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# Generation of 207-femtosecond pulses from a ytterbium figure-of-eight fibre laser*

Zhao Wei(赵 卫)†, Zhang Wei(张 伟), Ma Hai-Quan(马海全),
Liu Chang(刘 畅), Chen Guo-Fu(陈国夫), and Lu Ke-Qing(卢克清)

*State Key Laboratory of Transient Optics and Photonics, Xi'an Institute of Optics and Precision Mechanics, Chinese Academy of Sciences, Xi'an 710068, China*

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We report the generation of 207-fs pulses with 1.2 mW average power at 1036 nm directly from a passively mode-locked Yb-doped fibre laser with a nonlinear optical loop mirror for mode-locking and pairs of diffraction gratings for intracavity dispersion compensation. These results imply a 4-fold reduction in pulse duration over previously reported figure-of-eight cavity passively mode-locked Yb-doped fibre lasers. Stable pulse trains are produced at the fundamental repetition rate of the resonator, 24.0 MHz. On the other hand, this laser offers a cleaner spectrum and greater stability and is completely self-starting.

**Keywords:** fibre laser and amplifiers, ultrafast optical techniques, nonlinear optics
**PACC:** 4255N, 4280W, 4265

## 1. Introduction

Fibre lasers have been the subject of intensive investigation[1−15] because of their excellent stability, free from misalignment, compact size, and low cost. They have the potential to supplant solid-state lasers in some applications. The primary limitations of fibre lasers is insufficient environmental stability for use outside basic research laboratories. This environmental stability arises from uncontrolled birefringence. The best performance in fibre lasers is currently provided by stretched-pulse lasers[7,8] with nonlinear polarization evolution (NPE) for amplitude modulation, which reduce the effective nonlinearity of the system by stretching and compressing the pulses within the cavity. The buildup of pulses from noise and subsequent stabilization requires the use of a fast saturable absorber, such as a nonlinear optical loop mirror (NOLM),[9] a nonlinear amplifying loop mirror (NALM),[10] and nonlinear polarization evolution.[11] For the maximum environmental stability, fibre lasers can be constructed from polarization-maintaining (PM) fibre. However, this approach precludes the use of NPE, which is based on elliptical polarization rotation. NOLM is capable of fast and deep modulation in a simple scheme and can be constructed from PM fibres. In the past years, several advances on the performance of Yb-doped fibre lasers have been reported in both fibre ring lasers and figure-of-eight fibre lasers. In Yb-doped fibre ring lasers, 52-fs-long and 2.2-nJ pulses were achieved by Lim *et al* using gratings as delay dispersion line (DDL) inside the laser cavity,[12] soon thereafter 36-fs pulses have been made by Ilday *et al*[13] using the same laser cavity, and it is the shortest pulses from Yb-doped fibre lasers. Compared with Yb-doped ring fibre lasers, there is much less work on Yb-doped figure-of-eight fibre lasers. Thus far, only 850 fs mode-locked pulses at 1065 nm have been generated by a Yb-doped figure-of-eight fibre laser,[14] which incorporates the DDL system based on the holey fibre. However, it is difficult to adjust the dispersion of the fibre laser system because of the technological challenges of interfacing holey fibres with low loss.

In this paper we demonstrate a passively mode-locked Yb-doped fibre laser by using a NOLM for the mode-locking and pairs of diffraction gratings for intracavity dispersion compensation. The laser produces 207-fs, 1036 nm pulses with an average power of 1.2 mW, which represents a 4-fold reduction in pulse duration compared with that of the previously reported passively mode-locked Yb-doped figure-of-eight fibre laser,[14] offers a cleaner spectrum and greater stability, and is completely self-starting. Sta-

*Project supported by the National Natural Science Foundation of China (Grant Nos 60537060 and 10390160).
†E-mail: weiz@opt.ac.cn

ble pulse trains are produced at the fundamental repetition rate of the resonator, 24.0 MHz.

