Beam quality and photodarkening comparison of tandem-pumped and directly diode-pumped ytterbium-doped fiber amplifiers

Hailong Yu (于海龙), Xiaolin Wang (王小林)*, Pu Zhou (周朴),
Hu Xiao (肖虎), and Jinbao Chen (陈金宝)

Institute of High Energy Laser, College of Optoelectronic Science and Engineering,
National University of Defense Technology, Changsha 410073, China
**Corresponding author: chinawxllin@163.com*

Received March 25, 2014; accepted May 3, 2014; posted online September 10, 2014

Compared with the conventional diode-pumped ytterbium-doped fiber amplifiers (YDFAs), tandem-pumped YDFAs are regarded as a better solution for high power scaling. In this letter, we compare and analyze the two types of pumping scheme with respect to beam quality (BQ). The numerical model adopted by us is based on steady-state rate equations with consideration of transverse mode competition. The results show that tandem pumping is not only suitable for high power scaling but also has an advantage over direct diode pumping in BQ. For instance, the power fraction of fundamental mode in tandem pumping at 1030 nm is about 4% higher than its corresponding value in direct diode pumping at 976 nm under the condition of counter-propagating pumping configuration with the same fiber parameters except cladding diameter. Mode selection by controlling dopant distributions and coiling the fibers is also simulated and discussed. Moreover, the simulation results show that the tandem-pumped YDFAs have lower photodarkening rate than the conventional YDFAs at part area of gain fiber, but there is no obvious difference between them from the mean perspective of entire gain fiber.

OCIS codes: 060.2320, 060.3510, 060.2290, 140.3615.
DOI: 10.3788/COL201412.S20604.

Owing to the astonishing progress of large-mode-area double-cladding fiber manufacturing process and laser diode (LD) pumping technique, the output power of ytterbium-doped fiber amplifiers (YDFAs) has increased a lot in the past few years[1–3]. However, the power scaling of YDFAs has been limited by some factors, such as high thermal load and the pump brightness of LDs[4]. Tandem pumping is proposed to partly overcome these critical limitations, which is regarded as a better pumping scheme than direct diode pumping for high power scaling of YDFAs, for its outstanding features such as low quantum defect and high pump brightness[4–6]. IPG Photonics has accomplished 10-kW single-mode continuous-wave laser output in tandem-pumped YDFAs[2]. Besides, tandem pumping is also shown to be helpful to control the excess unsaturated gain[7], to increase the mode instability threshold[8], and thus to improve the beam quality (BQ) of output laser. It also has less serious photodarkening (PD) than the traditional one[7,9].

In this letter, we compare the BQ of tandem-pumped and conventional diode-pumped YDFAs under relatively reasonable conditions by numerical simulations. The fundamental mode power fraction of output in tandem-pumped and conventional diode-pumped YDFAs is calculated and analyzed under various dopant profiles and different bending radii. Moreover, we also calculate and compare the PD spatial distribution between tandem-pumped and directly diode-pumped YDFAs. Different from the previous studies[7,9], we analyzed the PD rate from the standpoint of entire gain fiber.

When comparing and analyzing the BQ of tandem-pumped and directly diode-pumped YDFAs, we establish the theory model based on the steady-state rate equations[10] considering transverse mode competition and make numerical simulations following the multilayered method proposed by Gong *et al.*[11]. In ytterbium-doped gain fibers, the cross sections of tandem-pumping wavelengths between 1010 and 1030 nm are much smaller than that of 9XX nm, which makes it difficult to compare the optical properties between the tandem-pumped and diode-pumped YDFAs with the same fiber parameters. One way is to assume that the cladding absorption coefficient is identical at pump wavelengths of 976 and 1018 nm[12]. Another way is to set the length of the gain fibers to absorb the same pump light[9]. Both the ways have some drawbacks. Owing to the different cladding absorption coefficients at the pump wavelengths of 9XX and 1010–1030 nm range, the gain fibers need to be longer to absorb the same pump light in tandem-pumped YDFAs. However, the length of the gain fibers is an important parameter for high-order-mode amplification[13], so it is necessary to compare the BQ of tandem-pumped and directly diode-pumped YDFAs with the same fiber length. The lengths of the gain fibers are identical based on the assumption that the cladding absorption coefficients are same at 9XX and 1010–1030 nm range, but it goes against the basic physic fact.

