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Abstract: We demonstrate the effective removal of Gordon–Haus (GH) jitter in mode-locked fiber lasers based on the narrow bandpass filtering, verified from large positive dispersion to large negative dispersion. Simulations and experiments indicate that there exists an optimum filtering bandwidth for the near-zero GH jitter along with the constant directly coupled jitter. The corresponding measured root-mean-square timing jitter (10 kHz to 10 MHz) is restrained within 0.6 dB, even though the net dispersion is largely varied by 70% of the intracavity fiber dispersion. The demonstrated effective GH jitter elimination free of the dispersion management gives an easy way for the low-jitter laser design and the related high-precision applications outside the laboratory.

Index Terms: Mode-locked lasers, fiber lasers, ultrafast lasers.

1. Introduction

Accurate timing signal generation is a prerequisite in large scientific apparatus such as X-ray free-electron lasers [1] and synthetic aperture imaging systems [2], in which the ultimate resolution is fundamentally limited by the timing jitter of carrier signals. Mode-locked fiber lasers (MLFLs) are being actively explored due to their inherent capability of ultra-short pulse train generation with ultra-low short-term timing jitter [3]. Till now, strategies on the timing jitter suppression in MLFLs are mainly focused on the Gordon-Haus (GH) jitter [4], either by the careful dispersion management [5], [6], or by the band-pass filtering [7]–[9] in the laser cavity. However, for the dispersion-management scheme, the low-jitter operation in the vicinity of zero dispersion usually comes at the expense of complex cavity design and multi-pulse instability, which obstructs further applications outside the laboratory. By contrast, in MLFLs with the large normal intra-cavity dispersion, the GH jitter can be reduced by inserting a narrow band-pass filter. Even though advances of the filter-induced intra-cavity restoring force for the GH jitter suppression have been experimentally observed [7], detailed and quantitative discussions of its influence under distinct intra-cavity dispersion and filtering conditions are still lacking.

In this paper, we report on the effective removal of GH jitter in MLFLs with the intra-cavity dispersion varied from large normal to large anomalous values by use of the narrow band-pass filtering.
Results show that the timing jitter component coupled via the net dispersion can be gradually removed as the intra-cavity band-pass filter becomes narrow enough. It is found numerically and experimentally that there exists an optimum filter bandwidth, with which the near-zero GH jitter and constant directly-coupled jitter can be achieved at the same time. The measured root-mean-square (RMS) timing jitter integrated from 10 kHz to 10 MHz is restrained within 0.6 dB, even though the net intra-cavity dispersion has been varied in a large range of 0.014 $ps^2$, 70% of the dispersion induced by the fiber segments. The demonstrated GH jitter elimination free of the net dispersion regimes gives an easy way for the low-jitter MLFL development outside the laboratory.

2. Numerical Simulations and Discussion

2.1 Numerical Model

First, the timing jitter coupling mechanism is investigated in terms of the intra-cavity dynamics. Schematic of the MLFL model with a removable spectral filter is shown in Fig. 1(a). To characterize the Amplified Spontaneous Emission (ASE) induced timing jitter, two almost identical cavity models are needed. One of them is noise-free, while the other contains ASE component within the gaining fiber [10]. Once the intra-cavity pulse evolution is convergent for a specific set of cavity parameters, the converged pulse is used as the initial input of both models. The ASE-induced perturbation is usually so small that it barely affects the convergence. When the temporal position of output pulses from each model is recorded for several loops, timing jitter spectra of corresponding mode-locking regimes can be extracted.

In this section, the numerical model is verified with a typical soliton laser, which can also be accurately characterized with analytical model due to its simple intra-cavity dynamics. The simulated MLFL contains 55 cm of single mode fiber (SMF) 1, 80 cm of Yb-doped fiber (YbF), and 25 cm of SMF 2. The repetition rate is set to 100 MHz. The small-signal gaining coefficient of the YbF is 3.2/m and the output coupling rate is 78%. Analytical calculation is based on the formulas in [11] and the simulated pulse parameters at each cavity position. At $-0.05 ps^2$ net dispersion, the pulse energy is amplified from 71 pJ to 430 pJ during a single pass through the gaining fiber, where the average pulse width is 567 fs. As shown in Fig. 1(b), the simulated Power Spectral Density (PSD) corresponds well with that of the analytical calculation, indicating that the numerical model used here is proper and sufficient to characterize the timing jitter of MLFLs.

