A 350MHz Ti:sapphire laser comb based on monolithic scheme and absolute frequency measurement of 729nm laser

Wei Zhang Hainian Han Yanying Zhao Qiang Du Zhiyi Wei*

Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100080, China

**Corresponding author: zywei@aphy.iphy.ac.cn*

Abstract: We realized a novel frequency comb based on femtosecond Ti:sapphire laser with 350MHz repetition rate and monolithic scheme for carrier-envelope-offset frequency generation. Long-term stabilization of more than 9 hours was demonstrated by simultaneously locking repetition rate (f_{rep}) and carrier-envelope-offset frequency (f_{ceo}) to an atomic clock. The Allan deviations of f_{ceo} and f_{rep} are 2.3×10^{-13} and 1.5×10^{-15} at 100s averaging time, respectively, and the reproducibility of f_{ceo} with high accurate performance is also verified by comparison of the locking results recorded in 3 different days. By avoiding the extra noise induced by photonic crystal fiber, we obtained the accumulated phase error increase from in-loop to out-of-loop as small as 12 mrad [1Hz, 100kHz]. Furthermore, the absolute optical frequency of a stabilized 729nm Ti:sapphire laser which is referenced to a ultra-low expansion (ULE) cavity is measured by the comb and determined to be 411041985391583±10Hz.

OCIS codes: (320.7090) Ultrafast lasers; (320.7160) Ultrafast technology; (120.3940) Metrology.

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1. Introduction

The advent of the femtosecond optical frequency comb represents a breakthrough of high precision optical frequency measurement [1,2]. In 1999, the optical frequency measurement with the frequency comb based on Ti:sapphire mode-locked laser has opened a revolutionary progress in frequency metrology [3]. Since then, lots of results about the direct optical frequency measurement have been reported [4-7]. At present, as the bridge of the microwave and optical frequency standard, optical frequency combs based on femtosecond lasers have been widely used in frequency metrology and optical frequency synthesizing.

Up to now, most frequency combs are based on the technology of self-reference scheme, or termed the *f-2f* method [8,9]. Repetition rate as high as 10GHz is possible with the novel femtosecond Ti:sapphire laser [10]. However, because of the photonic crystal fiber (PCF) [11] for octave-spanning spectrum generation, the output power steeply decreases and the frequency comb is very sensitive to alignment, noise and shock. In recent years, the great progress toward octave-spanning Ti:sapphire laser with high repetition rate [12,13] gives a way to eliminate the PCF and simplify the optical frequency measurements. Specially, a self-referenced octave-spanning Ti:sapphire laser with 2.166GHz has been reported [14], where f_{ceo} can be directly generated from laser output spectrum. While, the octave-spanning Ti:sapphire oscillator involves a difficult technology and the interferometer has still to be used. With advantages of compact size, feasible configuration and low cost, the frequency comb based on the Er-doped fiber laser [15-17] is also widely accepted. Nevertheless, the weakness of large noise from fibers and low repetition rate (typically less than 200MHz) limits the accuracy in many precision measurements.

In 2005, Fuji *et al*. reported a carrier-envelope phase-stabilization scheme based on the difference frequency generation (DFG) in bulk material [18]. Compared with the conventional *f-2f* method, the new scheme replaces the PCF and the interferometer with a single MgO:PPLN crystal, then obviates the need for octave-spanning spectrum generation and simplifies f_{ceo} measurement, result in a even more compact configuration. By injecting the pulse with broadband spectrum from a sub-10fs Ti:sapphire laser at 75MHz repetition rate into a MgO:PPLN crystal, f_{ceo} with low noise can be well detected and locked. In this case, the so-called monolithic scheme provides a simple and feasible way for the long-term stabilization of f_{ceo}, which has been used in attosecond pulse

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generation [19].

