Frequency comb based on a narrowband Yb-fiber oscillator: pre-chirp management for self-referenced carrier envelope offset frequency stabilization

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Abstract: Laser frequency combs are normally based on mode-locked oscillators emitting ultrashort pulses of ~100-fs or shorter. In this paper, we present a self-referenced frequency comb based on a narrowband (5-nm bandwidth corresponding to 415-fs transform-limited pulses) Yb-fiber oscillator with a repetition rate of 280 MHz. We employ a nonlinear Yb-fiber amplifier to both amplify the narrowband pulses and broaden their optical spectrum. To optimize the carrier envelope offset frequency (f_{CEO}), we optimize the nonlinear pulse amplification by pre-chirping the pulses at the amplifier input. An optimum negative pre-chirp exists, which produces a signal-to-noise ratio of 35 dB (100 kHz resolution bandwidth) for the detected f_{CEO}. We phase stabilize the f_{CEO} using a feed-forward method, resulting in 0.64-rad (integrated from 1 Hz to 10 MHz) phase noise for the in-loop error signal. This work demonstrates the feasibility of implementing frequency combs from a narrowband oscillator, which is of particular importance for realizing large line-spacing frequency combs based on multi-GHz oscillators usually emitting long (>200 fs) pulses.

OCIS codes: (140.3425) Laser stabilization; (140.3510) Lasers, fiber; (190.7110) Ultrafast nonlinear optics.

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1. Introduction

Femtosecond laser frequency combs are femtosecond mode-locked lasers with their repetition rate ($f_{\rm rep}$) and carrier-envelope offset frequency ($f_{\rm CEO}$) phase-stabilized to a frequency standard [1]. Many applications (e.g., optical arbitrary waveform generation and calibration of astronomical spectrographs) demand frequency combs with line spacing >10 GHz such that each individual comb-line can be accessed. Such a requirement has stimulated recent research endeavors in developing femotosecond lasers with >1 GHz repetition rate. Although 10 GHz repetition-rate operation has been achieved in a Kerr-lens mode-locked Ti:sapphire laser (and frequency comb) [2], scaling up repetition-rate is being intensively pursued in femtosecond lasers incorporating Yb-doped gain materials which can be directly diode pumped and exhibit excellent power scalability [3–10]. A survey of high repetition-rate (>1 GHz) femtosecond lasers with Yb-doped gain media (Table 1) shows that most of these lasers are of relative narrow bandwidth supporting pulse durations of well-exceeding 100 fs. The only exception is the Kerr-lens mode-locked Yb:KYW laser reported in [8], which produces 105 fs pulses. In addition to the lack of self-starting, such a laser employs minimal output coupling in favor of Kerr-lens mode-locking and thus produces only 6 pJ pulse energy [8]. Other femtosecond lasers in Table 1 are all capable of self-starting with mode-locking initiated and stabilized by a saturable absorber mirror (SAM); however the produced pulses feature narrowband and long transform-limited pulse duration as a result of reduced nonlinear effects due to the lower intra-cavity pulse energy for GHz repetition rate. Especially for repetition rates ≥3 GHz, the SAM mode-locked lasers produce optical bandwidths of ≤5.5 nm, corresponding to ≥200 fs transform-limited pulses.

In implementing a self-referenced frequency comb, stabilization of $f_{\rm CEO}$ is rather challenging. It normally involves nonlinearly broadening the laser spectrum inside a highly nonlinear fiber to generate supercontinuum (SC) spanning an octave. $f_{\rm CEO}$ is then detected by heterodyning the short-wavelength edge of the SC with a frequency-doubled copy of the long-wavelength edge. A high-quality SC featuring excellent coherence is crucial to achieve a

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low-noise f_{CEO} that ensures a stable frequency comb. Detailed experiments and numerical simulations have found that the SC coherence is primarily determined by the input pulse duration coupled into the nonlinear optical fiber [11]. As a rule of thumb, pulses of 100 fs (or even shorter) produce SC with good coherence to detect and stabilize f_{CEO}. Therefore, it is not surprising that most demonstrated frequency combs are based on lasers with direct output of <100 fs pulses. As for multi-GHz lasers featuring long output pulses (≥200 fs), the following question naturally arises: is it possible to fully stabilize narrowband lasers to achieve self-referenced frequency combs possessing multi-GHz line spacing?

