A long-term frequency-stabilized erbium-fiber-laser-based optical frequency comb with an intra-cavity electro-optic modulator*

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We demonstrate an optical frequency comb based on an erbium-doped-fiber femtosecond laser with the nonlinear polarization evolution scheme. The repetition rate of the laser is about 209 MHz. By controlling an intra-cavity electro-optic modulator and a piezo-transducer, the repetition rate can be stabilized with a high-bandwidth servo in a frequency range of 3 kHz, enabling long-term repetition rate phase-locking. The in-loop frequency stability of repetition rate is about 1.6×10^{-13} in an integration time of 1 s, limited by the measurement system; and it is inversely proportional to integration time in the short term. Furthermore, using a common path f–$2f$ interferometer, the carrier envelope offset frequency of the comb is obtained with a signal-to-noise ratio of 40 dB in a 3-MHz resolution bandwidth. Stabilized carrier envelope offset frequency exhibits a deviation of 0.6 mHz in an integration time of 1 s.

Keywords: optical frequency comb, fiber laser, frequency stabilization, frequency instability

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1. Introduction

Optical frequency combs, based on Ti:sapphire femtosecond laser, were invented at the end of 1990s.[1,2] Two scientists from Germany and USA won the Nobel Prize for physics in 2005 due to this invention. Nowadays, optical frequency combs are widely used in many areas, including attosecond science,[3] spectroscopy,[4] astronomical spectrograph,[5] low-noise microwave generation,[6] distance measurement,[7] time and frequency transfer,[8] optical clock development and application,[9] etc. Requirements of various applications have motivated scientists and engineers to develop new optical combs based on different laser sources, such as Cr:LiSAF,[10] Er:fiber,[11] Cr:forsterite,[12] Er:Yb:glass,[13] Yb:fiber.[14] Especially, erbium-doped fiber frequency comb attracts much attention because of its compactness, reliability, low power consumption, and directly covering telecommunication wavelength. As a result, Er:fiber frequency comb rapidly evolves, and its performance is as good as that of the best comb; the frequency stability of optical spectrum transfer can reach $\sim1\times10^{-17}$ in an averaging time of 1 s.[15]

Since the optical frequency comb was invented, ultra-high-resolution optical frequency measurement has become one of the most important applications. In order to meet the need of this application, some critical techniques were proposed to improve the frequency stability of the comb.[16–19] Optical frequency of a comb can be expressed as $\nu_n = f_{ceo} + nf_r$,[20] where f_{ceo} is the carrier envelope offset frequency, f_r is the repetition rate, n is an integer of $10^5 \sim 10^6$. A small frequency fluctuation of f_r can lead to a significant frequency variation of ν_n. Consequently, f_r definitely needs controlling in a high bandwidth to overcome the unexpected changes introduced by environmental noises or others. Traditionally, f_r is controlled only with a piezo-transducer (PZT), whose response bandwidth is usually well below 10 kHz. To improve the control bandwidth of f_r, scientists in JILA (USA) first realized fast servo of the repetition rate ($\sim$ 230 kHz) by using an intra-cavity electro-optic modulator (EOM).[16] In China, a few research groups are developing a fiber-based comb system with an intra-cavity EOM.[21–23]

In this paper, we present the progress of an erbium-fiber-laser-based optical frequency comb used for strontium optical clock frequency measurement. Its repetition rate (f_r) is about 209 MHz. In order to control f_r, an intra-cavity EOM and a long-range PZT are used as the feedback terminals simultaneously. Based on this configuration, f_r can be stabilized continuously for more than one week. The response bandwidth of f_r control is improved to megahertz, and the tunable range is 3 kHz. Moreover, the carrier envelope offset frequency (f_{ceo}) of the Er:fiber frequency comb, with a signal-to-noise ratio

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(SNR) of 40 dB in 3-MHz resolution bandwidth (RBW), is detected by a common path f–$2f$ interferometer. After stabilization, f_{ceo} exhibits a deviation of 0.6 mHz in an integration time of 1 s.

2. Experimental setup

Figure 1 shows the setup of the optical frequency comb, which is based on an Er:fiber femtosecond laser. The laser output is divided into three parts. One part is the optical frequency comb output for the subsequent applications; the other two are used for detecting and stabilizing of f_{ceo} and f_r respectively.

