Passive harmonic mode locked all-normal-dispersion Yb-doped fibre lasers

Kong Ling-Jie(孔令杰), Xiao Xiao-Sheng(肖晓晟), and Yang Chang-Xi(杨昌喜)†

State Key Laboratory of Precision Measurement Technology and Instruments, Department of Precision Instruments, Tsinghua University, Beijing 100084, *China*

(Received 7 June 2010; revised manuscript received 2 August 2010)

Passive harmonic mode-locking of dissipative solitons is demonstrated in all-normal dispersion Yb-doped fibre lasers. A difference equation model of the mode-locked fibre lasers is adopted to simulate the intra-cavity nonlinear dynamics. Hysteresis phenomena around the mode-locking threshold, and the effect of introducing linear phase bias are discussed. The passive harmonic mode-locking as one kind of multipulsing operations is revealed. Moreover, the simulation shows the bistability between multipulsing and single-pulse or period multiplication.

Keywords: fibre laser, mode-locking, ytterbium

PACS: 42.55.Wd, 42.60.Fc **DOI:** 10.1088/1674-1056/20/2/024207

1. Introduction

High repetition rate pulse trains have great applications in many fields, such as telecommunications, optical sampling, biological imaging, micro-machining and optical parametric oscillator pump.[1−6] Harmonic mode-locking (HML) is proposed to achieve high repetition rate generation directly from lasers. Active HML utilizes a modulator driven at a harmonic of the round-trip cavity frequency, which makes the setup complex. While passive HML can generate high repetition rate pulses with simple cavity setup. Repetition rate as high as 2 GHz has been achieved by passive HML of Yb-doped double-cladding fibre laser.[1]

Repetition rate scalability has been demonstrated with passive HML mode in fibre lasers of different regimes. In soliton fibre lasers, Grudinin *et al.* achieved 400-MHz to 1-GHz pulses by passive HML of an Er–Yb-doped fibre ring laser,[2] Shian *et al.*[3] achieved 1.5 GHz pulses by passive HML of Yb fibre laser. In the stretched-pulse lasers, Abendin *et al.*[4] realized 220-MHz pulses by passive HML of Er-doped fibre laser.

Recently, all-normal-dispersion (ANDi) fibre lasers have attracted great interest for their simplification of laser cavity and potentiality to achieve higher pulse energies.[7−14] The question naturally arises whether the passive HML exists for dissipative solitons[8,9] in fibre lasers of this novel regime. Even though Zhao *et al.*[10] has demonstrated passive HML in gain-guided Er-doped fibre lasers,[10] the output energy achieved is only 0.54 nJ. To the best of our knowledge, few reports are focused on passive HML in ANDi Yb-doped fibre lasers, which makes use of benefits of Yb-doped fibre, such as broad gain bandwidth, large saturation fluence, and high dope concentration.

In this paper, we present our experimental observation of passive second HML of dissipative solitons in ANDi Yb-doped fibre lasers. Based on a difference equation model of the mode-locked fibre lasers, we study the hysteresis phenomena around the mode-locking threshold. The effect of introducing linear phase bias is also discussed. The HML as one kind of multipulsing operations is revealed. According to the simulation, bistability exists between multipulsing and single-pulse or period multiplication as experimentally observed.

2. Experimental setup and results

Figure 1 shows the experimental setup, which is similar to that in our experiments in Refs. [11] and [12]. The unidirectional ring cavity, whose length is about 11 m, includes approximately 48-cm Yb-doped fibre, a polarization-independent fibre isolator, two quarter-wavelength plates, one half-wavelength plate,

†Corresponding author. E-mail: cxyang@tsinghua.edu.cn

© 2011 Chinese Physical Society and IOP Publishing Ltd

and two polarization beam splitters and a birefringent plate. The 980-nm pump is coupled into the cavity through wavelength division multiplexer (WDM). The output is coupled out from the ejection port of polarization beam splitter 1 (PBS1). The combination of the two PBS and a birefrigent plate makes up a birefrigent filter.

This fibre laser is passively mode-locked by nonlinear polarization rotation (NPR). It is well known that NPR, as the saturable absorber (SA), has a sinusoidal dependence of transmittance on intensity. For ANDi laser, the accumulated chirp is so large that NPR can also act as a filter.

