Experimental demonstration of single-mode fiber coupling using adaptive fiber coupler*

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Coupling plane wave into a single-mode fiber (SMF) with high and steady coupling efficiency is crucial for fiber-based free-space laser systems, where random angular jitters are the main influencing factors of fiber coupling. In this paper, we verified a new adaptive-optic device named adaptive fiber coupler (AFC) which could compensate angular jitters and improve the SMF coupling efficiency in some degree. Experiments of SMF coupling under the angular jitter situation using AFC have been achieved. Stochastic parallel gradient descent (SPGD) algorithm is employed as the control strategy, of which the iteration rate is 625 Hz. In closed loop, the coupling efficiency keeps above 65% when angular errors are below 80 μrad. The compensation bandwidth is 35 Hz at sine-jitter of 15 μrad amplitude with average coupling efficiency of above 60%. Also, experiments with simulated turbulence have been studied. The average coupling efficiency increases from 31.97% in open loop to 61.33% in closed loop, and mean square error (MSE) of coupling efficiency drops from 7.43% to 1.75%.

Keywords: single-mode fiber coupling, adaptive fiber coupler, adaptive optics, free-space optical communication

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1. Introduction

In some kinds of fiber-based free-space laser systems, such as free-space optical communication (FSOC), optical radar, and stellar interferometry, it is important to achieve maximum fiber (especially single-mode fiber, SMF) coupling efficiency to obtain the maximum received signal-to-noise ratio (SNR).[1–9] In practice, all systems operate in the presence of random angular jitter, which refers to the uncertainty of the instantaneous direction of the received optic axis with respect to a nominal axis of the fiber. The expression of mean SMF coupling efficiency was reported in the focal plane and the optimum relationships between the mode field size of fiber and a focused optical beam were discussed in the presence of random angular jitter in Ref. [1]. In contrast, Ma *et al.*[9] evaluated the mean coupling efficiency in the presence of random angular jitter in the pupil plane. Both papers drew the same conclusions that the mean coupling efficiency degrades seriously with the random angular jitter and it is significant to correct the jitter to achieve maximum fiber coupling efficiency. Hitherto, fast-steering mirror (FSM) was generally employed to correct angular jitters,[8] which are mainly induced by atmospheric-turbulence effects, vibration and thermal deformation of the mechanism, etc.

In recent years, Geng from the Key Laboratory on Adaptive Optics, Chinese Academy of Sciences (CAS) developed the adaptive fiber-optics collimator (AFOC) for tip/tilt control in beam combining applications.[10–15] Compared with FSM, the AFOC drives fiber tip directly with advantages of precise control, small inertia, high resonance-frequency, compactness, and convenience for assembling and integration. Based on the principle of optical reversibility, the AFOC has the potential for adaptive laser coupling. In this paper, we present a new adaptive-optic device named adaptive fiber coupler (AFC), which is similar to AFOC in structural configuration and could compensate angular jitters and improve SMF coupling efficiency in some degree.

The rest of this paper is organized as follows. The theories of SMF coupling in the presence of random angular jitter are discussed in Section 2. In Section 3, structure and performances of AFC are presented. In Section 4, SMF coupling experiments using AFC of correcting the angular errors, sine-jitters and simulated turbulence are achieved to verify the abilities of AFC in maximizing and stabilizing the mean coupling efficiency.

2. Theories of fiber coupling

Coupling plane wave into SMF and acquiring the maximum coupling efficiency are difficult since the core radius of SMF is only several microns. Here, the theories of fiber coupling in the absence or the presence of random angular jitter

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using the principle of mode field match are presented.

2.1. General coupling theory

The schematic diagram of fiber coupling is shown in Fig. 1. Uniform plane wave is focused by a thin, diffraction-limited lens, of which the diameter is D and focal length is f. The lens is located in the pupil plane A and the end of SMF is placed in the rear focal plane O of the lens. The distribution of the focused optical beam on the fiber end is an Airy pattern, of which the amplitude $E_{\mathrm{O}}(r)$ is given by[16]

$$E_{\mathrm{O}}(r) = \frac{\pi D^2}{4\lambda f}\left[2\frac{J_1(kDr/2f)}{kDr/2f}\right], \tag{1}$$

where λ is the optical wavelength, k is the wavenumber, r is the radius distance on the focal plane O, and $J_1(\cdot)$ is the Bessel function of the first kind of order zero.