Table 1. A survey of diode pumped, mode-locked femtosecond lasers with >1 GHz repetition rate. SBW: spectral bandwidth at FWHM, τ_p (TL): transform-limited pulse duration (assuming sech^2 pulse), SAM: saturable absorber mirror

f_{rep}	SBW	τ_p (TL)	Mode-locker	Gain medium	Reference
1.0 GHz	4.8 nm	240 fs	SAM	Yb:KGW	[3]
1.0 GHz	7.0 nm	160 fs	SAM	Yb:fiber	[4]
1.0 GHz	3.8 nm	280 fs	SAM	Yb:KYW	[5]
2.8 GHz	7.5 nm	150 fs	SAM	Yb:KYW	[6]
3.0 GHz	5.5 nm	200 fs	SAM	Yb:fiber	[7]
4.6 GHz	11.0 nm	105 fs	Kerr-lens	Yb:KYW	[8]
4.8 GHz	4.1 nm	280 fs	SAM	Yb:KGW	[9]
4.9 GHz	2.1 nm	555 fs	SAM	Yb:glass	[10]

This question has been partly addressed in [12] by comparing f_{CEO} detection using octave-spanning SC generated by pulses of different duration. The SC generated from 290 fs pulses exhibits poor coherence and f_{CEO} is not detectable. As the 290 fs pulses are first spectrally broadened and then compressed to 100 fs using a passive fiber-compressor, the spectral coherence of the resulting SC is substantially improved, and consequently f_{CEO} is detected showing a signal-to-noise ratio (SNR) >27 dB at 100 kHz resolution bandwidth (RBW) [12]. However the authors did not reference the f_{CEO} to a frequency standard to demonstrate a fully stabilized frequency comb.

In this paper, we present a self-referenced frequency comb based on a 280 MHz Yb-fiber oscillator which is intentionally mode-locked with output spectral bandwidth of 5-nm corresponding to 415 fs transform-limited pulses. Different from the passive compression of the long pulses, we employ a nonlinear Yb-fiber amplifier which amplifies the narrowband pulses as well as broadens their optical spectrum. The power amplified and spectrally broadened pulses are then compressed prior to SC generation. To optimize the f_{CEO} signal, we optimize the nonlinear pulse amplification by pre-chirping the pulses at the amplifier input. An optimum negative pre-chirp exists that produces the best-quality compressed pulse for SC generation and leads to a detected f_{CEO} signal with 35 dB SNR measured with 100 kHz RBW. We phase stabilize the f_{CEO} using a frequency shifting method [13], which results in 0.64-rad (integrated from 1 Hz to 10 MHz) phase noise for the in-loop error signal.

2. Narrowband, 280 MHz Yb-fiber oscillator

The 280 MHz Yb-fiber oscillator, schematically shown in Fig. 1(a), is configured as a linear cavity pumped by a laser diode providing an average power up to 600 mW centered at 976 nm. The laser cavity consists of an 8.3-cm highly doped Yb-fiber (from Coractive SCF-YB550-4/125-19) to provide gain and three dispersion-compensating mirrors (DCM) for managing the cavity dispersion. The flat end of the gain fiber is firmly attached to a dichroic mirror that transmits pump and reflects the intra-cavity lasing beam. The wave-plates and polarization beam cubes allow six bounces of the optical beam from the DCMs per round trip; each bounce leads to a negative group velocity dispersion of –2000 fs^2/mm [14]. A SAM with < 1 ps recovery time and 15% modulation depth initiates and stabilizes the mode-locking.

