Suppressing the stimulated Brillouin scattering in high power fiber amplifiers by dual-single-frequency amplification

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Abstract: We demonstrate the suppression of stimulated Brillouin scattering (SBS) in high power fiber amplifiers by a dual-single-frequency amplification. The output power of dual-single-frequency fiber amplifiers in all-fiber configuration is boosted to 275 W with seeds central wavelength of 1063.7 and 1064.4 nm, respectively. The power conversion efficiency is 76.6%. The maximum output power is limited by the pump power and no significant SBS has been detected even at the highest output power. The effect of the delivery fiber length, the optical output spectra and polarization of the amplified laser are also studied experimentally. The relative magnitude of the two single-frequency signals is maintained in the amplification process and the maximal output power of dual-single-frequency amplifiers can be increased by a factor of more than 2 compared with single-frequency amplification.

Suppressing the stimulated Brillouin scattering in high power fiber amplifiers by dual-single-frequency amplification

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1. Introduction

There have been many remarkable advances in high power single-mode fiber lasers and amplifiers recently. In particular, a 10 kW broadband near-diffraction limited fiber laser was announced by IPG in June of 2009 [1]. Scaling to much higher powers with good quality will require combination of many of these high power output. This can be achieved by either coherent or spectral beam combining [2–5], where a narrow spectral linewidth will be required to maintain good beam quality and efficiency. However, stimulated Brillouin scattering (SBS) usually limits the output power for single-frequency operation [6,7].

A number of methods have been applied in single-frequency fiber amplifiers to suppress SBS and increase the output power of amplifiers. Special fibers have been designed to differentiate acoustic and optical waves and reduce their overlap, thereby to eliminate the stimulated process of Brillouin scattering [8–10]. More than 500 W amplified single-frequency laser has been achieved by using large mode area fibers to reduce the power density [11]. The temperature and strain gradients along the fibers can broaden the effective SBS linewidth and thereby reduce the effective gain which has been demonstrated to be a good approach to mitigate SBS [12,13]. However, due to
the overlap in the effective Brillouin gain bandwidth induced by these techniques, the full improvement could not be obtained when they are used in conjunction [13].

As a new approach to suppress SBS, two-tone amplification have attracted many researchers [14–20]. In general, the two-tone amplification can be divided into two sorts according to the output spectrum lines which are single-frequency signal output [15–20] or quasi-single-frequency signal output [14]. The first case where a narrow linewidth fiber amplifier is co-seeded with a broad linewidth seed can output single-frequency signal under proper selection of wavelengths and see power ratio. In this amplification scheme, the SBS process can be mitigated effectively due to the shorter effective SBS gain length and thereby an increased output power will be obtained. It should be emphasized that this SBS suppression scheme should be executed in the main amplifier stage of the master oscillator-amplifier (MOPA) system which means high power wavelength division multiplexer (WDM) is essential. This will restrict the maximal output power. For the latter sort of two-tone amplification, two single-frequency signals are amplified simultaneously throughout the whole amplification system resulting in a quasi-single-frequency signal output. Although the final output signals are not exact single-frequency which means that they are not suitable for efficient nonlinear frequency conversion and gravitational wave detection, they still could be used to improve the output power of individual elements in coherent beam combination (CBC) and spectral beam combination (SBC). The principal limiting factor for this two-tone amplification scheme is deemed to be the complex optical output spectra caused by four-wave mixing (FWM). Nevertheless, the simulated results pronounced that the FWM effects will be low enough to be neglected in Yb-doped amplifiers due to the relatively short length of gain fiber [15]. Besides, a dramatic advantage of this SBS suppression technique is its usability in each stage of MOPA system gaining the freedom from the high power WDM which will promote the output power of the main amplifier stage greatly profiting from the increased seed power. In our experiments, two single-frequency seeds with central wavelengths around 1064 nm are co-amplified in a MOPA system and the maximal output power is boosted to 275 W, the highest power to the best of our knowledge, which is limited by the pump power. Approximately a factor of 2 enhancement on the output power is obtained. Besides, the relative magnitude of the two signals is maintained in amplified laser and no significant SBS has been detected even at the highest output power.

2. Experimental setup

Two single-frequency seeds are used in the MOPA amplification system which are distributed feed back (DFB) laser (laser 1) and Ytterbium-doped fiber (YDF) short-cavity structured fiber laser [21] (laser 2) with the linewidths of about 20 and 2 kHz, respectively, measured by the heterodyne detection system built in our laboratory. The central wavelengths of two single-frequency seeds are 1064.4 nm for laser 1 and 1063.7 nm for laser 2, respectively. The total power of the seeds is 40 mW. The experimental setup is depicted in Fig. 1. Two YDF preamplifiers, and a power scaling amplifier which is based on a large mode area (LMA) non-polarization maintaining YDF are employed for power operation. A 7 W maximal output power of signal laser can be achieved from the second preamplifier. The power scaling stage is based on the LMA YDF for high-power operation. The 4 m long LMA YDF fabricated by Nufern exhibits a 30/250 μm core/inner cladding diameter with 0.06/0.46 NA. The average absorption coefficient is 8.5 dB/m got from the data sheet. The 7 W signal laser and 350 W pump power from 6 laser diodes (LDs) with 976 nm central wavelength are launched into the core and inner cladding of the LMA fiber respectively via a (6+1)×1 pump and signal combiners. The LDs are divided into two groups which consist of 4 and 2 LDs, respectively, and are driven by two separate laser drivers. A 1.2 m long Ge-doped double-clad fiber with same core/inner cladding diameter and NA as the LMA YDF is spliced to the LMA fiber for power delivery. The spliced region is covered in high-index gel to strip the residual pump laser and ensure pure laser output from the amplifier. The delivery fiber’s output end is angle cleaved to suppress parasitic oscillation. Furthermore, the gain fiber is immersed in the gel with high coefficient of heat conductivity. Then the gel is laid on a thermal conductor made of aluminium with cold water circulating inside to exhaust the heat in time. To avoid the optical damage caused by SBS, a tap is employed in the system which picks up a part of the back
scattering light from the final amplifier. Once the backscattered power detected departs from the linear dependence on output signal power, which indicates the onset of SBS, the power supply loaded on the four LDs would be cut off automatically, thus the SBS-induced catastrophic damage can be avoid in time.