2.2 Results and Discussion

With the verified numerical model, systematical investigations of the intra-cavity dynamics and the corresponding timing jitter coupling issue at different mode-locking regimes are performed. Specific to the fiber laser studied here, lengths of SMF 1, YbF, and SMF 2 are 40 cm, 25 cm and 15 cm, respectively. The repetition rate of the laser is fixed at 160 MHz. The intra-cavity
dispersion induced by the fiber segments is $+0.02$ ps$^2$. When the laser cavity is filter-free, typical pulse evolution patterns at different net dispersion varies significantly from one another. Firstly, with the net dispersion set to $+0.008$ ps$^2$, the pulse broadens in both segments of the passive SMF, while the spectral width almost remains the same throughout the whole circulation, as shown in Fig. 2(a). Such dynamics at normal dispersion corresponds to the passive self-similar evolution [12]. Secondly, with the net dispersion set to 0 ps$^2$, the temporal width breathes twice within one circulation, and its spectral width also undergoes dramatic variation, as shown in Fig. 2(b). Such successively-breathing dynamics results from the alternating overcompensation induced by equal amount of normal and anomalous dispersion, indicating the stretched-pulse mode-locking [13]. Thirdly, with the net dispersion set to $-0.03$ ps$^2$, both the temporal and spectral width of the pulse remain in a rather small value throughout the whole circulation, as shown in Fig. 2(c). Such nearly-constant pulse evolution at large anomalous net dispersion corresponds to soliton mode-locking [14].

Then, a second-order Gaussian spectral filter with 3-dB bandwidth of 7.5 nm is then added before the DC part of the numerical model. Pulse evolution patterns at $+0.008$ ps$^2$, 0 ps$^2$ and $-0.03$ ps$^2$ are shown in Fig. 2(d), (e), (f), respectively. On contrary to the filter-free cases, with the spectral filter, the intra-cavity pulse evolution follows the similar pattern. The temporal and spectral RMS widths are almost the same at corresponding cavity positions, even though the net dispersion varies from large positive to large negative values. During its propagation along the gain fiber, the pulse broadens exponentially in both the temporal and spectral domain. Such features indicate the nonlinear attractor effect of the quasi-amplifier-similariton evolution [15].

Then, the timing jitter at the aforementioned mode-locking regimes is simulated and summarized in Fig. 3. For the cases without filter, the spectral distribution of timing jitter reveals the combination of directly- and indirectly-coupled components. As shown in Fig. 3(a) and (b), both the PSD curves at $+0.008$ ps$^2$ and $-0.03$ ps$^2$ show typical transition of slope from $1/f^2$ to $1/f^4$ in the offset frequency range below 20 MHz, corresponding to indirectly-coupled timing jitter, i.e., GHJitter [16]. The jitter level and knee point of slope transition is mainly affected by the net dispersion and intra-cavity dynamics. Due to the larger chirping induced by normal dispersion, the GHJitter at $+0.008$ ps$^2$ is almost at the same level with that at $-0.03$ ps$^2$, although the modulus of net dispersion is much
In the offset frequency range from 20 MHz to the Nyquist frequency, the PSD curves follow a $1/f^2$ slope, corresponding to the directly-coupled timing jitter. In both cases, the GH jitter is at least 10 dB higher than the directly-coupled component in the low offset frequency range, making it the main obstacle in timing jitter optimization of large-dispersion MLFLs.

