1. Introduction

Tremendous progress in the area of high-power fiber laser systems with near-diffraction-limited beam quality has been achieved in the past few years, which is due to their numerous applications, especially in the coherent lidar system, nonlinear frequency conversion, and coherent beam combining [1–4]. However, power scaling of ytterbium-doped fiber laser systems with near-diffraction-limited beam quality is now limited by the sudden onset of mode instabilities (MIs), which deteriorates the beam quality and pointing stability [5, 6], and limits the application of fiber lasers in the aforementioned areas. Concerning the rapid power scaling of fiber lasers in the mid-infrared spectral range [7, 8], it may be only a matter of time until MI also becomes a problem for other rare-earth-doped fiber lasers [9], which means that MI is one more fundamentally nonlinear challenging aspect for the power-scaling capabilities of fiber laser. Due to the far-reaching impact of MI, lots of work has been carried out to gain a deep insight into this phenomenon, which influences a variety of fiber parameters, i.e. the core diameter [10–12], the core NA [13], the shape and size of the dopant area [14–17], and the pump-cladding diameter [11, 12, 15]. The dopant concentration of ytterbium ions is an important parameter of fiber. By increasing the dopant concentration, the length of the gain fiber can be shortened, which has the advantage of suppressing nonlinear effects without decreasing the MI threshold. This provides a method of maximizing the power output of fiber laser, taking into account the stimulated Brillouin scattering, stimulated Raman Scattering, and MI thresholds simultaneously.

Keywords: fiber amplifier, dopant concentration, modal instability, thermal effects

(Some figures may appear in colour only in the online journal)
2. Theoretical study

The fundamental mechanism leading to MI is thought to be stimulated thermal Rayleigh scattering [11, 21], which stems from the creation of a thermally induced index grating written in the fiber by modal interference [5, 22], and has been employed widely in numerical investigation. Based on the aforementioned physical principle, and for the case where MI is seeded by the intensity noise of the signal laser, the fraction of the high-order mode (HOM, LP11 in the paper) at the output end can be expressed as [12, 23]

\[
\xi(L) = \xi_0 \exp \left[ \int_0^L \int_0^L g(r, \phi, z) (\psi_2 \psi_2 - \psi_1 \psi_1) r dr d\phi \right] 
\]

\[
\times \left( 1 + \frac{2\pi}{\int_0^L P_b(z) |\chi''(\Omega_0)| dz} \right) \exp \left[ \int_0^L P(z) \chi(\Omega_0) dz \right] 
\]

where \( \Omega = \omega_1 - \omega_2, \omega_1 \) and \( \omega_2 \) is the angular frequency of the fundamental mode and the HOM, \( g(r, \phi, z) \) is the gain distribution in the fiber, \( \psi_1(r, \phi) \) and \( \psi_2(r, \phi) \) are the normalized mode profiles of the fundamental mode and the HOM, \( R_0(\Omega) \) is the relative intensity noise of the input signal, \( \xi_0 \) is the initial HOM content, \( L \) is the total length of the gain fiber, and \( P(z) \) is the power distribution of the fundamental mode. \( \chi(\Omega) \) is the nonlinear mode coupling coefficient, \( \Omega_0 \) denotes the frequency corresponding to the maximum of \( \chi(\Omega) \), and \( \chi''(\Omega) \) denotes the second derivative of \( \chi(\Omega) \) with respect to \( \Omega \). \( \chi(\Omega) \) can be expressed as

\[
\chi(\Omega) = \frac{2n_0 \omega_0^2}{c^2} \Im \left( \frac{1}{n_0 \eta} \int \frac{d\Omega'}{\Omega'} \frac{1}{\Omega''(\Omega)} \right)
\]

where \( n_0 \) is the core refractive index, \( \varepsilon_0 \) is the vacuum permittivity, \( c \) is the speed of light in vacuum, \( \beta_2 \) is the propagation constant of the HOM. Other parameters are given as

\[
\bar{n}_{12}(r, \phi, z) = \frac{\eta}{\pi \rho C} \left( \frac{v_p - v_s}{v_s} \right) \sum_{m=1}^{\infty} \frac{J_m(\delta_m, r)}{\alpha \delta_m - \beta_0} B_{12}(\phi, z) N(\delta_m) \Omega_0 - \beta_0 = \beta_0 - \Omega_0
\]