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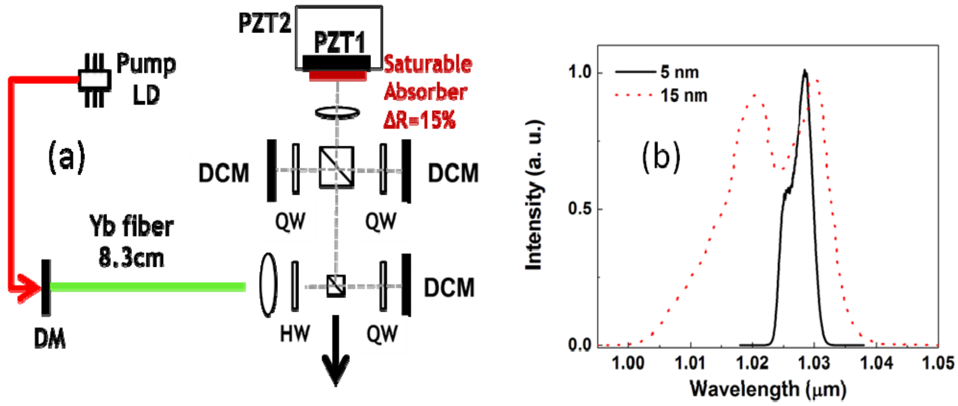

Fig. 1. (a) schematic setup of the Yb-fiber oscillator. DM: dichroic mirror, LD: laser diode, HW: half wave-plate, QW: quarter wave-plate, DCM: dispersion compensating mirror, PZT: piezo-electric transducer. (b) narrowband (black solid curve) and broadband (red dotted curve) spectra of the Yb-fiber oscillator mode-locked.

Mode-locking self-starts at a pump power of 250 mW. With 350 mW pump power, the oscillator outputs 90 mW average power with 5 nm bandwidth (FWHM) centered at 1028 nm, shown as the black curve in Fig. 1(b). This spectrum supports 415 fs transform-limited pulses. We measured the relative intensity noise (RIN) of the oscillator in a coarse enclosure. The integrated RIN (often referred to as instability) from 1 Hz to 10 MHz is 0.3%. The RIN of laser oscillator showed considerable environmental disturbances (e.g. mechanical resonance, air current, temperature drifting) which, however, can be effectively suppressed using better laser isolation from the environment.

By adjusting the output coupling ratio with the half-wave plate and choosing different SAMs, we can mode-lock the oscillator with different output bandwidth. For example, use of a different SAM generates 15-nm bandwidth shown as the red-dotted curve in Fig. 1(b). To demonstrate the feasibility of achieving frequency combs from narrowband oscillators, we intentionally run the oscillator with 5-nm bandwidth during our experiments.

3. Frequency comb based on the narrowband Yb-fiber oscillator

Figure 2 illustrates the self-referenced frequency comb by stabilizing the repetition rate and the carrier-envelope offset frequency of the narrowband Yb-fiber oscillator. The stabilization is enabled by four optical building blocks: (1) a grating pair for pre-chirp management prior to the nonlinear amplification, (2) a 2-stage Yb-fiber nonlinear amplifier to boost power and broaden the optical spectrum, (3) another grating pair for pulse compression of the amplified pulses, and (4) a f-to-$2f$ interferometer to generate the f_{CEO} signal which is stabilized using a feed-forward method based on an acousto-optic frequency shifter (AOFS) [13].

