Design and implementation of low-cost and high-efficient 1550nm short-pulse fiber laser

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This paper developed a low-cost, simple, and good efficient short-pulse fiber laser using the concept of polarization additive-pulse mode-locking (P-APM). Three different types of pulsed lasers were proposed. The pulse widths were about 5 ns, 20 ns, and 400 ns. The average power and repetition rate used to calculate the pulsed energy of 2.34, 3.98, and 86.2 nJ, respectively. The average output power of the pulsed laser increased when connecting with a high-power Erbium/Ytterbium co-doped fiber amplifier (EYDFA) at the fiber laser output. Using the 3A driving current of the pumped laser diode, the gain of EYDFA went up to 28.36 dB with 0 dBm input power. When the amplifier pump laser source operated at 7A, the three kinds of short-pulse lasers were 13.02, 13.27, and 15.67 mW. While the pulse energy were effectively promoted to 367.22 nJ, 606.11 nJ, and 11.46 μJ with 157, 152, and 133 times of amplification, respectively.

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1. Introduction

Compared to semiconductor lasers, optical fiber laser has many advantages. Its all-fiber structure can overcome harsh environments, such as high temperature, high vibration, dust and other situations [1-2]. Moreover, the optical fiber has excellent flexibility, which allows the laser package volume of the optical fiber to reduce and is highly compatible with the optical fiber system [3].

A continuous wave (CW) laser has fixed optical output power without the external modulation mechanism. It has a small bandwidth so is suitable for making the measurement and analyses precise. If a higher intensity laser application is required, a modulated mechanism can be used to produce high laser power. The output power of a pulsed laser with time structure is lower than that of a CW laser, but it has the characteristics of a short time, high intensity and wide bandwidth. According to the Fourier transform theory, when the frequency width is more extensive, different pulse width will also be narrower, which can be used to measure fast-moving objects. The modulation mechanism of pulse laser is mainly Q-switching or mode-locked [4-6].

In general, Q-switched and lock mode are methodologies to achieve short-pulse lasers. The pulse width of the Q-switched laser is about microsecond (μs) to nanosecond (ns), while the pulse width of the lock mode laser is from nanosecond (ns) to femtosecond (fs) [7-8]. For the saturable absorber families. The saturable absorber materials (graphene etc.) were used in [9-10]. Graphene and graphite have an ultra-wide wavelength modulation range [11]. In this work, the nonlinear polarization rotation technique is used. Several passively mode-locked mechanism have been proposed for ultrafast fiber lasers such as nonlinear amplification loop mirror, saturable absorber, and nonlinear polarization rotation (NPR) [12-14] with convenience and good performance. Because the pulse can be either single pulse or multiple pulses, it can produce high peak power in a short time. Its characteristics include high time resolution, high spatial resolution, high bandwidth and high intensity [15]. It may be used in many aspects such as high-precision processing, laser cutting, medical beauty laser and even minimally invasive surgery [16-17]. Chaolin Yang et al. demonstrated an efficient, pulse-pumped fiber ring laser with a compact and cost-effective all-fiber configuration. The laser pulses with an 8.71 μs duration were generated; the laser pulses have a repetition rate of 4 kHz [18]. Gao W. L. et al. proposed a mode-locked non-polarization maintaining Er-doped fiber laser. The laser pulses are 44.6 fs, the laser pulses have a repetition rate of 257 MHz, and the single-pulse energy is 0.4 nJ [19]. Usha et al. controlled the opening time of the acoustic-optic modulator (AOM) modulation window to produce a stable time pulse between the sub cavity and back in the all-fiber Yb doped Q-switched fiber laser. The laser had a repetition rate of 80 kHz, pulse energy of 240 μJ, a peak power of 4.4 kW, and a pulse width of 50-55 ns[20]. In this paper, we chose the lock mode pulse laser with adjustable pulse width and wide range. The pulse width can reach the order of nanosecond (ns) to femtosecond (fs). It has a higher pulse repetition rate and can be selected with different pulse widths.

To reduce the high-power induce fiber nonlinearity inside the fiber cavity and/or fiber end-face damage, a master oscillator power amplifier (MOPA) scheme may be adopted which means having a high-power fiber amplifier located after the short-pulse laser, to improve the output power [21-23]. The high-power fiber amplifier is a gain medium with double cladding excited by a multimode high-power pump laser which can effectively improve the laser power. The high absorption of Ytterbium ions and efficient energy transfers between Erbium ion and Ytterbium ion can be used to pump the Erbium ions effectively. Therefore, double cladding fiber can make the core diameter effectively larger. This is a way to obtain effective absorption of the pump laser source to develop a more reasonable and suitable short-pulse laser [24-25].

In this paper, two high-power multimode pump laser sources at 980 nm are used to excite double-clad Erbium ytterbium co-doped fibers. This method can improve the gain by connecting a short-pulse laser with a high-power fiber amplifier architecture to increase the average laser power. A simple optical architecture with low-cost optical elements is used to build a relatively high power 1550 nm short-pulse fiber laser, using the MOPA scheme. We achieve an adjustable pulse width by varying the single-mode fiber (SMF) based resonant cavity length.

