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Mitigation of stimulated Raman scattering in kilowatt-level diode-pumped fiber amplifiers with chirped and tilted fiber Bragg gratings

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Abstract

The average power of diode-pumped fiber lasers has been developed deeply into the kW regime in the past years. However, stimulated Raman scattering (SRS) is still a major factor limiting the further power scaling. Here, we have demonstrated the mitigation of SRS in kilowatt-level diode-pumped fiber amplifiers using a chirped and tilted fiber Bragg grating (CTFBG) for the first time. The CTFBG is designed and inscribed in large-mode-area (LMA) fibers, matching with the operating wavelength of the fiber amplifier. With the CTFBG inserted between the seed laser and the amplifier stage, an SRS suppression ratio of ~10 dB is achieved in spectrum at the maximum output laser power of 2.35 kW, and there is no reduction in laser slope efficiency and degradation in beam quality. This work proves the feasibility and practicability of CTFBGs for SRS suppression in high-power fiber lasers, which is very useful for the further power scaling.

Keywords: fiber Bragg gratings; fiber lasers; high power; stimulated Raman scattering

1. Introduction

In the past decade, due to the advantages of diffraction-limited beam quality, compactness, high efficiency, stability and robustness, high-power fiber lasers have been intensively researched and used in many applications[1–3]. With the deepening of research on limitation factors of power scaling in fiber lasers, such as pump brightness, nonlinear effects and thermal induced modal instability (TMI), the output power has experienced an outstanding increase. Considering convenience and cost, laser diode is the most common pump source for kilowatt-level fiber lasers. Among the limitation factors, stimulated Raman scattering (SRS) is one of the primary limits for further power scaling and reliability of diode-pumped fiber laser systems. Once SRS effect occurs, the energy of pump light would convert to that of Stokes light, which leads to the decline of signal power. At the same time, the backward propagating Stokes wave is a threat to the whole system and will seriously affect the normal operation of the seed oscillator. Therefore suppression of SRS has become a quite essential research content for fiber lasers.

So far, researchers have proposed many methods for SRS suppression in fiber systems, such as the application of large-mode-area (LMA) fibers or enlarging the fiber mode area[4], spectrally selective fibers[5–8], or lumped spectral filters[9–11] like long-period gratings (LPGs). It might be the most effective technique to suppress SRS by enlarging the fiber mode area of LMA fibers. But the enlarging of fiber mode area must be combined with controlling numerical aperture (NA) for the operation of fundamental mode. Otherwise it will lead to a decreased TMI threshold in fiber lasers, which also limits further power scaling. It is quite difficult to realize by today's material and manufacturing technologies of fibers. The designing of spectrally selective fibers is usually very complex. Besides, it is also not easy to manufacture such fibers and it is still limited by the maximum fiber core size that can be employed. The working principle of lumped filters is similar to that of spectrally selective fibers, but it is much easier to design and fabricate such filters. LPGs have good filtering properties by coupling the Raman light from the core mode to the cladding mode[9], but the filtering characters of LPGs are unstable for their high sensitivities to the environment variables such as temperature, strain or humidity. Chirped and tilted fiber

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Bragg gratings (CTFBGs) have similar filtering properties by special mode coupling, and could offer another interesting choice for SRS suppression in fiber laser. CTFBGs have a continuous broadband spectral profile, a better stability and an easily adjustable wavelength range, which can be made sufficiently wide to block a full SRS bandwidth as a rejection filter. It has been proposed and discussed in the concept of wideband adjustable band-rejection filters based on CTFBGs[12–14]. In our previous works, CTFBGs have been fabricated on single-mode fiber HI1060 and applied in fiber amplifiers for the suppression of SRS[15, 16], and initial experimental results have demonstrated that effective filtering for Raman light could be achieved by CTFBGs. However, the experiment is conducted under the condition of low-power level and the grating is fabricated in single-mode fibers HI1060, which is not suitable for high-power fiber oscillators and amplifiers, where LMA double-cladding fibers are used. Recently, we reported the combination of CTFBG and LMA fibers[17], which lays the foundation of CTFBGs-based SRS suppression in high-power fiber laser systems.

