Low-noise compact fiber laser based on nonlinear polarization evolution in an all-polarization-maintaining figure-8 cavity

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We demonstrate an all-polarization-maintaining (APM) fiber mode-locked laser based on nonlinear polarization evolution (NPE). A well-designed Sagnac fiber loop is employed to establish the nonlinear polarization evolution process in a polarization beam splitter (PBS) figure-8 fiber laser. Nonlinear loss curves are calculated to verify the saturable absorption characteristic of this NPE-based APM oscillator. Then, we simulate the pulse propagation process in the cavity to demonstrate the pulse mode-locked formation. Finally, we also design a realizable compact scheme to further reduce noise disturbances, achieving a 101-fs mode-locked pulse train with a 0.3-mrad integrated phase noise and a 0.006% integrated relative intensity noise (RIN). This figure-8 fiber laser provides a new scheme for compacting low-noise compact APM fiber lasers based on the NPE mode-locked mechanism.

Keywords: ultrafast laser; fiber laser; polarization-maintaining.
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1. Introduction

Ultrafast fiber lasers have been widely used in scientific research and their use has accelerated the exploration of more applications outside the laboratory¹–⁴. In these applications of mode-locked fiber lasers, robustness is an essential parameter for assessing the performance of femtosecond pulses. External disturbances will change the index profile, the bending loss, and the effective length of optical fiber, directly affecting the operation and noise characteristics of ultrashort pulses. A polarization-maintaining (PM) fiber is applied in oscillators to resist environmental disturbances, such as mechanical vibration and temperature changes. Various robust PM fiber oscillators have been demonstrated employing different mode-locked technologies⁵–⁹. Real saturable absorbers and nonlinear magnifying loop mirrors are often used for achieving mode-locking in PM fiber lasers, whose nonlinear responses are separately achieved by material characteristics and nonlinear phase, leading to a rapid recovery time and a transient response. The nonlinear polarization evolution (NPE) mode-locked technique can flexibly adjust a polarizer to guarantee an easier mode-locked process, facilitating the development of femtosecond lasers in new wavebands¹⁰,¹¹. In general, NPE mode-locking is challenging in the birefringence fibers because polarization evolution will induce polarization mode dispersion (PMD), causing pulse walk-off in the time domain¹².

Controlling the PMD is a significant technical improvement in achieving PM fiber mode-locked lasers based on NPE. Initially, the Faraday mirror was used to compensate for PMD and to establish NPE in the PM-fiber laser¹³. Angled splicing and a Faraday mirror can also cancel the PMD and enable the NPE mode-locked fiber laser¹⁴,¹⁵. Recently, the cross-splicing method has been proposed to compensate for the PMD and to successfully realize NPE-based mode-locked fiber lasers¹⁶–²¹. Well-designed structures enable mode-locking in the all-polarization-maintaining (APM) fiber laser without polarization controllers¹⁷,²⁰. A typical cross-splicing fiber oscillator includes several PM fiber segments with calculated matching lengths. These two methods have the same principle but different effects. The first method with the Faraday mirror can completely cancel the PMD¹³–¹⁵. In recent work, NPE mode-locked fiber lasers in a linear cavity with the Faraday mirror have been demonstrated²²,²³. However, the cross-splicing fiber lasers are limited by the measurement accuracy and the fusion process because there is an irretrievable length error in the actual fiber segments. For example, in the references²⁰,
the length of the three optical fibers is challenging to control accurately for absolute PMD compensation. Under the condition of the fiber length mismatch, it is difficult to establish stable mode-locking, and non-uniform environmental disturbances to the fiber segments will give extra noises to the oscillator.

In this Letter, we demonstrate a new scheme for achieving an NPE mode-locked fiber laser in an APM-fiber structure. We consider how to achieve NPE in one PM fiber segment instead of several PM fiber segments spliced crossly. A compact fiber device consisting of a pair of polarization beam splitters (PBSs) and a half-wave plate is designed to form a polarization-dependent fiber loop, which avoids PMD and provides adjustable nonlinear polarization evolution. Comprehensive polarization evolution analysis and intensity-dependent nonlinear loss prove the operation of a polarization-dependent fiber loop as a saturable absorber. The characteristics of the stretched pulse fiber laser were investigated both experimentally and numerically. We show that a self-starting and environmentally stable mode-locked operation is achieved with a 101-fs pulse duration and a 98.9 MHz repetition rate. The laser performs low-noise characteristics with 0.3-mrad integrated phase noise and a 0.006% integrated relative intensity noise (RIN).

