Experimental study on high efficiency of Ti:sapphire laser to single-mode fiber coupling

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Received December 19, 2012; accepted January 25, 2013; posted online April 24, 2013

We experimentally investigate an optimum scheme of coupling a collimated light from a Ti:sapphire laser source into a standard single-mode fiber (SMF). By adjusting the effective numerical aperture (NA) of coupling lens and eliminating the chromatic aberration, a coupling efficiency of around 70% is finally obtained. This result is close to the maximum value predicted by theoretical simulation. It is well demonstrated that high coupling efficiency between Ti:sapphire laser and SMF can also be obtained by optimizing certain parameters of a coupling lens, without employing any special optical components, or the specific fiber with complex structure.

OCIS codes: 060.2430, 010.3310, 140.3325.

doi: 10.3788/COL201311.050605.

With the rapid development of fiber technology in the past twenty years, the fiber was commonly utilized in a wide range of applications, such as communication[1−3], fiber amplifier[4,5], lidar[6,7], sensor[8], interferometer[9], and spectroscopy[10]. These fiber-integrated devices have the desirable features of compactness, stableness, and high efficiency. Practically, most of fiber-integrated devices have to collect the light from a laser source and couple it into fibers. Hence, optimizing the coupling efficiency of laser-to-fiber becomes a key issue for optical fiber components. Up to now, several groups have investigated it theoretically and experimentally. The simulation and experimental results have demonstrated that the key factors, such as misalignment[11], aberration[12], atmospheric turbulence[13], and random jitter[14], might have a great influence on the efficiency of laser-to-fiber coupling.

In this letter, we experimentally investigate the optimized coupling scheme of ultrafast laser beam from a Ti:sapphire laser source into a standard single-mode fiber (SMF). It is discovered that the maximum coupling efficiency can be obtained by adjusting the effective numerical aperture (NA) of coupling lens and eliminating the chromatic aberration. Our result well demonstrates that high efficient coupling between laser and SMF can be easily obtained without employing any special optical components, or the fiber with complicated structure.

An optical fiber is a cylindrical waveguide consisting of two or more dielectric material layers. Different modes that propagate through the fiber are described by Maxwell's equations along with the bounding conditions. Only the first mode, the fundamental mode F_{01}, can propagate through the SMF. Its profile can be approximated by Gaussian[15]:

$$F_{01}(r) \approx e^{-(\frac{r}{\omega})^2}, \tag{1}$$

where ω denotes the fundamental mode radius. The conventional mode of laser to SMF coupling is shown in Fig. 1. A uniform optical beam is incident on the plane A, and then is focused by a thin lens. The end face of fiber is placed close to the focal plane in the coupling plane B. Coupling efficiency η, is defined as the ratio of the power coupled into the fiber to the power available in the pupil plane.

Conventionally, optimum coupling can be achieved if the end face of fiber is located at the focal plane and the spot size of converging light at the focus point is match to the fundamental mode radius of the fiber. However, the radius of the light at the focus point is limited by the Rayleigh diffraction limitation:

$$R' = 0.61 \cdot \frac{\lambda}{\sin\beta} \approx 1.22 \cdot \frac{\lambda \cdot f}{D}, \tag{2}$$

where λ is the central wavelength of the laser, β is the converging angle, f is the focal length of lens, and D is the diameter of the light incident on the plane A. Hence, the relationship between R' and ω may play a dominant role in optimizing the coupling efficiency. Ruilier[16] found that the maximum coupling efficiency of laser-to-fiber could be 81% in theory, not 100%.

The scheme of experimental setup is shown in Fig. 2. The laser source employing in the experiment is a diode-pumped Ti:sapphire laser, which produces the light with diameter of spot size about 2.5 mm, central wave length of 790 nm, spectral width of 100 nm, and beam divergence of 0.8 mrad. After passing through a collimated system comprised by two confocal lenses, the laser beam is incident on the coupling lens and concentrated into a receiver fiber. The fiber used in experiment is a 1-m SMF (780-HP, Nufern, USA) with operating wavelength of 780–970 nm, mode-field diameter (MFD) of 5.0±0.5 μm@850 nm, NA of 0.13. A high sensitivity power detector (Newport, USA), which can detect a minimum power down to 1 μW, is employed at the output of the fiber.

In previous reports, many lenses with distinct geometric structures were selected for laser-to-fiber coupling[17−20], and microscope objective lens was proved

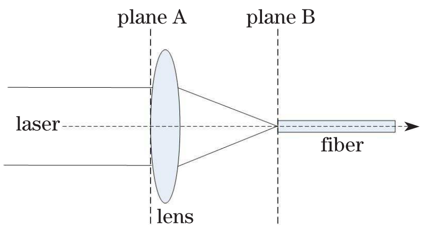

Fig. 1. Geometry of laser-to-fiber coupling.

