High repetition rate all-normal dispersion Yb: fiber laser for minimum pulses

Hongyu Yang (杨弘宇)[1], Aimin Wang (王爱民)[1*], Yunfeng Ma (麻云凤)[2,3], Zhongwei Fan (樊仲维)[2,3], Gang Niu (牛 岗)[2], Jin Yu (余 锦)[3], Yang Liu (刘 洋)[3], Xue Zhang (张 雪)[3], and Zhigang Zhang (张志刚)[1]

[1] *Institute of Quantum Electronics, State Key Laboratory of Advanced Optical Communication System and Networks, School of Electronics Engineering and Computer Science, Peking University, Beijing 100871, China*
[2] *Beijing GK Laser Technology Co., Ltd, Beijing 100085, China*
[3] *Academy of Opto-electronics, Chinese Academy of Sciences Beijing 100080, China*
[*] *Corresponding author: wangaimin@pku.edu.cn*

Received August 18, 2011; accepted September 29, 2011; posted online December 8, 2011

Simulation and experimental results for high repetition rate all-normal dispersion Yb:fiber ring lasers are demonstrated for the cavity dispersion from 0.01 to 0.025 ps^2. The simulation shows that the pulse spectrum has the potential to reach $>$ 30 nm for the dispersion of 0.014 ps^2 under practical pump power. This potential is proved by the experiment. Maximum spectral width of 30 nm is achieved at the repetition rate of 285 MHz under the 850-mW pump power. Average output power is 550 mW and dechirped pulse is 78 fs.

OCIS codes: 320.7090, 140.3510.
doi: 10.3788/COL201210.033201.

All-normal dispersion fiber laser[1] without intracavity dispersion compensation has been extensively studied in low repetition rate operation for high pulse energy delivery[2−5]. However, high repetition rate operations have been rarely explored. Given the rapid development of frequency combs, which are moving toward large frequency spacing, all-normal dispersion fiber lasers become a promising candidate because of their superior advantages in simplicity and low intracavity loss.

All-normal dispersion linear cavity Yb:fiber lasers have the potential to run at a fundamental repetition rate up to gigahertz (GHz) level. Mode locking can be started simply by saturable absorbers such as semiconductor saturable absorbers[6]. However, the saturable absorber pulse shaping mechanism in linear cavity limits the spectral bandwidth to a few nanometers. Ring cavity fiber lasers have been proved to be capable of producing shorter pulses through nonlinear polarization evolution with intracavity polarizing elements. However, the cavity length of the ring cavity is limited not only by fibers, but also by the wavelength division multiplexer (WDM) and collimators. Mode locking is also difficult to start at a high repetition rate because the individual pulse energy becomes smaller as the cavity is shortened under the same pump power.

Fortunately, the ultimate spectrum bandwidth of the pulse gets broader as the cavity group delay dispersion (GDD) is reduced under the same pump power[7]. The simulation was confirmed for the cavity GDD $>$ 0.033 ps^2 at a pump power up to 900 mW. The Yb:fiber laser with a repetition rate up to 130 MHz was achieved and the pulse width was 77 fs[7]. This simulation and experimental result implies that under the same pump power, as the cavity GDD is reduced, the pulse width can be shorter so that the peak power-induced nonlinearity is not reduced. This finding opens the route for minimum pulse generation in all-normal dispersion fiber lasers, particularly for the large-mode spacing frequency comb that can be benefited from the short pulses.

Higher repetition rate operation up to 570 MHz in all-normal dispersion fiber laser was demonstrated by Wilken *et al.* in an Yb:fiber ring laser[8], where its cavity GDD falled in 0.019 ps^2. However, due to the strong filtering effect of the grating, it delivered a pulse as broad as 840 fs at the required pump power above 1 W. Note that the pump power was spatially coupled into the cavity rather than with a WDM to shorten the cavity length. Obviously, the spatial coupling may introduce concerns regarding the environmental stability.

In this letter, we demonstrate the simulated and experimental results for high repetition rate all-normal dispersion Yb:fiber ring laser. The modeled pulse spectrum as a function of cavity GDD and pump power indicates that at the cavity GDD $<$ 0.025 ps^2, the pulse spectrum has the potential to reach $>$ 30 nm under the realistic pump power. A WDM coupled, all-normal dispersion Yb:fiber ring laser operating at a repetition rate up to 285 MHz is presented.