2. Experiments design and setup

The experimental setup, as is shown in Fig. 1, is to use nonlinear polarization rotation (NPR) technology to produce a polarization additive-pulse mode-locked (P-APM) laser. The mode-locking of the superposition wave is to generate a pulse compression effect via pulse coherency addition. Here, nonlinear polarization rotation is used to generate nonlinear interference. The non-polarized light is converted into linear polarization by a polarizer. The direction of polarized light can then rotate into an elliptically polarized light by a polarization controller (PC) or wave plate.

We added two PCs to the ring laser structure and the polarization-dependent isolator (PDI) to polarize additive-pulse mode-locked. The PDI characteristic is that the input light is polarized into vertically polarized. Then, the Faraday polarizer rotates 45 degrees of its polarization state. Finally, the second PCs will allow the light to pass through the PDI, which will combine both the linear polarization and optical isolation effects. After properly adjusting the PC, a linear polarization laser formed at the output end, and the reverse light was blocked. Therefore, we did not use the original saturable absorber in the experimental structure, and the mode-locked polarization superposition wave showed a pulse with a broader frequency width. Here, we added two PCs to the ring laser structure and the PDI to polarize the additive-pulse mode-locked laser. The characteristic of the PDI is that the input light is polarized into vertically polarized light by the polarizer. Then, the Faraday polarizer will rotate 45 degrees of the laser polarization state. Finally, the second PC will allow the light to pass through the PDI, which will combine both effects of linear polarization and optical isolation. After properly adjusting the PC, a linear polarization formed at the output end, and the reverse light is blocked. The threshold current of the proposed mode-locked laser was 54.3 mA and the output power against the pump current is shown in Fig. 2(a). When the pump current increases to 300 mA, the 3-dB bandwidth of laser can reach 7.8 nm as shown in Fig. 2(b). The digital oscilloscope used in this experiment is Tektronix DPO5104. The maximum bandwidth that can be measured is 1 GHz with a sampling rate of 10 GS/s. By using the digital oscilloscope to observe the short-pulse laser, the pulse width and pulse repetition rate are 328 fs and 15.6 MHz, respectively.

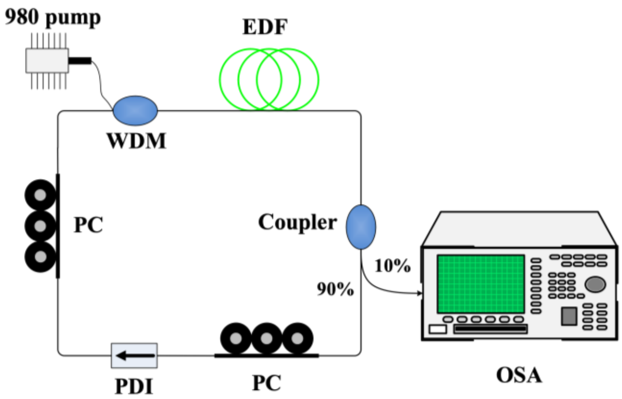
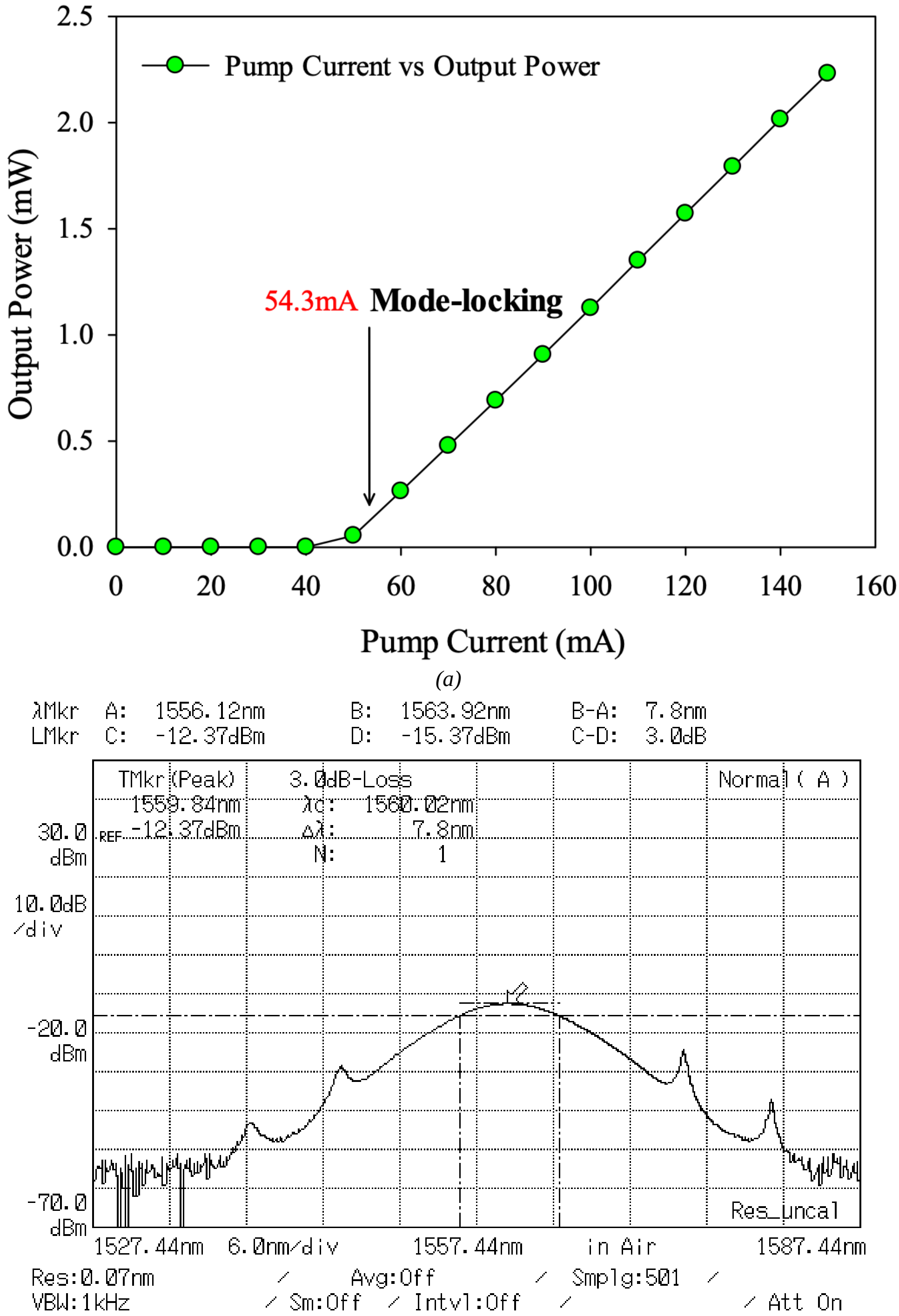


