Transition state to mode locking in a passively mode-locked erbium-doped fibre ring laser*

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The transition state between the continuous wave region and the mode-locked region in a passively mode-locked erbium-doped fibre ring laser has been experimentally observed by utilizing the nonlinear polarization rotation technique. When the pump power reaches the mode-locked threshold, the metastable pulse train with a tunable repetition rate is obtained in the transition from the continuous wave state to the passive mode-locked state via proper adjustment of the polarization controller. A simple model has been established to explain the experimental observation.

Keywords: transition state, erbium-doped fibre laser, mode locking, nonlinear polarization rotation

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1. Introduction

As an excellent ultra-short optical pulse source, the passively mode-locked fibre laser has attracted considerable attention and has been extensively investigated.[1−8] The mode locking in a nonlinear polarization rotation (NPR) passively mode-locked fibre laser is achieved by employing the nonlinearity in the form of an artificial saturable absorber. The effect of cross-phase modulation (XPM) between orthogonally polarized modes results in uneven polarization states for optical components of different intensities, and the polarization-dependent loss caused by the polarizer inserted in the laser cavity is used to suppress the low-level radiation and to achieve the mode locking.[9]

So far, the passive mode locking has been well understood. However, the transition from the continuous wave (CW) state to the mode-locked state still needs further investigation and attracts much attention.[10−14] The transition state can be considered as the middle status that leads the lasing operation to switch from the CW to the mode-locked state. It has been pointed out that the noise power is the mechanism dominating the operation state of a laser. The transition between the CW state and the passive mode-locked state can be obtained by changing the power level of the intrinsic noise in a laser.[12] Recently, Zhan *et al.*[13] have demonstrated experimentally the transition state in the form of rational harmonic mode locking in a figure-eight fibre laser. Zhan's study focuses on a laser of figure-eight cavity and realizes mode locking via employing a nonlinear amplified loop mirror. Wang *et al.*[14] have also observed experimentally the transition states in an erbium-doped fibre ring laser. However, the transition states observed in Wang's work are based on a dissipative soliton system and are between two mode-locked states. The transition states in Zhan's and Wang's works are realized through changing the pump power. Thus, it is interesting to observe the transition states from the CW to the mode-locked state via controlling the cavity noise level with the adjustment of the polarization controller (PC).

In this paper, we report the experimental observation of the transition state in a passively mode-locked fibre ring laser using the NPR technique. The transition state is realized by appropriately controlling the intrinsic noise level of the cavity. It shows that the mode locking is not obtained directly when the pump power reaches the mode-locked threshold. Instead, the transition state performing metastable

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pulse train with controllable repetition rate always exists during the procedure of switching to the mode-locked operation from the CW state. The results are helpful for further understanding the procedure for realizing the mode-locked operation.

2. Experimental setup

The schematic diagram of our experimental setup is shown in Fig. 1. The fibre laser consisted of a 5 m erbium-doped fibre pumped by a 980 nm laser diode and a 12.3 m standard single mode fibre. The corresponding fundamental repetition rate was 11.52 MHz. Two PCs (General Photonics, PLC-005) were employed to adjust the polarization state of the lasing light. The polarization-dependent isolator (PD-ISO) assured the unidirectional operation and provided polarization selectivity. The output was realized by a 5% fibre coupler. An optical spectrum analyzer and an oscillograph were used to study the pulse spectrum and the output pulse-train, respectively. In addition, an optical power meter was employed to measure the output power. In order to avoid the external perturbations, all the fibres were fastened to the optical table. Unlike usual laser cavity, it is noticeable that the enhanced insertion loss caused by the defective fibre connector was deliberately introduced into our design to assist the observation of the transition state.

