Theoretical study of power amplification in tapered fiber with multi-seed parallel injection

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We proposed the concept of parallel injection power amplification. A tapered fiber amplifier with multi-seed sources by the way of parallel injection was studied. The lower-order modes are excited and more than 90% of the input signal power remains in the fiber core if optimal injection and taper design are set. The power in the doped-core is amplified with high optical-optical efficiency. When light is propagating along the fiber, the higher-order modes are filtered which results in the high output beam quality. Incoherent combination of multi-seed lights launched through the wide end gives rise to the output power of several kW.

Keywords: design of specific laser system, optical propagation transmission and absorption, physical optics

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1. Introduction

The high power fiber lasers and amplifiers have attracted significant interest during the last decade. They have greatly increased the achievable output power of continuous wave single-mode fiber lasers. For a decade or so, the output power of these lasers has extended well into the kW regime. In 2005, Gapontsev V and his co-workers reported an all-fiber format single-mode ytterbium Continuous Wave (CW) fiber laser with output power 1.96 kW and $M^2 < 1.2$.[1] Jeong Y *et al.* demonstrated a highly efficient cladding-pumped ytterbium-doped fiber laser, generating kW several of continuous-wave output power at 1.1 μm with near diffraction-limited beam quality factor.[2–4] In 2011, Hu *et al.* demonstrated a tandem pumped fiber amplifier; the output power can be raised by increasing the pump power and optimizing the gain fiber length.[5] One of the interesting strategies to increase the output power and improve the beam quality is the active tapered double-clad fiber (T-DCF), which has several distinct advantages compared with the common fiber (whose diameter does not vary along the longitudinal direction). One of the essential advantages of this kind of tapered fiber laser is that they can be pumped by a low-brightness source through the wide end of the tapered structure. Another attractive feature is the narrow section can be a mode filter, providing transverse mode selection. Over 600-W output power with high beam quality ($M^2 \leq 1.08$) and a slope efficiency of 63% in the fundamental spatial mode regime have been reported.[6] An efficient ytterbium laser based on T-DCF as the active medium, producing an output power of 750 W with a slope efficiency of 81.9% and near diffraction-limited beam quality ($M^2 = 1.7$) has been demonstrated experimentally.[7] An actively Q-switched scheme by the T-DCF approach has been achieved by generation of 1.6 mJ, 64-ns pulses at very low repetition rates.[8] In addition, the large-dimensional wide end of tapered fiber achieves multi-seed sources injection, so beam combination is implemented, as we studied in this paper. The coherent or incoherent combination of fiber lasers to a single beam with near diffraction limited beam quality enables the high output power. Coherent combining requires a rather precise phase control of single-frequency radiation from each channel by active or passive control method, such as coherent combining by digital holography,[9] coherent combining from a multiple core fiber,[10,11] the phase locking using a self-imaging resonator[12] or an all-optical feedback loop,[13] and all-fiber passive coherent combining of laser array using the fused fiber couplers.[14] On the other hand, incoherent beam combining could be a more direct and simpler way to combine multiple beams without any control of the phase. The incoherent beam combining using seven fiber lasers to get an output power of 4 kW has been demonstrated with beam parameter product (BPP) of 2.5 mm × mrad.[15] Recently, incoherent beam combining of multiple single-mode fiber lasers with fused tapered bundle (FTB) has been reported.[16] However, according to the review of the literature, the tapered fiber usually was used in the oscillator, and sometimes the beam quality of incoherent beam combination of fiber lasers could not be improved.

In this paper, we proposed the concept of parallel injection power amplification (PIPA) which has the advantages of tapered fiber and incoherent beam combining simultaneously. Multi-seed sources are launched through the wide end of a tapered fiber by means of parallel injection. The input power will remain in the fiber core if optimal injection and taper design are set. The power amplification and brightness enhancement of output beam were studied. The section of the narrow end serves as a mode filter which leads to high beam quality.

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In the tapered amplifier, the propagation power is amplified. Incoherent combination of multi-seed lights gives rise to the output power of several levels of kW. The beam quality of incoherent beam combination of multi-seed sources is improved by the use of tapered shape. In theory, a PIPA system with the output power of 3.9 kW, the beam quality factor of 3.82 and the optical-optical efficiency of 71.78% was demonstrated, when the diameters of wide and narrow ends and the length of the fiber are 90 μm and 60 μm and 10 m, respectively.

