Scaling of Yb-doped photonic crystal fiber to 200 μm core diameter for high beam quality laser output*

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The rare earth-doped active fibers not only have ten thousands of square-micron core-area but also deliver a laser with near-diffraction-limited beam quality. However, they have been studied little. In this paper, we design a 200-μm-core-diameter Yb^{3+}-doped photonic crystal fiber with a large pitch in the air-hole cladding region. Simulations demonstrate that only fundamental mode (FM) with a mode field area (MFA) of ∼ 28000 μm^2 can be amplified and propagated at the gain saturation, and the beam quality M^2 is about 1.5. It is predicted that almost 105 mJ single-pulse energy is available from such a 1.5-meter-length fiber.

Keywords: photonic crystal fiber (PCF), fundamental mode (FM), very large mode area (VLMA), fiber amplifier

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1. Introduction

In the past decade, high power fiber lasers and amplifiers[1–6] have been rapidly developed and widely used in industry, national defense, medical treatment, etc. However, the peak power and pulse energy of pulsed fiber laser suffer the bottleneck caused by several factors such as core diameter, the numerical aperture of fiber core, and different kinds of nonlinear effects. Expanding the fiber core is the most direct method, which not only raises the nonlinear threshold but also enlarges storage-energy space in the ion-doped fiber. However, output beam quality will be worsen by enlarging the fiber core where more high-order modes (HOMs) appear. For example, conventional step-index fiber faces multi-modes output when its core-diameter is longer than 15 μm.[7] HOMs' discrimination by bending fiber,[8] distributing index, and doping-ion concentration[9] in the fiber core can expand the mode-field diameter (MFD) to 50 μm. However, single FM operation in step-index fibers with the MFDs greater than 50 μm based on the above approaches can hardly be realized. In addition, the gain-guided index-anti-guided fiber has made great progress in scaling core diameters for single FM output, but it is still facing the problems of lower pump efficiency and lower optical–optical conversion efficiency than others.[10]

The PCF has a great flexibility in the modulation of cladding index compared with other fibers. For example, the index-guiding PCF[11] with very low numerical aperture in the fiber core can effectively increase the MFA of the FM. Recently, a novel approach for single FM output has been realized in a very large-mode-area (VLMA) rod-type PCF which has the large-pitch air-hole array around the core.[12] The remarkable character of the PCF is that HOMs can be effectively attenuated by being delocalized into the cladding, and only FM is kept in the core area of the fiber because of its lower propagation loss. Stutzki *et al.*[13] reported that this kind of fiber with a 135 μm core diameter had been used in a *Q*-switched fiber-laser system for realizing 26 mJ per pulse output. To date, it should be the largest core-diameter PCF ever-reported for only FM output in experiment.

In the paper, we design a 200-μm-core-diameter PCF with a similar structure to that discussed above. In the outer cladding layer of the fiber, the dense-air-hole cladding layer described in Ref. [13] is replaced by the lower-index macromolecule material in order to confine the pump laser inside. This mainly considers the problem that dense air holes easily suffer collapsing in the fiber drawing procedure. The mature technology of fabricating the highly dense air-hole clad layer is available from only a few companies in the world. Therefore, the simplified outer cladding structure is convenient to obtain for most companies. In addition, the designed fiber is more reasonable to be applied to a high-energy pulsed amplifier working at low-repetition frequencies (< 5 kHz) because pump laser can be injected into the PCF through pulses modulated with low average power, therefore avoiding damaging the fiber induced by heat accumulation at the interface between the outer and inner cladding layers. The whole technological process includes two main parts: drawing and coating. The glass fiber is drawn by the middle decladding Yb-doped fiber perform rod and surrounding periodically-stacked capillary tubes

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and rods fabricated by a fiber pulling machine. Then, the fiber is coated with lower-index macromolecule material, and it is guaranteed that laser leakage will not happen easily.