Fig. 1. The schematic of the proposed short pulse fiber laser (color online)



(b)

Fig. 2. (a) The output power against pump current, and (b) the output spectrum with a 90/10 fiber ratio coupler (color online)

The total length of the fiber cavity was 13.3 m, which includes SMF and Erbium-doped fiber. Therefore, the pulse repetition rate (R) is obtained according to:

$$R = \frac{1}{\Delta t} = \frac{c}{nL} = \frac{3\times10^8}{1.45\times13.3} \approx 15.56 \text{ MHz} \quad (1)$$

In the formula above, c is the speed of light in a vacuum, n is the refractive index of the fiber core, and L is the length of the resonant cavity. After calculation, we found that the pulse repetition rate was 15.56 MHz. When the mode-locked reached its threshold current, the apparent difference between the mode-locked state and the un-mode-locked state is shown in Fig. 3. The black dash line shows that when the mode-locked state is not reached, the narrow bandwidth fiber laser observed in the spectrum diagram and the central wavelength will not be significantly broadened or arc-shaped. When the mode-locked state is reached, the spectrum diagram will be a solid red line, and the spectrum diagram is visible. The structure can be used as a front-end seed laser. An Erbium/Ytterbium co-doped fiber amplifier can be constructed at the back-end to improve the overall average output power. A radio frequency (RF) spectrum analyzer was used to measure the pulse repetition rate.