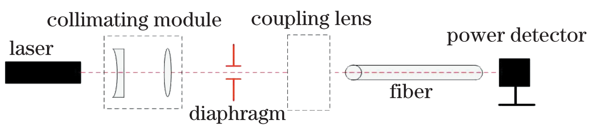

Fig. 2. Schematic of experimental setup.

Table 1. Coupling Efficiencies and Diffractive Limitation Widths of Light at Focus Corresponding to Different Objectives

Lens	Diffractive Limitation Width (μm)	Coupling Efficiency
4×	29.3	33%
10×	15.6	45%
20×	7.8	56%

to obtain a high coupling efficiency[21,22]. In our experiments, three objective lenses with different magnifications (4×, 10×, and 20×) were used for laser-to-fiber coupling. Each lens has different focal length, namely 37.5 mm for 4× objective, 20 mm for 10× objective, and 10 mm for 20× objective, respectively. In the experiments, the high-precision fiber adjusting mount with five degrees of freedom was employed for coupling the light into bare fiber. The end face of fiber was polished (gradient $< 0.3°$) and cleaned. The maximum coupling efficiencies and diffractive limitation widths of spot size corresponding to different focal lengths are shown in Table 1. With decreasing the magnification of objective lens, the diffractive limitation width of spot size at focus point increased from 7.8 to 29.3 μm, but the coupling efficiency dropped from 56% to 33%. Hence, the maximum coupling efficiency might much depend on the spot size of converging light at focus.

Although the 7.8-μm spot size of converging light at focus is mostly approached to the MFD of fiber (5.0 μm), but the coupling efficiency is still much lower than the theoretical value. The NA of fiber may also have a great influence on the coupling efficiency. Therefore, in order to obtain a higher coupling efficiency, the NA of coupling lens must match to the fiber. As we know, if the aperture of lens is much smaller than the focal length, we could define the parameter NA_{eff} as the effective NA of the incident pupil of coupling lens:

$$NA_{eff} \approx \frac{D}{2f}. \quad (3)$$

In order to obtain consecutive value of NA_{eff}, it can be realized by adjusting the ratio between a variable D and a fixed f. In experiments, we inserted a 2× beam expander and selected 20× objective as coupling lens. The spot size was doubled before the light was incident onto the objective. The aperture diaphragm was used to make the spot size D of laser pulses changing in the range from 1.8 to 3.6 mm.

Figure 3 shows the relationship between the maximum coupling efficiency and the different NA_{eff} obtained from the experiments and theoretical simulation. The simulation in theory was based on

$$\eta = \frac{2}{\chi^2}(1 - e^{-\chi^2})^2, \quad (4)$$

$$\chi = \frac{\pi}{\lambda} \cdot \frac{D}{2f} \cdot \omega_f, \quad (5)$$

where η is coupling efficiency, ω_f is the MFD of fiber[16]. It is clear that the experimental results agree well with the simulation result. The maximum coupling efficiency was about 62% in experiment, while it was 81% in theory. Both of them were obtained at the optimum NA_{eff} of 0.11, which was somewhat smaller than the NA (0.13) of fiber.

Wagner *et al.*[12] discovered that the aberration might have a great influence on the efficiency of laser-to-fiber coupling. In the experiments, the objective was replaced by an aspheric lens, which was achromatic and had a lower transmission loss. The focal length of the aspheric lens was chosen as 11 mm, in order to match the diameter of laser beam (2.5 mm) to get NA_{eff} of 0.11. The experimental result is shown in Figs. 4 and 5. The coupling efficiency measured by using aspheric lens was about 8% higher than that measured by using normal objective. The maximum efficiency was around 70% at the optimum NA_{eff} of 0.11 or spot diameter of 2.42 mm. In theory, the maximum efficiency of laser-to-fiber was about 78%, if the Fresnel reflection of the fiber end face was taken into account[23]. The maximum coupling efficiency about 70% obtained in experiment was much approached the maximum value in theory, and all of these were realized by just using a simple lens and a bare standard SMF without employing any special optical components, or the fiber with complex structure.