2. Principle

As we know, a typical coupler-based Sagnac fiber loop can split linearly polarized pulses into two opposite-direction propagating pulses. At equal-distance optical paths, this structure of the Sagnac loop offers two divided pulse trains with different nonlinear phases, mainly arising from the pulse energy and asymmetry of the loop. As shown in Fig. 1(a), if we can use a PBS to replace the fiber coupler, the NPE on the two cross-polarization pulse trains can be established in an APM Sagnac fiber loop. After propagating through a half-wave plate and PBS, the initial linearly polarized pulse train is split into clockwise (CW) and counterclockwise (CCW) beams. Then, the CW and CCW linearly polarized beams are separately coupled into both ends of a fiber loop along the slow axis. Although these two opposite-direction pulse trains propagate through the equal-distance optical paths, they also have different intensity-dependent nonlinear phases when the splitting ratio of the PBS is asymmetric. Due to these intensity-dependent nonlinear phases bias, a larger polarization variation is produced on the pulse peaks rather than on the pulse bases, which helps to achieve the NPE in the PM fiber. Then, the equal-distance optical paths guarantee that the temporal walk-off effect is avoided for these two pulse trains, providing a capacity to combine these two branches into one pulse train after propagating through the PBS again. As shown in Fig. 1(a), when the nonlinear phase bias is \( \pi \), the polarization will be exactly rotated by 90°. The Sagnac fiber loop plays an important role in the NPE section. Figure 1(b) shows the ideal polarization evolution at the pulse peak in the NPE-based laser. A polarization analyzer offers an intensity-dependent nonlinear polarized loss to the output pulse, establishing a similar saturable absorber mechanism. Then a polarization rotator adjusts the pulse polarization to meet the maximum transmission condition of the polarization analyzer, forming a polarization-selective laser resonator. As depicted in Figs. 1(c) and 1(d), in addition to the wave plates used in the NPE fiber lasers, well-designed PM fiber and Faraday rotator units can also be employed as effective polarization rotators. For example, in the all-fiber ring cavity\(^{[15,18]}\), a fiber isolator working on the slow axis is employed as the polarization analyzer while the PM fiber serves as a rotator.

3. Numerical Analysis

Figure 2 shows the schematic of the NPE mode-locked figure-8 fiber laser, consisting of a PBS-based single-direction-propagating (SDP) fiber loop, a half-wave plate, and a PBS-based opposite-direction-propagating (ODP) fiber loop. This half-wave plate between two fiber loops is employed to manage the splitting ratio of the right ODP Sagnac fiber loop, achieving an intensity-dependent NPE process. We notice that laser pulses can propagate through the left fiber loop with a polarization-selected clockwise direction while a \( \pi \) nonlinear phase bias is achieved in the ODP Sagnac fiber loop, achieving an intensity-dependent NPE process. We employed the same laser configuration and
parameters to ensure consistency between the experimental and numerical simulation. The cavity was structured with all-PM fiber components, including a 0.70-m erbium-doped fiber (EDF), a 1.20-m PM1550 passive fiber, and 0.1-m free-space, resulting in a 98.9-MHz pulse train generation. We did not manage the intracavity dispersion well, with a second-order dispersion coefficient of $\beta_2 = -21.6 \text{ps}^2/\text{km}$ for the passive fiber and $\beta_2 = +20.6 \text{ps}^2/\text{km}$ for the gain fiber. The simulation parameters were set as $n_2 = 3.60 \times 10^{-16} \text{cm}^2/\text{W}$, $A_{\text{eff}} = 78.50 \mu\text{m}^2$, small-signal gain $g_0 = 35 \text{dB/km}$, $\lambda_s = 1550 \text{nm}$, and $P_{\text{peak}} = 500 \text{W}$.

