the SMF coupling efficiency drops from 81% without phase distortion to 10% when phase root mean square value equals 0.3λ. The simulations of SMF coupling with adaptive optics (AO) indicate that it is inevitable to compensate the high-order aberrations for SMF coupling over relatively strong turbulence. The SMF coupling efficiency experiments, using an AO system with a 137-element deformable mirror and a Hartmann–Shack wavefront sensor, obtain average coupling efficiency increasing from 1.3% in open loop to 46.1% in closed loop under a relatively strong turbulence, $D/r_0 = 15.1$.

OCIS codes: (060.2605) Free-space optical communication; (010.1080) Active or adaptive optics; (060.2430) Fibers, single-mode; (010.1330) Atmospheric turbulence.

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1. INTRODUCTION

Free-space optical communication, with high speed and high confidentiality, is the key technology for achieving a high-speed broadband network of satellite–satellite, satellite–ground, and deep-space links in the future. To achieve higher link capabilities and longer link distance, fiber optical components, such as transmitter and receiver modules, erbium-doped fiber amplifiers, and multiplexer units, are required. In such a system the received signal beam must be coupled into a single-mode fiber (SMF) before being amplified and detected. However, propagation through the atmospheric turbulence seriously degrades the spatial coherence of the signal beam and limits the SMF coupling efficiency [1,2]. Therefore, the way to improve SMF coupling efficiency has become one of the key technologies for high-speed free-space optical communications. A considerable improvement is expected using adaptive optics (AO) in the system that can compensate the wavefront distortion caused by atmospheric turbulence [3,4].

The SMF coupling efficiency for partially coherent light through horizontal atmospheric channel was discussed by Winzer and Leeb in 1998 [2]. The influence of the random angular jitter caused by turbulence for SMF coupling efficiency has also been studied extensively [5]. Arimoto *et al.* describe a method to increase the SMF coupling efficiency using a fast steering mirror [6]. However, it can only be used over weak turbulence. In 2005, the method using a coherent fiber array as a receiver was investigated [7]. However, beam combination in the high-speed optical communication systems introduces mismatches of the code elements. Weyrauch *et al.* describe a fiber coupling system for free-space optical communications using an AO system without wavefront sensors [8]. It has the ability to correct the high-order aberrations caused by the atmospheric turbulence and increases the coupling efficiency significantly. However, the low convergence rate of the system limits the range of the strength of the atmospheric turbulence to which it can be applied.

In this study, we analyze the relationships between atmospheric turbulence and the SMF coupling efficiency with the theory of pattern matching. After that, we present the method to increase SMF coupling efficiency over relatively strong turbulence with, first, the implementation of preliminary coupling by using a fast steering mirror to correct the tip and tilt aberration. Second, the AO system, with a 137-element deformable mirror (DM) and a Hartmann–Shack wavefront sensor, is used to compensate the high-order phase aberrations that should not be neglected over relatively strong turbulence.

2. SMF COUPLING EFFICIENCY

The schematic diagram of SMF coupling is shown in Fig. 1. A uniform optical beam is focused by a coupling lens with an effective aperture diameter of D and a focal length of f. The lens is located in the plane A and the end side of an SMF is placed on the focus plane B of the lens.

The coupling efficiency of the freely propagating optical field into an SMF, η_f, is defined as the ratio of the average power coupled into the fiber, $\langle P_f \rangle$, to the average available power in the focus plane, $\langle P_i \rangle$, and is given by [2]

$$\eta_f = \frac{\langle P_f \rangle}{\langle P_i \rangle} = \frac{\left\langle \left| \int_B E_B(x,y) F_B^*(x,y) \mathrm{d}x\mathrm{d}y \right|^2 \right\rangle}{\left\langle \int_B \left| E_B(x,y) \right|^2 \mathrm{d}x\mathrm{d}y \right\rangle}, \quad (1)$$

where $E_B(x,y)$ is the distribution of the focused optical beam on the focal plane B, and $F_B(x,y)$ is the normalized fiber-mode profile when the normalized frequency V of the SMF is in the range of $1.9 \leq V \leq 2.4$. A schematic of an ideal plane wave coupled with the SMF mode field on the focal plane is shown in Fig. 2. The SMF mode field can be approximated to a Gaussian beam with 1% error as in Fig. 2(a), and the