In this paper, we further developed the monolithic scheme for the application of frequency metrology. A novel optical frequency comb based on a home-made sub-10fs Ti:sapphire laser with 350MHz repetition rate was established [20]. To our best knowledge, this is the highest repetition rate in monolithic schemes. By simultaneously locking f_{ceo} and f_{rep} to two microwave frequency synthesizers which were referenced to an atomic clock, continuous running time up to 9 hours was demonstrated. The reproducibility of the locked f_{ceo} signal was also verified by comparing the results recorded in 3 different days. The accumulated out-of-loop phase error of the stable f_{ceo} signal was 242 mrad [1Hz, 100kHz], or 100as timing jitter corresponding to the center wavelength of 790nm. Meanwhile, the accumulated phase error for in-loop was 230 mrad in the same integrated interval. The difference between the in- and out-of-loop phase errors is calculated to be 12 mrad. On the contrary, the typical result of accumulated phase error for out-of-loop is twice as large as that for in-loop in *f-2f* scheme [21]. Based on the progress above, the absolute optical frequency of a CW Ti:sapphire laser referenced to an ultra-low expansion (ULE) cavity was measured by the frequency comb and can be determined to be 411041985391583±10Hz.

2. Experimental setup

Different from the oscillator as the seeding source for laser amplifier, the desirable repetition rate for frequency comb is multi-100MHz, or even gigahertz. As is known to all, given a constant laser average power, each mode power of the comb linearly increases with the repetition rate. Therefore, frequency comb with high repetition rate is more helpful for optical frequency measurements. For

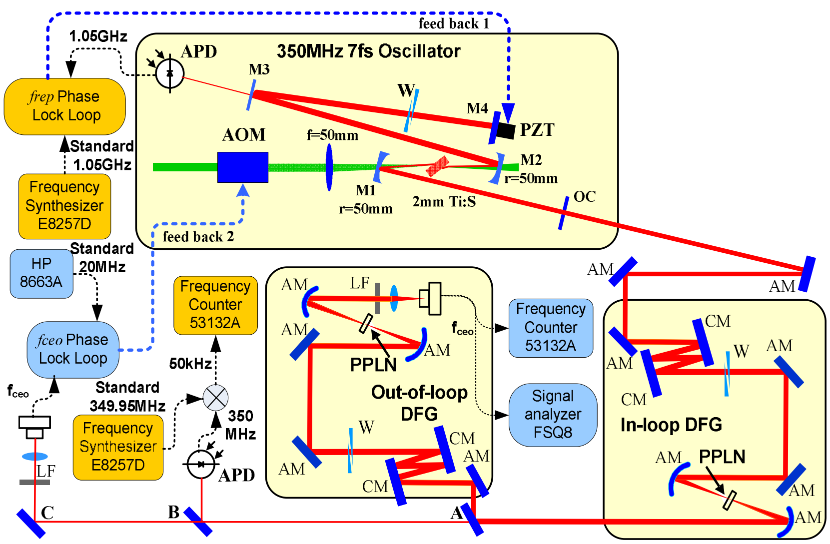

Fig. 1. Setup of the monolithic frequency comb, the femtosecond Ti:sapphire laser is depicted in the above block. M1 and M2: concave chirped mirrors, M3 and M4: plane chirped mirrors, OC: output coulper, AOM: acousto-optic modulator, W: wedge, AM: Ag mirror, CM: chirped mirror, LF: long-pass filter, feed back 1: PZT driver for f_{rep} control, feed back 2: AOM driver for f_{ceo} control.

