Impact of amplified spontaneous emission noise on the SRS threshold of high-power fiber amplifiers

Wei Liu(刘伟)[1,2,3], Shuai Ren(任帅)[1], Pengfei Ma(马鹏飞)[1,2,3,†], and Pu Zhou(周朴)[1]

[1] *College of Advanced Interdisciplinary Studies, National University of Defense Technology, Changsha* 410073, *China*
[2] *Nanhu Laser Laboratory, National University of Defense Technology, Changsha* 410073, *China*
[3] *Hunan Provincial Key Laboratory of High Energy Laser Technology, National University of Defense Technology, Changsha* 410073, *China*

(Received 7 June 2022; revised manuscript received 20 July 2022; accepted manuscript online 22 July 2022)

Impact of amplified spontaneous emission (ASE) noise on the stimulated Raman scattering (SRS) threshold of high-power fiber amplifiers is demonstrated numerically through a spectral evolution approach. The simulation results confirm that ASE noise in the Raman wavelength band could reduce the SRS threshold of high-power fiber amplifiers significantly. As for ASE noise originated the main amplifier, it becomes stronger and reduces the SRS threshold at shorter operation wavelength below 1052 nm. As for ASE noise originated from the seed laser, it reduces the SRS threshold at different operation wavelength under the condition that the Raman ratio is over −90 dB in the seed laser. The theoretical method and results in this work could provide a well reference to extend the operation wavelength of high-power fiber lasers.

Keywords: high-power fiber amplifiers, amplified spontaneous emission, stimulated Raman scattering

PACS: 42.55.Wd, 42.60.Da, 42.65.Dr **DOI:** 10.1088/1674-1056/ac833e

1. Introduction

High-power continuous-wave fiber lasers with diffraction-limited beam quality are attractive light sources in many industrial and scientific applications.[1–5] To match the diverse demand of those applications, it is highly desired to improve the spectral purity and to extend the operation wavelength of high-power fiber lasers. For example, the spectral purity and operation wavelength are critical in the applications of spectral beam combination[6,7] and nonlinear frequency conversion.[8] Unfortunately, the power scaling of single-mode fiber lasers is currently limited by the multiple restrictions of pump brightness, stimulated Raman scattering (SRS), and transverse mode instability (TMI).[9] Furthermore, the spectral property of signal laser could have a significant impact on the SRS threshold and TMI threshold of high-power fiber amplifiers,[10–12] which increases the difficulty to adjust and control the spectral property of high-power fiber lasers.

Amplified spontaneous emission (ASE) noise is a common issue which degrades the spectral performances of high-power fiber lasers. ASE noise ultimately arises from the unavoidable spontaneous emission noise and could reduce the spectral purity of fiber lasers directly.[13] More importantly, ASE noise could become serious and prevent the power scaling of fiber lasers operating at special wavelengths,[14] when the gain coefficient at desired wavelength is much smaller than that at other wavelength. Correspondingly, the power of single-mode fiber lasers operating at special wavelengths, such as below 1030 nm,[15–17] is significantly lower than that at common wavelengths. Specifically, the output power of single-mode fiber lasers has exceeded 5 kW at common operation wavelengths from ∼ 1064 nm to ∼ 1080 nm.[18–21]

It should be noted that ASE noise triggers SRS effect, and SRS effect restricts the power scaling of fiber amplifier operating at special wavelength.[17] Furthermore, due to the wide gain spectra of active fiber, ASE noise in the long-wavelength region could always cover the Raman wavelength band, act as a seed source, and contribute to amplification of the Raman Stokes light in high-power fiber lasers. Accordingly, SRS effect enhanced by ASE noise may be a critical issue in extending the operation wavelength of high-power fiber lasers. However, few works analyze the impact of ASE noise on SRS effect of high-power fiber lasers, especially for fiber lasers operating at different wavelengths.

In this work, we aim to demonstrate the impact of ASE noise in the Raman wavelength band on the SRS threshold of high-power fiber amplifiers operating at different wavelengths. A spectral evolution approach is utilized to analyze the overall spectral property of high-power fiber amplifiers operating at different wavelengths. The source of ASE noise in the Raman wavelength band of high-power fiber amplifiers is analyzed, and the dependency of SRS threshold on the operation wavelength is given according to the theoretical analysis.