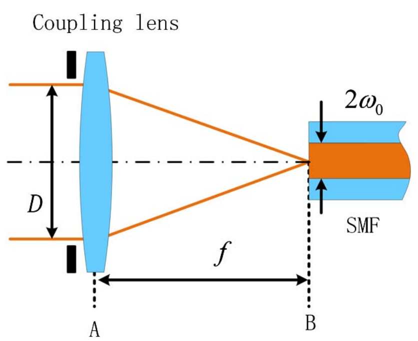

Fig. 1. Schematic diagram of the SMF coupling.

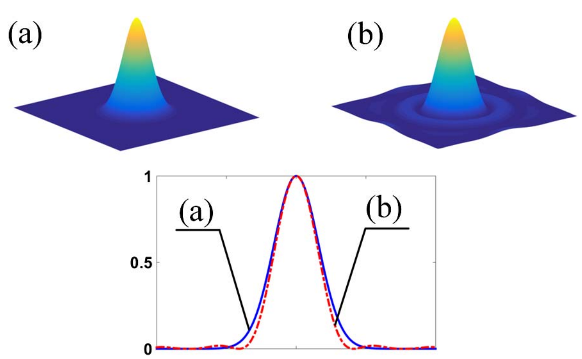

Fig. 2. Schematic of an ideal plane wave coupled with the SMF mode field.

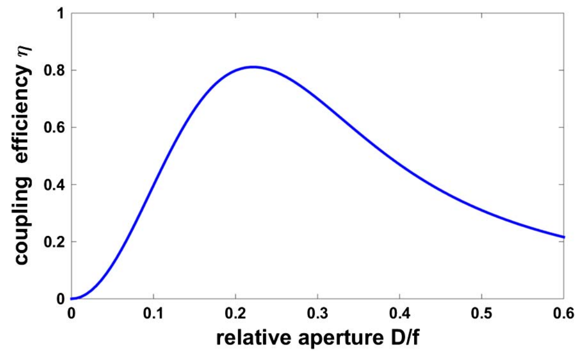

Fig. 3. Relationship between coupling efficiency and the relative aperture of the coupling lens.

distribution of the plane wave on the focal plane is an Airy pattern as in Fig. 2(b).

As it is much more convenient to evaluate the above overlap integral in aperture plane A, we apply the backpropagating formalism to fiber mode $F_B(x,y)$, yielding the backpropagated fiber mode $F_A(x,y)$. The coupling efficiency then follows as

$$\eta_f = \frac{\langle P_f \rangle}{\langle P_A \rangle} = \frac{\left\langle \left| \int_A E_A(x,y) F_A^*(x,y) \mathrm{d}x\mathrm{d}y \right|^2 \right\rangle}{\left\langle \int_A \left| E_A(x,y) \right|^2 \mathrm{d}x\mathrm{d}y \right\rangle}, \quad (2)$$

where $E_A(x,y)$ represents the incident optical field into the aperture in plane A. Considering a plane wave influenced by the atmospheric turbulence, $E_A(x,y)$ is given by

$$E_A(x,y) = P \exp[j2\pi\varphi(x,y)], \quad (3)$$

where P is the amplitude distribution of the beam and $\phi(x,y)$ represents the phase distortion caused by turbulence. The backpropagated fiber mode $F_A(x,y)$ can be expressed as [9]

$$F_A(x,y) = \frac{\sqrt{2\pi}\omega_0}{\lambda f} \exp\left[-\left(\frac{\pi\omega_0}{\lambda f} \right)^2 (x^2 + y^2) \right], \quad (4)$$

where λ denotes the light beam's wavelength and f is the focal length of the coupling lens. Parameter ω_0 represents the mode field radius of the fiber core. For a coupling system without atmospheric turbulence, the coupling efficiency depends on the parameters of the coupling lens.

Figure 3 shows the relationship between coupling efficiency η_f and the relative aperture D/f of the coupling lens. In this paper, with the purpose of obtaining the maximum fiber coupling efficiency, the parameters of the system are given by $\lambda = 1550$ nm, $\omega_0 = 5$ μm, and $D/f = 0.23$.