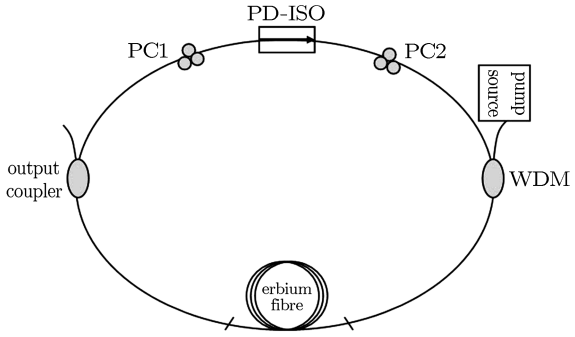


Fig. 1. Schematic diagram of the fibre ring laser. WDM: wavelength-division multiplexer.

3. Experimental results

Initially, we pumped the laser with high power and tuned the PCs carefully to obtain stable mode-locked pulses. Then we fixed the PCs and gradually increased the pump power from zero. The laser did not become mode locked until the pump power was beyond 41 mW. We set the power level in various values below 41 mW (i.e., 40, 39, 38 and 35 mW), no mode-locked phenomenon could be observed at any position of PC setting. Therefore, we believe that 41 mW is the threshold of the pump power for achieving mode locking.

For observing the transition state, we fixed the pump power at 41 mW and fastened one PC at a proper orientation. Through adjusting the other PC carefully, metastable pulse trains appeared in a specific range. In order to look into the details of how the transitional pulse evolved along with the phase shift, we fixed the pressure applying knob on the PC and set the rotational angle of the rotatable fibre squeezer as $\Delta\alpha = 0°$ when six pulses coexisted in the laser cavity. Successively, with further rotating the squeezer around the fibre axis unidirectionally, the repetition rate of the output pulse train decreased. As shown in Fig. 2, the metastable pulse trains with the repetition rates ranging from sextuple to double the fundamental one were observed, corresponding to the rotational angles $\Delta\alpha$ being 0°, 1.2°, 2.3°, 3.4° and 4.3°, respectively. In Fig. 2(d), though it seems that there were five pulses coexisting in the cavity, the repetition rate shown in the oscillograph was only triple the fundamental one due to the weak intensities of sub-pulses. The amplitude distribution of the pulse train has a periodic structure that transforms intensively when the rotational angle is switched among different values.

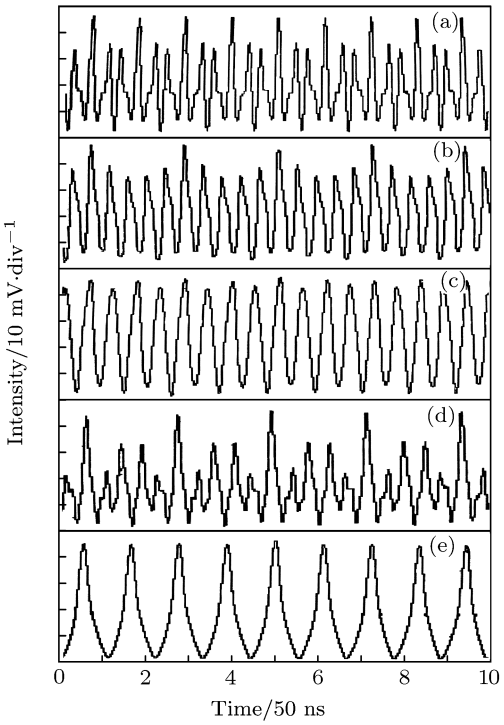


Fig. 2. Transitional pulse trains corresponding to different rotational angles $\Delta\alpha$ under a pump power of 41 mW. From (a) to (e), $\Delta\alpha$ are equal to 0°, 1.2°, 2.3°, 3.4° and 4.3°, respectively.

Except for the case shown in Fig. 2(e), the amplitude distribution of the pulse train is nonuniform. Besides, neither the pulse shape nor the pulse-to-pulse interval of the transitional pulse train is unified.

The corresponding spectrum of the transitional pulse is shown in Fig. 3. The central wavelength is 1581.15 nm and the 3-dB bandwidth is 0.70 nm. Distinguished from the metastability in the time domain, the optical spectrum of the pulse train is stable. Moreover, the spectrum character changes very little for different repetition rates.

