

312 MHz, compact all-normal-dispersion Yb: fiber ring laser with an integrated WDM-ISO

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A compact and stable all-normal-dispersion mode-locked ring fiber laser with the repetition rate of 312 MHz is obtained with a wavelength-division multiplexing isolator. The compressed pulse is nearly transform-limited and the pulse width is 118 fs. It exhibits an optical efficiency of 50% and the maximum output power is about 205 mW with a 410 mW pump.

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Costless, compact, and high repetition rate passive mode-locked femtosecond fiber lasers have attracted much attention for their applications in frequency metrology, astronomical spectroscopy, and high-speed optical sampling^[1-3]. When a simple structure and highly doped Yb fiber are used, the fundamental repetition of linear cavity configuration mode-locked fiber lasers achievable by a saturable absorber has been up to the gigahertz (GHz) level^[3-5]. The ring cavity fiber lasers based on nonlinear polarization evolution (NPE) have shown themselves to be a promising mechanism for shorter and larger output energy pulse generation than the linear configuration^[6], whereas it is very difficult to get a high rate from a passive mode-locked pulse. To increase the fundamental repetition of ring cavity fiber lasers, much work has been done recently^[7-12]. A dichroic mirror has been used to replace fiber wavelength-division multiplexing (WDM) to couple the pump and obtain as high as a 570 MHz ring cavity all-normal-dispersion (ANDi) fiber laser^[7]. A 330 MHz ring mode-locked fiber laser was reported with a semi-WDM collimator^[8], and subsequently an ANDi and self-similar mode-locked fiber laser with a repetition rate of 605 and 750 MHz were both obtained^[9,10]. Except the fiber WDM, the high cost and the large-volume bulk Faraday rotator are also practical limiting factors to further decrease the size and increase the repetition rate of the ring fiber passive mode-locked laser. The fiber isolator (ISO) is less expensive and more compact, but its pigtail will increase the fiber length of the passive mode-locked fiber laser. The disadvantage of the fiber ISO can be overcome by an optical integrated module, which was used in an all-fiber ring laser^[11]; however, the average output power and optical efficiency of the ring fiber laser needs to improve.

In this Letter, a stable and compact ANDi Yb: fiber ring laser with a repetition rate of 312 MHz is reported with a WDM-ISO. The compressed pulse is nearly transform-limited and the pulse width is 118 fs. It exhibits an optical

efficiency of 50%; the maximum output power is about 205 mW with a 410 mW pump.

Figure 1 shows the configuration and photograph of the integrated WDM-ISO. As shown in Fig. 1, the WDM-ISO consists of three main parts. From left to right, they are a filmed fiber collimator with two pigtails (the highly transmission and reflection wavelength are 1060 and 980 nm, respectively), a common 1060 nm fiber isolate core, and a fiber laser collimator with single pigtail. When the integrated WDM-ISO is used in the fiber laser, the 1060 nm signal laser input arises from the right-hand collimator while the pump laser input arises from Port 2. The signal laser transmits the right-hand collimator and fiber isolate core while the pump reflects by the left-hand collimator, and they all couple out from Port 3; therefore, the integrated WDM-ISO can offer the function of both a WDM and an ISO. The tested insert losses of the signal laser at 1060 and 1030 nm are 0.9 and 1.9 dB, respectively, while the insert loss of the pump is about 0.4 dB. The isolation of the signal laser at 1060 and 1030 nm are more than 30 dB

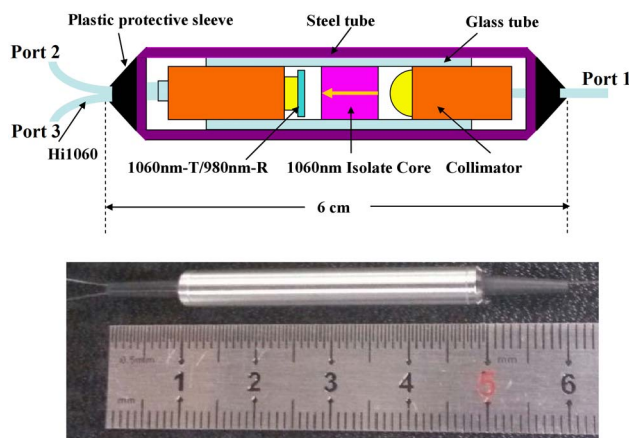


Fig. 1. Top, configuration of integrated WDM-ISO; bottom, photograph of integrated WDM-ISO.

and the maximum average optical power to damage the WDM-ISO is about 2 W.

