Few-femtosecond timing jitter from a picosecond all-polarization-maintaining Yb-fiber laser

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Abstract: We characterize the timing jitter of a picosecond all-polarization-maintaining (all-PM) Yb-fiber laser using the optical cross-correlation method. For the 10 MHz all-normal dispersion mode-locked laser with ~0.5 nm spectral bandwidth, the measured high-frequency jitter is as low as 5.9 fs (RMS) when integrated from 10 kHz to the Nyquist frequency of 5 MHz. A complete numerical model with ASE noise is built to simulate the timing jitter characteristics in consideration of intracavity pulse evolution. The mutual comparison among simulation result, analytical model and experiment data indicate that the few femtosecond timing jitter from the picosecond fiber laser is attributed to the complete elimination of Gordon-Haus jitter by narrow bandpass filtering by a fiber Bragg grating (FBG). The low level of timing jitter from this compact and maintenance-free PM picosecond fiber laser source at a low MHz repetition rate is promising to advance a number of femtosecond-precision timing and synchronization applications.

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References and links


1. Introduction

Passively mode-locked lasers can inherently generate optical pulse trains with extremely high periodicity. The theoretically predicted quantum-limited timing jitter from a standard soliton fiber laser is well below 1 fs above 100 kHz offset frequency [1, 2]. In recent years, timing jitter optimization in various passively mode-locked lasers has been the subject of intense study [3–16]. One straightforward way for timing jitter reduction is to shorten intracavity pulse duration because amplified spontaneous emission (ASE) noise directly adds to pulse train timing error with a quadratic dependence on pulse width. Record low timing jitter of less than 13 as have been demonstrated from a 10 fs Ti:sapphire laser [3]. An ASE induced center frequency fluctuation can also indirectly couple to timing jitter through non-zero cavity dispersion, which is known as the Gordon-Haus jitter [17]. By carefully balancing cavity dispersion, few tens of attosecond timing jitter has been achieved from a stretched pulse Er-fiber laser [4]. Particularly, it has also been shown, both theoretically and experimentally, that intra-cavity filtering can act as a restoring force to reduce the dispersion-induced timing jitter in passively mode-locked lasers [12–16].

The research on laser timing jitter has been mostly concentrated on femtosecond lasers, where the directly coupled timing jitter from ASE noise can be naturally minimized. Recently, there has been rapid progress in the development of alignment-free and turn-key operating passively mode-locked all-fiber lasers which emit transform-limited pulse duration in the picosecond regime [18–21]. Power amplification can be achieved by a following slab, thin-disk or rod-type fiber technology by preserving a low MHz repetition rate [22–25]. Femtosecond synchronization between such a high average power, MHz repetition rate picosecond laser source and other photonic or RF references enables a number of applications, such as mid-infrared (MIR) optical parametric chirped-pulse amplification (OPCPA) [24–28], high repetition rate free-electron lasers (FEL) [29, 30] and nonlinear bio-imaging [31–33]. For broadband MIR OPCPA, a promising layout makes use of a 1.55 μm Er-fiber seed and a high power picosecond laser working at 1.06 μm [27]. Active pump-seed pulse synchronization with femtosecond residual timing jitter is mandatory for an affordable MIR power fluctuation. In large scale FEL facilities, a picosecond laser is used to generate the electron bunch by photoemission from the cathode in the injector or to seed an OPCPA-based pump-probe laser system [24, 30]. The picosecond laser should be tightly synchronized with a remote optical master oscillator. For some nonlinear bio-imaging methods, such as stimulated Raman scattering microscopy, the generation of two synchronized trains of picosecond pulses with narrow bandwidth and independent tunability over a wide spectral range will be required, which is usually realized by synchronized two-color picosecond lasers with a phase-locked repetition rate [33–36]. In the above areas, minimizing the timing jitter in the picosecond laser oscillator sets a prerequisite for advancing the synchronization performance.