\[
B_{12}(\phi, z) = \int_0^{2\pi} d\phi' \int_0^{\infty} J_0(\delta_m, r') \cos \phi - \phi' \frac{\psi_1(r', \phi') \psi_2(r', \phi')}{(1 + I_0/I_{\text{saturation}}^2)} r' dr'
\]

\[
g_0 = \frac{P_0(\zeta)(\sigma_p^a \sigma_e^a - \sigma_p^a \sigma_e^b)/h v_p A_p - \sigma_p^a \Omega_0(\zeta, \phi)}{P_0(\zeta)(\sigma_p^a + \sigma_e^a)/h v_p A_p + 1/\tau}
\]

\[
I_{\text{saturation}} = P_0(\zeta)(\sigma_p^a + \sigma_e^a)/h v_p A_p + 1/\tau \frac{h v_s}{\sigma_p^a + \sigma_e^a}
\]

\[
N(\delta_m) = \int_0^\infty r R_m^2(\delta_m, r) dr
\]

where \( \alpha = \kappa / \rho C \) (\( \rho \) is the density, \( C \) is the specific heat capacity, and \( \kappa \) is the thermal conductivity), and \( J_m \) represents Bessel functions of the first kind, and \( \delta_m \) is the positive root of \( \delta_m J_{\alpha m}(\delta_m R) + h_\eta / k J_{\alpha m}(\delta_m R) = 0 \) (\( h_\eta \) is the convection coefficient for the cooling fluid). \( \nu_p(\zeta) \) is the optical frequency, \( \eta \) is the thermal-optic coefficient, \( R \) is the radius of the pump cladding, \( L_0 \) is the total intensity of the fundamental mode and the HOM, \( \sigma_s^a \) and \( \sigma_p^a \) are the signal absorption and emission cross sections, respectively, \( \sigma_p^a \) and \( \sigma_e^a \) are the pump absorption and emission cross sections, respectively, \( N_{\text{vol}}(r, \phi) \) is the doping profile, \( P \) is the pump power, \( A_p \) is the area of the pump cladding, and \( \tau \) is the ion upper-state lifetime. Equation (3a) corresponds to the antisymmetric temperature distribution in the fiber while equations (3c) and (3d) correspond to the small-signal gain and the saturation intensity, respectively.

In equation (2), only heat resulting from quantum defect has been considered. The influence of the absorption background loss and the photodarkening can be taken into consideration by adding a linear absorption term as in [24]. Owing to the rapid development of fiber manufacturing technology, the background loss, which includes the absorption and scattering loss, is far smaller than 1 dB m\(^{-1}\), which means that its contribution to the volume heat-generation density can be neglected. On the other hand, it is shown that the photodarkening has a significant impact on MI [25–27]. However, the origin and physical causes of the phenomenon are still under debate [28–31], and widely accepted models are being developed [32–35]. So the model has not taken the effect of the photodarkening into consideration. In addition, benchmarking techniques have been developed to mitigate the effect of the photodarkening [36], which has mitigated its influence [35, 37, 38].

Based on equation (1), we calculated the MI threshold, under different dopant concentrations for different pump configurations, which is shown in figure 1. The fiber parameters are listed in table 1. All the fiber is fully doped. As the dopant concentration of the fiber varies, other parameters remain unchanged except the fiber length, which is adjusted accordingly to the minimum value necessary to achieve high efficiency, defined as the total small-signal pump absorption of 13 dB. It shows from figure 1 that the MI threshold is independent of the dopant concentration regardless of the pump schemes. Because the power evolution is different...
in different pump schemes, the bi-directional pump has the highest MI threshold, which can be understood straightforwardly by dividing the amplifier into two parts: the first is the fore part, while the second is the back end. For the case where the total pump power is the same, the pump power in the first part for the bi-directional pump is lower than that of the co-pump scheme, while the pump power in the second part for the bi-directional pump is lower than that of the counter-pump scheme. Lower pump power tends to enhance the effect of the spatial hole-burning, and thus increases the MI threshold [17]. Here, the counter-pumped case has a slightly lower threshold than that of the co-pumped case, which seems different from the results in [11]. This is caused by the difference in the fiber parameters, which results in different gain saturation and leads to the difference in these cases [11].