In this paper, we demonstrate the mitigation of SRS in practical kilowatt-level diode-pumped fiber amplifiers using a CTFBG for the first time. According to the operating wavelength of the fiber amplifier, we design the filtering center wavelength of the CTFBG and inscribe it in LMA fibers by the method of rotating phase mask[15]. The CTFBG is inserted between the seed laser and the amplifier stage to filter the Stokes light or noise of the seed laser, and the performance comparisons are made under different pumping schemes. A maximum SRS suppression ratio of 8 or 10 dB is achieved in spectrum at maximum output power with co-pumping or bi-pumping schemes, respectively, in the kilowatt regime. Moreover, increase of equivalent Raman threshold and decrease of Stokes power are observed with no reduction in laser efficiency and degradation in beam quality. Experimental results validate the efficiency and superiority of CTFBGs and their extensive application value for SRS suppression in practical high-power fiber amplifier systems. In the future, a number of CTFBGs could be concatenated one after the other in higher power systems for a better suppression.

2. Principle and experimental setup

The CTFBG is inscribed by the method of rotating phase mask with 248 nm ultraviolet (UV) light beam produced by an excimer laser (COMPexPro110, made by Coherent Corporation, using KrF) with single pulse energy of 120 mJ and a repetition rate of 36 Hz. The UV light is finally focused on the phase mask by a cylindrical lens. We only rotate the phase mask around the axis of UV light beam to introduce tilting in fiber grating. Due to the low photo-sensitivity of LMA-GDF-20/400-M (manufactured by Nufern), we have to take PS-GDF-20/400-M (manufactured by Nufern) as an alternative, which could be used in the high-power fiber system for matching the passive 20/400 fiber well. According to the simulation[17], we take 4° as the tilting angle of phase mask. A linearly chirped phase mask with a period of 785.8 nm and a chirp rate of 2 nm/cm is used. The transmission spectrum of CTFBG used in our following experiments is shown in Figure 1. TFBG possesses a periodic refractive index modulation along the fiber axis, but the tilt angle between fiber cross section and grating plane leads to more complex mode coupling. We can see a number of discrete resonances in the short wavelength range corresponding to core–cladding mode coupling in the transmission spectrum. With chirping, they overlap each other as a smooth envelope. The resonances caused by core–cladding mode coupling do not show up in the reflection spectrum because the power carried by these modes gets stripped away. We can see that the cladding mode envelop has a 3 dB bandwidth about 13.44 nm, and a central depth deeper than −30 dB at 1133.2 nm. The insertion loss at 1080 nm is measured to be about 0.39 dB by the standard cutoff method and the residual reflection of Bragg resonance peak is less than 5% at 1144.5 nm.

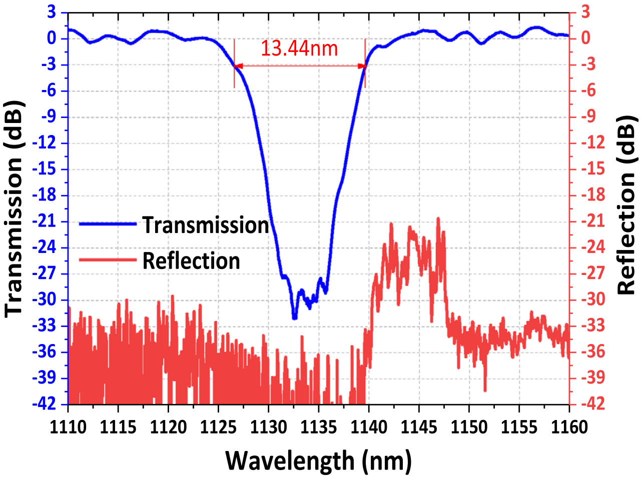

Figure 1. The measured spectrum of the CTFBG fabricated for the following experiments.

