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Long-term frequency-stabilized optical frequency comb based on a turnkey Ti:sapphire mode-locked laser

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We report a long-term frequency-stabilized optical frequency comb at 530–1100 nm based on a turnkey Ti:sapphire mode-locked laser. With the help of a digital controller, turnkey operation is realized for the Ti:sapphire mode-locked laser. Under optimized design of the laser cavity, the laser can be mode-locked over a month, limited by the observation time. The combination of a fast piezo and a slow one inside the Ti:sapphire mode-locked laser allows us to adjust the cavity length with moderate bandwidth and tuning range, enabling robust locking of the repetition rate (f_r) to a hydrogen maser. By combining a fast analog feedback to pump current and a slow digital feedback to an intracavity wedge and the pump power of the Ti:sapphire mode-locked laser, the carrier envelope offset frequency (f_{ceo}) of the comb is stabilized. We extend the continuous frequency-stabilized time of the Ti:sapphire optical frequency comb to five days. The residual jitters of f_r and f_{ceo} are 0.08 mHz and 2.5 mHz at 1 s averaging time, respectively, satisfying many applications demanding accuracy and short operation time for optical frequency combs.

Keywords: optical frequency comb; Ti:sapphire mode-locked laser; phase lock; optical atomic clock.

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1. Introduction

With the advent of optical frequency combs (OFCs)[1,2], optical frequency measurements have become realizable, since OFCs directly connect the frequencies of optical waves with those of microwaves in a single step. In 2000, a PCF was used to broaden the spectrum of a Ti:sapphire mode-locked laser to an optical octave, and the frequency of an iodine-stabilized laser at 282 THz was measured directly relative to a Cs frequency standard[3]. Later on, diversified new applications of OFCs have sprouted, including trace-gas sensing[4], attosecond science[5], exoplanet searches[6], generation of low-noise microwaves[7–9], and optical frequency synthesis [10,11]. The applications of OFCs in precision measurement are of the most importance. OFCs play an irreplaceable role in absolute frequency measurements[12–14] and frequency ratio measurements of optical atomic clocks[15–17], exploration of the variation of fundamental constants[17,18], etc.

The first generation of OFCs used Kerr-lens mode-locked Ti:sapphire lasers[19], which have been demonstrated to be reliable. Later, OFCs based on fiber mode-locked lasers became more widespread, largely due to their robustness. Fiber combs started to develop in 2003[20–22], and they matured in the following decade. By employing a semiconductor saturable absorbing mirror as a mode locker[23], fiber-based mode-locked lasers can achieve turnkey operation. Fiber combs can be built with all-fiber elements, including gain fibers, fiber amplifiers, and nonlinear fibers. All-fiber designs enable easy and quick assembling, as well as insensitivity to misalignment. With the use of polarization-maintaining (PM) fibers and PM components, polarization-drift-induced loss of mode locking and spectral shift is largely eliminated. The robustness of fiber combs is demonstrated with a fiber mode-locked laser on a satellite with 1 year mode-locked operation[24] and a fiber-based OFC launched on a sounding rocket[25,26].

Although fiber combs have merits of robustness, they are not perfect. (1) In order to obtain enough lasing gain, commercial fiber combs[25–27] have a cavity length larger than 0.8 m, corresponding to a repetition rate of no more than 250 MHz. However, a comb with a larger repetition rate at the gigahertz (GHz) level will provide more power in each comb line, more likely to obtain a beating signal with a good signal to noise ratio (SNR) when beating against a continuous-wave (c.w.) laser. Meanwhile, combs with a higher repetition rate can increase the update rate in dual-comb distance measurement and spectroscopy[28,29]. (2) The spectrum of OFCs based on Er-doped fiber lasers and nonlinear fibers for spectrum broadening usually covers 1–2 μm. However, the wavelength of optical atomic clocks or their fundamental lasers is in the region of 250–1130 nm[30]. In order to beat against optical atomic clocks, the output of Er-fiber combs is usually separately amplified and frequency doubled in different branches[31–33]. Such an arrangement introduces excess noise onto comb lines between different branches. Single branch design and real-time phase tracking are introduced to reduce the uncorrelated noise between comb lines[31,34]. Fortunately, a Yb-doped fiber comb covers 600–1200 nm[35], which is comfortable in applications relating to optical atomic clocks. (3) Since fiber combs use fibers with a length at the meter level as the laser cavity, they are more likely to pick up environmental perturbations, e.g., acoustic noise, vibration, temperature fluctuation, etc. For this reason, intracavity electro-optic modulators (EOMs) are employed to enable tight phase locking by achieving a servo bandwidth at the megahertz (MHz) level[35–37]. However, cross talk between the stabilizations of f_r and f_{ceo} occurs when an intracavity EOM is used[35].

