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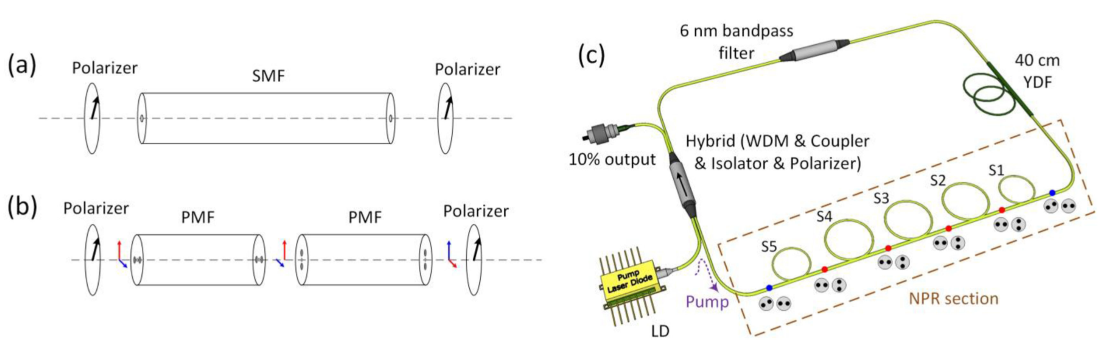


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# Nonlinear Polarization Evolution Mode-Locked YDFL Based on All-PM Fiber Cavity

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**Abstract:** Polarization-maintaining (PM) all-fiber cavity is always essential to realize stable ultrafast-pulse generation. With the help of five sections of PM fibers with independently specific splicing angles, we successfully obtain a femtosecond pulse output from a PM Ytterbium-doped fiber laser (YDFL) mode-locked by the nonlinear polarization evolution (NPE) technique. Using a hybrid component, the PM all-fiber cavity can be greatly simplified. Ultrafast-pulses with 24.5-MHz repetition rate, 20-nm spectral bandwidth, and 260-fs pulse duration after external compression can be steadily generated. In comparison with the non-PM fiber cavity, the proposed YDFL has excellent long-term environmental stability, making it ideal for various practical applications.

**Index Terms:** Fiber lasers, mode-locked lasers, ultrafast technology.

## 1. Introduction

Passively mode-locked fiber laser as a flexible source of ultrafast optical pulses has been widely investigated over past decades, due to its advantages of compact size, high stability, and simple configuration [1]–[3]. In addition, such fiber lasers also act as a convenient experimental platform for the investigation of nonlinear waves subject to periodic boundary conditions. In order to achieve the turn-key mode-locking, numerous techniques have been proposed, including the nonlinear polarization evolution (NPE) [4], [5], nonlinear optical loop mirror (NOLM) [6], nonlinear amplifying loop mirror (NALM) [7], semiconductor saturable absorber mirror (SESAM) [8], [9], as well as a variety of two-dimensional optical materials [10]–[12]. At the normal dispersion region where the mode-locked fiber laser usually generates dissipative solitons (DSs) for the ease of high power pulse generation, it is identified that real saturable absorber (SA) materials suffer from low energy damage threshold and the limited lifetime [13], [14]. Moreover, real SA materials normally have long recovery time, which restricts the generation of sub-picosecond pulses. Therefore, artificial SAs are commonly used in all-fiber cavities for the purpose of DSs generation. Meanwhile, considering practical applications of mode-locked fiber laser, polarization-maintaining (PM) all-fiber configuration is always essential and ideally desired to realize stable output and reliable operation. For mode-locked fiber lasers based on NOLM and NALM mechanism, it is relatively easy to build up the PM all-fiber configurations to realize the passively mode-locking [15], [16]. However, as for NPE, despite of its comprehensive phenomena and easy implementation, its mode-locked mechanism relies on the polarization evolution characteristics along the fiber cavity. Therefore, it is challenging to realize good long-term stability for NPE-based fiber laser. Recently, many techniques have been investigated to overcome the challenges. In 2007, Nielsen *et al.* firstly reported the NPE mode-locking in a PM all-fiber cavity [17]. They obtained a pulse duration of 5.6 ps at a repetition rate of 5.96 MHz and at an average power of 8 mW. The environmental stability was substantially improved by the use of a Faraday mirror (FM). However, the laser operated at the noise-like mode-locked regime instead of DSs. Wang et al. proposed a cross-splicing method to compensate the birefringence effect in a PM fiber and realized NPE [18]. Single pulse energy of 2.1 nJ was generated at pump power of 460 mW, while spectral bandwidth and pulse duration were 17.5 nm and 11.7 ps, respectively. Although mode-locking can be obtained with this method, the laser cavity includes some bulk optical components, instead of all-fiber structure, which may do harmful to its stability. To realize the PM all-fiber mode-locking, another approach was reported to use three sections of PM fibers formed by a sequence of the special angle splicing [19]. The fiber laser can generate DSs at a 20.54-MHz repetition rate with the de-chirped pulse duration of 150 fs and 0.85 nJ single pulse energy. However, such fiber cavity was not completely stable, as it was still sensitive to mechanical perturbations. Most recently, Zhou et al. reported DSs with long-term stability using NPE arising in an all-PM fiber laser [20]. The laser generated 2.9-nJ single pulse energy and 2.9-ps pulse width. The monitored optical power over 2 hours indicated the excellent mode-locking stability. However, the use of FM leads to the enhancement of structure complexity and laser cost, which may restrict its practical applications.