In our simulation, we adjust the cladding/core area ratio to compensate the small absorption of pump light at 1010–1030 nm range, based on the theoretic analysis by Codemard *et al.*[7]. We choose all fiber parameters listed in Table 1 based on the commercial ytterbium-doped double-cladding fiber (which is commonly used in high-power fiber amplifiers). All the fiber parameters are the same in our numerical simulation, except the cladding diameter. The cladding diameter of the fiber

Table 1. Fiber Parameters used for Simulation

Fiber Parameter	Value	Fiber Parameter	Value
D_{core} (μm)	30	α_s (m^{-1})	6×10^{-4}
D_{clad} (μm)	Shown in Fig. 1	λ_p (nm)	915, 976, 1010, 1020, 1030
NA_{core}	0.06	σ_{ap} (m^2)	6.7×10^{-25}, 2.5×10^{-24}, 9.7×10^{-26}, 7.8×10^{-26}, 4.5×10^{-26}
L (m)	10	σ_{ep} (m^2)	2.3×10^{-26}, 2.5×10^{-24}, 5.1×10^{-25}, 6.7×10^{-25}, 6.4×10^{-25}
N_{amp} (m^{-3})	9×10^{25}	λ_s (nm)	1080
Γ (ms)	0.85	σ_{as} (m^2)	4.9×10^{-29}
α_p (m^{-1})	3×10^{-3}	σ_{es} (m^2)	2×10^{-25}

The meaning of all symbols is in accordance with that given by Gong *et al.*[11].

is adjusted to guarantee the same fiber length at all the pump wavelengths (as shown in Fig. 1), which is reasonable for amplifiers with counter-pumped scheme. Moreover, the real tandem-pumped fiber amplifiers usually use the gain fiber with a much larger cladding/core area ratio than the traditional ones, so the adjustment of the cladding diameter is reasonable.

On the basis of the analysis described in the earlier paragraph, a tandem-pumped and a directly diode-pumped fiber amplifier could be quantitatively compared in relatively fair and reasonable manner. We compare the BQ of fiber amplifier at different pump wavelengths (915, 976, 1010, 1020, and 1030 nm). The BQ is represented by the power fraction of LP01 mode. In our simulation, the amplifier is counter-pumped with a pump power of 2000 W. The initial signal powers of LP01, LP11, LP21, LP02, and LP31 modes are 200, 20, 15, 10, and 5 W, respectively. The initial power fraction of LP01 mode is 80%. The fiber length (10 m) has been optimized until the signal is amplified close to the maximum power value at different pump wavelengths. The simulation results are shown in Fig. 2. When the fiber amplifier is directly diode-pumped with pump wavelengths of 9XX nm, the power fraction of LP01 mode changes a little, whereas when the pump wavelength is in the range of 1010–1030 nm, the power fraction of LP01 mode increases quickly, as shown in Fig. 2(a). Thus, the power fraction of LP01 mode in tandem pumping at 1030 nm is about 4% higher than its corresponding value in direct diode pumping at 976 nm. It is clearly shown that the high-order mode is amplified more quickly when diode-pumped at 9XX nm than tandem-pumped, as shown in Fig. 2(b). This is due to the higher inversion rate and then the higher unsaturated gain at the edge of the fiber core in diode-pumping scheme (as shown in Fig. 3), which means high levels of amplified spontaneous emission, high loss of signal power and degradation of BQ[7]. This clearly shows that tandem pumping is not only suitable for high power scaling but also has an advantage over direct LD pumping in BQ.