2. Spectral evolution approach to analyze the impact of ASE noise on SRS effect

A primary issue to analyze the impact of ASE noise on SRS effect in high-power fiber amplifiers is to describe the strength of ASE noise and SRS effect during amplification. As for ASE noise, it covers a wide spectral range among the gain spectra of active fiber, and it is more appropriate to an-

†Corresponding author. E-mail: shandapengfei@126.com
© 2023 Chinese Physical Society and IOP Publishing Ltd

alyze ASE noise through the spectral evolution approach. As for SRS effect, it could be described through the unified spectral evolution of an optical field envelope covering both the signal and Raman wavelength bands[22] or the separated spectral evolution of two optical field envelopes at the signal and Raman wavelength bands, respectively.[23] Accordingly, it is more appropriate to analyze the impact of ASE noise on SRS effect in high-power fiber amplifiers through the unified spectral evolution of an optical field envelope to cover the whole spectral range of ASE noise.

Then the set of unidirectional spectral-spatial equation describing the evolution of an optical field envelope during amplification could be established through incorporating the gain coefficient and ASE noise into the generalized nonlinear Schrödinger equation

$$\frac{\partial \tilde{A}}{\partial z} = \frac{g-\alpha}{2}\tilde{A} + \frac{\mathrm{i}\beta_2}{2}\omega^2\tilde{A} - \frac{\mathrm{i}\beta_3}{2}\omega^3\tilde{A} + \mathrm{i}\gamma\left(1+\frac{\omega}{\omega_0}\right)\cdot F\left\{A\cdot R\otimes|A|^2\right\} + f_{\mathrm{SE}}, \quad (1)$$

where $\tilde{A}$ and A are the complex amplitudes of optical field envelope in frequency domain and time domain, respectively, g and α are the gain and loss coefficients, respectively, β_2 and β_3 are the dispersion coefficients, γ is nonlinear Kerr coefficient, ω is the reference angular frequency, ω_0 is the carrier angular frequency of the signal laser, $F\{*\}$ denotes the operation of Fourier transform, R is the nonlinear response function, $\otimes$ denotes the operation of convolution, and f_{SE} is complex amplitude of the spontaneous emission noise.

Moreover, the gain coefficient g and nonlinear response function R could be expressed as

$$g(\omega) = \Gamma\left[N_2\sigma_{\mathrm{e}}(\omega) - N_1\sigma_{\mathrm{a}}(\omega)\right], \quad (2)$$

$$R(t) = (1-f_{\mathrm{R}})\,\delta(t) + f_{\mathrm{R}}h(t), \quad (3)$$

where Γ is the power overlap factor of signal laser, σ_{a} and σ_{e} are the absorption and emission cross sections of doped ion at signal wavelength, respectively, N_1 and N_2 are the total numbers of doped ion per unit volume in a ground state or excited state respectively, $N_1+N_2=N$, and N is the dopant density in fiber core, f_{R} is the fractional contribution of Raman response to the total nonlinearity, $\delta(t)$ is the Dirac function, and $h(t)$ is the Raman response function.

To apply the spectral evolution approach requires to construct the seed lasers. ASE noise could originate from both the seed laser and the main amplifier in a high-power fiber amplifier. Thus, apart from the operation wavelength, it is also required to adjust the strength of ASE noise in the seed lasers. In order to keep the temporal intensity of seed lasers as possible, the phase-modulated single-frequency lasers incorporating a weak intensity noise are selected to construct the seed lasers, whose complex amplitude could be expressed as

$$A_{\mathrm{s}}(t) = \sqrt{P_0}\left[\exp(\mathrm{i}\varphi t) + \sqrt{I_n}(X_0 + \mathrm{i}X_1)\right], \quad (4)$$

where P_0 is the seed power, φ is the phase modulation signal, I_n is the relative strength of intensity noise, X and X_1 are two standardized random variables. In Eq. (4), the set of $I_n \ll 1$ could ensures that the temporal intensity of seed lasers always keeps relatively stable. In addition, the phase modulation signal barely impacts the SRS threshold of high-power fiber amplifiers, thus we do not analyze the impact of the phase modulation signal in the following analysis.