In this submission we design and experimentally investigate a compact and stable femtosecond fiber laser in the PM all-fiber cavity. With the help of five pieces of PM fibers with individually 30° or 90° splicing angles, NPE technique can be introduced within the PM fiber cavity in order to realize mode-locking. The mode-locked fiber laser operated at 1030 nm can generate DSs with pulse durations of 2.8 ps and 260 fs, respectively, before and after external compression. In particular, the mode-locking is self-started and immune to the environmental perturbations.

## 2. Experimental Setup

First, we illustrate the mode-locking principle of the NPE technique arising in the PM fibers, as shown in Fig. 1. Fig. 1(a) shows the typical NPE arising in a single mode fiber (SMF). Normally, a segment of linearly birefringent optical fiber is placed between two polarizers. Light with arbitrary polarization state incident to the configuration is transferred into a linearly polarized light by the polarizer before the fiber. When the light further propagates over the fiber, it will split into two components along two orthogonal axes of the SMF. After passing through the SMF, the state of polarization of light becomes elliptically polarized due to the intensity induced nonlinear birefringence. Therefore, the transmission of light through the configuration will become light intensity dependent, leading to an artificial SA effect. Based on similar principle, we can also form an artificial SA from the PM fibers, as shown in Fig. 1(b). If all PM-fiber sections are spliced with the matched slow axes, there may be no NPE phenomenon. However, for the case that a specific splicing angle is intentionally introduced between two sections of PM fibers, we can obtain two light components along two orthogonal polarization axes of PM fiber, as shown with blue and red arrows in Fig. 1(b). Equally, with the help of nonlinear birefringence, a light intensity dependent transmission can be realized. In order to compensate the group velocity mismatch between two