3. SIMULATED ANALYSIS

A. Influence of the Atmospheric Turbulence

From Eqs. (2) and (3), it is indicated that the SMF coupling efficiency, which is regarded as a pattern matching between fiber mode field and incident light beam, is influenced by the wavefront phase distortion, as shown in Fig. 4. When the wavefront phase is an ideal plane wave and the distribution on the focal plane is an Airy pattern, the pattern matching is

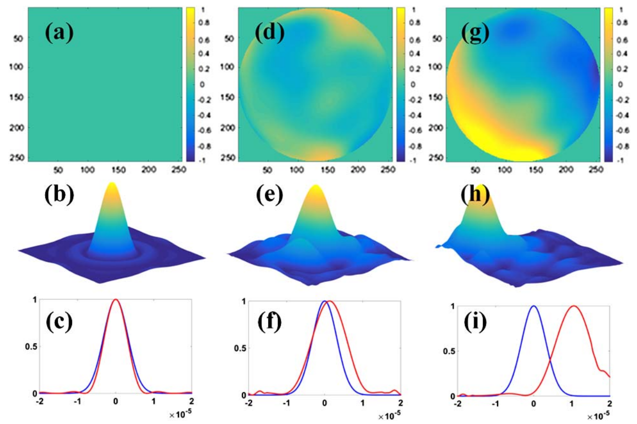

Fig. 4. Schematic of the fiber coupling over different turbulence.

mostly coincident, as presented in Figs. 4(a)–4(c). However, if the wavefront phase is affected by the atmospheric turbulence, the distribution on the focal plane of the incident beam will become distorted and the pattern matching degrades, especially with serious tilt, as shown in Figs. 4(d)–4(i).

The simulated relationship result between wavefront phase $\phi(x, y)$ and coupling efficiency η_f according to Eq. (2) and Eq. (5) is shown in Fig. 5. In order to describe the wavefront phase distortion quantitatively, we use phase root mean square (RMS) value to analyze the degree of the distortion. It is clearly shown that wavefront phase distortion degrades the coupling efficiency. When wavefront phase RMS $> 0.3\lambda$, the average coupling efficiency is about 10%.

As for the atmospheric optical communication link, we often use atmospheric coherence length r_0 based on the Kolmogorov model to describe the strength of the turbulence. It is given by [10]

$$r_0 = \left[0.423k^2 \int_L C_n^2(z)\mathrm{d}z\right]^{-3/5}, \quad \textbf{(5)}$$

where $k = 2\pi/\lambda$, and C_n^2 represents the atmospheric refractive index structure parameter. The telescope aperture D is the key parameter to describe the strength of the turbulence. Ignoring the scintillation of the light intensity caused by the atmospheric turbulence, the strength of the turbulence increases quickly with increase in the aperture. Figure 6 shows the influence

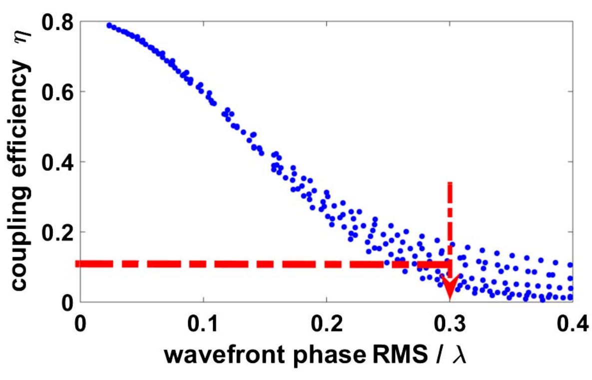

Fig. 5. SMF coupling efficiency over different phase RMS.

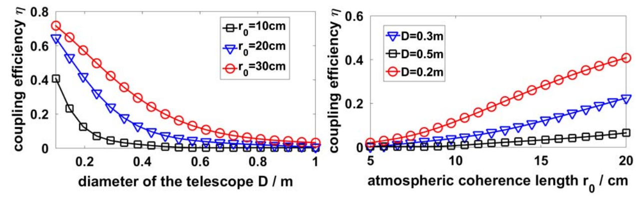

Fig. 6. (a) SMF coupling efficiency over different telescope diameter D and (b) The SMF coupling efficiency over different atmospheric coherence length r_0.

of the telescope aperture D and the atmospheric coherence length r_0 on the coupling efficiency. Decrease in the aperture is one effective way to decrease the influence of the turbulence and increase the coupling efficiency.

