A 168-W high-power single-frequency amplifier in an all-fiber configuration

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We present a high-power, single-frequency, narrow linewidth fiber amplifier based on master oscillator power amplification chains in an all-fiber configuration. The effect of the delivery fiber on the maximum output power is studied. A home-made 1064-nm seed laser with a 20-kHz linewidth is boosted to 129 W, and limited by stimulated Brillouin scattering (SBS) when the delivery fiber is 1.2 m long. By shortening the delivery fiber length to 0.7 m, the SBS threshold is increased efficiently and the maximum output power rises to 168 W with an 82.9% power conversion efficiency. The experimental results indicate that the output power can be further raised by shortening the delivery fiber length and increasing the pump power.

Keywords: fiber amplifier, single frequency, all-fiber, stimulated Brillouin scattering

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1. Introduction

High-power, single-frequency fiber lasers are desirable for many applications, including coherent beam combinations, gravitational wave detection, nonlinear frequency conversion, range findings and laser radars.[1−2] High-power, single-frequency lasers are generally realized using the master oscillator power amplification (MOPA) configuration rather than a laser oscillator, due to its long cavity and high operation power threshold.[2−8] The output power of single-frequency fiber lasers has increased dramatically in recent years. In 2005 Hildebrandt *et al.* reported a 148 W single-frequency output with a photonic crystal fiber amplifier.[5] In the same year, Jeong *et al.* presented a single-frequency, single-mode, plane-polarized ytterbium-doped all-fiber master oscillator power amplifier source at 1060 nm, generating 264 W of continuous-wave (CW) output power.[6] Gray *et al.* reported a 502-W YDF amplifier in 2007.[7] Jeong *et al.* also reported a 511-W random-polarized MOPA source in the same year.[1] However, all these high-power amplifiers employed combinations of single fibers and bulk optics. The use of all-fiber-based components can significantly simplify the system configuration and thus become much more compact and robust. However, reports on high-power, single-frequency and all-fiber CW amplifiers are very rare.[9] The high-power operation of single-frequency fiber amplifiers is usually limited by the onset of stimulated Brillouin scattering (SBS),[2,3] because of the tight confinement of the laser in the fiber core and the long interaction length. A number of approaches, such as the use of thermal gradients,[1,10] large mode area fibers[11] and acoustically tailored fibers,[2,12] have been either demonstrated or suggested to suppress SBS in fiber amplifiers. Nevertheless, Liu[13] predicted in theory that the all-fibrized single-frequency amplifier is limited to several hundred watts output until some key breakthroughs have been made to mitigate SBS in passive delivery fibers. A passive delivery fiber is a length of un-doped fiber spliced to the output end of a gain fiber for delivering a high-power laser beam into the work station. Liu[13] regarded the length of the delivery fiber as one of the most influential parameters that has a great impact on amplifier performance.

In this article, we describe the amplification of a home-made, 1064 nm single-frequency, narrow-linewidth (less than 20 kHz) fiber laser in an MOPA structured all-fiber configuration. We also experimentally investigate the effect of delivery fiber length on SBS threshold and amplifier performance. A 129-W maximum output power is achieved, limited by SBS

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when the delivery fiber is 1.2 m long. After the delivery fiber is shortened to 0.7 m, the maximum output power is stabilized at 168 W.