3. Results and discussion

The output power for single-frequency MOPAs with the incremental pump power is shown in Fig. 2. The stable maximal output power of 105.9 and 129.7 W are achieved with 175.7 and 203.2 W launched pump power, which are limited by the SBS, for laser 1 and laser 2, respectively. The seed powers are both about 3.5 W for these two amplifiers. The differences between the SBS threshold of the two signals may be induced by the wavelength instability of laser 2. The maximal output power is increased to 256.0 W with the pump power of 334.3 W when laser 1 and laser 2 co-seed, which is a bit more than the sum of the two separate maximal output powers and the greater temperature gradient may be a reasonable physical explanation for the phenomenon. In this amplifier, the seed power is 7 W. In our experiment, the pump group with 4 LDs is started up firstly and the other group with 2 LDs is standby. The inflexion on the curve of two-tone amplifier with the pump power of about 240 W is due to the startup of the stand-by 2 LDs.
When the delivery fiber length is shortened from 1.2 to 0.7 m, the SBS thresholds of three different seeds are all raised, as shown in Fig. 3. The amplifier seed powers all keep the same as mentioned above. The maximal output powers are increased to 120.0 and 168.0 W for laser 1 and laser 2. The output power for dual-single-frequency amplifier is 275.0 W with power conversion efficiency of 76.6%. It should be noted that the maximal output power of the dual-single-frequency fiber amplifier is limited by the maximal 350 W pump power for the moment. Besides, no significant backscattered light has been detected by the photo detector at the maximal output.

The detailed spectra of the seed and amplified laser in dual-single-frequency amplifier are shown in Fig. 4. As we can see, the wavelength difference between the two seeds is about 0.7 nm, which is more than the Brillouin bandwidth of the fiber. Fig. 4b shows wide spectrum scale of amplified laser at maximal output power. From this spectrum we can see that the remnant pump power is negligible and the amplified spontaneous emission (ASE) is suppressed by over 35 dB. Fig. 4c illustrates the detailed spectrum around 1064 nm, which demonstrates that the relative magnitude is maintained in amplified laser. Besides, the additional frequency-sidebands are generated with identical frequency spacing due to the FWM effects of two 1064 nm signals. However, the FWM effects are suppressed by over 15 dB, in correspondence with the prediction in [15].

Considering the effect of the polarization on the threshold of SBS [22], the polarization extinction ratios (PERs) of seeds and amplified lasers have been measured for the three amplifiers with a commercial extinction ratio meter (Thorlabs ERM1000). The PERs of seeds for three amplifiers shown in Fig. 3 are measured to be more than 20 dB. The PERs of amplified lasers shown in Fig. 5, which have been taken at the full output power, have some differences. Nevertheless, the average values of the PERs are measured to be about 20, 18, and 12 dB for laser 1, laser 2, and dual-single-frequency laser, respectively, which exclude the effects of polarization on the SBS threshold.

4. Conclusion

In conclusion, we have presented the detailed characteristics of a stable MOPA structured high power dual-single-frequency amplifier in all-fiber configuration. When the delivery fiber is 1.2 m, the two single-frequency seed can be stably boosted to maximal output powers of 105.9 and 129.7 W, respectively, limited by the effect of SBS. With the same amplifier configuration, the dual-single-frequency laser can be amplified to 256.0 W limited by SBS, which is more than the sum of the maximal power for each single seed. When the delivery fiber length is shortened to 0.7 m, the maximal output powers for single seed can be increased to 120.0 and 168.0 W, respectively. The maximal output power for the dual-single-frequency laser.

Figure 5 (online color at www.lasphys.com) PERs of amplified lights: (a) – laser 1, (b) – laser 2, and (c) – dual-single-frequency laser
amplifier is 275.0 W, which is limited by the available pump power. The relative magnitude of the two seeds is maintained in the amplification process and no significant backscattered light has been detected at the maximal output. The PERs have been also measured in our experiments in order to eliminate the effect of polarization on the SBS threshold. The coherent beam combination of three dual-single-frequency fiber amplifiers has been executed [23]. The experimental results suggest that multi-single-frequency amplification technique is a feasible way to improve the power of the single chain for CBC. Furthermore, proving experiments should be done to examine the compatibility of this SBS suppression technique with other suppression schemes, such as additional extra temperature and strain gradients and specially designed acoustic tailored gain fibers, in the future.

References


