Timing-Jitter Reduction by Use of a Spectral Filter in a Broadband Femtosecond Fiber Laser

Xing Li, Weiwen Zou, *Senior Member, IEEE*, Kan Wu, and Jianping Chen

***Abstract*— We demonstrate an experimental reduction of timing jitter in a nonlinear-polarization-evolution-based passively mode-locked fiber laser. This laser operates on the stretched pulse regime at 201 MHz repetition rate. By incorporating a proper bandpass filter (BPF) into the cavity, the effect of the BPF on pulse output characteristics is investigated. The timing jitter of the output pulse is reduced significantly from 29.9 to 17.4 fs (both integrated within 1 kHz–10 MHz) and the full-width at half-maximum is >60 nm. This high repetition rate, low timing jitter, broadband fiber laser could be an excellent candidate for high-speed, and high-resolution photonic analog-to-digital conversion system.**

***Index Terms*— Fiber laser, mode-locking, ultrafast, band pass filters.**

I. INTRODUCTION

HIGH repetition rate, low timing jitter Er-doped fiber lasers are desirable for many applications in femtosecond laser frequency comb generation for frequency metrology [1], ultralow phase-noise microwave signal generation [2], and ultrafast optical sampling [3]. For applications such as high-speed high-resolution photonic analog-to-digital conversion (PADC) based on optical wavelength division multiplexing (WDM) technique [3], [4], the output spectrum of the fiber laser should be sliced to tens of channels. The fundamental repetition rate and the spectral width determine the sampling rate of the system. Hence optical spectrum wider than 50 nm is highly desired. In addition, the timing jitter is the key parameter deciding the effective number of bits (ENOB) of the PADC system and lower timing jitter could provide more precise PADC system [4].

Many theoretical and experimental studies on the pulse timing jitter characteristics of the mode-locked lasers have been proposed. Haus and Mecozzi proposed an analytical theory of timing jitter in mode-locked soliton pulse lasers [5]. Further improvement of this theory was used to evaluate the timing jitter of various other mode-locked lasers [6]–[8]. Based on the above theory, several experimental methods have been demonstrated to reduce the timing jitter of mode-locked fiber laser, such as adopting the phase-locked loop (PLL) to control the cavity length or pump power fluctuations [9]–[12], introducing an active intracavity phase modulation [13], optimizing the intracavity dispersion or the intracavity loss [14], [15], or employing spectral filtering effect [16], [17]. However, there is still one issue to be solved. The output optical spectrum is fairly narrow in most lasers although the timing jitter has been greatly improved. As well known, nonlinear polarization evolution (NPE) with intracavity polarizing elements is promising to generate ultrashort pulses with high fundamental repetition rates due to large modulation depth and rapid saturation absorption mechanism [18]–[20]. Besides, the timing jitter of NPE based lasers has also been proven to be very low under soliton regime [21] or self-similar regime [22].

In this letter, we experimentally demonstrate a reduction of timing jitter of a NPE based passively mode-locked fiber laser with a broadband spectrum by use of an intracavity BPF. This laser operating on the stretched pulse regime was capable of generating femtosecond pulse trains with repetition rate greater than 20 MHz and full width at half maximum (FWHM) of 148 nm [23]. When a proper BPF is employed into the laser's cavity, the FWHM is 61.4 nm and the pulse duration is 73.9 fs. Significant reduction of the timing jitter from 29.9 fs to 17.4 fs is successfully achieved. Furthermore, the effect of BPF on other pulse characteristics of the laser is essentially studied. This broadband ultrafast fiber laser with high repetition rate and low timing jitter is desirable for many applications, including femtosecond laser frequency comb generation for optical distance measurements, ultra-low phase noise generation of radiofrequency and microwave signals, and high-speed, and high-resolution optical coherence tomography [24]–[26].

II. PRINCIPLE AND EXPERIMENTAL SETUP

As shown in Fig. 1, the femtosecond pulse fiber laser investigated in this letter is a typical passively mode-locked ring fiber laser based on NPE [19]–[22]. Dispersion and nonlinearity management is applied so that the net GVD of the laser cavity is managed to near-zero at 1550 nm [23]. The commercially available BPF (Lattice Electro Optics, 1550F10-10) with 40-nm bandwidth, 60-% transmittance and 1550-nm center wavelength is sandwiched between the polarization beam splitter (PBS) and isolator to improve noise