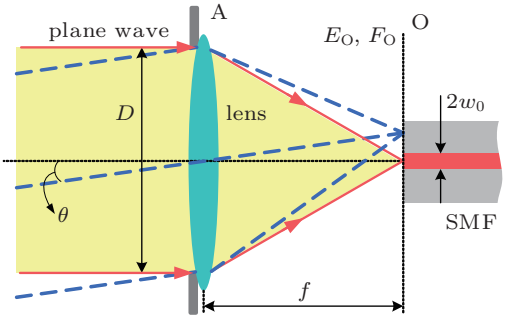


Fig. 1. (color online) Schematic diagram of fiber coupling.

When the normalized frequency V of the SMF is in the range of $1.9 \le V \le 2.4$, the distribution of optical beam in SMF can be approximate to a Gaussian beam within 1% error, of which the amplitude $F_{\mathrm{O}}(r)$ is expressed by[1]

$$F_{\mathrm{O}}(r) = \sqrt{\frac{2}{\pi w_0^2}}\exp\left(-\frac{r^2}{w_0^2}\right), \tag{2}$$

where w_0 is the mode field radius of the fiber core.

Fiber coupling efficiency η is defined as the ratio of the power coupled into the SMF to the power available in the focal plane, and given by[2]

$$\eta = \frac{\left|\iint E_{\mathrm{O}}(r)F_{\mathrm{O}}(r)\,\mathrm{d}s\right|^2}{\iint |E_{\mathrm{O}}(r)|^2\,\mathrm{d}s \iint |F_{\mathrm{O}}(r)|^2\,\mathrm{d}s}, \tag{3}$$

where $F_{\mathrm{O}}(r)$ is normalized as $\iint |F_{\mathrm{O}}(r)|^2\,\mathrm{d}s = 1$. Substituting Eqs. (1) and (2) into Eq. (3), the fiber coupling efficiency is given by

$$\eta = 2\frac{\left[1-\exp\left(-\beta^2\right)\right]^2}{\beta^2}, \tag{4}$$

where $\beta = \pi D w_0/(2\lambda f)$ is the coupling parameter. The numerical results of the fiber coupling efficiency η as a function of the coupling parameter β are shown in Fig. 2. The maximum fiber coupling efficiency, $\eta = 0.81$, is obtained when $\beta = 1.12$. In this paper the parameters of function β are given by $w_0 = 5$ μm, $\lambda = 1.064$ μm, $f = 0.12$ m, and $D = 18$ mm.

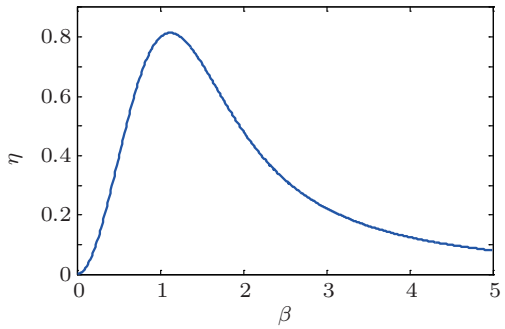


Fig. 2. (color online) Fiber coupling efficiency η as a function of the coupling parameter β.

2.2. Fiber coupling efficiency in the presence of angular jitter

Angular error θ of plane wave relative to the optical axis of the focusing lens is equal to a static radial offset ($\rho = \theta \cdot f$) of the focused beam from the nominal axis of the fiber core in the lens' rear focus plane. When static angular error θ is present, the distribution of optical beam in SMF is given by the Nakagami–Rice distribution[1,17]

$$F_{\mathrm{O}}(r,\rho) = \frac{2\sqrt{2\pi}r}{w_0}\exp\left(-\frac{r^2+\rho^2}{w_0^2}\right)\mathrm{J}_0\left(\frac{2r\rho}{w_0^2}\right), \tag{5}$$

where $\mathrm{J}_0(\cdot)$ is the modified Bessel function of order zero. Substituting Eqs. (1) and (5) into Eq. (3), the coupling efficiency is expressed by

$$\eta = \left|\int \frac{2\sqrt{2}}{w_0}J_1(kDr/2f)\exp\left(-\frac{r^2+\rho^2}{w_0^2}\right)J_0\left(\frac{2r\rho}{w_0^2}\right)\mathrm{d}r\right|^2. \tag{6}$$