Figure 2 shows the experimental configuration for the mitigation of SRS in kilowatt-level diode-pumped fiber amplifiers. We take a homemade all-fiber laser oscillator pumped by 976 nm laser diodes (LDs) as the seed laser of our system. The linear laser cavity consists of a pair of fiber Bragg gratings (FBGs) whose central reflective wavelength is 1080 nm and a gain fiber with a length of 13 m. The reflectivity of high reflection (HR) FBG is 99.9% while that of output coupling (OC) FBG is 9%. CTFBG is inserted between the seed laser and the amplifier stage without any other change to the system. A cladding light stripper (CLS) is made before the amplifier stage to prevent the seed laser from unabsorbed backward pump laser. The gain fiber of

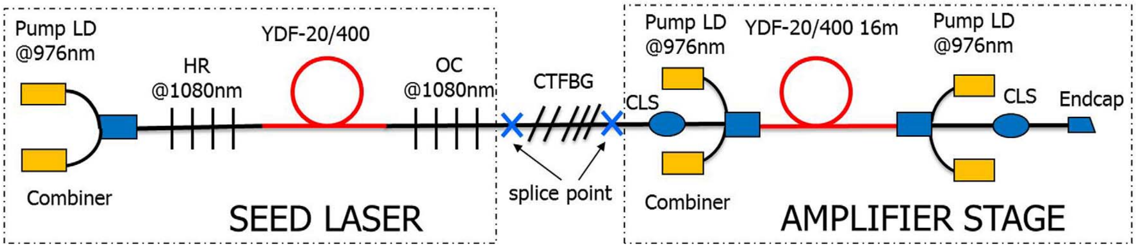

Figure 2. Experimental configuration for the mitigation of SRS in a bi-directional pumping fiber amplifier. HR: high reflection FBG, OC: output coupler FBG, LD: laser diode, YDF-20/400: LMA-YDF-20/400-M by Nufern, CLS: cladding light stripper.

our amplifier is a piece of LMA-YDF-20/400-M, which is chosen to be 16 m in our experiment for adequate total pump absorption. The amplified signal power is led out from the signal port of backward pumping combiner and a pigtailed endcap is spliced to the output port to eliminate probable harmful feedbacks at output facet. A CLS is also made to provide protection to the endcap. After the endcap, we use a power meter, optical spectrum analyzer (OSA), and beam quality analyzer (M^2-200) to record power, optical spectrum and beam quality, respectively.

3. Experimental results and discussion

Co-pumping and bi-pumping are the common pumping schemes for fiber amplifier systems. The co-pumping scheme is the simplest and therefore the most common, but it is unfavorable for suppression of various nonlinear effects. In comparison, the bi-pumping scheme can restrain the nonlinear effect and also make the heat distribution more uniform, which is beneficial for heat management. We have carried out experiments under both pumping schemes for detailed performance of the CTFBG.

