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Research Article

Over 19 W Single-Mode 1545 nm Er,Yb Codoped All-Fiber Laser

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We report a high-power cladding-pumped Er,Yb codoped all-fiber laser with truly single transverse mode output. The fiber laser is designed to operate at 1545 nm by the use of a pair of fiber Bragg gratings (FBGs) to lock and narrow the output spectrum, which can be very useful in generating the eye-safe ~1650 nm laser emission through the Stimulated Raman Scattering (SRS) in silica fibers that is of interest in many applications. Two pieces of standard single-mode fibers are inserted into the laser cavity and output port to guarantee the truly single-mode output as well as good compatibility with other standard fiber components. We have obtained a maximum output power of 19.2 W at 1544.68 nm with a FWHM spectral width of 0.08 nm, corresponding to an average overall slope efficiency of 31.9% with respect to the launched pump power. This is, to the best of our knowledge, the highest output power reported from simple all-fiber single-mode Er,Yb codoped laser oscillator architecture.

1. Introduction

High-power fiber lasers in the eye-safe wavelength regime around 1.5–1.6 μm have attracted considerable attention in various applications such as spectroscopy, remote sensing, range finding, and free-space and satellite communications. Cladding-pumped Er,Yb codoped fiber laser systems provide a common approach to produce high-power laser emissions in this wavelength region owing to the commercially available efficient double clad gain fiber and high-power InGaAs laser diodes at ~980 nm as a pump source [1–6]. In 2007, Jeong et al. achieved 297 W of output power at 1.567 μm in an Er,Yb codoped fiber laser, which is the highest output power achieved with the Er,Yb codoped fibers until now [1]. However, the vast majority of high-power Er,Yb codoped laser systems reported so far were implemented with large mode area (LMA) gain fibers supporting tens or even hundreds of modes to mitigate the harmful nonlinear effects, which, unfortunately, degrade the output laser beam quality [2–4]. In addition, many high-power laser configurations incorporate several free-space optical components, increasing the complexity of the system and thus cost of maintenance. Nevertheless, for many applications in the eye-safe wavelength range, the requirement for high output power is also accompanied by the need of good beam quality and high efficiency resulting from simple laser structures. All-fiber geometries without free-space optics can offer alignment-free, efficient, compact, and reliable laser architecture. Single-mode all-fiber Er,Yb codoped laser systems have naturally become an attractive candidate for achieving high output power level while maintaining good laser beam quality to meet the requirement for particular applications. Nowadays, more than 10 W output

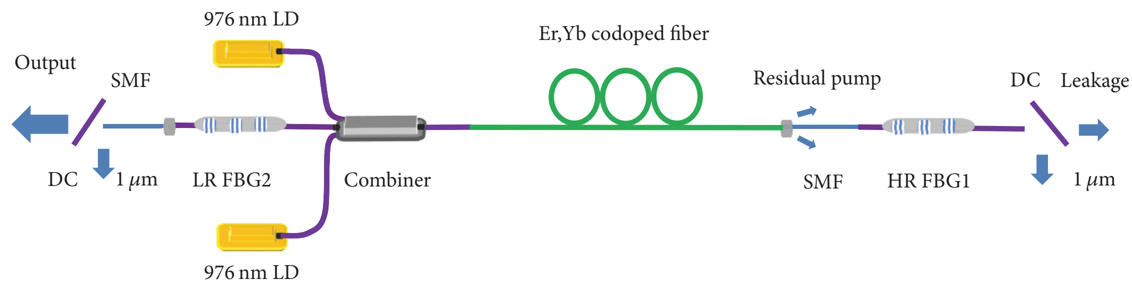

Figure 1: Experimental schematic of the single-mode all-fiber Er,Yb codoped laser. DC: dichroic mirror; SMF: standard single-mode fiber; FBG: fiber Bragg grating.

powers of single-mode laser emissions at ~1.5 μm in the Er,Yb codoped laser systems have been achieved based on the more complex master oscillator power amplifier (MOPA) configurations [7, 8], while the extremely simple all-fiber Er,Yb codoped fiber laser oscillators still remain of a limited output power level of several watts [9–11].