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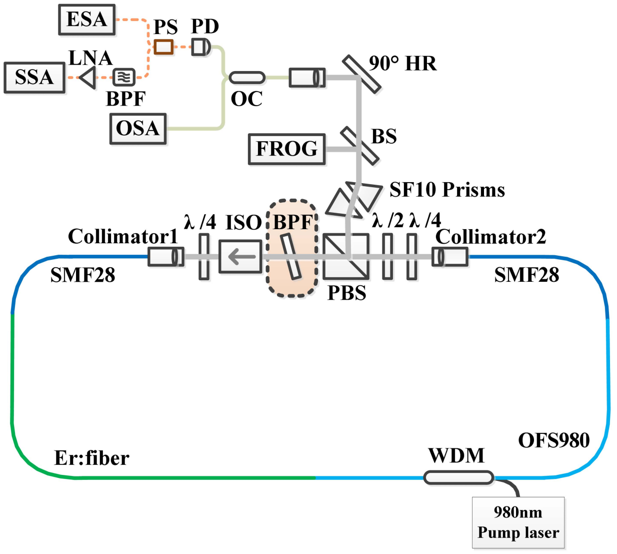


Fig. 1. Configuration of the fiber laser and its measurement setup. PBS, polarization beam splitter; ISO, isolator; $\lambda/2$, half waveplate; $\lambda/4$, quarter waveplate; WDM, wavelngth-division multiplexer; BPF, bandpass filter; OC, output coupler; HR, high reflector mirror; PD, photodetector; PS, power splitter; LNA, low-noise amplifier; ESA, electrical spectrum analyzer; SSA, signal source analyzer.

performance of the laser. The pump power is fixed at 700 mW in the following experiment.

To systematically investigate the pulse characteristics of the laser, we configure the following measurement setup. The output pulse is split into three branches by using a beam splitter and a fiber coupler. The first branch is used to measure the frequency-resolved optical gating (FROG) trace of output pulse via a commercial FROG (Grenouille & Frog15-40) and the second to monitor the optical spectrum by an optical spectrum analyzer (Yokogawa AQ6370C, resolution 0.02 nm). The third branch is detected by a 10 GHz photodetector (EOT, ET-3500F) and split into two arms by a power splitter (PS). One arm is connected with an electrical bandpass filter (K&L 5B120-1550/T200, 1.55 GHz, 200 MHz) and a low-noise amplifier (Cernex CBL01023805RX, 13.5 dBm output power), which is measured by a signal source analyzer (Agilent 5052B) for phase noise characterization detection. The other is used for RF spectrum measurement via an electrical spectrum analyzer (R&S FSUP50).

III. Results and Discussion

We investigate the general characteristics of the NPE based mode-locked fiber laser without and with the BPF in the cavity. The dashed curve in Fig. 2(a) depicts the optical spectrum of the laser without the BPF, providing the center wavelength of 1562 nm and the full width at half maximum (FWHM) of 148 nm [23]. The RF spectrum of the fundamental mode beat is shown in Fig. 2(b) with a signal-to-background ratio of 85 dB at a resolution bandwidth of 300 Hz. Compared in Figure 2(a), the optical spectrum of the output pulses with 40 nm BPF becomes non-flat. The central wavelength moves towards 1550 nm and the FWHM is reduced to 61.4 nm. The spectrum around 1530 nm decreases seriously when compared to that without the BPF. There are two reasons. First, the incorporating of a BPF increases the entire insertion loss of the laser cavity for any wavelength (including 980 nm). Second, the ground state absorption in the gain fiber was not fully stimulated by 980 nm pump light suffering the above insertion loss. The other pulse output characteristics are also modified by the BPF. Figure 2(c) illustrates the RF spectrum when the BPF is employed, displaying a noise suppression of greater than 90 dB. It verifies a clean, single-pulsing mode-locked state and also proves a better improvement of the relative intensity noise (RIN). It is noted that the fundamental frequency slightly decreases, which is attributed to the elongated optical path by the BPF.

