Mechanism and elimination of spectrum filtering in a high power mode-locked fibre laser with a free output coupler*

Zhang Yu-Ying(张玉颖), Zhang Chi(张 驰), Hu Ming-Lie(胡明列)†, Wang Si-Jia(王思佳), Song You-Jian(宋有建), Chai Lu(柴 路), and Wang Qing-Yue(王清月)

Ultrafast Laser Lab, School of Precision Instruments and Optoelectronics Engineering, Key Laboratory of Optoelectronic Information Technical Science, Tianjin University, Tianjin 300072, *China*

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The filtering mechanism of a free output coupler mode-locked laser based on large-mode-area photonic-crystal fibre is analysed. A filtering-soliton mode-locked laser with 495 fs pulse width and 21 nJ pulse energy is achieved. Another novel cavity configuration is established to eliminate the filtering effect. Pulses, each 457 fs in width and 16.5 nJ in energy, are obtained in a soliton-like regime. Pulses, each 387 fs in width and 15.8 nJ in energy, are also generated in a stretched pulse regime and could be dechirped to 119 fs externally to the cavity.

Keywords: femtosecond laser, mode-locked laser, fibre laser, large-mode-area photonic-crystal fibre
PACC: 4255N, 4280W, 4260D

1. Introduction

Mode-locked fibre lasers are developing towards high power, high pulse energy and compact size. Rare earth doped fibres have been successfully used to establish passive mode-locked fibre lasers.[1,2] Owing to its simple energy level structure, low quantum defect, and broad gain bandwidth, the ytterbium ion has great advantages when doped into the fibre core and used as gain medium, especially for the generation of high power and high energy pulses. Pulses, each 14 nJ in energy and 100 fs in duration, were achieved from an Yb-doped fibre laser system utilizing a nonlinear polarization evolution (NPE) effect.[3] However, standard fibre cannot support a higher pulse energy[4] in the anomalous dispersion regime due to its small core diameter, which induces nonlinear chirp accumulation and finally leads to wave-breaking.[5] The invention of large-mode-area photonic-crystal fibre (LMAPCF) solves the problem and greatly increases the output pulse energy.[6] Recently, high power mode-locked fibre lasers based on Yb-doped LMAPCF have been investigated.[7−9] In a fibre laser system based on rod-type photonic-crystal fibre (PCF) with a mode-field area of 4000 μm^2, the highest pulse energy of 265 nJ with 5.5 ps pulse duration was obtained in the all-normal dispersion regime.[6] We conducted a series of experiments based on the LMAPCF previously, and mode lockings were achieved in all-normal dispersion,[10,11] anomalous dispersion[12,13] and the stretched pulse regime[14] separately.

However, the mode-locked LMAPCF lasers in all of the previous reports have a bulk of polarization control components to extract a laser beam from an optical resonator. In the present paper, firstly, we establish a compact fibre laser system with a free output coupler in which a fine polished facet of the LMAPCF is directly used as a cavity mirror and also an output coupler. A pair of gratings acts not only as the dispersion compensation element, but also as the spectrum filter, owing to the focus lens and semiconductor saturable absorber mirror (SESAM) right behind it. With this unique cavity configuration, the mode-locked fibre laser works in the filtering-soliton regime. Filtering conduces to the development of mode locking but restricts the broadening of the spectrum bandwidth, thereby limiting the shortening of pulse width. Another cavity configuration is established to elimi-

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†Corresponding author. E-mail: huminglie@tju.edu.cn
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nate the spectrum filtering (SF). After separating dispersion compensation from SF, the laser works in the soliton-like regime and stretched pulse regime instead of the filtering-soliton regime. The output spectrum width can increase to more than 10 nm and support much shorter output pulses.