Stable self-starting mode-locking pulses can be generated by appropriately adjusting the waveplates, and with the pump power above the threshold (about 168 mW in this setup). Once it is mode-locked, the pump power can be decreased to ∼120 mW without losing mode-locking, which shows hysteresis. In the progress of increasing pump power, the fibre laser may lose mode locking as a result of over-driving the NPR-based SA. This can be solved by introducing a linear bias via adjusting waveplates, which will increase the over-driving energy. The fundamental repetition rate of the mode-locking pulse is about 18.9 MHz. Under 513-mW pump power, the output power is 47 mW. The single pulse energy is about 2.5 nJ. The spectrum of mode-locking pulses is shown in Fig. 2. It exhibits a characteristic shape with sharp peaks near its steep edges, which is induced by large normal dispersion of the cavity.[7−9] The central wavelength is 1047.8 nm, and the −20 dB-bandwidth is 8.6 nm. The full width at half maximum (FWHM) of the autocorrelation, taken with a long-scan range autocorrelator, is 22.5 ps. The pulse duration is 14.6 ps if sech^2 pulse is assumed, which is much larger than the transform limited duration 338 fs due to the large chirp in ANDi cavity. The pedestal in the autocorrelation arises from the steep sides of the spectrum and large chirp of the pulses.

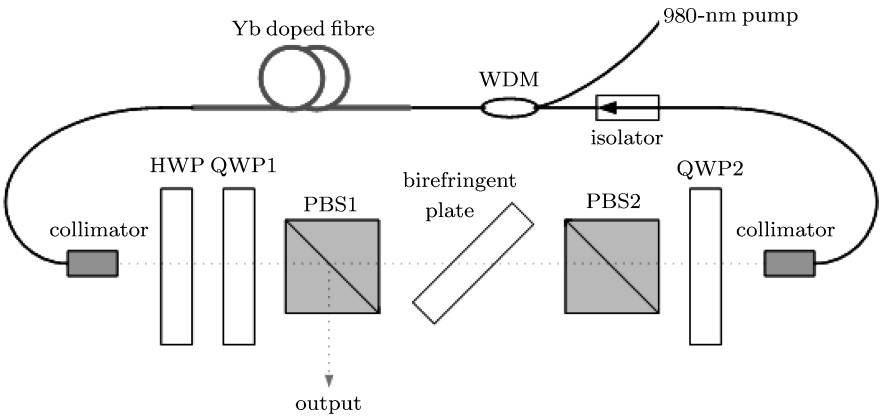


Fig. 1. Schematic diagram of all-normal-dispersion mode-locked fibre laser, WDM: wavelength division multiplexer, HWP: half wave plate, QWP: quarter wave plate, PBS: polarization beam splitter.

Over-driving of the NPR-based SA may also lead to pulse-breaking.[5,6] By changing the modulation depth and output coupling ratio of the laser with adjusting waveplates, period-doubling (i.e. two stable intra-cavity pulse energies alternate in every round trip) and pulses bunches can be observed. Limited by our available pump, we decrease the output coupling ratio to ensure large energy of intra-cavity pulse for overdriving the SA. Under proper orientations of the waveplates, stable second HML (i.e. two pulses with the same energy distributed uniformly in one cavity roundtrip) is achieved. Figure 4 shows the second HML mode (37.8 MHz, twice that of fundamental mode) with the same pump level as in Fig. 3. The output power is 44 mW, and the single pulse energy is about 1.2 nJ. Its spectrum is also shown in Fig. 2 (dash line), with the same central wavelength but the −20-dB bandwidth is broadened to 9.8 nm, compared to fundamental mode-locking case. The FWHM of autocorrelation shown in Fig. 4 is 19.6 ps, thus the FWHM duration of the sech^2 pulses is 12.7 ps, larger than its transform limited duration 300 fs for the chirp.

The theoretical explanations of passive HML are under debate. Possible mechanisms[5] include soliton–soliton attraction or repulsion, soliton–dispersive wave interactions, recovery dynamics in the saturated gain medium, and the acoustic effects in fibres.