The operation wavelength and the strength of ASE noise are adjusted through the carrier wavelength of signal laser and the relative strength of intensity noise, respectively. Figures 1(a) and 1(b) illustrate the normalized spectra of the constructed seed lasers when the carrier wavelength of signal laser or the relative strength of intensity noise is different. As shown in Fig. 1, ASE noise in the seed lasers is relatively flat, and the overall spectrum properties of seed lasers in different cases are consistent to each other.

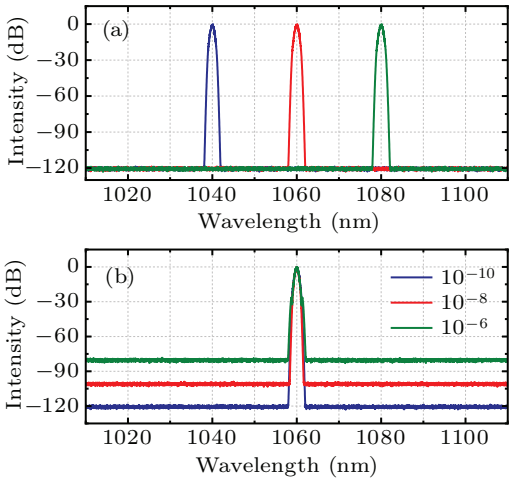


Fig. 1. Normalized spectra of the seed lasers when adjusting: (a) carrier wavelength, (b) intensity noise.

Due to overlap between ASE noise and Raman Stokes light in the Raman wavelength band, it is difficult to distinguish them strictly during amplification. Thus, the power ratio of spectral component in the Raman wavelength band is defined uniformly as Raman ratio. For convenience of comparisons, the Raman wavelength band is selected to be the spectral range of the reference wavelength from 20 nm to 60 nm, and the reference wavelength is obtained by subtracting the operation wavelength from the actual wavelength.

3. Impact of ASE noise on the SRS threshold of high-power fiber amplifiers

Based on the spectral evolution approach, we analyze the SRS threshold of a typical Yb-doped fiber amplifier (YDFA). The YDFA is bidirectional-pumped by laser diodes at 976 nm, and the ratios of forward and backward pump powers is set to be 1:2. The core diameter and inner cladding diameter of the Yb-doped fiber (YDF) are set to be 20 μm and 400 μm, respectively. The cladding absorption coefficient of the YDF is

set to be 1.2 dB/m at 976 nm, and the length of the YDF is set to be 16 m. The other major simulation parameters of the YDF are listed as follows: $\alpha_s = 15$ dB/km, $\beta_2 = 20$ ps^2/km, $\beta_3 = 0.04$ ps^3/km, $\gamma_s = 0.48$ W^{-1}/km (at 1060 nm), $f_R = 0.245$, and $P_0 = 50$ W.

3.1. Impact of ASE noise originating from the main amplifier

To demonstrate the impact of ASE noise in the Raman wavelength band which originates from the main amplifier, we set $I_n = 10^{-10}$ and simulate the output property of the fiber amplifier at different operation wavelengths. Figure 2 compares the normalized output spectrum of signal laser at a pump power of 2 kW, when the operation wavelength is set to be 1060 nm, 1050 nm, 1040 nm, and 1034 nm, respectively. As shown in Fig. 2, the spectral shapes near the operation wavelength in the four cases are similar to each other, while the intensity in the Raman wavelength band enhances at shorter operation wavelength. Specifically, the Raman ratio of signal laser is calculated to be ~ -75.3 dB, ~ -62.5 dB, ~ -40.5 dB, and ~ -18.6 dB in the four cases, respectively.

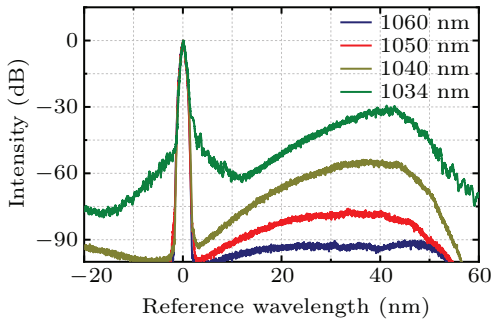


Fig. 2. Output spectrum of signal laser at a pump power of 2 kW for different operation wavelengths.

