Demonstration of an optical frequency synthesizer with zero carrier-envelope-offset frequency stabilized by the direct locking method

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Abstract: We developed an optical frequency synthesizer (OFS) with the carrier-envelope-offset frequency locked to 0 Hz achieved using the "direct locking method." This method differs from a conventional phase-lock method in that the interference signal from a self-referencing f-2f interferometer is directly fed back to the carrier-envelope-phase control of a femtosecond laser in the time domain. A comparison of the optical frequency of the new OFS to that of a conventional OFS stabilized by a phase-lock method showed that the frequency comb of the new OFS was not different to that of the conventional OFS within an uncertainty of 5.68×10^{-16}. As a practical application of this OFS, we measured the absolute frequency of an acetylene-stabilized diode laser serving as an optical frequency standard in optical communications.

OCIS codes: (120.5050) Phase measurement; (140.3425) Laser stabilization; (260.7120) Ultrafast phenomena.

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1. Introduction

The femtosecond mode-locked laser (FML) has become an essential tool for a variety of applications, such as absolute optical frequency measurements [1, 2, 3, 4], high-resolution spectroscopy [5], and determinations of fundamental physical constants [6] over the past decade with exceptional optical frequency traceability to microwave frequency standards. Such achievements were made possible by the advent of the stabilizing technology for the optical comb that allowed it to be used as an optical frequency synthesizer (OFS), where the repetition frequency (f_{rep}) and the carrier-envelope-offset frequency (f_{ceo}) should be stabilized to a precise frequency reference, such as a Cs clock, by the phase-locked loop (PLL) method. The mode frequencies of the optical comb are then given as the sum of f_{ceo} and Nf_{rep}, where N is an integer of an order of 10^6. Although this OFS stabilization scheme has shown unprecedented absolute frequency accuracy, satisfying numerous applications in precision science, this method is inconvenient for the formulation of a zero f_{ceo} when the OFS frequencies must have the exact harmonics of f_{rep}. An OFS with zero f_{ceo} has several advantages; the optical frequency measurement can be made simpler without measuring f_{ceo}, the optical clockwork can be made easier and thus potentially more stable [7], and the frequency grid for optical communication channels, which should be exact multiples of a prescribed frequency spacing [8], can be realized easily.

There have often been attempts to formulate a zero f_{ceo}. One approach is to insert an acousto-optic modulator (AOM) in one arm of a self-referencing f-2f interferometer to give the comb frequency a pre-shift by the same amount of the frequency used for f_{ceo} stabilization but with an opposite sign [9, 10]. Another approach involves adopting the generation of the difference frequency in a nonlinear crystal (DFG) [7, 11, 12], utilizing the fact that the difference frequency between two modes from the same frequency comb cancels f_{ceo} as contained simultaneously in the two modes. On the other hand, in the field of ultrafast phenomena, a new approach known as the "direct locking method (DLM)" [13, 14, 15, 16] has been developed, satisfying the need for carrier-envelope-phase (CEP) stabilization. The DLM is a time-domain approach with no pulse-to-pulse phase slip, in contrast to other CEP stabilization approaches operating in the frequency domain. This method was developed for ultrafast laser-matter interactions in a few optical cycle regimes, such as above-threshold ionization and high-harmonic generation [17, 18]. The DLM directly uses the beat signal from an f-2f interferometer as an error signal and quenches it through negative feedback to the FML, generating pulses with identical CEP values, or equivalently zero f_{ceo} values. This method does not require any reference RF signal to be generated by a high-quality local oscillator. Instead only a low-noise dc reference is required because a feedback signal is generated directly from the f-to-2f beat signal in the time domain. Furthermore, it does not require a highly sensitive RF phase detector, a RF spectrum analyzer for monitoring, or a frequency-referenced frequency counter for f_{ceo} measurements. In addition to these advantages, the fact that the output pulses have zero f_{ceo} values implies that the DLM can be utilized an alternative method of constructing an OFS with zero f_{ceo}, as it is naturally achieved.

In this paper, an OFS with zero f_{ceo} realized by a DLM is demonstrated. To evaluate the accuracy of its frequency, the frequency of the OFS was compared to that of an OFS stabilized by a conventional PLL method using the direct comb comparison technique [19] in which a comb-injection lock was utilized. As an example of a practical application, we measured the absolute frequency of an acetylene-stabilized diode laser used as an optical frequency standard in optical communications.

