PHOTONICS Research

Effective suppression of stimulated Raman scattering in half 10 kW tandem pumping fiber lasers using chirped and tilted fiber Bragg gratings

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The average power of fiber lasers has been scaled deeply into the kW regime in the past years. However, stimulated Raman scattering (SRS) is still a major factor limiting further power scaling. Here, we have demonstrated for the first time, to the best of our knowledge, the suppression of SRS in a half 10 kW tandem pumping fiber amplifier using chirped and tilted fiber Bragg gratings (CTFBGs). With specially self-designed and manufactured CTFBGs inserted between the seed laser and the amplifier stage, a maximum SRS suppression ratio of >15 dB in spectrum is observed with no reduction in laser efficiency. With one CTFBG, the effective output power is improved to 3.9 kW with a beam quality M^2 factor of ∼1.7 from <3.5 kW with an M^2 factor of >2; with two CTFBGs, the effective laser power reaches 4.2 kW with an increasing ratio of 20% and an M^2 factor of ∼1.8, and further power improvement is limited by the power and performance of the 1018 nm pump sources. This work provides an effective SRS suppression method for high-power all-fiber lasers, which is useful for further power scaling of these systems.

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1. INTRODUCTION

High-power fiber lasers have attracted much attention in many applications due to their diffraction-limited beam quality, compactness, high efficiency, stability, and robustness [1–3]. During the past two decades, with the development of pump brightness and the double-clad (DC) fiber manufacturing technique, the output power of fiber lasers has experienced an outstanding increase. However, further increases to the output power might still be limited by the brightness of the pump source, nonlinear effects, optical damage, and thermally induced modal instability (TMI) [4,5]. The tandem pumping technique is a promising solution for the brightness limitation and modal instability and was employed to demonstrate the first 10 kW level single-mode fiber laser in 2009 [6]. Therefore, tandem pumping fiber lasers have been a research focus in recent years. But stimulated Raman scattering (SRS) is still one of the main limits for further power scaling and the reliability of fiber laser systems with tandem pumping. The SRS effect would generate Stokes waves in the forward- and backward-propagating directions of fiber. Once the SRS threshold is achieved, the forward Stokes light would grow rapidly, leading to the decline of the signal power. The high-power backward-propagating Stokes light is a danger to the seed oscillator and fiber components, which will seriously affect the normal operation of the whole system. Thus, SRS controlling or suppressing becomes essential for further increasing the output power of fiber lasers.

By now, many methods have been proposed for SRS suppression in fiber laser systems, such as enlarging the fiber mode area of large-mode-area (LMA) fibers [7], the application of spectrally selective fibers [8–11], or lumped spectral filters [12–14] such as long-period fiber gratings (LPFGs). LMA fiber was used for suppression of SRS in earlier times but was limited. Theoretically, enlarging the fiber mode area is an effective technique to suppress the SRS. However, a too-large core diameter of the gain fiber will lead to a decreased TMI threshold in fiber lasers, which also becomes an important power scaling limitation. Besides, a low numerical aperture is needed for mode controlling, which brings new challenges for the fiber material and manufacturing technologies. Spectrally selective fibers usually possess highly complex designs and are also limited by the maximum fiber core size that can be employed. This is quite difficult for practical large-scale application in fiber laser systems. Similar to spectrally selective fibers, lumped spectral filters can provide high loss at the Stokes wavelength, which is a promising method with easier design and production. By coupling the Raman light from the core mode to the cladding mode, LPFGs have good filtering properties [12], but instabilities resulting from numerous cross-sensitivities limit their applications. Specially designed CTFBGs could offer another interesting choice for SRS suppression in fiber lasers. Compared with LPFGs, CTFBGs have a continuous broadband spectral profile, better stability, and an easily adjustable wavelength range that can be changed to different tilt angles to meet various requirements, which can be made sufficiently wide to block a full SRS bandwidth as a rejection filter. The concept of wideband adjustable band-rejection filters based on CTFBGs has been proposed and discussed [15–17]. In our previous work, CTFBGs for the suppression of SRS in fiber amplifiers have been fabricated on single-mode HI1060 [18], and initial experimental results have demonstrated that CTFBGs could be employed as an effective SRS filtering component. Then, we reported the combination of CTFBGs and large-mode-area DC fibers [19], which lays the foundation of CTFBG-based SRS suppression in high-power fiber laser systems.