2. Experimental setup of a free output coupler LMAPCF laser system working in the filtering-soliton regime

The experimental setup is shown in Fig. 1. The laser is based on the Fabry–Perot (F–P) linear configuration. The active fibre is of a 1.5 m-long LMAPCF (Crystal Fibre A/S, Denmark) which is highly doped with Yb^{3+} and has a pump light absorption of 9 dB/m. The transverse section of the fibre is shown in the inset in Fig. 1. It has a typical double-cladding structure. The mode-field area of the fibre is 660 μm^2, with a numerical aperture (NA) of 0.03. The inner cladding which works as a core for pump light has a diameter of 200 μm, with NA=0.55. The small air holes in the inner cladding and large air holes in the outer cladding guarantee the single-mode guidance for the laser beam and the high absorption efficiency for the pump light. The laser system is pumped by a fibre-coupled (200 μm, NA=0.22) laser diode (LD) emitting at 976 nm. One facet of the fibre is finely polished to 0° and works as one cavity mirror with 96% output couple rate and 4% feedback due to Fresnel reflection. The other facet of the fibre is polished to 8° in order to avoid self-excitation at high pump power. The pump light is collimated by two aspheric lenses (ALs) AL_1 and AL_2 ($f_1 = f_2 = 11$ mm), and then coupled into the LMAPCF. A dichroic mirror (DM) with a transmission ratio larger than 96% at 976 nm and a reflection ratio larger than 99% at 1040 nm is used to separate pump light from laser emission. Then the laser beam passes through a pair of gratings (600 lines/mm) to achieve dispersion compensation. A half wave plate inserted before the gratings has achieved an optimal reflection ratio. Via the grating pair, the laser beam is focused on SESAM by AL_3 ($f = 8$ mm). The SESAM (BATOP GmbH) is used to start mode locking and serves as the other cavity mirror. It is based on a molecular beam epitaxial InGaAs quantum well single layer grown on a GaAs/AlAs Bragg reflection mirror, and has a modulation depth of 35%, an absorption intensity of 65%, a saturation fluence of 20 $\mu J/cm^2$, and a relaxation time of 500 fs. The mode locking is monitored by a 4 GHz oscilloscope together with a 200 ps rise time photodiode. The pulse spectrum and the pulse duration are measured by a high resolution spectrometer and a long scan-range autocorrelator.

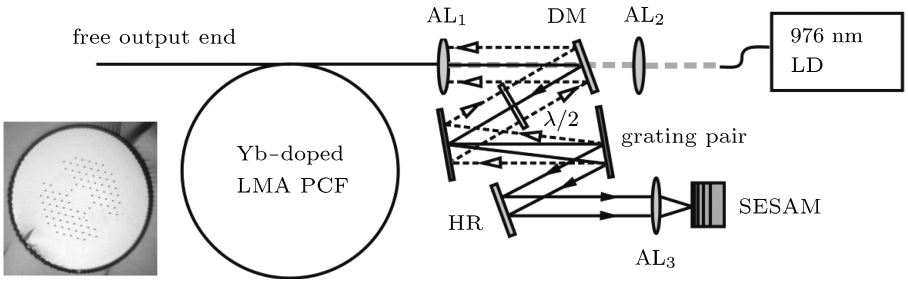


Fig. 1. Experimental setup of the free output coupler LMAPCF laser system. AL_1–AL_3: asphere lens, DM: dichroic mirror, HR: high reflector, $\lambda/2$: half wave plate.

3. Mechanism of dispersion compensation combined with spectral filtering in the laser system

The laser beam is expanded spatially by a grating-pair. Via AL_3 and SESAM, long and short wavelength components exchange their spatial positions. It is expanded even more widely after passing the grating-pair once again. Only part of the spectrum components can be coupled into the fibre core due to the small NA of the core. Therefore, the SF occurs as shown in Fig. 2(a). Only a simple geometry deduce is needed to prove that the dispersion compensation is still achieved in this condition. Figure 2(b) demonstrates the dispersion

compensation mechanism of the grating-pair in a traditional way. It can be easily proved that the difference in optical path between the long wavelength (dot line) and the short wavelength (dash line) in Fig. 2(a) is equal to that in Fig. 2(b) as shown below:

$$2D_1F_1 - E_1B_1 = 2D_2F_2 - 2C_2E_2,$$

i.e. the grating-pair with filtering has the same amount of dispersion compensation as that in the traditional way.