2.1. Er:fiber-based mode-locked laser

As shown in Fig. 1, the Er:fiber femtosecond laser source has a ring cavity including four wave plates, a polarization beam splitter (PBS), two collimators, a WDM with isolator, an EOM, and fibers. A 2-cm PZT mounted on a stage is employed to control the cavity length. The cavity contains 39-cm SMF-28 fiber, 8-cm HI-1060 fiber, and 39-cm highly erbium-doped fiber (Liekki ER110-4/125). The net dispersion of the cavity is assumed to be slightly negative, considering all components and fibers in the cavity. The laser is pumped with two single-mode 980-nm pigtailed diode lasers, whose powers are both up to 0.6 W. By setting wave plates at proper angles, the laser can start mode-locking automatically while the pumping power is 1 W. Unfortunately, the mode-locked laser works in a multi-pulse state in this condition. In order to avoid this situation, we reduce the pump power to around 350 mW. The output power is $\sim$ 50 mW, and the duration of the pulse emitted from PBS is $\sim$ 83 fs with a 3-dB optical spectrum width of $\sim$ 50 nm.

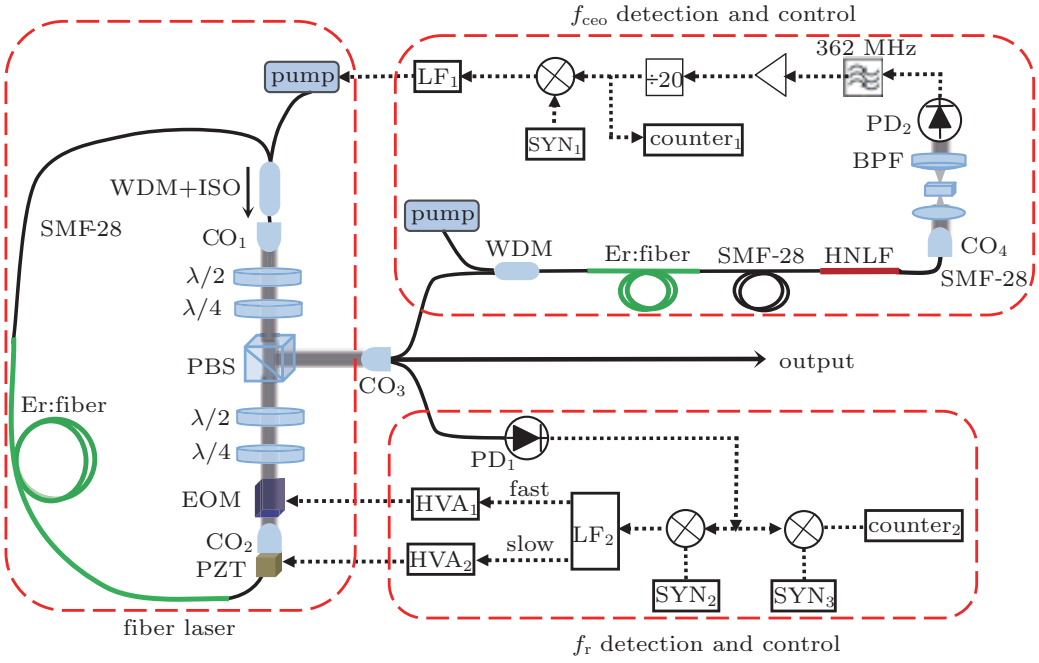


Fig. 1. (color online) Schematic diagram of the Er:fiber femtosecond laser frequency comb. The thick solid lines represent free-space paths, the thin solid lines represent fiber paths, and the dotted lines represent electrical paths. $\lambda/2$: half-wave plate; $\lambda/4$: quarter-wave plate; WDM: wavelength division multiplexer; ISO: isolator; PBS: polarization beam splitter; CO: collimator; PD: photodetector; BPF: bandpass filter; PPLN: periodically poled lithium niobate; HNLF: highly nonlinear fiber; LF: loop filter; HVA: high voltage amplifier; SYN: synthesizer.

Two feedback terminals, an EOM and a PZT, are employed to control f_r. The EOM is an 8-mm long lithium niobate crystal with $\sim$ 800 fs^2 dispersion at a wavelength of 1550 nm. To measure the response bandwidth of the EOM, we set up a Mach–Zehnder interferometer which contains the EOM in one arm. Then, we drive the EOM with an external radio-frequency (RF) source and monitor the phase response of the EOM at the output of the interferometer using a 2-GHz bandwidth photodetector (PD). The 3-dB bandwidth in magnitude is about 10 MHz, while the phase delay is close to $\pi/2$. The monotonic change of f_r caused by EOM is about 60 Hz while tuning the offset voltage of EOM from -200 V to 200 V. The tuning range of the PZT (from 0 V to 200 V) is measured to be around 3 kHz with a response bandwidth of hundreds of Hertz.

