Spectral Broadening Suppressed by a Gain-Enhanced Fiber in Polarization Maintaining High-Power Systems

Shibiao Liao, Tao Luo, Runheng Xiao, Yingbo Chu, Haiqing Li, Yingbin Xing, Jinyan Li, and Nengli Dai

***Abstract*—A gain-enhanced 10/125 μm polarization-maintaining Yb-doped fiber (PMYDF), with the cladding absorption of 7.5 dB/m at 976 nm, for narrow linewidth linearly polarized fiber oscillator or amplifiers is presented. By utilizing the gain-enhanced PMYDF in an all-fiber laser oscillator, an output power of 123 W is achieved with applying appropriate bending strategies and thermal management, corresponding to the slope efficiency of 86.7%. By applying the gain-enhanced PMYDF in seed, an increase of 34% in the longitudinal mode interval is effectively achieved compared to the commercial PMYDF, while the number of longitudinal modes is only 75%. According to the main oscillation power amplification (MOPA) system, the total amount of spectral broadening applying the seed with the gain-enhanced PMYDF are only 67%, 64% and 54% of applying the seed with the commercial PMYDF, corresponding to co-pumping, bi-pumping and counter-pumping schemes, respectively.**

***Index Terms*—Spectral broadening, gain-enhanced polarization maintaining fiber, fiber oscillators, high power fiber amplifiers.**

I. Introduction

HIGH-power narrow linewidth (NL) fiber amplifiers with linearly polarized have earned a solid reputation due to their remarkable capacity in gravitational wave detection (GWD), nonlinear frequency conversion (NFC), spectral beam combining (SBC) and coherent beam combining (CBC) [1], [2], [3], [4], [5] etc. By taking into the various strategies of seed sources, some conventional methods to realize high-power NL linearly polarized fiber amplifiers are to use phase modulated single-frequency laser (PMSFL) seeds [6], [7], super-fluorescent (SF) seeds [8], random fiber laser (RFL) seeds [9] and fiber oscillator laser (FOL) seeds [10], [11], [12], [13]. Over the last few years, many excellent works have been achieved. In 2021, Wang et al realized a 3.25 kW linearly polarized all-fiber amplifier with 20 GHz linewidth based on a PMSFL seed [6]. Recently, by using a 20/400 μm polarization maintaining Yb-doped fiber (PMYDF) and applying appropriate strategies for mitigation of the mode instability (MI), a near-single-mode linearly polarized fiber laser with the highest output power exceeding 4.5 kW of a 0.33 nm linewidth was achieved by Ren [7], to the best of our knowledge. In relation to a SF seed and a RFL seed source, an 800 W linearly polarized amplifier with a 3 dB linewidth of 0.2 nm was obtained by Ma et al. [8] and a 1.01 kW amplified RFL with a 0.212 nm linewidth was achieved by Xu et al. [9] respectively. Considering the above seed sources, multi-stage pre-amplifier and main-amplifier schemes make the whole system complicated and expensive. Correspondingly, the systems based on the FOL seeds only have one-stage amplification, and the construction will be so convenient and affordable.

To date, the highest NL linearly polarized output power record based on the FOL seeds is maintained by the Wang et al. [10] with the 3.08 kW of a 0.2 nm linewidth. However, due to the multi-longitudinal modes effects, several pernicious nonlinear processes such as self-phase modulation (SPM) and four-wave-mixing (FWM) [14], [15] can menace the high-power performance by the spectral broadening in the scaling of power. Hence, applying the appropriate strategies in suppressing the spectral broadening will make the main oscillation power amplification (MOPA) system based on the FOL seed applicable and universal. Currently, starting from optimizing the structure of the system, some experimental studies have reported on the relationship between the number of multi-longitudinal modes and spectral broadening [10], [16], [17], [18], [19]. In the oscillators, for example, reducing the length of the active fiber in cavity is the most popular strategy to suppress the spectral broadening [10], [18]. The results show us that amplified spontaneous emission (ASE) or more complex construction will be inevitably brought into the system and cause damage in the scaling. Introducing the gain-enhanced PMYDF with the highly-improved absorption coefficient into the systems is an effective way to eliminate the spectral broadening in essence while maintaining the great performance.

