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All-fiber linearly polarized laser oscillator by fiber coiling loss control*

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In this paper, we demonstrate an all-fiber linearly polarized fiber laser oscillator. The single polarization of the oscillator is achieved through the careful designing of the active fiber coiling. The relationship between fiber coiling diameter and polarization extinction ratio and optical efficiency is studied, whose results lead to an optimized system. The thermal management of the oscillator is also refined, which allows the oscillator to reach a maximum output power of 44.1 W with an optical-to-optical efficiency of 57.9%. A high average polarization extinction ratio of 21.6 dB is achieved during a 2-hour stability test. The oscillator also owns a narrow 3-dB bandwidth of 0.1 nm, as well as near-diffraction-limit beam quality of $M^2 \sim 1.14$.

Keywords: fiber laser oscillator, linearly polarized, all-fiber

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1. Introduction

Fiber laser with linear polarization and narrow bandwidth has achieved extensive applications in various fields such as laser coherent beam combining and nonlinear frequency conversion.[1–3] In the last decade, all-fiber linearly polarized fiber laser (LPFL) has reached significant achievement.[4–9] Among them, the power scaling to the kW-level was chiefly accomplished via a master-oscillator-power-amplifier (MOPA) configuration. In 2015, Ma *et al*. presented an LPFL at a power level of 1.3 kW. The system, which consisted of a two-stage pre-amplified seed laser and one-stage amplifier, had a maximum output power of 1261 W and a polarization extinction ratio (PER) of 90%.[6] In 2015, Huang *et al.* demonstrated an all-fiber linearly polarized fiber laser with an output power of 1.5 kW, along with a PER of 13.8 dB and a spectral bandwidth of 5.8 nm.[7] Also in 2016, Ma *et al*. managed to refresh the record power level to 1.89 kW by adopting a three-stage phase modulated seed laser to suppress the stimulated Brillouin scattering (SBS) effect. They also achieved a 3-dB bandwidth as narrow as 0.17 nm, and a PER of 15.5 dB.[8] There has also been progress in single-frequency LPFL. In 2016, Huang *et al*. set the record for the single-frequency LPFL at 414 W with a three-amplifier-stage MOPA configuration fiber laser.[9]

As is well known, for an MOPA configuration fiber laser, the seed laser is vital to the entire system. Therefore, there have been plenty of researches on how to improve the performance of a linearly polarized fiber laser oscillator. In general, the single polarization of the oscillator can be achieved in several methods. One is by using a pair of fiber Bragg gratings (FBGs) with narrow bandwidth, and the fast axis wavelength of one grating should match the slow axis wavelength of the other. Then one grating should be spliced to the gain fiber with fiber aligned while the other one spliced to the other end of the gain fiber after rotating 90°. Thus, only one polarization can be selected by the cavity. In this method, a 100-W 1120-nm LPFL oscillator was achieved by Wang *et al*. in 2012 with a 3-dB bandwidth of 0.207 nm and a PER of 15 dB.[10] In 2016, Jiang *et al*. achieved a 32.7-W output laser power and 52-pm narrow spectrum bandwidth with a single-mode-multimode-single-mode cavity.[11] Nevertheless, given the narrow gap between the wavelength in the fast axis and that in the slow axis, this approach implies harsh demand for the bandwidth and central wavelength mismatch control of FBG. Not only will it raise the cost of FBG and face the difficulty in fusion splicing, but also the manufacture error and temperature induced wavelength shift of FBG could possibly lead to a severe central wavelength mismatch that might even cause the oscillation of the other polarization.

Another method to acquire a single polarization oscillator is based on the fact that the two polarizations in the polarization maintaining (PM) fiber have different bending losses. Therefore, a single polarization can be realized by coiling the active PM fiber to a proper radius. In 2005, with a 33-m long 20/400 μm Yb-doped fiber coiled to 9-cm diameter, Liu *et al*. realized 306-W output power with a bandwidth of 1.1 nm.[12] In 2015, Huang *et al*. achieved a 30-W linearly polarized fiber laser output through coiling the 15/130-μm gain fiber to

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a diameter of 5.6 cm.[7] These results seem to suggest that a smaller core size calls for a smaller coiling diameter of the gain fiber. Also, this method has little requirement for FBG, which reduces the cost and difficulty of the oscillator system.