In this paper, we first demonstrate the suppression of SRS in a high-power tandem pumping fiber laser amplifier using CTFBGs. The CTFBGs are fabricated in LMA fibers by the rotating phase mask method, and the filtering center wavelength is designed according to the operating wavelength of the fiber laser. With CTFBGs inserted between the seed laser and amplifier stage, an effective SRS suppression of >15 dB in spectrum is observed with no reduction in laser efficiency, which greatly helps the improvement of the output laser power and beam quality. The effective output power is improved from 3.5 to 3.9 kW with one CTFBG and 4.2 kW with two CTFBGs; meanwhile, the beam quality remains good with an M^2 factor of about 1.7. The laser output power can be further promoted by improving the power and performance of the 1018 nm pump source. This work provides an effective SRS suppression method for high-power all-fiber lasers; in the future, a number of CTFBGs concatenated one after the other can be used in the power scaling.

2. EXPERIMENTAL SETUP

The CTFBGs are inscribed with an ultraviolet (UV) laser beam by the rotating phase mask method [18,19]. The 248 nm UV light is produced by an excimer laser (COMPexPro110, made by Coherent Corporation, using KrF) and finally focused on a chirped phase mask by a cylindrical lens. As for tilting, we only rotate the phase mask around the axis of the light beam. The photosensitivity of passive 20/400 fiber is not enough for us to write a CTFBG. Instead, we take the corresponding photosensitive 20/400 fiber, which matches the passive 20/400 fiber well and could be used in the high-power fiber system. During the process of inscription, the excimer laser produces UV light with a single-pulse energy of 120 mJ and a repetition rate of 36 Hz. According to the simulation results [19], we take 4° as the tilting angle of the phase mask. A linearly chirped phase mask with a period of 785.8 nm and a chirp rate of 2 nm/cm is used.

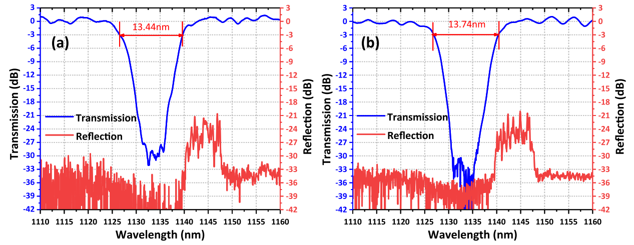

Fig. 1. Measured spectrum of CTFBGs fabricated for the following experiments: (a) CTFBG I and (b) CTFBG II.

Figure 1 shows the transmission spectra of the two CTFBGs used in our experiments. From Fig. 1, we can see that the 3 dB bandwidths are ~13.44 and ~13.74 nm, respectively, and both the central depths of the cladding mode envelop are deeper than −30 dB at 1133.2 nm, which matches well with the SRS peak wavelength of the fiber amplifier. The insertion losses at 1080 nm are measured to be ~0.39 dB and ~0.5 dB by the standard cut-off method. The residual reflections of Bragg resonance peaks are both less than 5% at the wavelength of 1144.5 nm. Besides, we also tested the central wavelength shift with the temperature and the temperature enhanced with the laser power of the CTFBG. Results show that the CTFBG has good temperature stability with a wavelength shift factor of about 6 pm/°C, and the temperature of the CTFBG is about 34°C with cooling and package at the operation of 300 W at 1080 nm, which meets the requirements of long-term high-power operation.

The experimental configuration for the suppression of SRS in a tandem pumping fiber amplifier is shown in Fig. 2. The seed laser of our system is a homemade all-fiber laser oscillator pumped by 976 nm laser diodes (LDs). The linear laser cavity consists of a pair of FBGs whose central reflective wavelengths are 1080 nm and a gain fiber with a core/cladding diameter of 20/400 μm. The reflectivity of the highly reflective (HR) fiber Bragg grating (FBG) is 99.9% and that of the output coupling (OC) FBG is 9%. The length of gain fiber used is 13 m. The output port of the OC FBG is directly fused into the signal port of a combiner to provide seed power to the amplifier stage, and the cladding light stripper (CLS) is made at this point to avoid unabsorbed backward pump laser injection to the seed laser. The core/cladding diameter of the signal and output fiber of the combiner and the gain fiber of our amplifier is 30/250 μm. In our experiments, the active fiber length is chosen to be 41 m to ensure adequate total pump absorption. Two self-made combined 3000 W 1018 nm fiber lasers are used