In this paper, a gain-enhanced 10/125 μm PMYDF for suppressing the spectral broadening in high-power NL system is demonstrated. The measured cladding absorption at 915 nm and 976 nm are 2.48 dB/m and 7.5 dB/m, respectively. Applying the gain-enhanced fiber, an all-fiber laser with output power of 123 W is achieved with the PER>17.5 dB and the beam quality factor of $M^2_x = 1.10$ and $M^2_y = 1.08$, while the slope efficiency

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is 86.7%. During the process of comparative experiments, an increase of 34% in the longitudinal mode interval has been effectively obtained while the number of longitudinal modes is 75% with the gain-customed PMYDF. In the scaling experiments, the total amount of spectral broadening applying the seed with the gain-enhanced PMYDF are only 67%, 64% and 54% of applying the seed with the commercial PMYDF, corresponding to co-pumping, bi-pumping and counter-pumping schemes, respectively.

II. Experimental Details and Discussions

A. Fiber Fabrication and Characterization

The Yb/Al co-doped phosphosilicate core preform is manufactured by modified chemical vapor deposition (MCVD) and conventional solution doping process (SDP). At present, the internationally used fiber cladding diameter is 125 μm, and the active fiber with a core diameter of 10 μm is usually used as the gain fiber of the seed source [6], [10], [11]. Therefore, the core and inner cladding dimensions of the PMYDF are designed and determined to be 10 μm and 125 μm, respectively. Firstly, the normalized frequency V value less than 2.405 is a necessary condition for the single-mode operation of the laser in the fiber. After calculation, the numerical aperture (NA) of the fiber must be controlled at about 0.082. In order to increase the doping concentration of Yb^{3+}, the doping concentration of Al^{3+} and P^{5+} must be increased at the same time when the solution is proportioned, so that the solubility of Yb^{3+} is increased in the fiber core. At the same time, the multi-lying deposition method will be used for element doping. The introduction of three kinds of ion doping will greatly increase the NA of the fiber, so the doping concentration of F^{-} must be increased at the same time to reduce the NA of the fiber core and ensure a high doping concentration of Yb^{3+} ions as much as possible.

Specifically, the preform was fabricated by MCVD process with the five well-known main steps: (1) barrier layer and soot layer deposition, (2) rare-earth (and aluminum) solution doping, (3) thermal drying, (4) sintering, (5) collapse. Different from the preparation of conventional Yb-doped fiber (YDF), the preparation of PMYDF also adds two sets of processes: preform drilling and boron rod assembly. Finally, after achieving a well-prepared polarization maintaining (PM) preform, at temperatures of 1980 °C, the preform assembly was pulled into a 10/125 μm fiber with a circular cladding and coated with a low index polymer.

The reflective index profile of the prepared preform was measured by a preform analyzer (P104, Photon Kinetics, Inc.) and depicted in Fig. 1(a). Small refractive index fluctuations over the core of the preform was achieved, demonstrating an excellent homogeneity. Fig. 1(b) is the cross section of the drawn fiber exhibiting a 11 μm Yb-doped core with a core NA of 0.09. Two aspects lead to a little higher value of NA than the expected. On the one hand, a certain amount of Al^{3+} and P^{5+} should be co-doped with the highly doped Yb^{3+}, which leads to the higher value of NA. On the other hand, the volatilization of F^{-} results in no reduction of NA which should have been reduced during the fabrication of preforms at high temperatures. The size fluctuation of the fiber core is normal in the range of 1 μm. At the same time, the birefringence value of the fiber is tested to be $2.9 \times 10^{-4} \sim 3.0 \times 10^{-4}$.

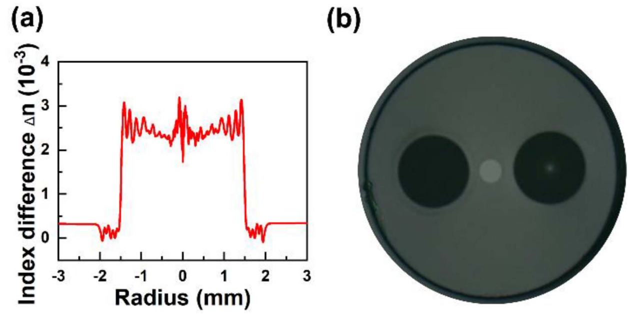

Fig. 1. Characteristics of the gain-enhanced PMYDF 10/125 μm. (a) Refractive index profile of the preform before being drawn into fiber. (b) Image of the PMYDF cross section.