In this work, we study the timing jitter characteristics in picosecond all-fiber laser oscillators. An all-normal dispersion 10-MHz repetition rate, all polarization-maintaining (PM) mode-locked Yb-fiber laser with few picoseconds pulse duration is used for test. A self-started mode-locking is achieved with a semiconductor saturable absorber mirror (SESAM) and is stabilized by a narrow bandwidth fiber Bragg grating (FBG). An optical cross-correlation method [37] is employed for timing jitter characterization with sub-femtosecond temporal resolution, where a femtosecond stretched-pulse Yb-fiber laser serves as an optical...
reference. The characterized root-mean-square (RMS) timing jitter is 5.9 fs when integrated from 10 kHz to 5 MHz (Nyquist frequency) offset frequency. The experimental result is compared with noise theory of mode-locked lasers and a numerical model of intracavity pulse evolution in consideration of ASE noise. The comparison reveals a quantum-limited timing jitter dominated by the direct effect of ASE in the gain medium of the picosecond fiber laser. Timing jitter indirectly coupled through the large normal intracavity dispersion is completely suppressed by the FBG filtering.

2. Alignment-free all-PM picosecond fiber laser

The design for the picosecond all-PM fiber laser is shown in Fig. 1. The laser oscillator is based on a Fabry-Perot (FP) cavity configuration. A segment of 100 cm PM Yb-doped fiber with a pump absorption of 250 dB/m at 975 nm (Nufern, PM-YSF-6/125-HI) serves as gain medium, which is core-pumped by a 976 nm laser diode (LD) via a PM wavelength division multiplexer (WDM). A SESAM directly butt-coupled to the PM fiber is used as one end reflector of the FP cavity for self-started passive mode-locking of the fiber laser. It has a modulation depth of 33%, a relaxation time of 500 fs and a saturation fluence of 78 μJ/cm² (Batop, SAM-1064-50-500fs). A PM-FBG is used as the other end reflector. The FBG yields a Gaussian spectral filtering at a center wavelength of 1064.1 nm with a 3 dB bandwidth of ~0.5 nm. The laser consists of a total PM fiber length of ~10 m, which results in a large normal cavity round trip dispersion of + 0.46 ps² and a laser repetition rate of ~10 MHz. The laser works in an all-normal dispersion regime where the mode-locking is stabilized by the narrow bandpass filtering of FBG. The generated laser pulse train is coupled to the output by a 45:55 PM fiber coupler. The output port of the fiber laser oscillator is fused with an all PM fiber pre-amplifier. A PM fiber isolator (ISO) is installed between the laser oscillator and the preamplifier in order to avoid back-reflections. The collimated output from the PM fiber preamplifier is dechirped by using a pair of fused silica transmission gratings with 1200 lines/mm groove density. An optical spectrum analyzer (YOKOGAWA, AQ6370B) with a resolution of 0.02 nm is employed to record the output optical spectrum from the laser. The radio frequency (RF) spectrum of the laser pulse train is measured by using a high speed photo-detector (Thorlabs, DET10A/M) and an RF analyzer (Agilent, 8560EC). The direct output and the dechirped pulse duration is characterized by using a commercial optical autocorrelator (APE, PulseCheck).

Figure 2 shows the output characteristics of the picosecond all-PM fiber laser. The average output power of the laser oscillator is 0.5 mW at a 70 mW pump power. The measured optical spectrum is shown as the red solid line in Fig. 2(a). The central wavelength locates at 1064.10 nm and the 3dB spectral bandwidth is 0.3 nm. The first harmonic of the pulse train RF spectrum is shown in Fig. 2(b), which shows a pulse train repetition rate of 10.4 MHz. The 80 dB RF signal-to-background ratio at 10 Hz resolution bandwidth, shown in Fig. 2(b), indicates excellent output power stability by using an all-PM fiber laser design. The average output power after the pre-amplifier is 50 mW at a pump power of 350 mW. The optical spectrum of the amplified laser pulses is shown as blue solid line in Fig. 2(a). There is

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obvious spectrum broadening due to self-phase modulation (SPM) during power amplification in gain fiber. The measured autocorrelation trace of the amplified output laser pulse is shown as solid line in Fig. 2(c), which overlaps well with a Gaussian fitting (red dashed line). The full width at half maximum (FWHM) of the laser pulse is 6.63 ps assuming a Gaussian shape. The characterized pulse autocorrelation trace after dechirping is shown in Fig. 2(d). The dechirped pulse duration is 1.44 ps assuming a Lorenz pulse shape.