3.1. Performance of co-pumping scheme

First, we test the performance of the fiber amplifier under co-pumping scheme. The seed power is fixed to be 36 W as its working point, which is relatively low for a higher long-term operation stability. Figure 3(a) shows the changing spectra without CTFBG under different pump power levels. The total output power is 1385 W with pump power 2069 W. The Stokes light near 1134 nm, corresponding to the Raman shift wavelength of 1080 nm, could be observed at pump power 1582 W, then increases rapidly. Here, we define the equivalent Raman threshold as the pump power when the difference between signal and Stokes light reaches 40 dB in spectrum, and it is 1582 W. Without any change except CTFBG inserted, the output spectra are shown in Figure 3(b). Due to the loss of two splicing points added and insertion loss of CTFBG, we have to increase the output power of seed laser to meet its working point. The total output power is still 1385 W with pump power 2069 W. The Stokes light starts to be observed at pump power 1756 W, and the equivalent Raman threshold is 1913 W, higher than that without CTFBG. Current research has shown that the Raman noise level of seed laser in high-power continuous-wave fiber amplifier would affect SRS of the whole system, even when it is much weaker than the seeded signal light[18]. When the seeded Raman power exceeds a certain value, the Raman threshold decreases with increasing seeded Raman power. CTFBG could block Raman noise or Stokes light and effectively reduce the Raman noise of seed laser. Thus the equivalent Raman threshold could be improved and SRS could be suppressed by inserted CTFBG. It can be seen that the level of Stokes light is lower than that without CTFBG at the same pump level, and the Raman signal is strongly suppressed at higher power level. Compared with the results in our previous work[15], the Raman random laser caused by residual Bragg resonance peak of CTFBG has not been excited even at maximum pump power level. It is the low Raman noise level of seed laser at working point that leads to the difference. Figure 3(c) shows the comparison of normalized spectra at pump power 2069 W. The level of noise base in Figure 3(a) and Figure 3(b) is different. For an accurate comparison, we adjust the intensity level of spectrum at 2069 W in Figure 3(b) to make the intensity at 1080 nm be the same as that in spectrum at 2069 W in Figure 3(a). The whole process is called normalization. The difference between signal and Stokes light is 30 dB or 38 dB without or with CTFBG, respectively, which means a suppression ratio of 8 dB on spectra. The suppression ratio is much lower than the depth of cladding mode envelop of inserted CTFBG, which is mainly due to the relatively low Raman noise level of seed laser. Besides, given the exponential growth of Raman light, a different SRS intensity would be achieved at same pump power level under different Raman threshold, and the difference is related to the degree that how much pump power is beyond threshold, which could be shown as the difference between signal and Stokes light. With a higher power level, the suppression ratio would grow. Figure 3(d) shows the signal ratio of total output, calculated by spectral integral. Here the signal ratio is defined as the ratio of signal light (centered at 1080 nm) to the total output in spectrum. A deeper dive can be observed without CTFBG, which means the decrease of Stokes ratio.