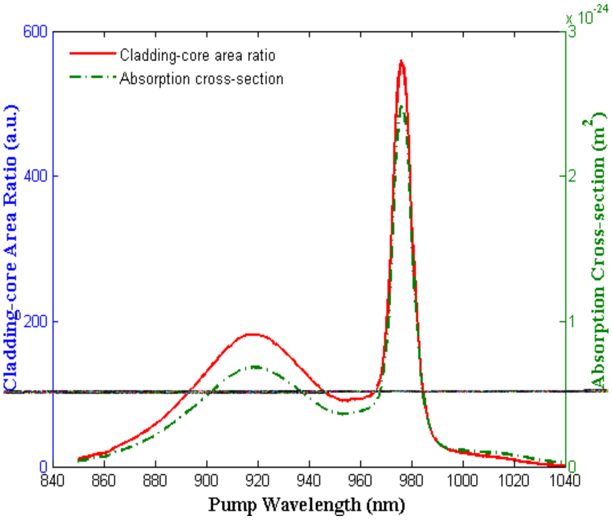

Fig. 1. Absorption cross-section spectrum and the calculated cladding/core area ratio.

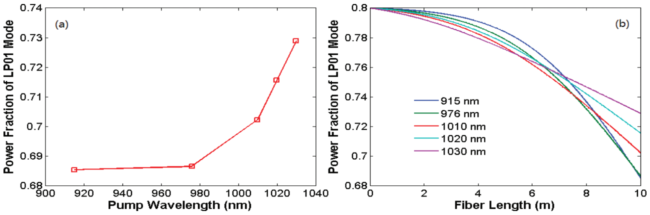

Fig. 2. (a) The relationship of pump wavelengths and power fraction of LP01 mode. (b) The evolution of power fraction of LP01 mode along the longitudinal direction of the fiber.

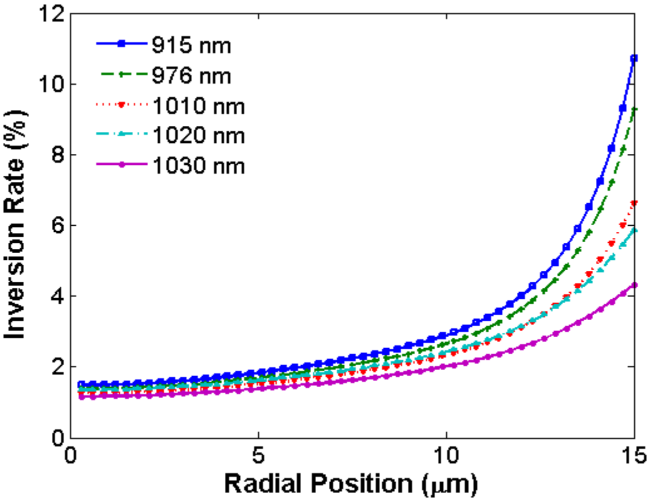

Fig. 3. Transverse inversion distributions at the end of the gain fiber under different pump conditions.

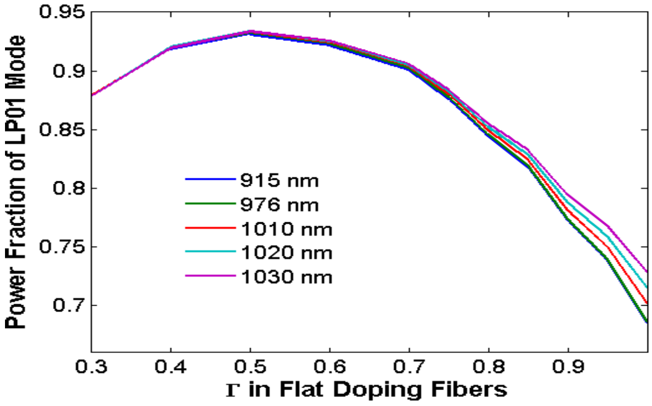

Fig. 4. Power fractions of LP01 mode versus flat doping confinement factors with different pump wavelengths.

