A linearly-polarized passively mode-locked yb-doped fiber laser with nanosecond pulses

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Abstract

A linearly-polarized, all-normal dispersion (ANDi), passively mode-locked ytterbium-doped fiber laser is demonstrated with a master oscillator power amplifier (MOPA) structure. Using a cascaded long-period fiber grating as an all-fiber format spectral filter, the mode-locked pulse is achieved by nonlinear polarization evolution (NPE) effect. Nanosecond pulses with a low repetition rate of 1.53 MHz and a output power of 363 mW when the seed source after amplifier, and the pulses duration can be tuned from 0.78 ns to 3.57 ns with a polarization extinction ratio of >20 dB. The preliminary experiment shows that the nanosecond pulses output from the ANDi fiber laser could be used as an ideal seed source for all-fiber amplifier system.

Keywords: Fiber Optics; Fiber Laser; All-Normal Dispersion; Amplifier

1 Introduction

Compact, linearly polarized, and high power output fiber lasers with nanosecond optical pulses have attracted signifycant interesting recently for their potential applications in mang fields of sensing, micromachining, biomedical diagnostics, optical measurement instruments and lidar systems [1-8]. Conventional Q-switched lasers are not suitable for these applications due to long pulse duration (~tens of ns). In 2008, Renninger et al [9] reported an all-normal dispersion (ANDi), passively mode-locked fiber lasers with giant chirp and high energy pulse due to the large normal group-velocity dispersion (GVD) in the laser cavity. The giant chirped long-pulse and mode-locked output suggests the usefulness of such a source for chirped-pulse amplification (CPA) schemes, where the need for a stretcher, pulse-picker, and pre-amplifier could be eliminated. After that, several groups reported very long pulses (nanosecond scale), low repetition rates, and relatively low average powers but high pulse energies from passively mode locking large normal dispersion, ultra-long cavity, Yb-based or Er-based fiber lasers [10-17].

Both theoretical and experimental results have shown that the spectral filter is very critical for the pulse generation, pulse quality, pulse energy and the stability of the ANDi system [18]. Without spectral filter, stable mode locking has been achieved only with a very short laser cavity or other specially designed cavity [19]. An achromatic quarter-wave plate (AQWP) as a pulse stabilizer in the ANDi and polarization-maintaining linear laser cavity has been reported [20]. However, bulk components such as interference filters or briefringent filters were also employed in the laser cavity, which sacrificed the advantages of all-fiber format. Recently Özgören et al reported an ANDi mode-locked fiber femtosecond laser with fiber-based lyot filter [21], however, the output pulses is not linearly polarized.

In this paper, a linearly polarized, low-repetition-rate, passively mode-locked Yb-doped fiber laser was reported and demonstrated. Using a cascade long-period fiber grating (C-LPFG) as an all-fiber format spectral filter for the strong pulse shaping, nanosecond pulses with Gaussian-shaped spectrum with a repetition rate of 1.53 MHz are achieved as a master seed. After master oscillator power amplifier (MOPA) structure, the maximum average power of the amplified output is 363 mW and the pulse duration can be continuously tuned from 0.78 ns to 3.57 ns, in addition, linearly polarized pulses with a polarization extinction ratio large than 20 dB and an overall efficiency of 59%.

2 Theory

In our experiment, a CO_2 laser was used for the C-LPFG fabrication. For precise analysis of the CO_2-induced C-LPFG, a three-layer modeling for single-mode fiber is used [22]. For a light coupling from a guided mode to cladding mode in an optical fiber, the electric field can be written as:

$$E(z) = [A_{01}^{co}(z)e^{-j\delta_m z}]e^{j\beta_{01}^{co} z} + [A_{01}^{cl}(z)e^{-j\delta_m z}]e^{j\beta_m^{cl} z} \quad 0 \le z \le L, \tag{1}$$