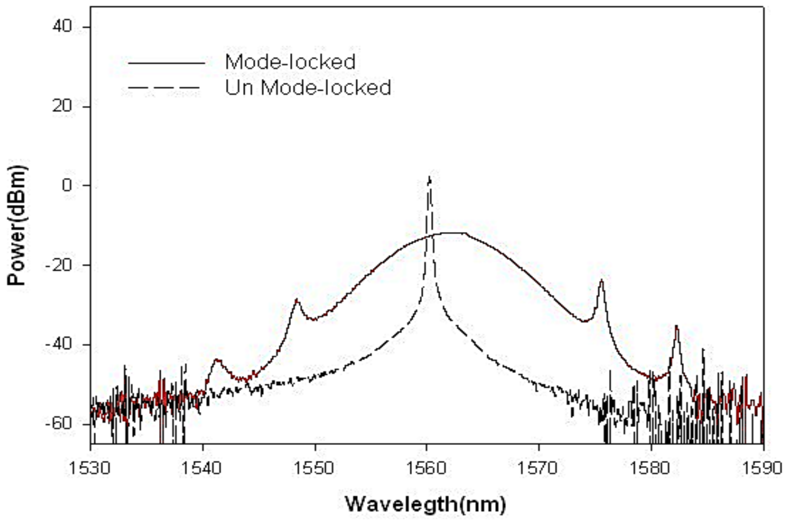
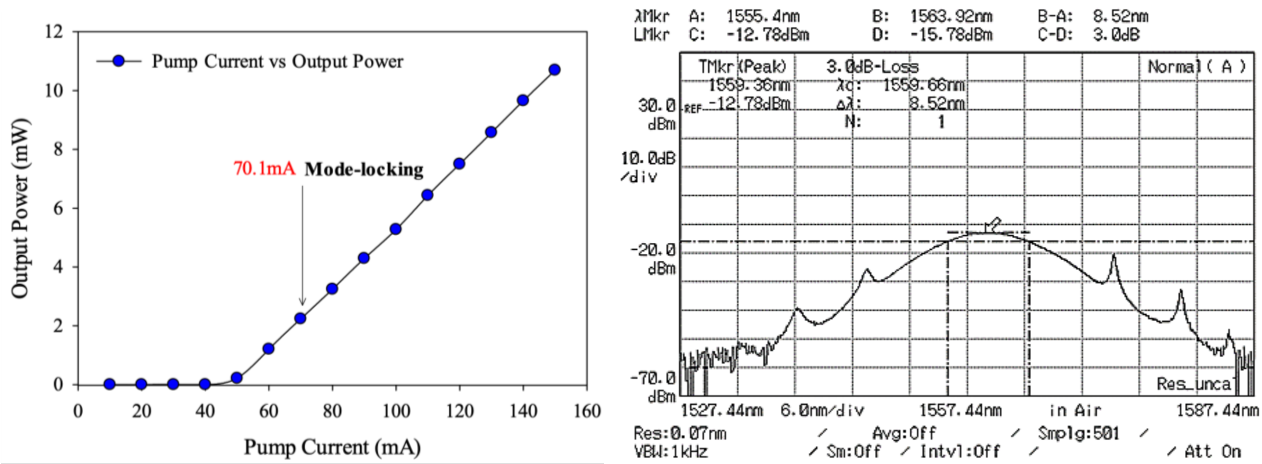


Fig. 3. The output spectral of the mode-locked and un-mode-locked fiber lasers (color online)

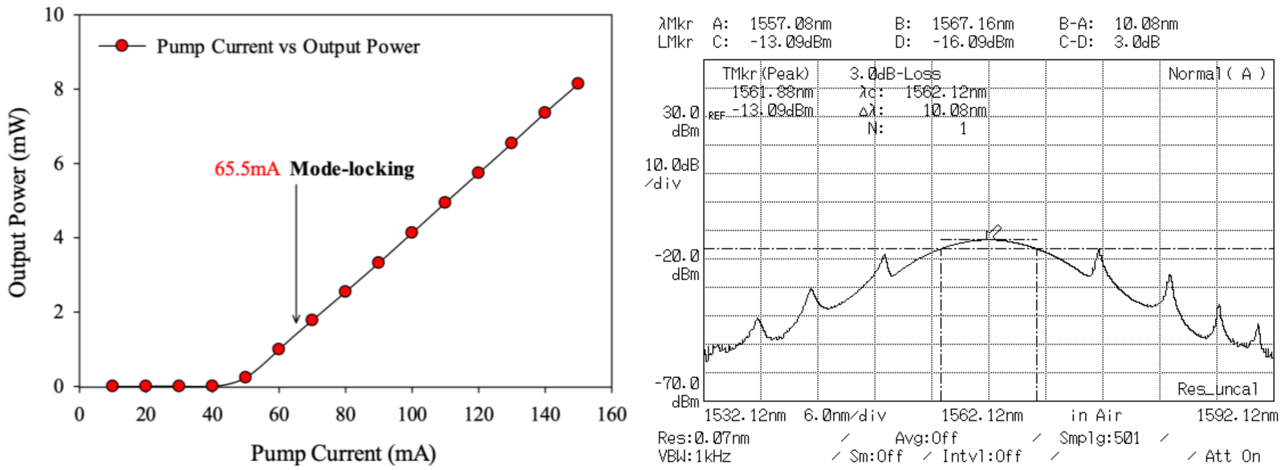
3. Fiber ratio couplers replacement in fiber lasers

To avoid affecting the laser pulse performance, we inserted a WDM coupler in the structure and connected it to filter out the residual pump power. As the pump laser source current increased to 70.1 mA, the mode-locking was generated by adjusting the optical PC. When the ratio coupler is 50/50, the L-I curve of pump laser is shown in Fig. 4(a) and the output power spectrum is shown in Fig. 4(b) with 3dB bandwidth of 8.52 nm when the pumping current is 70.1 mA. We found that the required threshold current is higher when a 50/50 coupling beam splitter is used instead of a 90/10 coupling beam splitter. The reason is that 50/50 coupling beam splitter allows less power of the laser to travel back to the resonant cavity. When the ratio coupler is changed to 70/30 as is shown in Fig. 5(a). As the driver current reaches 65.5 mA, mode-locked can be generated by adjusting the PC. We found that the 3-dB bandwidth reaches 10.08 nm as shown in Fig. 5(b). It is found that the threshold current from the largest to the smallest is 50/50, 70/30 and 90/10. The higher proportion of energy in the laser resonator, the more easier it is to produce mode-locking effect. As the the pump current is adjusted to 300 mA and the PC is adjusted to mode-locked state, the central wavelength and 3dB bandwidth of the laser are 1560 nm and 10.08 nm, respectively.