3. Timing jitter characterization of the picosecond all-PM fiber laser

As the most important parameter for high-precision synchronization applications, the timing jitter of the picosecond all-PM fiber laser is characterized by an optical cross-correlation method, where the picosecond laser under test (LUT) is optically heterodyned with an independent reference laser by using sum-frequency generation (SFG) in a piece of nonlinear crystal, as illustrated in Fig. 3. The LUT and the reference laser are shown in Fig. 3(a) and Fig. 3(b), respectively. The reference laser is a nonlinear polarization rotation (NPE) mode-locked femtosecond Yb-fiber laser with 156 MHz repetition rate. It works in a stretched-pulse regime with close-to-zero cavity dispersion, which characterizes only 0.3 fs timing jitter (when integrated from 10 kHz to 10 MHz offset frequency), as used in our earlier work [13]. Since the reference laser has negligible jitter compared to the picosecond LUT, the direct optical cross correlation between the two lasers yields an absolute measurement of the jitter of the LUT.

The output from the reference laser is dechirped to ~100 fs by a Gires-Tournois Interferometer (GTI) mirror pair. Pulse trains from the LUT and the reference laser after dispersion compensation are beam combined by a polarization beam splitter (PBS) and are directed to the optical cross-correlator. The design of optical cross-correlator is shown in Fig. 3(c). A type-II phase-matched beta-barium borate (BBO) is used for sum-frequency generation from the combined beams with orthogonal polarization. The sum-frequency signal is detected by a high-sensitivity photo-detector (Thorlabs, PDB210A). The inset in Fig. 3 shows the output from the optical cross-correlator as a function of the difference in time.
between the two laser pulses. The relative timing jitter between the two lasers is proportional
to the intensity fluctuations of the cross-correlation signal, particularly when the two pulses
are offset in time by 1/2 of the pulse width. This linear range, as indicated by a yellow line in
the cross-correlation trace, characterizes a timing error discrimination slope of 2.774 mV/fS.

![Experimental setup for timing jitter characterization based on optical cross-correlation
method. BBO: beta-barium borate crystal; DM: dichroic mirror; FFT: Fast Fourier transform;
GTI: Gires-Tournois Interferometer mirror; HR: high reflective mirror; PBS: polarization beam
splitter; PD: photo-detector; PI: proportional-integral servo controller; PZT: piezoelectric
transducer.]

In order to confine the timing jitter measurement of the LUT in the linear detection range
of the cross-correlation trace, the two lasers are synchronized by phase-locked loop (PLL).
The timing error signal generated by the optical cross-correlator is used to lock the repetition
rates of the two lasers by controlling the cavity length of the reference laser via actuating a
cavity mirror glued upon piezoelectric transducer. It is noteworthy that repetition rate of the
LUT is synchronized to the 1/15th harmonic of the repetition rate of the reference laser. The
residual timing jitter spectral density is jointly characterized by a fast Fourier transform (FFT)
analyzer (Stanford research systems, SR770) and an RF analyzer (Agilent, 8560EC), as
shown as the black solid line in Fig. 4. The integrated RMS timing jitter is plotted in the same
figure. The timing jitter spectrum is suppressed below 1 kHz offset frequency which
corresponds to the bandwidth of the PLL. The effect of PLL fades out at higher offset
frequencies and diminishes at 10 kHz. Offset frequencies above 10 kHz characterizes a −20
dB/decade slope up to 1 MHz, representing the intrinsic timing jitter spectrum of the free-
running picosecond all-PM-fiber laser. The timing jitter spectrum falls below detector noise
floor above 1 MHz offset frequency. The resulting RMS timing jitter is 5.9 fs when integrated
from 10 kHz to the Nyquist frequency of 5 MHz with a negligible noise floor contribution of
0.46 fs.