Figure 2 shows the ANDi ring cavity configuration with the integrated WDM-ISO. To decrease the length of the gain fiber, a highly doped Yb: fiber (Coracitive YB406) with a length of 12 cm is used. The gain fiber is pumped by a 976 nm laser diode with a maximum output power of 410 mW through the WDM-ISO. A half-wave plate (HWP), two quarter-wave plates (QWPs), and a polarization beam splitter (PBS) between two collimators form the saturable absorber via the NPE. The coupling loss of the two collimators is about 0.7 dB. A spectral filter with the center wavelength of 1040 nm and FWHM of 8 nm is also inserted in the collimators. The spectral filter is an interference filter with an insertion loss of 1.5 dB. The laser output is taken from the rejection port of the PBS. All single-mode fibers (SMFs) used in the ring ANDi fiber laser cavity are HI-1060 SMFs. The length of the SMF between the WDM-ISO and highly doped Yb: fiber is about 10 cm, and the length of SMF1 and SMF2 are 18 and 17 cm, respectively. The total length of the SMF and Yb: fiber is about 56 cm, and the total dispersion in the fiber laser cavity is about 0.012 ps^2 , where the dispersion of the SMF and Yb: fiber is about $0.022 \text{ ps}^2/\text{m}$.

As shown in Fig. 2, the integrated WDM-ISO used in the ANDi fiber laser has two advantages. On one hand, compared to using the WDM and ISO separately, the pigtailed connecting the WDM and ISO are no needed. On the other hand, since there is no bulk Faraday rotator, the free-space section between the two collimators can decrease more. In reasonable designs, the length of the free-space is about 8 cm and the length of the ANDi fiber laser cavity is about 64 cm. The whole fiber laser is very compact.

In our work, the laser can be mode-locked by carefully adjusting the three wave plates for the pump being set at 350 mW. The average output power is about 175 mW, and the energy of single pulse is 0.56 nJ. Figure 3 displays the RF spectrum of the output pulse for the pump of 350 mW. Figure 3 shows that the repetition rate is $\sim 312 \text{ MHz}$, which correctly corresponds to the fundamental frequency

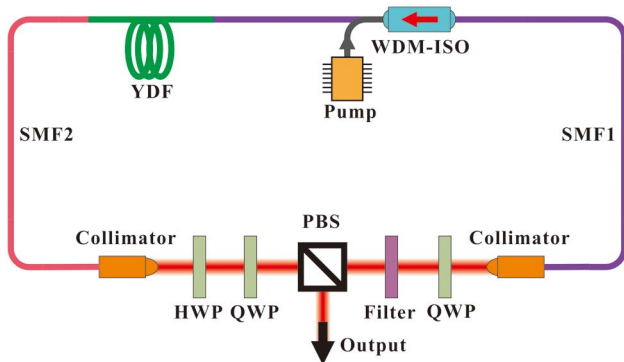


Fig. 2. Schematic of the ANDi Yb: fiber ring laser.

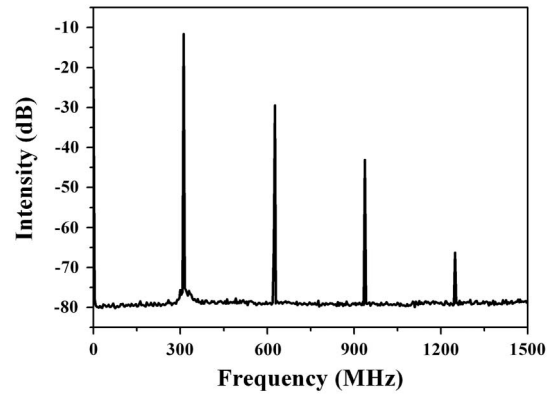


Fig. 3. RF spectrum from 0 to 1.5 GHz with a resolution bandwidth of 10 kHz.

of the fiber laser. The RF spectrum shows that the signal-to-noise ratio is more than 65 dB, which indicates the good performance of the fiber laser.