We also investigate the power propagation of LP01 mode under flat doping with different confinement factors (Γ) defined as the same as by Gong *et al.*[11]. The results of simulation at different pump wavelengths are shown in Fig. 4. On decreasing the value of Γ from 1 to 0.5, the power fraction of LP01 mode increases from about 0.7 to 0.93. When the value of Γ is below 0.5, the gain of fundamental mode is limited and the power fraction decreases gradually. Moreover, the power fraction of LP01 mode in diode-pumped scheme increases more quickly than that in tandem-pumped scheme. When the value of Γ is below 0.6, no obvious difference is observed in the power fractions of LP01 mode under diode-pumping and tandem-pumping conditions. It is because the finite doping area effectively suppresses the high unsaturated gain at the edge of the fiber core in diode-pumped scheme, which makes the BQs identical between diode pumping and tandem pumping.

Coiling the fiber is also an effective way to suppress the high-order modes because of the discriminate loss factors among different modes. We also simulate the effect of bending radius on suppressing the high-order modes. The fiber amplifier is still a counter-pumping scheme with flat doping (Γ = 1). The bending loss is calculated based on the theoretical analysis given by Marcuse[14]. The results are shown in Fig. 5. It can be seen that on decreasing the bending radius, the power fraction of LP01 mode increases a lot. When the bending radius is 7 cm, LP21, LP02, and LP31 modes are completely suppressed, and LP11 mode is partly suppressed, the power fraction of LP01 mode increases from 70% to 84% at the pump wavelength of 976 nm and from 74% to 87% at the pump wavelength of 1030 nm. It can also be seen that the increase of power fraction of LP01 mode at all pump wavelength is approximately similar. It is because the bending loss factors for high-order modes are the same no matter what the pump wavelength is. So, even when the bending radius is 7 cm, the BQ of tandem-pumped YDFAs is still better than that of directly diode-pumped YDFAs.

PD has strong effect on the efficiency, reliability, stability[15], and even BQ of high-power fiber amplifiers by reducing the thresholds of mode instability[16,17]. The mechanism of PD is still debated. Many theories have been proposed to explain it, mainly including the formation of divalent ytterbium ion and Aluminum-Oxygen Hole Centers[18–20] or the intrinsic defects[21,22] in pristine fibers. Some studies[23,24] have experimentally found that the PD rate depends on the ytterbium excitation level with an exponent of 7[23] or 4.3[24].

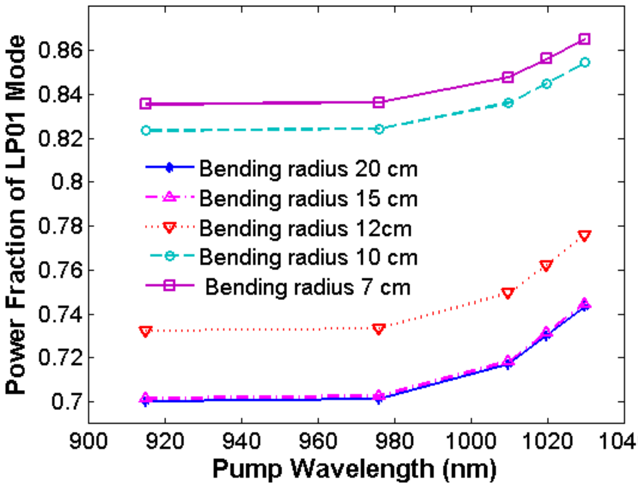

Fig. 5. Power fractions of LP01 mode versus the pump wavelengths with different bending radii.

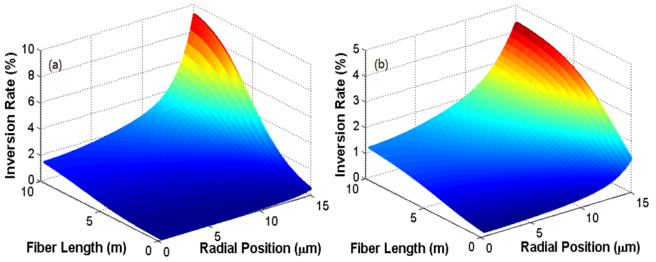

Fig. 6. Spatial distributions of PD at the pump wavelength of (a) 976 and (b) 1030 nm.