2.2. The f_r detection and stabilization

To detect the repetition rate, we send a fraction of the output from the mode-locked laser into an InGaAs PD (EOT-3000A) with a bandwidth of 2 GHz. At the output of the PD,

we obtain a current pulse train exhibiting $m \times f_r$ in frequency domain, where m is an integer. Usually, we do not stabilize f_r directly, but stabilize its high order harmonics, so as to reduce technical noise induced by the phase-locking process. However, no high frequency microwave synthesizer is available for the moment in our laboratory. Eventually, we lock the phase of the fourth harmonics of the repetition rate (838 MHz) to a reference signal.

The repetition rate is stabilized with a standard phase-locked loop technique. The phase detector is an RF mixer which produces an error signal indicating phase difference between $4f_r$ signal and the reference signal. Following the mixer, a home-made loop filter converts the error signal into a negative feedback signal for driving EOM with high bandwidth and PZT with long range. Although the EOM has a response bandwidth of about 10 MHz, the control bandwidth of EOM servo-loop is estimated to be 100 kHz–200 kHz according to the response measurement results of the home-made loop-filter and high voltage amplifier. The PZT control-loop has a bandwidth lower than 100 Hz for compensating only the temperature drift effect.

In addition, f_r keeps being phase-locked while the box of the laser is hit, because EOM control-loop cancels the vibration influence efficiently. The peak-to-peak temperature fluctuation is about 1 °C in the laboratory, and well below 1 °C in the laser box, so that PZT control-loop can eliminate the thermal drift effect independently. Extra thermal control is not required. As a result, f_r of the laser can be continuously phase-locked onto the reference signal over a week.

2.3. The f_{ceo} detection and stabilization

We use f–$2f$ interference method to produce f_{ceo} signal; and lock f_{ceo} to an extra-reference (radio-frequency RF) signal in phase by controlling the ring laser's pump power.

In order to perform f–$2f$ interference, we first prechirp the seed pulses for reducing the pulse peak's power, aiming to reduce the nonlinear effect in amplification stage. Secondly, the prechirped pulses are delivered into an erbium-doped fiber amplifier with a selective optimum gain of $\sim$ 14 dB. Thirdly, laser pulse width is compressed by dechirping the amplified pulses with an SMF-28 fiber, thereby yielding $\sim$ 50-fs pulses as shown in Fig. 2(a). Fourthly, these narrow pulses are fed into a short highly nonlinear fiber (HNLF), resulting in an octave-spanning supercontinuum (SC) as shown in Fig. 2(b). This figure gives the optical spectrum of the SC spanning from 950 nm to 2250 nm for 25-dB bandwidth. Most of the energy shifts into two solitons with 1-μm and 2-μm wavelengths respectively. It is worth noting that these two solitons have exactly the right wavelength for f–$2f$ interference. After that, all optical powers go through a 1-mm thick PPLN crystal for frequency-doubling. Finally, we pick-up 1-μm-wavelength light with a 10-nm-wavelength bandpass filter and obtain a beatnote signal of f–$2f$ interference with an InGaAs PD.

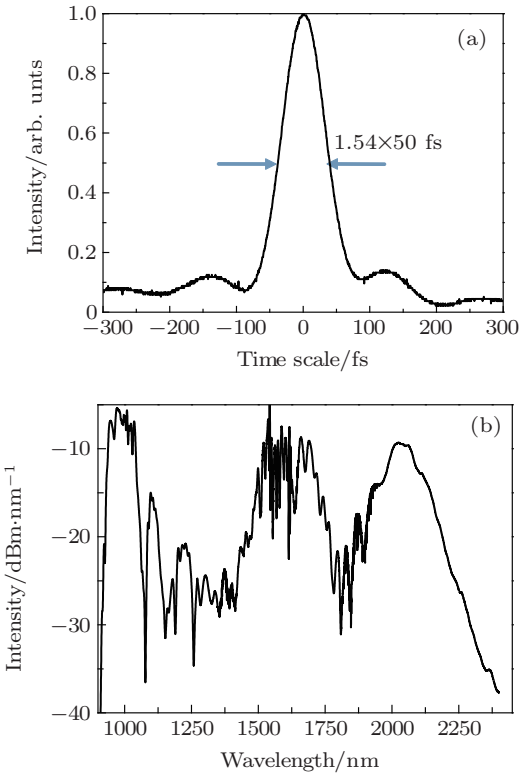


Fig. 2. (color online) (a) Measured intensity autocorrelation of the compressed pulse; (b) octave-spanning supercontinuum produced with HNLF.