In this paper, we use a simple and compact cavity design with two pieces of standard single-mode fiber incorporated into the laser resonator and the output port, respectively, and demonstrate a truly single-mode high-power Er,Yb codoped all-fiber laser based on a slightly multimode gain fiber. The operating wavelength of the fiber laser is locked at 1545 nm, which corresponds to the first-order Stokes wavelength of 1658 nm that can be used to precisely generate the dual mid-IR laser emissions of 2.7 μm and 4.3 μm through the nonlinear optical parametric frequency conversion [12–14]. A maximum overall output power of 19.2 W is obtained at 1544.68 nm with a FWHM spectral width of 0.08 nm and an overall slope efficiency of 31.9%, limited only by the available pump power. To the best of our knowledge, this is so far the highest output power reported from all-fiber single-mode Er,Yb codoped laser oscillators.

2. Experiment

The experimental schematic of the single-mode all-fiber Er,Yb codoped fiber laser is shown in Figure 1. The gain medium was a 3 m long Er,Yb codoped multimode double clad fiber (Nufern, MM-EYDF-12/130) with a nominal cladding-pump absorption of 3.10 dB/m at 915 nm, which had a core of 12 μm diameter and ~0.2 NA, and a pure silica inner-cladding of 130 μm diameter and ~0.46 NA covered with a low refractive index Acrylate outcladding also as protective coating. The gain fiber had a V number (cut-off frequency or normalized frequency) of 4.8, suggesting the number of laser modes that the gain fiber can support is around 11. Therefore, a piece of standard single-mode-fiber was inserted as a spatial filter into the new laser cavity with the output port made of another piece of standard single-mode fiber, in order to guarantee truly single-mode laser output and at the same time eliminate the residual pump in the cladding and other unwanted laser modes coupled into the cladding by using a high-index gel. The splicing between the unmatched fibers was carefully carried out by a specialty splicer (Fujikura, FSM-100P+) with splicing loss of below 0.2 dB. The heat load yielded from quantum defect over the gain fiber was dissipated by simple fan-cooling.

The lasing feedback was provided by a pair of FBGs written in a compatible single-mode double clad passive fiber (Nufern, GDF-1550). FBG1 is highly reflective with a peak reflectivity of 99% and spectral bandwidth of 0.5 nm at 1544.5 nm. FBG2 is a 10% low-reflection output coupler with the center wavelength of 1544.6 nm and bandwidth of 0.7 nm, as shown in Figure 2. Due to limited effective reflectivity and slight shift of center wavelength and bandwidth for the two FBGs, as well as possible laser spectral broadening in the high-power operation, some power leakage may occur through the high-reflection FBG1 end. Thus, we also monitored the possible power leakage and corresponding spectrum from the free end facet of FBG1. Both output end facets of the fiber laser were angle-cleaved at ~8° to suppress the impact of Fresnel reflections from the uncoated fiber facets on the laser stability as well as the corresponding broadband feedback and then to reduce the ~1 μm parasitic lasing resulting from transitions of some Yb ions excluded from the energy transfer process between Yb and Er ions. Two 45° dichroic mirrors with high-reflection at the laser wavelength and high-transmission in the ~1 μm wavelength band were inserted into the output path to steer the laser beam from the possible ~1 μm parasitic laser for measurement. Two commercial fiber-coupled 35 W wavelength stabilized 976 nm laser diodes were served as the pump source, the output ports of which were directly spliced to a (2 + 1) × 1 pump combiner to cladding-pump the gain fiber in the backward pumping regime. Both pump laser diodes were spectrally narrowed and locked at 976 nm by a volume Bragg grating with a 3 dB spectral width of 0.5 nm to match the absorption peak of the Er,Yb codoped fiber. The spectral characteristics of the laser output were recorded using an optical spectrum analyzer (AQ6370C, Yokogawa).