2. Theoretical analysis of power amplification and beam quality improvement of PIPA

2.1. Structure of PIPA

The schematic diagram of the tapered fiber amplifier is shown in Fig. 1. This system includes the multi-seed sources, the pump lights, and a tapered double-clad fiber and a cladding mode filter. The signal and pump light are injected through the wide facet, and the multi-seed sources are inputted parallelly. The signal light propagates through the fiber core whose diameter has a linear dependence on the axial length L, with the diameters of the wide and narrow ends being D_1 and D_2, respectively. The angle of this linear taper is given by $\alpha = (D_1 - D_2)/(2L)$. The power amplification and beam quality improvement can be realized simultaneously in the tapered fiber with multi-seed sources by parallel injection - PIPA. For this purpose, the core-doped double-clad fiber is drawn into a tapered fiber with the wide and narrow ends. Let the wide end be the incident facet of seed sources and pump light, the wide input-face reduces the stress of pump-coupling, which makes it possible to achieve high power pumping and multi-seed sources injection. The narrow end is the output facet and the narrow section of the tapered fiber serves as a spatial mode filter for the higher-order modes, which results in the output laser with high power and beam quality.

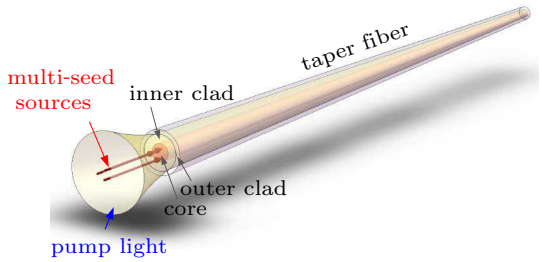


Fig. 1. (color online) The schematic diagram of tapered fiber amplifier.

2.2. Power amplification properties of PIPA

2.2.1. Model

The propagation of a beam in a fiber can be modeled by scalar Helmholtz equation

$$\nabla^2 E(x,y,z) + k_0^2 \varepsilon_r E(x,y,z) = 0, \tag{1}$$

where $k_0 = 2\pi/\lambda_0$, λ_0 is the wavelength in vacuum, $\varepsilon_r = n(x,y,z)^2$, $n(x,y,z)$ is the refractive index profile of step-index fiber. According to the slowly varying envelope approximation (SVEA), the wave function $E(x,y,z)$ is expressed as follows:

$$E(x,y,z) = \phi(x,y,z)\exp\left\{-\mathrm{i}\left[\frac{2\pi(n_{\mathrm{cl}}+\Delta n)}{\lambda_0} + \mathrm{i}\Delta g\right]z\right\}. \tag{2}$$

Here, n_{cl} is the index in cladding, Δg is amplitude gain coefficient, substituting Eq. (2) into Eq. (1), we obtain

$$\frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial y^2} + \frac{\partial^2\phi}{\partial z^2} - \mathrm{i}2k_0 n_{\mathrm{cl}}\frac{\partial\phi}{\partial z} + 2k_0^2 n_{\mathrm{cl}}\Delta\tilde{n}\phi = 0. \tag{3}$$

Here, $\tilde{n}$ is the complex index difference between core and inner cladding of step-index fiber (Fig. 2), which is written as

$$\tilde{n} = \Delta n + \mathrm{i}\frac{\lambda_0}{2\pi}\Delta g. \tag{4}$$

According to the wave equation Eq. (3), the beam propagation properties in a fiber were investigated numerically by using beam propagation method (BPM).[17] The step-index schematic representation of this fiber is shown in Fig. 2.

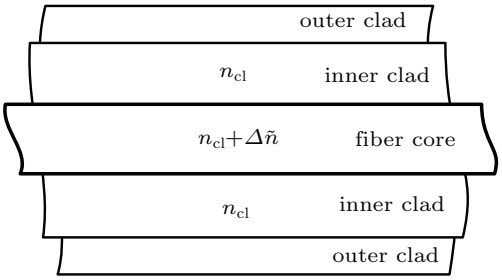


Fig. 2. The schematic of index profile of step-index fiber.