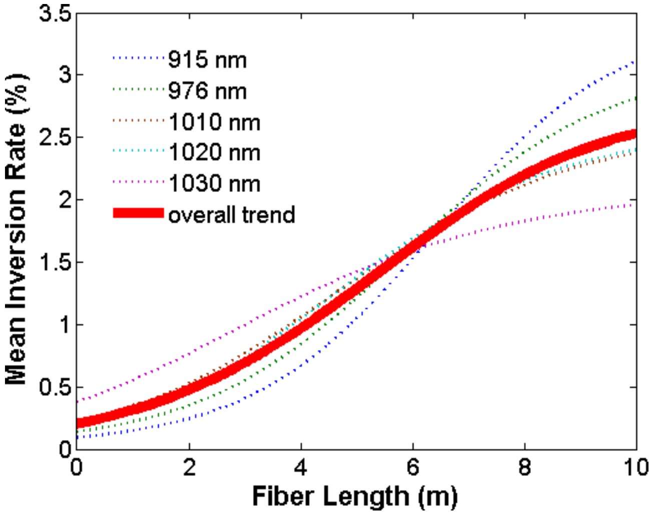

Fig. 7. Mean value of transverse inversion rates along the longitudinal direction of the gain fibers.

Codemard *et al.*[7] had roughly estimated that fiber tandem-pumped by 1045 nm has up to one million times smaller PD rate than that diode-pumped by 910 nm due to its low ytterbium excitation level. Hao *et al.*[9] compared the PD rate based on the fact that the selected gain fibers are different for tandem-pumping and diode-pumping structures. Both Codemard *et al.*[7] and Hao *et al.*[9] calculated the PD rate by the maximum inversion level. In fact, PD has spatial distribution[25,26] in the gain fiber.

On the basis of the model established earlier, we calculate and compare the PD spatial distribution between tandem-pumped and diode-pumped YDFAs. The computation parameters are the same as listed in Table 1 and the gain fibers are counter-pumped scheme with flat doping ($\Gamma = 1$) and no bending loss. We change the inner-cladding diameters to keep the same fiber length under different pump conditions. Fiber length is an important parameter that can largely affect the inversion rate[27], and it is a fact that the inner-cladding diameter of the gain fiber in real tandem-pumped YDFAs is usually smaller than that in conventional one owing to the high pump brightness. Except that, all the fiber parameters are similar in each case. The longitudinal and transversal distribution of PD is shown by two examples, as shown in Fig. 6. It is obvious that the maximum inversion rate at the end of the gain fiber pumped at 976 nm is higher than that in tandem pumping at 1030 nm, but it is too early to say that tandem pumping is better than diode pumping with respect to PD. We calculate the mean value of transversal inversion rate along the longitudinal direction and plot the results as shown in Fig. 7. The results show that the mean inversion rates under different pump conditions are close with each other. So, the tandem-pumped amplifier has lower PD rate than the conventional one at part area of gain fiber, but there is no obvious difference between them from the mean perspective of entire gain fiber. However, we must admit that numerical simulation has its limitations and the PD of gain fiber is affected by many factors[9]; the real properties of PD in tandem-pumped and diode-pumped fiber amplifiers need further experimental research.

In conclusion, the BQ of tandem-pumped and directly diode-pumped YDFAs is compared by numerical simulations. The simulation results and analysis show that tandem pumping has an obvious advantage over direct diode pumping in BQ. For instance, the power fraction of fundamental mode in tandem pumping at 1030 nm is about 4% higher than that in direct diode pumping at 976 nm under the condition of counter-propagating pumping configuration with the same fiber parameters, except cladding diameter. These features make it attractive for further power scaling of YDFAs with a high BQ. Controlling the dopant distributions can effectively suppress the gain for high-order modes and narrow the difference of BQ between tandem pumping and diode pumping. Coiling the fibers can also improve the BQ, but the improved extent is similar between the tandem-pumped and directly diode-pumped YDFAs. Moreover, we have shown the spatial distribution of PD. The simulation results show that the tandem-pumped YDFAs have lower PD rate than the conventional one at part area of gain fiber, but there is no obvious difference between them from the mean perspective of entire gain fiber.