On the contrary, OFCs based on Ti:sapphire mode-locked lasers have moderate repetition rates from hundreds of MHz to 10 GHz[8,38–40], suitable for applications relating to optical frequency synthesis, optical atomic clocks, astronomical spectrograph calibration, dual-comb distance measurement, and spectroscopy. Additionally, the spectrum of Ti:sapphire combs after spectrum broadening usually covers 500 nm–1100 nm. It directly covers the wavelength of Sr (698 nm), Sr^+ (674 nm), Yb (578 nm), and Ca^+ (729 nm) optical clocks. It also covers the fundamental light (before frequency doublers) of Yb^+ (467 nm and 436 nm), Hg^+ (282 nm), Al^+ (267 nm), and Hg (266 nm) optical clocks. This unique merit makes Ti:sapphire OFCs outstanding in applications related to optical atomic clocks. Moreover, the gain medium of Ti:sapphire mode-locked lasers is a Ti:sapphire crystal with a length at the millimeter level. Thus, compared with fiber combs, Ti:sapphire combs suffer less frequency noise, preferable in precision measurement. To date, Ti:sapphire combs have made milestones in the demonstration of the uniformity of comb line spacing better than 10^{-19}[39,41], absolute optical frequency measurement relative to the International System of Units (SI) unit of time at the SI limit[42], and frequency ratio measurement of optical atomic clocks at the 10^{-18} level[16].

However, easy operation and long continuous operation are the weakness of Ti:sapphire combs. Normally, Ti:sapphire mode-locked lasers are not easy to get mode-locked. Unfortunately, they lose mode locking easily due to their sensitivity to environmental perturbations, e.g., temperature variation, airflow disturbance, dust contamination, etc. As a result, it is difficult to keep a Ti:sapphire comb mode-locked for more than one day. Secondly, actuators to phase lock f_r and f_{ceo} have limited servo bandwidth and tuning range, which cannot sustain environmental perturbations.

In this Letter, to solve these problems, firstly, the cavity of the Ti:sapphire mode-locked laser is designed to have low dust contamination and small light misalignment, enabling the Ti:sapphire laser to keep mode-locked for more than a month, limited by the observation time. In order to stabilize f_r for a long time, both a fast and a slow piezo-transducers (PZTs) are employed as actuators to compensate the fluctuation and drift of the cavity length. By combining a fast analog feedback to the pump current of the Ti:sapphire mode-locked laser and a slow digital feedback to an intracavity wedge and the pump power of the Ti:sapphire laser, f_{ceo} is stabilized robustly. After taking the above measures, both f_r and f_{ceo} of the Ti:sapphire OFC are stabilized to a hydrogen maser (denoted H maser) for 5 days, a significant step towards long-term operation compared with previous Ti:sapphire combs. The frequency instability of phase-locked f_r and f_{ceo} is 0.08 mHz and 2.5 mHz at 1 s averaging time, respectively. Such a continuously frequency-stabilized Ti:sapphire OFC is believed to be a reliable and accurate tool in precision measurement.

2. Experimental Setup

The mode-locked laser used in this paper is a commercial Ti:sapphire mode-locked laser pumped by a 532 nm solid-state laser (Laser Quantum, Taccor 10). The laser cavity is a ring cavity, which consists of six mirrors, as shown in Fig. 1. Five of the cavity mirrors are installed in fixed mirror mounts without adjusting knobs in order to avoid cavity misalignment, and one cavity mirror (lower left) is mounted in a motorized mirror mount. The alignment of the laser cavity is optimized with the motorized mirror mount by monitoring the laser output power. The Ti:sapphire mode-locked laser achieves automatic mode locking by controlling a motor to knock one of the cavity mirrors (lower right). As long as it is mode-locked, it outputs a pulse train with an average power of more than 2 W and a pulse duration of 30 fs. To extend the mode-locked time, the laser cavity is sealed and circulated with filtered air, preventing dust contamination on