this reason, we firstly established a mode-locking Ti:sapphire laser with 350MHz repetition rate based on chirped mirrors for dispersion compensation. Figure 1 is the schematic layout of the frequency comb system. After dispersion pre-compensating outside the cavity by a pair of chirped mirrors, the output laser with average power of 300mW and pulse duration of 7 fs is focused on a 2mm-thick MgO:PPLN crystal for DFG. As shown in Fig. 2 (a), the fundamental spectrum of the sub-10fs Ti:sapphire laser covers from 600nm to 1000nm and does not obviously change the shape after the MgO:PPLN crystal. Transmitting a long-pass filter (LF), the infrared spectrum attributed to self-phase modulation (SPM) and DFG is measured (1μm-1.6μm) and depicted in Fig. 2(b). With optimizing alignment, the beatnote between the DFG and SPM, i.e., f_{ceo} with signal-to-noise ratio (SNR) of 40dB (100 kHz resolution bandwidth) is directly observed [20] and performs better stability than that one in the *f-2f* scheme. This greatly enhances the feasibility for further locking with servo electronics. Figure 1 shows the experimental setup for f_{ceo} and f_{rep} locking. In our preliminary experiment, the signal analyzer, three microwave frequency synthesizers and two frequency counters are all referenced to a 10MHz standard signal derived from a local Rb-TV clock.

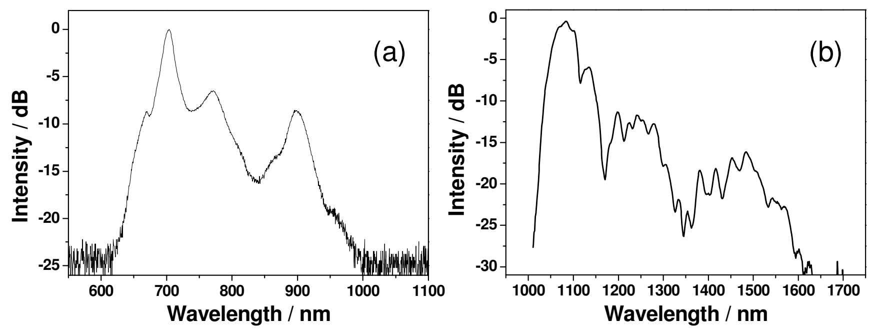

Fig. 2. (a). Laser spectrum generated by the 7-fs Ti:sapphire laser, covering from 600nm to 1000nm. (b). Infrared spectrum after MgO:PPLN crystal.

To measure the out-of-loop phase noise of f_{ceo}, we use another MgO:PPLN crystal to generate a second f_{ceo} signal. The chirped mirror A is used as diachronic beam splitter after the first MgO:PPLN crystal. The reflected portion with main part of fundamental beam (600nm-1000nm) is focused on the second crystal to generate an independent f_{ceo} signal for the out-of-loop phase error measurement (discussed in detail below). If necessary, the reflected light can also be used to generate the heterodyne frequency between an unknown single frequency-stabilized laser for optical frequency metrology. The electrical signal of f_{ceo} from the out-of-loop part is then divided into two parts; one is used for phase error analysis, and the other for counting f_{ceo} signal. The residual fundamental beam leaking from mirror A is reflected by mirror B (bandwidth 750nm-850nm) and received by an APD for f_{rep} signal recording. Reflected by a silver mirror C and passing through a long-pass filter LF, the transmitted portion with infrared light is detected by a photoreceiver (NewFocus 1811-FC) for f_{ceo} locking. Another APD (APD210, Menlo Systems) in the laser cavity is used to receive the visible portion of the beam leaking from mirror M3 to generate f_{rep} signal and its harmonics.

The repetition rate of the femtosecond laser, i.e., f_{rep}, is phase locked to a standard 1.05GHz signal from a frequency synthesizer E8257D (Agilent Inc.) and stabilized by controlling the cavity length. In the phase lock loop for the stabilization of f_{rep}, the 3rd harmonic of f_{rep} is extracted and mixed with a standard output signal of 1.05GHz from the E8257D. The phase error signal is directly fed back to the Ti:sapphire laser oscillator by a PZT mounted on the end mirror M4 to stabilize the cavity length. By mixing the f_{rep} signal, which is generated by the APD around the mirror B, with a standard signal of 349.95MHz from the second frequency synthesizer E8257D, the locking result is then counted at (f_{rep} -349.95MHz) and recorded by an universal frequency counter 53132A (Agilent Inc.).