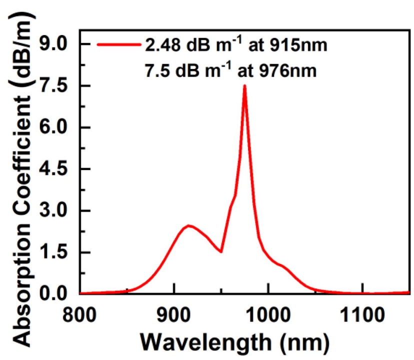

Fig. 2. The absorption coefficient spectrum of the gain-enhanced PMYDF.

B. Absorption Testing

Using the model 2500 fiber analysis system (Photon Kinetics, Inc.) measures the absorption coefficient of the fiber in the range of 600–1600 nm by the cut-back method. The results of data are immediately provided by the instrument. The measured pump absorption coefficient spectrum of the gain-enhanced PMYDF is shown in Fig. 2.

The cladding absorption coefficients of the gain-enhanced PMYDF at 915 nm and 976 nm are 2.48 dB/m and 7.5 dB/m, respectively. Compared with the commercial PMYDF, the effective absorption coefficients at 915 nm and 976 nm of the gain-enhanced PMYDF are increased by 50% and 52%, respectively. The experimental results turn out that the goal of improving the absorption coefficient of PMYDF has been achieved. Although the value of NA exceeds our expectations, the value of absorption coefficient has increased by more than 50%, and the result is still satisfactory. In the next experimental operation, the bending loss of the higher-order modes (HOMs) can be increased by reducing the bending radius to ensure the single-mode operation in the core to deduct the multi-mode operation caused by the unexpected excessive part of the NA.

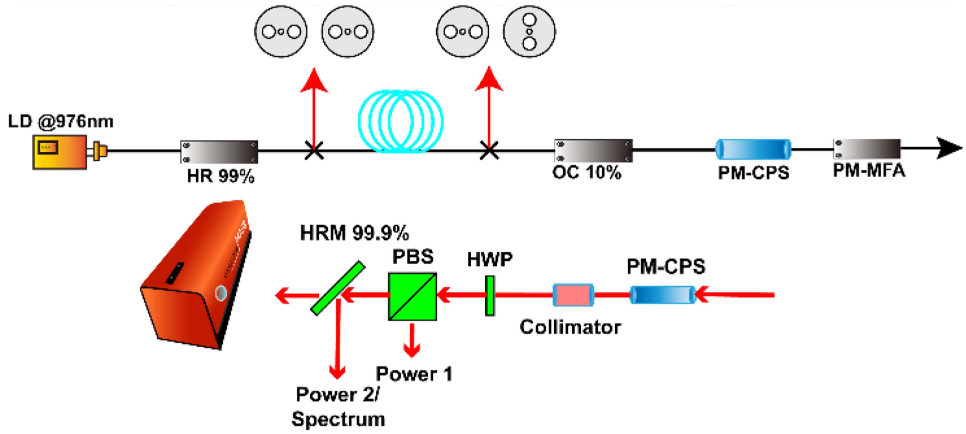

Fig. 3. Structure diagram of all-PM fiber laser based on oscillator structure.

C. Laser Performance

The all-fiber laser oscillator system and the pump lasers are cooled by a water chiller with the temperature of 16 °C during the experiments. The experimental setup of the all-PM fiber laser based on oscillator structure is shown in Fig. 3. The front end of the setup is a 976 nm wavelength-stabilized laser diode (LD) with a total pump power of 140W, which is connected to a PM high-reflection (HR) fiber Bragg grating (FBG) with a center wavelength of 1064 nm. The reflectivity of the HR FBG at 1064 nm is 99%. Then, it is spliced with the PMYDF by parallel fusion, and the other end of the PMYDF is fused with PM output coupler (OC) FBG by Orthogonal fusion shown the inset of the Fig. 3. For the sake of suppressing the generation of HOMs, the slope efficiency and beam quality of the laser generated by active fibers with different bending diameters were tested. When the bending diameter of the active fiber was above 9 cm, such as 10 cm, the beam quality would deteriorate to the M^2 of 1.13 and 1.14. Hence, the results turned out that it was appropriate to coil the gain fiber with a 9 cm diameter. The fast axis wavelength of the HR-FBG matches with the slow axis wavelength of the OC-FBG for the purpose of polarization selection. The full width at half maximum bandwidth of the HR-FBG is 0.25 nm and 0.05 nm for the OC-FBG. To compare the laser performance of our gain-enhanced PMYDF, the conventional commercial PMYDF was also experimented with the same total absorption. In order to ensure that the pump light can be fully absorbed, the fiber length with a total absorption of about 19.5 dB is adopted. The lengths of the gain fiber used are 4 m and 2.6 m respectively. The detailed experimental parameters of the two fibers are shown in Table I. A PM cladding power stripper (CPS) is fused to the OC-FBG in order to avoid the leakage of the unabsorbed pump light. Since the beam quality of the laser is an essential feature, a follow-up setup is utilized to measure it, including a PM mode field adapter (MFA) with 10/125 μm input and 20/400 μm output, a 20/400 μm PM CPS and a 20/400 μm PM collimator. A half-wavelength plate (HWP) and a polarization beam splitter (PBS) are used to split two polarized modes of the laser. The laser is reflected by a highly reflective sheet. By rotating the HWP and recording the maximum power (Power 2) and the minimum power (Power 1) reflected by the PBS, the polarization extinction ratio (PER) is calculated by the following formula (1):

