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LETTER

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Spectral beam combining of 2.8 μm fiber laser based on telescope system

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We reported a spectral beam combining (SBC) of 2.8 μm erbium-doped fluoride glass fiber laser based on a telescope system. The application of the telescope system compressed the spectra of SBC significantly and allowed more fiber lasers to be combined. The SBC of three fiber lasers with a beam combining the efficiency of 68% was demonstrated. This work shows the ability of SBC in fluoride fiber power scaling.

Lasers around 3 μm have attracted much attention due to their promising applications in laser surgery, remote sensing, frequency conversion, and spectroscopy.[1–7] However, these applications are strongly affected by the power and stability of the laser. Er-doped zirconium fluoride fiber (Er:ZrF_4) laser has made great progress in recent years due to the progress of high-power laser diodes and improved double-clad fluoride fibers.[8] However, compared to silica fiber, fluoride fiber suffers more from a high heat load because of its poor thermal properties and OH diffusion process.[9] Therefore, many works were performed to reduce the heat load on fiber. By pumping from one end of the fiber, 10 W level 2785 nm continuous wave (CW) Er-doped fluoride fiber laser was reported in 2006.[10] By pumping the fiber from both ends to distribute the heat load and cooling the entire fiber in fluorocarbon liquid, a 24 W 2.8 μm fluoride fiber laser is demonstrated, which is the highest reported power obtained from 2.8 μm fiber laser without fiber Bragg gratings (FBG) up to now.[11] With the help of FBG, up to 42 W setup were reported successively.[12–14] These works are heading to the theoretic power limit of fluoride fiber, for further power upscaling, the beam combination technique is a straightforward approach.

Spectral beam combining (SBC) can combine several lasers together with enhanced power while maintaining beam quality close to one laser.[15–18] SBC is a very suitable technique for fluoride fiber laser power scaling because it can spread the heat load to many fibers. The laser number combining in the SBC is limited by the gain bandwidth of fiber due to the broadening of the spectrum. As a reference, Zhu reported a wavelength-tunable fiber laser using 6 mol% Er-doped fluoride fiber, which can be tuned from 2705 to 2805 nm at 1 W 975 nm laser diode pump, but the wavelength-tunable range shrank to 20 nm at 20 W pump power.[19] Combining more laser beams in less than 20 nm wavelength range is a big challenge for SBC of fluoride fiber lasers.

In this letter, a stable three-fiber-lasers SBC system of fluoride fibers was demonstrated using a telescope system to compress the spectral spacing, which is as low as 6.4 nm. The output performance was investigated, and the stability was measured.

The experiment setup was shown in Fig. 1. The fiber used is 70 000 ppm Er:ZrF_4 fiber fabricated by *Le Verre Fluoré*. Each fiber is about 2.5 m long and has a core diameter of 15 μm with a numerical aperture (NA) of 0.12. This fiber has two claddings to improve pump absorption. The inner one is a truncated circular (double D-shaped) cladding with a short/long diameter of 240/260 μm and a NA of 0.46, the outer circular cladding is 290 μm in diameter.

Three laser diode pump sources are operated at 976 nm with a cooling water temperature of 15 °C. They are collimated and coupled respectively into three fibers in free space using aspheric lenses (L1 and L2, $f = 10$ mm, $\phi = 12.7$ mm, NA = 0.54). Dichroic mirror DM1 is coated with reflectivity $R > 99.9\%$ at 2800 nm and transmissivity $T > 99.5\%$ at 976 nm for 0° incidence. A CaF_2 window with anti-reflection (AR) coating at 2800 nm is used to protect the fiber ends. After collimation using lens L3 ($f = 4$ mm, $\phi = 7$ mm), three 2800 nm lasers with 5 mm separation gap are obtained. Dichroic mirror DM2 coated with $R > 99.9\%$ at 2800 nm and $T > 98.0\%$ at 976 nm for 45° angle filters the pump laser and reflects the target laser beam into the telescope system. The telescope system is composed of two plano-convex lenses, L4 and L5. They are set to minify the input light by the ratio of their focal length. In our configuration, L4 is 25.4 mm in diameter and has a focal length of 250 mm, and L5 is 25.4 mm in diameter with a focal length of 40 mm. They are placed to share the same focal point. With the help of Flourier transform lens L6 ($f = 100$ mm, $\phi = 25.4$ mm), the three minified laser beams are focused on a grating. The grating is a 12.5 × 25.0 mm reflective diffraction grating designed for a 3.1 μm wavelength. It has 450 grooves mm^{-1} facet spacing and 32° blaze angle. For 2.8 μm usage, the average diffraction efficiency is 86% for perpendicular polarization and 28% for parallel polarization. The CaF_2 output coupler (OC) is coated with $R = 12.0\%$ at 2800 nm.