On the other hand, the aperture is usually expected to be larger in the free-space optical communication systems in order to obtain higher received optical power.

B. Coupling Efficiency with AO Compensation

In the atmospheric aberration theory, the wavefront aberration is usually described by the Zernike polynomial [11]; any wavefront phase distortion $\varphi(r, \theta)$ over a circular aperture of unit radius can be expanded as a sum of Zernike modes:

$$\varphi(r, \theta) = a_0 + \sum_{k=1}^{N} a_k Z_k(r, \theta), \quad \textbf{(6)}$$

where $Z_k(r, \theta)$ is the kth Zernike polynomial and a_k represents the Zernike coefficients.

In the studies, the coefficients of the Zernike polynomials of the turbulent wavefront are generated using Zernike polynomials. The number of the Zernike modes used to generate the turbulent wavefront is 66. Equation (2) is used to calculate the coupling efficiency after the residual turbulent wavefront phase is generated using the residual Zernike coefficients.

In AO, we use the parameter D/r_0 to present the atmospheric turbulence strength. We call it the normalized atmospheric turbulence strength. For a telescope with diameter less than 1 m, we divide the normalized atmospheric turbulence strength into primarily three sections. For the weak turbulence condition, D/r_0 is around 2. For the moderate turbulence condition, D/r_0 is around 10. For the relatively strong turbulence condition, D/r_0 is around 15.

The SMF coupling efficiency with an ideal AO system over different normalized atmospheric turbulence strength is shown in Fig. 7. Without the compensation of the AO system, the coupling efficiency reaches 0.43 when $D/r_0 = 0.8$. When considering the moderate turbulence condition D/r_0 above 5, the coupling efficiency approaches zero. Therefore, only when D/r_0 is not larger than 1 can the SMF coupling system work well without any compensation.

When the normalized atmospheric turbulence strength is weak, for example, $D/r_0 = 2$, the coupling efficiency increases significantly from 0.09 to 0.61 with only the tip and tilt compensated, and increases to 0.75 for the 8 Zernike modes correction. This is 7 or 8 times improvement. Considering a stronger turbulence, for example, $D/r_0 = 4$, the coupling efficiency still reaches 0.38 for only the tip and tilt compensation.

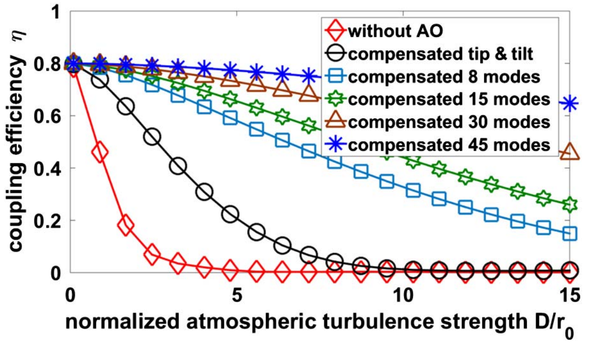

Fig. 7. SMF coupling efficiency with and without AO compensation over different normalized atmospheric turbulence strength D/r_0.

Therefore, under the condition of weak turbulence, $D/r_0 < 4$, the SMF coupling system can work well for only the tip and tilt compensation.

When the normalized atmospheric turbulence strength is moderate, for example, $D/r_0 = 10$, only the tip and tilt compensation is not enough. It may need to correct 15 or more modes. When the normalized atmospheric turbulence strength is relatively strong, for example, $D/r_0 = 15.1$, the 30 or more Zernike modes should be considered to improve the SMF coupling efficiency from nearly zero to 0.5.

4. SMF COUPLING EXPERIMENT OVER RELATIVELY STRONG TURBULENCE

According to the simulated analysis, under the condition of relatively strong turbulence, only the tip and tilt compensation is not enough. Higher-order aberration compensation is required. In order to verify the effectiveness of the AO technology applied for the SMF coupling system, we designed an experimental system, as shown in Fig. 8.