The random jitter distribution m as a function of the radial offset ρ can be expressed by the Rayleigh distribution with a zero mean and variance of σ^2

$$m(\rho) = \frac{\rho}{\sigma^2}\exp\left(-\frac{\rho^2}{2\sigma^2}\right). \tag{7}$$

Thus, the average coupling efficiency with respect to the random jitter is given by[2,9]

$$\langle\eta\rangle = \frac{\left|\iiint E_{\mathrm{O}}(r)F_{\mathrm{O}}(r)m(\rho)\,\mathrm{d}\rho\,\mathrm{d}s\right|^2}{\iint |E_{\mathrm{O}}(r)|^2\,\mathrm{d}s}. \tag{8}$$

Substituting Eqs. (1), (2), and (7) into Eq. (8), the analytical expression of the average coupling efficiency can be written as

$$\langle\eta\rangle = \frac{2}{\left\{\left[2(\sigma/w_0)^2+1\right]^2\beta^2\right\}} \times \left\{1-\exp\left[-\left[\left(\left(\frac{\sigma}{w_0}\right)^2+1\right)\right]\beta^2\right]\right\}^2. \tag{9}$$

3. Adaptive fiber coupler

A new adaptive-optic device named adaptive fiber coupler (AFC) which could correct angular jitter and improve the SMF coupling efficiency in some degree for fiber-based free-space laser applications is developed in the Key Laboratory on Adaptive Optics, CAS. The AFC contains a focusing lens and a fiber-tip positioner which consists of a cross-beam and four bimorph piezoelectric actuators, as depicted in Fig. 3(a). The tip of the fiber is fixed in the central hole of the cross beam, deviated in the rear focal plane (X–Y) of the focusing lens. Angular control of the focused input is based on four bimorph actuators, two of which drive the X direction and another two drive the Y direction. The bimorph actuator consists of two piezoelectric sheets glued on both sides of a sheet metal. The applied driving voltages induce the contraction of one sheet and the expansion of another, actuators bend and force the cross beam with the fiber tip to translate ΔX in the rear focus plane. The correctable tip/tilt angle θ of the focused beam is due to $\Delta X/f$, where f is the focal length of the lens.

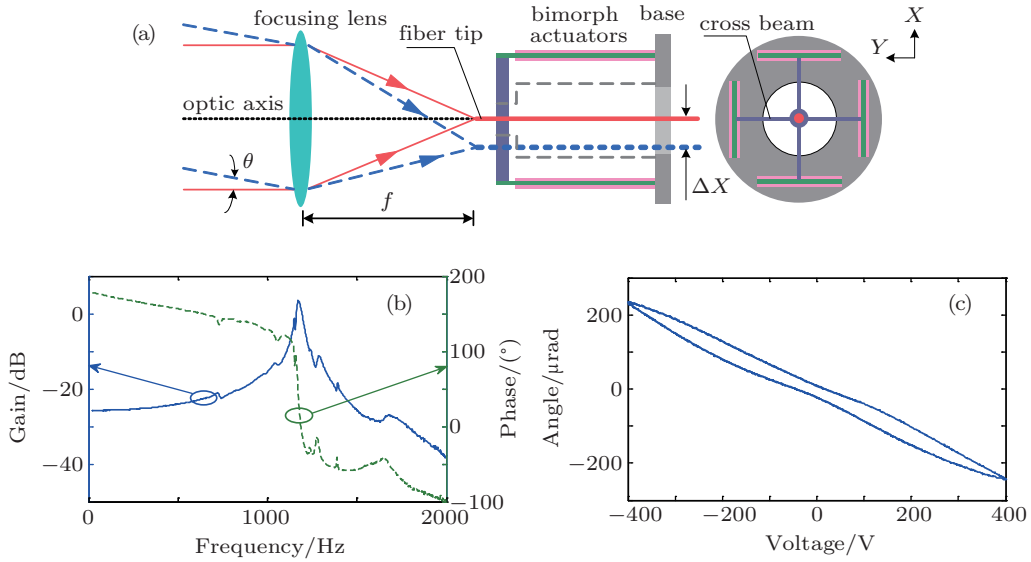


Fig. 3. (color online) A new adaptive-optic device named AFC. (a) Mechanism; (b) frequency response curve; (c) correctable deviation curve.