2. Fiber structure

According to the structure of the large-pitch photonic-crystal fiber (LPF), we design a VLMA fiber with 200 μm core diameter. The fiber core is solid glass surrounded by two rings of air holes in a hexagonal lattice, which demonstrates the highest mode discrimination:[14] pitch $\Lambda = 110$ μm and air hole diameter $d = 20$ μm for air-hole array in the inner cladding layer; the inner air-clad diameter $D = 630$ μm, the outer clad index 1.36, and the inner glass index 1.4571 corresponding to the numerical aperture NA (~ 0.5) of the inner cladding, ignoring the influence of the air-hole index modulating effect. The schematic structure of this LPF is displayed in Fig. 1. The whole fiber length is set to be 1.5 m, mainly because the slight bend induced by excessive length of fiber will worsen laser gain, which is ascribed to the high bending sensitivity of the mode area and the beam quality. The signal wavelength is set to be 1040 nm. All the simulations in the paper are based on the finite element method combined with the multi-pole method and the assumption that the inner cladding is infinite for calculating mode discrimination, i.e., differential propagation loss of mode.[14] Because all modes are lossless if the leaky area is surrounded by low index cladding for pump light guidance, the evaluation of mode discrimination is only strictly valid for core-pumped active fibers. In this case, the evaluations of the effective mode area and the beam quality are valid for the LPF.

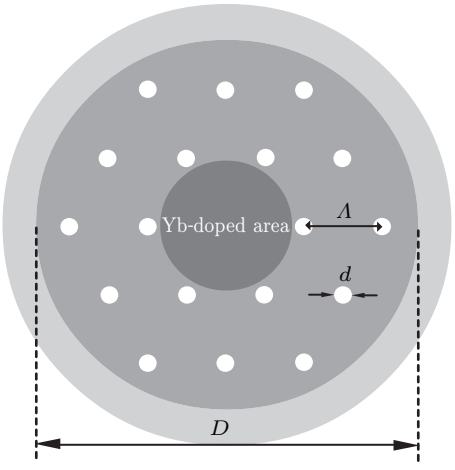


Fig. 1. Schematic structure of Yb^{3+}-doped double-clad LPF.

For the above designed structure, the MFD of FM is about 190 μm (MFA ~ 28000 μm^2) indicated by the simulation results. The fiber core area with 180 μm diameter smaller than the MFD of FM is designed as the Yb^{3+}-doped region is beneficial to single FM amplified. Given that the doping concentration of the active core of fiber Δn is 3×10^{25} ions/m^3, the largest extractable energy per pulse from this fiber can rise to 70 mJ/m according to the formula of storage energy $E_p = h\nu\Delta nV$.[15] The small signal gain factor is about 9.3 m^{-1} (~ 40 dB/m) based on the formula $g_0 = \Delta n\sigma(s,e)\Gamma$.[10] The $\sigma(s,e)$ represents the signal emitting section, and Γ means the overlap between mode field and the doped area. The fiber core index will be uplifted when doping Yb^{3+} ions into it. Simulation results show that HOMs will arise in the LPF just like that in the common index-step fiber with large core while the raised index fiber core is more than 1×10^{-5} compared with the cladding index. Thus, in order to avoid the negative effect, the preliminary glass-rod as fiber core with index depression compared with the surrounding cladding material can be designed to neutralize the rising of the index by doping Yb^{3+} ions, which should be a technological challenge to the manufacturers.[14] In our simulations and calculations, it is supposed that the core index is equal to that of the cladding material, and the feasibility for realizing the high-energy per pulse and single FM amplified from our designed PCF will be discussed in detail in the following section.

3. Numerical algorithm of fiber amplifier

Numerical modeling of transverse mode competition in fiber laser and amplifier has been discussed in detail in the common active multimode fiber based on the rate equations.[16,17] For the pulse amplification in a short rod-type PCF, equation (2) in Ref. [16] can be simplified into the following form:

$$(g-\alpha)\,\mathrm{d}z = \mathrm{d}E/E, \tag{1}$$

on the assumption that the number of population inversion is constant along the axis z and the coupling interaction between modes is negligible.

