Ultrafast PM fiber ring laser mode-locked by nonlinear polarization evolution with short NPE section segments

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Abstract: We demonstrate a nonlinear polarization evolution (NPE) mode-locked polarization maintaining (PM) Yb-doped fiber laser with short NPE section segments by setting proper splicing angle. With a theoretical analysis, we propose that an appropriate deviation splicing angle exists to maximize the adjustable range of transmission modulation. The simulation results are highly consistent with theoretical conclusions. Experimentally, using the optimal splicing angle predicted by the theoretical calculation, we have achieved an environmentally stable mode-locking fiber laser at 111-MHz repetition rate with corresponding pulse energy of 0.47 nJ. Additionally, the noise performance of this PM fiber laser is characterized. The measured RMS timing jitter and amplitude noise are 6.41 fs and 0.0052% respectively (1 kHz-10 MHz), which are competitive to the low phase noise performance of the typical fiber laser.

OCIS codes: (140.4050) Mode-locked lasers; (140.3510) Lasers, fiber; (060.2420) Fibers, polarization-maintaining; (060.2320) Fiber optics amplifiers and oscillators.

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1. Introduction

Over the past decades, passively mode-locked fiber lasers have been extensively applied in many fields such as the material processing, frequency metrology, pure microwave generation, and THz generation. Typically, the intrinsic saturable absorbers (the semiconductor saturable absorber mirrors, carbon nanotubes and graphene), and additive pulse mode-locking schemes [1, 2], are two main strategies to achieve mode-locking in fiber lasers. The NPE mode-locking technique is a prominent additive pulse mode-locking scheme. And it has been widely used in ultrashort pulse generation since the early 1990s [3, 4]. Although the NPE fiber laser has shown its advantages in the damage threshold, response time, and intrinsic noise, the primary drawback of this technique is sensitive to environmental fluctuation. One effective solution to eliminate the environmental instabilities and extend the laser applications to beyond laboratory environments is to replace the single-mode fiber by PM fiber.

Schemes to achieve the NPE mode-locked laser in the PM fiber have been refined for years. The proposed schemes can be easily classified into Fabry-Perot type cavity and ring type cavity. In Fabry-Perot cavities, the birefringence effect is compensated by the Faraday mirror (FM). Fermann et al. presented a linear cavity based on a section of a high birefringence fiber, which produced 360-fs soliton pulses at a 27-MHz repetition rate by placing the fiber between a Faraday rotator and an FM [5]. Nielsen and Keiding reported the generation of a noise-like pulse by using an angle splicing method to obtain unequal intensity, and an FM to replace the reflecting mirror in the linear cavity [6]. Boivinet et al. presented a ~17.8-ps 948-kHz pulse generation from a linear cavity with the cavity length of more than 100 m by using an FM [7]. However, using an FM to compensate the walk-off effect is an invalid solution in ring resonators. Recently, a cross-splicing method have been proposed to compensate the group velocity mismatch introduced by the birefringence fiber [8]. Combined with the prepared elliptical-polarization-state light, an NPE mode-locking laser was achieved, which generated a dissipative soliton with a repetition rate of 43.8 MHz with a 460-mw pump power. In 2017, Jan Szczepanek et al. proposed an all-PM-fiber laser at a repetition rate of 20.54 MHz [9]. An all-fiber ring cavity, where NPE formed in a three-piece fiber, could deliver stable pulse trains in the range of pump power range of 280-340 mW. However, no detailed analysis of the splicing angles are presented in this article, which is very important to the NPE section. So far, most schemes have been modestly successful, but all of them need relative long NPE section segments, which impact the stability of the laser. Therefore, there is no report on a repetition rate above 100 MHz in such schemes.

In this letter, we demonstrate an ultrafast PM fiber ring laser mode locked by NPE with a 111-MHz repetition rate in the short NPE section segments. With a theoretical analysis, we present an appropriate deviation splicing angle is exist to maximize the adjustable range of transmission modulation. The simulation results are highly consistent with theoretical conclusions. Experimentally, using the optimal splicing angle which predicted by theoretical calculation, an environmentally stable mode-locking fiber laser is achieved. The measured RMS timing jitter and amplitude noise are 6.41 fs and 0.0052% respectively (1 kHz-10 MHz).