(a) *(b)*

Fig. 4. (a) The output power against pump current, and (b) the output spectrum by using a 50/50 fiber ratio coupler (color online)



(a) (b)

Fig. 5. (a) The output power against pump current, and (b) the output spectrum with a 70/30 fiber ratio coupler (color online)

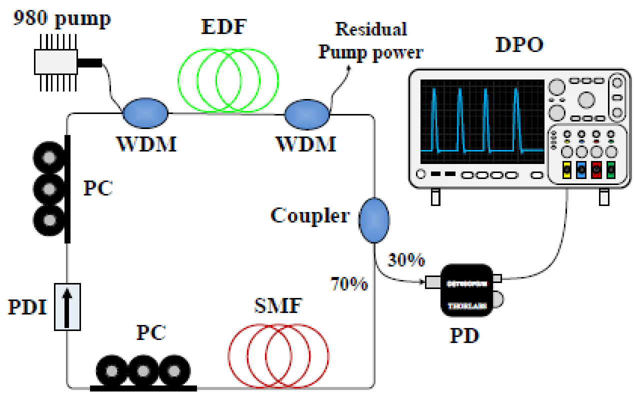
According to the analysis and comparison, we know that 50/50 and 70/30 ratio coupler have similar pulse energy. Their average pulse output power is five times than that of the 90/10 spectrometers. The output energy of the 50/50 splitter is slightly higher than that of the 70/30 ratio coupler. While the 70/30 ratio coupler has the largest optical signal to noise ratio (OSNR) and 3dB bandwidth. All results of three different ratio couplers are summarized in Table 1.

Table 1. Three parameters comparison

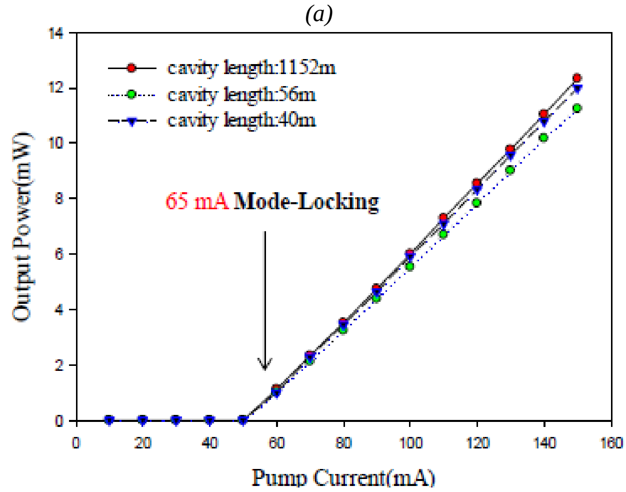
Ratio coupler	3-dB bandwidth	Pulse width
90/10	7.8 nm	328 fs
50/50	8.52 nm	299.9 fs
70/30	10.08 nm	254 fs

4. Cavity length replacement in fiber lasers

The larger the positive dispersion value is, the wider the laser pulse width. We inserted a SMF into the laser resonator to enhance the dispersion effect in the resonator and achieved the effect of pulse width broadening, as shown in Fig. 6(a). In the experiment, three different lengths of SMFs of 1137 m, 41 m, and 25 m were measured. We found out the threshold current of each length of the mode-locked pulse laser and inserted three lengths of the SMF into the resonant cavity one by one. Since the original cavity length is 15 m, the final laser cavity length is 1152 m, 56 m, and 40 m. The method for finding the threshold current is the same as the previous experiment. We turned the pump laser sources of various cavity lengths to 150 mA, respectively, and the results are shown in Fig. 6. We found that the average output power of the laser with a cavity length of 1152 m is slightly higher than that of the other two structures, and the threshold current of the three structures used to achieve mode-locking is about 65 mA. All three structures use 70/30 coupling beam splitters, the result confirms that the higher the energy in the cavity, the easier it is to achieve mode-locking.



(a)



(b)

Fig. 6. (a) Single-mode fiber is added to the pulse laser structure to control the cavity length. (b)The output power against the pump current with different lengths of fiber cavity (color online)

As mentioned above, when the mode-locked threshold current is reached, the pulse width will not change even when the pump current increase. The pulse width results of short pulses laser with different lengths are shown in Figs. 7(a)(b)(c).