## 2. Experimental setup and results

The experimental system is shown in Fig.1. It is a figure-of-eight fibre laser, which consists of a NOLM and a linear loop. The NOLM consists of a polarization controller (PC1) and a 4.8 m long lucent 980 fibre. The PC1 sets the linear bias in the NOLM. A fibre coupler 1 (coupling ratio is 47:53) is used in the NOLM, which permits fine adjustment of the peak switching intensity. In point of fact, the NOLM is a Sagnac interferometer, and its operation is based on interference between two counter-propagating laser beams, which acquire different amounts of phase shift upon rotating in the nonlinear loop. A PC2, a grating-based DDL (1200 gr/mm), a wavelength division multiplexer (WDM) coupler (980 nm/1053 nm), a section of Yb-doped fibre of about 1800ppm $Yb^{3+}$-ion concentration, a polarization insensitive isolator, and a fibre coupler 2 (coupling ratio is 3:97) are used in the linear loop. The PC2 sets the linear bias in the linear loop. The Yb-doped fibre is 1.5 m long, which is pumped at 976 nm by a laser diode that is capable of supplying as much as 250 mW of power into the single-mode fibre. The polarization insensitive isolator provides unidirectional operation in the linear fibre loop. Evidently, we have made compensation for intracavity dispersion by using pairs of diffraction gratings, and the dispersion delay line has not been in the Sagnac interferometer. Our laser differs from the figure-of-eight fibre laser in Ref.[14], of which intracavity dispersion is compensated by using the holey fibre and the dispersion delay line is in the Sagnac interferometer. In this case, the only means of adjusted dispersion is either that the holey fibre is truncated or that the holey fibre is added, and the holey fibre is spliced with difficulty. For the dispersion delay line based on pairs of diffraction gratings, it is very easy to change and match the dispersion. In our experiment, we adjust the grating spacing by employing the precision displacement platform, which does not mangle gratings.

The figure-of-eight cavity passively mode-locked Yb-doped fibre laser output is taken from the 3% output port of the fibre coupler 2, and its spectral and temporal characteristics are measured with an optical spectrum analyser (Ocean-Optics SD2000), an autocorrelator (APE Pulse-Check), and a high-speed optoelectric lightwave converter whose electrical output is connected to an oscilloscope (Tektronics 485).

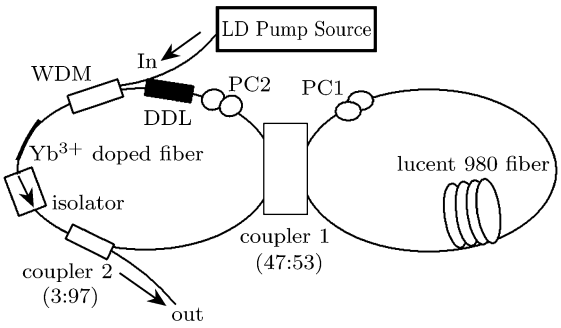



**Fig.1.** Experimental setup: PC, polarization controller; DDL, dispersive delay line; WDM, wavelength division multiplexer.

In the figure-of-eight cavity passively mode-locked Yb-doped fibre laser with the experimental setup of Fig.1, we obtain mode-locked operation by adjusting the coupling ratio of fibre coupler 1, varying the group-velocity dispersion (GVD) of the cavity (by adjusting the grating spacing in the DDL), and setting the linear phase bias with PC1 and PC2. Mode-locked operation is uninterrupted over three days of continuous operation. The laser is stable against environmental effects (mechanical perturbations and temperature variations). The stability is presumably due to the fact that NOLM operation does not depend on polarization directly but is affected indirectly as changes in birefringence of the fibre shift the linear bias.[15]