where $A_{01}^{co}(z)$ and $A_{01}^{cl}(z)$ are the amplitudes of input LP_{01} guided mode and the LP_{0m} coupled cladding mode along the LPFG length, respectively. L is the length of LPFG. β_{01}^{co} and β_m^{cl} are the respective propagation constants. $\delta_m = (1/2)[(\beta_{01}^{co}) - (\beta_m^{cl}) - 2\pi/\Lambda]$ is the detuning from the resonance wavelength, where Λ is the period of the LPFGs. The coupled-mode equations of LPFG are then expressed as:

$$\begin{cases} \dfrac{dA_{01}^{co}}{dz} = j[\delta_m A_{01}^{co} + \kappa_m A_m^{cl}] \\ \dfrac{dA_m^{cl}}{dz} = j[-\delta_m A_m^{cl} + \kappa_m A_{01}^{co}] \end{cases}, \tag{2}$$

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where κ_m is the LP_{0m} cladding mode coupling coefficient and $\kappa_m L$ is called coupling strength. The composite LPFG in our experiment is treated simply as two gratings ($LPFG_1$, $LPFG_2$) separated by a phase shift φ and a length of fiber l. When $\phi = 0$ and $l = 0$, it becomes a conventional LPFG, when $l = 0$ and $\phi \neq 0$, it called a phase-shifted LPFG, and when $d \neq 0$, we call it a cascaded LPFG. Considering the boundary conditions $A_{01}^{co}(0) = 1$, $A_m^{cl}(0) = 0$, the amplitude transmittance T and LP_{0m} cladding mode coupling ratio R are solved from equation (2) and express as:

$$\begin{bmatrix} T \\ R \end{bmatrix} = \begin{bmatrix} T_2 & R_2 \\ R_2 & T_2^* \end{bmatrix} \begin{bmatrix} e^{j\pi(n_{01}^{co}-n_{0m}^{cl})d/\lambda} & 0 \\ 0 & e^{-j\pi(n_{01}^{co}-n_{0m}^{cl})d/\lambda} \end{bmatrix}, \times \begin{bmatrix} e^{j\phi/2} & 0 \\ 0 & e^{-j\phi/2} \end{bmatrix} \begin{bmatrix} T_1 & R_1 \\ R_1 & T_{1*} \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix} \quad (3)$$

where n_{01}^{co} and n_{0m}^{cl} are LP_{01} core mode and LP_{0m} cladding modes refractive indexes. Thus, R_i and T_i described the conventional grating $LPFG_i$ (i=1, 2) cladding mode coupling radio and core mode transmission radio and are solved from equation (2) as

$$\begin{cases} T_i = \cos(s_m L_i) + j\dfrac{\delta_m}{s_m}\sin(s_m L_i) \\ R_i = j\dfrac{\kappa_m}{s_m}\sin(s_m L_i) \end{cases}, \quad (4)$$

where $s_m = \sqrt{\kappa_m^2 + \delta_m^2}$ is effective detuning. Substituting equation (4) into equation (3), we obtain [8, 9]

$$\begin{cases} T = e^{[j\pi(n_{01}^{co}-n_{0m}^{cl})d/\lambda+\phi/2]}T_1T_2 + e^{-[j\pi(n_{01}^{co}-n_{0m}^{cl})d/\lambda+\phi/2]}R_1R_2 \\ R = e^{[j\pi(n_{01}^{co}-n_{0m}^{cl})d/\lambda+\phi/2]}T_1R_2 + e^{-[j\pi(n_{01}^{co}-n_{0m}^{cl})d/\lambda+\phi/2]}R_1T_2^* \end{cases}, \quad (5)$$

where $\varphi = 0$ and $l = 0$, equation (5) reduces to conventional LPFG, expressed by equation (4) with a length of L_1+L_2. Since energy is conserved, $|R|^2 + |T|^2 = 1$, we need only to discuss power transmission and we have for the power transmittance:

$$T = \left| e^{[j\pi(n_{01}^{co}-n_{0m}^{cl})d/\lambda+\phi/2]}T_1T_2 + R_1R_2 \right|^2. \quad (6)$$