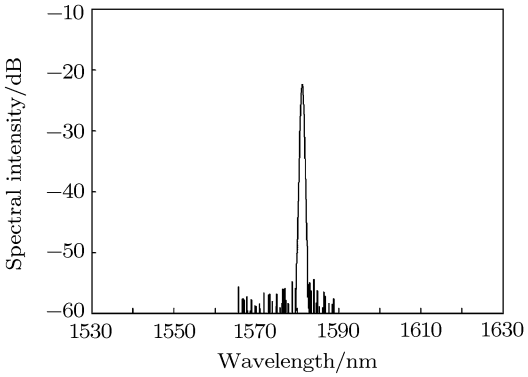


Fig. 3. Optical spectrum of the transitional pulse. The central wavelength is $\lambda_c = 1581.15$ nm and the 3-dB bandwidth is $\Delta\lambda = 0.70$ nm.

The PC was further adjusted carefully to decrease the repetition rate step by step. As the operation was carried out, the laser became mode locked and only one pulse was left in the cavity. The temporal appearance and the spectrum of the mode-locked pulse are shown in Figs. 4 and 5, respectively. In comparison with the transitional pulse, the amplitude distribution of the mode-locked pulse is uniform, the pulse-to-pulse interval is equidistant and the peak

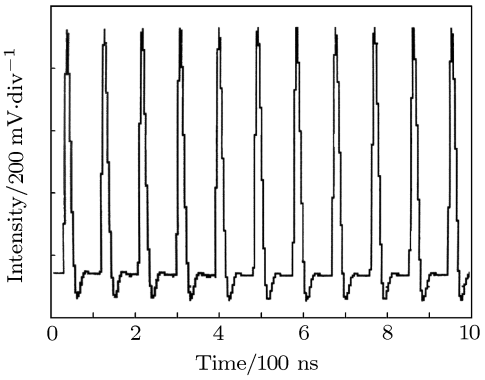


Fig. 4. Pulse distribution of the mode-locked state. The pump power is 41 mW and the corresponding rotational angle is $\Delta\alpha = 5.7°$.

intensity is much stronger than that of the transitional one. In the spectral domain, the most obvious difference is that the 3-dB bandwidth of the mode-locked pulse is much wider than that of the transitional one. We note that the soliton sideband vanishes in Fig. 5, which is because the dispersive wave is filtered by the polarizer in the cavity.[15]

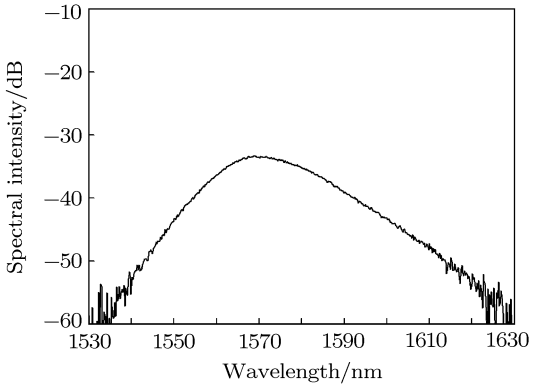


Fig. 5. Optical spectrum of the mode-locked pulse. The central wavelength is $\lambda_c = 1571.94$ nm and the 3-dB bandwidth is $\Delta\lambda = 24.15$ nm.

Figure 6 shows the calculated peak power of the output pulse versus the rotational angle $(2\pi+\Delta\alpha)$. At the first threshold, $\Delta\alpha = 0°$, the transition from the CW state to the transition state occurs and the pulse peak power increases to several watts. In the transitional region, the peak power of the output pulse increases almost linearly along with the rotational angle. With the rotational angle increasing, the laser becomes mode-locked at $\Delta\alpha = 5.7°$ and the pulse peak power increases to hundreds of watts instantly. It is important to note that the peak power of the pulse generated in an anomalous dispersion cavity is higher than that of the mode-locked pulse in a dissipative soliton fibre laser.[16]