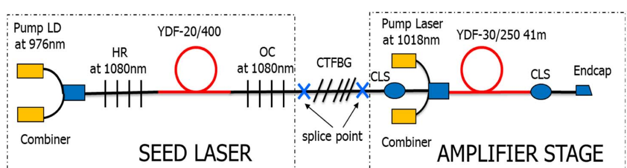

Fig. 2. Experimental configuration for the suppression of SRS in a tandem pumping fiber amplifier. HR, highly reflective FBG; OC, output coupler FBG; LD, laser diode; YDF-20/400, Yb-doped 20/400 fiber; YDF-30/250, Yb-doped 30/250 fiber; CLS, cladding light stripper.

as the pump source. The amplified signal power is led out by a pigtailed endcap, which is spliced to the gain fiber to eliminate probable harmful feedback at the output facet. Another CLS is also made before the connection point of the endcap to provide protection to the endcap. After the endcap, we use a power meter and an optical spectrum analyzer to record power and optical spectrum, respectively. One or two CTFBGs are inserted between the seed laser and amplifier stage without any other change to the system.

3. EXPERIMENTAL RESULTS AND DISCUSSION

A. Performance with One CTFBG

First, we test the performance of our fiber amplifier with one CTFBG. The effective seed power (injecting into the amplifier) is fixed to be 180 W as its working point. The amplifier output power variation curve with the pump, the output spectra, and the beam qualities are shown in Fig. 3. Figure 3(a) shows the changing spectra without CTFBGs under different pump levels. The total output power is 3490 W with maximum pump power of 4190 W. The Stokes light near 1134 nm,

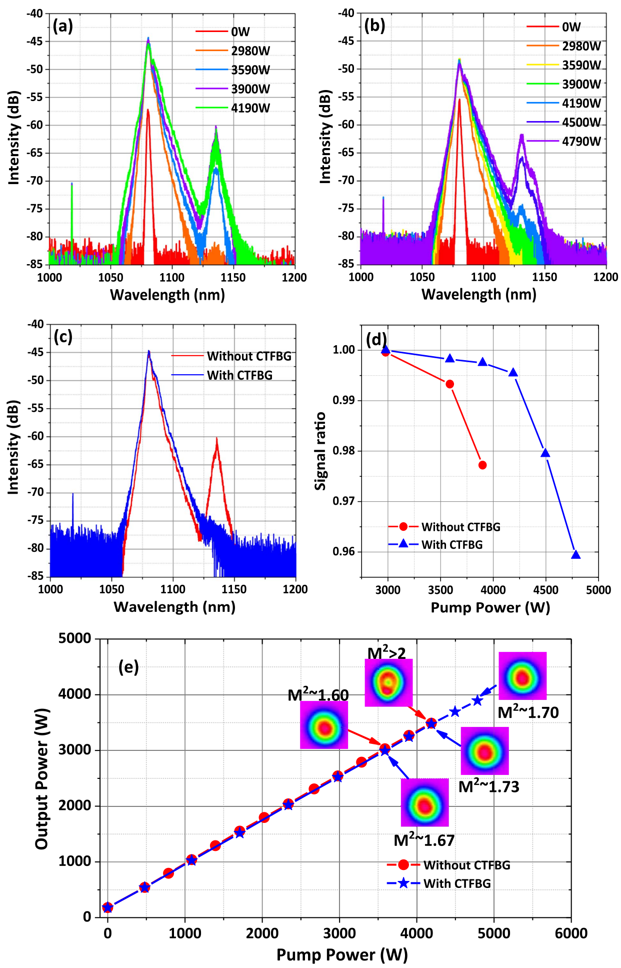

Fig. 3. Changing spectra of output as the pump power increases (a) without and (b) with a CTFBG inserted, and comparison of (c) spectra at pump power 3490 W, (d) signal ratio, and (e) output power versus pump power with and without CTFBG I together with the beam quality and profile of the output.