This work was financially supported by the Projects of Scientific Research Foundation of National University of Defense Technology under Grant No. JC12-07-03.

References

1. Y. Jeong, A. J. Boyland, J. K. Sahu, S. Chung, J. Nilsson, and D. N. Payne, J. Opt. Soc. Kor. **13**, 416 (2009).
2. E. Stiles, in *Proceedings of the Fifth International Workshop on Fiber Lasers* **4** (2009).
3. C. Jauregui, J. Limpert, and A. Tünnermann, Nat. Photonics **7**, 861 (2013).
4. D. J. Richardson, J. Nilsson, and W. A. Clarkson, J. Opt. Soc. Am. B **27**, B63 (2010).
5. J. W. Dawson, M. J. Messerly, R. J. Beach, M. Y. Shverdin, E. A. Stappaerts, A. K. Sridharan, P. H. Pax, J. E. Heebner, C. W. Siders, and C. Barty, Opt. Express **16**, 13240 (2008).
6. J. Zhu, P. Zhou, Y. Ma, X. Xu, and Z. Liu, Opt. Express **19**, 18645 (2011).
7. C. A. Codemard, J. K. Sahu, and J. Nilsson, IEEE J Quantum Electron. **46**, 1860 (2010).
8. S. Naderi, I. Dajani, J. Grosek, T. Madden, and T. Dinh, Proc. SPIE **8964**, 89641W (2014).
9. J. Hao, P. Yan, Q. Xiao, D. Li, and M. Gong, Chin. Phys. B **23**, 14203 (2014).
10. I. Kelson and A. A. Hardy, IEEE J. Quantum Electron. **34**, 1570 (1998).
11. M. Gong, Y. Yuan, C. Li, P. Yan, H. Zhang, and S. Liao, Opt. Express **15**, 3236 (2007).
12. H. Xiao, "Study on tandem pumping technology of ytterbium-doped fiber lasers," Ph.D. Thesis (National University of Defense Technology, 2012).
13. S. Chen, "Theoretical and experimental study on the key techniques of main amplifier in high power master-oscillator power-amplifier fiber laser source," Ph.D. Thesis (National University of Defense Technology, 2009).
14. D. Marcuse, J. Opt. Soc. Am. **66**, 216 (1976).
15. L. O. Norin and M. Engholm, in *Workshop on Specialty Optical Fibers and their Applications* (2013).
16. A. V. Smith and J. J. Smith, Proc. SPIE **2013**, 860101 (2013).
17. A. V. Smith and J. J. Smith, Opt. Express **21**, 2606 (2013).
18. S. Jetschke, A. Schwuchow, S. Unger, M. Leich, M. Jäger, and J. Kirchhof, Opt. Mater. Express **3**, 452 (2013).
19. S. Rydberg and M. Engholm, Opt. Express **21**, 6681 (2013).
20. T. Deschamps, H. Vezin, C. Gonnet, and N. Ollier, Opt. Express **21**, 8382 (2013).
21. C. G. Carlson, K. E. Keister, P. D. Dragic, A. Croteau, and J. G. Eden, J. Opt. Soc. Am. B **27**, 2087 (2010).
22. S. Yoo, C. Basu, A. J. Boyland, C. Sones, J. Nilsson, J. K. Sahu, and D. Payne, Opt. Lett. **32**, 1626 (2007).
23. J. Koponen, M. Soderlund, H. J. Hoffman, D. A. Kliner, J. P. Koplow, and M. Hotoleanu, Appl. Opt. **47**, 1247 (2008).
24. S. Jetschke and U. Röpke, Opt. Lett. **34**, 109 (2009).
25. J. Hao, P. Yan, and M. Gong, Opt. Commun. **287**, 167 (2013).
26. J. Koponen, M. Laurila, and M. Hotoleanu, Electron. Lett. **44**, 960 (2008).
27. J. Koponen, M. Laurila, and M. Hotoleanu, Appl. Opt. **47**, 4522 (2008).