2. Experimental setup and Results

The OFS with zero f_{ceo} frequency was realized using a DLM, as shown in the upper part of Fig. 1. The femtosecond Ti:sapphire laser, FML1, had a standing-wave configuration with a prism pair to compensate for the group velocity dispersion, generating 15-fs pulses with a repetition frequency of 100 MHz. The average output power of FML1, pumped by a 6-W 532-nm laser (Verdi 6 from Coherent Inc.), was 600 mW and the center wavelength was approximately 800 nm with a spectral width of 50 nm.

The repetition frequency (f_{rep1}) of the FML1 was initially stabilized for the generation of a precise mode expanse of the frequency comb in the frequency domain. The f_{rep1} value was controlled by altering the applied voltage with a piezoelectric actuator mounted at an output coupler mirror and detected with a fast photo-diode at a bandwidth of 1-GHz. The 10th harmonic of f_{rep1} was extracted by a band-pass filter to reduce the background noise during the detection process. An error signal was produced by a phase comparison between the detected

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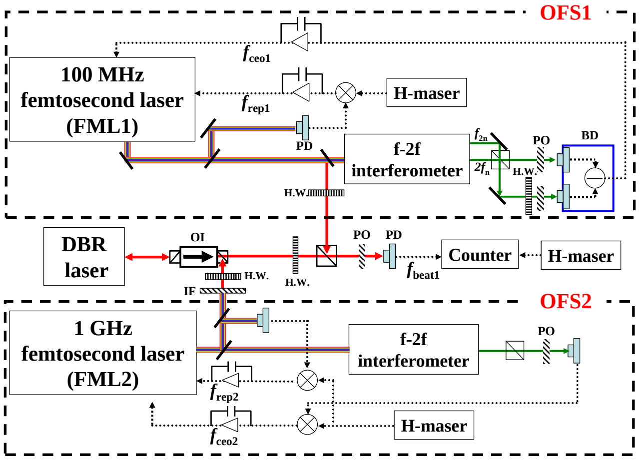

Fig. 1. Experimental scheme for the realization of an optical frequency synthesizer (OFS1) with a zero carrier-envelope-offset frequency using the direct locking method (upper part) and the evaluation of its accuracy in a direct comparison (middle part) with an optical frequency synthesizer (OFS2) stabilized by a conventional PLL method (lower part). H.W., half-wave plate; IF, interference filter; OI, optical isolator; PO, polarizer; PD, high speed photodiode; BD, balanced detector; DBR, distributed-Bragg-reflector.

10th harmonic signal and the reference frequency of 1 GHz received from an RF synthesizer phase-locked to a hydrogen maser (H-maser) with a frequency stability of 2×10^{-13} at 1 s. The error signal corrected any change in the f_{rep1} of FML1, maintaining the stability of the frequency comb comparable to that of the H-maser.

The carrier-envelope-offset frequency (f_{ceo1}) of FML1 was then stabilized by the DLM. In our system, the carrier-envelope-phase (CEP) was stabilized both by changing the power of the pumping laser using an AOM to stabilize varying CEP components rapidly within 100 Hz - 100 kHz and by tilting the FML1 end mirror, having a much wider dynamic range, for the long-term stabilization of CEP components below 100 Hz. An f-to-2f interferometer with a Mach-Zehnder configuration was used to generate a beat signal containing the CEP. The output of FML1 was focused into a photonic crystal fiber to generate an octave-spanning optical comb ranging from 500 nm to 1100 nm. The long-wavelength part of the octave-spanning optical frequency comb around 1060 nm was frequency-doubled by a BBO crystal and overlapped with the short wavelength part around 530 nm. A delay line was used in the short-wavelength arm to match the optical path length. The beat signal in this f-2f interferometer was measured with a fast photodiode, obtaining a signal-to-noise ratio higher than 30 dB. In a conventional PLL method, the f_{ceo1} signal from the f-2f interferometer is compared with a fixed frequency reference to produce an error signal for f_{ceo1} stabilization. However, in the DLM, the beat signal itself was used as an error signal in near-zero frequency, automatically obtaining zero f_{ceo1} by quenching the beat signal [$I_{f_{2n}-2f_n} = \sqrt{I_{f_{2n}} I_{2f_n}} sin\phi_{cep}(t) \approx \sqrt{I_{f_{2n}} I_{2f_n}} \phi_{cep}(t)$, [14]]. Here, f_{ceo1} stabilization by the DLM did not require a high-quality reference oscillator, a highly sensitive RF phase detector, monitoring of the RF spectrum analyzer, or a frequency counter, in contrast to the conventional PLL method.