For C-LPFG, the phase delay is from the light propagating along the core and the cladding of the fiber along the length *l* separating the two gratings. The phase delay is wavelength dependent and the transmission spectrum is modulated with multiple peaks. This device is similar to a Mach-Zehnder interferometer with the two gratings act as two couplers and the guided and cladding modes in the fiber between them acting as the two arms in the interferometer. The wavelength spacing between two neighbours transmission peaks are obtained from equation (6) and written as

$$\Delta\lambda \approx \lambda^2 / [(n_{01}^{co} - n_{0m}^{cl})l]. \quad (7)$$

3 Experimental setup

In our experiment, a C-LPFG is used as the all-fiber-format spectral filter in the system, and the transmission spectrum of the C-LPFG is shown in figure 1. The C-LPFG was fabricated with a CO_2 laser focused on a Corning HI1060 single-mode fiber (SMF) with NA=0.12 and for wavelength λ =1.0 μm. The C-LPFG was cascaded by two conventional LPFGs with the central wavelength of 1025nm and 1038nm, respectively. The pitch of the two cascaded grating was 316 μm and 346 μm, respectively. The number of the periods of both gratings is 50. The central wavelength of C-LPFG transmission spectrum is at 1034 μm with the full width at half maximum (FWHM) is approximately 7 nm and the wavelength spacing is $\Delta\lambda$ =13nm.

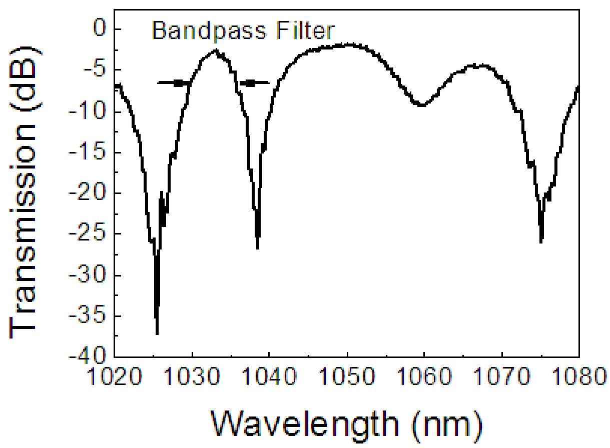

FIGURE 1 The transmission spectrum of the CLPFG

We will use the C-LPFG as a spectral filter in the ANDi system for mode-locking. Figure 2(a) shows the experimental setup of a MOPA structured passively ANDi Yb-doped fiber laser, which was built in a unidirectional cavity for self-starting operation. The total length of the cavity is 126 m, and all components of the laser have normal group velocity dispersion (GVD). A 28cm piece of Yb-doped gain fiber (612 dB/m absorption at 976 nm) was placed after 118 m of single-mode fiber (SMF). The pump laser (pump diode) was a 976 nm grating-stabilized laser diode, which delivers up to 530mW to the gain fiber through a 980/1060 wavelength-division multiplexer (WDM). A C-LPFG is used as a spectral filter connecting with the gain fiber. The passband of the C-LPFG determines and coincides with the central wavelength of our laser output. Mode-locking operation was initiated and stabilized by nonlinear polarization evolution (NPE), which was implemented with quarter-wave plates (QWPs), a half-wave plate (HWP), and a polarizing beam splitter (PBS). The output of the laser was directly from the NPE rejection port by output 2.

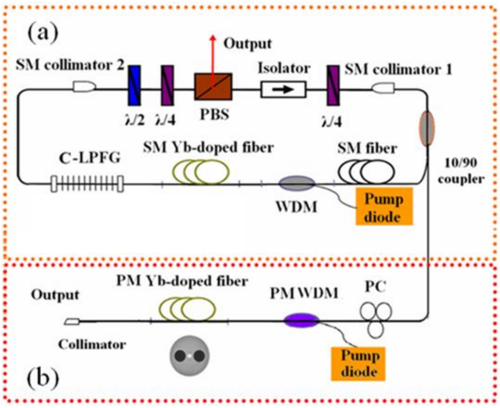

FIGURE 1 (a) Configuration of MOPA structured ANDi passively mode-locked Yb-doped fiber laser cavity. (b) The amplifier setups; (λ/4, λ/2: quarter and half waveplates, PC: polarization controller, PM: polarization maintaining)