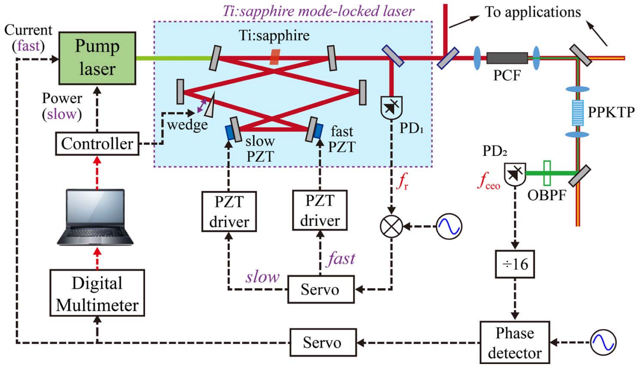

Fig. 1. Experimental setup of the frequency-stabilized Ti:sapphire OFC. The solid lines represent the light path, while the dashed lines represent the electrical path. PPKTP, periodically poled $KTiOPO_4$ crystal; OBPF, optical bandpass filter; PCF, photonic crystal fiber; PD, photo detector.

cavity mirrors and the Ti:sapphire crystal. Moreover, the Ti:sapphire crystal is shifted once in 200 h to ensure that the crystal is in excellent status. The base plate of the Ti:sapphire mode-locked laser is temperature-controlled at 23.5°C, eliminating cavity misalignment due to temperature fluctuation. Benefitting from the special laser design, the Ti:sapphire laser can keep continuously mode-locked for over a month, limited by our observation time.

To fully stabilize each comb line, two degrees of freedom need to be stabilized, f_r and f_{ceo}. The detection and frequency stabilizations of f_r and f_{ceo} are shown in Fig. 2.

The repetition rate, f_r, is directly detected on the photo detector (PD_1) with an SNR of 70 dB under a resolution bandwidth (RBW) of 300 kHz. The SNR of f_r is stable from day to day. Figure 2(a) shows the frequency drift of f_r in free running. It fluctuates within 4 kHz in 4 days, which is mainly related to the room temperature fluctuation. The frequency instability of f_r is ~1 Hz at 1 s averaging time, which is introduced by noise at the frequency of a few hertz, i.e., the vibration noise and air perturbation.

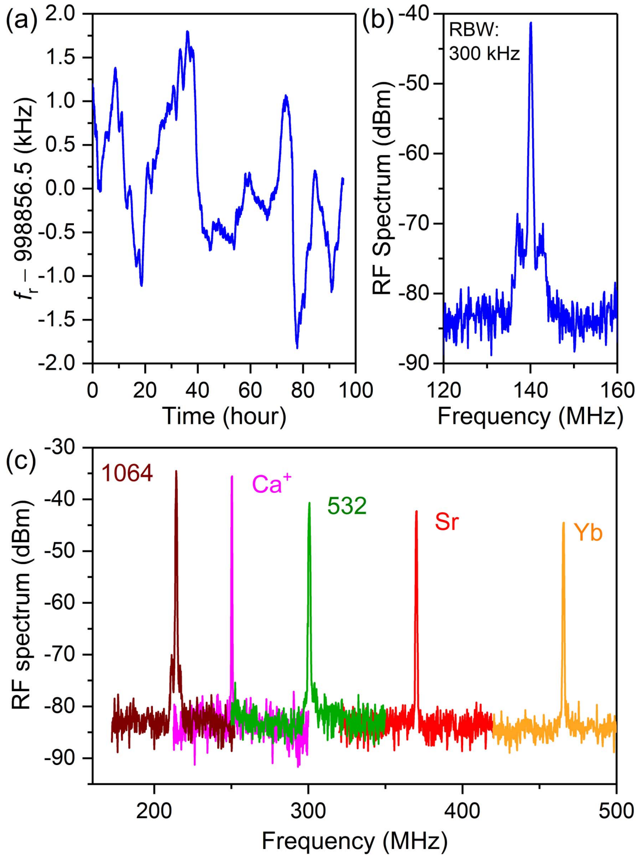

Fig. 2. (a) Frequency fluctuation of f_r when it is free running. (b) f_{ceo} detected at 532 nm with an RBW of 300 kHz. (c) Optical beat signals of the Ti:sapphire comb against a cavity-stabilized laser at 1064 nm (in dark wine), a 729 nm laser (Ca$^+$ clock, in magenta), a 698 nm laser (Sr clock, in red), a 578 nm laser (Yb clock, in yellow), and an 532 nm laser (iodine optical reference, in green) with an RBW of 300 kHz.

The signal of f_r (nearly 1 GHz) is mixed on a double-balanced mixer (DBM) against a radio frequency signal at a frequency of ~1 GHz synthesized from an H maser. The output of the DBM (error signal) is low-pass filtered and sent to a servo. To achieve long-term and robust frequency stabilization, we employ a fast and a slow servo loop to stabilize f_r. The fast servo controls the fast PZT to compensate the rapid fluctuations of the cavity length. The fast servo provides a servo bandwidth of more than 50 kHz but a limited servo range of ±1 kHz. To compensate slow drift of the cavity length due to environmental temperature drift, the slow servo integrates the error signal with a time constant of 100 s to control the slow PZT, which provides a tuning range as large as ±12 kHz.