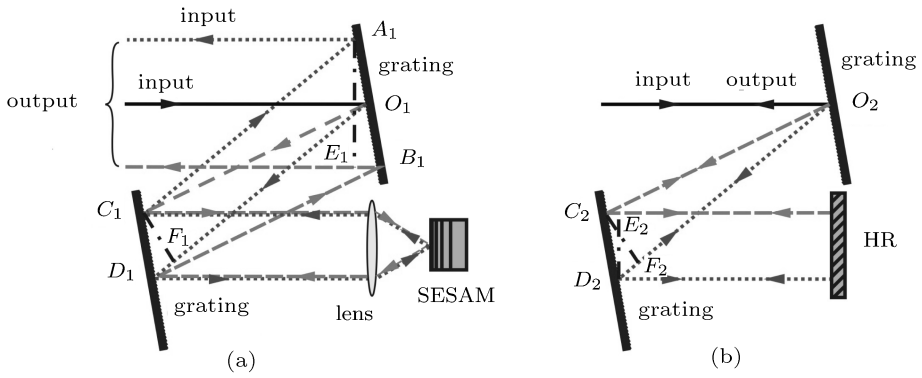
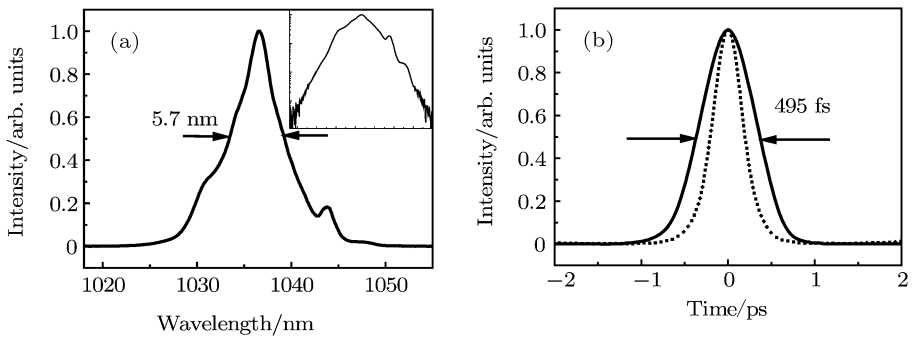


Fig. 2. Diagrams of the mechanism of the dispersion compensation section of the free output fibre laser (a) and a traditional one (b).

4. Experimental results of the free output coupler LMAPCF laser system working in the filtering-soliton regime

The group-velocity-dispersion (GVD) of the fibre is 0.019 ps^2/m at 1040 nm. The 1.5 m-long fibre induces 0.057 ps^2 GVD in one cavity round trip. The gratings contribute to -0.078 ps^2 GVD with a distance of 25 mm and a beam incident angle of 0°, resulting in -0.021 ps^2 net GVD per cavity round trip. At a pump power of 8 W, a mode-locked output power of 1.2 W with a repetition rate of 56.7 MHz is obtained, corresponding to 21 nJ pulse energy. The output spectrum and auto-correlation trace are shown in Figs. 3(a) and 3(b). The direct output pulse duration is 495 fs, and it could be dechirped to 286 fs externally to the cavity as indicated by the dash line in Fig. 3(b). Compared with a typical soliton-like mode-locked spectrum,[12] the soliton sidebands[15] are successfully suppressed in filtering-soliton conditions.

Reducing the grating distance to 20 mm, a round trip GVD brought by the gratings is -0.060 ps^2 that corresponds to a net GVD of -0.003 ps^2 per round trip. At a pump power of 8 W, a mode-locked output power of 1.0 W at a repetition rate of 56.7 MHz is obtained, which corresponds to 17.6 nJ pulse energy. The measured spectrum and autocorrelation trace are shown in Figs. 3(c) and 3(d) respectively. Output pulses, each with a duration of 482 fs, are directly obtained and can be dechirped to 256 fs by external-cavity compensation as shown by dash line in Fig. 3(d). Compared with the previous results in a stretched pulse regime,[14] the spectrum width is narrow due to the filtering effect, and thus pulses with a similarly short duration cannot be obtained.