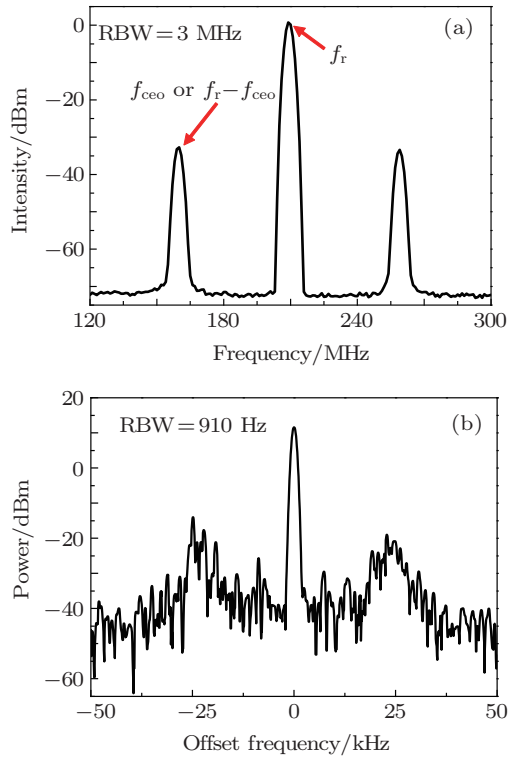


Fig. 3. (color online) (a) Spectrum of the f–$2f$ interference in 3-MHz RBW; (b) spectrum of the frequency-divided f_{ceo} signal in 910-Hz RBW.

Figure 3(a) shows the spectrum of the f–$2f$ interference

with 3-MHz RBW, showing an SNR of f_{ceo} to be 40 dB. The linewidth of the free-running f_{ceo} beat is about 500 kHz observed in fine RBW. The SNR is about 20-dB higher than that of the previously reported Er:fiber domestic system.[22] High SNR enables the system to generate a clean feedback signal for controlling the pump power and stabilizing f_{ceo} on a reference frequency provided with a synthesizer. A 20× frequency divider is used to improve the phase locking tolerance, making the phase-locked loop more robust. The control bandwidth of the loop is about 25 kHz indicated by the gain-bump as shown in Fig. 3(b). The accumulated noise power in a frequency range of 50 kHz–10 Hz from the carrier is about 1%, indicating that the linewidth of frequency-divided f_{ceo} should be well below 1 Hz. More accurate evaluation will be shown later with frequency stability.

The longest continuous phase-locking time of f_{ceo} is more than one day. However, some unknown noises coupled from electric ground (introduced by other events) disturb the phase-locked loop from time to time. We suppose that f_{ceo} can be stabilized much longer if the electric ground turns clean.

3. Results and discussion

Frequency stability of the optical frequency comb is one of the most important parameters. Measurement of the comb's absolute (out-of-loop) frequency instability requires two independent systems which are unavailable now. Here, we measure only in-loop frequency instability which does not include part of the fiber noise in comparison with the out-of-loop one.

3.1. In-loop frequency stability of f_r

As shown in Fig. 1, down-converted frequency of $4f_r$ at 1 MHz is recorded with a frequency counter (Agilent 53230A). Figure 4(a) shows the frequency fluctuation of $4f_r$, measured over a week. The result exhibits a root-mean-square (RMS) value of about 0.1 mHz. The frequency stability ($\Delta f_r/f_r$) shown in Fig. 4(b) is about 1.6×10^{-13} in an integration time of 1 s. However, this result is limited by the noise floor as shown with solid squares, which is measured by using the same counter recording a 1-MHz reference signal. On the other hand, the frequency stability is inversely proportional to $\tau^{1/2}$, where τ is the integration time, because the dead-time decouples the data relationship in measurement system and converts the white phase noise into a white frequency noise.[24] For a phase-locked loop, the stabilized signal should exhibit the white phase noise, and its frequency stability should be inversely proportional to τ. This is verified by eliminating dead-time effect with different gate times as shown with a dashed line in Fig. 4(b). Note that the first point of calculated Allan deviations has no dead-time effect. Therefore, the frequency stability of f_r is about 1.6×10^{-13} in an integration time of 1 s and rolls down with a slope of $1/\tau$ for short-term stability.