2.2.2. Mode excitation of parallel injection

The intensity pattern of parallel injection beam is shown in Fig. 3 which includes three LP_{01} modes (Fig. 3(a)) or three LP_{11} modes (Fig. 3(b)). The white circle represents the incident facet or the wide end of tapered fiber core with the diameter D_1. The mode excitation in a fiber for different incident positions when LP_{01} and LP_{11} mode are launched, respectively, is shown in Fig. 4, where d is the distance of the incident position from the center of incident facet, and the beam-width of input mode field is 20 μm. The wavelength is $\lambda_0 = 1064$ nm. The core diameter and numerical aperture of the fiber are D_1 = 90 μm and 0.06, respectively, which means that there are 33 modes in the core of this fiber.

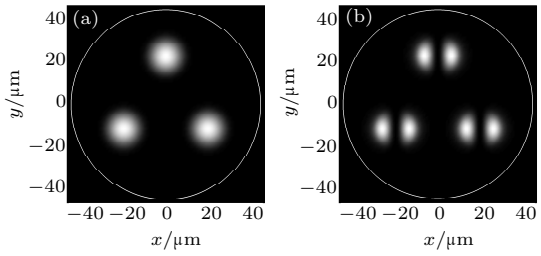


Fig. 3. The intensity pattern of incident beam: (a) LP_{01} mode; (b) LP_{11} mode. (The circle represents for the incident facet).

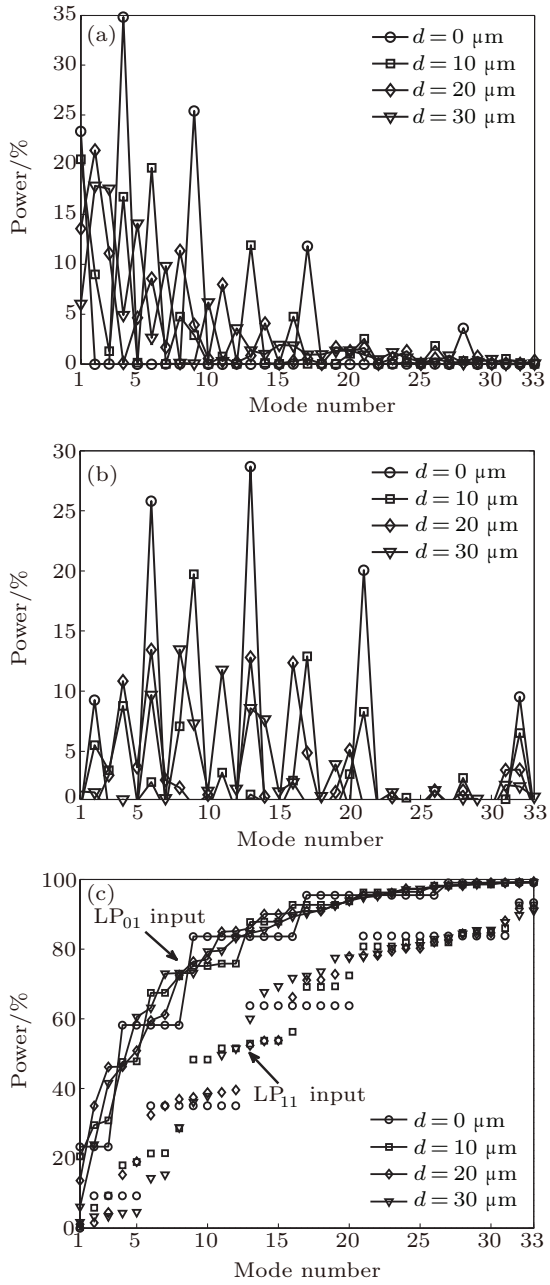


Fig. 4. Mode excitation: (a) LP_{01} incidence; (b) LP_{11} incidence; (c) the sum of the first N-order mode power.