In the above equation, the gain coefficient g can be expressed as

$$g = g_0(1+E/E_0)^{-1}, \tag{2}$$

where g_0 is the unsaturated gain coefficient, and E_0 is a saturation parameter, equal to the signal power density at which the gain falls to $g_0/2$. Combining Eq. (1) and Eq. (2) can be expressed as

$$g_0\,\mathrm{d}z = (1+\beta)\,\mathrm{d}\beta/\beta[1-\alpha/g_0(1+\beta)], \tag{3}$$

while E/E_0 is replaced by β. When integrating it over a path L in the fiber, we have

$$\begin{aligned}&(g_0-\alpha)L\\ &= \ln(\beta_2/\beta_1) - g_0/\alpha\ln\{[g_0-\alpha(1+\beta_2)]/[g_0-\alpha(1+\beta_1)]\},\end{aligned} \tag{4}$$

where β_1 and β_2 represent the normalized input and output power density, respectively.

4. Results and discussion

For small signal input, whether latent modes are amplified can be evaluated by contrasting the approximately invariable values of g_0 and α. Therefore, single FM amplified is guaranteed by demanding the losses of all HOMs to be more than 40 dB/m, which is identical with the fact that the gain factor should exceed 9.3 m^{-1}. In experiment, we usually operate the main amplifiers by injecting a high intensity signal into such a very large-mode-area active fiber in order to extract as much as the storage energy. For a high signal input, the signal gain will become smaller with input signal intensity rising according to the formula $g = g_0(1+E_{in}/E_s)^{-1}$, where E_{in} and E_s are respectively the input signal intensity and the signal saturation intensity at which the gain g falls to $g_0/2$. At the gain saturation point $E_{in} = E_s$, we compute the output signal intensity $\beta(= E_{out}/E_s)$ for different lengths of the LPF at the gain coefficient $g_0 = 9.3$ m^{-1} according to Ref. [18]. It is found that the input signal cannot be amplified while mode propagation loss $\alpha \geq g_0/2$ (4.65 m^{-1}), as demonstrated in Fig. 2. Consequently, single FM amplified in the LPF can be ensured while the lowest loss of all HOMs is 20 dB/m when working at the gain saturation. The above discussion is built on the assumption that $\Gamma = 1$ for all modes in the LPF. In fact, the values Γ of the HOMs are almost less than that of the FM in the LPF, which will be more beneficial for amplifying FM and restraining HOMs.

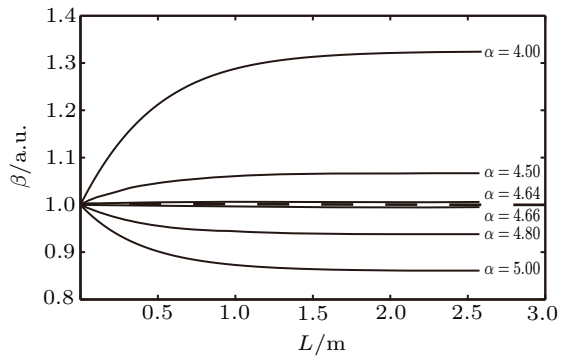


Fig. 2. Normalized output power densities versus fiber length when the values of loss factor α (m^{-1}) fluctuate near $g_0/2$ at the gain saturation point ($E_{in} = E_s$), where the dash line denotes the balanced level of $E_{out} = E_{in}$.