TABLE I
CHARACTERISTIC OF TWO KINDS OF PMYDF

Fiber samples	NA	Absorption @915nm	Absorption @976nm	Fiber length in system
Commercial PMYDF	0.075	~1.65dB/m	~4.95dB/m	4m
Gain-enhanced PMYDF	0.09	~2.48dB/m	~7.5dB/m	2.6m

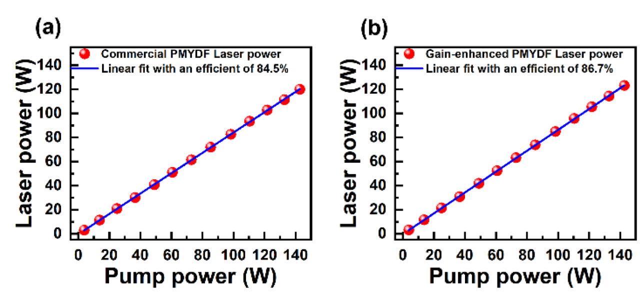

Fig. 4. The laser power versus pump power. (a) the commercial PMYDF. (b) the gain-enhanced PMYDF.

$$PER = 10\left(\log\frac{Power2}{Power1}\right) \tag{1}$$

Fig. 4 depicts the graphs of the laser power of two kinds of PMYDF versus the pump power under the oscillator structure, which correspond to linearly-fitted slope efficiency of 84.5% and 86.7%, respectively. Here, the high laser efficiencies indicate that the splice losses in the overall system are small, and even with greatly increased doping concentration of Yb^{3+}, the background losses from fiber fabrication are lower compared to commercial fibers.

During the power scaling experiments, the PER of the laser had been maintained at about 17.5 dB, which showed the good

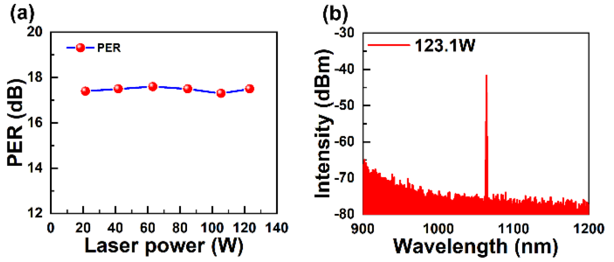

Fig. 5. The performance of the gain-enhanced PMYDF. (a) the value of PER varies with laser power. (b) the output spectrum at 123.1 W.

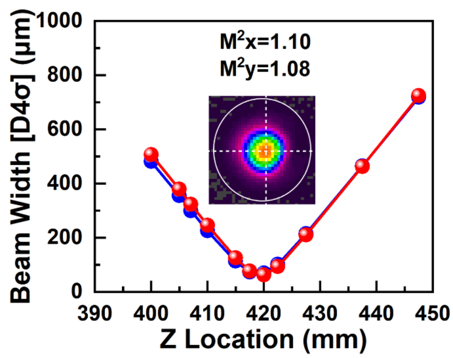

Fig. 6. The image of the beam quality at the highest laser power.

stability of the system, as displayed in Fig. 5(a). At the same time, the PER of the laser applying the commercial PMYDF exhibited at about 18 dB to 18.5 dB. The results turn out that the polarization maintaining ability of our gain-enhanced PMYDF was nearly the same as the commercial PMYDF. Fig. 5(b) showed the output laser spectrum with the characteristic peak around 1064 nm. It was observed that only the signal laser was found in the spectrum, and further power scaling is limited by the pump power. In Fig. 6, the beam quality M^2 factor was shown at the maximum output power which was achieved by the Beam Squared (BSQ) manufactured by Spiricon. Though the large-mode-field fibers was applied in system, the $M^2x = 1.10$ and $M^2y = 1.08$ indicated the near-diffraction-limited beam quality of the oscillator system. Finally, by using the gain-enhanced PMYDF and applying appropriate bending strategies, a near-diffraction-limited output beam without any sign of nonlinear effects is achieved up to 123.1 W.