In this paper, we employ a 10/125-PM Yb-doped fiber as the gain fiber of an all-fiber laser oscillator with single polarization operation. The coiling diameter of the 10/125-μm active fiber is carefully optimized through a series of comparative experiments, aiming to acquire both a high PER and a high linearly polarized laser power. The coiling pattern is also designed for better thermal management. The laser system finally achieved a 44.1-W output power with a narrow 3-dB bandwidth of 0.10 nm (26.5 GHz). The output laser also has a near-diffraction-limit beam quality of $M^2 = 1.14$. An average PER of 21.6 dB is measured over a 2-hour stability test.

2. Experimental setup

A linear polarization monolithic fiber laser system was constructed as illustrated in Fig. 1. A total of 76.2-W pump power came from a 975-nm wavelength-stabilized random-polarized laser diode (LD). A pair of fiber Bragg gratings (FBGs) made of polarization maintaining fiber formed a resonant cavity. The central wavelengths of both FBGs were 1064 nm, with a full width at half maximum (FWHM) of 1 nm and 0.1 nm for high-reflectivity (HR) FBG and output-coupler (OC) FBG, respectively. This difference in FWHM was designed to achieve a narrow output spectrum while minimizing the influence of temperature induced wavelength shift. Even if the central wavelength of the OC FBG does shift by a few pm from changing temperature, it is still matched within the relatively broad bandwidth of the HR FBG. The length of the polarization maintaining (PM) Yb-doped fiber (YDF) as the gain medium is 4 m. The active fiber was coiled in four separate groups of circles as illustrated in Fig. 1. In this way, the heat generated inside the active fiber was dispersed. Considering that the small coiling diameter will result in a high temperature in the active fiber, this method provided improved thermal management for the increasing heat load. At the cross point where one fiber spiral overlapped with another, adhesive with high thermal conductivity was used between the cross point and cooling plate to lower the local temperature. Meanwhile, because the active fiber was coiled in spirals, there was space between each circle, which led to an evitable difference in coiling diameter. Compared with the case that the active fiber is coiled in one spiral line, the active fiber was coiled in four groups of spirals, which means that the less circles there are in each group, the smaller the difference in coiling diameter will be. All the PM fibers share an identical core and cladding diameters of 10 μm and 125 μm. The numerical aperture (NA) of the active fiber core and inner cladding are 0.075 and 0.46, respectively. The inherent birefringence of the active fiber is 3×10^{-4}. After the OC FBG, a cladding light stripper (CLS) was adopted to remove the remnant laser in the fiber cladding, ensuring an accurate PER measurement. The cladding light stripping ratios of the CLS were designed to be gradually growing for system safety. An end cap was installed at the output end of the system.

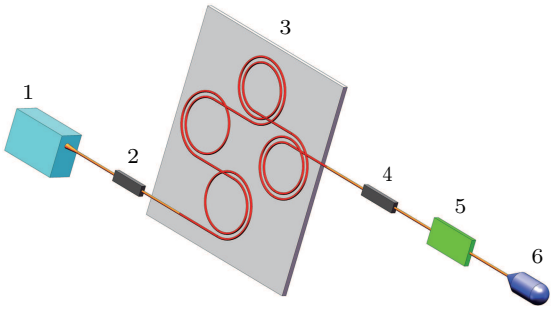


Fig. 1. (color online) Schematic diagram of the experimental setup of the linearly polarized fiber laser. 1: 975-nm wavelength-stabilized LD; 2: HR FBG; 3: 10/125-μm PM Yb-doped fiber; 4: OC FBG; 5: CLS; 6: end cap.