Figure 2 shows the power of three fiber lasers and after combining, measured by a thermal power sensor. The power of every single fiber laser was measured by inserting a gold mirror placed at 45° between L4 and DM2. The combined power by SBC is about 2.14 W, corresponding to a combining efficiency of 68.0%. As a proof-of-principle experiment, the fibers used are single-mode fiber with a rather short length, which are the main limitation of power.

The combining efficiency is not remarkably high is mainly due to the diffraction loss of grating. The diffraction loss is determined by grating diffraction efficiency and laser polarization properties. The measured polarization of the combined laser is 89% in perpendicular (to the groove of the grating) orientation and 11% in parallel orientation. According to the diffraction efficiency curve of the grating, the diffraction efficiencies of the grating are respectively 86%

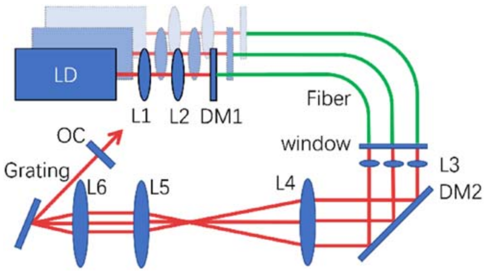

Fig. 1. (Color online) Experimental setup for Er:ZrF_4 fiber laser SBC with telescope system. LD, laser diode; L1, L2, aspheric lenses; DM1, DM2, dichroic mirrors; L3, L4, L5, L6, CaF2 lenses; OC, output coupler.

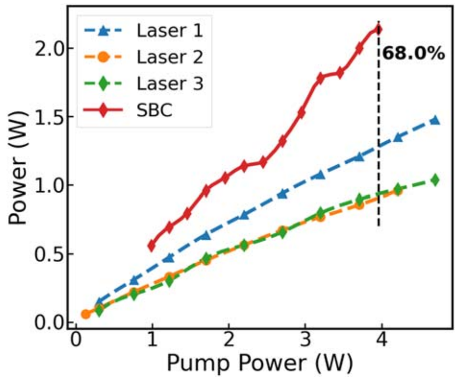

Fig. 2. (Color online) Continuous wave output power curves of three separate fiber lasers and SBC. *X* axis corresponds to the incident pump power for each individual fiber laser. SBC is operated by applying the same pump power for each fiber laser.

and 28% at perpendicular and parallel polarization. It can figure out the overall diffraction efficiency of the grating is about 70%. A grating with high diffraction efficiency at a perpendicular polarization state will significantly improve the combining efficiency.

The high reflectivity of OC and the optical loss of lenses also affect the combining efficiency. The reflectivity of OC is 12%, while at free running the fiber facet and CaF_2 window provide about 4% Fresnel reflection. This leads to a power difference under the same pump power. Combined with the optical loss of lenses in the light path, a 68% combining efficiency is obtained.

Figure 3 shows the spectra of SBC with and without a telescope system, measured by an optical spectrum analyzer (OSA207, Thorlabs Inc.). The measured interval between

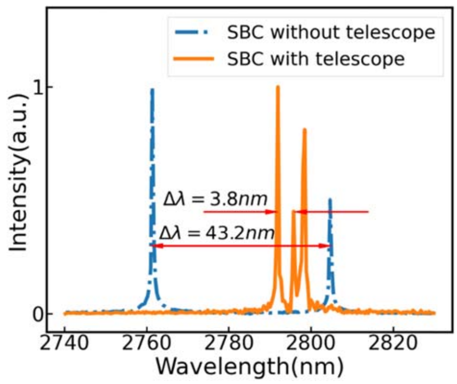

Fig. 3. (Color online) The spectra of SBC of two fiber lasers without telescope system and three fiber lasers with a telescope system.

neighbor peaks is 43.2 nm and 3.8 nm. For a first order diffraction grating, the diffracted light obeys the grating equation, given by $d\cdot(\sin\theta + \sin\alpha) = \lambda$, where d is the groove spacing of the grating, θ is the angle of the incident wave, α is the angle of the diffracted wave, and λ is the wavelength for this light wave. In an SBC configuration, different beams share the same diffraction angle α, and the wavelength difference $\Delta\lambda$ between two adjacent beams can be described as

$$\Delta\lambda = d \cdot 2\cos\theta_0 \cdot \sin(\Delta\theta/2) \approx 2d \cdot \frac{f_2}{f_1} \cdot \cos\theta_0 \cdot D \cdot \frac{1}{f}, \quad (1)$$

where θ_0 is the average incident angle, which should be close to the Littrow angle for maximum diffraction efficiency. D is the spacing between fiber lasers, f is the focus length of the Flourier transform lens, f_1 and f_2 are the focus length of L4 and L5. To reduce the spectrum bandwidth, it should reduce the groove spacing d, decrease laser spacing D, decrease the f_2/f_1 ratio and increase the focus length f if possible.