From Fig. 4, the number of modes which are excited increases with the growth of distance d. For example, only five modes, which are LP_{01}, LP_{02}, LP_{03}, LP_{04}, and LP_{05}, are excited when $d = 0$ μm; ten modes are excited when $d = 10$ μm. Moreover, more lower-order modes are excited with LP_{01} mode incidence, as shown in Fig. 4(a); more intermediate-order modes are excited with LP_{11} mode incidence, as shown in Fig. 4(b). The proportion of the first N-order modes power in total input power is described in Fig. 4(c); this proportion is not affected by the distance d obviously. We see that the first 17-order modes have more than 90% of the input power when LP_{01} mode is launched, and about 70% of the input power is in the first 17-order modes when LP_{11} mode is launched. In conclusion, in a fiber with core diameter of 90 μm and numerical aperture of 0.06, the lower-order modes are excited when the LP_{01} mode with beam-width of 20 μm is launched; and the incident position does not affect obviously the power proportion of the first N-order modes power in the total input power.

2.2.3. Light propagation properties without gain

When the signal light ($\lambda_0 = 1064$ nm) propagates along z axis of the tapered fiber direction, the ratio of total power which remains in the fiber core at length z to the input total power is expressed by P_z/P_0. The incident field pattern as shown in Fig. 3, the beam-width of each mode is 20 μm and the center distance is 40 μm, and the incident modes are incoherent with each other, and the numerical aperture of core is $NA_{c0} = 0.06$, the index of inner cladding is $n_{cl} = 1.458$.

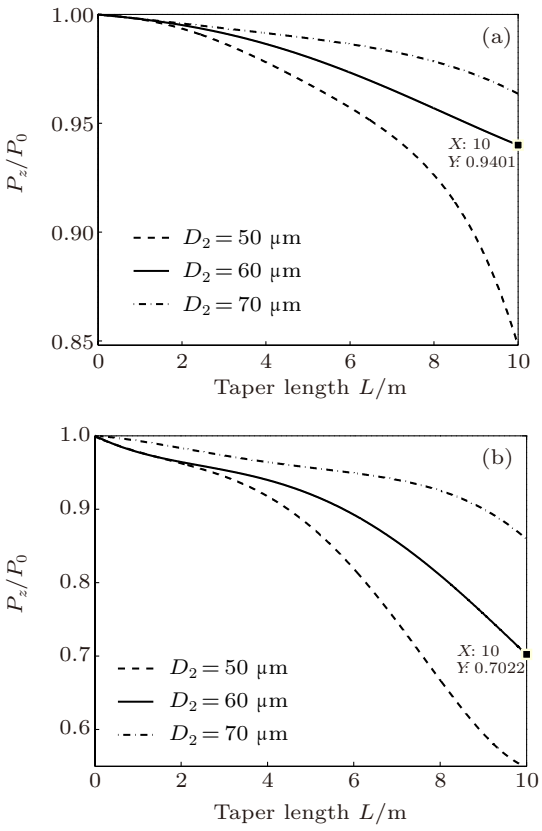


Fig. 5. The power ratio P_z/P_0 against length L of passive tapered fiber ($\Delta g = 0$ in Eq. (4)) for different diameter D_2 of narrow end: (a) LP_{01} mode input; (b) LP_{11} mode input.

The power ratio P_z/P_0 of signal light against the length L of passive tapered fiber ($\Delta g = 0$ in Eq. (4)) corresponding to three different diameters D_2 of narrow ends when the diameter of the wide end is $D_1 = 90$ μm was analyzed, as described in Figs. 5. The incident lights are LP_{01} modes and LP_{11} modes in Fig. 5(a) and Fig. 5(b), respectively. It is seen that the power ratio P_z/P_0 decreases monotonically with the growth of length L, and the power leaks more quickly when the diameter of the narrow end is smaller. It is well known that, in a step-index fiber, the propagating modes are characterized by the dimensionless V parameter - $V = 2\pi/\lambda) \times a \times NA$, here, a is the core radius of the fiber and NA is the numerical aperture of the fiber

