Experimental study on kilowatt fiber laser in an all-fiber configuration

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A high-power fiber laser in an all-fiber format is reported. The system consists of 36 pump ports, which use both counter and forward pump configuration. In the experiment, 1 008-W output power is obtained when 24 pump ports are used with a total pump power of 1 477 W. The optical-to-optical conversion efficiency is 68% and the 3-dB bandwidth of laser output increases with output power. Presently, the output power is only limited by the pump source. It can be predicted that the laser power can be further scaled if more pump sources are utilized.

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Silica-based fiber lasers and amplifiers are of great interest because of their excellent beam quality, large heat dissipation, high power handling, and robustness, which give significant advantages over traditional gas or crystal-based lasers. Among all the rare-earth doped fiber lasers, research has significantly increased on ytterbium-doped fiber (YDF) lasers for its high efficiency and great potential for power scaling. Since 1999, all the record-breaking near-diffraction-limited fiber lasers are Yb doped[1]. The superior power scaling property of Yb-doped lasers is mainly attributed to its low quantum defect, which is only 10% when pumped by 975-nm laser diodes. This can significantly reduce thermal load inside the fiber and make high doping concentration achievable without concentration quenching[2], both of which are important factors for power scaling[1]. Power scaling of YDF lasers and amplifiers is advancing rapidly with the development of high-power laser diode (LD) sources and the advances in double-clad fiber (DCF) design and fabrication.

Kilowatt-level fiber lasers in an all-fiber configuration are also commercially available from several companies[3,4]. IPG, for example, announced that a 10-kW tandem-pumped single mode fiber laser was achieved in 2009[5]. Extensive investigations have also been conducted in China. Zhou *et al.* obtained 714-W laser output power based on a home-made double clad YDF in 2006[6]. In the same year, a kW-level fiber laser was achieved by Zhao *et al.*[7]. Lou *et al.* also reported a 1.75-kW fiber laser based on a home-made gain fiber in 2009[8]. Nevertheless, these high-power fiber lasers were based on bulk optic configurations with large sizes and massive weights. The use of all-fiber-based components can significantly simplify system configuration and thus make it much more compact and robust. Zhao *et al.*[9] reported a 404-W bi-directionally pumped laser in an all-fiber configuration in 2010[9]. Duan *et al.*, in 2009, demonstrated a kW-level fiber amplifier in an all-fiber configuration consisting of a seed laser and a two-stage fiber amplifier chain[10]. In this letter, the experimental result of an all-fiber YDF laser which is only one stage of resonant cavity is presented. The maximum output power is 1 008 W when 1 477-W pump power is launched into the laser cavity. The fiber laser's output power can be further enhanced with a more powerful pump source.

The experimental setup is shown in Fig. 1. The fiber laser consists of 20-m double-clad YDF, two (6+1) ×1 signal and pump combiners, twelve 3×1 pump combiners, and a pair of fiber Bragg gratings (FBG) centered at 1 080 nm. The gain fiber (LMA-YDF-20/400 Nufern) has a 20-μm diameter core with numerical aperture (NA) of 0.06. The inner cladding diameter is 400 μm, and its NA is 0.46. The nominal cladding absorption coefficient of the gain fiber is 1.26 dB/m at 975 nm. The signal delivery fibers of the two (6+1) ×1 combiners made by ITF laboratories have the same parameters as the gain fiber. The core and cladding diameters of the pump input fibers are 200 and 220 μm, respectively. The pump sources of the fiber laser are 24 pigtailed LDs purchased from Apollo Instruments with an average output power of 65 W. The output fiber of these LDs are 105/125-μm multimode (MM) fibers, which are mismatched with the pump delivery fiber of the (6+1)×1 combiner (C1). The pump power may not be launched efficiently into the gain fiber if the two types of fibers are spliced together directly. Thus, twelve 3×1 pump combiners (C2) are used to solve this problem. The input fibers of this kind

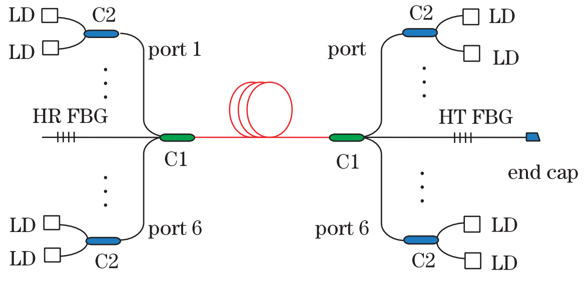

Fig. 1. Experimental setup.

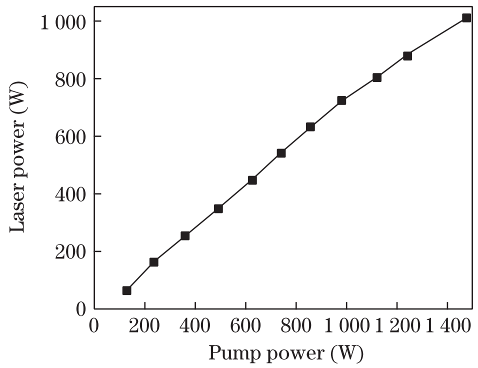

Fig. 2. Output laser power versus pump power.