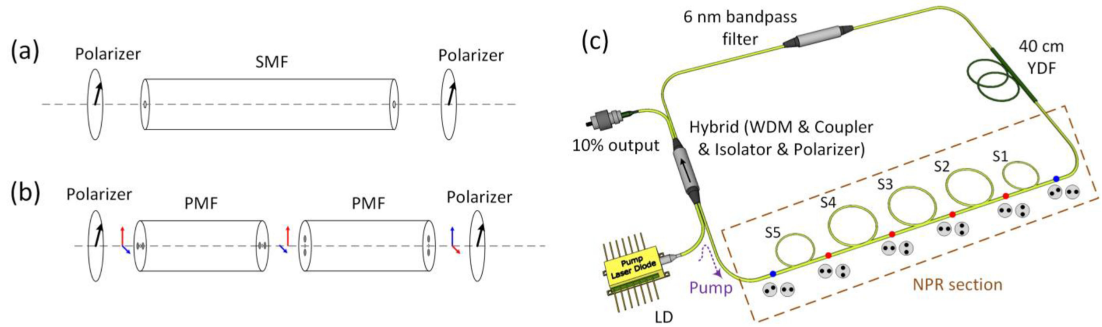


Fig. 1. Schematic of NPE arising in (a) single mode fiber, and (b) polarization maintaining fiber. (c) Schematic diagram of fiber laser cavity. The circles with dots represent orientations of polarization maintaining fiber. WDM: wavelength division multiplexer, YDF: Ytterbium-doped fiber, LD: laser diode, blue dot: splicing point with 30° splicing angle, red dot: splicing point with 90° splicing angle, and S1-S5: PM fiber sections.

orthogonal polarizations, normally more than one piece of PM fiber is necessary to ensure the same length of PM fibers which have orthogonal slow axes.

The setup of the proposed fiber laser is schematically shown in Fig. 1(c). A 976-nm laser diode (LD) with maximum output power of 400 mW acts as a pump source for a 40-cm PM Ytterbium-doped fiber (YDF, PM-YDF-5/130-VIII) via a 980/1035 nm reflection-type wavelength division multiplexer (WDM). An isolator is used to guarantee unidirectional propagation and suppress detrimental reflections. The laser output is achieved by a 10:90 optical coupler (OC). Note that the WDM, isolator and OC are integrated in a hybrid fiber optical component, which also contains a polarizer to ensure the fiber cavity operate under the fast-axis-blocked condition. This polarization filtration also introduces amplitude modulation to stimulate the mode-locking. An in-line optical bandpass filter with a central wavelength of 1030 nm and 3dB bandwidth of 6-nm is utilized to reduce the spectrum and realize the pulse shaping.

The NPE based mode locker is a significant part of the fiber cavity. Here, we use five PM fiber segments with 2.6-nm beat length to realize the NPE based mode locker, which are accurately measured and spliced together by a PM fusion splicer (Fujikura, PSM-45PM). The implementation of the multi-segment scheme contributes to the symmetrization of the spectral and temporal profile of the pulse, as well as an overall pulse shape improvement [19]. Theoretically, the symmetry increases with the number of segments, which would make the PM cavity more stable. However, considering the ease of implementation, we finally choose five fiber sections to construct the NPE section. For the first splice point, a 30° splicing angle between the slow axes of PM fibers is used to divide the intensity into 1:3 ratio along two orthogonally polarized axes. After the propagation over a 0.5-m PM fiber section (S1), the pulses arrive at second splicing point with 90° angle between two PM fiber sections. Then, the pulses propagate through three 1-m fiber section (S2, S3 and S4) as well as three splicing points with a 90° rotation. The last fiber of NPE section (S5) is 0.5 m with 30° rotation with respect to that of the hybrid component. In the NPE section, the total travel lengths of pulses along two orthogonally polarized axes are both 2 m, so that the linear phase shift can be accommodated, while only nonlinear phase shift contributes to the NPE based mode-locking

The NPE section is purposely placed right after the YDF where the average power and nonlinearity are supposed to be the highest inside the fiber cavity. All optical components are with PM fiber pigtails, which are fusion spliced, in order to construct a fiber ring cavity with total length of around 8.4 m. Apart from the NPE section, which is formed by PM fibers, this cavity only contains three optical components (YDF, hybrid and filter), which greatly enhances the laser simplicity and stability.