In order to obtain the shortest pulses with maximum stability, we changed the length of NOLM, causing the mode-locking to become very difficult in the figure-of-eight cavity, the stability of the mode-locked operation to be insufficient, and the phenomenon of $Q$-switched mode-locking to be observed in the experiment. To increase the nonlinear effects, we used the highest available pumping power (250 mW) to pump the fibre laser, resulting in a multiple-pulsing operation. The reason for this may be that the pumping power is very high and the pulse duration is very short, thus the pulse peak power is very high in the cavity. In this case, the artificial saturable absorber (e.g., NOLM) is overdriven, which leads to multiple-pulsing operation. Moreover, the length of the NOLM cannot be further shortened; otherwise, the laser becomes unstable with a tendency of $Q$-switched mode-locking at a higher repetition rate.[12] On the other hand, we optimize the cavity dispersion map and the polariza-

tion state. In our experiment, the grating spacing was gradually changed, and the width of pulse was simultaneously measured. The optimized cavity dispersion map is that the negative dispersion introduced by adjusting the grating spacing compensates intracavity positive dispersion. The DDL efficiency is then enhanced, making a reduction of the inserted loss of the DDL system. The diffraction efficiency of the grating pairs is very great for the polarization light (∼85%). However, when the light passes through the diffraction grating pairs many times, the inserted loss of the DDL becomes big. To enhance the efficiency of the DDL system, we set the incidence angle of light approximately to the Littrow angle and adopt collimators with big optical aperture for reducing coupling loss. When the length of the NOLM is 4.8 m, the grating spacing is 3.1 cm, and the length of the fibre coupler 2 output port is 1 m, a shortest pulse duration of 207-fs (a Gaussian profile is assumed throughout this work) supported by a 20 nm spectrum bandwidth can be obtained (see Figs.2 and 3). The repetition rate of the mode-locked pulses is 24.0 MHz. The mode-locking is initiated by a perturbation in the NOLM. Figure 2 shows an oscilloscope trace of the pulse train and an autocorrelation at 1.2 mW output signal power. The full width at half maximum (FWHM) of the autocorrelation is 305-fs, corresponding to a 207-fs pulse assuming a Gaussian profile. This represents a fourfold reduction in pulse duration compared with that previously reported for the figure-of-eight cavity passively mode-locked Yb-doped fibre lasers.[14] A long range scan of over 80 ps has been performed to verify the presence of a single pulse within the 80 ps resolution limit of the sampling oscilloscope.