2. Theoretical analysis

A typical NPE mode-locked fiber ring laser should include three key parts: the polarizer, Kerr medium and analyzer. Figure 1(a) shows one of the nonlinear Mach-Zehnder interferometer [10] where the Kerr medium is consisted of the PM fiber segments.
In this structure, the polarizer can be implemented by a quarter wave plate [8] or setting splicing angle before the Kerr medium [9]. Considering that the polarization states change periodically in effective beat length, the polarizers in both methods are basically used to make unequal intensity along two orthogonal axes. We choose the latter for demonstration purposes. The amplitudes of the pulses along the two axes can be described as 
\[ A_x(z,t) = A(z,t)\cos \theta, \quad A_y(z,t) = A(z,t)\sin \theta. \]

The Kerr medium is advised to use the scheme of three-fiber segments to compensate for the group velocity mismatch, which makes the lagging pulse affected by both the rising and falling edge of the leading pulse [9]. The difference in the nonlinear phase shifts of the two orthogonal components is usually used to characterize the NPE effect, namely the nonlinear phase bias (NPB). It has been successfully deduced in birefringent fibers when the pulse width is longer than 100 ps [11, 12]. However, when the pulse width is as short as several picoseconds, the walk-off effect cannot be ignored, and the phase equation can be expressed as Eqs. (1) and (2). \( n_2, k_0, \phi_x, \phi_y, n_x \) and \( n_y \) are the nonlinear refractive index coefficient, propagation constant, phases and refractive indexes of the two orthogonal axes [2]. The coefficients of the self-phase modulation \( (\alpha(z,t) \text{ and } \alpha'(z,t)) \) and cross-phase modulation \( (b(z,t) \text{ and } b'(z,t)) \) represent that the walk-off induced changes are recorded at any position. In the scheme of three-fiber segments, the pulse is symmetrically distributed along the fibers. The coefficients of the two orthogonal axes are equal after summation if the envelope shape variation is neglected, and the NPB can be expressed as Eq. (3). Accordingly, the relationship between the deviation angle \( \theta \) and the NPB can be shown as the black line in Fig. 1(b) black.
line. With the increasing of intensity difference between two orthogonal axes, more NPB is also accumulated.

\[
\phi_i (L) = n_r k_0 L + \pi \left( \sum_{\ell=0}^{\infty} |a(z, t)|^2 + \sum_{\ell=0}^{\infty} |b(z, t)|^2 \right) k_0 L. \tag{1}
\]

\[
\phi_j (L) = n_r k_0 L + \pi \left( \sum_{\ell=0}^{\infty} |a'(z, t)|^2 + \sum_{\ell=0}^{\infty} |b'(z, t)|^2 \right) k_0 L. \tag{2}
\]

\[
\Delta \phi_{el} = \pi \left( \sum_{\ell=0}^{\infty} |a(z, t)|^2 - \sum_{\ell=0}^{\infty} |b(z, t)|^2 \right) \left| A(t) \right|^2 k_0 L \cos(2\theta). \tag{3}
\]

The analyzer is used to select a specific polarization state to form the generation of stable pulse train. It can be realized by setting splicing angle between PM fiber segments [9], or using the combination of wave plates and PBS [8]. We chose the latter for its flexibility. The transmittance of the interferometer can be calculated by Jones matrix method as shown in Eq. (4). The slow varying amplitude envelopes of the output electric field have the form

\[
E_{\text{out}} = J_r R_f \rho \phi R_f \psi \rho J_r R_f E_{\text{in}}, \]

where \(\theta, \phi, \phi, \psi\) are the deviation angle, phase of pulse, angles of half wave plate and quarter wave plate [13]. Figure 1(c) shows the transmission while the NPB varies from \(-10\) to \(10\) rad at different deviation angles. We find that the difference of the maximum and minimum transmission is relevant to the deviation angle, as shown in Fig. 1(d). It represents the adjustable range of the transmittance with the fixed NPB.