Generally, the SBC of silica glass fiber lasers requires a micro-lens array to collimate lasers while maintaining a small laser space gap, mostly from 400 μm to 2 mm. However, the micro-lens array is highly difficult to obtain for 2800 nm wavelength. Thus, a plano-convex lens as small as 4 mm in diameter was used as a collimation lens to achieve a small D. With 1 mm spacing for mounting adjustment, the total gap between two adjacent lasers is 5 mm. In this setup, the SBC of two fiber lasers was achieved and the wavelength interval is 43.2 nm as shown in Fig. 3 in dash–dot line. Because of the limit of the gain bandwidth, it is impossible to combine more fiber lasers at high power operation. Since D is limited by the collimation lens, a compressed image imaging by a telescope system can be used to reduce $\Delta\lambda$. With a 250:40 telescope system, the wavelength interval is expected to be compressed to 6.9 nm. Three peaks in the 6.4 nm wavelength range were measured, while the interval between neighbor peaks is 3.8 nm.

The difference between theory and experiment is because of the aberration of the telescope system and mounting error. The telescope system consists of two plano-convex lenses with a diameter of 25.4 mm, which introduced aberration that could affect the beam compress ratio and beam quality. By using specially optimized aspherical lenses, the compress ratio can be precisely controlled. And by using a telescope system with a larger compress ratio and larger lens diameter, SBC of more fiber lasers can be achieved.

One advantage of the SBC technique is adding up power from every laser while maintaining high beam quality. At 2.14 W of SBC power, the beam quality M^2 is, respectively, 2.3 and 2.0 in the beam combining direction and perpendicular to the beam combining direction as shown in Fig. 4. The beam quality is measured by ISO Standard 11142 method.[20] The output beam is focused with a lens ($f = 100$ mm) and captured by a CCD camera (Pyrocam IV, Ophir Photonics). The result shows a little decline compared to the M^2 of single fiber laser, which is 1.2 and 1.3. Since each fiber laser is collimated separately and manually, the three output beams cannot be perfectly paralleled, along with the broadening of the spectrum and

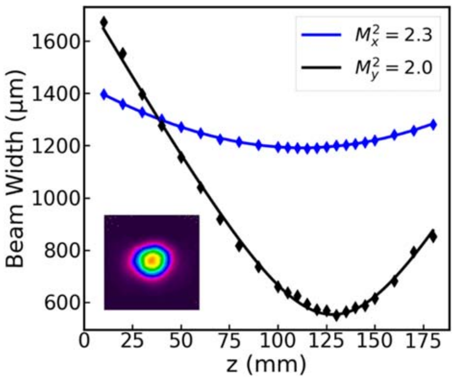

Fig. 4. (Color online) The beam quality M^2 of SBC laser in x and y direction, which was measured at maximum output power. The inset is the lasing spot.

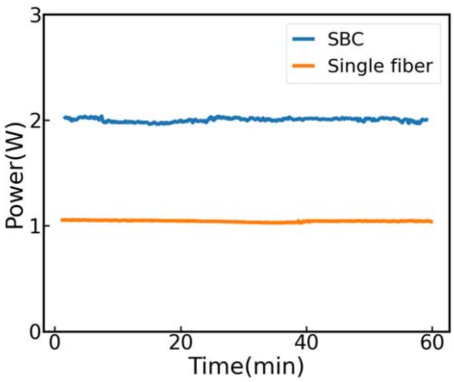

Fig. 5. (Color online) Temporal stability of the SBC and single fiber laser output power over one hour time span, as measured with a power meter with a response time of 1 s and with a resolution of 1 mW.

the aberration of the optical system, affecting the beam quality of SBC.

The stability of this SBC system at 2 W output power was tested. As shown in Fig. 5, the SBC laser beam has more fluctuation than a single fiber laser, but both have root-mean-square (RMS) fluctuations less than 1.0001% in the 1 h test. The result indicates that the fluoride fibers and SBC system are all stable.

In summary, we have demonstrated a stable SBC of 2.8 μm Er:ZrF_4 fiber lasers, which is the first application of SBC in a fluoride fiber laser. The beam combining efficiency is 68%. The spectrum bandwidth is compressed to 6.4 nm by a telescope system. By using longer fibers, designing grating with higher diffraction efficiency, and customizing optical lenses with a larger diameter, SBC setup with higher output power, higher beam combining efficiency, and more fiber lasers are predictably available. This letter proved the possibility of using SBC to obtain high-power fluoride laser source.

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