The offset frequency of the femtosecond laser pulse, i.e., f_{ceo}, received by a photoreceiver, is phase locked to a standard 20MHz radio reference frequency derived from a frequency synthesizer 8663A (Hewlett-Packard). The phase error signal is then fed back to control the AOM driver for pump power adjust. The locking result of f_{ceo} is recorded by another universal frequency counter 53132A. Both frequency counters for f_{rep} and f_{ceo} are synchronously gated and read by PC-based software via a GPIB interface. For measuring the out-of-loop phase noise of f_{ceo}, we use a second PPLN crystal to generate a second f_{ceo} signal and a signal analyzer FSQ8 (Rohde & Schwarz Inc.) to

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obtain the single-side-band phase-noise power spectral density.

3. Optical frequency comb stabilization base on monolithic scheme.

According to the optical and electrical configuration of the femtosecond Ti:sapphire laser, both f_{rep} and f_{ceo} can be simultaneously locked to a standard reference frequency based on a local Rb clock. Furthermore, the locked status of both f_{rep} and f_{ceo} should be remained considerable long-term because of its all-solid-state and simple design. The following results verify the points we have mentioned here.

Compared with the *f-2f* scheme based on a piece of PCF for octave-spanning spectrum generation and an interferometer for f_{ceo} detection, the monolithic scheme for f_{ceo} generation without PCF can make great and outstanding contribution to the long-term stabilization. Although mechanical isolation, noise shielding and temperature stability are not good enough in our experiment, and there is no addition servos applied, the continuous locking time can be exceeded to 32673s (gate time 1-s), i.e., more than 9 hours, which is about twenty-fold longer compared to the result we have reported [22,23]. During this period, the SNR of f_{ceo} maintains above 40dB (100 kHz resolution bandwidth, inset in Fig. 3). The locked result of f_{ceo} over the whole period is shown in Fig. 3 and the standard deviation is about 2.6 mHz. As shown in Fig. 4, the instability of locked f_{ceo} in time domain is described by the Allan deviation corresponding to different averaging time. The Allan deviation starts from 2×10^{-11} (1-s gate time) and drops close to τ^{-1} (red line in Fig. 3), which is expected for the phase-locked signal.

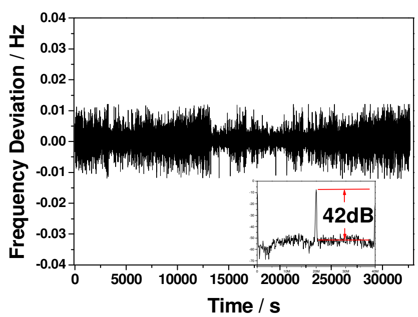

Fig. 3. The locking result of f_{ceo}, recorded directly by the counter at 1-s gate time, and the inset is f_{ceo} signal with S/N of 42dB

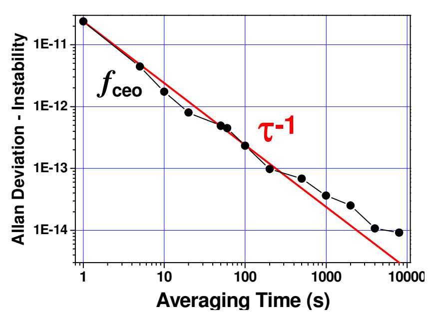

Fig. 4. Allan deviation of f_{ceo} at different averaging time

Furthermore, we investigate the reproducibility of f_{ceo} by comparing the locking results in 3 different days and then make statistical analyses for the mean and the distribution. Because the three groups are collected in different days, it is reasonable to assume that they are independent. Table 1. shows the number of date and standard deviation for each group (1-s gate time). Figure 5 gives a more convenient comparison among the three groups. The red triangle represents the mean value of each group, and the blue whisker is the brand of standard deviation. A normality test for each group has been made in order to confirm that the scatter of the data can be fitted to Gaussian.