core. Therefore, if NA is a fixed value, the fiber with larger diameter has more modes, namely, the cut-off of modes is proportional to the core diameter. For this reason, in a tapered fiber, while light is propagating along the tapered fiber, the cut-off of modes decreases with the decrease of core diameter of the narrow end, which causes the light power to leak into the inner cladding. The smaller the diameter of the narrow end, the quicker the decrease of the mode cut-off, which gives rise to the light power leaking more quickly, e.g., $P_z/P_0 = 0.9401$ for $D_2 = 60$ μm and P_z/P_0 = 0.8481 for D_2= 50 μm at length of $z = 10$ m for LP_{01} mode incidence in Fig. 5(a). We also note that the power leaks more for LP_{11} mode launching than that for LP_{01} mode launching in the same tapered fiber, e.g., $P_z/P_0 = 0.9401$ for LP_{01} mode launching and $P_z/P_0 = 0.7022$ for LP_{11} mode launching at length of $z = 10$ m when diameter of the narrow end is $D_2 = 60$ μm; this is because more high-order modes are excited when LP_{11} mode launches, as shown in Fig. 4(b). The high-order mode can be filtered by the taper; as a result, the beam quality of the output beam becomes better.

2.2.4. Light propagation properties with gain

2.2.4.1. Power gain coefficient

Due to the core diameter of tapered fiber varying along the longitudinal direction, it is difficult to calculate the gain coefficient in a tapered fiber. Hence, we study a common straight fiber with the core diameter of $D_{co} = (D_1 + D_2)/2$ to evaluate quantitatively the gain coefficient in the tapered fiber laser with core diameters of D_1 and D_2. From Eq. (2), we can obtain that the power quantity at length z_0 is

$$L_{dB} = 10\log_{10}\left(\frac{P_{out}}{P_{in}}\right) = 10\log_{10}\left[\frac{|\phi(x,y,z_0)|^2}{|\phi(x,y,0)|^2}\exp(2\Delta g z_0)\right]. \tag{5}$$

Therefore, the gain coefficient is

$$g = \frac{L_{dB}}{z_0}. \tag{6}$$

The ratio of output power to input power (P_{out}/P_{in}) at length of $z_0 = 10$ m in the fibers with $NA_{co} = 0.06$ and $D_{co} = 65$ μm, 70 μm, and 75 μm which correspond to the tapered fibers with $D_1 = 90$ μm and $D_2 = 40$ μm, 50 μm and 60 μm, was computed for LP_{01} mode with beam-width of 20 μm launching. So the power gain coefficient which depends on the amplitude gain coefficient Δg can be obtained by Eqs. (5) and (6). The power quality L_{dB} as a function of Δg is shown in Fig. 6; we can see that L_{dB} increases linearly with the growth of Δg, but it is not affected obviously by different core diameters D_{co} of the fibers.

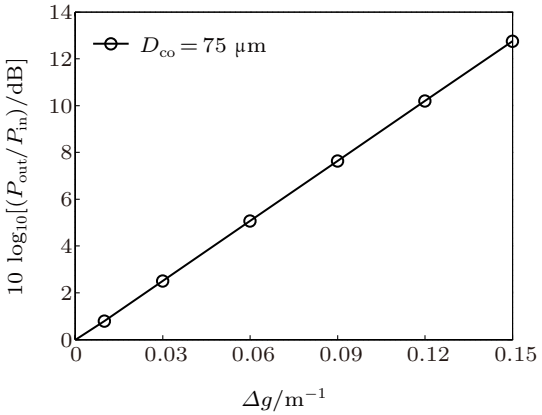


Fig. 6. Power quality L_{dB} as a function of amplitude gain coefficient Δg for core diameter $D_{co} = 75$ μm.

2.2.4.2. Power amplification

The PIPA of signal light in active tapered fiber ($\Delta g = 0.06$ m^{-1} in Eq. (4) corresponding to $g = 0.5$ dB/m in Fig. 6) was simulated. The power ratio P_z/P_0 depending on the length L for four diameters of narrow ends when LP_{01} mode and LP_{11} mode launching, are depicted in Figs. 7(a) and 7(b), respectively. It shows that the initial power is amplified, but the power amplification ratio P_z/P_0 increases to a maximum, and then decreases along the fiber if the diameter of the narrow end is small enough, e.g., $D_2 = 30$ μm in Fig. 7. We know