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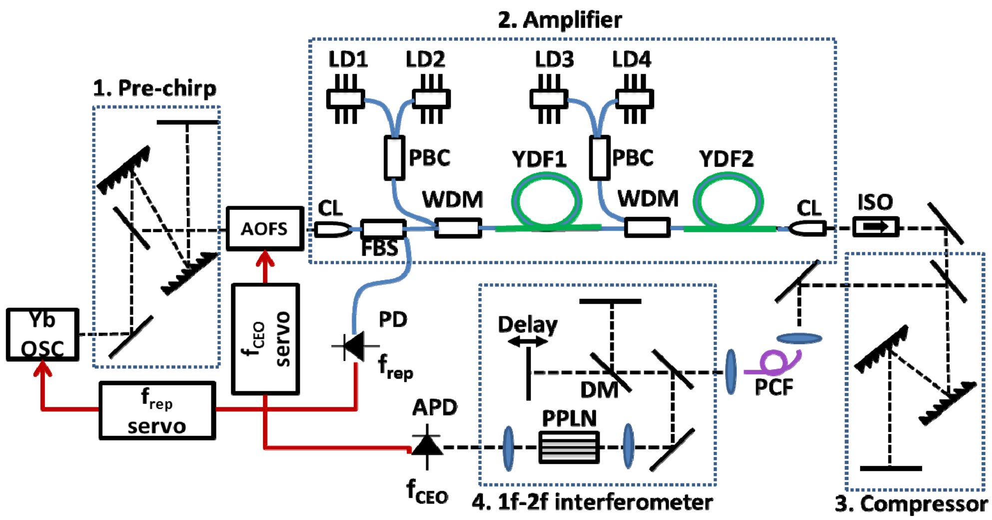

Fig. 2. Fully stabilized frequency comb based on a 280-MHz narrowband Yb-fiber oscillator. OSC: oscillator, AOFS: acousto-optic frequency shifter, PD: photo-detector, CL: collimating lens, PBC: polarization beam combiner, WDM: wavelength division multiplexer, YDF: Yb-doped fiber, ISO: isolator, DM: dichroic mirror, PCF: photonic crystal fiber, PPLN: periodically poled lithium niobate, APD: avalanche photo-detector.

3.1 Pre-chirp management for spectral broadening and pulse compression

In general, one needs > 1 nJ pulses with < 100 fs duration for low-noise SC generation in a highly nonlinear optical fiber to detect the f_{CEO} signal with high enough SNR. Here we employ a 2-stage Yb-fiber amplifier to amplify the oscillator pulses as well as spectrally broaden their optical spectrum. This nonlinear amplification, however, may add strong nonlinear phase shift causing optical pulse breaking and phase noise owing to amplitude-to-phase noise conversion and amplified spontaneous emission. Therefore the amplifier has to be optimized for improving the compressed pulse quality. Recently, we have investigated, by detailed numerical modeling, the dependence of compressed pulse quality on the fiber amplifier parameters including input pulse chirp, duration, and power, and the gain fiber's doping concentration and length [15, 16]. Our simulation results verified by experiments indicate that pre-chirping the oscillator pulse prior to the nonlinear amplification plays a critical role for optimizing the system to achieve high-quality compressed pulses. In particular, an optimum *negative* pre-chirp exists for the best pulse compression quality.

In Fig. 2, the diffraction-grating (groove density of 600 lines/mm) pair before the Yb-doped fiber amplifier (YDFA) provides a variable pre-chirp for the pulses to be amplified. The grating pair has a dispersion of −1500 fs^2/mm with 60% transmission efficiency at the Littrow incident angle. Each stage of the 2-stage YDFA is constructed from 2-m Yb-fiber forward-pumped by two 650 mW laser diodes (centered at 976 nm) combined with a polarization beam combiner. The pre-chirped oscillator pulses are amplified up to 1.4 W and become 1 W after the isolator, and then 550 mW after the grating-pair compressor.