Table 1. Summary of experimental results of f_{ceo} in three different days

Month /Date	**Number**	**Mean deviation from 20MHz+standard deviation**
12/04	**3561**	$2.69\times10^{-4}\pm0.00589Hz$
12/05	**19354**	$4.13\times10^{-4}\pm0.00402Hz$
12/06	**32673**	$3.79\times10^{-4}\pm0.00267Hz$

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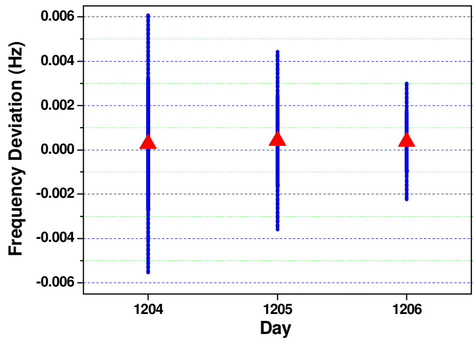

Fig. 5. The comparison of three groups recorded in three days. Red triangle-mean value. Blue whisker-standard deviation

To check the reproducibility of the locking results of f_{ceo}, we examine the homogeneity of means and uniformity of distributions of the three independent groups. A Tukey-test can be used to find out whether data from different several groups have a common mean. Base on the statistical analysis, the population means are not significant different at the indicated significance level of 0.05. The distributions of the three groups are uniform corresponding to a 95% confidence level determined from a Mann-Whitney test.

The locking result of f_{rep} is illustrated in Fig. 6. The continuous locking time is 32673s (1-s gate time), and the standard deviation is 220μHz. Figure 7 shows the Allan deviation of locked f_{rep}, starting from 6×10^{-14} (1-s averaging time) and depending on close to τ^{-1} (red line in Fig. 7).

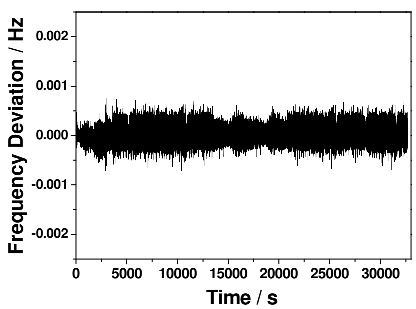

Fig. 6. The locking result of f_{rep}, recorded directly by the counter at 1-s gate time

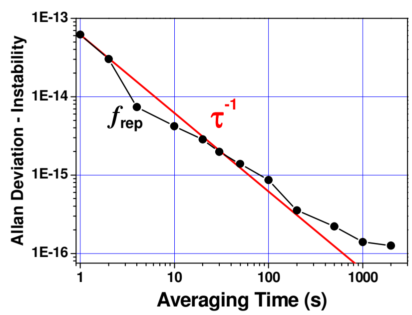

Fig. 7. Allan deviation of f_{rep} at different averaging time

4. In- and out-of-loop CEO phase error measurement

To verify the monolithic scheme is superior to the conventional *f-2f* scheme for f_{ceo} control, we use another MgO:PPLN crystal for an independent out-of-loop phase noise measurement of stabilized f_{ceo}. The laser beam directly from the oscillator is separated into two parts by a half-to-half beam splitter (mirror A). One is focused onto the first MgO:PPLN crystal for f_{ceo} control just as described above, the other part is focused onto the second MgO:PPLN crystal for an independent out-of-loop phase noise measurement. Though the SNR of f_{ceo} for each part is about 35dB (100kHz resolution bandwidth), which is lower because the input power of each beam decreases to only one half than before, it is still sufficient for control and phase noise measurement. The in- and out-of-loop single-side-band (SSB) phase-noise power spectral densities (PSD) of f_{ceo} are obtained by injecting these signals into a signal analyzer FSQ8 (Rohde & Schwarz Inc.). The measured SSB phase-noise PSD of f_{ceo} and the noise floor of FEQ8 are shown in Fig. 8, respectively. The phase error integrated from 1Hz to 100kHz is about 230mrad for in-loop and 242 mrad for out-of-loop. There is a typical 12 mrad increase from in-loop accumulated phase noise to out-of-loop. On the contrary, in the