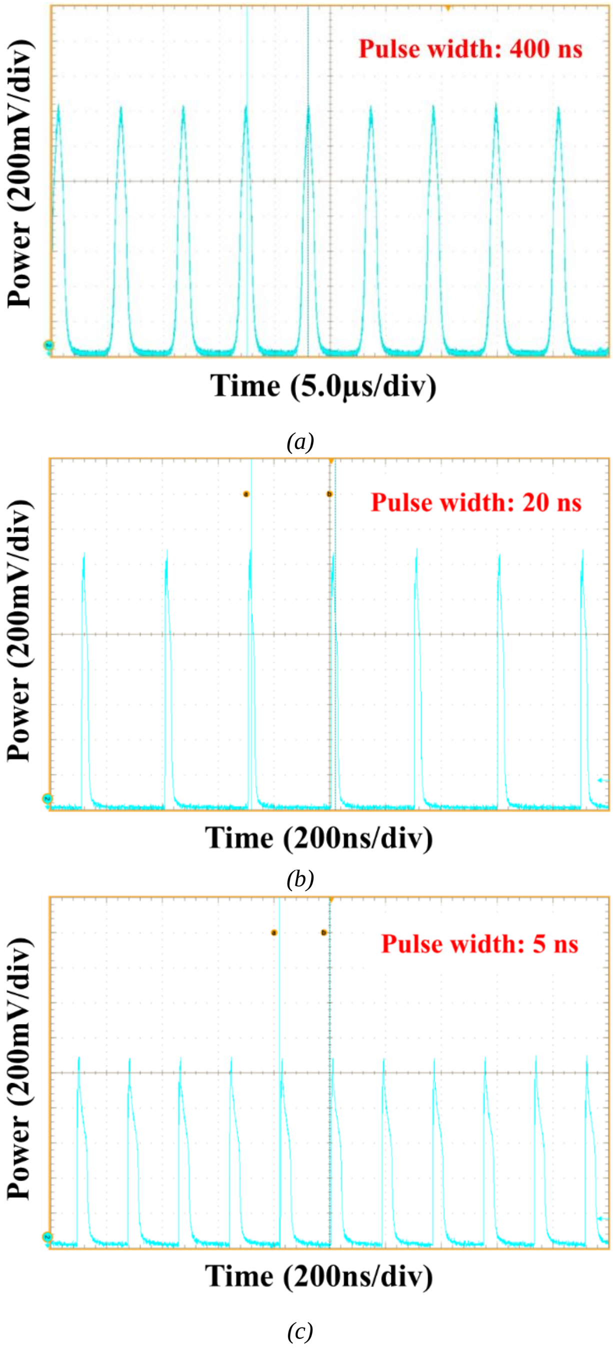


Fig. 7. The output pulse of the laser cavity length are (a) 1152 m (b) 56 m and (c) 40 m (color online)

5. Development of high-power amplifier

To increase the pulse laser power, we designed a high-power Erbium/Ytterbium co-doped fiber amplifier (EYDFA) to connect with the proposed pulse laser as shown in Fig. 8. A pump combiner is used to couple two high-power pump laser diodes (LDs). Optical isolators are inserted to block the backward ASE so as to prevent optical power damage to the LDs. Here, the gain medium of the high-power fiber amplifier we used were Erbium/Ytterbium-doped fiber (EYDF), which has double cladding architecture. There was a considerable energy leakage when double cladding fiber was fused with SMF. Therefore, we inserted a mode field adaptor (MFA, as is shown in Fig. 9) between the EYDF and SMF. The MFA comprises a large mode area fiber, single-mode area fiber, and a graded-index fiber. The MFD has operating wavelength from 1450 to 1565 nm. In Fig. 9, the connection loss of EYDF/MFD interface at the left-hand side and MFD/SMF interface at the right-hand side has a total of 0.3 dB connection loss.

Under the experimental architecture shown in Fig. 10, the short pulse laser results from different fiber lengths were summarized. When the cavity length is 1152 m, the pulse width is about 400 ns, and the pulse repetition rate is 181.8 kHz. When the cavity length is 56 m, the pulse width is about 20 ns, and the pulse repetition rate is 3.33 MHz. When the cavity length is 40 m, the pulse width is about 5 ns, and the pulse repetition rate is 5.55 MHz. The pump current increased to 7 A, and the average output power of the laser can reach more than 33 dBm. Using EYDFA, the average power of the laser is under different driving currents as shown in Fig. 11.