As we know, the out put power does not reflect the real value of coupling efficiency, while the laser beam profile at the fiber exit determines the real coupling value. The coupling must be in the core, not in the cladding. Figure 6 shows the experimental setup for measuring the profile of the laser spot at the fiber exit. A lens with focal length of 18 mm was place at about 20 mm far from the end

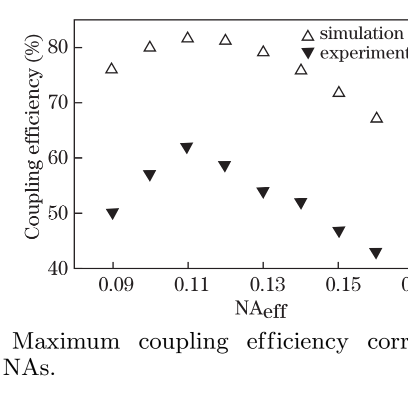

Fig. 3. Maximum coupling efficiency corresponding to different NAs.

face of fiber, and a change-coupled device (CCD, DCC1240X, Thorlabs, USA) camera was used to capture the pattern of laser spot. The image and the profile of near-field mode of laser spot captured by CCD camera are shown in Figs. 7(a) and (b).

Furthermore we used a 0.1-mm reticule to calibrate the scale of laser spot in near-field mode. The diameter at $1/e$ of laser spot on CCD camera could be measured about 143 μm, corresponding to 5.3 μm/pixel. Referring to the 2.8 mm of reticule captured by CCD camera, the laser spot diameter in near-field mode was calculated to be about 5.1 μm, which was comparable to the MFD of fiber (5.0 μm). Hence, we can confirm that the power of laser pulse transmitting through the fiber is only in the core, not in the clad. It is demonstrated that the output power absolutely reflect the real value for coupling efficiency.

In conclusion, we experimentally investigate an optimum coupling of a collimated light from Ti:sapphire laser source into a bare standard SMF. It is discovered that the spot size of converging light at the focus point and the effective NA may play a dominant role in laser-to-fiber coupling. Moreover, about 70% coupling efficiency is obtained experimentally with optimized NA, which is realized by just using a simple lens and a bare standard SMF. It demonstrates that an optimum efficiency of laser-to-fiber coupling can also be obtained by adjusting the effective NA of lens, without employing any other optical components, or a fiber with complex structure.

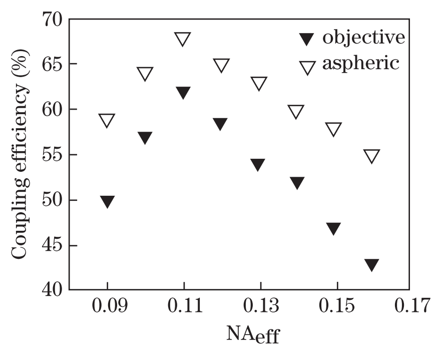

Fig. 4. Coupling efficiency corresponding to different effective NAs.

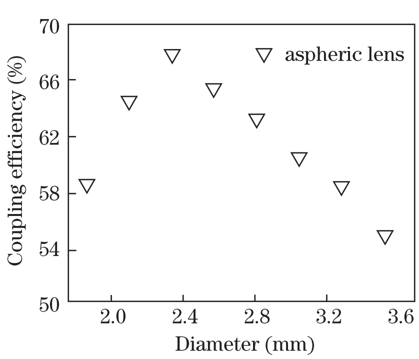

Fig. 5. Coupling efficiency corresponding to different spot diameters of laser pulse.

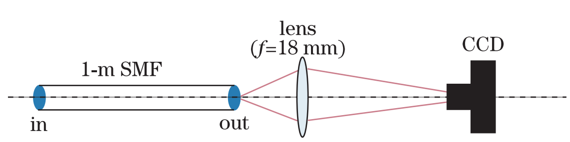

Fig. 6. Experimental setup for measuring the image and profile of the laser spot.

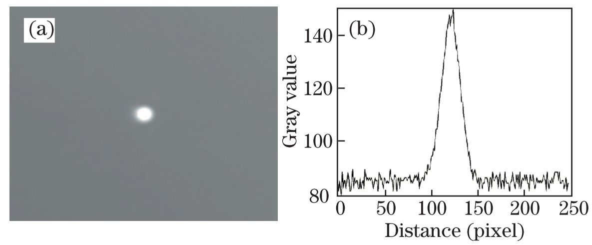

Fig. 7. Image and profile of laser spot: (a) the image captured by CCD camera; (b) the profile of near-field mode of laser spot.

This work was supported by the "Hundreds of Talents Programs" of Chinese Academy of Sciences (No. J08-029), the Innovative Project of Chinese Academy of Sciences (No. YYYJ-1123-4), the National Basic Research Program of China (No. 2007CB310405), and the CAS/SAFEA International Partnership Program for Creative Research Teams.

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