Because SC generation is extremely sensitive to the intensity noise of the driving pulses [17–19], we measured the RIN of the amplified pulses at different pre-chirp settings. Figure 3(a) shows the integrated RIN from 100 Hz to 10 MHz as a function of the group-delay dispersion (GDD) for pre-chirping the oscillator pulses. Indeed, the integrated RIN reaches a minimum of 0.075% at the pre-chirp GDD of −0.09 ps^2 (indicated by the blue circle in Fig. 3(a)). As comparison, it increases to 0.093% at the pre-chirp GDD of 0.01 ps^2 (green circle in Fig. 3(a)). Figure 3(b) plots the RIN spectra corresponding to these two pre-chirp GDDs (i.e., −0.09 ps^2 versus 0.01 ps^2), indicating that the RIN is considerably reduced especially at higher frequency (>10 kHz) for the pre-chirp GDD at –0.09 ps^2 (blue curve in Fig. 3(b)) compared with the case of applying 0.01 ps^2 GDD (green curve in Fig. 3(b)).

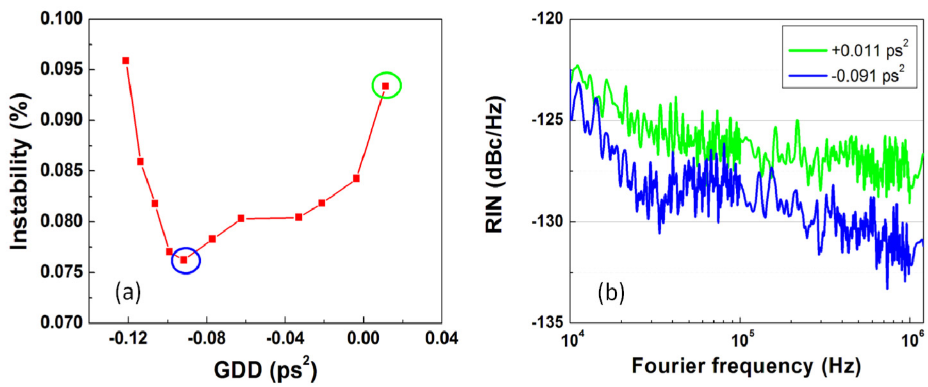

Fig. 3. (a) Instability (i.e., integrated RIN) for the amplified pulses as a function of pre-chirping GDD. Black-dotted line: oscillator instability. (b) RIN for different pre-chirp GDD: + 0.01 ps^2 (green curve) and –0.09 ps^2 (blue curve).

With the pre-chirp GDD of –0.09 ps2 where the minimum RIN is achieved for the amplified pulses, the compressed pulses reach the minimum duration as well. The red curve in Fig. 4(a) shows the corresponding optical spectrum at the amplifier output, showing that the nonlinear amplification broadens the oscillator spectrum (black, dashed curve in Fig. 4(a)) from 5 nm to >15 nm; such a broadened spectrum accommodates a transform-limited pulse of 90 fs. We measured the resulting compressed pulse using an autocorrelator and the autocorrelation trace is shown in Fig. 4(b) as the red curve. As a comparison, the autocorrelation trace of the transform-limited pulse calculated from the broadened spectrum is plotted in the same figure as the blue curve. The good overlap between the two autocorrelation traces indicates that the compressed pulse has 86% pulse energy in the main peak.

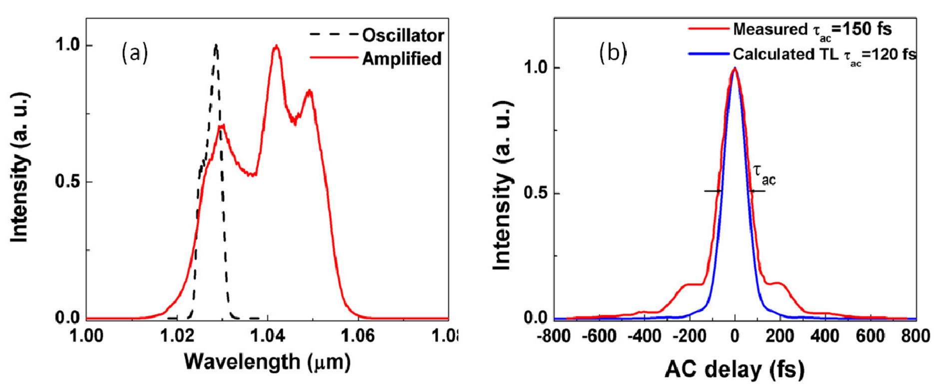

Fig. 4. (a) Oscillator spectrum (black-dashed curve) and spectrum after the amplifier (red curve). (b) Experimentally measured autocorrelation trace for the amplified pulses (red curve). Blue curve shows the autocorrelation trace of the transform-limited pulse calculated from the amplified spectrum in (a).