The performances of AFC used in the following experiments, where $w_0 = 5$ μm, $\lambda = 1.064$ μm, $f = 0.12$ m, and $D = 18$ mm, are tested. The first resonance frequency of the AFC is about 1.17 kHz, and the correctable deviations of input beams are in range 200 μrad (24 μm/f = 200 μrad) for a chosen focal length of 120 mm, respectively, as depicted in Figs. 3(b) and 3(c).

4. Experiments of fiber coupling using AFC

4.1. Experimental configuration

Fiber coupling in the presence of angular jitters and simulated turbulence using AFC was experimentally examined. Figure 4 shows the experimental configuration. A uniform plane wave laser beam with the wavelength of 1064 nm is sent to a fast-steering mirror (FSM) which is used to introduce angular jitters, and then focused and coupled into a SMF by a focusing lens, a part of the AFC. The mode-field diameter of the SMF used here is 10 μm and cladding diameter is 125 μm. A photodetector (PD) is located behind the tail of SMF to detect coupled optical power. Stochastic parallel gradient descent (SPGD) algorithm[10–15] is employed as the control strategy, where the detected power from PD is used as metric function J and the algorithm's iteration rate is 625 Hz. HVA is a high-voltage amplifier by which control signals are amplified one hundred times. When angular jitters are loaded on the plane wave input beam, the AFC and corresponding SPGD-based control system correct the errors adaptively to obtain the maximum metric function J, which is equal to maximize coupling efficiency. The steps of adaptive coupling using SPGD algorithm can be briefly described below.

1) Generate a group of random voltage perturbations $\Delta \boldsymbol{U}$, which obey the Bernoulli probability distribution with zero mean.

2) Apply the signals $\boldsymbol{U} + \Delta \boldsymbol{U}$ on AFC and obtain the corresponding metric function J_+; then apply the signals $\boldsymbol{U} - \Delta \boldsymbol{U}$ on AFC and obtain the metric function J_-.

3) Update the control-voltage signals on the AFC,

$$\boldsymbol{U} = \boldsymbol{U} + \gamma \Delta \boldsymbol{U}(J_+ - J_-)/2, \tag{10}$$

where γ is the gain coefficient of SPGD algorithm.

4) Go to step 1 and continue the process, until the control procedure is stopped manually.

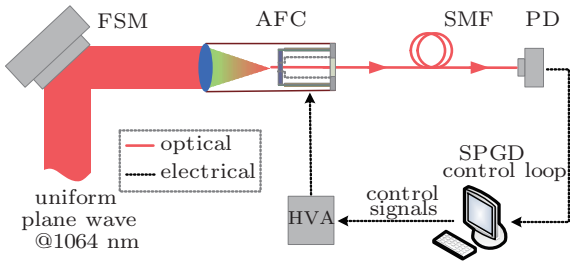


Fig. 4. (color online) Experimental setup of fiber coupling using the AFC.

4.2. Coupling efficiency with angular errors

When the experimental setup described above is adjusted to the optimum position, an optical power of 6.03 mW is coupled into SMF and obtained by a power detector. The 9 mW total optical power of the plane wave laser beam is tested by a power detector before, and we can conclude that the maximum SMF coupling efficiency here is about 67% (6.03/9 = 67%). A series of different angular errors introduced by FSM are applied to the plane wave beam, and the curve of SMF coupling efficiency η as a function of angular error θ is achieved theoretically and experimentally, as shown in Fig. 5, respectively. The maximum experimental coupling efficiency is about 67%, a little lower than the theoretical coupling efficiency 81%, which is mainly caused by the 4% reflectance on the SMF's end and the quality of the Airy disc of focused beam. When angular error is above 60 μrad, the coupling efficiency is below 10%, that is to say only 7.2 μm (60 μrad × 120 mm = 7.2 μm) offset of the focal spot results in sharp decrement of coupling efficiency which is related to the 5 μm mode field radius of the fiber employed.