3. System parameters optimization

The single polarization operation was obtained by coiling active fiber to eliminate fast axis polarization whose bending loss grows faster than the other polarization with coiling diameter decreasing. The optimized coiling diameter was determined through a series of experiments. Starting from 12 cm, the coiling diameter gradually decreased. Meanwhile, with the pumping LD operating at 1 A, we observed the output spectrum changing with coiling diameter, as shown in Fig. 2. With larger coiling diameter, the spectrum presented a doublet whose peaks are at 1063.05 nm and 1063.26 nm, corresponding to the central wavelength of two polarizations along the fast and slow axes. This dual-peak spectrum was due to the difference in central wavelength of the FBGs between the fast axis and the slow axis. Also, the bandwidth of the OC FBG was narrower than the central wavelength difference, which gave rise to the dual-peak spectrum. Therefore, when adjusting the active fiber coiling diameter, we could judge the polarization composition by monitoring the output spectrum. When the active fiber was coiled with a diameter smaller than 8 cm, the fast axis spectrum peak gradually declined, and finally vanished when the coiling diameter was reduced to 6 cm or less. Therefore, the coiling diameter ought to be restricted within 6 cm in order to guarantee the single polarization output. In practice, we arranged three experiments with coiling diameters of 6 cm, 5 cm, and 4 cm to compare their performances.

First, the total output powers of three fiber lasers were measured as depicted in Fig. 3. The corresponding optical-to-optical efficiencies of 6 cm, 5 cm, and 4 cm were 76.7%, 57.9%, and 21.4%, respectively. This descending trend of optical-to-optical efficiency with the decreasing of coiling diameter is due to the rising amount of laser leaking into the

cladding and finally being removed by the CLS. From the comparison, it could be seen that the fiber laser with a coiling diameter of 4 cm had an extremely low optical-to-optical efficiency. Besides, in the 4-cm coiling diameter experiment, even with the improved thermal management by dispersing heat in four fiber groups, we still observed fairly high temperature in the active fiber, endangering the safety of the laser system. Taking these shortcomings into consideration, the coiling diameter of active fiber should be larger than 4 cm.

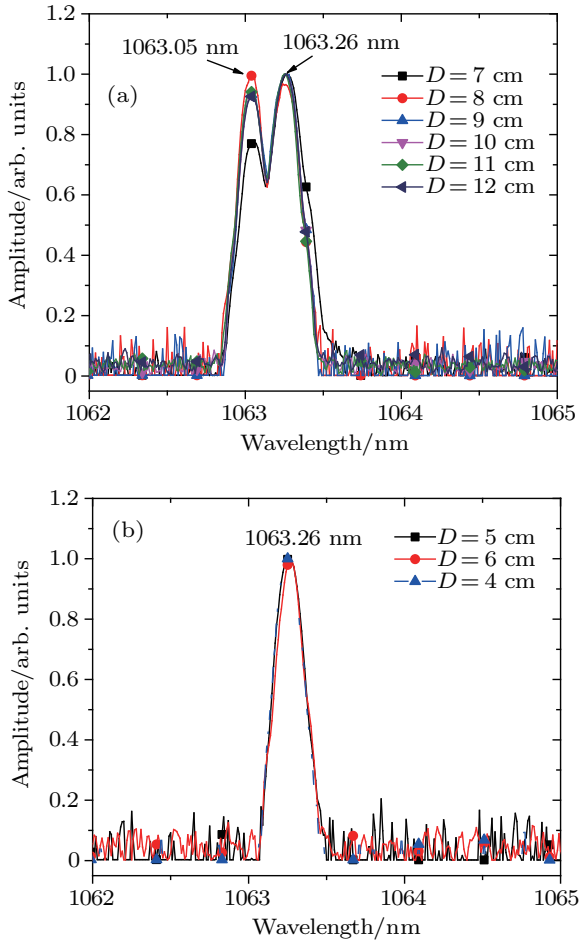


Fig. 2. (color online) Output spectra with different coiling diameters.