To fully stabilize the OFC, f_{ceo} is also detected and stabilized. The pulse train of the Ti:sapphire mode-locked laser is dispersion-compensated by chirped mirrors (not shown in Fig. 1) before focusing into two pieces of PCF (FemtoWHITE 800) for spectrum broadening to more than one octave, e.g., 530–1100 nm.

The broadened spectrum output from one of the PCFs (not shown in Fig. 1) allows us to obtain beat-notes against optical atomic clocks and c.w. lasers with an SNR more than 40 dB (RBW = 300 kHz). Figure 2(c) shows the beating signals against a cavity-stabilized laser at 1064 nm[43], a 729 nm laser (corresponding to Ca$^+$ ion clock), a 698 nm laser (corresponding to Sr optical lattice clock), a 578 nm laser (corresponding to Yb optical lattice clock[44]), and a 532 nm laser (corresponding to iodine-stabilized laser). The SNR of the beat-notes varied less than 5 dB during day-to-day operation, making it feasible for applications like optical frequency measurement and laser frequency stabilization.

The broadened spectrum output from the other PCF allows us to detect the signal of f_{ceo} near 140 MHz in a collinear $1f$–$2f$ interferometer[45] with an SNR of more than 40 dB (RBW= 300 kHz), as shown in Fig. 2(b). The frequency of f_{ceo} is divided by 16 before sending it to a phase detector. An error signal relating to the phase difference between f_{ceo} and a signal at 8.75 MHz referenced to the H maser is generated in the phase detector. The error signal is sent into the f_{ceo} servo with both fast and slow feedback loops. The fast servo controls the current of the pump laser of the Ti:sapphire mode-locked laser, which has a servo bandwidth up to 350 kHz and a tuning range of about ±1.5 MHz. This limited tuning range of the pump current makes f_{ceo} lose phase locking when there is accumulated cavity dispersion change over one or two days.

3. Methods and Results

To extend the tuning range of f_{ceo}, we design a digital servo of f_{ceo} to compensate its long-term drift by adjusting the intracavity dispersion via an intracavity wedge and the pump power of the Ti:sapphire mode-locked laser. The logical block diagram is shown in Fig. 3. In this digital servo, the output voltage (V_x) of the fast servo for f_{ceo} is read once a second on a digital multimeter (Keithley 2000) to a computer. When V_x is larger than

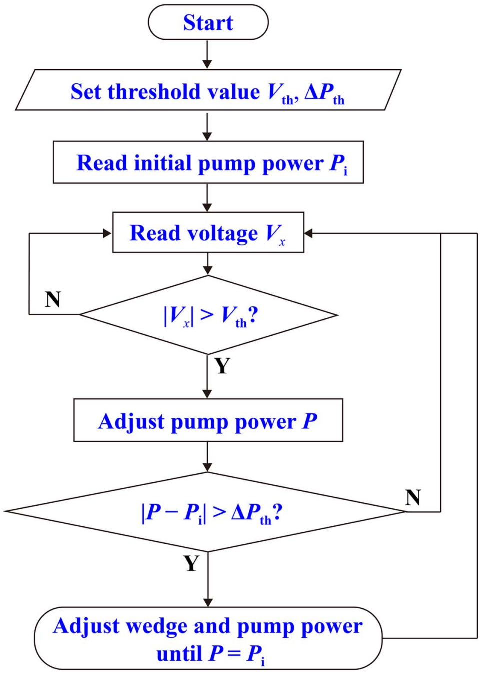

Fig. 3. Logic block diagram of digital servo of f_{ceo}.

a preset value V_{th}, the computer will send a command to adjust the pump power by a step of 1 mW. The value of V_{th} is preset to 30 mV, slightly smaller than the maximum input voltage of the Ti:sapphire laser pump current. However, when the change of the pump power is accumulated by more than 50 mW, there will be undesirable noise appearing on f_{ceo}. For this reason, when the pump power is changed by an accumulated mount larger than ΔP_{th} (ΔP_{th} is set as 50 mW here), the computer will precisely move the wedge inside the laser cavity and adjust the pump power back to its initial value ($P = P_i$). With this additional digital slow servo, the output voltage of the f_{ceo} fast servo is kept in a range of ±30 mV, and f_{ceo} can keep stabilized for a few days.