Along the output port, an optical spectrum analyzer (OSA, ANDO AQ6317B) with a resolution of 0.02 nm is used to monitor the optical spectrum. Meanwhile, a real-time digital oscilloscope

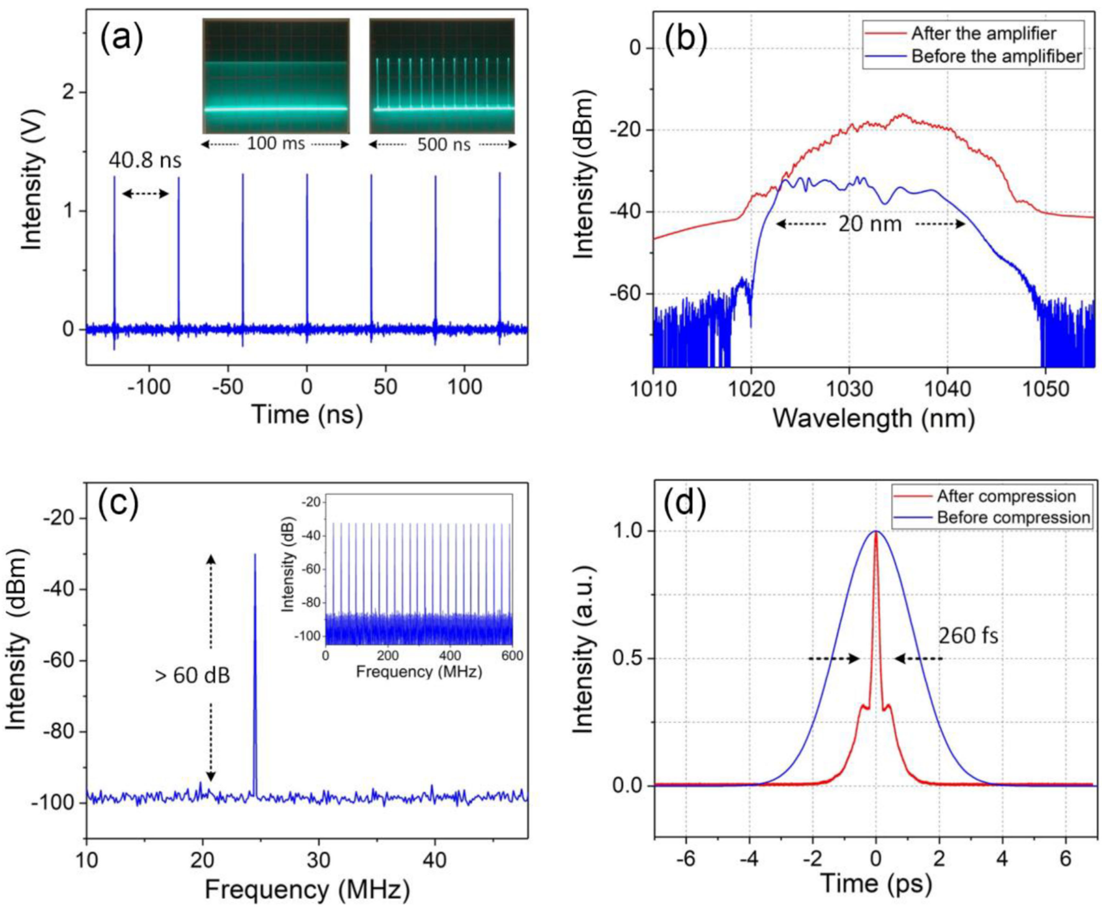


Fig. 2. Mode-locking at 200-mW pump power: (a) oscilloscope trace of the pulse-train, (b) optical spectrum, (c) RF spectrum, (d) autocorrelation trace before (blue), and after (red) compression.

(OSC, Agilent 54855A) with a 6-GHz bandwidth and 12-GSa/s sampling rate is used to characterize the pulses with the help of a 12.5-GHz InGaAs photodetector (EOT, ET-3500F). Moreover, the radio-frequency (RF) spectrum is characterized by a signal source analyzer (Agilent E4446A). Moreover, the autocorrelation traces of the pulses are measured with a commercial autocorrelator (Femtochrome, FR-103MN).