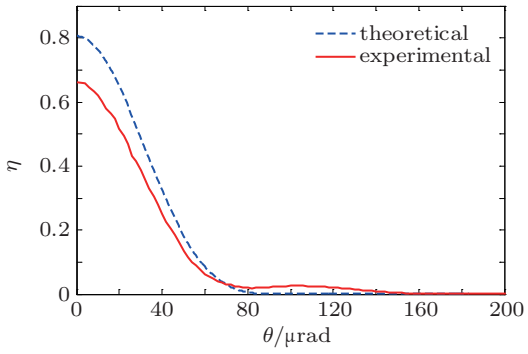


Fig. 5. (color online) Fiber coupling efficiency η as a function of angular error θ.

4.3. Experiments with angular errors

Experiments of fiber coupling with different angular errors using AFC are demonstrated. Figure 6 shows the experimental results of fiber coupling correcting angular errors. As shown in Fig. 6(a), the SMF coupling efficiency comes to about 67% under static angular error of 15 μrad, 30 μrad, 45 μrad, and 60 μrad, respectively, when the closed loop is achieved. The correcting process only takes about 20 SPGD iterations, which is equal to a correcting time of 32 ms (20/625 Hz = 32 ms), and the angular error is smaller, the correcting time is shorter. Figure 6(b) depicts the average value of coupling efficiency of 2500 SPGD iterations in closed loop as a function of static angular error θ. The average SMF coupling efficiency keeps above 65% when the angular error is below 80 μrad. Once the angular error is above 80 μrad, the SMF coupling efficiency drops to below 5% immediately because of the deviation of the Airy disc from the SMF core.

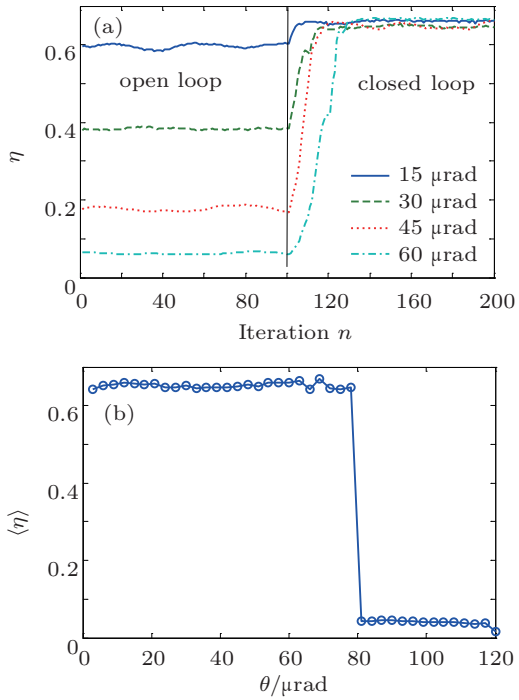


Fig. 6. (color online) Experimental results of fiber coupling in different angular errors. (a) Evolution curve of the coupling efficiency in open loop and closed loop; (b) correctable angular errors of the AFC and corresponding control system.

4.4. Experiments with sine-jitters

Here, a kind of sine angular jitter with frequency of 2 Hz and amplitude of 30 μrad (the driving voltage on FSM is 0.15 V) is loaded on the plane wave laser beam and corresponding experiments of SMF coupling using AFC are studied. Figure 7 depicts the evolution curve of fiber coupling efficiency with the given sine-jitter. The SMF coupling efficiency η in open loop is sinusoidal variation with an average value of 51.28% and mean square error (MSE) of 9.93%, while in closed loop the average SMF coupling efficiency increases to 65.72% with MSE of 0.61%.

Figure 8 shows the average SMF coupling efficiency in closed loop as the function of frequency of sine-jitter with different amplitude. When the amplitude of sine-jitters is fixed, the average SMF coupling efficiency decreases with the increment of jitter's frequency. The same conclusion is obtained when the frequency of sine-jitters is fixed. If the average SMF

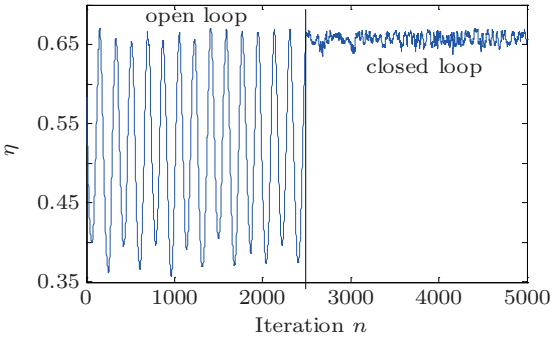


Fig. 7. (color online) Evolution curve of fiber coupling efficiency with a sine-jitter.