corresponding to the Raman signal of 1080 nm, could be observed at pump power 2980 W and then increase rapidly. When the pump power reaches 4190 W, the TMI occurs, which leads to a degraded beam quality together with SRS, as shown in Fig. 3(e). Without any change, except the CTFBG I being inserted, the output spectra are shown in Fig. 3(b). Due to the total losses of the two splicing points and the inserted CTFBG, we have to increase the output power of the seed laser to meet its working point. In our experiment, the loss induced by the splices is around 0.8 dB. It is the mismatch in fiber type, 20/400 and 30/250, that results in the relatively big loss. The total output power is 3900 W with maximum pump power of 4790 W. The Stokes light starts to be observed at a pump power of 3900 W, which means a larger Raman threshold is achieved. 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 a higher power level. Compared with the results in our previous work [18], the Raman random laser caused by the residual Bragg resonance peak of the CTFBG has not been excited even at the maximum pump power level. It is the low Raman noise level of the seed laser at the working point that makes the difference. Figure 3(c) shows the comparison of normalized spectra at a pump power of 3900 W. The difference between the signal and Stokes light is 15 and 30 dB without and with a CTFBG, respectively, which means a suppression ratio of 15 dB on spectra at this power level. Figure 3(d) shows the ratio of signal contents in the output spectrum, calculated by spectral integration, and we name it the signal ratio. A bigger change in the curve could be observed without CTFBG, but the signal ratio is big enough that we can hardly see the decrease in slope efficiency. The amplifier output laser power versus the pump power without and with the CTFBGs is shown in Fig. 3(e). Both of them have a slope efficiency of ~79%. Because of the low ratio of the Stokes light to the total output power, there is hardly any difference in the output before the beam quality degradation, and the slope efficiencies are nearly the same. We stop the measurement with one CTFBG for a too-high Stokes level in the spectrum. For the situation without a CTFBG, in addition to the above reason, the degraded beam profile also makes us stop the measurement. Figure 3(e) also shows the beam quality and profile of the output without or with CTFBG I. When the pump power reaches 4190 W, the beam quality degrades rapidly, and the M^2 factor changes to greater than 2 from 1.60 without CTFBG I, while there are almost no variations when CTFBG I is inserted. Even at the maximum pump power of 4790 W, the M^2 factor still remains at 1.70, which is much better than that without the CTFBG, and an improvement in the output power, 400 W, is also achieved. Here, the improvement of beam quality with a CTFBG is mainly due to the suppression of SRS in the system, which leads to a delayed TMI threshold. Researchers have found that, by suppressing the SRS, the TMI is mitigated and beyond the TMI threshold, and increasing the intensity ratio of the Raman Stokes to the signal beam has a direct effect on the stronger distortion of the beam profile [20]. Experimental results demonstrate that CTFBGs could be practically applied for SRS suppression and further enhancement of the output power in high-power fiber amplifier systems.

B. Performance with Two CTFBGs

Then, we test the performance of our fiber amplifier with two CTFBGs inserted. The effective seed power is fixed to be 130 W as its working point due to the performance of the seed laser and insertion losses of two CTFBGs. The power variation curve, the output spectra, and the beam qualities are shown in Fig. 4. Figure 4(a) shows the changing spectra with CTFBG I under different pump levels. The total output power is 3870 W with a pump power of 4790 W. Without any change except CTFBG II being inserted, the output spectra are shown in Fig. 4(b). The maximum effective output power reaches 4250 W with a pump power of 5370 W. It can be seen that the level of Stokes light is lower than that with only CTFBG I at the same pump level, and the Raman signal is strongly suppressed at a higher power level. Similar to the aforementioned situation, the Raman random laser caused by the residual Bragg resonance peak has not been excited even at maximum pump power. Figure 4(c) shows the comparison of the normalized spectra at a pump power of 4790 W. The difference between the signal and Stokes light is 14 and 29 dB without and with CTFBG II, respectively, which means a suppression ratio of ∼15 dB on spectra. Figure 4(d) shows the ratio of signal contents in the output spectrum, calculated by spectral integration. The output power versus the pump power of the amplifier stage is shown in Fig. 4(e). Both of them have the same laser slope efficiency of 79%. Similar to the aforementioned situation with only one CTFBG, as the ratio of the Stokes light to the total output power is very small, there is also hardly any difference, so the slope efficiencies are nearly the same. Figure 4(e) also shows the beam quality and profile of the output with only CTFBG I and with both CTFBGs. Under both conditions, little difference could be observed in beam quality, and the M^2 factor is about 1.80 before the beam quality degradation. When the pump power reaches about 4800 W, the beam quality degrades rapidly with only CTFBG I, while there are almost no variations when the CTFBG II is inserted. Even at the maximum output laser power of 4250 W, which is limited by the power and performance of the 1018 nm pump sources, the M^2 factor still maintains ∼1.8. Experimental results proved the efficiency and superiority of CTFBGs and their extensive application value for SRS suppression in practical high-power fiber amplifier systems, and a number of CTFBGs concatenated one after the other is an effective method for SRS suppression and further power scaling. For additional high-power applications, the most important problem may be the insertion loss of CTFBG, which will lead to the power loss of the seed and the temperature enhancing of itself. With an optimized inscription system, better CTFBGs could be made for higher-power fiber lasers.