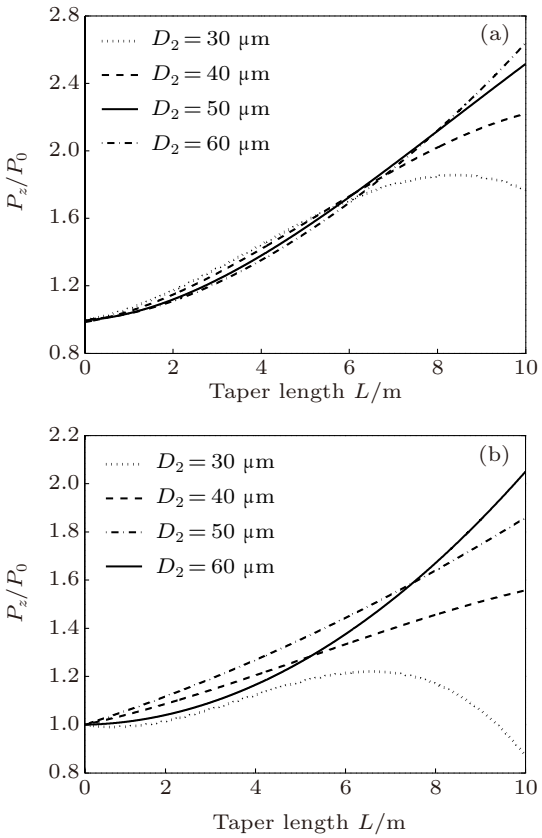


Fig. 7. The power amplification ratio P_z/P_0 against length L of active tapered fiber ($\Delta g = 0.06$ m^{-1} in Eq. (4)) for different diameter D_2 of narrow end: (a) LP_{01} mode incidence; (b) LP_{11} mode incidence.

that, the smaller the diameter of the narrow end, the smaller the mode cut-off, and the more power loss. Therefore, the power amplification is more than power loss before a propagation distance, and then the power loss dominates, when the diameter of the narrow end is small enough. However, when D_2 is big enough, P_z/P_0 increases monotonously with the growth of length L, e.g. $D_2 = 40$ μm, 50 μm, and 60 μm in Fig. 7. If D_2 is large enough, the power amplification is always more than power leakage along the whole fiber. Moreover, the power amplification for LP_{01} mode launching is more than that for LP_{11} mode launching, which agrees with the power leakage in Fig. 5.

2.2.4.3. Optical-optical efficiency

Due to the irregular spatial structure of the tapered fiber, the light propagation properties and power amplification in a tapered fiber are different from those in a common straight fiber. In order to estimate the optical-optical efficiency of the tapered fiber amplifier, the power amplification properties in a tapered fiber with the core diameter of wide and narrow ends being D_1 and D_2, respectively, are compared with the power amplification properties in a common straight fiber with the core diameter of $D_{co} = (D_1 + D_2)/2$. In this calculation, the core diameter of the wide end is $D_1 = 90$ μm, and the diameter of the narrow end D_2 varies from 20 μm to 80 μm, the obtained core diameter D_{co} is from 55 μm to 85 μm. The input beam is an LP_{01} mode with beam-width of 20 μm. The power amplification factors at length of $z = 10$ m are P_1 and P_2 for the tapered fiber and the common straight fiber, respectively, the difference between them is $\Delta P = P_1 - P_2$. Assuming that the optical-optical efficiency of the common straight fiber amplifier is T_{com}, then the optical-optical efficiency of the tapered fiber amplifier can be estimated by $T_{tap} = T_{com} - (\Delta P/P_2)$. The ratio T_{tap}/T_{com} as a function of the diameter D_2 is shown in Fig. 8. It is seen that the ratio T_{tap}/T_{com} increases with the growth in diameter D_2. For instance, we assume that $T_{com} = 80\%$, so T_{tap} will be 26.16%, 43.41%, 56.34%, 65.52%, 71.78%, 75.91%, 78.77% corresponding to different diameters of narrow ends D_2 of 20 μm, 30 μm, 40 μm, 50 μm, 60 μm, 70 μm, and 80 μm.