In the LPF, the propagation loss of mode is sensitive to the size of air hole diameter in the inner cladding, which can be demonstrated from Fig. 3. Reducing the air hole area in the inner cladding can increase the propagation loss of HOM. In the simulations, it is found that the propagation losses of the modes of TM03 and HE21 increase to more than 20 dB/m while the air hole diameter decreases below 20 μm, and only the mode EH13 keeps almost unchanged with the propagation loss of about 21 dB/m as shown in Fig. 3(b). It is shown that the propagation losses of all of the three HOMs will go beyond 20 dB/m while the air hole diameter decreases by less than 20 μm. Simulations also demonstrate that the propagation losses of other HOMs far exceed those of the three HOMs shown in Fig. 3(b). Here, we can ignore their effects on laser amplification. On the basis of the proof that the HOMs with the losses beyond 20 dB/m will be annihilated in the above adjacent paragraph, only FM can be amplified when the air hole diameter is designed to be below 20 μm. However, the decrease of air hole diameter will simultaneously give rise to the propagation loss of the FM (equal to HE11) as shown in Fig. 3(a). Figure 4 shows the variations of output power intensity with fiber length for different losses of HE11. It is found that the net gain of signal is attenuated rapidly while the propagation loss of HE11 exceeds 1 dB/m both at small signal input and at gain saturation. Weighing the two aspects, i.e., the propagation losses of HOMs and the net gain of FM, the diameter of 20 μm is the most reasonable for the inner-cladding air holes. The simulation of our designed structure shows that HE11 has a propagation loss of 0.9 dB/m which is logical for high gain output, and all HOMs keep at high losses more than 20 dB/m seen from Fig. 5. The HOM with the lowest propagation loss is only TM03 with 20 dB/m. An additional three HOMs (HE21, EH13, TM02) respectively have the propagation losses of 20.7 dB/m, 20.9 dB/m, and 30.5 dB/m adjacent to TM03 as shown in Figs. 5(c)–5(e). Other HOMs not shown in the paper have the propagation losses of more than 30 dB/m.

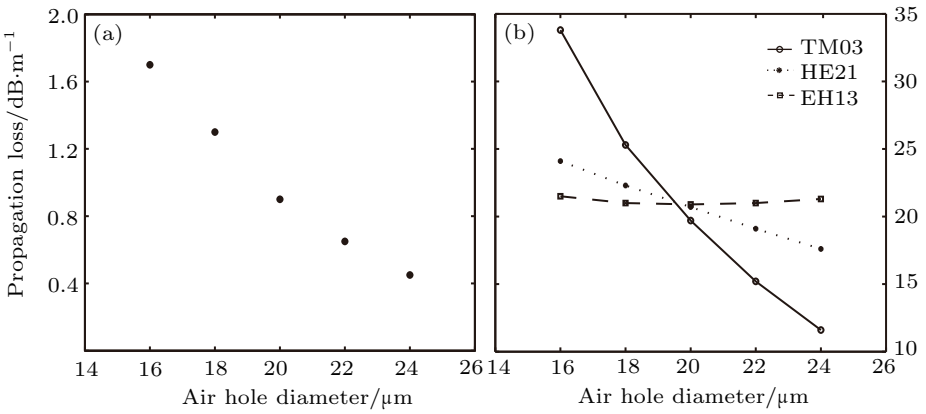


Fig. 3. Propagation losses versus air hole diameter of (a) FM and (b) three HOMs with the lowest losses.

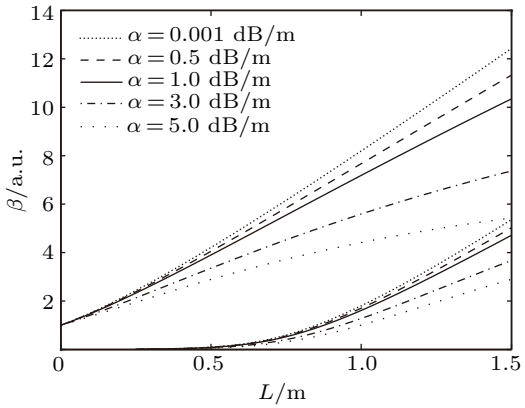


Fig. 4. Normalized output power densities versus fiber length for five different loss values of HE11 at the gain saturation point ($E_{in} = E_s$) and small signal point ($E_{in} = 0.001E_s$) (bottom right).