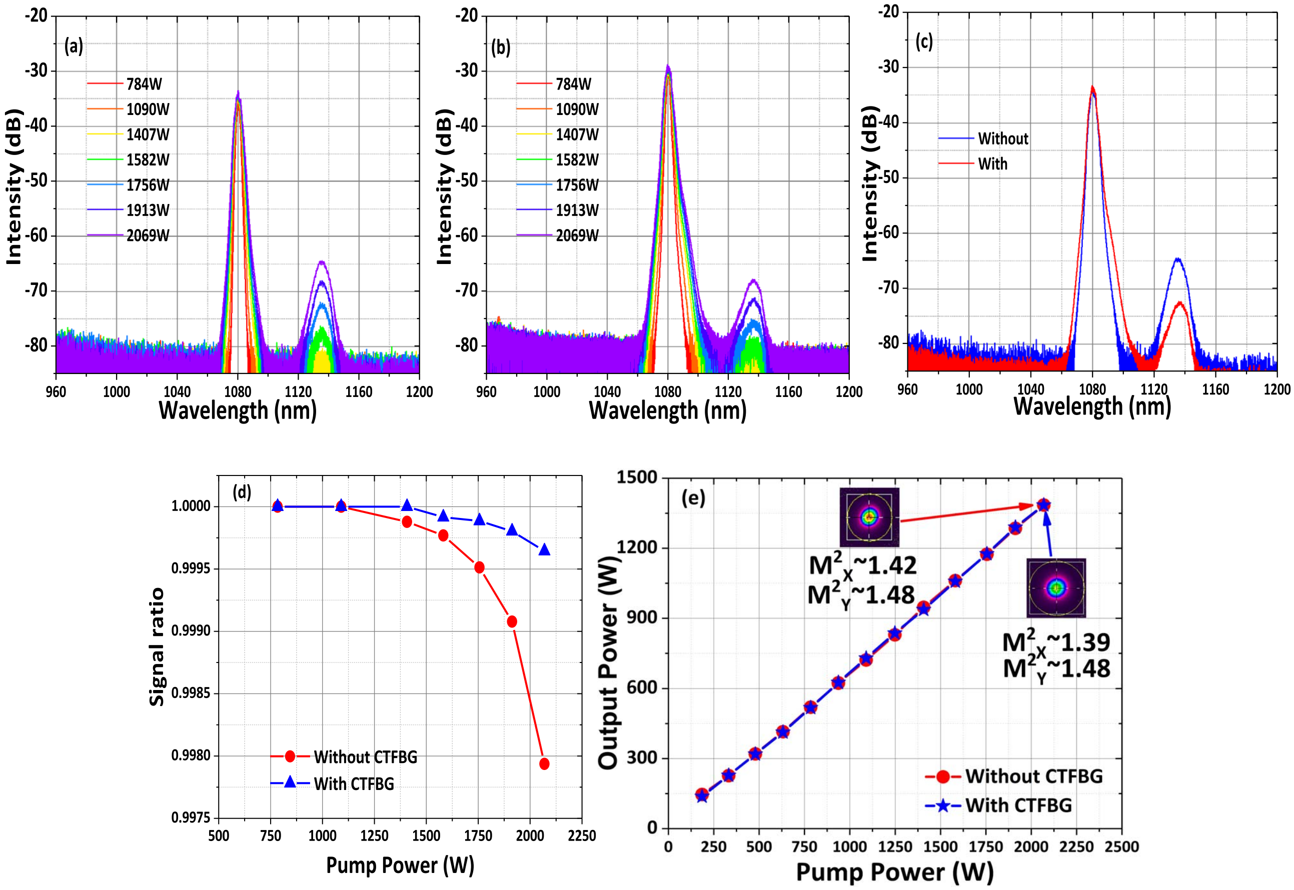

Figure 3. Changing spectra of output as the pump power increases (a) without and (b) with CTFBG inserted, (c) comparison spectra at pump power of 2069 W, (d) signal ratio and (e) output power versus pump power with and without CTFBG.

But the signal ratio is such big that we could hardly see the decrease in slope efficiency. The output power versus pump power of amplifier stage is shown in Figure 3(e). Both of them have a slope efficiency of 65%. Because of the low Stoke light ratio of total output, there is hardly a difference in output power without or with CTFBG inserted, and the slope efficiencies are nearly the same. Figure 3(e) also shows the beam quality and profile of the output without or with CTFBG inserted. There is almost no difference in the beam quality of output, and the M^2 factor maintains $\sim$1.48. Experimental results demonstrate that CTFBG could be practically applied in co-pumping high-power fiber amplifier systems for SRS suppression.

3.2. Performance of bi-pumping scheme

Then we test the performance of our fiber amplifier under bi-directional pumping scheme. The seed power is fixed to be 36 W as its working point, too. We increase pump powers from both directions at beginning until total pump power reaches 2944 W, and then only counter pumping can be added. The power variation curve and output spectra are plotted in Figure 4. Figure 4(a) shows the changing spectra without CTFBG under different pump levels. The total output power is 2350 W with pump power 3569 W. Here the equivalent Raman threshold is defined as the pump power when the difference between signal and Stokes light reaches 33 dB in the spectrum. It is 2944 W here, and 1913 W in Figure 3(a). Compared with results with co-pumping scheme, the equivalent Raman threshold is much larger and the intensity of Stokes light is much lower at the same total pump power, which shows the advantage of bi-pumping scheme on SRS suppression. The output spectra with CTFBG inserted are shown in Figure 4(b). The total output power is still 2350 W with pump power 3569 W. The equivalent Raman threshold is 3418 W, higher than that without CTFBG. It can be seen that the level of Stokes light is lower than that without CTFBG at the same pump level, and the Raman signal is strongly suppressed at higher power level. Similar to the aforementioned situation, the Raman random laser cannot be observed. Figure 4(c) shows the comparison of normalized spectra at pump power 3569 W. The difference between signal and Stokes light at pump power 3569 W is 22 dB or 32 dB without or with CTFBG inserted, respectively, which means a suppression ratio of 10 dB on spectra. The suppression ratio is larger than that