## 3. Results and Discussion

The continuous wave (CW) lasing starts with the pump power of 60 mW. When the pump power is increased to 200 mW, typical mode-locked pulses can be observed, as shown in Fig. 2, with an average output power of 4.5 mW. This relatively high mode-locked threshold and low output power can be explained from two aspects. On the one hand, the NPE section needs adequate power to accumulate the nonlinearity. On the other hand, as for the hybrid component, the OC is integrated after the polarizer. Thus, power is severely attenuated before the leaving cavity. The repetition rate of the pulse-train is 24.5 MHz, corresponding to the cavity length of 8.4 m, as shown in Fig. 2(a). We can estimate the single pulse energy to be 0.2 nJ. Two pictures of pulse-train on the analogue oscilloscope with 10-ms and 50-ns time ranges are presented in insets. Fig. 2(b) shows the typical spectrum of DSs at the normal dispersion region with 20-nm spectral bandwidth. The 1030-nm central wavelength is determined by the optical bandpass filter. It should be noticed the output coupler is placed after the gain fiber, indicating a spectral broadening inside YDF resulting from high

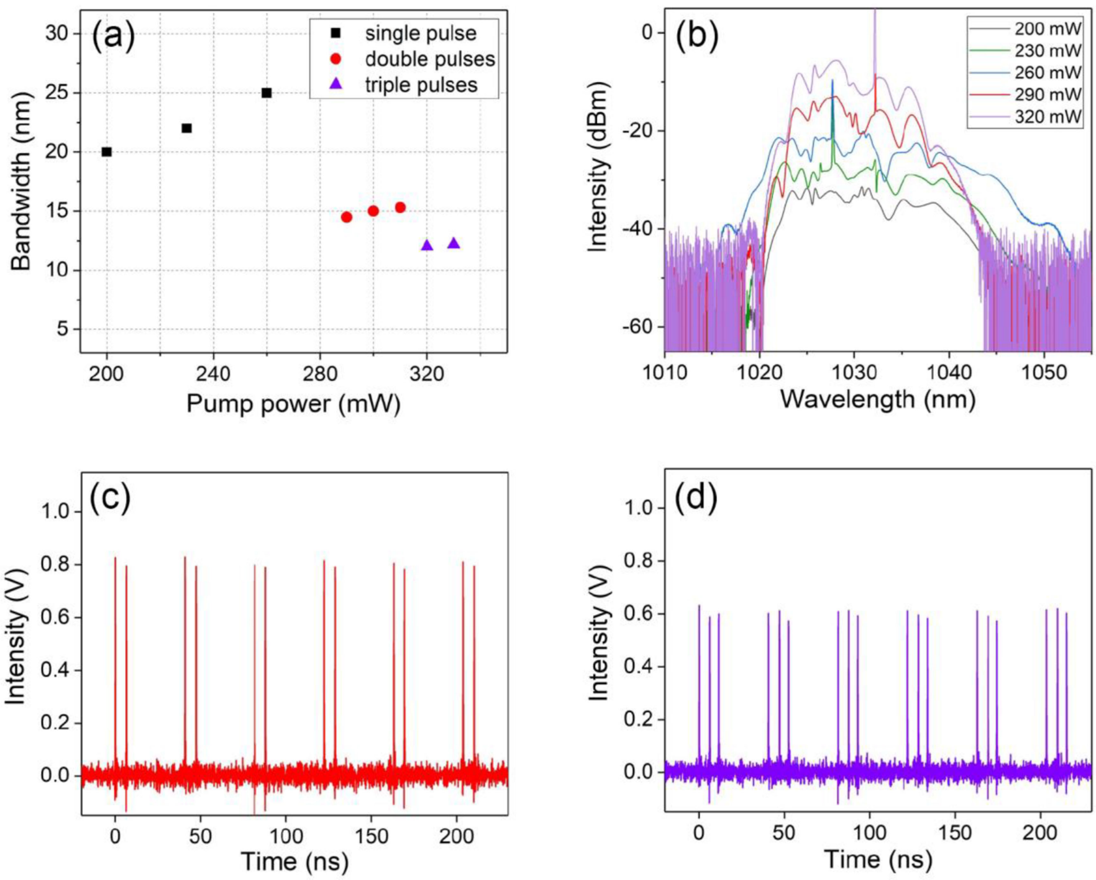


Fig. 3. Mode-locking with growing pump power: (a) spectral bandwidth at different pump powers, (b) optical spectra at pump power of 200 mW, 230 mW, 260 mW, 290 mW and 320 mW with 5-dB intensity off-set between each spectrum, (c) dual solitons pulse-train at 260 mW, and (d) triple solitons pulse-train at 320 mW.