3. Results and Discussion

The lasing characteristics of the single-mode all-fiber Er,Yb codoped laser were evaluated. Figure 3 shows the output powers from the single-mode fiber output end as a function of the launched pump power. The laser reached threshold at a launched pump power of ~1 W and generated an output

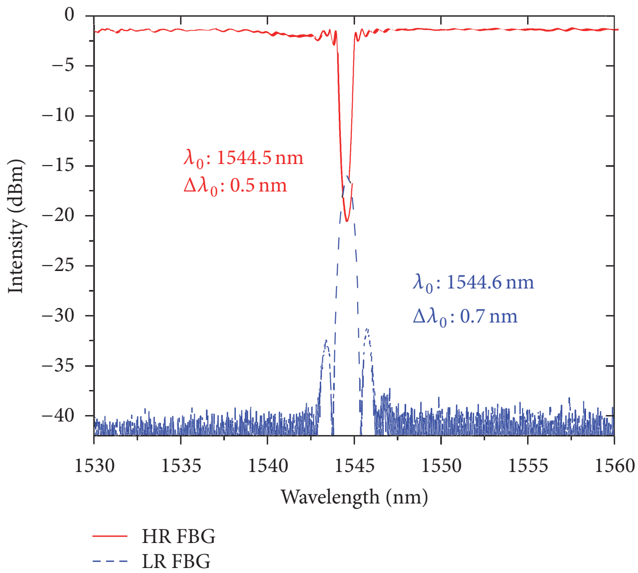

FIGURE 2: Measured transmission spectrum and reflection spectrum of the high-reflection (HR) FBG (red line) and low-reflection (LR) FBG (blue dash), respectively.

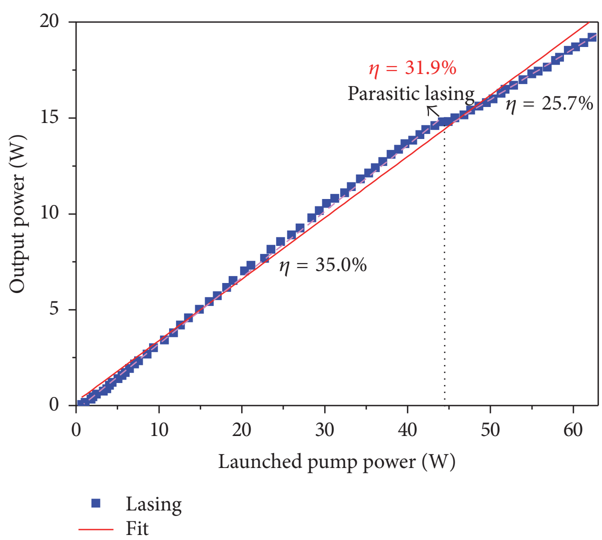

FIGURE 3: Laser output powers as a function of the launched pump power.

power of 19.2 W for the maximum launched pump power of 62.3 W, corresponding to an average slope efficiency of 31.9% with respect to the launched pump power. The output laser powers showed a linear dependence with the launched pump power over the whole pump range. The output powers remained quite stable during the whole measurement. However, parasitic lasing of Yb at 1060.4 nm began to oscillate at the launched pump power of 44.2 W, and an overall output power of 2.1 W was yielded at the maximum launched pump power from both fiber ends. The ~1 μm parasitic oscillation reduced the lasing slope efficiency from 35% to 25.7%, which can be seen obviously in Figure 3. Despite this, no roll-off

