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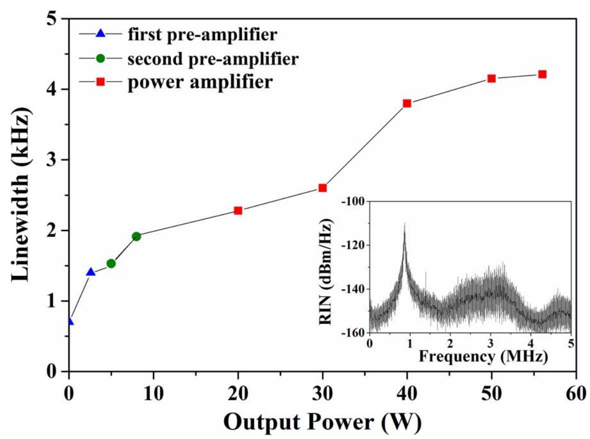
Xiaolei Bai
Quan Sheng
Haiwei Zhang
Shijie Fu
Wei Shi
Jianquan Yao



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High-Power All-Fiber Single-Frequency Erbium–Ytterbium Co-Doped Fiber Master Oscillator Power Amplifier

Xiaolei Bai, Quan Sheng, Haiwei Zhang, Shijie Fu, Wei Shi, and Jianquan Yao

College of Precision Instrument and Optoelectronics Engineering, Tianjin University, Tianjin 300072, China

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Abstract: We report herein an all-fiber single-frequency master oscillator power amplifier (MOPA) at 1550 nm with Er/Yb-codoped active fiber and wavelength-stabilized 976-nm LD pump source. A pump-limited maximum continuous-wave output power of 56.4 W was achieved under the pump power of 150 W, with corresponding slope efficiency being 37.0%. Via the self-heterodyne method, the evolution of spectrum linewidth during the amplification was investigated for the high-power MOPA-based single-frequency fiber laser. The linewidth and relative intensity noise at the maximum output power are 4.21 kHz and –110 dBm/Hz, respectively.

Index Terms: Single-frequency laser, all fiber, erbium–ytterbium, laser amplifiers, fiber laser.

1. Introduction

The single-frequency coherent sources around 1.5-μm wavelength are of significant importance because of the "eye-safe" property and applications in spectroscopy, communication, and light-imaging detection and ranging (LIDAR) [1]–[4]. Several mature methods, such as optical parametric oscillators [5], Raman lasers [6], and Er- or Er/Yb-codoped fiber laser and amplifiers [7], [8], could generate the eye-safe output efficiently. However, the Er/Yb-codoped fiber master oscillator power amplifier (MOPA) is the only way capable of realizing both tens of watts of output power and narrow linewidth of several kilohertz, so far.

In 2007, Jeong *et al.* obtained 297 W output power at 1.5 μm with an Er/Yb-codoped fibers (EYDF) oscillator, which is the highest output power with the EYDF up until now [9]. In the important single-frequency regime, power scaling of the ultra-narrow-linewidth laser is limited by the nonlinear effects, especially the stimulated Brillouin scattering (SBS). Alegria *et al.* reported an 83-W free-space-coupled EYDF MOPA seeded by a single-frequency fiber laser in 2004 [10]. The linewidth at the maximum output power is measured to be 13 kHz without SBS. Then, in 2005, Jeong *et al.* increased the maximum output power of single-frequency fiber MOPA to 151 W

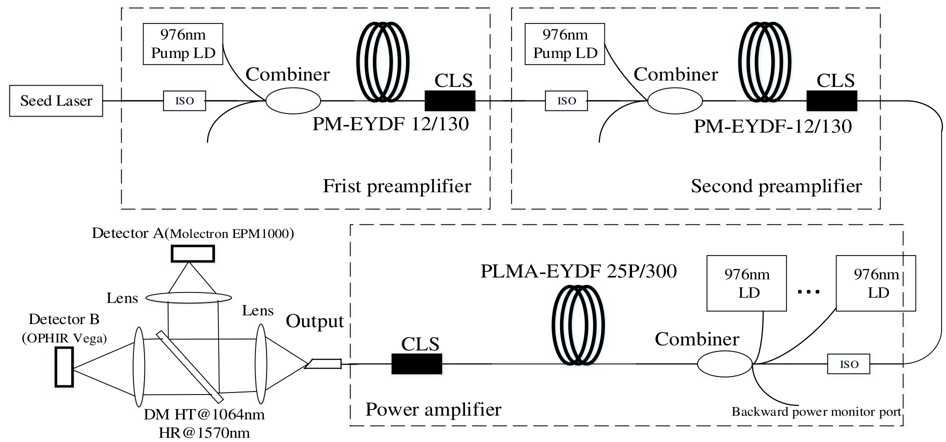

Fig. 1. Schematic diagram of the experimental setup. ISO, isolator; Pump LD, pump laser diode; CLS, cladding light striper.

by using a single-frequency diode laser with ~1 MHz linewidth as the seed, which helps to avoid the SBS [11].