nonlinearity. Fig. 2(c) illustrates the fundamental frequency with a signal-to-noise ratio (SNR) of more than 60 dB. No extra RF component is observed around the RF spectrum peak, indicating of the good quality of single pulse mode-locking condition. The inset shows the RF spectrum with 600-MHz frequency range. The all-normal dispersion cavity generates typical chirped pulses with a full-width at half maximum (FWHM) of 2.8 ps, referred from the autocorrelation trace of Fig. 2(d). With the help of an ytterbium-doped fiber amplifier (YDFA) to obtain sufficient energy, as well as a pair of diffraction gratings with 600 lines/mm to compensate the linear chirp, a compressed pulse with 260-fs pulse duration can be obtained. Note that, via optical spectrum from the laser, the transform-limited pulse duration can be estimated to be 180 fs. After passing through the optical amplifier, the spectrum shape may be slightly changed, corresponding to a new transform-limited pulse duration of 192 fs. Therefore, the measured 260-fs pulse duration indicates that the compressed pulses still contain nonlinear chirp which cannot be simply compensated by a grating pair.

When the pump power is further increased from 200 mW to 330 mW, the central wavelength stays unchanged. As for the 10-dB spectral bandwidth, it becomes wider first and drops back to 15 nm under the condition of 290 mW pump power, then turns wider again and falls to 12 nm at 320 mW. The entire process is shown in Fig. 3(a) and (b). These drops can be explained as the pulse breaking, due to the pulse peak clamping effect [21], [22]. Moreover, pulse broadening in the time domain gives rise to the narrow spectrum. Under the same principle, triple solitons can also be generated in case the pump power is further increased to 320 mW. Fig. 3(c) and (d) present

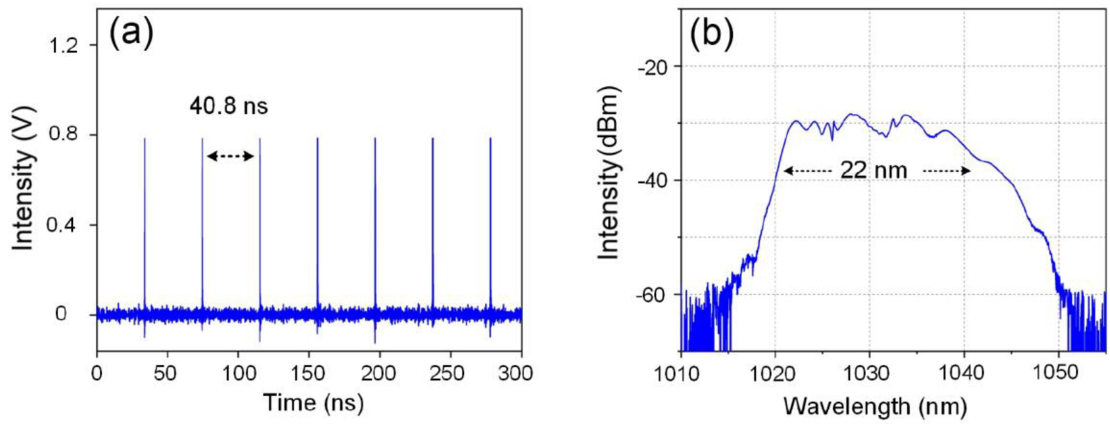


Fig. 4. Mode-locking with SMF-based PC: (a) oscilloscope trace of the pulse-train, and (b) optical spectrum.