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3.2 SC generation and f_{CEO} detection

The compressed pulses with >15 nm bandwidth were coupled into 40 cm photonic crystal fiber (PCF) with 55% coupling efficiency, corresponding to 1-nJ pulse energy. The commercially available PCF has a core diameter of 3.2 μm with the zero-dispersion-wavelength at 945 nm. The generated SC spans from 660 nm to 1400 nm as shown in Fig. 5(a). The SC is launched into an *f*-to-2*f* interferometer which includes a 10 mm-long and 1 mm-thick periodically-poled lithium niobate crystal for second harmonic generation (SHG) of the 1360 nm wavelength range. We adjusted the crystal temperature to finely tune the poling period and thus optimized the conversion efficiency. The group delay mismatch between the fundamental frequency and the SHG frequency was compensated by a tunable delay path. Figure 5(b) shows the heterodyned f_{CEO} beat-note detected by a Si-avalanche photo-detector. With a SNR of ~40 dB, the f_{CEO} signal exhibits a Lorentzian line-shape with a free-running linewidth of <140 kHz (FWHM), which is typical for fiber laser combs [20].

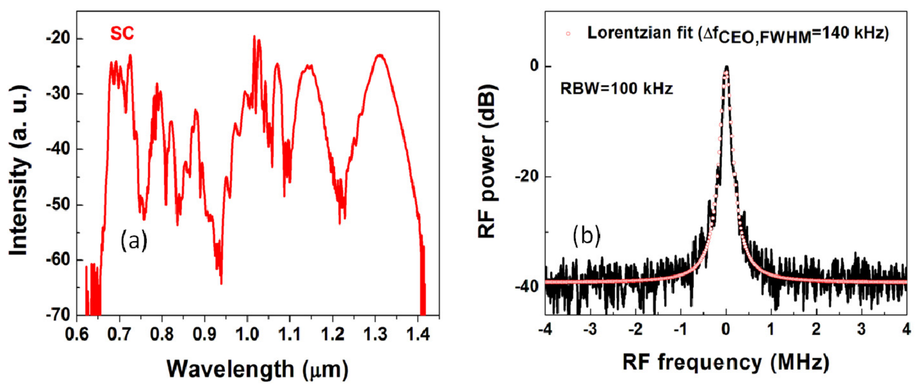

Fig. 5. (a) Octave spanning supercontinuum generation using 40 cm PCF. (b) Measured f_{CEO} (x-axis: f_{CEO} −190 MHz) and its linewidth with RBW = 100 kHz.

3.3 Stabilization of f_{rep} and f_{CEO}

f_{rep} is stabilized by controlling the cavity length using a fast single stack PZT attached to the back of the SAM. Long-term f_{rep} stabilization is ensured using a slow PZT to move the translation stage on which the SAM is mounted. To control f_{CEO}, we implement a frequency shifting technique via an AOFS in feedback configuration, providing broader control bandwidth than that of pump power modulation and allowing for decoupling of the f_{CEO} stabilization [13, 21] from the laser dynamics and repetition rate lock. The AOFS made from a TeO_2 crystal has 1-mm active aperture with the RF center frequency at 175 MHz. The AOFS <1 dB insertion loss is set between the first grating pair and the YDFA. To increase the modulation response, we focus the beam to the AOFS with a lens (60 mm focal length), resulting in 100 μm focal spot size. The first order diffracted beam is shifted by applying a RF signal which is generated from a voltage controlled oscillator and then amplified by a linear RF power amplifier. With 1.8 W RF signal power applied to the AOFS, we achieved 25% diffraction efficiency. For f_{CEO} stabilization, the f_{CEO} beat-note was bandpass-filtered, amplified, and then heterodyned with a local RF synthesizer; the resulting heterodyned signal was bandpass-filtered, divided with a pre-scaler, and fed into a digital phase detector which is able to track a ± 32π phase difference. The signal was finally compared with another local RF synthesizer in the phase detector to generate the error signal to control the AOFS for a complete feedback loop.