In addition, simulations show that FM (HE11) has a higher overlap ratio between its mode area and the Yb^{3+}-doped core area than HOMs (Fig. 5). Therefore, FM should have a greater superiority in mode competition[20] than HOMs. Calculations based on the transversally-resolved rate equations demonstrate that all HOMs are annihilated, and only FM is amplified from the LPF at the gain saturation point. Computed by the second moment method, the beam quality M^2 of FM at the horizontal and vertical axes are both ~ 1.5, which is near-diffraction-limited.

The concentration of Yb^{3+} ions doped in the core of the LPF is also related tightly to pulse energy and beam quality of the output laser. Higher concentration gives rise to more storage energy in the LPF, and higher gain of signal which results in greater pulse energy of output laser. On the other hand, it simultaneously leads to higher gains than the propagation losses for some HOMs, which may induce HOMs to acquire the advantage in mode competition. Ultimately, the output beam quality will be worse because of HOMs acting as the participants. Therefore, it should be circumspect to set the doping concentration of the fiber core in order to ensure both high storage energy for high-energy pulse output and HOMs gains less than their losses for only FM being amplified. In consideration of both aspects, it is reasonable that the doping concentration Δn is set to be 3×10^{25} ions/m^3.

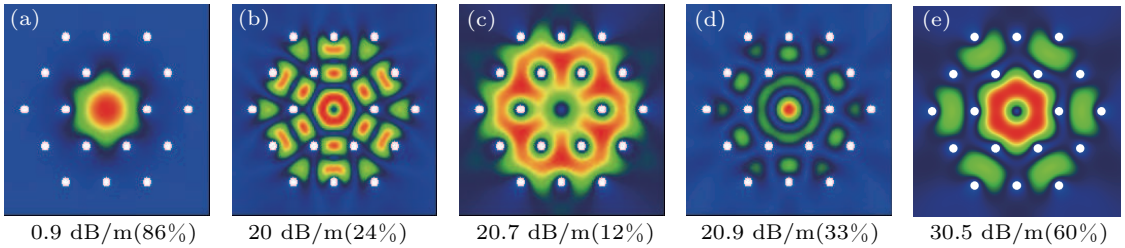


Fig. 5. Modal intensity profiles of the LPF: (a) HE11, (b) TM03, (c) HE21, (d) EH13, and (e) TM02, with the values of corresponding propagation loss and overlap factor Γ (in brackets) at the bottom.

Because realizing single FM amplified in the LPF is required to work at the gain saturation, the value E_{in} of the energy per pulse injected into the LPF should be evaluated as the reference data in experiment. For the doping concentration designed, the output power intensity is 10.5 times the input signal at the gain saturation point $E_{in} = E_s$, and the value of E_s is about 11 mJ, based on Ref. [19]. It means that almost 105 mJ energy per pulse available can be extracted from the 1.5-m-length LPF by injecting the signal with an 11 mJ energy per pulse. For the input signal with such large single pulse energy, it is more suitable for the LPF to be used in the main amplifiers or regenerative amplifiers, such as the role played in Ref. [13].

The threshold powers of most nonlinear effects are directly related to the MFA, such as stimulated Raman scattering (SRS), stimulated Brillouin scattering (SBS), self-phase modulation (SPM), and self-focusing. Enlarging the core diameter of the fiber and expanding the MFA can effectively improve the threshold power of the nonlinear effect. It was reported that both the output spectrum and pulse shape from the LPF with 135 μm core diameter were little influenced by the nonlinear effects, and only weak shrinkage of the MFD was induced by the self-focusing.[13] Indeed, a peak power of 3.8 GW is achieved in a fiber chirped-pulse amplification system by combining active phase shaping equipment with such a 105-μm-core-diameter LPF which can efficiently reduce the nonlinear phase.[21] It can be predicted that the threshold power of SRS is about 3.1 GW according to Refs. [25] and [26] for the active LPF with 200 μm core diameter, which is about hundreds of times that of SBS in the normal course of events.