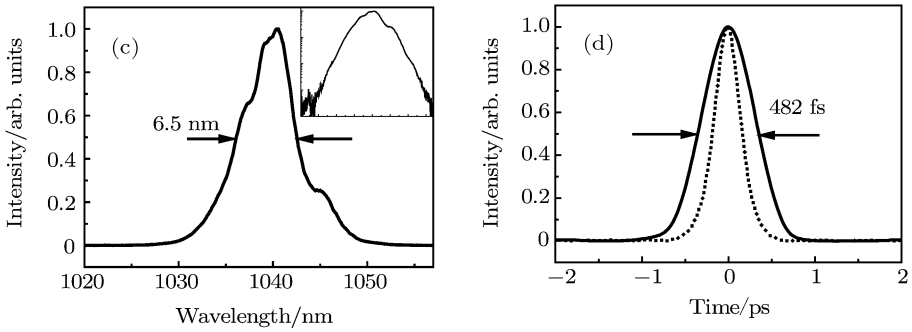


Fig. 3. Output characteristics of the filtering-soliton mode-locked fibre laser. Panel (a) displays the measured spectrum with a 25 mm grating distance, where the inset shows the same spectrum but on a logarithmic scale. Panel (b) indicates the corresponding autocorrelation traces of direct output pulses and external-cavity dechirped pulses (dash curve). Panel (c) exhibits the measured spectrum with a 20 mm grating distance, where the inset shows the same spectrum but on a logarithmic scale. Panel (d) refers to the corresponding autocorrelation traces of direct output pulses and external-cavity dechirped pulses (dash curve).

5. Experimental setup of the spectral filtering-free LMAPCF laser system with a free output coupler

Although the laser system mentioned above can suppress the soliton sideband, the narrow spectrum width of the output cannot support ∼100 fs pulses even in the stretched pulse regime. This is due to the unique cavity configuration which couples an unavoidable filtering effect into dispersion compensation. The elimination of the filtering effect is necessary to acquire a wider spectrum and shorter pulse duration from a fibre laser with a free output coupler. For this purpose, another cavity configuration is established and schematically shown in Fig. 4.

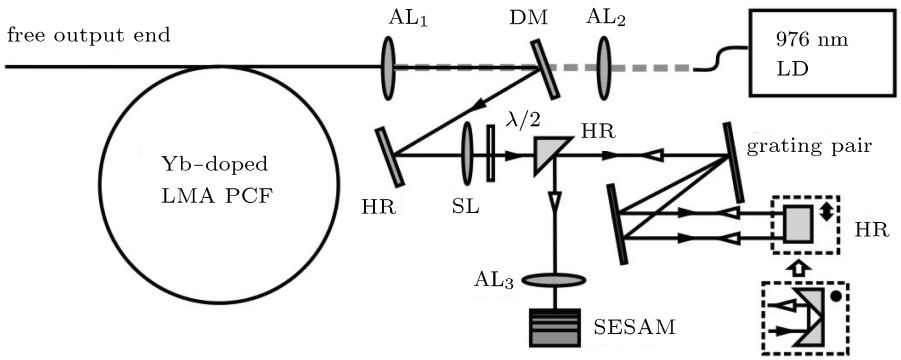


Fig. 4. Experimental setup of the spectral filtering-free LMAPCF laser system with a free output coupler. LD: laser diode; AL: asphere lens; SL: sphere lens; HR: high reflector; DM: dichroic mirror; $\lambda/2$: half wave plate.

A subtle change is adopted in order to avoid the filtering effect, then only the grating-pair for dispersion compensation remains there. After separation by the DM, the laser beam is collimated by a sphere lens (f = 400 mm) and diffracted by the grating-pair. A half wave plate is inserted before the gratings have achieved an optimal reflection ratio. A pair of 45° angle-mirrors is located behind the grating pair. The expanded laser beam is reflected back to the grating pair along the original route but with a relative height of 5 mm. Different spectral components are recombined together, then reflected by an HR and focused on SESAM to achieve mode locking.

6. Experimental results of the spectral filtering-free LMAPCF laser system with a free output coupler

It can be proved that the value of dispersion compensation in the experimental setup of Fig. 4 is twice that of Fig. 1, on the assumption that the grating-pairs in two conditions have the same distances and incident angles.

With 13 mm distance, the dispersion compensation part in Fig. 4 offers -0.078 ps^2 GVD in a cavity round-trip. The net GVD is -0.021 ps^2 (0.057 ps$^2-0.078$ ps^2) per round trip, and the laser system works in the soliton-like regime. At 7.5 W pump power level, mode locking with 720 mW average output is obtained at 43.6 MHz repetition rate, corresponding to 16.5 nJ pulse energy. The output spectrum of the mode locking is shown in Fig. 5(a). Without the filtering effect, typical soliton sidebands appear. The asymmetry of the sidebands is caused by the unbalanced absorption of the SESAM. The auto-correlation trace is shown in Fig. 5(b), indicating that the direct output pulse is 457 fs in duration.