A multi-channel frequency counter (K + K Messtechnik GmbH) is employed to measure f_{ceo} and f_r when they are phase-locked to the H maser. The counter with a gate time of 1 s shares the same H maser time base. Both signals are mixed down to 1 MHz to achieve a better frequency counting resolution.

The total locking period of the comb is about 5 days, as shown in Figs. 4(a) and 4(b). By the end of the fifth day, the room temperature was raised by 3 K, leading to a large length change of the slow PZT in order to compensate the cavity length change. This made the locking state of f_{ceo} get worse (stay frequency-stabilized but with more frequency jumps) due to the coupling between the tuning of f_r and that of f_{ceo}.

During the locking period, the position of the wedge was adjusted 12 times, and a total of 27 data points of f_{ceo} are removed from Fig. 4(a) since a cycle slip of f_{ceo} happened when the wedge was adjusted. The wedge is installed on a step motor, which tunes f_{ceo} with a minimal step of ~100 kHz in a short time, leading to the cycle slip of f_{ceo}. The frequency instabilities of phase-locked f_{ceo} and f_r, as shown in Fig. 4(c), are 2.5 mHz and 0.08 mHz at 1 s averaging time, respectively. The results demonstrate that the OFC based on the Ti:sapphire mode-locked laser can be frequency-stabilized over 5 days. Although the relative frequency instability of each comb line is only 10^{-13} at 1 s averaging time, limited by the H maser, this Ti:sapphire comb can support coherence transfer or optical frequency division with an additional frequency instability of 10^{-17} at 1 s averaging time and an uncertainty at the 10^{-21} level[10], with the help of the transfer oscillator scheme and an optically referenced time base.

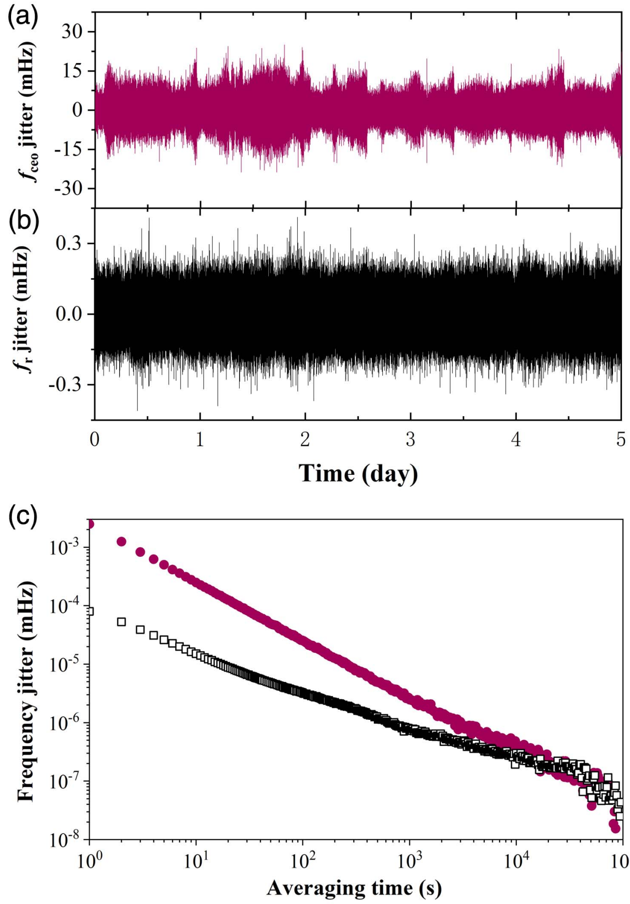

Fig. 4. Frequency jitters of (a) f_{ceo} and (b) f_r when phase-locked to an H maser. (c) The frequency instability of f_{ceo} (purple dots) and f_r (black squares).

In the near future, the OFC based on the Ti:sapphire laser will be improved to achieve longer frequency stabilization time. Firstly, the OFC could be enclosed in a temperature-controlled chamber to protect from room temperature fluctuation. Secondly, in order to avoid a cycle slip of f_{ceo}, the step motor used to tune the wedge position could be replaced by a PZT to adjust f_{ceo} smoothly. Thirdly, the coupling issue between the tuning of f_r and that of f_{ceo} still needs to be solved in the following study.

4. Conclusion

In this paper, we demonstrate a turnkey Ti:sapphire mode-locked laser with continuous mode-locking time over a month.

By employing both fast actuators for wide servo bandwidth and slow actuators for large tuning range to control f_r and f_{ceo}, the OFC based on the Ti:sapphire mode-locked laser can be continuously frequency-stabilized over 5 days. Such a frequency-stabilized Ti:sapphire OFC is believed to be a reliable and accurate tool in precision measurement.

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