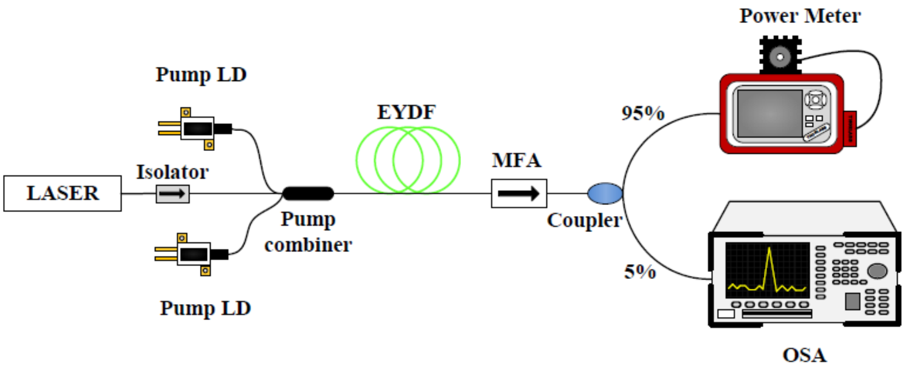


Fig. 8. The structure of home-made EYDFA

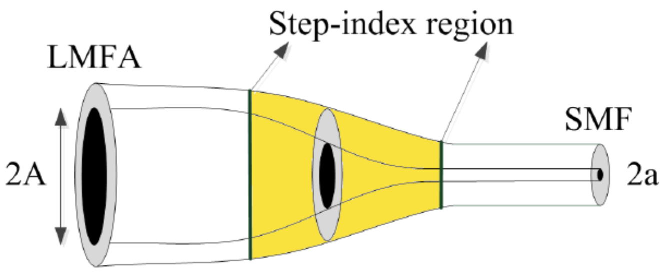


Fig. 9. Mode field adaptor, MFA

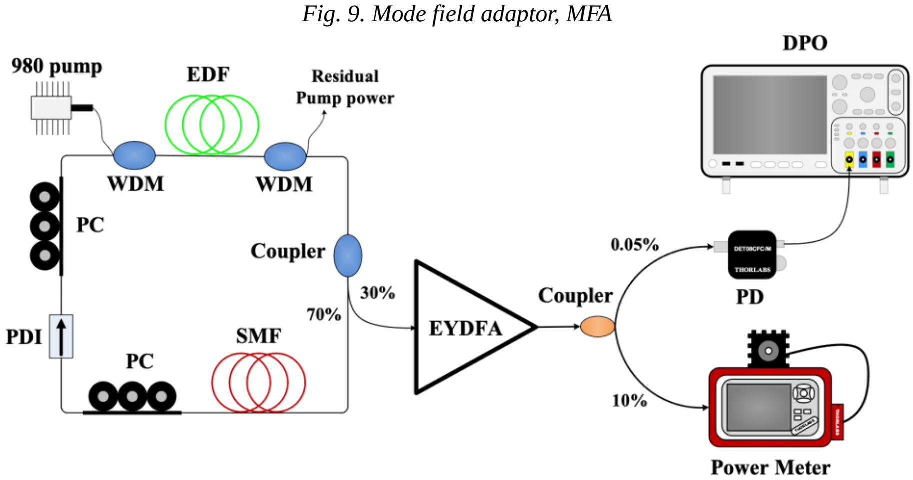


Fig. 10. Combination of short pulse laser and an optical amplifier (color online)