In combination with the relationship between NPB and deviation angle in Fig. 1(b), we can obtain the modulation range of the adjustable range varying with the deviation angle (Fig. 1(e)). In conclusion, modulation range at deviation angle of \(14^\circ\) to \(32^\circ\) (or \(59^\circ\) to \(77^\circ\)) is more suitable for obtaining the stable mode-locking pulses. Moreover, the optimal deviation angle is set at \(\sim 23^\circ\) (or \(\sim 68^\circ\)), according to the theoretical analysis.

\[
T = \left\{ \frac{1 - i \cos(\theta) e^{i\phi}}{2} \left[ \cos(2\phi)(1 + \cos(2\psi)) + \sin(2\phi)\sin(2\psi) \right] \right. \\
+ \left. \sin(\theta) e^{i\phi} \left[ \sin(2\phi)(1 - \cos(2\psi)) + \cos(2\phi)\sin(2\psi) \right] \right\}^2. \tag{4}
\]

3. Cavity design and numerical simulation

![Fig. 2. Schematic diagrams of the configuration. LD, laser diode; WDM, wavelength division multiplexer; YDF, Yb-doped gain fiber; C1, C2, collimators; Grating, reflection grating; PBS, polarization beam splitter; QWP, quarter wave plates; HWP, half wave plate; ISO, Isolator.](image)

Although the PM fiber is tolerable to random birefringence, the fiber length can be influenced by environmental disturbance. According to the above analysis, the stable mode-locked
pulses is sensitive to the fluctuations of the Kerr medium length. To minimize this impact, it is necessary to shorten the fiber length of Kerr medium as much as possible. The PM fiber ring laser was constructed as illustrated in Fig. 2. The polarizer is implemented by setting splicing angle of 23° (position 1). The scheme of three-fiber segments is adopted to be the Kerr medium, with length of 25cm, 50cm and 25cm respectively.

In order to verify the theoretical analysis, the configuration mentioned above is numerically simulated by solving the combining coupled Ginzburg-Landau equations [14]. The following parameters are adopted in our simulations: $\beta_2 = 0.0404 \text{ ps}^2 \text{ m}^{-1}$, $\gamma = 3 \text{ W}^{-1} \text{ km}^{-1}$ and the beat length $L_B = 0.6 \text{ cm}$, the bandwidth of the filter (The combination of a reflecting grating and a collimator) is 6 nm, and the total fiber length is 1.9 m. In order to control the loss of the cavity, a saturated absorption model is used instead of the analyzer model: $S=1-q_0/(1+P(\tau)/P_p)$, $q_0 = 0.15$, $P(\tau)$ is the instantaneous pulse power and $P_p$ is the pulse peak power. In this way the ultimate steady states at different deviation angles can be the same.

Fig. 3. The nonlinear phase shift along the fast and slow axis and NPB at the deviation angle of 3° (a), 23° (b) and 43° (c).

After about 200 cycles, the initial white noise evolves into the stable Gaussian pulse. Figures 3(a)-3(c) show the NPB and nonlinear phase shift along the fast and slow axis at different deviation angles in the Kerr medium. The nonlinear phase shift gradually increases along propagation in the fibers. But the NPB is decrease when the deviation angle changes from 3° to 43°. To further explain, the stable pulse at position 4 is extracted to pass through an analyzer. We define the transmissivity adjustable range as the range of the difference between the transmittance of the pulse center and edge. Obviously, it is closely related to angle of HWP and QWP. We calculated all the conditions (the angle of HWP and QWP varies from 0° to 180° at an interval of 1°) in these three cases of different deviation angles. The results show the case with the deviation angle of 23° has the maximum adjustable range (4%). In addition, more angles were investigated. Figures 1(b) and 1(e) shows the NPB and the adjustment range results at the deviation angles from 0° to 90° at an interval of 5°. The simulation results are highly consistent with theoretical conclusions.
For the sake of the pulse evolution characteristic, the proposed cavity is numerical simulated by the analyzer instead of the saturated absorption model. The angle of QWP and HWP are set as 57° and 70°. After about 500 cycles, the initial white noise evolves into the stable pulse train.

In the Kerr medium, the temporal and spectral profiles at position 1, 2, 3, 4 is shown in Fig. 4. As it can be seen in the diagram that when the pulses along the fast and slow axes are not completely overlapped in the time domain, their spectrum is asymmetrical. Besides, when the pulses coincides again, their spectral shape become different.