In this paper, we demonstrate a high-power all-fiber-based single-frequency Er/Yb-codoped fiber cascaded MOPA system operating at 1550 nm with the slope efficiency of 37.0%. The maximum output power of 56.4 W was achieved with the pump power of 150 W. The linewidth was measured to be 4.21 kHz under the maximum output power. The polarization extinction ratio (PER) and optical signal-to-noise ratio (SNR) were ~21 dB and > 40 dB, respectively. Neither SBS nor other wavelength lasing was observed in the three-stage MOPA system. The linewidth characteristics of high-power single-frequency fiber laser at different pump power was analyzed with delayed self-heterodyne method.

2. Experimental Setup

The schematic of the three-stage all-fiber-based single-frequency EYDF MOPA is shown in Fig. 1. A commercial polarized narrow-linewidth single-frequency fiber laser with the output power of 30 mW and linewidth of 700 Hz was served as the master oscillator (seed). The first pre-amplifier was based on 3-m-long Er/Yb-codoped double-cladding fiber with 12-μm core and 130-μm cladding diameter (Nufern, PM-EYDF-12/130) cladding pumped by wavelength-stabilized 976-nm laser diode (LD) through a $(2+1)\times 1$ pump combiner. The wavelength of pump laser diode was stabilized at 976 nm in order to match the peak of absorption cross section. The measured cladding absorption coefficient of this active fiber is 6.5 dB/m at 976 nm. A cladding light stripper (CLS) was spliced to the end of the PM-EYDF to eliminate the residual pump in the cladding and the signal coupled to the cladding. In order to prevent the backward light, the signal from the first pre-amplifier was launched into the second stage through an isolator (ISO). The second stage pre-amplifier, in which the length of active fiber was 2 m, was the same as the structure of the first stage. Before the signal was coupled into the power amplifier stage, a CLS and an ISO were spliced to the output end of the gain fiber in sequence. The power amplifier comprised a 4-m-long polarization-maintained large-mode area Er/Yb-codoped double cladding fiber with the core and the cladding diameters of 25 and 300 μm (Nufern, PLMA-EYDF-25P/300), which was pumped by two high-power wavelength-stabilized 976-nm pump LDs via $(6+1)\times 1$ combiner. The cladding absorption of this gain fiber was measured to be 4.4 dB/m at 976 nm. We spliced a 50-cm-long passive fiber that matches the gain fiber, and the end of the passive fiber was angle-cleaved (~8°) to launch out the amplified single-frequency signal laser after a cladding light striper (CLS).

In the experiment, the backward power was monitored via one of the idler pump port of the combiner on concern of backward amplified spontaneous emission (ASE) and SBS signal. A

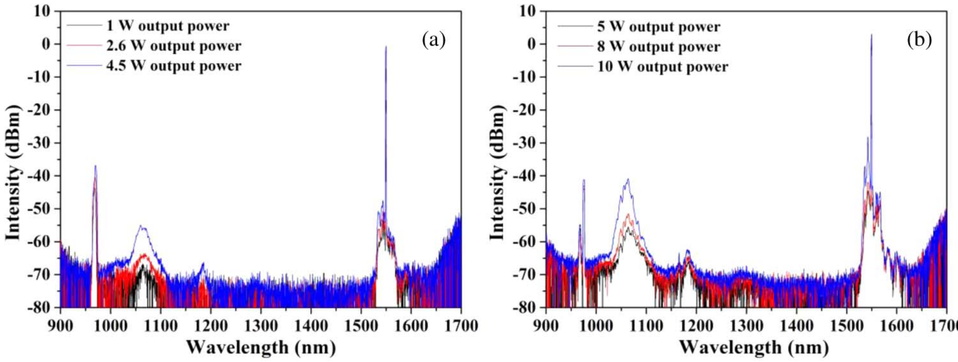

Fig. 2. Output spectra with different output power of (a) the first pre-amplifier and (b) the second pre-amplifier.