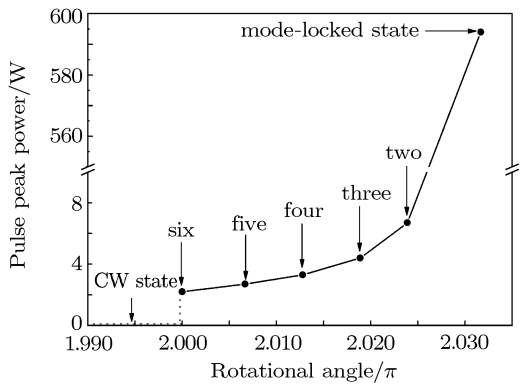


Fig. 6. Calculated peak power of the output pulse versus the rotational angle $(2\pi + \Delta\alpha)$. The six, five, ..., two represent that the repetition rates are six, five ..., two times of the fundamental one and the corresponding peak powers are: 2.2, 2.7, 3.3, 4.4 and 6.7 W, respectively.

For further understanding the transition state, we kept the PC within the transitional range ($\Delta\alpha = 0°$–$5.7°$) for a pump power of 41 mW and gradually increased the pump strength. Except for the variation in the intensity, transition states observed at other pump levels were similar to that at 41 mW. Even though the PC needed to be set at different positions, the mode locking could always be realized from the transition state at those pump levels. It further confirms that the transition state exists in the procedure of passive mode locking.

4. Analysis

In order to show the procedure in which a laser operation switches from the CW region to the mode-locked region and to explain our observation, we introduce a simple but practical model to describe the laser cavity.[17,18] As demonstrated in Fig. 7, the α and the β represent the angles that the polarization directions of the polarizer and the analyzer deviate from the vertical birefringent axis y, respectively. Provided that a pulse becomes linearly polarized after passing through the polarizer, then the polarization state of the pulse evolves from linear to elliptical due to the linear (mode birefringence) and the nonlinear (self-phase modulation and XPM) phase shifts during the propagation. The analyzer only let the component whose polarization angle is aligned with β pass through. Therefore, via adjusting the PC, we can change the polarization state of the pulse and control its transmission coefficient. The transmission coefficient T can be expressed as

$$T = \sin^2\alpha\sin^2\beta + \cos^2\alpha\cos^2\beta + \frac{1}{2}\sin(2\alpha)\sin(2\beta)\cos(\Delta\phi), \quad (1)$$

where $\Delta\phi = \Delta\phi_{\rm l} + \Delta\phi_{\rm nl}$ and $\Delta\phi_{\rm l}$, $\Delta\phi_{\rm nl}$ denote the linear and the nonlinear phase shifts, respectively.

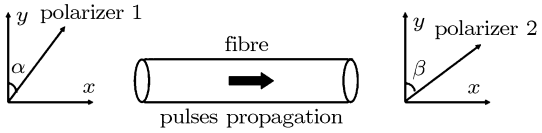


Fig. 7. Descriptive model of the laser cavity. The x and y are the orthogonal birefringent axes of the optical fibre, respectively.

A curve describing the changing tendency of T with the total phase shift $\Delta\phi$ is shown in Fig. 8. It is obvious that the transmission coefficient varies in the wake of the phase shift with a period of 2π and becomes maximum at $\Delta\phi = (2n+1)\pi$, where n is an arbitrary integer. Therefore, the intensity of specific optical ingredients including the noise in the cavity can be controlled by tuning PC or by changing the pump power in the experiment.

In a mode-locked laser, fluctuations of several physical quantities, e.g., gain, length of the cavity, refractive index, spontaneous emission, can introduce noise into the cavity. Specifically, the noise caused by spontaneous emission fluctuations is the dominant one in our experiment.[19] As the noise power is sufficient to supply the energy to compensate the excess loss in the cavity, the modulation instability (MI) is inhibited.[20] On the other hand, the possibility of the emergence of the pulsed state is extremely small due to the rigorous condition demanded in the laser system. As a result, the laser traps in a CW state at the beginning, despite that the input power exceeds the threshold of mode locking.

