Studies on Ytterbium-doped Fibre Laser Operating in Different Regimes

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Abstract. An ytterbium-doped fibre laser with a unidirectional ring cavity containing a polarizer placed between two in-line polarization controllers is presented. Depending on an equivalent saturable absorber, this laser operates in continuous, Q-switched mode-locked or CW mode-locked regimes. The passive method described here allowed us to choose the operating regime of the fibre laser by rotating the two polarization controllers and adjusting the pump power. Results of numerical simulations of pulse propagation in such a mode-locked fibre ring laser are presented, which reveals that the Q-switched mode-locked or CW mode-locked regimes can be achieved by aligning the polarizer near the slow or the fast axes of the fibre.

1. Introduction

Stable, low-noise sources of ultrashort pulses are interesting for many applications, such as ultrafast phenomena research, nonlinear optical research, optical communications, multiphoton microscopy, and the pumping of parametric devices [1-2]. Passively mode-locked fibre lasers are of great importance in mode-locked fibre lasers. Different experimental methods have been used to achieve mode-locking operation [3-9].

In this paper we are interested in mode-locking through nonlinear polarization rotation. This technique has been successfully used to obtain short pulses in different rare-earth doped fibre lasers [3-8], and is of self-starting. Depending on the equivalent saturable absorber, the laser operates in continuous, Q-switched mode-locked or CW mode-locked regimes. The passive method presented here allowed us to choose the operating regimes of the fibre laser by rotating the two polarization controllers and adjusting the pump power. The results of our numerical simulations of the pulses propagation in such a mode-locked fibre ring laser are presented, which reveals that the Q-switched mode-locked or CW mode-locked regimes can be achieved by aligning the polarizer near the slow or the fast axes of the fibre.

2. Experimental set-up and theory

The experimental setup is shown in Figure 1. Schematic of the laser includes a polarization-sensitive isolator and two polarization controllers in a fibre ring cavity. A small portion of the fibre is
ytterbium-doped, which is pumped by a wavelength division multiplexed (WDM) coupler at 976 nm and provides gain to the cavity. The mode-locked soliton pulse train is coupled out through a 90/10 coupler, 10% of the pulse energy is coupled out. The two primary experimental parameters that can easily be adjusted are the polarizer angles relative to the fast and slow axes of the fibre, which are determined by the polarization controllers and the pump power.

![Experimental configuration of pulse fibre laser.](image)

**Figure 1.** Experimental configuration of pulse fibre laser.

Pulse shortening occurs in a laser through nonlinear polarization rotation. An initial pulse is linearly polarized through the polarization-sensitive isolator, and then made to be elliptically polarized with a quarter-wave plate (PC1). The light then passes through a Kerr medium (optical fibre) where elliptical rotation occurs and the peak of the pulse rotates more than the pulse wings [9]. At the output of the fibre, the half-wave plate (PC2) orients the pulse so that the peak of the pulse passes through the polarizer while the wings of the pulse are extinguished, thus achieving pulse shortening.

3. **Experimental results**

In the experiment, with the increase of the pump power and proper adjustments of polarizer orientations, we can achieve different operation modes.

3.1. **Q-switched mode-locking**

With the increase of the pump power, the Q-switched mode-locked pulses will appear with proper polarization controllers orientations. A deeper intensity modulation can be observed with higher pump power. When the pump power is increased to 135mW, self-mode-locking in Q-switched pulses is observed (see figure 2) by adjusting the PC1 and PC2 carefully, in which the modulation period is approximately 50ns.

![Q-switched mode-locked pulse train.](image)

**Figure 2.** Q-switched mode-locked pulse train.
3.2. CW mode-locking
If we further increase the pump power to 165mW, the CW mode-locked threshold is achieved, and because of the nonlinear polarization rotation effect, CW mode locking will be observed by adjusting the PC1 and PC2 carefully. As shown in Figure 3, the pulse interval is approximately 50ns. The mode-locking spectrum is presented in Figure 4, and the full width at half maximum is 13.4nm.

According to the mode-locking theory, the time interval between two adjacent pulses is \( \Delta t = nL/c \), where \( L \) is the cavity length and \( c \) is the speed of light in vacuum. From this equation, we can see that, when the cavity length is 10m, the interval between two adjacent pulses is 50ns, which is in accordance with our experimental results. According to \( \Delta v \Delta t = 0.315 \), we can also estimate that the minimum pulse width is about a hundred femtoseconds.

4. Numerical modeling
Following Kim et al. [7,10], the model of pulse propagation in such a ring cavity fibre laser that includes a polarizer and polarization controllers can be given by the following equations:

\[
\frac{dP}{d\xi} = \left( I/3 \right) B I \eta \sin(2P) \sin(2\psi) \\
\frac{d\psi}{d\xi} = (-4/3) B I \eta \cos(2P) \sin^2(\psi) + 2K \\
\frac{dn}{d\xi} = -2c\eta \\
\frac{\pi^2}{2} \frac{d\xi}{dc} = \eta^4 - \pi^2c^2 - I\eta^3 \left[ 1 - B \sin^2(2P) \sin^2(\psi) \right] \\
P_+ = \tan^{-1} \left[ \alpha \tan \left( P_0 - \theta \right) \right] + \theta
\]

Equation (1)—(4) described the evolution of the slowly varying envelope of the electric field in an optical fibre subject to chromatic dispersion, Kerr nonlinearity, and polarization effects, and the Equation (5) models the polarizer as a periodic rotation of the pulse energy between the \( U \) and \( V \) polarization fields, here the \( U \) and \( V \) fields are orthogonally polarized components of the electric field of the pulse. Figure 6 is the pictorial description of the action of a polarizer on a propagating pulse. We have scaled the complex orthogonal fields \( U \) and \( V \) with the peak field power \( |E_0|^2 \). \( \xi \) is the physical distance divided by the dispersion length.