2. Experiment

The full MOPA chain used in our experiment is depicted in Fig. 1. A 1064-nm, 40-mW short-cavity structured fiber laser[14] with a linewidth less than 20 kHz is followed by three YDF amplification stages separated by isolators. The two preamplification stages and the power scaling stage are all built with all-fiber components. The first stage is a conventional polarization-maintaining (PM) single-mode amplifier that can boost the output power to 200 mW. The second stage is a double-clad YDF amplifier co-pumped by two 975 nm pigtailed laser diodes (LDs). The gain fiber in this stage has a 15 μm diameter core with a numerical aperture (NA) below 0.08. The diameter and the NA of the inner cladding are 130 μm and 0.46, respectively. The output power of this stage is tunable from 100 mW to 6 W. The two preamplification stages are conduction-cooled, which exhibits a small size, high reliability and is maintenance-free. The water-cooled power scaling stage is based on a large mode area (LMA) non-polarization maintaining YDF for high-power operation. The 4 m long LMA YDF exhibits a 30 μm/250 μm core/inner cladding diameter with 0.06/0.46 NA. The average absorption coefficient is 7.5 dB/m at 975 nm. In the amplifier, the fiber is co-pumped by four LDs at 975 nm. A 1:99 coupler is inserted at the input of the scaling stage to monitor the backscattered light. To avoid the optical damage caused by SBS, the 1%-output port of the coupler is spliced to a pigtailed photo detector, whose output is sent to a control circuit. Once the backscattered power detected departs from the linear dependence on output signal power, which indicates the onset of SBS, the power supply of the four LDs will be cut off automatically by the control circuit to avoid time-related SBS-induced catastrophic damage. A 1.2 m long Ge-doped double-clad fiber of the same core/inner cladding diameter and NA with the LMA YDF is spliced to the LMA fiber for power delivery. The spliced region is covered with high-index gel to strip the residual pump laser. The delivery fiber's output end is angle cleaved to suppress parasitic oscillation.

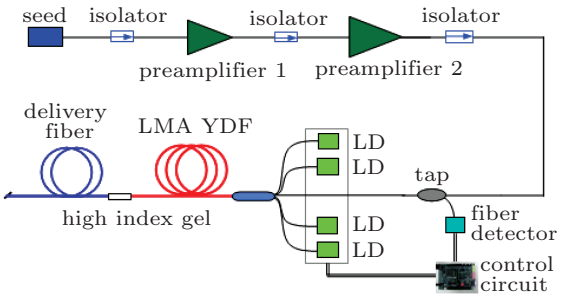


Fig. 1. (colour online) A schematic diagram of the single-frequency MOPA.

The output power measured at the incremental pump power is shown in Fig. 2. A stable maximum output of 129 W is achieved with 183 W launched pump power without generating significant SBS when the delivery fiber is 1.2 m long ($L = 1.2$ m). A further increase in pump power would lead to the power supply of the LDs being cut off for the onset of SBS. It is found in Fig. 2 that the slope of the curve gradually increases with pump power, which is induced by the center wavelength shift of the pump laser. The center wavelengths of the four LDs used in our amplifier have a 0.3 nm/°C dependence on temperature. As the output power increases, the rising temperature inside the LD leads to a gradual shift in the center wavelength to 975 nm, which is the absorption peak of Yb ions. Therefore, the power conversion efficiency is gradually increased.

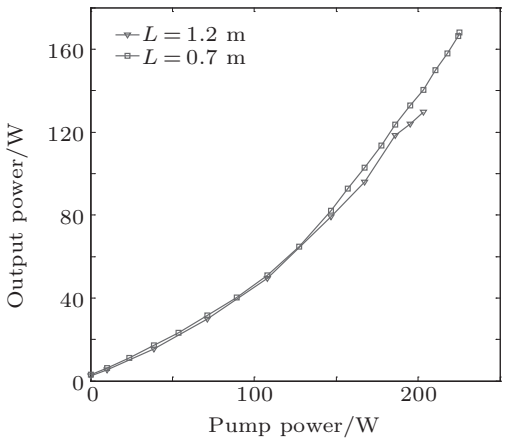


Fig. 2. Output signal power as a function of launched pump power.

When the delivery fiber length is shortened from 1.2 m to 0.7 m, the SBS threshold rises significantly and the stable maximum output power rises to 168 W with a 82.9% power conversion efficiency. The output power is only limited by the available pump power. Our experimental results have a good coincidence with

Liu's theory.[13] Note that the two curves in Fig. 2 depart gradually at high pump power. This is due to the fact that the coil diameter of YDF is increased for the convenience of measurement when the delivery fiber is shortened, and thus the bend loss is reduced. However, the measured results in the two cases still have a good similarity, which has demonstrated the amplifier's repeatability. At the maximum output power level, our amplifier operates for an hour with no obvious power fluctuations or other problems and has good stability.

Figure 3 shows the spectra of the seed laser and the amplifier measured at 168 W using an optical spectrum analyzer (Agilent 86142A) with a resolution of 0.06 nm. The linewidth is hardly broadened after the amplifier compared with the linewidth of the seed laser. Figure 4 shows the output spectrum in the range of 950–1100 nm at 168 W output power. It is observed that amplified spontaneous emission (ASE) has built up in the short wavelength region, but is very weak compared with the signal laser and thus has little effect on the amplifier's performance.