To further verify the intensity-dependent modulation of this NPE cavity, we calculate the correlation between the nonlinear loss and the nonlinear phase bias at different splitting ratios using the Jones matrix. $E_{\text{in}}$ and $E_{\text{out}}$ are electric fields before and after the isolator, respectively, and the propagation process in the cavity is described as

$$E_{\text{out}} = M_{\text{PBS}}M_{\lambda/2}M_{\text{loop}}M_{\lambda/2}E_{\text{in}},$$ \hspace{1cm} (1)

where $M_{\lambda/2}$, $M_{\text{loop}}$, and $M_{\text{PBS}}$ are Jones matrices of the half-wave plate, Sagnac loop, and the left PBS, respectively. The angle between the fast axis and polarization direction is $\alpha/2$, and the polarization accordingly rotates by $\alpha$. Therefore, $E_{\text{out}}$ can be calculated as

$$E_{\text{out}} = \begin{bmatrix} 0 & 1 \\ \sin \alpha - \cos \alpha & 0 \end{bmatrix} e^{i\phi_{\text{CW}}} \begin{bmatrix} \cos \alpha & \sin \alpha \\ \sin \alpha & \cos \alpha \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix},$$ \hspace{1cm} (2)

where $\phi_{\text{CW}}$ and $\phi_{\text{CCW}}$ are the phase shifts of the CW and CCW pulses in the Sagnac loop, respectively. To simplify the calculation, we assume that $\phi_{\text{CW}}$ is 0 while $\phi_{\text{CCW}}$ is equal to nonlinear phase bias ($\Delta \phi$). Then, the nonlinear loss can be described as

$$L_{\text{nl}} = 1 - \frac{|E_{\text{out}}|^2}{|E_{\text{in}}|^2} = 1 - |e^{i\phi}(\sin \alpha)^2 - (\cos \alpha)^2|^2.$$ \hspace{1cm} (3)

When the nonlinear phase bias is $\pi$, the loss in the SDP fiber loop can be minimized to 0 with a maximal modulation depth, which is the same as the analysis mentioned above. If the nonlinear phase bias is between 0 and $\pi$, the cavity has an equivalent nonlinear loss with saturable absorption, and the modulation depth is related to both $\Delta \phi$ and $\alpha$. According to Eq. (3), we simulate loss curves at $\alpha = 0^\circ$, $15^\circ$, $30^\circ$, $45^\circ$, $60^\circ$, $75^\circ$, and $90^\circ$, as shown in Fig. 3. It is noticed that the polarization rotates by $\alpha$ or $90^\circ - \alpha$, and the loss curves are overlapped. In this case, even the tiny $\Delta \phi$ also affects the modulation depth because of the equal initial energies of the CW and CCW pulses, which is similar to the traditional figure-8 laser.

To further characterize this NPE-based mode-locked laser, we preliminary demonstrate the mode-locked formation using numerical simulations based on the general nonlinear Schrödinger equation and the fourth-stage Runge–Kutta iterative method. As shown in Fig. 2, we set 5 locations (A, B, C, D, and E) to mark the isolator, the PBSs, and the EDF to analyze the pulse evolution. Also, we insert a constant loss of 20% to work as an output port (location O). Then, the nonlinear loss can be described as

$$L_{\text{nl}} = 1 - \sqrt{0.8|e^{i\phi}(\sin \alpha)^2 - (\cos \alpha)^2|^2.}$$ \hspace{1cm} (4)

Figure 4(a) shows the corrected nonlinear loss with an insert loss of 20%. It is noticed that the polarization rotates by $\alpha$ or $90^\circ - \alpha$, and the loss curves are not overlapped, producing a constant loss bias of 20%. Though all the cavity losses increase, the oscillator still has a similar saturable absorber mechanism. In the numerical simulation, the saturable absorber model is not included, and only nonlinear processes and polarization evolutions are considered in this simulation. Though the two PBSs are integrated into the fiber device, we set the equivalent fiber length of the BC (between B and C) as 0.04 m to distinguish their different functions. When $\alpha = 30^\circ$, the initial white noise evolves into a stable mode-locked pulse train after 600 cycles. The simulated evolutions of the pulse duration and the spectral width in the cavity are shown in Figs. 4(b) and 4(c). An initial pulse is split into CW and CCW pulses at position C. The two branches have different evolution processes in the asymmetrical Sagnac loop. The pulse durations are stretched and compressed under dispersion and nonlinearity effects. At position C, the two pulses are combined, and the combined pulse is not linearly polarized. Therefore, the pulse duration exists a step change at position B (left PBS), which verifies the function of the saturable absorption.
4. Experimental Results and Discussion