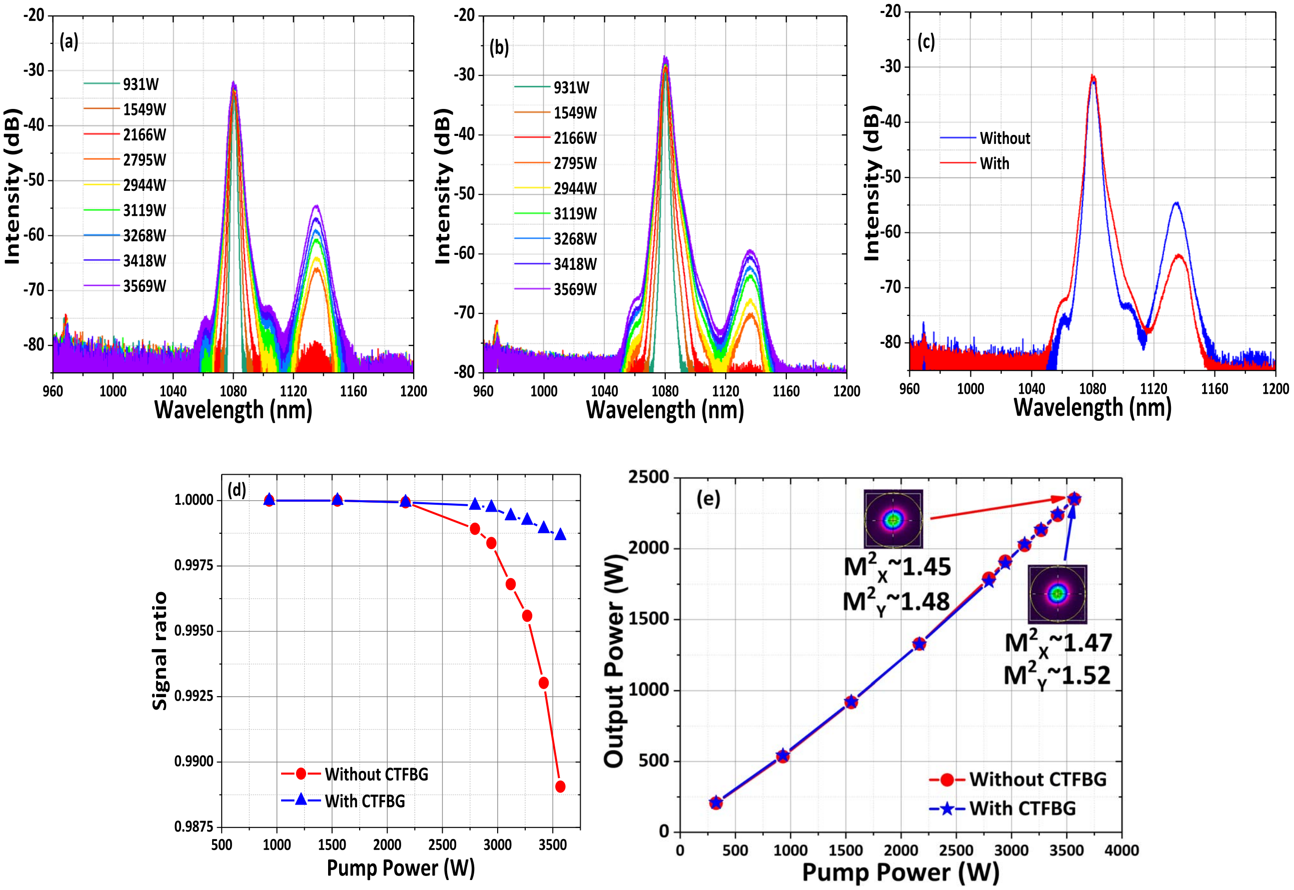

Figure 4. Changing spectra of output as the pump power increases (a) without and (b) with CTFBG inserted, (c) comparison spectra at pump power of 3569 W, (d) signal ratio and (e) output power versus pump power with and without CTFBG.

with co-pumping scheme, which is mainly due to a higher power level. Figure 4(d) shows the signal ratio of total output, calculated by spectral integral. A deeper dive could be observed without CTFBG, but the signal ratio is still quite large. The output power versus pump power of amplifier stage is calculated in Figure 4(e). Both of them have a slope efficiency of 65%, the same as the results with co-pumping scheme. There is still hardly a difference in output power without or with CTFBG inserted, and the slope efficiencies are nearly the same. Figure 4(e) also shows the beam quality and profile of the output, and no degradation in the beam quality of output can be observed. Even at the maximum output power of 2350 W, the M^2 factor still maintains ~1.5, similar to aforementioned situation. Experimental results show the advantages of bi-pumping scheme and prove the efficiency and superiority of CTFBGs and their extensive application value for SRS suppression in practical high-power fiber amplifier systems.