In equation (1), the first term on the right-hand side corresponds to the amplification of the HOM by the laser gain, while the second term corresponds to the amplification by the nonlinear mode coupling due to the stimulated thermal Rayleigh scattering. Because the second term on the right-hand side in equation (1) corresponds to the amplification by the nonlinear mode coupling, this term was specifically analyzed to explain the above theoretical results. By normalizing the fiber length to 1, the second term can be rewritten as

\[
1 + \frac{1}{4} \int \frac{2\pi}{(N_{Yb}L) \int_0^1 P(LZ)\chi(\Omega_0)d\Omega_0} R_0(\Omega_0) \\
\times \exp \left[ (N_{Yb}L) \int_0^1 P(LZ)\chi(\Omega_0)d\Omega_0 \right] (4)
\]

with

\[
R_0(\phi, LZ) = \int_0^{2\pi} d\phi' \int_{R_{ap}} R_0(\phi', r') \cos(\phi - \phi') \psi_0(\phi') \psi_0(\phi') \frac{1}{(1 + h_I)_{sat}} d\phi' (5a)
\]

\[
\bar{g}_0 = \frac{P_0(LZ)\sigma_p^s - \sigma_p^a}{P_0(LZ)(\sigma_p^s + \sigma_p^a)/h\nu_A + 1/\tau} (5b)
\]

\[
l_{saturation} = \frac{h\nu_A}{\sigma_p^s + \sigma_p^a} (5c)
\]

where \(R_{ap}\) is the radius of the doping area, and the other parameters are the same as in equation (3). In equation (4), \(N_{Yb}\) is extracted from equation (3c), which results in equation (3c) changing into the form of equation (5b). By adapting the fiber length accordingly, the total small-signal pump absorption remains the same as the dopant concentration changes, which results in the term \((N_{Yb}L)\) in equation (4) being unchanged. On the other hand, although the dopant concentration has changed, the pump/signal power distribution along the normalized fiber length remains the same as shown in figure 2(a), which results in \(g_0\) and \(I_{saturation}\) being the same, and ultimately causes the nonlinear mode coupling coefficients at different normalized fiber lengths to remain the same. The nonlinear mode coupling coefficients are far smaller than those in [16], which is because the term \(N_{Yb}\) has been extracted from equation (3c). It is revealed in figure 2 that, although the dopant concentrations in the fiber are different, the nonlinear mode coupling coefficients are the same at the same relative length. Finally, we can establish that the value of equation (4) is independent of the dopant concentrations, which means that, with the other parameters kept constant and the fiber length being adapted to maintain the same total small-signal pump absorption, the variation of the dopant concentrations has no impact on MI.

Based on the aforementioned study, we can also establish that the length of fiber has no impact on the threshold of MI as long as only the dopant concentration is varied to maintain the same total small-signal pump absorption, which is shown in figure 3(a). This is not in contrast with the results in [40], in which the pump cladding was adapted to maintain the same total small-signal pump absorption, and the dopant concentrations were kept the same. As with the case in [40], we can obtain similar results, which are shown in figure 3(b). As the diameter of the pump cladding increases (shown in figure 3(b)), the gain saturation becomes stronger, which results in the MI threshold increasing. Meanwhile, longer fiber is needed for a larger pump-cladding diameter to guarantee efficient pump absorption. Then it seems that the MI threshold is related to the fiber length [40–42].

### 3. Experimental study and discussions

To validate the aforementioned prediction, experimental investigation has been performed. The experiment setup is shown in figure 4. The main amplifier employed large mode area (LMA) ytterbium-doped fiber (YDF) with the core diameter being 30 μm and clad diameter being 250 μm, which is seeded by a 1080 nm seed with ~10W power, and pumped in the co-propagating direction by fiber-pigtailed laser diodes (LD) at 976 nm. A home-made cladding mode stripper (CMS) was employed to strip the residual pump laser and cladding mode. The output end of the delivery fiber is angle cleaved at 8°. The onset of MI was monitored by detecting the time fluctuation of scattering power with a photo-detector [43]. Gain fibers with different ytterbium-dopant concentrations have been employed in the experiment.