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conventional *f-2f* scheme, where a piece of PCF is used for octave-spanning spectrum generation, the phase noise for out-of-loop is usually increased by several times compared with that for in-loop. As reported in Ref. [21], the accumulated phase noise is 0.1 rad for in-loop and more than 0.2 rad for out-of-loop [1Hz, 100kHz], corresponding to an approximate two-fold increase. This significant difference originates from the conversion of amplitude fluctuations to phase fluctuations in PCF. Based on the monolithic scheme, however, there is no additional noise introduced by PCF, and then the difference between in- and out-of-loop is steeply decreased.

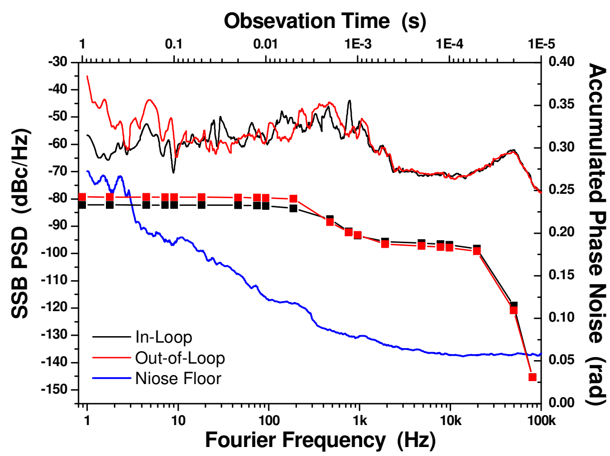

Fig. 8. Bottom-Left: the SSB noise power spectrum of f_{ceo} as the function of Fourier frequency. Black line: in-loop phase error. Red line: out-of -loop phase error. Blue line: the noise floor of the signal analyzer. Top-Right: the accumulated phase noise of in-loop (black closed square) and out-of-loop (red closed square) as the function of observation time.

5 Optical frequency measurement with frequency comb

To demonstrate the feasibility of the frequency comb based on monolithic scheme, we further measure the absolute optical frequency of a ULE-stabilized CW Ti:sapphire laser at 729nm. Due to the broadband output spectrum from 600nm to 1000nm and high averaging power of 200mW, there is no extra part of spectrum broadened for beatnote generation with the ULE-stabilized 729nm laser. The output laser from frequency comb reflected by the mirror A (as shown in Fig. 1) is used to generate the beatnote with the ULE-stabilized 729nm laser. The average power of the 729nm line in the comb is calculated to be about 0.2mW. The SNR of the beatnote is about 46dB (as depicted in Fig. 9, 100kHz resolution bandwidth), which is sufficient for direct record by the universal frequency counter 53132A (Agilent Inc.).

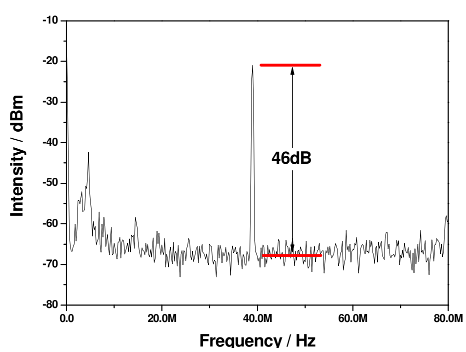

Fig. 9. Beatnote with SNR of 46dB between the frequency comb and ULE-stabilized cw 729nm laser

The absolute optical frequency can be determined by [1,2]

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$$f_{opt} = nf_{rep} \pm f_{ceo} \pm f_{beat}$$

where the integer n can be solved by using a calibrated wavemeter (WA-1500, Burleigh). The signs in the equation can be determined by observing the variation of the beatnote while increasing the f_{ceo} and f_{rep} .