D. Spectral Broadening Experiments

In the following, we tried to scale up the oscillator seed and investigated the association of the two seeds on linewidth growth under the different pumping methods. The experimental setup is based on the MOPA structure shown in Fig. 7. Adding a PM isolator to the seed part to prevent the damage from the seed, its function can be also applied to detect the power and composition of the backward light. The rest of the experimental setup is the same as the previous one. The lengths of passive optical fibers in the seed cavity are all 1.5 m. The resonator's output power of 8.8 W was sent to the amplification stage of the MOPA. At

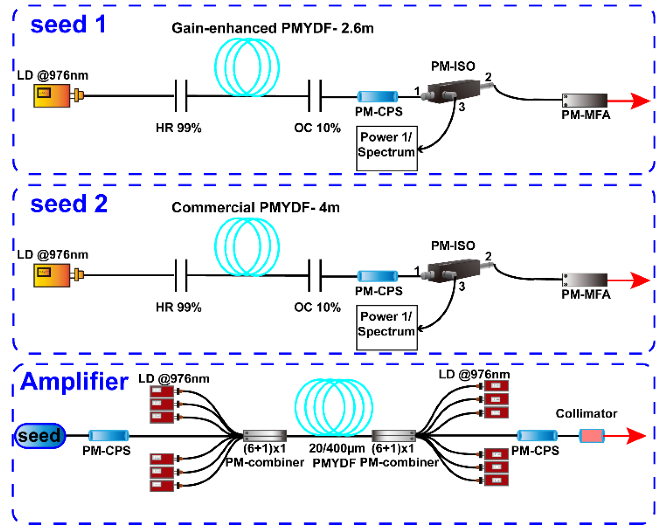

Fig. 7. The diagram of experimental setup for linewidth growth of different seed sources under the high-power system.

the next step of the experiments, the amplification system was made based on the following structure: six 140 W wavelength-stabilized LDs at 976 nm were spliced to a $(6+1) \times 1$ pump combiner and injected into the 9 m long 20/400 μm PMYDF. The pump ports of the combiner are six 220/242 μm fibers with a 0.22 NA, and its output signal port is a 20/400 μm PM fiber with the core and cladding NA of 0.06 and 0.46, respectively. The core diameter of 20/400 μm PMYDF is 20 μm (NA = 0.065), the inner cladding diameter is 400 μm (NA = 0.46), and its nominal absorption coefficient is 1.5 dB/m at 976 nm. The beams of the resonator and amplified laser were injected into the second combiner with the similar specification parameters to the first one. The pump configuration was also the same as before. A PM CPS was spliced to the pump combiner in order to remove the HMs and any unwanted light in the fiber cladding to prevent collimator from damage. The whole MOPA system was mounted on an active cooled heat sink to avoid thermal damages.

Fig. 8(a) shows the spectra of the seed 1 and the amplifier in the case of different pumping methods. As is shown in Fig. 8(a), the 3 dB linewidth of the seed 1 is 0.0297 nm. The 3 dB linewidth of the amplifiers are 0.0542 nm, 0.0477 nm and 0.0397 nm corresponding to co-pumping (655 W), bi-pumping (660 W) and counter-pumping (655 W), respectively. It is worth noting that when the amplifier is pumped in the bi-direction, the pump power is increased from co-pumping direction at the beginning. After the laser power is about 300 W, only the counter-pumping power is further increased. Fig. 8(b) shows the spectra of the seed 2 and the amplifier in the case of different pumping methods. As is shown in Fig. 8(b), the 3 dB linewidth of the seed 2 is 0.0360 nm. The 3 dB linewidth of the amplifiers are 0.0725 nm, 0.0642 nm and 0.0544 nm corresponding to co-pumping (655 W), bi-pumping (662 W) and counter-pumping (650 W), respectively.