---

**Table 1. Parameters of the test amplifier.**

| Parameter | Value |
|-----------|-------|
| \(R_{core}\) | 15 μm |
| \(R\) | 125 μm |
| \(n_{clad}\) | 1.45 |
| NA | 0.065 |
| \(\lambda_0\) | 976 nm |
| \(\lambda_s\) | 1064 nm |
| \(h_q\) | 5000 W m\(^{-2}\) K\(^{-1}\) |
| \(H\) | 1.2 \times 10^2 K\(^{-1}\) |
| \(\kappa\) | \(1.38 \times 10^{-1} \text{m}^2\) |
| \(\rho C\) | \(1.54 \times 10^{6} \text{J K}^{-1} \text{m}^{-3}\) |

---

**Note:** The above values are extracted from equation (3c), which results in equation (3c) changing into the form of equation (5b). By adapting the fiber length accordingly, the total small-signal pump absorption remains the same as the dopant concentration changes.
and the parameters are listed in table 2. Higher dopant concentration leads to the core NA of fiber B being larger than fiber A, but the difference of core NA on MI is negligible for the cases here [13]. In the experiments, relatively consistent launching conditions in two different fibers are achieved through the COTS combiner and monolithic splicing technology.

Employing the MI definition in [44], the measured MI thresholds are 440 W for fiber A and 446 W for fiber B, respectively. To avoid the impact of the photodarkening on the results, the MI thresholds are the power when MI was first encountered. It can be seen that, although the dopant concentration of ytterbium ions for fiber B is about twice that of fiber A, they have a similar MI threshold, which agrees with our previous theoretical results.

Based on the theoretical study in the previous section and the experimental study in this section, the dependence of MI on dopant concentrations has been investigated, which leads to an interesting finding: dopant concentration has little impact on the threshold of MI as long as only the fiber length is varied to maintain the same total small-signal pump absorption. Thus, higher dopant concentrations can be adopted without
decreasing the threshold of MI, which may find useful experimental and theoretical applications.

Various effective methods have been proposed to mitigate or suppress MI, such as tailoring the Yb-ion concentration \([14, 15, 41]\), shifting the pump wavelength \([23, 45, 46]\), and increasing the pump cladding diameter \([11, 15]\). In these methods, they have one aspect in common, which is that they all lead to a reduction in the small-signal pump absorption. If the dopant concentrations remain the same, longer fiber is required to achieve high lasing efficiency, which inevitably leads to a detrimental effect on the SBS and SRS threshold. It seems that the suppression of MI is in conflict with the suppression of SBS and SRS. However, with the conclusion achieved in the previous and this section, such contradictions can be solved by increasing the dopant concentrations. In conjunction with the proposed MI suppression methods, higher doped fiber can realize the suppression of MI and SBS and SRS simultaneously \([47]\). Take the cases in \([48]\) for example, in which the power-scaling capacity of the amplifier was limited to 2.6 kW by SRS, such that the SRS threshold can be further increased by employing fiber with a higher doping concentration while maintaining the merit of having no MI. Furthermore, the computation resources can be saved by increasing the dopant concentration to shorten the length of the fiber in the calculation of the MI threshold, which is useful for some time-consuming numerical models \([49, 50]\).

Nevertheless, in some methods, the suppression of MI is implemented through mode-specific loss by tight-coiling the fiber \([12, 26, 51]\), in which a longer length of fiber can provide higher high-order mode loss and stronger MI suppression. When adopting higher doped fiber to suppress the nonlinear effects in these cases, one should take the precaution of not reducing the fiber length too much so as to make the MI suppression invalid. A higher doped fiber operates at higher temperatures, and results in stronger longitudinal thermal gradients in the shorter fiber, which would be more effective in suppressing SBS. Higher temperatures also result in problems of thermal management, and would affect neither thermal lensing nor the Yb\(^{3+}\) absorption and emission cross sections directly \([52]\), which can be resolved by optimizing the cooling configurations \([53, 54]\). One more challenge of increasing dopant concentrations is the change of the optical and acoustic refractive index, which means the core materials should be designed carefully to maintain the same core refractive index \([55]\).

### 4. Conclusions

In summary, we studied the effects of dopant concentrations on MIs. The dependence of MI on ytterbium dopant concentrations has been investigated theoretically, which reveals that the MI threshold is independent of dopant concentration. Then the MI threshold of amplifiers using 30/250 fibers with dopant concentration of \(5.93 \times 10^{25} \text{ m}^{-3}\) and \(1.02 \times 10^{26} \text{ m}^{-3}\) has been experimentally examined. It shows that they have a similar MI threshold. The experimental results agree with the theoretical predictions, which mean that dopant concentration has little impact on MI. The results may find useful applications in areas that need to shorten the length of the fiber to suppress nonlinear effects, such as SBS and SRS, as well as to save the computation resources of numerical simulation.