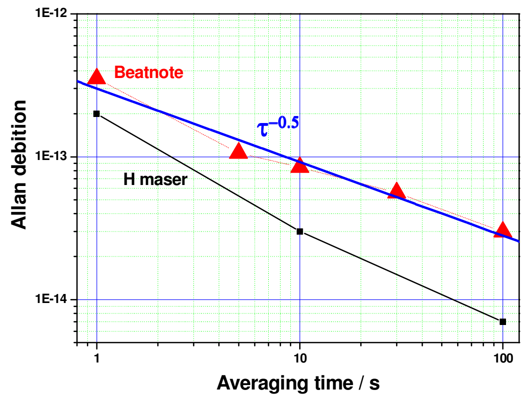

Fig.10. Allan deviation of optical frequency measurement at different averaging time

Figure 10 shows the Allan deviation of the measured optical frequency. The solid-triangle curve stands for the beatnote between the comb based on an H maser (CH1-75A Kavrz) and the CW 729nm laser referenced to the ULE cavity. To avoid the effect of the dead time, the averaging time is equal to the gate time of the frequency counter used to make the frequency measurements. The solid blue line is the linear fit of data points corresponding to different averaging time. The Allan deviation of the optical frequency measurement starts from 3.5×10^{-13} at 1s averaging time and drops as $\tau^{-0.5}$ as is expected. The black solid-square curve indicates the Allan deviation of H maser, which limits the measured instability especially in short term regime (<10s). The measurement result is shown in Table 2, including Allan deviation at different averaging time, number of recording points and the mean deviation from the center optical frequency 411041985MHz. The weighed mean of column 3 yields $0.391583\pm1.00272\times10^{-5}$ MHz, corresponding to a relative uncertainty of 2.4×10^{-14} at 411THz. Based on the results shown above, the absolute optical frequency measured by the frequency comb can be calculated to be

$$\boldsymbol{f_{opt} = nf_{rep} - f_{ceo} - f_{beat} = 4110419853\,91583 \pm 10 Hz}$$

Table 2. Summary of the optical frequency measured results at different gate time

Gate time(s)	**Number**	**Allan deviation**	**Mean deviation from 411041985 (MHz)**
1	1800	3.52537E-13	0.39359 ± 1.44908E-4
5	150	1.062E-13	0.39276 ± 4.36527E-5
10	57	8.46265E-14	0.39194 ± 3.4785E-5
30	37	5.61042E-14	0.39106 ± 2.30612E-5
100	10	2.97961E-14	0.39158 ± 1.22474E-5

6. Conclusion

We have realized a novel frequency comb based on a femtosecond Ti:sapphire laser with 350MHz

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repetition rate and monolithic scheme for carrier-envelope-offset frequency generation in MgO:PPLN crystal. In addition, long-term stabilization and precise control were demonstrated. The continuous locking time can be exceeded to more than 9 hours without additional servos. It is possible to remain the locked state in longer time duration if better mechanical isolation for frequency comb can be applied and more stable temperature stability for the whole system can be achieved. The reproducibility of f_{ceo} locked performance has been verified by comparing the data in three different days and using statistical analyses for the mean and distribution. By integrating the SSB phase-noise power spectral density from 1Hz to 100kHz, we measured the difference between the in- and out-of loop phase errors as small as 12 mrad. The feasibility was further verified by measuring the optical frequency of a CW 729nm laser referenced to an ULE cavity. The relative uncertainty of the optical frequency at 729nm can be calculated to be 2.4×10^{-14}. These results not only pave a solid way toward a robust optical frequency metrology with advanced specifications, but also demonstrate a feasible technology for the experiments related to CE-Phase sensitive phenomena.

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