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Both the ASE noise and the laser intensity noise can be coupled to the pulse train timing jitter via intracavity pulse dynamics. In order to explore the origin of the measured timing jitter, we have characterized the spectral density of relative intensity noise (RIN) of the LUT, as shown in Fig. 5(a). The RMS RIN is 0.0184% and 0.0233% integrated from 10 Hz to 2.5 MHz from the laser oscillator and the preamplifier, respectively. The integrated RIN is comparable to those of typical fiber laser sources [38,39]. The RIN from laser oscillator can couple to pulse train timing jitter through Kerr nonlinearity with self-steepening effect, or through Kramers–Krönig-related phase changes depending on limited gain bandwidth [2]. Moreover, additional timing jitter can also be observed by using an optical cross-correlation method because intensity noise from laser preamplifier can add to the detected error signal through sum-frequency generation. The converted timing jitter from these processes are plotted in Fig. 5(b). There is minor contribution of intensity noise-coupled timing jitter to the measured timing jitter spectrum, indicating an ASE noise-limited timing jitter performance for this picosecond fiber laser.

Fig. 5. Relative intensity noise (RIN) coupled timing jitter. (a) Measured RIN spectra (top) and integrated RIN (bottom) at the output of laser oscillator and preamplifier. (b) Spectral density of RIN-coupled timing jitter via various mechanisms.
4. Numerical model of the picosecond all-PM fiber laser with ASE noise

In order to study the quantum-limited timing jitter characteristics from a dynamic point of view, a numerical model governing pulse evolution in the picosecond all-PM fiber laser in the presence of ASE noise from gain medium is built based on a modified Ginzburg-Landau equation [40]:

\[
\frac{\partial U}{\partial z} + \frac{i}{2} \beta_2 \frac{\partial^2 U}{\partial T^2} - \frac{\beta_3}{6} \frac{\partial^3 U}{\partial T^3} = \frac{1}{2} g U + i \gamma |U|^2 U + S,
\]

where, \( U = U(z, T) \) is the slowly varying amplitude of the pulse envelope in a moving coordinate, \( \beta_2 \) and \( \beta_3 \) are the second-order dispersion (GVD) and third-order dispersion (TOD) parameters, respectively, \( \gamma \) is the nonlinearity parameter and \( g \) is saturated gain coefficient, which is determined by \( g = g_0 \left( 1 + \frac{W_p}{W_{sat}} + \frac{(\omega - \omega_0)^2}{\Delta \omega^2} \right) \) by assuming a Lorentzian line shape, where \( g_0 \) is small signal gain, \( W_p \) is intracavity laser power, \( W_{sat} \) is gain saturation power, \( \omega \) is optical angular frequency, \( \omega_0 \) is central angular frequency and \( \Delta \omega \) is FWHM gain bandwidth. \( S = S(z, T) \) is the noise source term. Considering the white noise nature of ASE, the spectral characteristics of the Fourier transform of the noise term is given by [41]:

\[
\left\{ \tilde{S}(z, \omega)\tilde{S}(z', \omega') \right\} = \frac{h \omega}{2\pi} \frac{1}{1 + (\omega - \omega_0)^2 / \Delta \omega^2} \theta(e^{\omega_l} - 1) \frac{l}{\delta(z - z') \delta(\omega - \omega')},
\]

where \( \tilde{S}(z, \omega) \) is Fourier transform of \( S(z, T) \), \( h \) is Planck constant, \( l \) is gain fiber length and \( \theta \) is enhanced spontaneous emission factor for a quasi-three-level gain medium.