### Acknowledgments

The research leading to these results has received funding from the program for the National Science Foundation of China under grant No. 61322505 and 61505260, the program for New Century Excellent Talents in University.

### References

1. Zhang L, Cui S, Liu C, Zhou J and Feng Y 2013 170W, single-frequency, single-mode, linearly-polarized, Yb-doped all-fiber amplifier *Opt. Express* **21** 5456–62
2. Mo S, Xu S, Huang X, Zhang W, Feng Z, Chen D, Yang T and Yang Z 2013 A 1014 nm linearly polarized low noise narrow linewidth single-frequency fiber laser *Opt. Express* **21** 12419–23
3. Anderson J P 2011 RGB laser generation from fiber MOPAs coupled to external enhancement cavities *Proc. SPIE* **7580** 75800G
4. Ma Y *et al* 2011 Coherent beam combination of 1.08 kW fiber amplifier array using single frequency dithering technique *Opt. Lett.* **36** 951–3
5. Smith A V and Smith J J 2011 Mode instability in high power fiber amplifiers *Opt. Express* **19** 10180–92
6. Eidam T, Wirth C, Jauregui C, Stutzki F, Jansen F, Otto H J, Schmidt O, Schreiber T, Limpert J and Tünnermann A 2011 Experimental observations of the threshold-like onset of mode instabilities in high power fiber amplifiers *Opt. Express* **12** 13218–24
7. Ehrenreich T, Leveille R, Majid I, Tankala K, Rines G and Moulton P 2010 1 kW, all-glass Tm:fiber laser *Presented at SPIE Photonics West*
8. Hemmimg A, Simakov N, Haub J and Carter A 2014 A review of recent progress in holmium-doped silica fibre sources *Opt. Fiber Technol.* **20** 621–30
9. Smith A V and Smith J J 2016 Mode instability thresholds for Tm-doped fiber amplifiers pumped at 790 nm *Opt. Express* **24** 975–92
10. Jansen F, Stutzki F, Otto H J, Eidam T, Liem A, Jauregui C, Limpert J and Tünnermann A 2012 Thermally induced waveguide changes in active fibers *Opt. Express* **20** 3997–4008
11. Smith A V and Smith J J 2013 Increasing mode instability thresholds of fiber amplifiers by gain saturation *Opt. Express* **21** 15168–82
12. Tao R, Ma P, Wang X, Zhou P and Liu Z 2015 1.3 kW monolithic linearly-polarized single-mode MOPA and strategies for mitigating mode instabilities *Photon. Res.* **3** 86–93
13. Tao R, Ma P, Wang X, Zhou P and Liu Z 2015 Influence of core NA on thermal-induced mode instabilities in high power fiber amplifiers *Laser Phys. Lett.* **12** 085101
14. Nadiri S, Dajani I, Madden T and Robin C 2013 Investigations of modal instabilities in fiber amplifiers through detailed numerical simulations *Opt. Express* **21** 16111–29

### Table 2. Parameters of the active fiber.

| Fiber  | Core NA | Dopant concentration |
|--------|---------|-----------------------|
| Fiber A | 0.065   | \(5.93 \times 10^{25} \text{ m}^{-3}\) |
| Fiber B | 0.07    | \(1.02 \times 10^{26} \text{ m}^{-3}\) |
Laser Phys. 26 (2016) 065103

[15] Robin C, Dajani I, Zeringue C, Ward B and Lanari A 2012 Gain-tailed SBS suppressing photonic crystal fibers for high power applications Proc. SPIE 8237 82371D

[16] Hansen K R, Alkeskjold T T, Broeong J and Lægsgaard J 2012 Thermally induced mode coupling in rare-earth doped fiber amplifiers Opt. Lett. 37 2382–4

[17] Smith A V and Smith J J 2013 Frequency dependence of mode coupling gain in Yb doped fiber amplifiers due to stimulated thermal Rayleigh scattering arXiv:1301.4277