The wavefront phase distorted signal beam with the wavelength of 1550 nm is created by a turbulence simulator that simulates the atmospheric turbulence by induced air flow. To characterize the turbulence created by the simulator, we use a Shack–Hartmann wavefront sensor to analyze the turbulence. The results are shown in Fig. 9. Figure 9(a) is the Zernike coefficient at a certain time and Fig. 9(b) is the wavefront. The RMS of the wavefront at this time is 1.26λ ($\lambda = 1550$ nm).

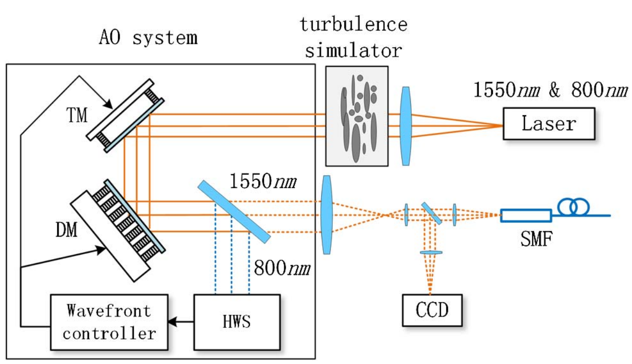

Fig. 8. Schematic diagram of the SMF coupling system with turbulence simulator and AO compensation.

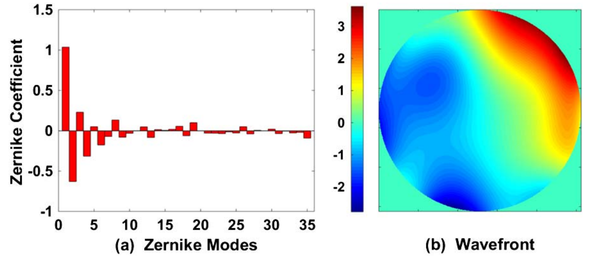

Fig. 9. Zernike coefficient and wavefront of the turbulence simulator.

We can see from Fig. 9(a) that the Zernike coefficient distribution of the aberration caused by the turbulence simulator is approximately similar to the one caused by the atmosphere.

Then the distorted beam is sent into the AO system composed by a piezoelectric fast tilting mirror, a 137-element DM, and a Hartmann–Shack wavefront sensor. Finally, the compensated beam is separated into two parts by a beam splitter. One part of the beam is focused into the CCD panel and another one is used for coupling.

Before the experiment, we analyzed the performance of the 137-element AO system for compensating the phase aberration. As shown in Fig. 10(a), the residual aberrations of the beam compensated by the AO system, described by the Zernike coefficients, are not corrected to zero except for tip and tilt aberrations. Figure 10(b) shows the maximum efficiency the system can obtain over different normalized atmospheric turbulence strengths. According to the normalized atmospheric turbulence strength $D/r_0 = 15.1$, created by the turbulence simulator in the experiment we present, the maximum coupling efficiency we can obtain is above 66% theoretically.

The experiment is carried out with the AO system and the diameter of the received telescope is 36 mm. The atmospheric coherence length is an average of 2.38 mm, which is measured by the Hartmann–Shack wavefront sensor. The D/r_0 is above 15.1; that is, the experimental turbulence condition belongs to the relatively strong turbulence. The closed-loop frequency of the system is above 1.3 kHz.

The intensity and centroid distributions of the far field for the experimental light beam are shown in Fig. 10. When the AO system is off, due to the influence of the turbulence, the

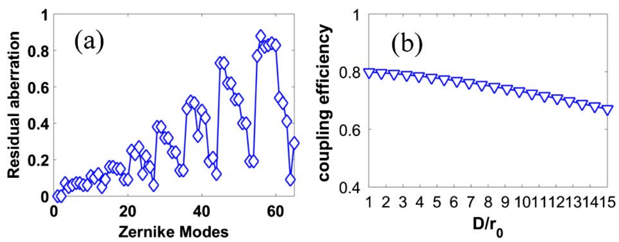

Fig. 10. (a) Residual aberration of the light beam compensated by the 137-element AO system in different Zernike modes; and (b) the theoretical maximum coupling efficiency of the system over different turbulence strengths.