The SRS threshold of the fiber amplifier could be obtained by simulating the output property at different pump power, and calculating the Raman ratio of signal laser at different output powers. Figure 3 illustrates the Raman ratio of signal laser at different output powers when the operation wavelength is set to be 1060 nm, 1050 nm, and 1040 nm. As shown in Fig. 3, the SRS threshold of the fiber amplifier is co-determined by the initial value and growth rate of the Raman ratio. By defining the SRS threshold as the output power when the Raman ratio reaches -25 dB, the SRS threshold of the fiber amplifier is estimated to be ~ 6.7 kW, ~ 5.7 kW, and ~ 3.3 kW in the three cases, respectively.

The results in Fig. 3 also indicate that the differences among the SRS thresholds are due to the diversity of the initial value, which corresponds to the seed power for the Raman Stokes light. In addition, the initial values of the Raman ratio in Fig. 3 are much larger than those of the seed lasers (~ -103 dB). Accordingly, the spectral component in the Raman wavelength band gets extra amplification after passing through the active fiber. This phenomenon could be understood through the re-absorption effect in the main amplifier. Figure 4 illustrates the distribution of Raman ratio along the fiber as a function of the operation wavelength, when the pump power is set to be zero. As shown in Fig. 4, the Raman ratio grows along the fiber for a specific operation wavelength, and grows more quickly for shorter operation wavelength. In addition, the Raman ratio is over -90 dB in most positions along the fiber and could reach over -50 dB at the fiber end when the operation wavelength is below 1041 nm. Therefore, it is the re-absorption effect in the main amplifier that leads to the enhancement of ASE noise in the Raman wavelength band at low output power. Furthermore, stronger ASE noise at shorter operation wavelength means higher seed power for the Raman Stokes light and lower SRS threshold for the fiber amplifier.

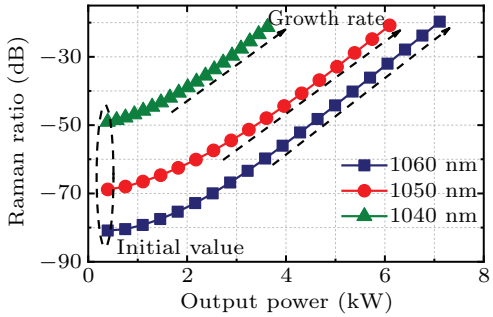


Fig. 3. Raman ratio of signal laser at different output power for different operation wavelengths.

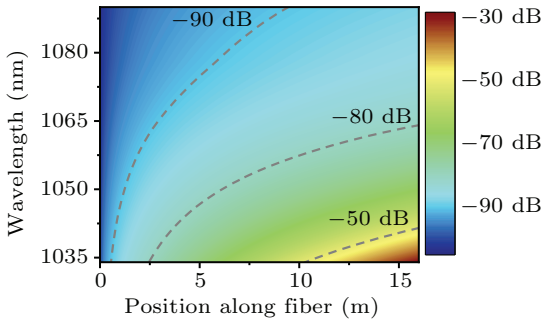


Fig. 4. Distribution of Raman ratio along the fiber versus operation wavelength.

Figure 5 illustrates the SRS threshold of the fiber amplifier as a function of the operation wavelength. As shown in Fig. 5, the SRS threshold of the fiber amplifier could be higher than 6 kW at most operation wavelengths from 1052 nm to 1110 nm and the maximum SRS threshold is ~ 6.8 kW at the operation wavelength of 1074 nm. In addition, the SRS threshold reduces quickly at the operation wavelength below 1052 nm, and is only ~ 1.3 kW at the operation wavelength of 1034 nm. Therefore, ASE noise in the Raman wavelength band originated from the main amplifier could reduce the SRS threshold of high-power fiber amplifiers at shorter operation wavelength below 1052 nm. We can notice that there exist two valley values at the operation wavelengths of 1092 nm and 1098 nm. This result could be understood through the

effect of ASE noise in the short wavelength region. ASE noise from 1040 nm to 1050 nm, the signal laser at the operation wavelengths of ∼ 1092 nm and ∼ 1098 nm, and the corresponding Raman Stokes light could satisfy the frequency matching condition. Accordingly, ASE noise from 1040 nm to 1050 nm could contribute the generation of the Raman Stokes light through the degenerate four-wave-mixing (FWM) effect[23] and lead to the decrease of the SRS threshold at the operation wavelength of ∼ 1092 nm and ∼ 1098 nm.