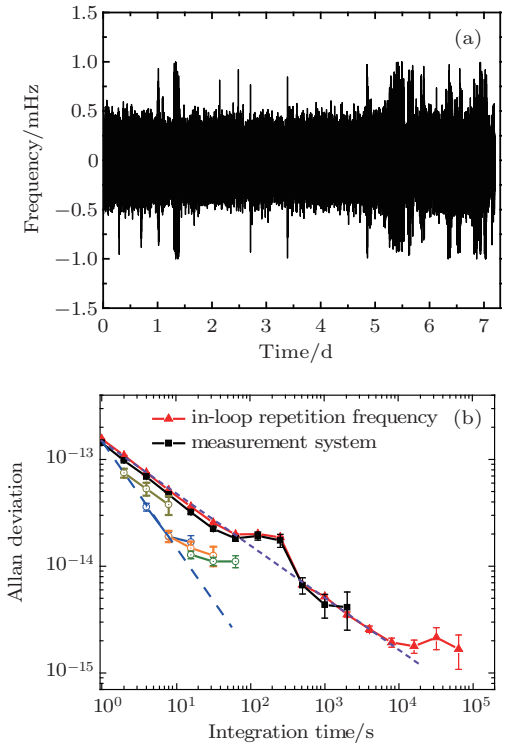


Fig. 4. (color online) (a) Residual fluctuations of the 4th harmonic of the repetition rate. The gate time is 1 s and the dead-time between samplings is about 0.2 s; (b) in-loop frequency stability of $4f_r$, measured with different gate (solid red triangle for 1 s, empty round for 2 s, 4 s, 8 s, and 16 s) times and measurement noise floor (solid black square).

3.2. In-loop frequency stability of f_{ceo}

The RMS of f_{ceo} fluctuation is about 0.6 mHz in an integration time of 1 s, and the peak-to-peak fluctuation is about

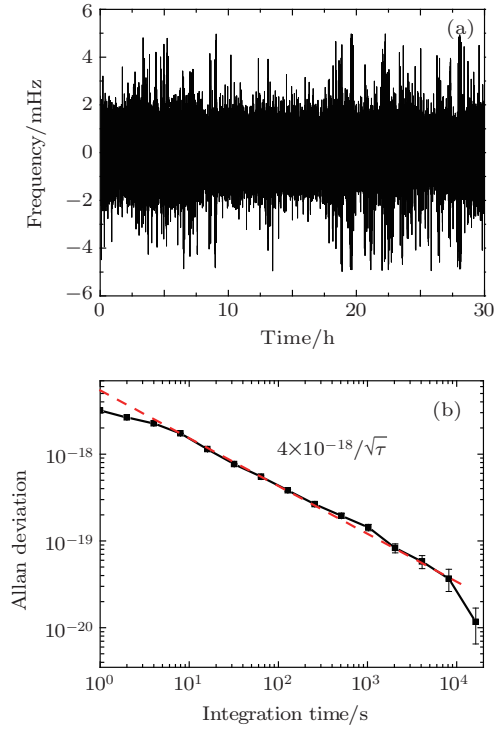


Fig. 5. (color online) (a) Residual fluctuation of the stabilized in-loop CEO frequency; (b) optical comb frequency instability induced by in-loop f_{ceo} fluctuation.

10 mHz as shown in Fig. 5(a). Considering the fact that the optical frequency is about 200 THz, the corresponding optical comb frequency stability induced by in-loop $f_{\rm ceo}$ fluctuation is about $4\times10^{-18}/\tau^{1/2}$ as shown in Fig. 5(b).

It is clear that the frequency stability induced by in-loop $f_{\rm ceo}$ fluctuation is negligible even compared with the highest stable atomic clock with a stability of $3.2\times10^{-16}/\tau^{1/2}$.[25,26]

4. Conclusion and prospect

In this work, we demonstrate a home-made Er:fiber-based optical frequency comb with an intra-cavity EOM. To the best of our knowledge, this optical frequency comb is the first domestically-made one with a fast $f_{\rm r}$ controller in the laser cavity. Both $f_{\rm r}$ and $f_{\rm ceo}$ of the comb can be stabilized continuously over a long time, owing to the high bandwidth frequency control and high SNR of frequency signals detection. The frequency instability of the system is well below 1.6×10^{-13} in 1 s and rolls down with a slope of $1/\tau$ for a short term. In the future, we will continuously optimize the system, and extend its operation frequency to strontium clock transition (698 nm) for frequency measurement.

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