For more stable operation of f_{ceo1}, a special precaution was taken, as introduced in an earlier study [14]. As the DLM operates in a low frequency range of f_{ceo1} near 0 Hz, the phase component of the error signal cannot be separated easily from the slow intensity fluctuation. Given that this dc noise can be converted into a carrier envelope phase noise, a homodyne balanced

Table 1. Measurement summary of the frequency difference between OFS1 and OFS2. The weighted mean of the difference frequencies (column 3) is calculated as (-0.05 ± 0.20)Hz, which corresponds to a relative uncertainty of 5.68×10^{-16} at 352 THz.

Gate time	Allan deviation	Weighted mean of comb frequency difference	Relative uncertainty	Approved readings
1 s	1.89×10^{-13}	-0.67 ± 1.02 Hz	2.89×10^{-15}	1633
3 s	8.23×10^{-14}	-0.49 ± 0.76 Hz	1.39×10^{-15}	651
10 s	2.18×10^{-14}	0.01 ± 0.33 Hz	9.37×10^{-16}	125
30 s	6.74×10^{-15}	0.03 ± 0.29 Hz	8.23×10^{-16}	51

detection method was adopted to select the pure beating signal from the f-to-2f interferometer, suppressing the dc noise in the f_{ceo1} signal. The combined laser beam in the f-to-2f interferometer was separated into two parts using a polarizer, as shown in Fig. 1, and the beat signal from each path was detected separately using the photodiode of a balanced detector. A half-wave plate was inserted in one path to make the phase difference between the two beat signals be out of phase (π). One beat signal was subtracted from the other in the balanced detector. This signal processing method cancelled the intensity part (dc part) of the f_{ceo1}, whereas the phase part (ac part) doubled. The experimental f_{ceo1} detection setup was placed in a closed box for a further reduction of the residual phase noise during the stabilization of f_{ceo1}, suppressing the air flow in the f-to-2f interferometer. Through these phase-locking processes, an OFS1 with zero f_{ceo1} was constructed. When f_{ceo1} was stabilized, the phase jitter of the f_{ceo1} error signal was measured to be 49 mrad from only the in-loop error signal of the lock servo. The residual frequency fluctuation of f_{ceo1} was estimated to be about 10 mHz by differentiating the phase error signal; this is comparable to that of an OFS stabilized by a conventional PLL method.

To evaluate general performance of the new OFS1 as a precise frequency metrology tool, its frequency was compared with another OFS stabilized by a conventional PLL method (OFS2), as shown in the lower part of Fig 1. The experimental setup for this comparison is shown in the middle part of Fig. 1. FML2 is a ring-cavity type of femtosecond Ti:sapphire laser with a repetition frequency near 1.03 GHz. The f_{ceo2} value of FML2 was stabilized to 345 MHz using a reference RF signal. As these two combs have greatly different repetition frequencies, it is difficult to directly compare the comb frequencies [20]. Thus, a single-mode distributed-Bragg-reflector (DBR) laser was used which was injection-locked to a single mode of OFS2 [19, 21, 22, 23]. The selected comb mode of OFS2 was amplified by a DBR laser and overlapped with OFS1 to compare the frequencies of these two optical frequency synthesizers. The heterodyne beat frequency between the DBR laser, which was injection-locked to the 342127$^{\text{th}}$ mode of OFC2, and the close-lying 3522154$^{\text{th}}$ mode of OFS1 was detected using a photodiode. The selected comb mode number of OFS2 was determined utilizing the D2 transition spectrum of a cesium atom around 852 nm, of which the absolute frequency is accurately known [24]. The frequency difference between these two comb modes was measured by a high-resolution frequency counter (53132A from Agilent Technologies, Inc.) which was referenced to the same H-maser used for the stabilization of OFS1 and OFS2. The signal-to-noise ratio of the heterodyne beat signal was more than 30 dB in a resolution bandwidth of 300 kHz, which ensured the correct frequency counting.

The frequency difference between OFS1 and OFS2 was measured in 17 data sets in total with counter gate times of 1, 3, 10, and 30 s. The weighted mean of the frequency difference for the respective gate time is shown in Table 1. The Allan deviation is derived from the frequency difference between the two OFSs at each gate time. The Allan deviation at a counter gate time of 1 second was found to be 1.89 parts in 10^{13} and was determined as inversely proportional

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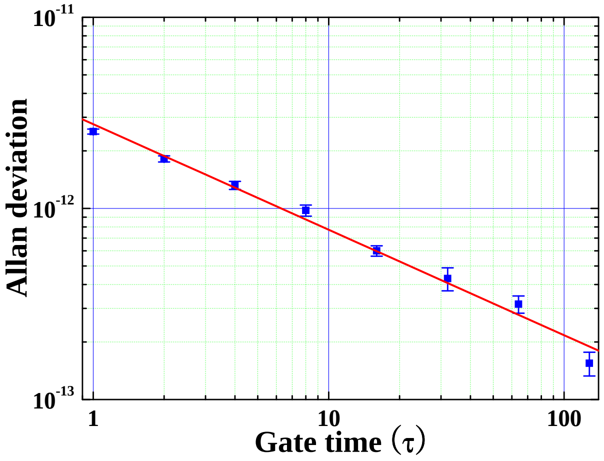