The crossing,[22] as an unfavorable phenomenon easily appearing in the PCFs, which leads to additional losses and beam deformations of modes, should be avoided. Usually, it easily arises between two modes when their effective refractive indices are very close to each other. For the LPF, the scaling of the inner cladding diameter D can effectively modulate the refractive indices of HOMs, which can enhance the avoided crossings or not. Simulations show that the profile of FM suffers great deformation by HE21 (different from the above referred mode) at $D = 700$ μm (Fig. 6), which can be attributed to the effective refractive index of HE21 excessively close to that of FM. When the diameter D falls to 630 μm, the simulated result demonstrates that there is no deformation toward the field profile of FM. Hence, setting the reasonable inner cladding diameter can effectively avoid the avoided cross-

ings between FM and HOMs for high beam quality output.

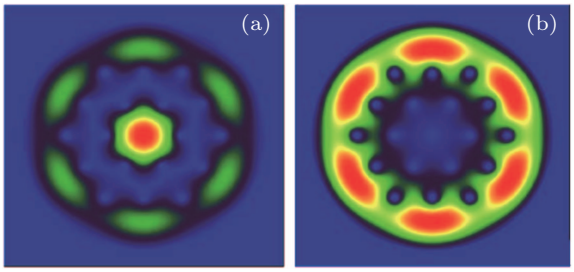


Fig. 6. Transverse mode profiles of FM deformed (a) by an HE21 mode, and (b) by the avoided crossing at $D = 700$ μm.

Coiling, as an intrinsic property of fiber, makes fiber laser more compact than solid laser. However, it is fatal for the LPF to bend because the sparse-air-holes array of the inner clad layer makes it difficult to locate FM in the core region. Simulations demonstrate that the propagation loss of FM increases up to 5 dB/m and the overlap factor decreases down to 65% when the bending radius of the LPF is 20 m. The field profile is shown in Fig. 7(a). While the bending radius drops to 10 m, the field shape of FM will deform almost beyond recognition and deviate from the fiber core just shown in Fig. 7(b). Great bending loss and large deformation of the transverse field of the mode compel the VLMA LPF to be operated as the straight rod in the experiment. Recently, many studies[23,24] have shown that setting dense or large-size air holes at the outside of the bending LPF can not only restrain the propagation loss of the FM but also retain great delocalization from the fiber core for the HOMs. It is believed that the shortcoming about bending loss of the LPF will be solved gradually.

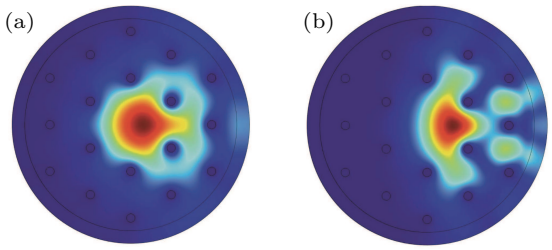


Fig. 7. Transverse mode profiles of FM at different bending radii: (a) 20 m, (b) 10 m.

5. Conclusions

In this work, we design a large-pitch PCF with 200-μm-core-diameter for fiber amplifiers at a low-repetition frequency. It is predicted that 105-mJ-energy per pulse can be extracted from the 1.5-m-long fiber. It is believed that only FM can be amplified and transmitted at the gain saturation and with the beam quality $M^2 = 1.5$. To the best of our knowledge, it has been the largest core-diameter active PCF designed for delivering the highest pulse energy with near-diffraction-limited beam quality to date. There is the potential for such huge pulse-energy output from the VLMA LPF to be used in remote detecting, intensive welding, and even in the national ignition project of nuclear fusion.