Modeling parameters are selected to be in accordance with experiment. The PM fiber has a GVD of 23,000 fs²/m and TOD of 70,000 fs³/m. The nonlinear coefficient of Yb-doped PM fiber and passive PM fiber are 4 W⁻¹km⁻¹ and 5.2 W⁻¹km⁻¹, respectively. The gain fiber has a FWHM gain bandwidth of 50 nm. The saturable absorber (SA) is modelled as an ideal fast absorber with an absorptance of 60% and a saturated power of 8 W. The PM fiber coupler has an output coupling ratio of 45%. Considering a linear cavity design, the coupler will introduce an extra loss of 45% due to the bidirectional pulse propagation. The FBG is modeled by a Gaussian shaped bandpass filter with 0.5 nm FWHM bandwidth centered at 1064.1 nm, which deviates from the gain peak wavelength of PM Yb-fiber (1036 nm) by 28.1 nm.

Firstly, we study pulse evolution in the PM fiber laser without ASE noise. The simulation starts from a white noise, which evolves into a stable picosecond pulse output after hundreds of cavity round trips. At an average saturated gain of \( g = 2.1 \) m, an output pulse energy of 35 pJ is obtained, which is the similar level with experiment. The stable intra-cavity pulse evolution in perspective of pulse duration and optical spectral width during one cavity round trip is depicted in Fig. 6. Overall, there is slight pulse width and spectral width change during one roundtrip, which implies a virtually chirp free pulse evolution in the laser. During each cavity roundtrip, the increased pulse duration by propagation in long PM fiber is balanced by pulse shortening in saturable absorber, while the nonlinear optical spectrum broadening in fiber is stabilized by a joint spectrum narrowing in FBG and saturable absorber. The pulse duration and spectral bandwidth are strictly determined by the narrow bandpass filtering of FBG. The simulated output pulse spectrum and autocorrelation trace is shown as orange dotted lines in Figs. 2(a) and 2(c), respectively. The time-bandwidth product of the laser pulse is estimated to be 0.6. There is a slight irregular structure close to the half-maximum of the measured optical spectrum which cannot be reproduced by this simulation. The simulated pulse spectrum after pre-amplifier is also shown as magenta dotted line in Fig. 2(a). The laser
output characteristics from numerical simulation essentially match with experiment except the slight irregular structure in the optical spectrum of the laser oscillator.

In order to simulate the timing jitter characteristics of the laser, ASE noise is added into the gain medium of the above numerical model which serves as a reference. We have calculated a sequence of output pulse temporal positions for 10,000 subsequent cavity roundtrips, from both the reference and the laser with ASE noise. The temporal deviation between the two pulse trains results in a sequence of timing errors, which are used to estimate timing jitter spectral density following the method in [42]. The simulated one-sided timing jitter spectral density characterizes a $-20 \text{ dB/decade}$ decay up to the Nyquist frequency. The numerical result is fully consistent with experiment by assuming an enhanced spontaneous emission factor of 4, as plotted in a gray line of Fig. 4.

5. Approach towards minimized timing jitter in the all-PM picosecond fiber laser

Up to now, both of experiment and numerical model have predicted few femtosecond quantum-limited timing jitter in spite of large intracavity normal dispersion from 10 meters PM fiber, which is supposed to introduce $\sim 20$ fs timing jitter indirectly via ASE induced center frequency fluctuations by itself. In this section, we will study the timing jitter reduction mechanism by comparing the numerical simulated results with the analytical model governing quantum-limited noise in mode-locked lasers.

Analytically, the direct contribution of ASE noise in gain medium to pulse train timing jitter follows a one-sided power spectral density as below [1,2]:

$$S_m(f) = 2k \frac{1}{(2\pi f)^2} \frac{h\omega \theta}{2\pi E_p T_{rt}} \tau_p^2,$$

where $\tau_p$ is FWHM pulse duration, $f$ is offset frequency, $T_{rt}$ is cavity round-trip time and $k$ is pulse shape factor, which is equal to 0.2647 and 0.1803 for sech$^2$-shaped pulse and Gaussian pulse, respectively. For the pulse shape of the LUT, we find that the pulse shape factor is equal to 0.2545. We set enhanced spontaneous emission factor as $\theta = 4$, which is in accordance with the numerical simulation. All the other laser parameters are also found in the numerical model of the stable operated fiber laser from Section 4. The calculated direct-coupled timing jitter spectral density following Eq. (3) is plotted as an orange dashed line in Fig. 4. The analytical result overlaps with experiment and numerical simulated jitter spectrum very well, indicating quantum-limited timing jitter dominated by the direct contribution from
ASE noise in this picosecond fiber laser, whereas the indirect-coupled timing jitter is supposed to be completely removed by the narrow bandpass filtering of FBG.