Fig. 2. Allan deviation derived from the beat frequency between one of the stabilized comb modes of OFS1 and an acetylene-stabilized laser. The decrease is inversely proportional to the square root of the counter gate time.

to the counter gate time, which implies that the signal is caused by white phase noise. This result is feasible because we compared the frequencies of two types of OFSs whose phases were stabilized to a common H-maser. Using standard statistical methods [25], we combined all the data to calculate the weighted mean with a total acquisition time of 6366s. The weighed mean of frequency difference between OFS1, which was stabilized using the DLM, and OFS2, which was stabilized using a conventional PLL method, was estimated to be -0.05 Hz with an uncertainty of 0.20 Hz. The relative uncertainty is thus 5.68×10^{-16}, as the optical frequency was compared at 352 THz. This result implies that the optical frequency of the newly demonstrated OFS1 with zero f_{ceo1} by the DLM coincides with that of the conventional OFS2 using a PLL method. Accordingly, the OFS1 is shown to be as capable as a conventional device used with the PLL method. This device can therefore be applied successfully in frequency metrology.

As an example of an application of this OFS1 in frequency metrology, we measured the absolute frequency of a diode laser stabilized to the P(16) transition line of acetylene ($^{13}C_2H_2$). This laser is recommended as a frequency standard in optical communications by the International Committee for Weights and Measures (CIPM) [26]. The acetylene-stabilized laser was a commercial laser (Neoark, model number C2H2LDS-1540). The acetylene cell pressure was 4 Pa, the frequency modulation width 1 MHz, the cell resonator finesse 200, and the fiber coupled output power was 1 mW. As all of these values are within the CIPM-recommended condition, this application can examine the quality of the new OFS in frequency metrology.

The measurement of the frequency proceeded as followings. Given the wavelength of the acetylene-stabilized laser, at 1542 nm, was out of range of the optical comb, a waveguide-type periodically-poled lithium niobate (PPLN) was used for a second harmonic generation after power amplification by an erbium-doped fiber amplifier (EDFA). The frequency of the beat signal between the frequency-doubled 771 nm radiation and the nearest comb mode of OFS1 was measured. The signal-to-noise ratio of the beat signal was about 30 dB at a resolution bandwidth of 300 kHz.

With the result of the measurement, the mean frequency, uncertainty, and the stability of the laser were determined. Figure 2 shows the Allan deviation of the measured beat frequency as a function of the counter gate time. It starts at 3×10^{-12} at 1 s and shows a dependence of $1/\sqrt{\tau}$, where τ is the gate time, implying that it is of white frequency noise. As the stability of OFS1, of

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which the repetition frequency was phase-stabilized by an H-maser, was better than that of the acetylene-stabilized laser by more than one order of magnitude, the observed instability (Allan deviation) was mainly attributed to the frequency instability of the acetylene-stabilized laser. The absolute frequency of the acetylene-stabilized diode laser was found to be 194 369 569 386.5 kHz with a statistical uncertainty of 0.2 kHz (1.1×10^{-12}). This measurement result is in good agreement with the CIPM-recommended value of 194 369 569 384(5) kHz. It also agrees well with the result of a recent study [27] in which the absolute frequency of an acetylene-stabilized laser was measured using an optical comb stabilized by a conventional PLL method. This result clearly shows that new OFS can provide a reliable optical comb that shows no differences in terms of the frequency accuracy from the conventional comb.

3. Conclusions

We demonstrated a new method for the construction of an optical frequency synthesizer based on a femtosecond mode-locked laser with a zero carrier-envelope-offset frequency. To do this, a simple and inexpensive DLM technique was adopted and the repetition frequency was stabilized to an H-maser with the well-known PLL method. It was verified through a direct comb comparison that this new type of OFS with a zero f_{ceo} value performed as feasibly as a conventional OFS in which f_{ceo} is stabilized by the PLL method. We also measured the absolute frequency of an acetylene-stabilized laser as a practical application of the OFS, and this result was in good agreement with the recommended frequency value. When combined with a comb injection technique that determines a single comb mode, we expect that this OFS will be utilized as a frequency-standard light source in optical communications as the frequency grid of the channels for dense wavelength-division multiplexing.

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