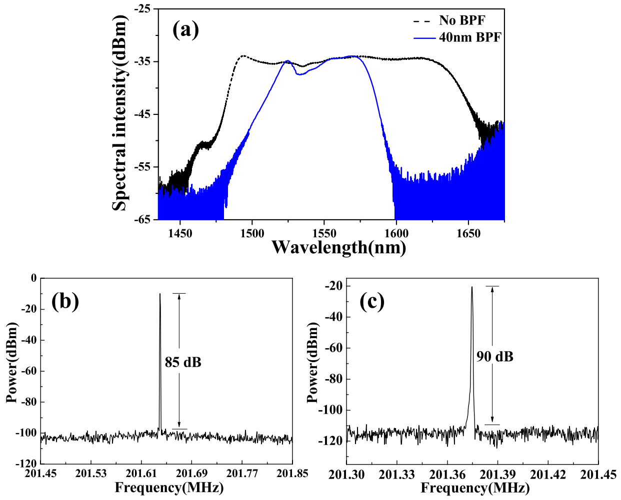


Fig. 2. (a) Spectrum of the output pulses without and with the BPF in the laser cavity. RF spectrum of fundamental mode beat at a resolution bandwidth of 300 Hz without inracavity BPF (b) and with 40 nm BPF (c).

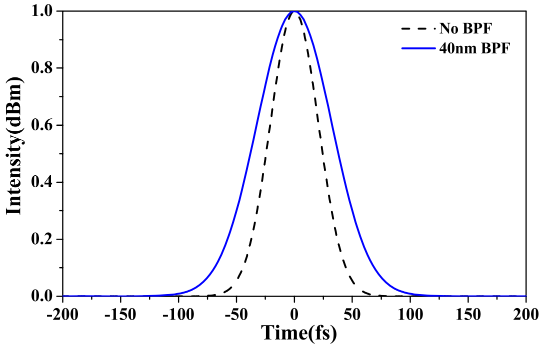
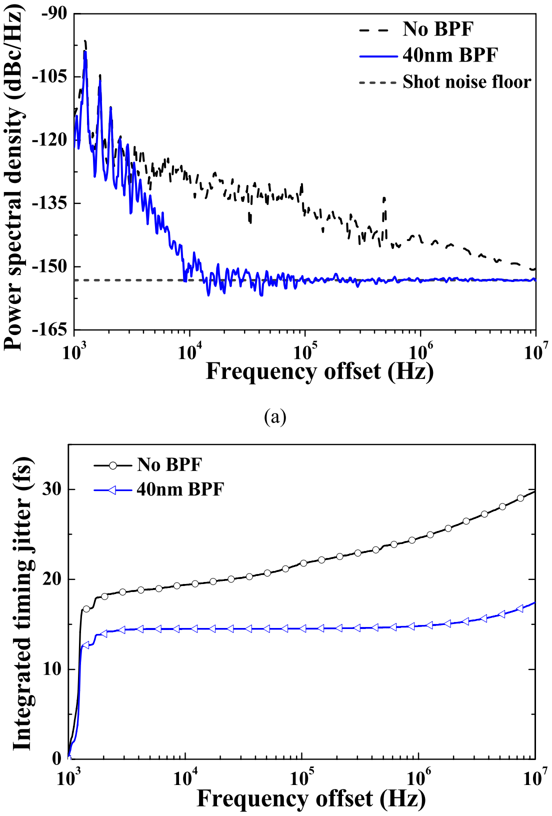


Fig. 3. Temporal waveform of the direct output pulses without and with the BPF.

Figure 3 depicts the temporal waveform of the pulses when the BPF is employed. For clear comparison, the pulse intensity of the output pulses without the BPF in the cavity is also plotted. With the BPF, the output pulse duration is increased from 49.1 fs to 73.9 fs while the corresponding time-bandwidth product is decreased from 0.908 to 0.567. This is because the central wavelength of the spectrum shifts to 1550 nm where the net GVD is managed to near-zero so that the output pulses contains more negligible dispersion chirp.



(a)

(b)

Fig. 4. Single sideband phase-noise power spectral density (a) and integrated timing jitter (b) without and with BPF. The gray dashed line indicates the shot-noise floor.

To investigate the timing jitter characteristics, we measure the power spectral density (PSD) of the single sideband phase noise at the 8th harmonic of the laser (i.e. 1.61 GHz) with and without the BPF in the cavity, which are compared in Fig. 4(a). The PSD shows approximately -10 dB/decade decrease in power from -95 dBc/Hz to -150 dBc/Hz within the offset range from 1 kHz to 10 kHz with the BPF in the cavity. Beyond the 10 kHz, the PSD gets saturated (see gray short-dash curve in Fig. 4(a)). It is due to the shot noise floor of the PD, which is approximately calculated to be about -153 dBc/Hz according to the following equation [27]:

$$L_{\phi}^{shot} = 10\log\left[\frac{e i_{avg} R}{P_{rf}}\right] \tag{1}$$

where $e = 1.6 \times 10^{-19}$ C is the elementary charge, $i_{avg} = 0.44$ mA is the average photocurrent created by the incident optical power of 1 mW, R is the load resistor of the PD (typically 50 Ω), $P_{rf} = -21.5$ dBm is the microwave carrier power of the 8th harmonic.