In order to investigate the characteristics of timing jitter reduction by FBG, we have simulated the timing jitter performance of the picosecond fiber laser by using different intracavity FBG bandwidth in the numerical model with ASE noise. The simulated timing jitter spectrum and RMS timing jitter (integrated from 100 kHz to Nyquist frequency) with the increase of FBG bandwidth is plotted in Fig. 7(a). It is noteworthy that the simulated timing jitter spectra virtually overlap at a low level for FBG bandwidth between 0.5 nm and 3 nm. Lower bandwidth (0.05 nm) will result in a much longer intracavity pulse duration, which leads to a dramatically increased timing jitter directly coupled from ASE. Above 5 nm FBG bandwidth, a rapid increase of timing jitter is also observed. Moreover, an obvious deviation from −20 dB/decade slope at high offset frequency range of the timing jitter spectra is resulted. The simulated timing jitter spectra of the picosecond fiber lasers with 0.5 nm and 7 nm FBG bandwidth are re-plotted in Fig. 7(b) to investigate the distinguished timing jitter characteristics at low bandpass filtering and high bandpass filtering. The corresponding timing jitter spectra from the direct contribution of ASE noise are estimated by using the analytical model of Eq. (3) and are plotted in the same figure. The comparison clearly indicates that 7 nm filtering cannot effectively reduce the indirectly coupled timing jitter, which contributes to the majority of pulse train timing jitter in this laser. As a result, numerical simulation indicates that a narrow bandpass filter down to ~1 nm bandwidth is favorable for reducing indirectly coupled timing jitter to obtain minimized timing jitter from a picosecond fiber laser. Note that the Gordon-Haus jitter reduction is independent of mode-locking regime. Picosecond Yb-fiber lasers can also work in a soliton mode-locked regime, where a chirped-FBG (CFBG) is used for intracavity dispersion compensation [43]. Considering that a CFBG characterizes a typical bandwidth of 1-2 nm, we can infer from Fig. 7(a) that the Gordon-Haus jitter can be well removed by narrow bandpass filtering. As a result, picosecond soliton fiber lasers using CFBG is expected to have a similar timing jitter performance compared with all-normal dispersion picosecond lasers using FBG. However, soliton lasers suffer Kelly sidebands, which is disadvantageous for a number of applications.

![Fig. 7. Impact of FBG filtering on timing jitter characteristics of picosecond fiber laser. (a) Simulated timing jitter spectra for the picosecond fiber laser with different FBG bandwidth. The inset shows the integrated timing jitter as a function of FBG bandwidth. (b) The simulated timing jitter spectra versus the corresponding analytically predicted timing jitter spectra of the direct contribution from ASE noise.](image-url)
6. Conclusion

In conclusion, we have investigated the timing jitter characteristics of an all-normal dispersion mode-locked picosecond all-PM fiber laser with low MHz repetition rate. A sub-femtosecond resolution optical cross-correlator is employed to measure the timing jitter spectrum of the laser at high offset frequency, demonstrating a record-low RMS timing jitter of 5.9 fs [10 kHz 5 MHz] from a picosecond fiber laser. The experimental result is compared with numerical and analytical models, indicating that a proper narrow bandpass filtering of ~1 nm bandwidth can completely remove Gordon-Haus jitter. As a result, few femtosecond timing jitter dominated by the direct contribution from ASE noise can be achieved in picosecond lasers. The low level of timing jitter from a compact and maintenance-free all-PM picosecond fiber source is likely to benefit a number of femtosecond-precision timing and synchronization applications.

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