While with the 7.5-nm band-pass filter inserted, the slope transition in the low offset frequency range disappears and all the PSD curves follow a $1/f^2$ slope throughout the whole Nyquist frequency range, as shown in Fig. 3(c). Furthermore, the overall jitter level almost remains the same in spite of large net dispersion variation. As demonstrated earlier in this paper, intra-cavity dynamics of the filtered lasers at various net dispersion values is identical. Therefore, the directly-coupled timing jitter, which is mainly determined by the pulse dynamics [17], should be equal to one another. Consequently, the GH jitter in all the filtered conditions is restricted to the same level. In consideration of the negligible GH jitter at 0 ps$^2$, it can be concluded that the GH jitter of lasers is effectively eliminated with the narrow band-pass filtering. Such phenomena can be essentially interpreted as enhancement of the intra-cavity restoring force. It is known that the GH jitter stems from the center wavelength fluctuations, which can be suppressed, to some extent, by the restoring force provided by the finite spectrum [17]. When the band-pass filter is inserted, the equivalent gaining bandwidth is further reduced, leading to much stronger suppression of the center wavelength fluctuations. As a result, GH jitter is restrained to a very low extent at various net dispersion values. In the meantime, the average pulse width within the gaining fiber in the filtered conditions is kept in a relatively-narrow level, resulting in low-and-constant directly-coupled jitter. The RMS timing jitter integrated from 80 kHz to the Nyquist frequency at various net dispersion values is summarized in Fig. 3(d). The net dispersion varies in a 0.038 ps$^2$ range, which is 190% of the fiber dispersion. It can be seen that the RMS timing jitter in the filtered conditions is restrained within 0.53 dB, while that of the unfiltered regimes varies in a 16.7 dB range. Such dispersion-insensitive jitter level is lower than that in most unfiltered conditions and can be easily achieved by inserting a band-pass filter, thus providing a simple and flexible alternative in low-jitter MLFL development.
In order to further explore the filter-induced GH jitter elimination effect, the timing jitter of lasers with various filter bandwidths is simulated and investigated at typical net intra-cavity dispersion values. The overall RMS jitter level integrated from 80 kHz to the Nyquist frequency is summarized in Fig. 4. As can be seen that, for the filter bandwidth narrower than 10 nm, the jitter level at different net dispersion overlaps with one another, indicating sufficient GH jitter suppression. For broader bandwidth, the integrated jitter level at different net dispersion starts to diverge towards those without filter due to weakened restoring force. It is also noteworthy that narrower filter bandwidth, which leads to stronger restoring force, doesn’t necessarily result in lower jitter level. While GH jitter can be further suppressed with narrower filter, the temporal width of pulses would be broadened, leading to a rise in directly-coupled jitter. Therefore, the filter bandwidth should be chosen to be able to effectively eliminate the GH jitter as well as to guarantee relatively narrow pulse width. Specific to the MLFL investigated here, the optimum filter bandwidth falls in between 7.5 nm and 10 nm.

3. Experiments and Results

3.1 Experimental Setup

To verify the simulated predictions, we conduct a series of experiments based on the setup shown in Fig. 5. In the laser under test (LUT), the fiber part consists of a segment of single-mode YDF and the pigtail of collimators and the wavelength division multiplexer (WDM). Length of each segment is the same as that in the numerical model, and the total dispersion induced by the fiber part and the isolator is $+0.02 \text{ ps}^2$. To achieve the soliton, stretched-pulse and passive self-similar evolutions, a pair of 600 groove/mm gratings is used to set the intra-cavity net dispersion to $-0.006 \text{ ps}^2$, $0 \text{ ps}^2$ and $+0.008 \text{ ps}^2$, respectively. In each condition, a second-order Gaussian filter centered at 1040 nm is inserted after the isolator with negligible distortion of intra-cavity optical alignment. The 3-dB bandwidth of the filter is chosen to be 7.5 nm according to the numerical simulations. The repetition rate of LUT is fixed at 160 MHz by altering the free-space optical length according to the separation of the grating pair. The output spectra of the mode-locking regimes investigated here are listed in Fig. 5(b). For the filtered conditions, both shape and bandwidth of the spectra are similar to each other, agreeing well with the simulated results. The corresponding compressed pulse durations (full-width at half maximum, FWHM) exhibit similar values of 88 fs, 92 fs and 95 fs at $-0.006 \text{ ps}^2$, $0 \text{ ps}^2$ and $+0.008 \text{ ps}^2$, respectively.