4. Experimental results

The laser is constructed as illustrated in Fig. 2. The pump source is a single-mode pigtailed laser diode emitting at 976 nm with a maximum output power of 500 mW. The pump lasing is launched through a WDM. A piece of 25-cm Yb-doped fiber (core absorption is 1200dB/m at 976 nm) is spliced at 23° to the pigtail fiber of the WDM. Two sections of single-mode PM fiber with length of 50-cm and 25-cm long are cross-spliced. The unidirectional running of the laser cavity is ensured by an isolator. The pulses are then aligned to slow axis of the PM fiber by adjusting the HWP before the grating. The combination of a reflecting blazed grating (groove density: 300 lines/mm) and a collimator serves as a Gaussian filter with 6-nm bandwidth central at 1030 nm. The zero-order diffraction light from the grating is used to characterize the orthogonal lasing from PBS port. All the passive single-mode PM fiber are PM980, which have normal group velocity dispersion. The total cavity length is 1.9 m, and the fiber length of Kerr medium is 1 m.
If wave plates are rotated to some appropriate degrees, a stable mode-locked pulse train can be obtained. The pump threshold to arouse mode locking is 203 mW, leading to 56 mW output power in PBS port and 8 mW in Grating port. When we gradually increase the pump power, the pulse train can still remain stable without polarization adjustment, and the output power and spectral bandwidths increase at the same time. But when the pump power is higher than 400 mw, the multy pulse or harmonic mode-locking can be observed [15]. In this case the shape of spectrum also changes. As it is shown in Fig. 5(b), the FWHM width of the pulse measured directly at PBS port is 1.9 ps, which gives a pulse duration of 1.32 ps (assuming the Gaussian pulse profile). These highly linear chirped pulses can be compressed to 192 fs with a grating pair. The output spectra is shown in Fig. 5(d). The central wavelength of the output pulse is 1029 nm, and 3-dB spectral bandwidths are 17.5 nm and 9nm in PBS and grating ports respectively. The measured results are in good agreement with the simulation temporal and the spectral profiles of the pulse (Figs. 5(a) and 5(c)). The spectral modulation from 980 nm to 1010 nm is regarded as the coherent coupling of spontaneous emission between the fast and slow axis, which reveals the essence of the additional pulse mode-locking. It can be explained via the linear phase term in Eqs. (1) and (2), where $k_0$ varies with wavelength.

The radio frequency (RF) spectrum centered at 111.087 MHz is shown in Fig. 6(a). A 70-dB peak-to-background ratio and a narrow spectral width indicate excellent pulse energy stability. The RF spectrum measured over 600 MHz range is shown in the insert of Fig. 6(a), consisting with the pulse-to-pulse interval of 9 ns.

We find that even a slight disturbance in Kerr medium can make the pulse train unstable, but laser will come back to stable mode-locking spontaneously when the disturbance stop in almost all cases. In other parts of the laser, the pulse can keep stable even the fiber is folded. As long as the group velocity mismatch is strictly compensated, the mode-locking state can always be reached in such scheme and be stable for days.

To investigate the impact of the environmental disturbance on the laser, phase noise measurements are recorded in free-running mode without any noise suppression. A part of the laser output from PBS port is detected by a photodiode, and then is measured by a signal source analyzer. The observed phase noise (PN) is shown in Fig. 6(b). The phase noise introduced by the environmental perturbation and cavity (between 100 kHz and 350 kHz) is between $-160$ and $-80$ dBc/Hz [16]. The relative intensity noise (RIN) is between $-150$ and
−120 dBc/Hz correspondingly in Fig. 6(c). The PN and RIN of the laser (see Figs. 6(b) and 6(c) blue line) are integrated in a frequency span from 1 kHz to 10 MHz. And the integrated PN is 1.46 mrad corresponding to the timing jitter of 6.41 fs, the integrated RIN is 0.0052%. Although the NPE section is sensitive to disturbance, we can still conclude that this construction has a strong resistance against the environmental noise and a great performance in both PN and RIN and is competitive to other low phase noise fiber lasers.

5. Conclusion

In summary, we have demonstrated a 111-MHz repetition rate ultrafast PM Yb-doped fiber laser mode locked by NPE at the pump power of 203 mW. With a theoretical analysis, we present an appropriate deviation splicing angle is exist to maximize the modulation of transmission. The simulation results are highly consistent with theoretical conclusions. Experimentally, using the optimal splicing angle which predicted by theoretical calculation, an environmentally stable mode-locking fiber laser is achieved. Besides, the noise characteristics of the laser is also studied. The integrated PN is 1.46 mrad from 1 kHz to 10 MHz corresponding to the timing jitter of 6.41 fs, and the integrated RIN is 0.0052%, which can be competitive to other low phase noise fiber lasers.

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