Notably, the total output power of fiber lasers at the operation wavelength from 1050 nm to 1110 nm with the spectral interval of 4 nm could reach over 100 kW. Therefore, in consideration of the SRS threshold, up to 100 kW output power could be achieved through the spectral beam combining of sixteen fiber lasers at the operation wavelength from 1050 nm to 1110 nm with the spectral interval of 4 nm.

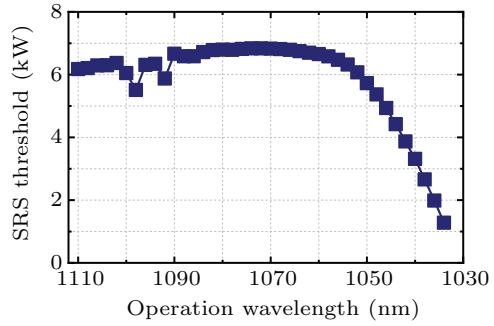


Fig. 5. SRS threshold of the fiber amplifier as a function of the operation wavelength.

3.2. Impact of ASE noise in the seed laser

To demonstrate the impact of ASE noise in the Raman wavelength band in the seed laser, we change the relative strength of intensity noise to adjust Raman ratio in the seed laser and simulate the output property of the fiber amplifier. The operation wavelength of the fiber amplifier is first set to be 1060 nm. Figure 6 illustrates the Raman ratio of signal laser at different output powers when Raman ratios in the seed laser are set to be −100 dB, −80 dB, and −60 dB, respectively. As shown in Fig. 6, the differences among the SRS thresholds are also due to the diversity of initial value. In addition, the SRS thresholds of the fiber amplifier in the three cases are estimated to be ∼ 6.7 kW, ∼ 6.1 kW, and ∼ 4.4 kW, respectively.

To obtain the region in which ASE noise in the seed laser dominates in the strength of ASE noise along the fiber, the distribution of Raman ratio along the fiber is also calculated. Figure 7 illustrates the distribution of Raman ratio along the fiber as a function of Raman ratio in the seed laser, when the pump power is set to be zero. As shown in Fig. 7, the Raman ratio grows along the fiber in different cases. Notably, when Raman ratio in the seed laser is less than −90 dB, it barely affects the distribution of Raman ratio along the fiber, and when Raman ratio in the seed laser is more than −90 dB, it could affect the distribution of Raman ratio along the fiber.

Figure 8 illustrates the SRS threshold of the fiber amplifier as a function of Raman ratio in the seed laser, when the operation wavelength is set to be 1060 nm, 1050 nm, and 1040 nm, respectively. As shown in Fig. 8, the overall trend of the SRS threshold is similar to each other in the three cases. Specifically, the SRS threshold keeps almost unchanged when Raman ratio in the seed laser is below −90 dB, and reduces almost linearly when further increases Raman ratio in the seed laser. In addition, the corresponding reduction rates for the operation wavelengths 1060 nm, 1050 nm, and 1040 nm are ∼ 80 W/dB, ∼ 88 W/dB, and ∼ 96 W/dB in the linear region, respectively. Thus, ASE noise among the Raman wavelength band in the seed laser could reduce the SRS threshold of high-power fiber amplifiers at different operation wavelengths under the condition that the Raman ratio is over −90 dB in the seed laser.

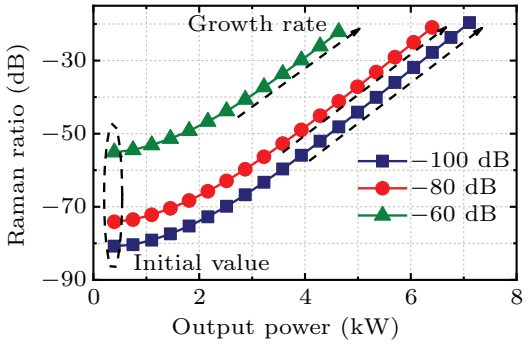


Fig. 6. Raman ratio of signal laser at different output powers as a function of Raman ratio in the seed laser.