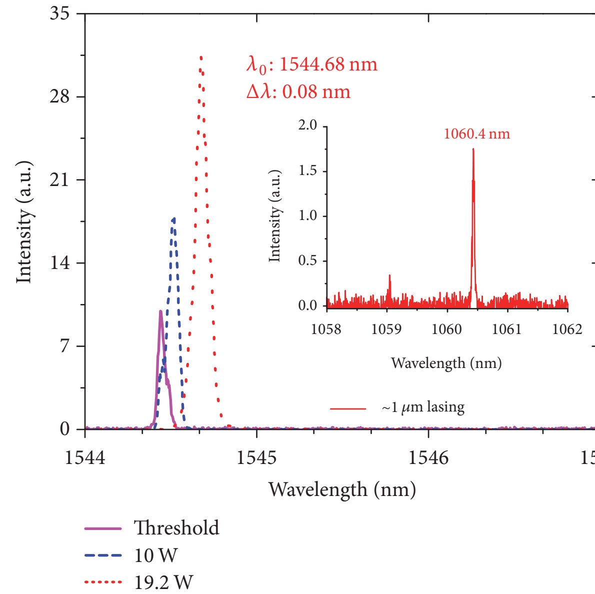

FIGURE 4: Laser output spectrum from standard single-mode fiber end and spectrum of the leaked laser from the high-reflection FBG1 end in comparison. Inset: measured spectrum of ~1 μm parasitic lasing.

resulting from the unfavorable nonlinear effects or thermal loading was observed. The leaked laser power from the FBG1 end was 0.2 W, which is acceptable due to the limited effective reflectivity of the high-reflection FBG. In addition, it is worth noting that the fiber laser was operated in the backward pumping regime to avoid any gain fiber burning adjacent to the combiner that commonly occurred in the forward pumping regime due to the abrupt change of temperature gradient in this position [15].

Figure 4 shows the output spectral evolution at different laser power levels from the standard single-mode fiber output end. We can see that the laser center wavelength is redshifted from 1544.44 nm near the threshold to 1544.68 nm at the output power of 19.2 W, which is primarily attributed to the temperature dependence of reflection wavelength of the FBGs. The spectral width was broadened from a FWHM linewidth of 0.04 nm to 0.08 nm correspondingly. Despite the spectral broadening, the oscillating laser modes still remained within the bandwidth of the two FBGs. In the lasing feedback of each round trip, FBG2 will sample a nominal 10% of the lasing components within its reflection band and reflect it back into the cavity. This portion of light will then be amplified in the backward direction. Upon reaching FBG1 the laser modes within the reflection band are highly reflected (99% in our case) and then successively amplified in the forward direction towards FBG2, where 90% of the laser will be outcoupled while the small reflected portion returns to the next lasing cycle. In our experiment the laser leakage from FBG1 was primarily attributed to its limited effective reflectivity since the bandwidth of FBG2 is slightly larger than that of FBG1. Despite this, the leaked laser from FBG1 was measured to have roughly the same spectral profile without central dip or any spectral ripples as that from the output end in terms of center wavelength and width. Thus, both output beams can be simply combined for certain applications. Alternatively, we can also use a high-reflection FBG with much higher reflectivity and broader bandwidth instead to reduce the leakage power from this end.

In addition, it is worth noting that the truly single-mode laser output was actually achieved literally through first a piece of standard single-mode fiber in the cavity and then another piece of standard single-mode fiber on the output end without sacrificing much laser output power loss. Although the Er,Yb codoped gain fiber was capable of supporting 11 laser modes at ~1.5 μm, the amount of output laser modes from the gain fiber was actually much less than specified, owing to the intense mode competition where only the modes with lowest loss survived. Besides, the standard single-mode fiber inserted in the cavity and single-mode double clad pig-tailed fiber of FBG2 connected to the Er,Yb codoped fiber further suppressed most of the higher order laser modes yielded in the gain fiber, which ensures a relatively low splicing loss with the standard single-mode fiber. The last piece of standard single-mode fiber in the output end guaranteed a truly single-mode laser output from the 1545 nm all-fiber laser.

4. Conclusions

We demonstrate a truly single-mode all-fiber high-power Er,Yb codoped laser at 1545 nm which is potentially significant for some applications. The laser output port is convinced with a piece of standard single-mode fiber to guarantee the truly single-mode output while keeping good compatibility with other standard fiber components. A maximum overall output power of 19.2 W at 1544.68 nm with a FWHM spectral width of 0.08 nm is obtained in the fiber laser, corresponding to an average slope efficiency of 31.9% with respect to the launched pump power. To the best of our knowledge, this is the highest single-mode output power achieved from a simple all-fiber Er,Yb codoped laser oscillator architecture.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Authors' Contributions

Jiadong Wu and Chunxiang Zhang contributed equally to the paper.

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