It is observed that the spectral broadening with the seed 1 performs better than seed 2. For the seed 1 injecting, the 3 dB

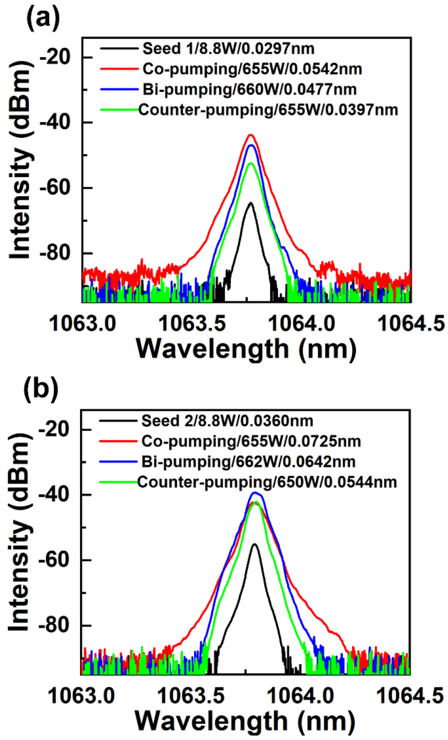

Fig. 8. The output spectra under different pumping methods. (a) Based on the seed 1. (b) Based on the seed 2.

linewidth of the amplifier grows from 0.0297 nm to 0.0542 nm, corresponding to a spectral broadening of 24.5 pm under the co-pumping scheme. In relation to the seed 2 injecting, the 3 dB linewidth of the amplifier grows from 0.0360 nm to 0.0725 nm, corresponding to a spectral broadening of 36.5 pm under the co-pumping scheme. By applying the scaling scheme of seed 1, the total amount of spectral broadening is only 67% of applying the seed 2 under the co-pumping configuration. Correspondingly, the bi-pumping and counter-pumping configurations are only 64% and 54%, respectively. The spectrum in Fig. 8 also shows that the co-pumping case exhibits the most severe spectral broadening, while the counter-pumping case exhibits the smallest broadening and the bi-pumping case exhibits a broadening that is intermediate.

A reasonable explanation for the above spectral broadening phenomenon can be described by the core laser intensity distribution varying along the fiber. The nonlinear impact is proportional to the combination of the laser intensity in the fiber core and the interaction fiber length, as described in nonlinear optics. Simultaneously, the length of the PMYDF in cavity between the seed 1 and seed 2 leads to the final difference of the amplifier's linewidth. According to the formula (2):

$$\Delta f = \frac{c}{2nL} \tag{2}$$

where Δf is the longitudinal mode interval, c is the light speed in vacuum, n is the refractive index of silica fiber, and L is the length of cavity. The longitudinal modulus N of the simultaneous oscillation in the cavity is shown by the formula (3):

$$N = \frac{\Delta f_o}{\Delta f} \tag{3}$$

where Δf_0 refers to the gain linewidth of the working substance. The total cavity lengths of seed 1 and seed 2 are 4.1 m and 5.5 m, respectively. Based on the above formula, an increase of 34% in the longitudinal mode interval of the seed 1 has been effectively achieved compared to the seed 2, while the number of longitudinal modes is only 75% of the seed 2. At the same time, the experimental results may also reveal that the linewidth growth of the MOPA system can be effectively controlled and tailored by the gain-customed fiber in oscillator.

III. Conclusion

In conclusion, we have demonstrated fabrication of the 10/125 μm PMYDF for narrow linewidth linearly polarized oscillators or amplifiers and the 1064 nm all-fiber oscillator with the output power of 123 W and the PER>17.5 dB at the highest power. The cladding absorption at 915 nm and 976 nm are 2.48 dB/m and 7.5 dB/m, respectively. A near-diffraction-limited output beam is realized with the $M^2_x = 1.10$ and $M^2_y = 1.08$ at the highest power. Using the gain-customed PMYDF in oscillator, an increase of 34% in the longitudinal mode interval has been effectively achieved compared to the commercial PMYDF, while the number of longitudinal modes is only 75%. During the power scaling experiments, the total amount of spectral broadening applying the seed with the gain-enhanced PMYDF are only 24.5 pm,18 pm and 10 pm, corresponding to co-pumping, bi-pumping and counter-pumping schemes, respectively. The results reveal that the gain-enhanced PMYDF has significant points in linewidth growth of the high-power narrow linewidth linearly polarized fiber lasers.

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