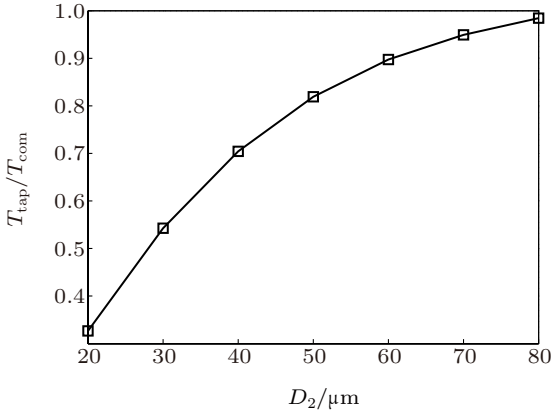


Fig. 8. The optical-optical efficiency ratio T_{tap}/T_{com} versus diameter of narrow end D_2 when the wide end diameter of the tapered fiber is $D_1 = 90$ μm.

2.3. Beam quality improvement of output laser

It is well known that beam quality is an important measure for how well a laser beam can be focused. It can be defined in different ways, and one of the ways is the beam quality factor, M^2 factor, defined as the beam parameter product which is the product of beam radius at the beam waist with the far-field beam divergence angle, divided by the corresponding product for a diffraction-limited Gaussian beam with the same wavelength,[18] i.e., $M^2 = \omega\theta/\omega_0\theta_0$, here, $\omega_0\theta_0 = 2\lambda/\pi$ for fundamental Gaussian beam, so M^2 factor can be written as $M^2 = \pi\omega\theta/2\lambda$.

The beam quality factor of the incident beam at incident facet with diameter of $D_1 = 90$ μm and the output beam at different narrow ends of tapered fiber core was calculated, respectively, on the computation of the far field profiles that we performed by Fraunhofer diffraction. The incident beam is three incoherent LP_{01} modes or LP_{11} modes, as shown in Fig. 3, the beam-width is 20 μm and the center difference of each beam is 40 μm, the M^2 factors of incident beam are 5.05 and 6.07 for LP_{01} mode and LP_{11} mode launching, respectively. As an example, the intensity pattern of the near field and far field of the output beam with LP_{01} and LP_{11} mode launching for the narrow diameter of $D_2 = 40$ μm is depicted in Fig. 9.

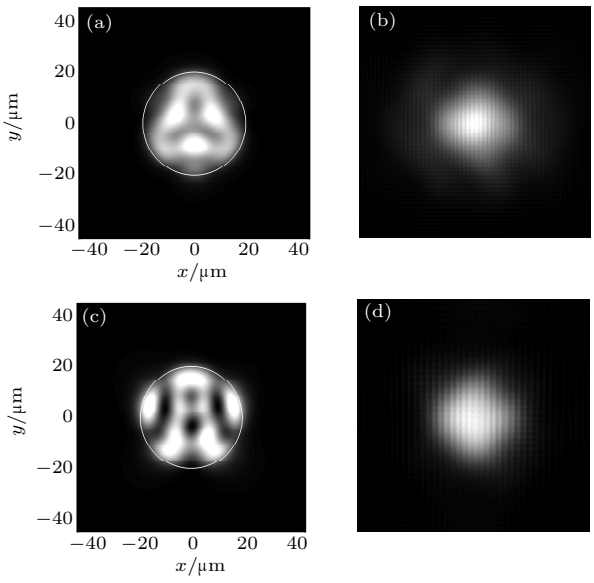


Fig. 9. (a) (c) Near field intensity pattern of output beam with $D_2 =$ 40 μm. (b) (d) Far field intensity pattern of output beam with $D_2 =$ 40 μm. Here, LP_{01} mode incidence ((a) and (b)); LP_{11} mode incidence ((c) and (d)).

The M^2 factor of the output beam depending on the diameter of the narrow end D_2 with three incoherent LP_{01} modes or LP_{11} modes injection whose M^2 factor is 5.05 or 6.07 by our computation, is shown in Figs. 10(a) and 10(b), respectively. Corresponding to each diameter of $D_2 = 20$ μm, 30 μm, 40 μm, 50 μm, and 60 μm, the M^2 factors of output beams are 1.36, 1.55, 2.13, 2.92, and 3.82 for LP_{01} launching or are 1.74, 2.15, 2.65, 3.49, and 4.71 for LP_{11} launching, respectively. It

is obvious that the M^2 factor of output beam increases with the growth of diameter D_2, but it is always smaller than the M^2 factor of the incident beam, which means that the beam quality is improved by the tapered fiber.