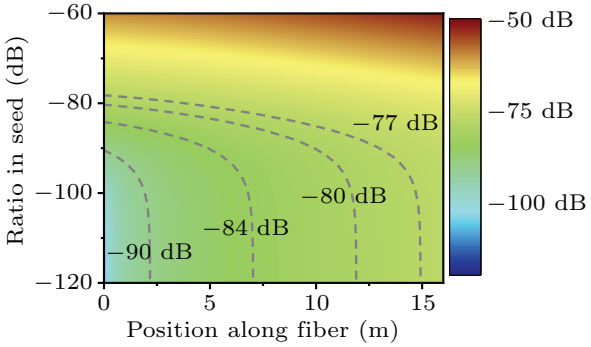


Fig. 7. Distribution of Raman ratio along the fiber as a function of Raman ratio in the seed laser.

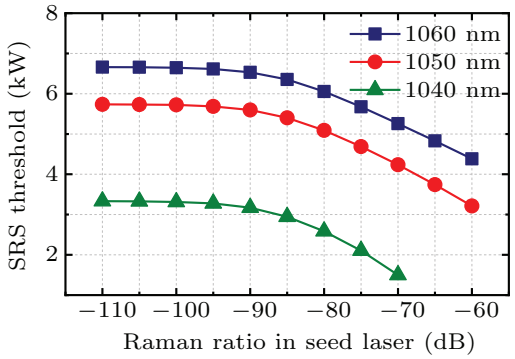


Fig. 8. SRS threshold of the fiber amplifier as a function of Raman ratio in the seed laser.

3.3. Improvement of the SRS threshold by controlling the strength of ASE noise

To this end, we have demonstrated that both ASE noise originated from the seed laser and the main amplifier could reduce the SRS threshold of the fiber amplifier significantly. Correspondingly, improving the SRS threshold of high-power fiber amplifiers requires to control the strength of ASE noise along the fiber through optimizations of the seed laser or the main amplifier. As for the optimization of seed laser, filtering out the spectral component in the Raman wavelength band could be beneficial under the condition that the Raman ratio is over −90 dB in the seed laser. This strategy has been fulfilled by incorporating a tilted fiber Bragg grating[24] or a long-period fiber grating[25] between the seed laser and the main amplifier. As for the optimization of main amplifier, it commonly requires highly doped and large-core fiber to increase the cladding absorption coefficient and to reduce the length of active fiber in the main amplifier.[26] Figure 9 illustrates the SRS threshold of the fiber amplifier at shorter operation wavelength as a function of the length of active fiber.

The total cladding absorption coefficient of the fiber amplifier is assumed to be constant in different cases. As shown in Fig. 9, the SRS threshold increases with shorter active fiber. Considering an output power of 5 kW, the lengths of active fiber for the operation wavelengths of 1040 nm, 1038 nm, and 1036 nm should be shortened to ∼ 11 m, ∼ 9 m, and ∼ 7 m, respectively. In addition, when the length of active fiber is shortened to ∼ 6 m, the SRS threshold of the fiber amplifier operating at 1034 nm could reach 4 kW.

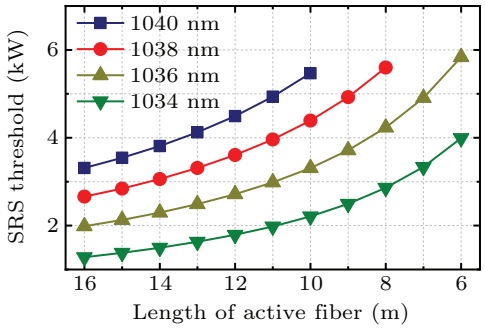


Fig. 9. SRS threshold of the fiber amplifier at shorter operation wavelengths as a function of the length of active fiber.

4. Conclusion

In summary, we have demonstrated the impact of ASE noise on the SRS threshold of high-power fiber amplifiers operating at different wavelengths numerically through a spectral evolution approach. The simulation results confirm that ASE noise in the Raman wavelength band could reduce the SRS threshold of high-power fiber amplifiers significantly. On the one hand, ASE noise in the Raman wavelength band could originate from the re-absorption effect in the main amplifier. It becomes stronger to reduce the SRS threshold of high-power fiber amplifiers at shorter operation wavelengths below 1052 nm. On the other hand, ASE noise in the Raman wavelength band could also originate from the seed laser. It reduces the SRS threshold of high-power fiber amplifiers at different operation wavelengths under the condition that the Raman ratio is over −90 dB in the seed laser. Furthermore, we have discussed the potential strategies to improve the SRS threshold via controlling ASE noise in the seed laser or the main amplifier. Overall, the theoretical method and results could provide a well reference to extend the operation wavelength of high-power fiber lasers.