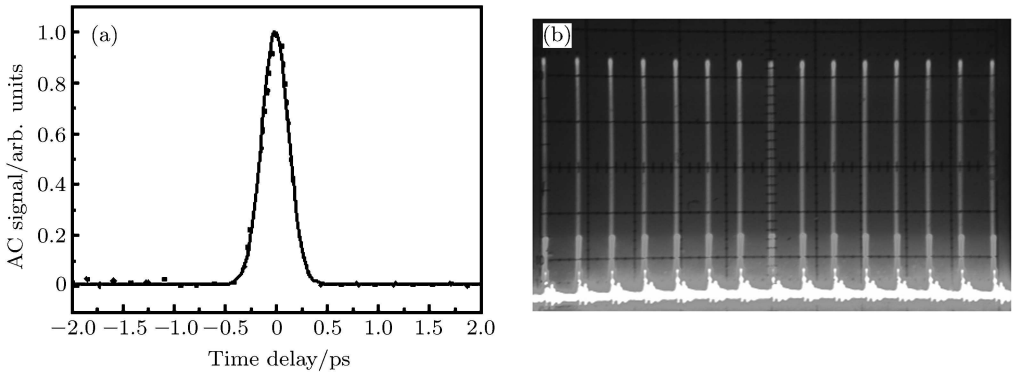



**Fig.2.** (a) Autocorrelation (dotted curve) and (b) pulse train in single pulse regime. Solid curve is for Gauss fit.

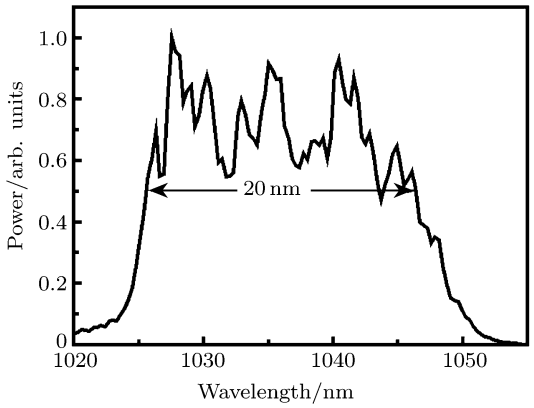



**Fig.3.** Spectra produced by the passively mode-locked Yb-doped figure-of-eight fibre laser.

The spectrum of the compressed pulses is presented in Fig.3. It shows a broadband envelope with FWHM of about 20 nm. This broadband optical spectrum indicates that the transform limited pulse width can be as short as ∼81.5 fs, that is to say, ∼81.5 fs pulses can be potentially generated from the passively mode-locked Yb-doped figure-of-eight fibre laser. However, the pulse width achieved in our experiment exceeds the transform limit by a factor of ∼2.5. We may obtain the shortest pulses from the passively mode-locked Yb-doped figure-of-eight fibre laser by varying the length of NOLM, by optimizing the cavity dispersion map and the polarization state, and by enhancing the DDL efficiency.

## 3. Conclusions

In conclusion, we have demonstrated a Yb-doped fibre passively mode-locked laser by using a NOLM for the mode-locking and pairs of diffraction gratings for

intracavity dispersion compensation. The laser can produce 207-fs pulses with 1.2mW average power at 1036 nm. This represents a fourfold reduction in pulse duration compared with that of previously reported figure-of-eight cavity passively mode-locked ytterbium fibre lasers.

## References


[1] Feng X M, Wang Y G, Liu Y Y, Lan Y S, Lin T, Wang J, Wang X W, Fang G Z, Ma X Y, Wang Y G and Zhang Z G 2005 *Chin. Phys. Lett.* **22** 391

[2] Lü G H, Ye H A, Li J Q, Sun X D and Zhang X M 2004 *Chinese Phys. Lett.* **21** 2201

[3] Fu S G, Fan W D, Zhang Q, Wang Z, Li L J, Zhang C S, Yuan S Z and Dong X Y 2004 *Chin. Phys. Lett.* **21** 1279

[4] Feng X H, Liu Y G, Sun L, Yuan S Z, Kai G Y and Dong X Y 2005 *Chin. Phys.* **14** 779

[5] Lu K Q, Zhao W, Yang Y L, Zhang M Z, Li J P and Liu H J 2006 *Chin. Phys.* **15** 403

[6] Liu N, Liu S H, Liao C J, Guo Q and Xu W C 2000 *Chin. Phys.* **9** 753

[7] Hofer M, Ober M H and Fermann M E 1992 *IEEE J. Quantum Electron.* **28** 720

[8] Tamura K, Ippen E P, Haus H A and Nelson L E 1993 *Opt. Lett.* **18** 1080

[9] Doran N J and Wood D 1988 *Opt. Lett.* **13** 56

[10] Fermann M E, Haberl F, Hofer M and Hochreiter H 1990 *Opt. Lett.* **15** 752

[11] Hofer M, Fermann M E, Haberl F, Ober M H and Schmidt A J 1991 *Opt. Lett.* **16** 502

[12] Lim H, Ilday F O and Wise F W 2003 *Opt. Lett.* **28** 660

[13] Ilday F Ö, Buckley J, Kuznetsova L and Wise F W 2003 *Opt. Exp.* **11** 3550

[14] Avdokhin A V, Popov S V and Taylor J R 2003 *Opt. Exp.* **11** 265

[15] Ilday F Ö, Wise F W and Sosnowski T 2002 *Opt. Lett.* **27** 1531