[18] Wang X, Zhou F, Xiao H, Ma Y, Xu X and Liu Z 2012 310 W single-frequency all-fiber laser in master oscillator power amplification configuration Laser Phys. Lett. 9 591–5

[19] Lægsgaard J 2016 Optimizing Yb concentration of fiber amplifiers in the presence of transverse modal instabilities and photodarkening Appl. Opt. 55 1966–70

[20] Tao R, Ma P, Wang X, Zhou P and Liu Z 2014 A novel theoretical model for mode instability in high power fiber lasers Presented at Advanced Solid State Lasers (Shanghai, China) (AMSA,2014)

[21] Dong L 2013 Stimulated thermal Rayleigh scattering in optical fibers Opt. Express 21 2642–56

[22] Jauregui C, Eidam T, Limpert J and Tünnermann A 2011 The impact of modal interference on the beam quality of high-power fiber amplifiers Opt. Express 19 3258–71

[23] Tao R, Ma P, Wang X, Zhou P and Liu Z 2013 Mitigating of modal instabilities in linearly-polarized fiber amplifiers by pumping with multiple wavelengths Opt. Lett. 17 045504

[24] Tao R, Ma P, Wang X, Zhou P and Liu Z 2013 Study of wave-length dependence of mode instability based on a semi-analytical model IEEE Quantum. Electron. 51 1600106

[25] Laurila M, Jørgensen M M, Hansen K R, Alkeskjold T T, Broeong J and Lægsgaard J 2012 Distributed mode filtering rod fiber amplifier delivering 292 W with improved mode stability Opt. Express 20 5742–53

[26] Smith A V and Smith J J 2013 Mode instability thresholds of fiber amplifiers Proc. SPIE 8601 860108

[27] Otto H J, Madschning N, Jauregui C, Limpert J and Tünnermann A 2013 Impact of photodarkening on the mode instability threshold Opt. Express 23 15265–77

[28] Peretti R, Gonnet C and Jurdyc A M 2012 Revisiting literature observations on photodarkening in Yb3+ doped fiber considering the possible presence of Tm impurities J. Appl. Phys. 112 093511

[29] Jetschke S, Schwuchow A and Unger S 2014 Transient absorption in pumped Yb fibers opens a path to photodarkening Laser Phys. Lett. 11 085101

[30] Bobkov K K, Rybaltskov A A, Vel’misskin V V, Likhachev M E, Bubnov M M, Dianov E M, Umnikov A E, Gur’yanov A N, Vechkanov N N and Shestakova I A 2014 Charge-transfer state excitation as the main mechanism of the photodarkening process in ytterbium-doped aluminosilicate fibers Quantum. Electron. 44 1129

[31] Rydberg S and Engholm M 2013 Experimental evidence for the formation of divergent ytterbiumb in the photodarkening process of Yb-doped fiber lasers Opt. Express 21 6681–8

[32] Koponen J, Söderlund M, Hoffman H, Kliuner D and Koplow J 2006 Photodarkening measurements in large mode area fibers Proc. SPIE 6453 64531E

[33] Jetschke S, Unger S, Röpke U and Krichhoff J 2007 Photodarkening in Yb doped fibers: experimental evidence of equilibrium states depending on the pump power Opt. Express 15 14838–43

[34] Taccheo S et al 2011 Concentration dependence and self-similarity of photodarkening losses induced in Yb-doped fibers by comparable excitation Opt. Express 19 19340–5

[35] Zervas M N, Ghiringelli F, Durkin M K and Crowe I 2011 Distribution of photodarkening-induced loss in Yb-doped fiber amplifiers Proc. SPIE 7914 79140L

[36] Ye C, Petit L, Koponen J, Hu I N and Galvanauskas A 2014 Short-term and long-term stability in ytterbium-doped high-power fiber lasers and amplifiers IEEE J Sel. Top. Quantum. Electron. 20 0903512

[37] Yagodkin R, Platonov N, Yusim A and Gapontsev V P 2016 > 1.5 kW narrow linewidth CW diffraction-limited fiber amplifier with 40 nm bandwidth Proc. SPIE 9728 972807

[38] Jørgensen M M, Laurila M, Noordegraaf D, Alkeskjold T T and Lægsgaard J 2013 Thermal recovery of modal instability in rod fiber amplifiers Proc. SPIE 8601 86010U