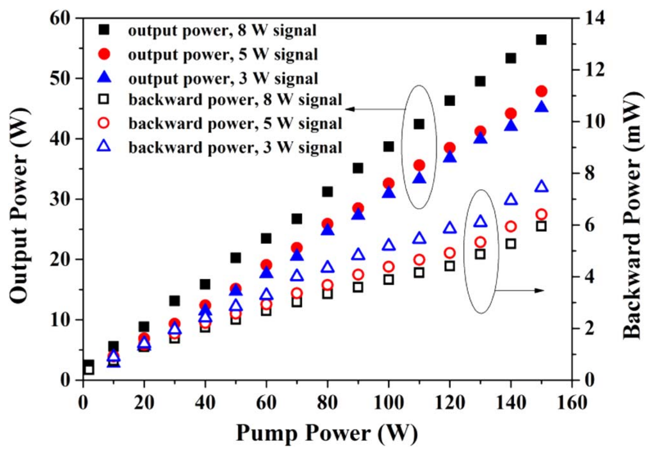

Fig. 3. Power amplifier output power and backward power versus pump power at different input power.

dichroic mirror (DM) 45°-coated for highly-transmissive (HT)@1064 nm and highly reflective (HR)@1570 nm was used to separate the 1-μm ASE and the 1.5-μm signal output. Two laser power meters, Molectron EPM1000 (Detector A in the schematic) and OPHIR Vega (Detector B) were used to measure the laser and ASE power, respectively.

3. Experimental Results and Discussion

First, we investigated the power performance of the power amplifier with different incident signal power. The 30-mW single-frequency seed at 1550 nm could be boosted to 10 W after the two stages of pre-amplifier. The output spectra of the first pre-amplifier with different output power were recorded by an optical spectrum analyzer as shown in Fig. 2(a). Only 7.5 W of pump was applied to the first pre-amplifier to avoid obvious 1-μm ASE and 2.6-W signal output with relatively pure spectrum was obtained. In the second pre-amplifier, the signal power could be boosted to 10 W with 25 W pump power. However, the power of 1-μm ASE increased while the output power of the second pre-amplifier raising from 5 W to 10 W. Fig. 2(b) indicates that the output spectrum at 10-W output power exhibits strong 1-μm ASE, which would be further amplified by the power amplifier, deplete the population inversion and thus decrease the efficiency seriously. Therefore, only 8 W of maximum signal power, with which the ASE was unobvious, was used in the experiment. Fig. 3 shows the 1550-nm signal output of the power amplifier as functions of launched pump power with different incident signal power of 3, 5, and 8 W. The backward

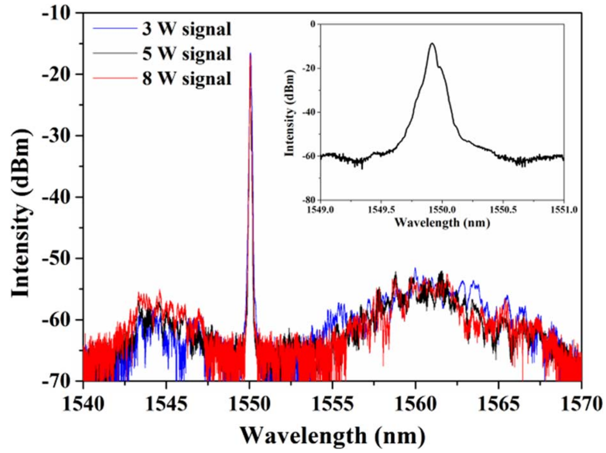

Fig. 4. Output spectra of the power amplifier with different input signal power. (Inset) Zoomed output spectrum at the centered 1550 nm.

power was also measured simultaneously at an idler port of the combiner to observe whether the SBS occurs. With the incident signal power of 8 W, a maximum output power of 56.4 W was obtained under the launched pump power of 150 W with no saturation, corresponding optical efficiency and slope efficiency are 37.6% and 37.0%, respectively. When the incident signal power was 5 and 3 W, the output power under the same maximum pump of 150 W are 47.9 and 45.1 W, with corresponding slope efficiency decreases to 31.8% and 30.7%, respectively, indicated that the signal was insufficient for efficient extraction. The backward power, which contained ASE at 1 and 1.5 μm, also increased from 5.9 mW to 6.4 and 7.5 mW when incident signal decreased from 8 W to 5 and 3 W because of the higher unextracted population inversion. The near linear increase of backward power indicates the absence of SBS. The 1-μm ASE power measured behind the dichroic mirror also exhibits a near linear increase and reaches 14.7 mW under the maximum pump power of 150 W, which reveals that there is no lasing at 1 μm.

Fig. 4 shows the output spectra of the power amplifier with different incident signal power and the fixed pump power of 150 W recorded by an optical spectrum analyzer (YOKOGAWA, AQ6375). The center wavelength is 1549.91 nm with over 40 dB optical SNR at the maximum power. Although the ASE was not split from the laser, considering the several milliwatts of backward power measured at the pump port of combiner, the forward ASE power around 1543 and 1560 nm should not exceed tens of milliwatt and was negligible compared with over 50 W total output power. The PER was measured to be 21 dB.