Simulations that extended the model in Ref. [7] to the cavity GDD region $<$ 0.025 ps^2 were performed. The simulation results are shown in Fig. 1. The four different curves in Fig. 1 correspond to the modeled pulse spectrum bandwidth as a function of cavity GDD under different pump powers of 600, 750, 900, and 1 050 mW, respectively, from bottom to top. The simulated spectral profiles of the output pulses for the marked points (a), (b), and (c) in Fig. 1 are shown in Fig. 2. As the pump power is increased or the cavity GDD decreased (i.e., to increase the repetition rate), the spectral width tends to be broader. At the cavity GDD $<$ 0.025 ps^2, the pulse spectrum is capable of reaching $>$ 30 nm. This can be a supplement to the Fig. 1 in Ref. [7], where

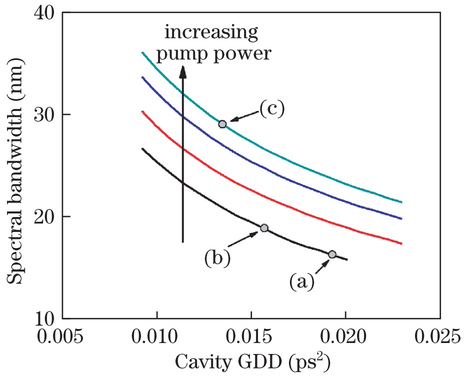

Fig. 1. Simulation results: pulse spectrum as a function of cavity GDD and pump power.

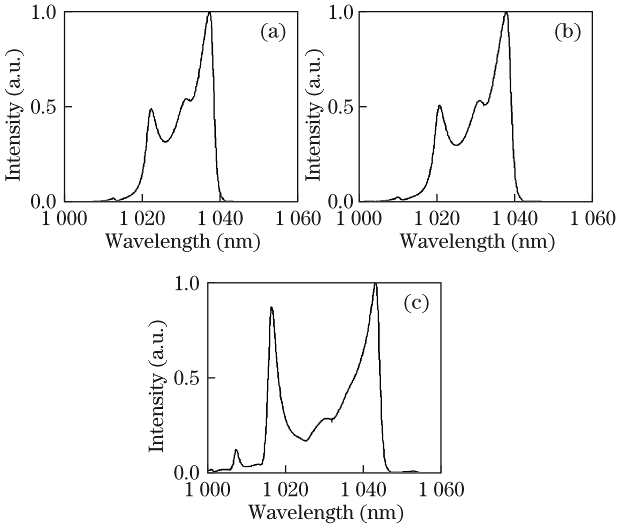

Fig. 2. Simulated spectral profile of the output pulses for the corresponding points in Fig. 1.

the simulation is made only for the GDD > 0.05 ps^2 and the achievable pulse spectrum is all below 30 nm. This conclusion encourages the effort to build a short cavity all-normal dispersion fiber laser that combines the high pulse energy and short duration for large mode spacing frequency combs.

Experimentally, an all-normal dispersion standard ring cavity laser with various cavity GDDs for fitting this model was constructed. The cavity configuration is shown in Fig. 3. The laser includes a gain fiber, two collimators, and several free-space polarization controlling components. The fiber section consists of 20 cm of HI1060 for WDM, 30-cm-long Yb:doped fiber, and minimized length of single-mode fiber (SMF). A Faraday isolator, a combination of waveplates, and a polarizing beam splitter (PBS) take about 15 cm free space.

Some typical experimental results with different repetition rates and pump powers are used to confirm our modeling results (Table 1). These three experimental results are shown to fit well with the modeled ones listed in Fig. 1. As the pump power increases and the cavity GDD decreases, the repetition rate and pulse spectrum bandwidth are also increased. The minimum cavity GDD of 0.0138 ps^2, corresponding to a repetition rate of 285 MHz, results in a spectral bandwidth of 30.8 nm.

At a repetition rate of 285 MHz, the laser was pumped by combined two single mode coupled diodes which supplyed a total power up to 850 mW. The mode locking was initialized with the rotation of the waveplates and the birefringent filter. At the maximum pump power, the CW output was ~600 mW (instrument type: Coherent FieldMaxII-TO laser power meters), indicating an efficiency of 70%. When mode-locked, the laser delivered an average output power of 550 mW, corresponding to a pulse energy of 1.93 nJ. The full-width at half-maximum of spectrum was 30 nm (shown in Fig. 4, instrumental type: HP70951A optical spectrum analyzer) and the profile was consistent with our simulation. Figure 5 presents the autocorrelation trace obtained with the 600grv/mm grating separation of 19.7 mm in the compressor. The pulse width was deconvoluted to be 78 fs for a Gaussian profile assumed.