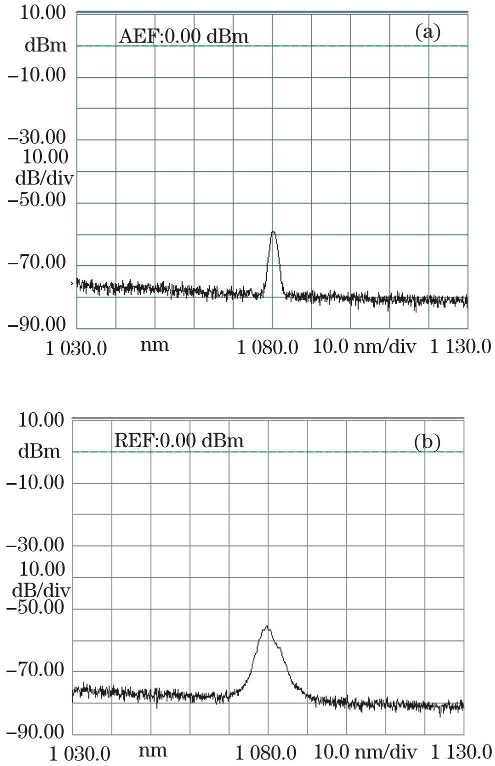

Fig. 3. Output spectra of the fiber laser at output powers of (a) 255 W and (b) 1 008 W.

of combiner are 105/125-μm MM fibers and the output is 200/220 MM fiber. The insertion loss (IL) of these combiners is typically lower than 0.2 dB. For each combiner, only two pump input ports are spliced with LDs and the third port is left unused (not depicted in Fig. 1). The reflectivities of the two FBGs at 1 080 nm are 99.9% and 10%, respectively. One end of the low-reflectivity FBG used as the output coupler is spliced to the signal delivery fiber of the (6+1) ×1 combiner while the other end is spliced with an end cap (Optoskand). The whole fiber laser system is mounted on an active cooled heat sink to avoid thermal damage.

The output power measured at the incremental pump power is shown in Fig. 2. A stable maximum 1 008-W output is achieved with 1 477-W launched pump power. The power conversion efficiency is 68%. At the maximum output power level, the laser system operates for half an hour with no obvious power fluctuations. The power stability is estimated to be within 1%. Presently, the output power is only limited by the pump source. It can be predicted that the laser power can be further enhanced if more pump sources are utilized.

Figures 3(a) and (b) show the fiber laser spectra at 255- and 1 008-W output powers, respectively. The spectra were measured by an optical spectrum analyzer (HP 86142A) with a resolution of 0.06 nm. The calculated full-width at half-maximum (FWHM) of the two output spectra are 1.1 and 3.2 nm, respectively. The FWHM at different power levels (depicted in Fig. 4) was measured to investigate the change of line width with the output power. Figure 5 shows that the FWHM of the output laser gradually increases with output power. This can be attributed to the thermal effect on FBG. The FWHM can be approximately expressed as[11]

$$\Delta\lambda = \lambda_{\mathrm{B}} s \sqrt{\left(\frac{\Delta n}{2n_0}\right)^2 + \left(\frac{1}{N}\right)^2}, \qquad (1)$$

where λ_{B} is the central wavelength of the FBG, s is determined by the reflectivity of the FBG, Δn is the index fluctuation, n_0 is the core index, and N is the number of grating period. The thermal load in the fiber core increases with the launched pump power, which leads to the density change of the fiber core. Thus, the refractive index of the core fluctuates and, in turn, the linewidth of the laser is broadened.

The spatial beam quality was measured using the developed defocus grating based-M^2 factor measuring system to further characterize the property of the kW high-power fiber laser beam[12,13]. The M^2 factor can be measured by snatching one image containing nine

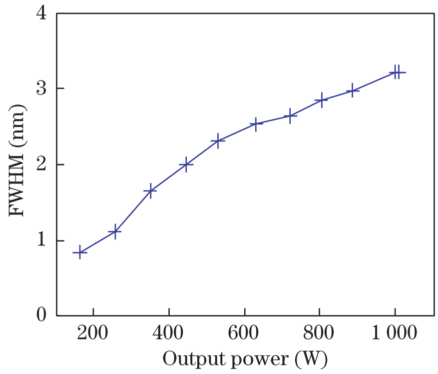

Fig. 4. FWHM of output laser versus output power.

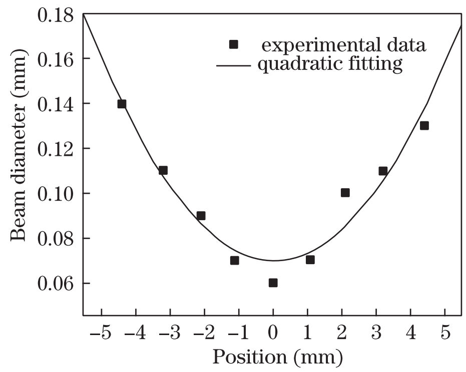

Fig. 5. Plot of beam diameters with positions.

intensity distributions at different defocus planes simultaneously. The results are recorded at its highest power level, as shown in Fig. 5. The computed M^2 factor of the high power fiber laser beam was 1.36.

In conclusion, a high-power bi-directionally pumped fiber laser in an all-fiber configuration is presented. The pump source limits the output power thus the fiber laser generates only 1 008-W output power. The power conversion efficiency is 68%. The FWHM of the laser output increases gradually with the output power and is 3.2 nm at 1 008-W output with an M^2 factor of 1.36. The long-term power stability is within 1%. Higher beam power can be achieved if more power is launched into the cavity.

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