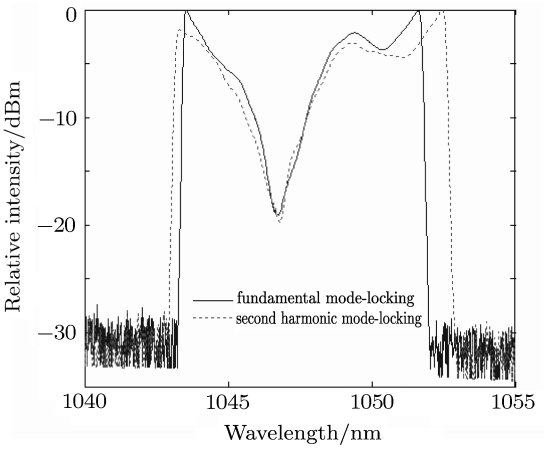


Fig. 2. Spectra of fundamental mode-locking and second HML pulses.

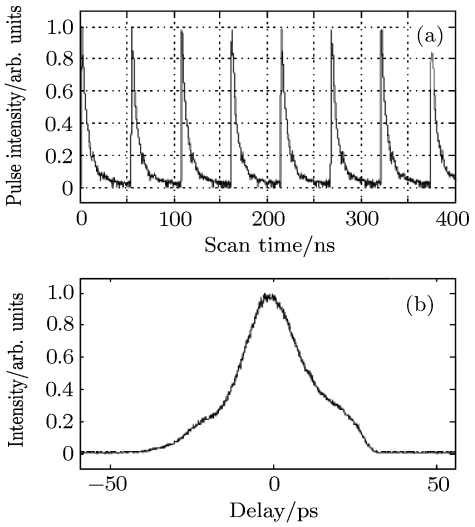


Fig. 3. Pulse train (a) and autocorrelation (b) of fundamental mode-locking.

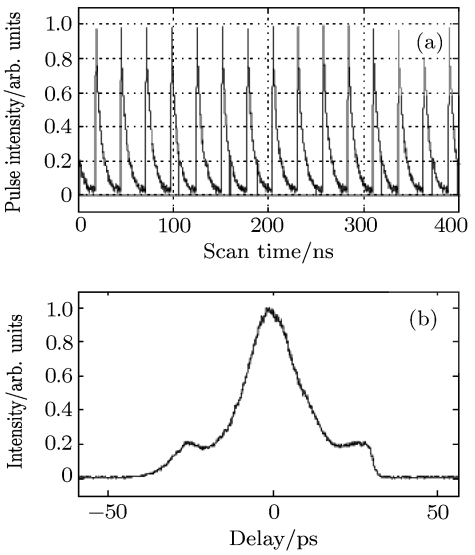


Fig. 4. Pulse train (a) and autocorrelation (b) of second HML.

3. Theoretical model and discussion

To study multipulsing in fibre lasers, Ilday developed a difference equation model,[14] which agrees with experiments qualitatively. Here we adopt this model to study the passive HML ANDi laser. Because NPR can act as spectral filter, as we demonstrated in Refs. [13] and [14], which plays an important role in dissipative soliton lasers. For simplicity, the model here neglects the birefringence filter in Fig. 1.

The evolution equation for the pulse energy of successive roundtrips is modeled with a difference equation[15]

$$E_{n+1} = \frac{1}{2}\frac{g_{\mathrm{net},0}}{1 + E_n/E_{\mathrm{sat}}}[1 - q'\cos(\pi E_n + \phi_0)]E_n, \quad (1)$$

where E_n denotes the soliton energy after the n-th roundtrip; $g_{\mathrm{net},0} = g_0/l_0$, g_0 is small signal gain, l_0 is linear loss, and E_{sat} stands for the gain saturation energy; q' is a modified parameter used for characterizing the modulation depth of NPR, and ϕ_0 is the linear bias of NPR. In the following, the influence of pump power is discussed instead of that of E_{sat}, because in the experiments E_{sat} can be controlled by adjusting the pump power of the gain fibre. For HML and multipulsing, equation (1) should be generalized to the coupled difference equations.[15] In our case, we adopt two coupled difference equations.