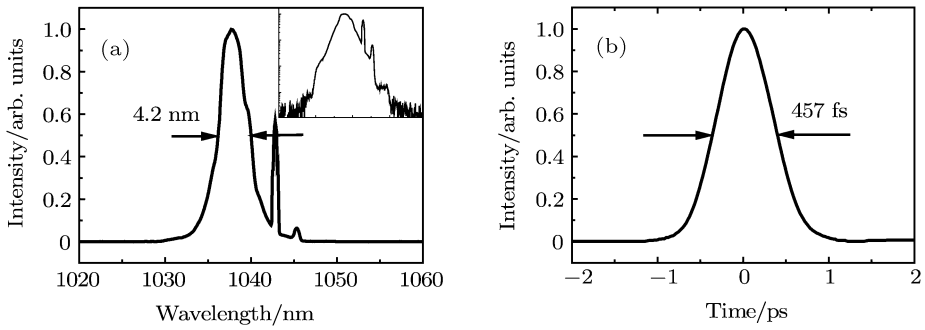


Fig. 5. Measured spectrum of the soliton mode locking, with inset showing the same spectrum on a logarithmic scale (a), and the corresponding autocorrelation trace (b).

Reducing the grating distance to 10 mm, the net GVD is -0.003 ps^2 per round trip and the mode locking works in the stretched pulse regime. Mode locking is achieved at 7.2 W pump power, the measured output spectrum and autocorrelation trace are shown in Figs. 6(a) and 6(b) respectively. The spectrum width increases to 10.8 nm, and the direct output pulse duration is 387 fs. The pulses can be dechirped to 119 fs externally to the cavity. The autocorrelation trace is shown by the dash line in Fig. 6(b). The repetition rate of the mode locking is 44 MHz, with 700 mW output power, corresponding to 15.8 nJ pulse energy.

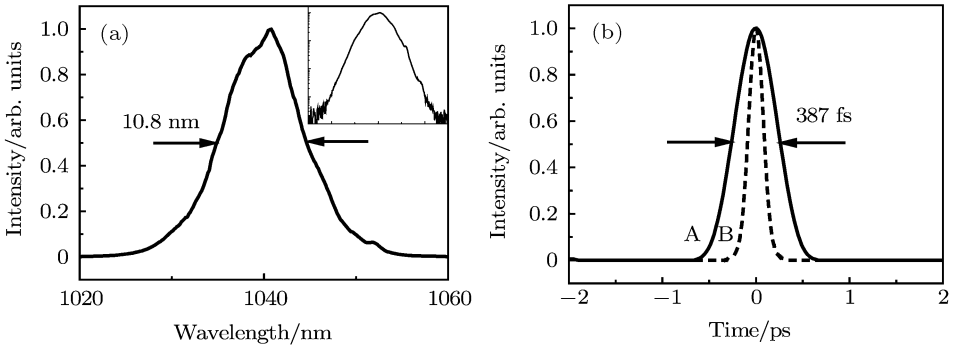


Fig. 6. Measured spectrum of the stretched-pulse mode locking, with inset showing the same spectrum on a logarithmic scale (a), and the corresponding autocorrelation trace of direct output pulses and dechirped pulses external to the cavity (dash curve) (b).

7. Discussion and conclusion

The two laser systems mentioned above, i.e. the free output coupler LMAPCF laser system and spectral filtering-free LMAPCF laser system, both have their own advantages. The former system is more compact and can suppress soliton sidebands, which can serve as a high-quality seed for PCF amplifiers. But the filtering effect coupled into dispersion compensation limits the spectrum width and thus cannot support narrower pulses. The latter system separates dispersion compensation from filtering and eliminates the filtering effects. The system can work in the stretched pulse regime and 119 fs-wide pulses are achieved. In both experiments the facet of the active LMAPCF is directly used as the output coupler, thereby making the mode-locked fibre lasers

more compact in structure. The free output end can be arranged at any desired location, which brings great convenience to the applications. The mode lockings are stable and can self-start.

We have established a high power free output coupler LMAPCF laser working in a filtering-soliton regime. The mechanism of the filtering effect is analysed. Pulses, each 21 nJ in energy and 495 fs in duration, are obtained. Considering the limitation of the filtering effect on the spectrum and pulse width, another cavity configuration which eliminates the filtering effect is established. The laser system works in the soliton-like regime with 16.5 nJ energy and 457 fs duration, and in the stretched pulse regime with 15.8 nJ energy and 387 fs duration, the pulses of which can be dechirped to 119 fs externally to the cavity.

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