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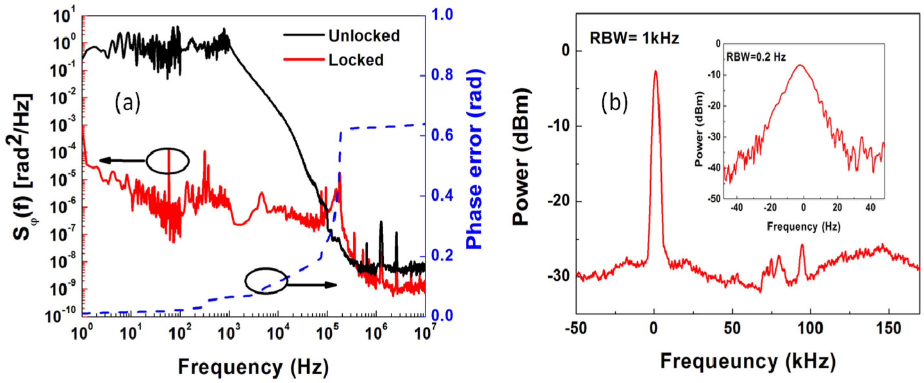

Fig. 6. (a) Power spectral density (PSD) and the RMS integrated phase noise; unlocked (black), locked (red), Phase error calculated by integrating noise PSD from 1 Hz to 10 MHz (blue), (b) Measured f_{CEO} linewidth (x-axis: f_{CEO}–190 MHz) with 1 kHz RBW; Inset with 0.2 Hz RBW.

Figure 6(a) presents the noise power spectral density, $S_{\varphi}(f)$ [rad^2/Hz], of the in-loop error signal when f_{CEO} is locked (red curve) or unlocked (black curve). With the phase-locked loop closed, the frequency noise of the error signal is substantially suppressed, showing a locking bandwidth of 150 kHz. The integrated RMS phase noise from 1 Hz to 10 MHz is 0.64 rad. As Fig. 6(b) shows, the corresponding f_{CEO} linewidth is <10 Hz with the resolution bandwidth of 0.2 Hz. The frequency shifting method suppresses broadband technical noise and further noise suppression can be achieved by isolating the comb from environmental disturbances, by implementing an active intensity noise eater in the oscillator [21], or by adding a phase compensation circuit to increase the servo-bandwidth.

4. Conclusion and discussion

In conclusion, we have demonstrated a well-stabilized frequency comb by phase-stabilizing a 280 MHz narrowband Yb-fiber oscillator with 5-nm bandwidth (corresponding to 415 fs transform-limited pulses). The narrowband output pulses were pre-chirped, then spectrally broadened in an Yb-fiber amplifier, and finally compressed to ~100 fs in duration. Optimization of the pre-chirping led to the shortest compressed pulses with minimum RIN, which is critical for the subsequent SC generation that determines the SNR of the f_{CEO} beat-note.

Due to the excellent power scalability of Yb-fiber amplifiers, we believe that the feasibility of fully stabilizing a narrowband Yb-fiber oscillator can be realized at repetition rates much higher than 280 MHz. Recently, we have demonstrated a 3 GHz, fundamentally mode-locked Yb-fiber oscillator with 5.5 nm bandwidth [7]. Currently we are working on employing the technique demonstrated in the paper to fully stabilize this oscillator to achieve a self-referenced 3 GHz frequency comb.

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