4. Conclusions

We have demonstrated the mitigation of SRS in kilowatt-level diode-pumped fiber amplifiers using a CTFBG inscribed in LMA fibers for the first time. The filtering center wavelength of the CTFBG is designed to match well with the operating wavelength of the fiber amplifier. With the CTFBG inserted between the seed laser and the amplifier stage, maximum SRS suppression ratios of 8 or 10 dB are achieved in spectrum at maximum output power with co-pumping or bi-pumping schemes, respectively, and increase of equivalent Raman threshold and decrease of Stokes power are observed with no reduction in laser efficiency and degradation in beam quality. This work proves the feasibility and practicability of CTFBGs for SRS suppression in high-power fiber lasers. Moreover, with a deeper rejection ratio and lower insertion loss, a number of CTFBGs could be concatenated one after the other, which is significant for power scaling in the high-power amplifiers in the future.

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References

1. D. J. Richardson, J. Nilsson, and W. A. Clarkson, J. Opt. Soc. Am. B **27**, B63 (2010).

2. J. Nilsson, S. Ramachandran, T. Shay, and A. Shirakawa, IEEE J. Sel. Top. Quantum Electron. **15**, 1 (2009).
3. C. Jauregui, J. Limpert, and A. Tünnermann, Nat. Photon. **7**, 861 (2013).
4. Y. Wang, C. Xu, and H. Po, Opt. Commun. **242**, 487 (2004).
5. J. Kim, P. Dupriez, C. Codemard, J. Nilsson, and J. K. Sahu, Opt. Express **14**, 5103 (2006).
6. L. Zenteno, J. Wang, D. Walton, B. Ruffin, M. Li, S. Gray, and A. Crowley, Opt. Express **13**, 8921 (2005).
7. J. M. Fini, M. D. Mermelstein, M. F. Yan, R. T. Bise, A. D. Yablon, P. W. Wisk, and M. J. Andrejco, Opt. Lett. **31**, 2550 (2006).
8. T. Taru, J. Hou, and J. C. Knight, Tech. Rep. Ieice Oft **107**, 711 (2007).
9. F. Jansen, D. Nodop, C. Jauregui, J. Limpert, and A. Tunnermann, Opt. Express **17**, 16255 (2009).
10. D. Nodop, C. Jauregui, F. Jansen, J. Limpert, and A. Tünnermann, Opt. Lett. **35**, 2982 (2010).
11. M. Heck, V. Bock, R. G. Krämer, D. Richter, T. A. Goebel, C. Matzdorf, A. Liem, T. Schreiber, A. Tünnermann, and S. Nolte, Proc. SPIE **10512**, 105121I (2018).
12. T. Osuch, T. Jurek, and K. Jedrzejewski, Proc. SPIE **8903**, 89030W (2013).
13. I. Riant, C. Muller, T. Lopez, V. Croz, and P. Sansonetti, in *Proceedings of IEEE Optical Fiber Communication Conference* (2000), p. 118.
14. F. Liu, T. Guo, C. Wu, B.-O. Guan, C. Lu, H.-Y. Tam, and J. Albert, Opt. Express **22**, 24430 (2014).
15. M. Wang, Y. Zhang, Z. Wang, J. Sun, J. Cao, J. Leng, X. Gu, and X. Xu, Opt. Express **25**, 1529 (2017).
16. M. Wang, Z. Li, L. Liu, Z. Wang, and X. Xu, Laser Phys. **28**, 125102 (2018).
17. M. Wang, Z. Li, L. Liu, Z. Wang, X. Gu, and X. Xu, Appl. Opt. **57**, 4376 (2018).
18. H. Ying, J. Cao, Y. Yu, M. Wang, Z. Wang, and J. Chen, Optik-Internat. J. Light Electron Opt. **144**, 163 (2017).