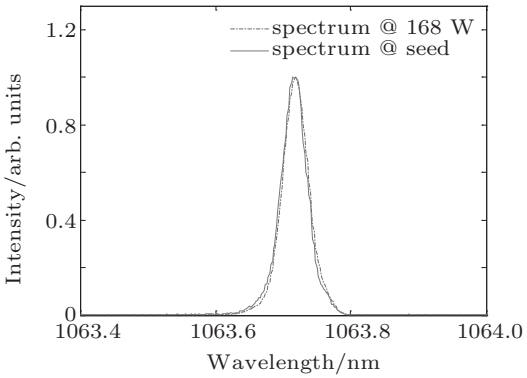


Fig. 3. The spectrum of the signal laser.

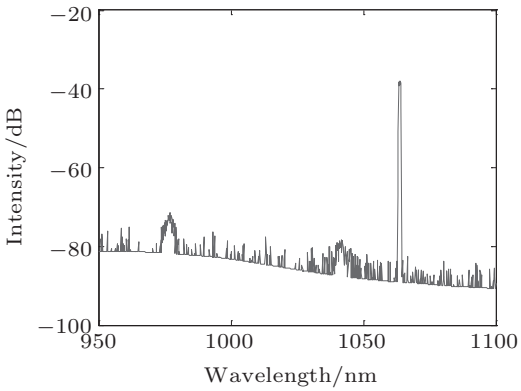


Fig. 4. The spectrum of the amplifier.

The polarization extinction ratio (PER) fluctuations of the seed laser and the amplifier measured by a commercial extinction ratio meter (Thorlabs ERM1000) are shown in Figs. 5 and 6, respectively. The seed laser exhibited steady polarization characteristics, with a PER higher than 22 dB. From Fig. 6 we can find that the PER of the output signal laser has degraded to an average level of 16 dB. This is due to the non-polarization maintaining property of the second and third amplification stages. Mechanical perturbations and temperature nonuniformity along the fiber are the main causes of PER degradation. Note that the PER will degrade more severely if the environmental conditions are worse.

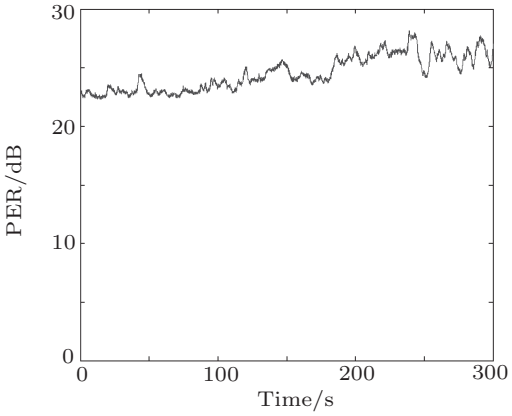


Fig. 5. The PER fluctuation of the seed laser.

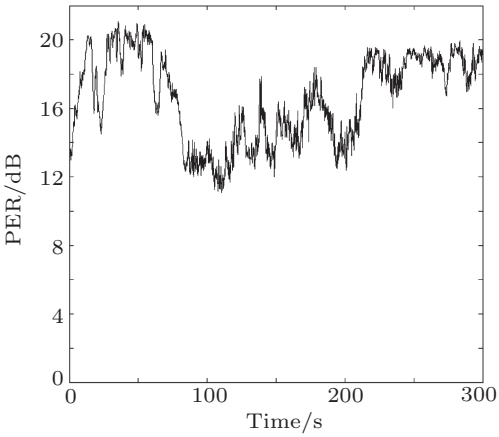


Fig. 6. The PER fluctuation of the amplifier.

3. Conclusion

In summary, we presented the detailed characteristics of a stable MOPA structured high-power single-frequency amplifier in an all-fiber configuration. The single-frequency seed laser can be stably boosted to

a 168-W maximum output without generating significant SBS when the delivery fiber length is 0.7 m. The amplifier exhibits good stability when operated at a high power level. Our experimental results have also demonstrated that the SBS threshold would change inversely with the length of the delivery fiber. The output power of the amplifier can be further increased with a shorter delivery fiber and a more powerful pump source.

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