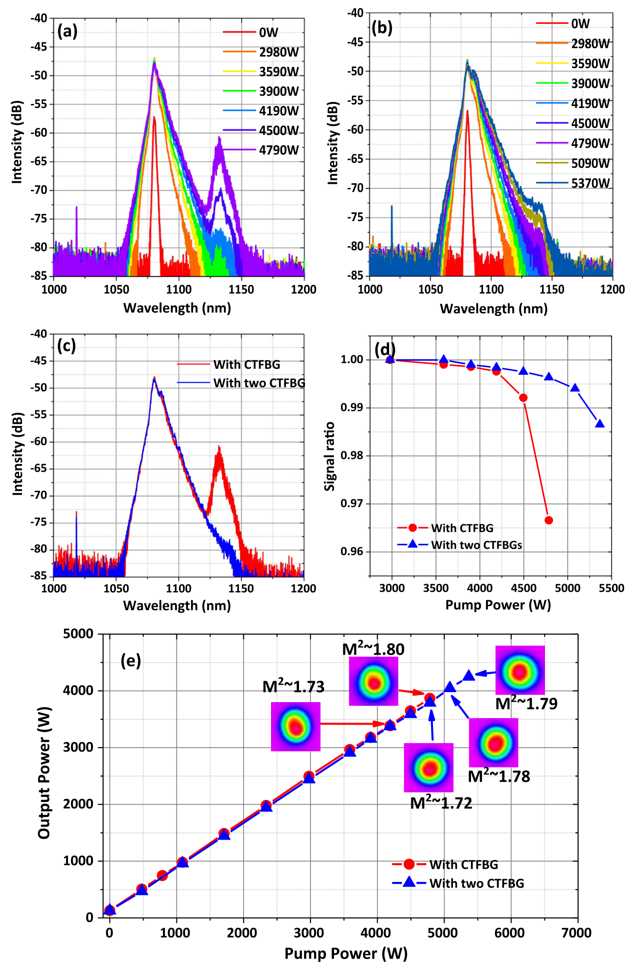

Fig. 4. Changing spectra of the output as the pump power increases with (a) CTFBG I and (b) CTFBGs I and II inserted. Comparison of (c) spectra at pump power 4790 W, (d) signal ratio, and (e) output power versus pump power with CTFBG I or both CTFBGs together with the beam quality and profile of the output.

4. CONCLUSIONS

We have first demonstrated the suppression of SRS in a half 10 kW tandem pumping fiber amplifier with CTFBGs inscribed in LMA DC fibers. The CTFBGs are designed and fabricated to match the peak Raman wavelength of the 1080 nm fiber laser. The Raman noise in the seed fiber laser is greatly suppressed by the CTFBGs inserted between the seed and the amplifier stage, leading to the increase of the Raman threshold in the amplifier. An effective SRS suppression of >15 dB in the spectrum is observed with no reduction in laser efficiency, which greatly helps the improvement of the output laser power and beam quality. With one CTFBG, the effective output power is improved to 3.9 kW with a beam quality M^2 factor of ∼1.7 from <3.5 kW with an M^2 factor of >2; with two CTFBGs, the effective laser power reaches 4.2 kW with an increasing ratio of 20% and an M^2 factor of ∼1.8. Further power improvement is limited by the power and performance of the 1018 nm pump sources. This work provides an effective SRS suppression method for high-power all-fiber lasers, and a number of CTFBGs concatenated one after the other can be used in further power scaling.

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