Timing jitter characterization is performed with the Balanced Optical Cross-correlation (BOC) method, in which another MLFL is used as the reference (REF) [18]. The structure of REF is almost identical to that of LUT, except that the $\sigma$-cavity configuration with tunable cavity length is employed. The net dispersion of the REF is fixed at about 0 ps$^2$ to work in the stretched-pulse regime with extremely-low timing jitter. Conceptual schematic of the complete timing jitter characterization system is shown in Fig. 5(c). The output pulses from LUT and REF are dispersion-compensated
Fig. 5. (a) Structure of LUT: YbF, Yb-doped fiber; ISO, isolator; SF, spectral filter; DC, dispersion compensation unit. (b) Spectra of MLFLs in terms of net dispersion and filtering conditions. (c) Conceptual schematic of the timing jitter characterization system. DM, dichroic mirror; PI, proportional-integral controller.

Fig. 6. (a) Measured (solid) and simulated (dashed) timing jitter at +0.008 ps². (b) Measured (solid) and simulated (dashed) timing at −0.006 ps². (c) Measured timing jitter with filter. (d) Integrated timing jitter measured at various net dispersion values: with filter (square); without filter (up triangle).
outside the laser cavity and guided into the BOC system, which is based on a 0.65-mm type II phase-matched BBO crystal [7]. Once the repetition rate of REF is synchronized to that of the LUT with low-frequency feedback loop, timing jitter of the LUT can be characterized with attosecond resolution.

### 3.2 Results and Discussion

The measured timing jitter of LUT is summarized in Fig. 6. For the cases without filter, the measured PSD curves of LUT are in reasonable agreement with the simulated results, even though the signature transition of slope is covered by the detector noise floor, as seen in Fig. 6(a) and (b). While for the cases with filter, the timing jitter level at $+0.008 \text{ ps}^2$ and $-0.006 \text{ ps}^2$ is 19 dB and 8 dB lower than that of the filter-free conditions, respectively. Again, the measured jitter level of filtered conditions at various net dispersion values overlaps with one another except that the noise floor in each condition is different, as shown in Fig. 6(c). Since the GH jitter at 0 ps$^2$ is approximately zero, it can be reasonably concluded that the GH jitter at large net dispersion is effectively eliminated by the intra-cavity narrow band-pass filter. As shown in Fig. 6 (d), the RMS timing jitter integrated from 10 kHz to 10 MHz of the filtered lasers is restrained within 0.6 dB, while that of the unfiltered conditions varies in a 12 dB range, corresponding to the largely varied net dispersion of 0.014 ps$^2$, 70% of the dispersion induced by the fiber segments. For the cases with narrow band-pass filter, the dominating jitter component is the directly-coupled timing jitter, and the similar jitter levels result from the similar pulse widths. Although the timing jitter level with filter is $\sim 3$ dB higher than that of the stretched-pulse regime, it can be achieved by simply inserting a spectral filter, thus leaving out complex optimization of net dispersion and mode-locking regime. Furthermore, the nonlinear attractor effect triggered by the narrow band-pass filter could stabilize the intra-cavity pulse evolution [15] and suppress the relative intensity noise [7] as well, making the filtered MLFLs more flexible and reliable in real-world applications.

### 4. Conclusion

We have demonstrated the numerical and experimental investigations on the GH jitter elimination in mode-locked fiber lasers under distinct intra-cavity dispersion and filtering conditions. The effective removal of GH jitter enabled by the narrow band-pass filtering is verified from large negative dispersion to large positive dispersion. In the meantime, the directly-coupled timing jitter is restrained in a constant level due to the fixed intra-cavity dynamics triggered by the narrow band-pass filter. There exists an optimum bandwidth of the filter for the effective GH jitter elimination along with low directly-coupled timing jitter. The studies here allow for low-jitter laser design free of the complex dispersion management, thus demonstrate the potential for practical high-precision applications outside the laboratory.

### References