To further investigate the linewidth evolution of the high-power single-frequency fiber MOPA during the amplification, a delayed self-heterodyne system was adopted, which contains a 50-km-long delay fiber and a 70-MHz acousto-optic modulator. A fiber-coupled InGaAs biased detector with 1.2 GHz bandwidth (THORLABS, DET01CFC) was used to detect the beat signal through a RF signal analyzer. The measured linewidth of each amplifier stage as function of output power is plotted in Fig. 5. The signal power was boosted to 2.6 W in the first pre-amplifier while the linewidth broadening to 1.42 kHz. In second pre-amplifier, the linewidth increased to 1.53 kHz when the output power was 5 W. When signal output power in the power amplifier was boosted from 8 W to its maximum value of 56.4 W as the pump power increased, the linewidth was broadened gradually from 1.91 to 4.21 kHz. Linewidth broadening is attributed to the increase of incoherent components, such as ASE in the active fiber. The spectral broadening in fiber amplifier linewidth can be explained in view of the ratio of signal to ASE [12]. With the raising of pump power, the ASE is boosted in the amplifier as well as the signal. The increment of the ASE within the signal bandwidth decreases the ratio of signal to ASE and thus broadens the linewidth [13]. Fig. 6 shows the recorded line shapes and Lorentzian fitting lines of the seed

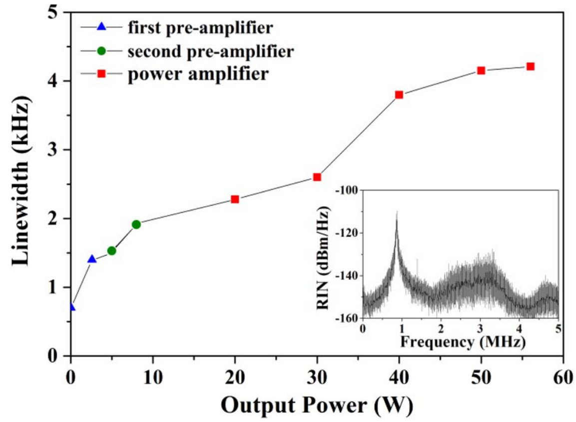

Fig. 5. Measured linewidth at different output power. (Inset) RIN of the MOPA at maximum output power.

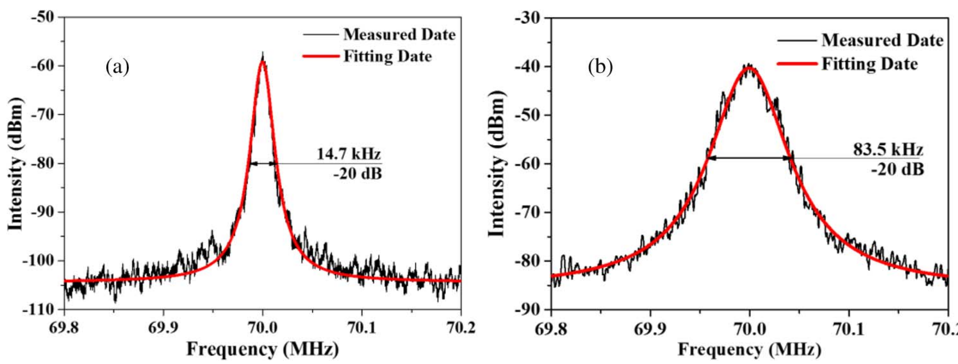

Fig. 6. Lineshape and the Lorentzian fitting lines measured using a delayed self-heterodyne method to (a) the seed laser and (b) the amplifier at the maximum output power.

laser and the amplifier at the maximum output power. The 20-dB linewidth measured were 14.7 and 83.5 kHz, corresponding to 3-dB linewidth of 0.73 and 4.21 kHz, respectively. The relative intensity noise (RIN) of the MOPA system at the maximum output power was measured using the InGaAs detector and RF signal analyzer. The RIN intensity was ~110 dBm/Hz with a frequency peak at 0.8 MHz, as shown in the inset of Fig. 5, which is mainly due to the ambient acoustics and vibration.

4. Conclusion

In conclusion, we demonstrated an all-fiber single-frequency Er/Yb-codoped fiber cascaded MOPA system operating at 1550 nm with a pump-limited maximum output power of 56.4 W and a slope efficiency of 37.0%. The linewidth evolution during amplification was investigated, and the linewidth with the 56.4 W maximum output power was only 4.21 kHz. The PER and optical SNR were ~21 dB and > 40 dB, respectively. The intensity of the RIN was ~110 dBm/Hz. Neither obvious SBS nor other wavelength lasing was observed for the investigated single-frequency three-stage MOPA system.

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