Figure 5(a) shows that the initial higher-energy noise pulse gets amplified and mode locked when the pump power is above the threshold ($E_{\mathrm{sat}} \sim 1$, Fig. 5(a)), but the other lower-energy one is inhibited. The mode-locking pulse energy increases with higher pump power until bifurcation occurs. The intra-cavity pulses begin to show period-doubling as experimentally observed.

Also, we study the experimentally observed hysteresis phenomena in simulation. We take high initial noise-pulse energy to model the decreasing of the pump power of stable mode-locking state in experiments. Because, when the pump power is decreased, the high-energy pulses of the original stable mode-locking will become the initial noise-pulses for mode-locking at a lower pump level. Figure 5(a) shows that in some pump power range, bistability exists between the mode-locked and the continuous regimes. When the pump power is decreased from mode-locking state

of high pump level, mode-locking can sustain till $E_{\rm sat}$ is decreased to 0.89, lower than the threshold.

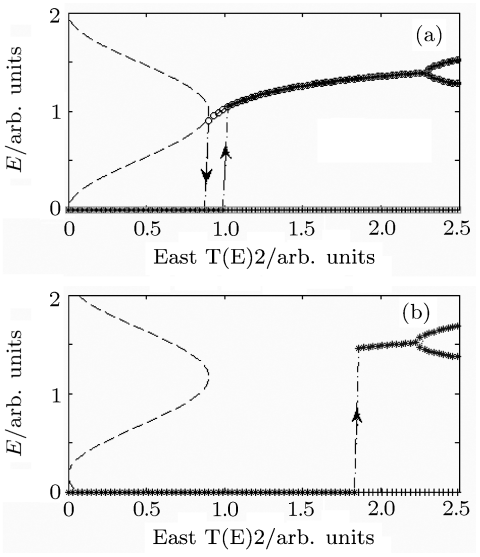


Fig. 5. The steady state pulse energies (E) under different pump powers ($E_{\rm sat}$). Also shown is the NPR transmission curve (dashed line) on the vertical axis. The marks '$*$, $+$' stand for the intra-cavity pulse energy with increasing pump power. The circle and square marks stand for intra-cavity pulse energy with decreasing pump power. $q' = 0.45$, $g_{\rm net,0} = 2.8$. (a) Hysteresis phenomena, with $\phi_0 = 0$, initial noise-pulse energies to be 0.68 and 0.18 for increasing pump power case, and 2.68 and 0.18 for decreasing pump power case. (b) Linear bias introduced to counter the over-driving of NPR, with the same value set as the increasing pump power case in (a) but $\phi_0 = -\pi/6$.

As mentioned above, in experiments the over-driving energy of NPR-based SA can be increased with introducing proper linear bias by adjusting waveplates. In simulations with a linear phase $-\pi/6$, the point of maximum transmittance moves to higher energy, as shown in Fig. 5(b), while the mode-locking threshold increases to $E_{\rm sat}$ =1.83. Higher pump power is needed to initiate mode-locking from intra-cavity noise in this case, which agrees with our experiments. And the maximum pulse energy (before period-multiplication happens) increases from 1.388 (Fig. 5(a)) to 1.514 (Fig. 5(b)) as expected.

By adjusting the waveplates, the modulation depth of NPR and net gain can also be changed. In the following simulation, they are changed to $q' = 0.56$, $g_{\rm net,0} = 3.6$ so as to agree with experiments. As shown in Fig. 6, the intra-cavity pulses undergo complex nonlinear dynamics at high modulation depth and high pump level. At low pump level, the laser works in continuous wave regimes. Once the threshold is reached, the laser can support one mode-locking pulse, same as in Fig. 5. With higher pump level, the intra-cavity pulses will be period-multiplication, and transit into chaos as shown in Fig. 6(a). At further increased pump, the second pulse can be supported stably with the same energy as the first one in every roundtrip. If these two pulses can self-organize with uniform separation, the second HML will be achieved as shown in our experimental observation. By increasing the pump further, two same period-doubling pulses in the cavity and chaos will happen again in the end. In experiments, we are limited by our pump level to observe this.