To experimentally verify the feasibility of this NPE-based mode-locking laser, an all-PM fiber laser is constructed to test the hypothesis of the NPE mode-locking. The oscillator consists of a fiber isolator, a laser diode, a wavelength division multiplexer (WDM), a piece of EDF, and a specially designed fiber coupler, as shown in Fig. 5(a). As we can see in Fig. 5(b), a pair of PBSs and a half-wave plate are integrated into the four-port fiber device to simplify the cavity. Moreover, a half-wave plate is inserted among two PBSs to realize any designed split ratio, which is a key point to achieving control of the nonlinear phase bias between the CW and CCW lights. The lengths of the EDF and passive fiber are 0.8 and 1.2 m, respectively. The WDM splits 20% of the CCW laser as an output port, corresponding to the designed constant cavity loss. Due to this integrated PBS-based fiber coupler, we can keep the intracavity fiber as short as possible and can ensure the potential for a high-repetition-rate ultrashort pulse. Though the APM fiber structure can guarantee a low-noise running condition, we also design a realizable compact scheme to further reduce noise disturbances, as shown in Figs. 5(c) and 5(d). Finally, this NPE-based mode-locking laser possesses the potential to achieve a small-volume low-noise turn-key APM femtosecond fiber laser.

Figure 6 shows the characteristics of this compact NPE fiber laser. With a 260-mW pump light at 976 nm, the laser can emit a pulse train with a 98.9 MHz repetition rate and a 5.2 mW average power. It is noticed that an ~0.6 m passive fiber is kept in the left fiber loop because of the limitations of fusion splicing technology. This fiber can be removed in theory if the effect of dispersion on mode-locking is not considered, and the repetition rate can be further improved. Figures 6(a) and 6(b) show the temporal electronic trace and radio frequency spectrum of the mode-locked pulses, respectively. The radio frequency...
Compared with cross-splicing, the method can completely avoid PMD. A new structured NPE fiber laser is designed based on the Sagnac fiber loop. The nonlinear loss function is verified by numerical calculation, and the formation of the mode-locking is demonstrated by theoretical simulation based on polarization evolution. We optimize the cavity and construct a compact NPE mode-locked fiber laser. The fiber laser enables high-repetition-rate pulse generation without extra phase bias. With 260 mW pump power, a pulse train with a 98.9 MHz repetition rate and a 5.2 mW average power is obtained. The pulse duration is compressed to 100 fs outside the cavity, and the APM laser performs low-noise characteristics with a 0.3-mrad integrated phase noise and a 0.006% integrated RIN. This APM oscillator based on NPE mode-locking can provide a new scheme for generating compact robust femtosecond lasers.

5. Conclusions

We propose an APM fiber laser based on NPE mode-locking. Compared with cross-splicing, the method can completely avoid PMD. A new structured NPE fiber laser is designed based on the

Fig. 7. (a) Measured single-band phase noise and (b) RIN of the repetition rate signal.

spectrum has a signal-to-noise ratio of 80 dB, which really corresponds to a low-noise working condition. The net dispersion in the cavity is anomalous, and we use an additional anomalous-dispersion fiber pigtail at the output port to compress the pulse duration. Due to the nonlinear effects in the fiber pigtail and the dispersion compensation fiber, the measured spectrum is broader than the simulated result, as shown in Fig. 6(c). These two spectrum profiles coincide well in the middle region, demonstrating that the experimental results are consistent with the simulation results. The measured spectral width is 30 nm, and the corresponding Fourier-transform-limited pulse duration is 100 fs. Figure 6(d) shows the autocorrelation measured by a frequency-resolved optical gating, and the Gaussian pulse duration is 101 fs, which is close to the Fourier-transform-limited pulse duration.

To characterize the noise of the generated ultrashort pulses, we measure the single-band phase noise and RIN of the repetition rate signal, as shown in Figs. 7(a) and 7(b), which can further assess the noise characteristics. The phase noise and RIN profile steeply rise with an offset frequency range of 10–100 Hz because the free-running mode-locked laser is mainly disturbed by the environmental noise. The integrated phase noise is 0.3 mrad in the 10 Hz–10 MHz range, and the integrated RIN is 0.006%. The levels of both the phase noise and the RIN can confirm that this NPE-based mode-locked fiber laser is working at a low-noise condition. Additionally, the active phase-lock control can effectively suppress these low-frequency environmental noises, and noise characteristics can be greatly improved.

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References