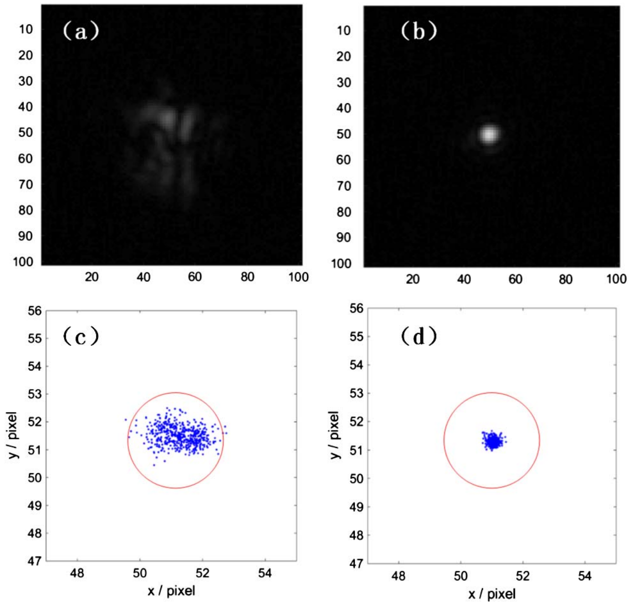

Fig. 11. Intensity and centroid distributions of the far field for the experimental light beam, (a) and (c) without AO; and (b) and (d) with AO.

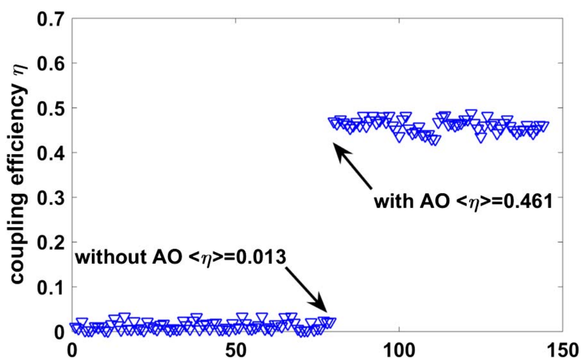

Fig. 12. Coupling efficiency obtained over relatively strong turbulence, $D/r_0 = 15.1$.

intensity and the centroid distributions are dispersive, as shown in Figs. 11(a) and 11(c). Conversely, when the AO system is working, the far-field intensity distribution approaches diffraction limit and the centroid distribution is relatively centralized, as shown in Figs. 11(b) and 11(d). That is, the AO system effectively compensates the wavefront phase distortion of the atmospheric turbulence.

The coupling efficiency obtained is shown in Fig. 12. The average value of the coupling efficiency with AO compensation is 46.1%, increasing almost 35 times compared with the value of 1.3% without AO compensation. The coupling lens we use is composed of several convex lenses in order to reach the optimal relative aperture. Considering the dynamic errors and the transmittance limitation of the lens, the difference between the average coupling efficiency of 46.1% and the maximum value of 67% in the system theoretically is acceptable.

5. CONCLUSION

In this study, the influence of the atmospheric turbulence for SMF coupling efficiency and the results of the SMF coupling experiment over relatively strong turbulence with AO systems are presented. It is shown that the wavefront phase distortion seriously affects the SMF coupling efficiency. When the normalized atmospheric turbulence strength D/r_0 is bigger than 2, the coupling efficiency decreases from 81% without the influence of atmospheric turbulence to below 10%. In the condition of moderate turbulence, for example, $D/r_0 = 4$, the coupling efficiency increases from near zero without compensation to 40% with only tip and tilt correction. However, under the condition of relatively strong turbulence, for example, $D/r_0 = 15$, the tip and tilt compensation only is not enough, and higher-order aberration modes are required to compensate.

The SMF coupling experiment is carried out with the 137-element AO system, and the normalized atmospheric turbulence strength D/r_0 of the experimental turbulence environment is 15.1. The result shows that the coupling efficiency increases from 1.3% without AO compensation to 46.1% with AO compensation. Considering the dynamic errors and the transmittance limitation of the lens, the difference between the average coupling efficiency of 46.1% and the maximum value of 67% in the system theoretically is acceptable. In the future, we will improve the experiment condition and expect to reach the theoretical result.

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