The pulse width and the pulse energy are comparable to those obtained in the repetition rate of 130 MHz[7], but with much higher repetition rate and average output power for the similar pump power. On the other hand, our laser works at relatively low repetition rate compared

Table 1. Experimental Parameters of Several High Repetition Rate All-normal Dispersion Yb:fiber Ring Lasers

Case	Dispersion (ps^2)	Pump Power (mW)	Repetition Rate (MHz)	Spectral Bandwidth (nm)
(a)	0.01978	550	178	16.8
(b)	0.01617	550	250	21.1
(c)	0.01380	850	285	30.8

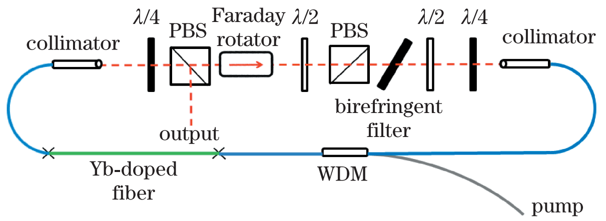

Fig. 3. Schematic of the laser. $\lambda/2$, half-wave plate; $\lambda/4$, quarter-wave plate.

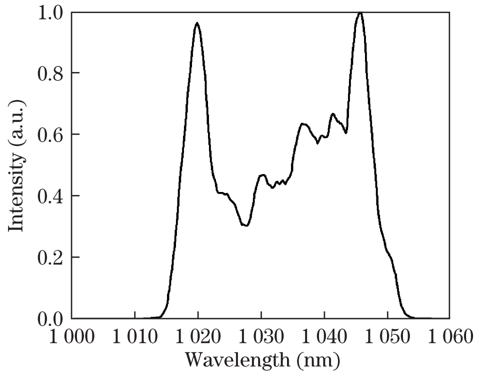

Fig. 4. Spectral profile of the output pulse for the laser operated at 285 MHz.

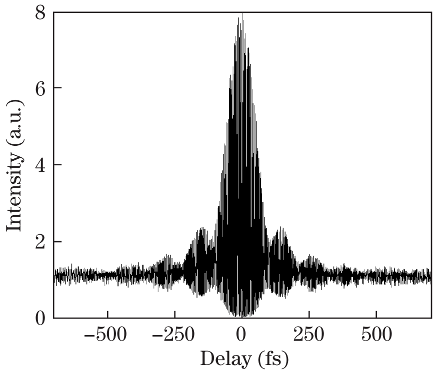

Fig. 5. Fringe-resolved autocorrelation trace of the output pulses at 285 MHz after compression.

with the 570 MHz[8], but with much shorter pulses.

The Yb:fiber cavity still has room to be shortened so that the laser can be operated at a repetition rate up to 600 MHz. However, mode locking becomes difficult, possibly due to the low nonlinear phase shift which is 1.64π. Further increasing the pump power is required for this high repetition rate operation. Determining to what extent the fiber cavity can be shortened without difficulty of mode locking requires more theoretical and experimental studies.

In conclusion, an Yb:fiber laser operated up to 285-MHz repetition rate of an all-normal dispersion Yb:fiber ring laser is demonstrated. The laser delivers an average output power of 550 mW at a pump power of 850 mW. The dechirped pulse is 78 fs. The low loss cavity and the WDM coupled pumping ensure the high average output power. The high repetition rate and high average power promise the all-normal Yb:fiber laser to be a possible direct source of octave spanning spectrum for frequency comb generation. A further higher repetition rate operation is possible with a higher pump power.

This work was partially supported by the National Science and Technology Supporting Program of China (No. 2006BAF03A20), the National Natural Science Foundation of China (Nos. 60927010, 10974006, 11027404, and 60907040), and the National "863" Program of China (No. 2008AA031901).

References

1. A. Chong, J. Buckley, W. Renninger, and F. Wise, Opt. Express **14,** 10095 (2006).
2. A. Chong, W. H. Renninger, and F. W. Wise, Opt. Lett. **32,** 2408 (2007).
3. A. Chong, W. H. Renninger, and F. W. Wise, Opt. Lett. **33,** 1071 (2008).
4. K. Özgören and F. Ö. Ilday, Opt. Lett. **35,** 1296 (2010).
5. B. Zhao, K. Duan, W. Zhao, C. Li, and Y. Wang, Chin. Opt. Lett. **8,** 404 (2010).
6. M. E. Fermann and I. Hartl, IEEE. J. Sel. Top. Quantum Electron. **15,** 191 (2009).
7. A. Chong, W. H. Renninger, and F. W. Wise, Opt. Lett. **33,** 2638 (2008).
8. T. Wilken, P. Vilar-Welter, T. W. Hänsch, Th. Udem, T. Steinmetz, and R. Holzwarth, in *Proceedings of CLEO 2010* CFK2 (2010).