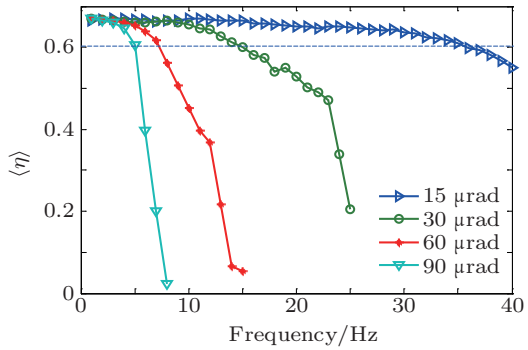


Fig. 8. (color online) Average SMF coupling efficiency in closed loop as a function of frequency of sine-jitter with different amplitudes.

coupling efficiency of 60% is thought to be great for fiber coupling, we can conclude that the maximum compensation bandwidth of sine-jitter is 35 Hz at 15 μrad amplitude, which could be improved by enhancing the dynamic performances of AFC and the control bandwidth of corresponding SPGD-based control system.

4.5. Experiments with turbulence

Experiments of SMF coupling using AFC with simulated turbulence are investigated. Here, air flow induced by air-conditioner is employed to simulate atmospheric turbulence. Figure 9(a) shows the evolution curve of coupling efficiency η in open and closed loop with stimulated turbulence. The average SMF coupling efficiency increases from 31.97% in open loop to 61.33% in closed loop, and the MSE of coupling efficiency drops from 7.43% to 1.75%. The blue solid curve and red dash curve in Fig. 9(b) stand for the frequency-spectrum-density analysis of the open loop curve and closed loop curve in Fig. 9(a), respectively, which indicates that the control bandwidth of 20 Hz has been achieved in this SPGD-based control system.

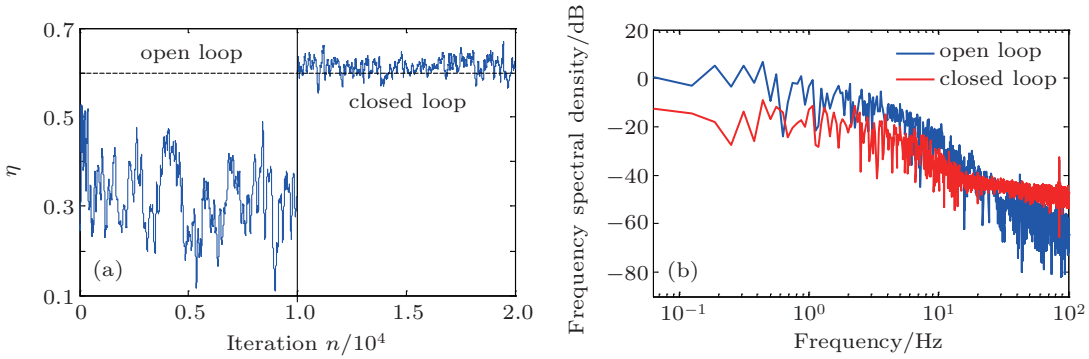


Fig. 9. (color online) Experimental results of fiber coupling with simulated turbulence. (a) Evolution curve of coupling efficiency η; (b) frequency-spectrum-density analysis.

5. Conclusion

In this study, the AFC, which could compensate angular jitter and improve the SMF coupling efficiency in some degree, was presented with the first resonance-frequency of 1.17 kHz and maximum correctable deviation of 200 μrad. Efficient and steady SMF coupling was realized by SPGD control in the presence of given angular jitters, where the SPGD iteration rate is 625 Hz. Experimental results show that maximum angular error of 80 μrad has been compensated in 32 ms with coupling efficiency up to 65%. The compensation bandwidth of sine-jitter is 35 Hz at 15 μrad amplitude with average coupling efficiency of above 60%. In addition, experiments with simulated turbulence have been studied, where the average coupling efficiency increases from 31.97% in open loop to 61.33% in closed loop and the MSE of coupling efficiency drops from 7.43% to 1.75%. In the future, we will improve the dynamic performances of AFC and the control bandwidth of corresponding systems. In addition, AFC array will be developed to compose a large aperture of optical receiver and be studied experimentally. We believe this kind of AFC and corresponding control system could be widely used in fiber-based free-space laser applications.

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