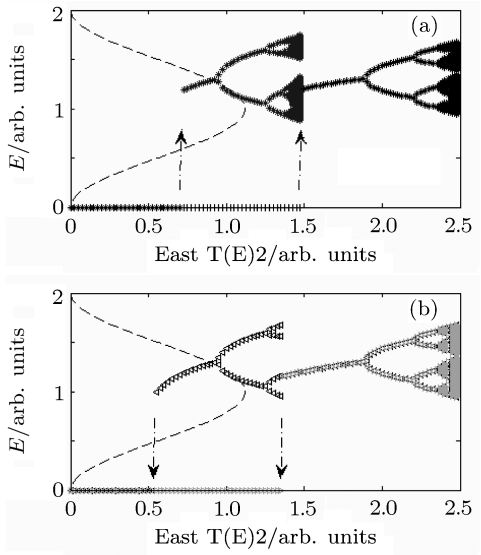


Fig. 6. The bifurcation diagram of multipulsing. Also shown is the NPR transmission curve on the vertical axis (dashed line). $q' = 0.56$, $g_{\rm net,0} = 3.6$, $\phi_0 = 0$. (a) Increasing pump power case, initial noise-pulse energies being 0.72 and 0.58. The marks '$*$, $+$' have the same meaning as in Fig.5. (b) Decreasing pump power case, initial noise-pulse energies being 2.7 and 0.9. The right and left triangle marks stand for intra-cavity pulse energy with decreasing pump power.

Based on the same method as in Fig. 5(a), we simulate the case of decreasing the pump power of stable mode-locking as shown in Fig. 6(b). The hysteresis phenomena around the mode-locking threshold can also be observed. Besides, multipulsing begins to occur at $E_{\rm sat} = 1.475$ (in Fig. 6(a)), while in the case of decreasing the pump power, the multipulsing can sustain till the $E_{\rm sat}$ is decreased to 1.325 (in Fig. 6(b)). It is shown that bistablity exists between multipulsing and single-pulse or period multiplication, which is also reported experimentally in Ref. [6].

It should be noted that, although this model fails to model the time distribution of multipulsing, it shows several main features of the mode-locking and multipulsing operations.

4. Conclusion

We have demonstrated passive second HML of dissipative solitons in ANDi Yb-doped fibre lasers experimentally. Simulations based on the difference equation model of the mode-locking fibre lasers have been carried out to study the intra-cavity nonlinear dynamics. Hysteresis phenomena around the mode-locking threshold, and the effect of introducing linear phase basis have been discussed. The model has also been simulated to study the HML as one kind of multipulsing operations, and the bistability between multipulsing and single-pulse or period multiplication.

References

[1] Ortac B, Hideur A, Martel G and Brunel M 2005 *Appl. Phys.* B **81**507

[2] Grudinin A B, Richardson D J and Payne D N 1993 *Electron. Lett.* **29** 1860

[3] Zhou S, Ouzounov D G, Sinclair C and Wise F 2006 *Opt. Lett.* **31** 1041

[4] Abedin K S, Gopinath J T, Jiang L A, Grein M E, Haus H A and Ippen E P 2002 *Opt. Lett.* **27** 1758

[5] Deng Y J and Knox W H 2004 *Opt. Lett.* **29** 2121

[6] Ortac B, Hideur A and brunel M 2004 *Opt. Lett.* **29** 1995

[7] Chong A, Buckley J, Renninger W and Wise F W 2006 *Opt. Express* **14** 10095

[8] Renninger W H, Chong A and Wise F 2008 *Phys. Rev.* A **77** 023814

[9] Wise F, Chong A and Renninger W 2008 *Laser & Photon. Rev.* **2** 58

[10] Zhao L M, Tang D Y, Cheng T H, TAM H Y and Lu C 2008 *Chin. Sci. Bull.* **53** 676

[11] Kong L J, Xiao X S and Yang C X 2009 *Conference on Lasers and Electro-Optics/International Quantum Electronics Conference*, Baltimore MD USA, JTuD70

[12] Kong L J, Xiao X S and Yang C X 2010 *Laser Phys.* **20** 834

[13] Kong L J, Xiao X S and Yang C X 2010 *Chin. Phys.* B **19** 074212

[14] Kong L J, Xiao X S and Yang C X 2010 *Laser Phys. Lett.* **7** 359

[15] Ilday F O 2004 *Theory and Practice of High-Energy Femtosecond Fibre Lasers Ph. D Dissertation*, Cornell University