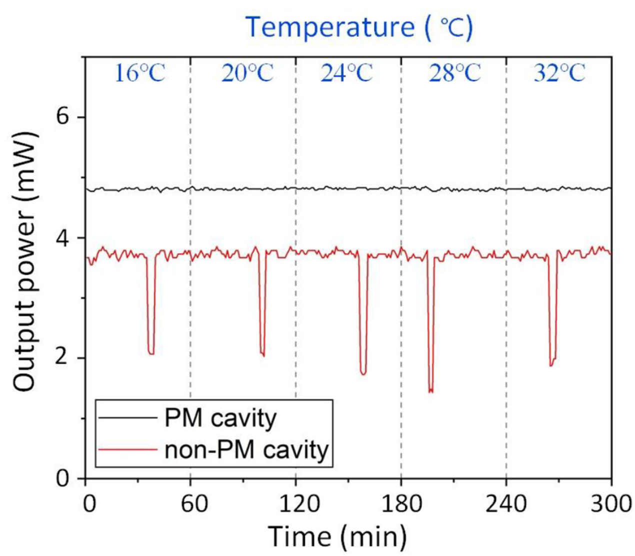


Fig. 5. Long-term stability measurement of PM (blue) and non-PM (red) cavity with increasing temperature.

the typical pulse-trains of dual solitons and triple solitons, respectively. If the pump power is further increased, the laser will become tremendously unstable and the mode-locking will no longer occur.

For the ease of performance comparison, we deliberately try to used 2-mm shorter fiber along one axis in the NPE section, and mode-locking would not be observed, which confirms the importance of linear phase compensation. Moreover, we also build up a non-PM cavity, where the NPE section is replaced by a SMF-based polarization controller (PC). The rest parts of two cavities are also built with the same components. In such case, based on normal NPE technology, mode-locking is convenient to realize as long as the PC adjustment is implemented. The mode-locked temporal and spectral results are shown in Fig. 4. The new pulse-train also has 24.5-MHz repetition rate while the 3dB spectral bandwidth becomes 22 nm. Due to the use of SMF, the environmental stability becomes worse as the cavity is sensitive to mechanical perturbations and temperature change. To compare the stability of PM and non-PM cavity, we repeatedly monitor the output power in 5 hours when the room temperature is deliberately varied from 16 °C to 32 °C, as shown in Fig. 5. For the PM cavity, it can always maintain the mode-locking operation during the temperature variation, and the power fluctuations are less than 1%. However, for the non-PM cavity, the mode-locking operation only maintains a short time and easily degrades to the CW output with an obvious power drop. Through the PC re-adjustment, the fiber laser output can recover to the mode-locking state but again become a CW output with the temperature variation. Therefore, we can conclude that benefiting from the all-PM fiber configuration, once the mode-locked operation is established, the PM cavity can resist the environmental perturbation. Moreover, the mode-locking is self-started every time once we kick off the pump driver.

## 4. Conclusion

We demonstrate a simple and compact PM all-fiber femtosecond laser source. Based on the NPE technique, environmentally stable mode-locking is achieved. The mode-locked fiber laser operates at 1030 nm with 20-nm spectral bandwidth and generates DSs with de-chirped pulse duration of 260 fs. The mode-locking is self-started and immune to the environmental perturbation. Therefore, we believe that such a femtosecond laser source is an ideal alternative for various practical ultrafast applications.

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