Acknowledgement

Project supported by the National Natural Science Foundation of China (Grant Nos. 62005313 and 62061136013).

References

[1] Richardson D J, Nilsson J and Clarkson W A 2010 *J. Opt. Soc. Am. B* **27** B63
[2] Zervas M N and Codemard C A 2014 *IEEE J. Sel. Top. Quantum Electron.* **20** 0904123
[3] Zhou P, Leng J, Xiao H, Ma P, Xu J, Liu W, Yao T, Zhang H, Huang L and Pan Z 2021 *Chin. J. Lasers* **48** 2000001 (in Chinese)
[4] An Y, Pan Z, Yang H. Huang L, Ma P, Yan Z, Jiang Z and Zhou P 2021 *Acta Phys. Sin.* **70** 204204 (in Chinese)
[5] Lin X, Zhang Z, Xing Y, Chen G, Liao L, Peng J, Li H, Dai N and Li J 2022 *Acta Phys. Sin.* **71** 034205 (in Chinese)
[6] Zhou T, Liang X, Li C, Zhao L, Wang J and Jing F 2016 *Chin. Phys. Lett.* **33** 124205
[7] Zheng Y, Yang Y, Wang J, Hu M, Liu G, Zhao X, Chen X, Liu K, Zhao C, He B and Zhou J 2016 *Opt. Express* **24** 12063
[8] Runcorn T H, Görlitz F G, Murray R T and Kelleher E J R 2018 *IEEE J. Sel. Top. Quantum Electron.* **24** 1400208
[9] Zervas M N 2019 *Opt. Express* **27** 19019
[10] Jauregui C, Otto H J, Stutzki F, Limpert J and Tunnermann A 2015 *Opt. Express* **23** 20203
[11] Liu W, Ma P, Lv H, Xu J, Zhou P and Jiang Z 2016 *Opt. Express* **24** 8708
[12] Ren S, Lai W, Wang G, Li W, Song J, Chen Y, Ma P, Liu W and Zhou P 2022 *Opt. Express* **30** 7845
[13] Desurvire E and Simpson J R 1989 *J. Lightw. Technol.* **7** 835
[14] Kurkov A S 2007 *Laser Phys. Lett.* **4** 93
[15] Beier F, Otto H J, Jauregui C, de Vries O, Schreiber T, Limpert J, Eberhardt R and Tünnermann A 2014 *Opt. Lett.* **39** 3725
[16] Tian J, Xiao Q, Li D, Liu Z, Yu W, Yan P and Gong M 2020 *J. Opt. Soc. Am. B* **37** 2514
[17] Chu Q, Shu Q, Liu Y, Tao R, Yan D, Lin H, Wang J and Jing F 2020 *Opt. Lett.* **45** 6502
[18] Kramer R G, Moller F, Matzdorf C, Goebel T A, Strecker M, Heck M, Richter D, Plotner M, Schreiber T, Tunnermann A and Nolte S 2020 *Opt. Lett.* **45** 1447
[19] Huang Z, Shu Q, Tao R, Chu Q, Luo Y, Yan D, Feng X, Liu Y, Wu W, Zhang H, Lin H, Wang J and Jing F 2021 *IEEE Photon. Technol. Lett.* **33** 1181
[20] Yang B, Wang P, Zhang H, Xi X, Shi C, Wang X and Xu X 2021 *Opt. Express* **29** 26366
[21] Ma P, Xiao H, Liu W, Zhang H, Wang X, Leng J and Zhou P 2021 *High Power Laser Sci. Eng.* **9** e45
[22] Liu W, Ma P, Lv H, Xu J, Zhou P and Jiang Z 2016 *Opt. Express* **24** 26715
[23] Liu W, Ma P, Zhou P and Jiang Z 2020 *Opt. Express* **28** 593
[24] Wang M, Wang Z, Liu L, Hu Q, Xiao H and Xu X 2019 *Photon. Res.* **7** 167
[25] Jiao K, Shen H, Guan Z, Yang F and Zhu R 2020 *Opt. Express* **28** 6048
[26] Naderi N A, Dajani I and Flores A 2016 *Opt. Lett.* **41** 1018