In the amplifier stage, the seed for amplifier was coupled from the mode-locked seed source partly through a coupler (1:9) by output 1 as shown in Figure 1(b). An 88 cm polarization-maintaining (PM) Yb-doped gain fiber (1611dB/m at 976 nm) was employed to amplify the pulses. The gain fiber was pumped by another laser diode with the maximum pump energy of 700 mW. A polarization controller (PC) was used to control the polarization state of the output laser. A high speed photodetector (rise time<40 ps) with a Tektronix DSA 72004 mixed digital oscilloscope (20 GHz bandwidth) and a frequency spectrum analyzer (Agilent E4447A) were used for the pulse shape measurement and the radio-frequency (RF) spectrum measurement. A Q-6370 spectrum analyzer was used for the spectral measurement.

4 Result and discussion

In the experiment, the threshold of the seed source laser is 210 MW. When the pump power is higher than 210 MW, a self-start stable mode-locked pulse is obtained as shown in Figure 2(a). From Figure 2(a), we can see that the central wavelengths of the mode-locked pulses are coincident very well with that of the pass-bands of the C-LPFG. The FWHM spectral width is 2 nm and the spectral shape shows steep edges with a Gaussian-shaped top which exhibits typical characteristics of ANDi fiber lasers. The repetition rate of the pulses is 1.53 MHz corresponding to the total cavity length of 126 m. It can be seen that the output laser pulse train is uniform and stable. There is no indication of residual sidebands caused by Q-switched mode-locking. Adjusting the quarter-waveplate, the pulse duration can be tuned from 760 ps to 3.57 ns as shown in Figure 2(b), which indicates the pulses with a high chirp.

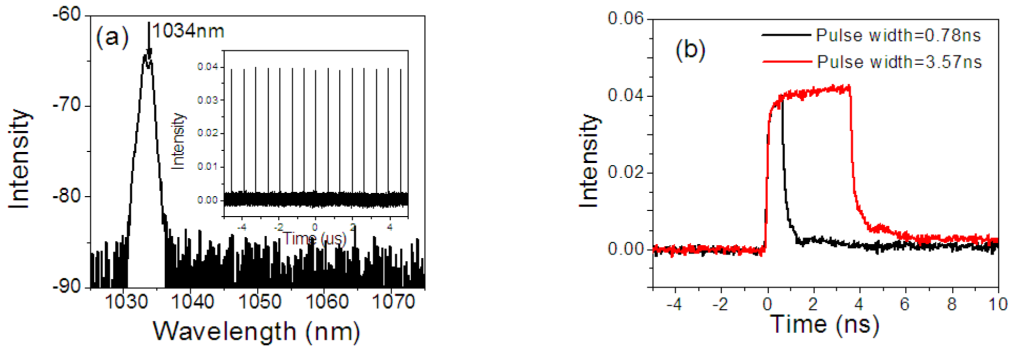

FIGURE 2 (a) Output spectrum and oscilloscope traces of the pulse train (the inset), (b) Oscilloscope traces of a single pulse

To demonstrate the feasibility of our oscillator served as a master seed for amplifier, we build a MOPA system as shown in Figure 1(b). For confirm the output laser with linear polarization, all the fiber compounds are polarization maintaining in the amplifier stage. Figure 3 (a) shows the comparison optical spectrum of the seed source with the amplifier output. We can see that the output power of the pulses is amplified about 10 dB than that of the seed without amplification. This indicates that the power from the seed laser is sufficient to suppress the ASE in the subsequent amplification stages. Figure 3(b) shows the temporal profile of the pulse output, from which we can see that the amplified pulses maintain the characteristics of the seed source. From Figure 3, it is believed that the passively mode-locked ANDi system can be used as an ideal master seed for an all-fiber amplifier system.