Furthermore, the PERs of the remaining two oscillator systems were measured via a polarization beam splitter as exhibited in Fig. 4. At the low power level, both oscillators have excellent PER higher than 20 dB. Nevertheless, the PER of the 6-cm coiling diameter fiber laser drastically degraded when the output power level exceeded a certain threshold. On the other hand, the PER of the 5-cm coiling diameter fiber has been steady and never below 19.9 dB in the whole power rising process. The reason for this phenomenon was speculated to be the additional thermally induced stress brought in by the increasing of temperature at high power, which will further lead to the depolarization and the decline of the PER. As for the 6-cm coiling diameter, the initial bending induced stress was relatively low compared with the 5-cm coiling diameter. Therefore, the additional thermal induced stress became more influential in the case of the 6-cm coiling diameter, leading to more evident depolarization. Thus, the coiling diameter of the active fiber was finally optimized to be 5 cm for the best overall laser performance.

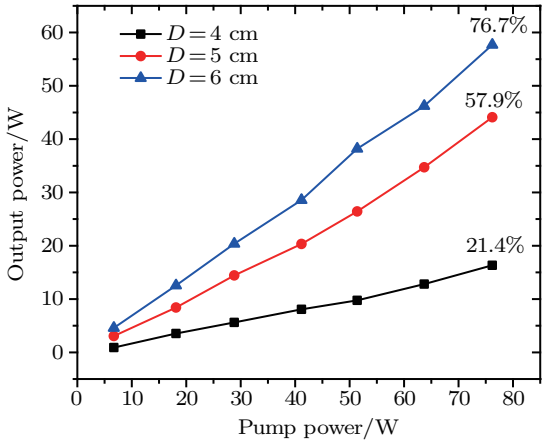


Fig. 3. (color online) Output laser powers versus pumping laser power of three experiments with different coiling diameters. The corresponding optical-to-optical efficiency is marked beside the curves.

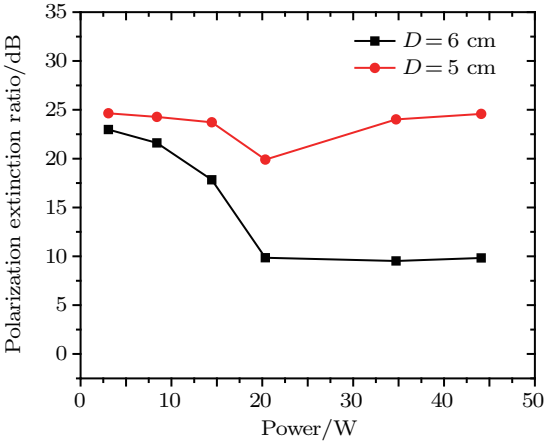


Fig. 4. (color online) Polarization extinction ratios versus output power with coiling diameter being 6 cm and 5 cm.

4. Experimental results

With the optimized structure, the fiber laser oscillator finally achieves a linear polarized output laser power of 44.1 W when pumping laser power is launched at 76.2 W, corresponding to an optical-to-optical efficiency of 57.9% as shown in the red line in Fig. 3. The relatively low efficiency results from the high bending loss in order to eliminate the laser in fast axis polarization, which is a compromise for a high PER of the output laser. The output laser spectrum as depicted in Fig. 5, centered at 1063.26 nm with a 3-dB bandwidth of 0.1 nm. The beam quality of the linearly polarized fiber laser is analyzed by a PRIMES HP-LQM laser quality monitor as shown in Fig. 6. The result indicates a near-diffraction-limitation beam quality with an M^2 factor of 1.14.

The stability of the fiber laser oscillator is vital to the stability and performance of the entire MOPA system. Thus, to

test the stability of the linearly polarized fiber laser system, a stability test is run on the oscillator system for 2 hours while monitoring the output laser power and the PER as shown in Fig. 7. The laser power varies between 43.1 W and 45.7 W, and their average value is 44.6 W. The PER, during the 2-hour operation, does not drop under 19.5 dB and on average it is 21.6 dB, verifying that the output laser always stays in the status of highly linear polarization. The stability test verifies the capability of the oscillator serving as the seed for further amplification.