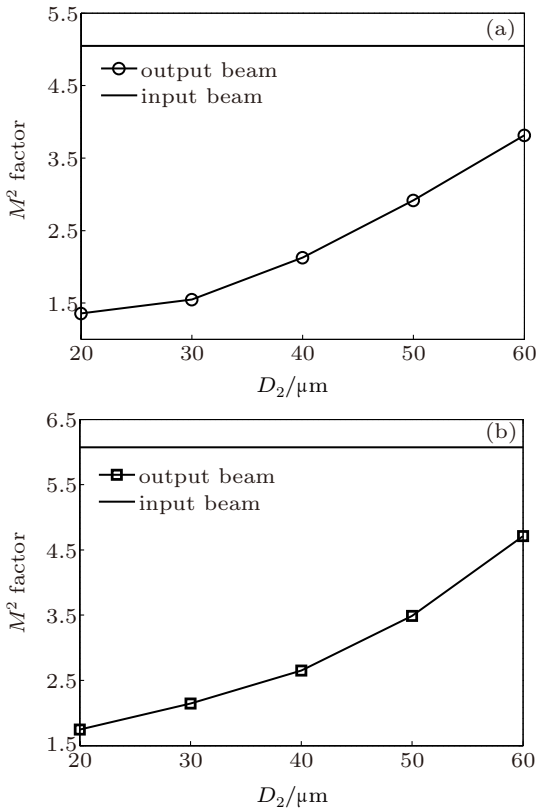


Fig. 10. The M^2 factor of input and output beams versus diameter of narrow end D_2: (a) LP_{01} mode input; (b) LP_{11} mode input.

2.4. Design of a PIPA fiber laser

The theoretical analysis above indicates that the power amplification and brightness enhancement can be demonstrated by optimal injection and taper design. According to the analysis of mode excitation and power properties in the tapered fiber, a design example is shown as follows. Three LP_{01} modes with 500 W input power of each beam, the intensity pattern as shown in Fig. 3(a), are launched into an active tapered fiber core with the diameters of D_1 = 90 μm and D_2 = 60 μm and numerical aperture of $NA_{co} = 0.06$. The beam-width of each mode is 20 μm and the central distance between two modes is 40 μm, which is a regular triangle arrangement, and its center overlaps with the center of the fiber core. The length of the main fiber is $L = 10$ m, amplitude gain efficient in the fiber core is $\Delta g = 0.06$ m^{-1}, the optical–optical efficiency is 71.78%. The total input power of signal light is 1.5 kW and the power of pump light is 3.4 kW. The signal and pump light launch through the wide end-face of the tapered fiber. The power of signal light is amplified to 3.9 kW, which is 2.6 times that of the total input power, at the narrow end-face. The M^2 factor of the input beam at the wide end-face is 5.05, due to the transverse mode selection of the tapered fiber, the M^2 factor of output beam at the narrow end-face becomes 3.82. The power of signal light is amplified by 2.6 times and the beam quality is enhanced in the active tapered fiber.

3. Conclusion

A tapered fiber amplifier with multi-seed sources parallel injection was investigated in theory. The theoretical analysis indicates that the low-order eigenmodes can be excited and over 90% of the input signal light power can remain in the fiber core if the appropriate fiber parameters are set. While the light is propagating along the tapered fiber, the modes with big propagation angle are filtered which leads to the high output beam quality. In addition, the incoherent combination of multi-seed sources gives rise to output power of several kW. As an example of PIPA, a tapered fiber amplifier with the diameters of wide and narrow ends of 90 μm and 60 μm, respectively, is designed; 94% of input power remains in the fiber core and the optical–optical efficiency is 71.78%. The signal power is amplified at least double when the amplitude gain efficient is 0.06 m^{-1}, and the beam quality factor (M^2 factor) is improved from 5.05 to 3.82 when three LP_{01} modes are parallelly injected. Briefly, a high-efficiency tapered fiber amplifier can be realized by optimizing the launching condition and the taper structure. This amplifier offers the potential application in high power monolithic fiber laser systems.

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