[39] Hansen K R and Lægsgaard J 2014 Impact of gain saturation on the mode instability threshold in high-power fiber amplifier Opt. Express 22 11267–78

[40] Jauregui C, Otto H, Stutzki F, Limpert J and Tünnermann A 2015 Simplified modelling the mode instability threshold of high power fiber amplifiers in the presence of photodarkening Opt. Express 23 20203–18

[41] Ward B G 2015 Maximizing power output from continuous-wave single-frequency fiber amplifiers Opt. Lett. 40 542–5

[42] Ward B 2016 Theory and modeling of photodarkening-induced quasi static degradation in fiber amplifiers Opt. Express 24 3488–501

[43] Tao R, Ma P, Wang X, Zhou P and Liu Z 2014 Study of mode instabilities in high power fiber amplifiers by detecting scattering light Presented at Int. Photonics and Optoelectronics Meetings (Wuhan, China)

[44] Tao R, Ma P, Wang X, Zhou P and Liu Z 2016 Comparison of the threshold of thermal-induced mode instabilities in polarization maintaining and non-polarization maintaining active fibers J. Opt. 18 065501

[45] Naderi S, Dajani I, Grosek J, Madden T and Dinh T N 2014 Theoretical analysis of effect of pump and signal wave-lengths on modal instabilities in Yb-doped fiber amplifiers Proc. SPIE 8964 89641W

[46] Hejaz K, Norouzya A, Poozhe A, Heidarizaa A, Roohforouza A, Nasirabad R R, Jafari N T, Golshan A H, Babazadeh A and Lafouti M 2014 Controlling mode instability in a 500 W ytterbium-doped fiber laser Laser Phys. 24 025102

[47] Ma P, Tao R, Huang L, Wang X, Zhou P and Liu Z 2015 608 W average power picosecond all fiber polarization-maintained amplifier with narrow-band and near-diffraction-limited beam quality J. Opt. 17 075501

[48] Andrea R G, Tobioka H, Abedin K, Dong H, Varallyay Z, Szabó A, Taunay T, Sullivan S and Headley C 2015 2.1 kW single mode continuous wave monolithic fiber laser Proc. SPIE 9344 93441G

[49] Smith A V and Smith J J 2013 Review of models of mode instability in fiber amplifiers (online) http://as-photronics.com

[50] Smith A V and Smith J J 2014 Overview of a steady-periodic model of modal instability in fiber amplifiers IEEE J Sel. Top. Quantum. Electron. 20 1–12

[51] Lei M, Qi Y, Liu C, Yang Y, Zheng Y and Zhou J 2015 Mode controlling study on narrow-linewidth and high power all-fiber amplifier Proc. SPIE 9543 95431L

[52] Smith A V and Smith J J 2012 Influence of pump and seed modulation on the mode instability thresholds of fiber amplifiers Opt. Express 20 24545–58

[53] Huang Z Y, Ng T Y, Seah C P, Lim S H T and Wu R F 2011 Thermal modeling of active fiber and splice points in high power fiber laser Proc. SPIE 7914 79142W

[54] Zintzen B, Langer T, Geiger J, Hoffmann D and Loosen P 2014 Comparison of reverse biasing point in Yb-doped fiber laser Proc. SPIE 9343 934313

[55] Smith A V and Smith J J 2014 Overview of a steady-periodic model of modal instability in fiber amplifiers IEEE J Sel. Top. Quantum. Electron. 20 1–12

[56] Lei M, Qi Y, Liu C, Yang Y, Zheng Y and Zhou J 2015 Mode controlling study on narrow-linewidth and high power all-fiber amplifier Proc. SPIE 9543 95431L

[57] Smith A V and Smith J J 2012 Influence of pump and seed modulation on the mode instability thresholds of fiber amplifiers Opt. Express 20 24545–58

[58] Huang Z Y, Ng T Y, Seah C P, Lim S H T and Wu R F 2011 Thermal modeling of active fiber and splice points in high power fiber laser Proc. SPIE 7914 79142W

[59] Zintzen B, Langer T, Geiger J, Hoffmann D and Loosen P 2014 Optimization of the heat transfer in multi-kW-fiber lasers Proc. SPIE 8673 867319

[60] Jen C K, Oliveira J E B, Goto N and Abe K 1988 Role of guided acoustic wave-modes in single-mode optical fiber design Electron. Lett. 24 1419–20