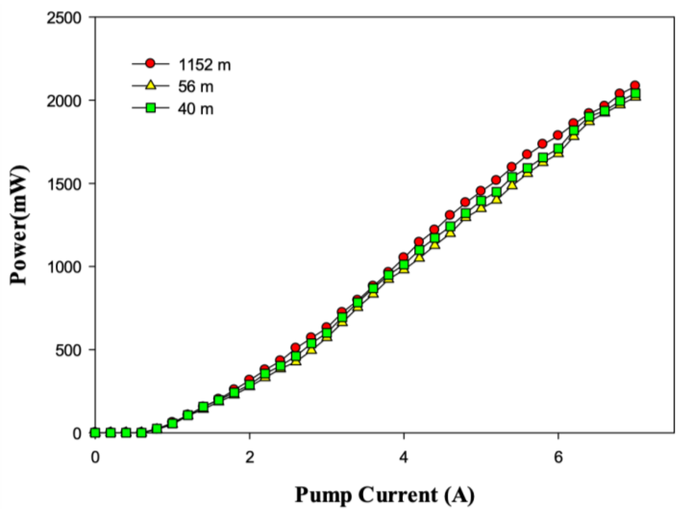
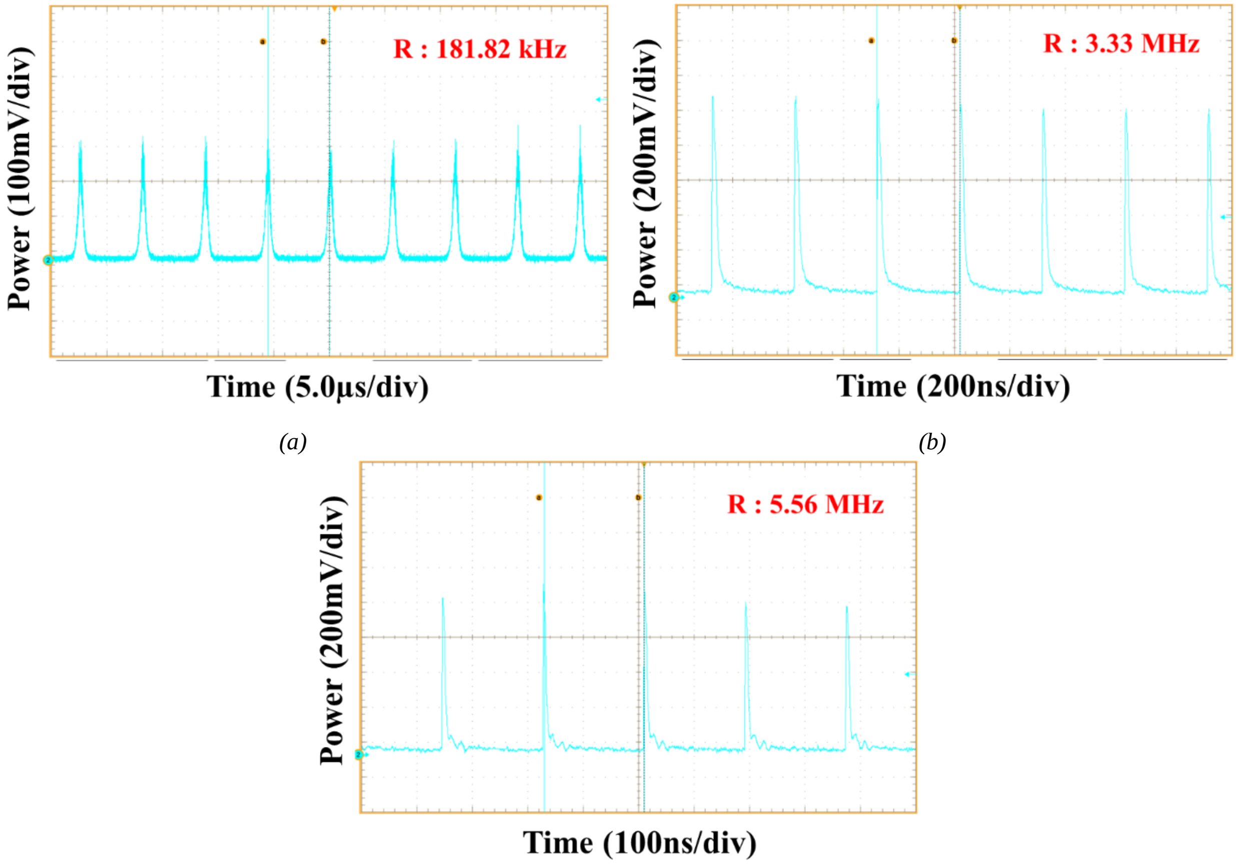


*Fig. 11. The laser output power under different driving current by using an EYDF*A



(c)

Fig. 12. The laser output when the driving current is 7A with different fiber lengths of (a) 1152 m (b) 56 m (c) 40 m, respectively (color online)

Using a master oscillation power amplifier (MOPA) scheme to amplify the short pulse laser, the MOPA is constructed by using an Erbium/Ytterbium co-doped fiber amplifier. When the pump current of the MOPA increases from 1 to 3 A, the pulse repetition rate and the pulse width were not significantly affected. Furthermore, when the pump current increases to 7 A, the average output power of three different cavity lengths was about 33 dBm. When the pump current increase to 7 A, the pulse spectral are shown in Fig. 12 (a)(b)(c).

The pulse repetition rate and pulse width of three different fiber cavities were consistent with the output results. The average output power was effectively amplified to more than 2 W. The performance of the short-pulse laser at 7A pumping current of the amplifier is shown in Table 2. The original single pulse energy of short pulse laser with resonant cavity lengths of 1152 m, 56 m, and 40 m are 86.2 nJ, 3.98 nJ, and 2.34 nJ, respectively. After amplification, the pulse energy increased to 11.46 μJ, 606.11 nJ, and 367.22 nJ. After comparing the data before and after the input amplifier, the pulse energy of the three resonant cavity lengths were 133, 152, and 157 times amplification in order.

Table 2. Comparison of laser characteristics under different fiber lengths

Seed pulse current: 200 mA EYDFA's pump current: 7 A				
Cavity length	**Pulse width**	**Average power**	**Pulse energy**	**Repetition rate**
1152 m	400 ns	2084.49 mW	11.46 μJ	181.82 kHz
56 m	20 ns	2018.37 mW	606.11 nJ	3.33 MHz
40 m	5 ns	2041.74 mW	367.22 nJ	5.56 MHz

6. Conclusion

This paper developed a low-cost and high-efficient 1550 nm short-pulse fiber laser. By inserting different lengths of SMF into the fiber cavity, different average power, pulse energy and repetition rate were obtained. The pulse widths were about 5 ns, 20 ns and 400 ns. The average power and repetition rate used to calculate the pulsed energy were 2.34, 3.98, and 86.2 nJ. The back-end amplifier and average output power can be increased by using a high-power EYDFA as MOPA. When the pump current of amplifier is 7 A, the average power of three short-pulse lasers with different cavity lengths can increase to 33 dBm. After MOPA amplification, the pulse energy of the three resonant cavity lengths are 133, 152 and 157 times increased accordingly.

Acknowledgements

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