Figure 4 shows the measured output spectrum and fringe-resolved autocorrelation traces of the pulse which was compressed by a 600 lines/mm extra-cavity grating pair. We can see from Fig. 4(a) that the spectral bandwidth is about 13.7 nm and with typical features of a dissipative soliton pulse spectrum^[6]. The spectrum is unsymmetrical and the spectral intensity of the long wavelength is higher than that of the short wavelength. The reason may be that the insert loss of the WDM-ISO at long wavelengths is lower than at short wavelengths. The direct output pulse was measured as 1.15 ps and compressed by a grating pair at a separation of 2.7 cm; the fringe-resolved autocorrelation trace shows a pulse width of 118 fs [Fig. 4(b)] which is close to the transform-limited pulse width of 109 fs.

We tested the dependence of the output power from the PBS on the pump power (Fig. 5). In our work, when the pump increased to 310 mW, the fiber laser self-started and the output power was about 155 mW. The output power increased linearly with the pump. When the pump increased to its maximum power of 410 mW, the output

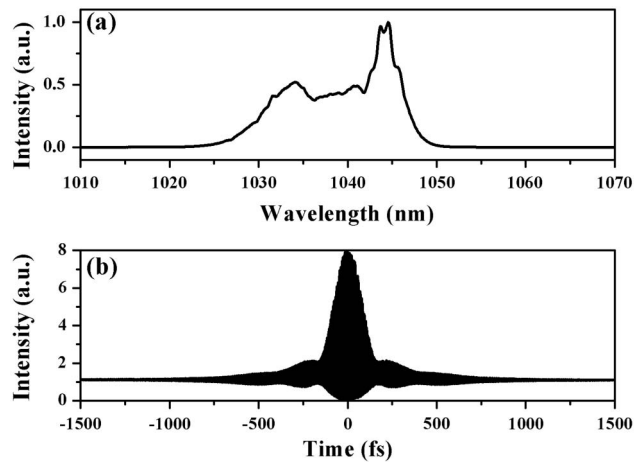


Fig. 4. (a) Measured output spectrum; (b) fringe-resolved autocorrelation trace of compressed pulse.

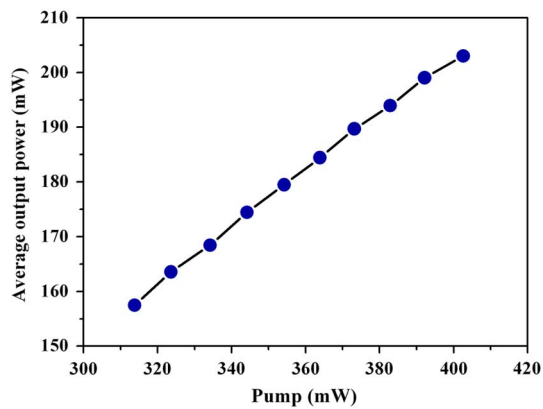


Fig. 5. Average output power as the function of the pump.

power was about 205 mW which indicated the overall efficiency is $\sim 50\%$.

In addition, the ANDi fiber laser with an integrated WDM-ISO is very stable; even touching the fiber cavity and slightly shaking the experimental platform will not make it lose its mode-lock, and it can self-start after placement in the laboratory for more than 30 days.

In conclusion, a stable and compact ANDi ring fiber laser with a repetition rate of 312 MHz is obtained with a WDM-ISO. The compressed pulse is nearly transform-limited and the pulse width is 118 fs. It exhibits an optical efficiency of 50% and the maximum output power is about 205 mW. The higher repetition rate operation, shorter pulse generation, and higher output power can be realized by using a shorter pigtail of the fiber device, a higher pump power, and a more highly doped Yb fiber.

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