In order to calculate the timing jitter integrated from 1 kHz progressively to 10 MHz, we refer to the following theory [28]:

$$\sigma = \frac{1}{2\pi n f_R}\sqrt{2\int_{f_{min}}^{f_{max}} L(f)\,df} \tag{2}$$

where $n = 8$ is the number of the harmonic at which the phase noise is measured, $f_R = 201$ MHz is the fundamental repetition frequency, and $f_{min} = 1$ kHz and $f_{max} = 10$ MHz are the lower and upper limits of the integral, respectively. The calculated results are illustrated in Fig. 4(b). Thanks to the phase noise reduction at high frequency offset, the entire timing jitter is reduced significantly by 42% (from 29.9 fs to 17.4 fs) when the filter is imposed in the laser. We estimate the time jitter integrated up to Nyquist frequency (100.7 MHz) by extrapolating the PSD of the phase noise that is limited by the PD. It is 28 fs or 42 fs for the BPF is used or not used, respectively.

Referred to Haus and Paschotta's model [5], [8], the PSD of the phase noise induced by spontaneous emission noise (i.e. quantum noise) for stretched-pulse fiber laser can be expressed by

$$L(f) \propto \frac{\tau_p^2}{(2\pi f)^2} + \left(\frac{D_2}{f T_{rt}}\right)^2 \frac{\Delta\nu_p^2}{(2\pi f)^2 + \tau_{vc}^{-2}} \tag{3}$$

where D_2 is the total group delay dispersion per resonator round trip, f^{-2} is the inverse square of the noise frequency, T_{rt} is the round-trip time, τ_p is the pulse duration, and $\Delta\nu_p$ is the spectral width (i.e. FWHM). $\tau_{vc} = T_{rt}\left(\frac{\Delta\nu_f}{\Delta\nu_p}\right)^2$ is the filter time constant which can reduce the fluctuations of the central frequency by providing a "restoring force" for the mean frequency, where $\Delta\nu_f$ is approximately the BPF's bandwidth. The first term of Eq. (3) corresponds to the direct contribution to the PSD of the phase noise. The second term denotes the indirect contribution of quantum noise to the timing jitter by causing the fluctuations of the optical frequency mean position, which further couples with the intracavity chromatic dispersion.

For no BPF and the 40 nm BPF, the pulse duration τ_p increases from 49.1 fs to 73.9 fs, respectively. It means that the first term of Eq. (3) becomes slightly larger. However, the FWHM of the output pulse is reduced from 148 nm to 61.4 nm and the ratio of $\Delta\nu_f/\Delta\nu_p$ is decreased from $+\infty$ to 0.651, which leads to a decrease of τ_{vc} and an increase of the "restoring force". Thus, the PSD of the fluctuations of the optical frequency mean position is decreased. Additionally, the BPF shifts the central frequency of the output pulse to ~1550 nm, where the net cavity dispersion (D_2) is optimized to near-zero [23]. As a result, the timing jitter of the output pulse is effectively reduced because the left term of Eq. (3) increases slightly but the second term decreases significantly.

IV. CONCLUSION

We have experimentally demonstrated that the timing jitter of a broadband femtosecond pulse fiber laser is improved by use of an intracavity BPF. This NPE-based dispersion-managed fiber laser is capable of generating a broad spectrum with a fundamental repetition rate of 201 MHz. The laser performances without and with the BPF are essentially compared. When the BPF is employed, the timing jitter is reduced significantly by 42% from 29.9 to 17.4 fs (1 kHz-10 MHz) due to the spectral filtering effect, which weakens the fluctuations of the optical frequency mean position induced by the quantum noise. Experimental results are in good agreement with theoretical analysis. The FWHM of 61.4 nm is achieved. This high repetition rate, low timing jitter, broadband fiber laser could be an excellent seed source for the high-speed and high-resolution PADC system [4]. However, further efforts must be made to reduce the timing jitter of our laser at the low-frequency range by use of a good pump source and locking the repetition rate to an electronic oscillator with better long-term stability. In addition, the dependence of the laser output parameters (such as pulse duration, spectrum width, and timing jitter) on the intracavity location of the BPF should also be investigated to further optimize the laser output characteristics, which is now under study.

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