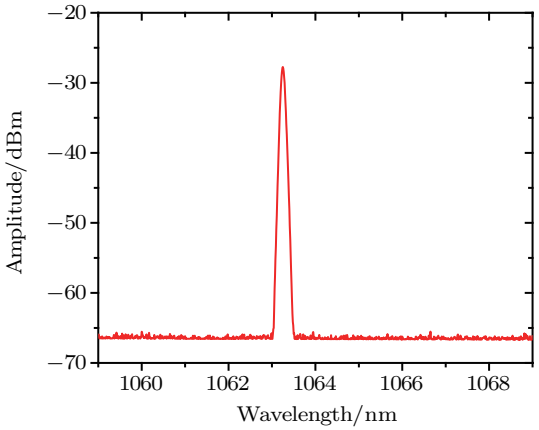


Fig. 5. (color online) Spectrum of the linearly polarized fiber laser.

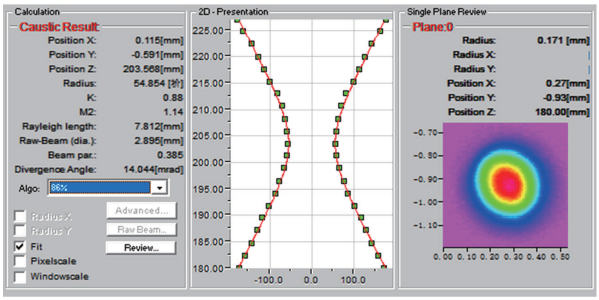


Fig. 6. (color online) Beam quality of the linearly polarized fiber laser.

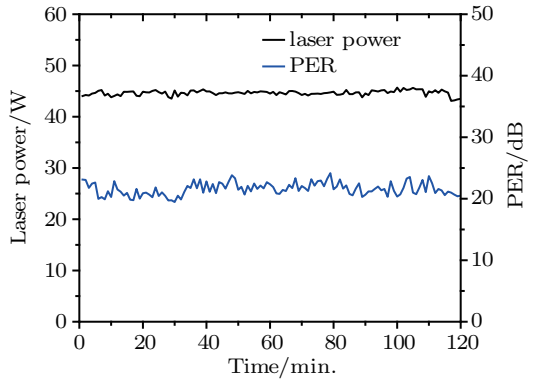


Fig. 7. (color online) Test results of system performance stability of the output linearly polarized laser in a time period of 2 hours, including the output power and PER. The data are taken every 1 minute.

5. Conclusions and perspectives

In this work, we demonstrate an all-fiber linear polarized fiber laser oscillator. The single polarization output is realized by controlling the bending loss of the active fiber. The structure of the oscillator is carefully designed. On the one hand, the coiling diameter of the active fiber is optimized to obtain high PER without sacrificing too much efficiency. In the process, we find out that the laser polarization can be reflected by the output spectrum, which would make it more convenient to adjust the coiling diameter while monitoring the polarization. On the other hand, the active fiber coiling pattern is designed to be a four-group pattern to disperse the generated heat load for a better thermal management. As a result, the laser power output from the oscillator reaches 44.1 W with a corresponding optical-to-optical efficiency of 57.9%. The output spectrum has a central wavelength of 1063.26 nm with a narrow 3-dB bandwidth of 0.1 nm. The near-diffraction-limit beam quality of $M^2 \sim 1.14$ is achieved from the oscillator. The output laser also has a high average PER of 21.6 dB, which is also due to the active fiber coiling control. The output performance stability of the oscillator is tested for 2 hours, verifying its ability to function as a seed laser for future laser amplification. In order to achieve a higher power level, thermal management improvement and structure refining would be necessary in the future.

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