Here we present Equation (1) in dimensionless form in which these pulses are approximately described by an amplitude and width fluctuation \( \eta \), a polarization angle \( P \), a relative phase \( \psi \), a total phase \( \phi \), and a quadratic chirp \( c \), \( I \) is the initial energy contained in the pulse.
The birefringence strength parameter, $K$, determines the relative phase velocity difference between the $U$ and $V$ fields. The material properties of the optical fibre determine the values of nonlinear coupling parameter $B$, for the physical system considered here, it takes on the specific values $B = 1/3$. The polarizer strength parameter, $a$, indicates the efficiency of the polarizer in attenuating components not aligned with polarizer’s angle $\theta$. To be consistent with physical values, we consider $a = 0.01$ such that the polarizer attenuates 99% of the pulse that is not aligned with the polarization angle.

We denote the polarization vector by $S = \begin{bmatrix} U \\ V \end{bmatrix}$ and introduce $P_{\pm}$ as the angles of the polarization vector $S_\pm$ relative to the fast-axis $U_\pm$ of fibre, and $\theta_\pm$ as the angles of polarizer relative to the fast-axis $U_\pm$ of fibre, the subscripts “-” and “+” denote the parameters before (-) and after (+) the polarizer, respectively. Here $U$ and $V$ represent the alignment of the fibre with the fast and slow-axes before and after passage through the polarizer. Figure 5 is the pictorial description of the action of a polarizer on a propagating pulse.

Figure 5. Equivalent model of action of a polarizer on a propagating pulse.

We model the optical fibre loop laser shown in Figure 1 by using Eqs. (1). Figure 6(a) is the amplitude, chirp, polarization, and phase evolution over 2000 round trips of the fibre cavity near the polarization-locked solution $P = 0.5\pi$, $K = 0.10$; Figure 6(b) is the amplitude, chirp, polarization, and phase evolution over 2000 round trips of the fibre cavity near the polarization-locked solution $P = 0.1\pi$, $K = 0.10$.

From the Figure 6(a), we can see, when the polarization angle $P = 0.5\pi$, that the amplitude fluctuation factor $\eta$ and the quadratic chirp $c$ exhibit periodic fluctuations. The Q-switched mode-locked pulse can be obtained due to this periodic perturbation.

Figure 6(a). Evolution of amplitude fluctuation $\eta$, polarization angle $P$, relative phase $\psi$ and quadratic chirp $c$ ($P = 0.1\pi$, $K = 0.10$).
From Figure 6(b), we can see, when the polarization angle $P=0.1\pi$, that the uniform amplitude and the quadratic chirp are achieved after 1500 round trips. This uniform mode-locked pulse trains are consistent with what we obtained in experiment.

**Figure 6(b).** Evolution of amplitude fluctuation $\eta$, polarization angle $P$, relative phase $\varphi$ and quadratic chirp $c$ ($P = 0.5\pi$, $K = 0.10$).

5. Conclusion
Conclusively, by rotating polarization controllers and adjusting the pump power, stable operation regimes of continuous, Q-switched mode-locked or CW mode-locked can be obtained in the fibre laser. Numerical simulation results of the pulse propagation in such a mode-locked fibre ring laser are presented, which reveals that the Q-switched mode-locked or CW mode-locked regimes can be achieved by aligning the polarizer with the slow or the fast axes of the fibre. The results of our numerical simulations are consistent with the experimental observation.

References
[1] Chu S et al 2003 Real-time second-harmonic-generation microscopy based on a 2-GHz repetition rate Ti:sapphire laser Opt. Express 11 933-938
[2] Schaffer C, Garcia J and Mazur E 2003 Bulk heating of transparent materials using a high repetition-rate femtosecond laser Appl. Phys. A 76 351-354
[3] Matsas V J et al 1992 Selfstarting passively mode-locked fibre ring soliton laser exploiting nonlinear polarization rotation Electron. Lett. 28 1391-93
[4] Tamura K, Haus H A and Ippen E P 1992 Self-starting additive pulse mode-locked erbium fibre ring laser Electron. Lett. 28 2226-28
[5] Nelson L E et al 1994 Ultrashort-pulse fibre ring lasers Appl. Phys. B 65 277-294
[6] Leblond H et al 2002 Experimental and theoretical study of the passively mode-locked Ytterbium-doped double-clad fibre laser Phys. Rev. A 65 063811
[7] Kim A D, Kutz J N and Muraki D J 2000 Pulse-train uniformity in optical fibre lasers passively mode-locked by nonlinear polarization rotation IEEE Jour. Quant. Electron. 36 465-471
[8] Nelson L E, Ippen E P and Haus H A 1995 Broadly tunable sub-500 fs pulses from an additive-pulse mode-locked thulium-doped fibre ring laser Appl. Phys. Lett. 67 19-21
[9] Hofer M et al 1991 Mode locking with cross-phase and self-phase modulation Opt. Lett. 16 502-504
[10] Spaulding K M, Yong D H, Kim A D and Kutz J N 2002 Nonlinear dynamics of mode-locking optical fibre ring lasers J. Opt. Soc. Am. B 19 1045-54