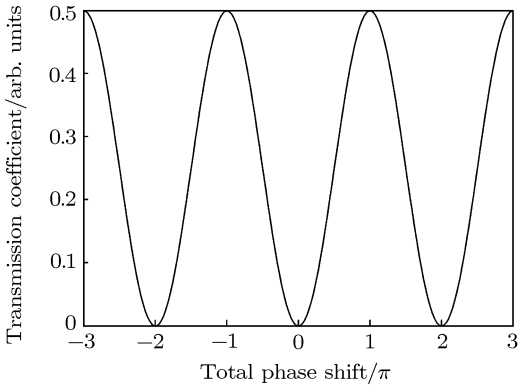


Fig. 8. The transmission coefficient T versus the total phase shift $\Delta\phi$. The period is 2π, the maximum value of T is 0.5 at $\Delta\phi = (2n+1)\pi$, where n is an arbitrary integer.

The transition from CW to transitional pulse or from the transition state to the mode-locked state should be attributed to the variation of the noise power in the cavity.[12] The polarization-dependent loss caused by the polarization-dependent isolator (PD-ISO) gives a positive or a negative feedback to the noise depending on the PC orientation. When the orientation of the PC makes the polarizations of most of noise components align with β, the noise endures a positive feedback and becomes enhanced. Conversely, the noise suffers a negative feedback and becomes smaller. The CW therefore becomes metastable and splits into multiple pulses, as the PC is adjusted to a position where the noise level is too low to inhibit MI, which is refered to as a transition state.

Since the feedback region is continuous in a limited tuning range, through further adjusting the PC unidirectionally, the noise becomes smaller and the lasing operation transfers to the mode-locked state from the transition state.

We further consider the reason for the nonuniform amplitude distribution of the transitional pulse train. Provided that several pulses with the same initial phase simultaneously form in the cavity and the round trip phase delays of the pulses are 2π or multiples of 2π, the polarization states of the pulses will align with the analyzer after each round trip. Thus, pulses experience the same loss and have uniform amplitudes. However, the transitional pulses in our experiment propagate to the analyzer with different polarization states due to their random initial phases as well as the linear and the nonlinear phase delays they experienced during the round trip. Since the effect of the analyzer on pulses is discrete, pulses with different polarization states endure different losses when they pass through the analyzer. The procedure continues until the polarization states of all the pulses align with the analyzer. Therefore, nonuniform pulse trains as shown in Fig. 2 occur in the cavity. We can obtain the pulse trains with different amplitude distributions and repetition rates by controlling the linear phase delay of the cavity with the same principle.

Analogous to the time domain, the combination of PC-PD-ISO-PC plays a role of polarization-dependent spectral filter in the spectrum domain,[21,22] and the adjustment of the PC changes the transmission wavelength. Suppose that various optical components with different wavelengths coexist in the cavity at the beginning, each goes through different phase delays and reappears with different polarization states after a round trip due to the fibre birefringence. Because energy loss depends critically on the vector product between the optical wave and the analyzer, only the spectral components with low enough energy loss will lase in the cavity after sufficient round trips. In our fibre laser, narrow optical spectrum emerged first in the transition region. Along with the adjustment of the PC, the transmission wavelength of the system was gradually changed. When the PC was set at a proper position for the mode-locked state, the spectral components lasing in the cavity were significantly increased and the spectral width broadened enormously.

To give a review, the main procedure in which a laser operation switches from the CW state to the mode-locked state is recognized here. Most of the time, the laser operates in the CW state because of the inhibition of MI caused by the relatively high noise power. We adjust the PC to find out a range, in which the noise level is low enough to support the laser operating in the transition state. We decrease the number of the pulse in the cavity one by one through fine adjustment of the PC. When there is only one pulse left in the cavity, the noise power is confined to a proper level, which is low enough to overcome the entropic barrier of the cavity but high enough to drive the laser to reach the mode-locked state. As the activated pulses evolve, the free energy in the cavity becomes minimum and the laser operates in the mode-locked state stably.

5. Conclusion

In summary, we observed the transition state performing metastable pulse train with tunable repetition rate in a passively mode-locked erbium-doped fibre ring laser by utilizing the NPR technique. The transition state was also investigated when the pump power was beyond the threshold. The experimental results and the analysis provide another approach to understand the procedure how a fibre laser realizes passive mode locking from a CW state.

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