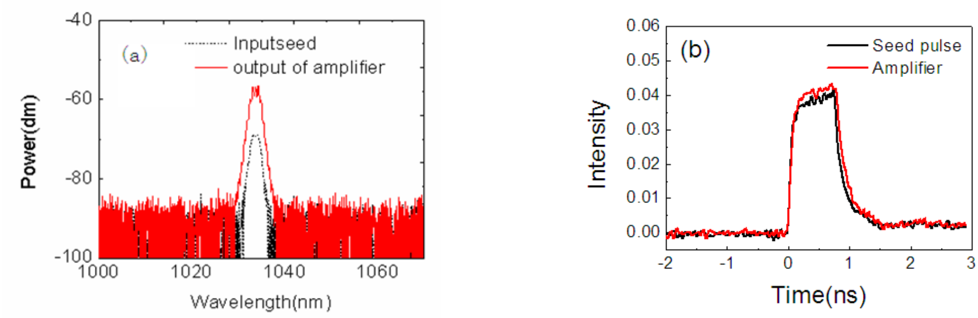

FIGURE 3 (a) Optical spectrum of seed and amplifier, (b) The temporal profile of the pulse output and amplifier

Figure 4 shows the output power of the amplified laser with increasing of the pump power. A maximum average power of the amplified laser output is 363 MW with a maximum pump power of 630mW, corresponding to a slope efficiency of 59%. In the amplifier output, the repetition rate is 1.53 MHz with a maximum average output power of 363 MW, which corresponds to single pulse energy of 237 nJ.

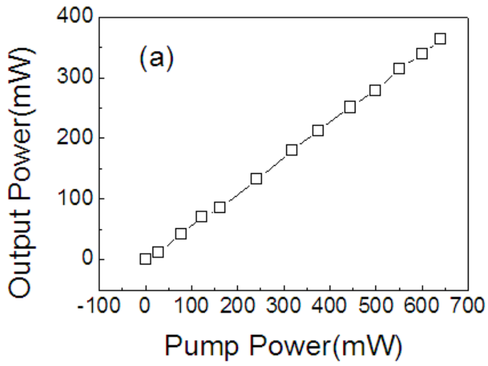

FIGURE 4 Output laser power vs. the pump power of the amplified part

To confirm the amplifier pulses with a good polarization maintain, a polarizer is located after the amplified laser for polarization extinction ratio measurement. Figure 5 shows the output power of amplified laser after polarizer when polarization state is changed. From Figure 5, we can seen that the polarization extinction ratio is larger than 20 dB when the angle of polarizer rotating, which indicates that the ANDi laser pulses can be used as an ideal linearly polarized seed source in the MOPA systems. Further work will be focused on improving the pump conversion efficiency of the amplifier by utilizing large mode area double-cladding (LMA DC) Yb-doped fiber to achieve higher pulse energy.

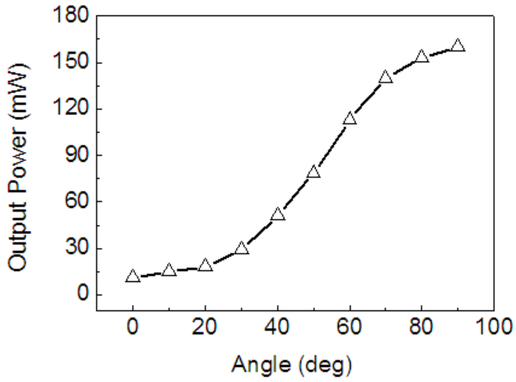

FIGURE 5 Polarization extinction ratio by adjusting polarizer angles

5 Conclusion

In summary, a flexibly controllable linearly-polarized passively mode-locked Yb-doped fiber laser in the all-normal dispersion regime was demonstrated with a MOPA structure. A C-LPFG was served as a spectral filter and NPE as the mode-locking effect, a repetition-rate of 1.53 MHz pulses with tuning pulses duration and a high polarization extinction ratio of >20 dB are achieved after the amplifier stage, which shows the ANDi pulses can be used as an ideal linearly polarized seed for all-fiber amplification systems.

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