References

[1] Shen X, Zhang H, Hao H, Li D, Li Q, Yan P and Gong M 2015 *Opt. Commun.* **345** 168
[2] Meng K, Zhang H, Liu M, Li D, Yan P and Gong M 2014 *J. Optics* **16** 1
[3] Zhang H, Shen X, Chen D, Zheng C, Yan P and Gong M 2014 *IEEE Photon. Technol. Lett.* **26** 2295
[4] Liu M, Zhang H, Gong M, Zhao Y, Cheng W, Meng K, Zheng C and Chen Y 2014 *Chin. Phys. B* **23** 44214
[5] Zhang H, Liu M, Yan P, Gong M, Zheng C, Meng K and Cheng W 2012 *Laser Phys.* **22** 1331
[6] Zhang H, Zheng C, Yan P, Gomg M, Xiao Q and Zhao Q 2012 *Laser Phys. Lett.* **9** 744
[7] Limpert J, Stutzki F, Jansen F, Otto H, Eidam T, Jauregui C and Tunnermann A 2012 *Light: Sci. Appl.* **1** 1
[8] Teodoro F D, Koplow J P, Moore S W and Kliner D A 2002 *Opt. Lett.* **27** 518
[9] Bhutta T, Mackenzie J I, Shepherd D P and Beach R J 2002 *J. Opt. Soc. Am. B* **19** 1539
[10] Hageman W, Chen Y, Wang X, Gao L, Kim G U, Richardson M and Bass M 2010 *J. Opt. Soc. Am. B* **27** 2451
[11] Mortensen N A, Folkenberg J R, Nielsen M D and Hansen K P 2003 *Opt. Lett.* **28** 1879
[12] Stutzki F, Jansen F, Eidam T, Steinmetz A, Jauregui C, Limpert J and Tünnermann A 2011 *Opt. Lett.* **36** 689
[13] Stutzki F, Jansen F, Liem A, Jauregui C, Limpert J and Tünnermann A 2012 *Opt. Lett.* **37** 1073
[14] Jansen F, Stutzki F, Otto H J, Baumgartl M, Jauregui C, Limpert J and Tünnermann A 2010 *Opt. Express* **18** 26834
[15] Digonnet M 2001 *Rare-Earth-Doped Fiber Lasers and Amplifiers* (New York: M. Dekker, Inc.)
[16] Zhang H T, Chen D, Hao J, Yan P and Gong M 2015 *Chin. Phys. B* **24** 24208
[17] Zhang H T, Chen D, Ren H, Yan P and Gong M 2015 *Chin. Phys. B* **24** 24207
[18] Koechner W 1999 *Solid-state Laser Engineering* (Herndon: Fibertek, Inc.)
[19] Rigrod W W 1963 *J. Appl. Phys.* **34** 2602
[20] Gong M, Yuan Y, Li C, Yan P, Zhang H and Liao S 2007 *Opt. Express* **15** 3236
[21] Eidam T, Rothhardt J, Stutzki F, Jansen F, Hädrich S, Carstens H, Jauregui C, Limpert J and Tünnermann A 2011 *Opt. Express* **19** 255
[22] Jansen F, Stutzki F, Jauregui C, Limpert J and Tünnermann A 2011 *Opt. Express* **19** 13578
[23] Napierala M, Nasilowski T, Beres-Pawlik E, Mergo P, Berghmans F and Thienpont H 2011 *Opt. Express* **19** 22628
[24] Napierala M, Nasilowski T, Beres-Pawlik E, Berghmans F, Wojcik J and Thienpont H 2010 *Opt. Express* **18** 15408
[25] Agrawal G P 2001 *Nonlinear Fiber Optics* (New York: Academic)
[26] Li Q H, Zhang H T and Gong M L 2015 *Opt. Express* **23** 28438