

Demonstration of an Optical Frequency Synthesizer with Zero Carrier-Envelope-Offset Frequency Stabilized by the Direct Locking Method

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INTRODUCTION

The optical frequency synthesizer (OFS) based on an octave-spanning femtosecond mode-locked lasers (FML) has ever shown the exceptional optical frequency traceability to microwave frequency standards based on Cs atoms in simple and reliable way. Owing to this feature it has become an essential tool for a variety of applications, such as absolute optical frequency measurement [1, 2, 3, 4], high resolution spectroscopy [5], and determination of fundamental physical constants [6] for the past decade. And the stabilizing technology is being developed incessantly to expand its use to wider application fields. The mode frequencies of the optical comb are then given as the sum of f_{ceo} and $N f_{\text{rep}}$, 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 as 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.

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 repetition frequency (f_{rep1}) of the FML1 was initially stabilized for the generation of a precise mode expansion 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 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.

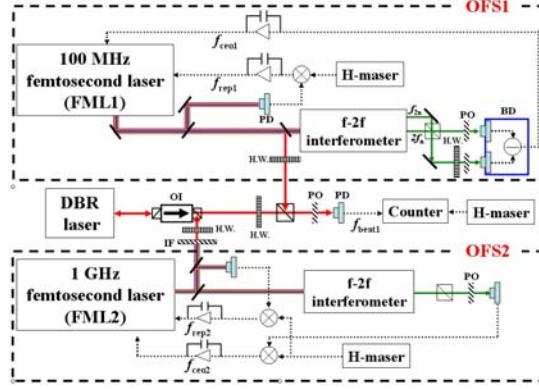


Fig. 1. Experimental scheme for the realization of an optical frequency synthesizer (OFS1) with a zero carrier-envelope-offset frequency using the direct locking method (upper part) and the evaluation of its accuracy in a direct comparison (middle part) with an optical frequency synthesizer (OFS2) stabilized 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.

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 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.

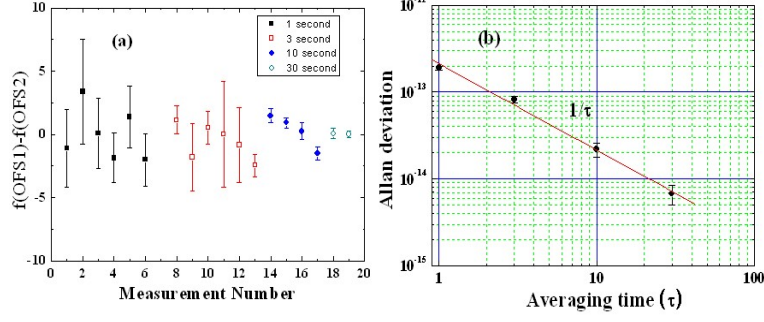


Fig. 2. (a) The results of comb comparison between OFC1 and OFC2 using comb-injection locking technique with different counter gate times of 1 s, 3 s, 10 s, and 30 s. The error bars represent the standard errors. (b) The Allan deviation of the frequency difference between two combs.

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 342127th mode of OFC2, and the close-lying 3522154th 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 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 measured frequency difference between the OFS1 and the OFS2 is shown in Fig. 2(a). We measured the comb frequency difference with the counter gate times of 1, 3, 10, and 30 s. The error bars in Fig. 2(a) represent the standard errors, which are the standard deviations divided by the square root of the data number of each measurement. Figure 2(b) shows the Allan deviation derived from the frequency difference between the two OFCs at the gate times of 1, 3, 10, and 30 s. The Allan deviation at a counter gate time of 1 second was measured to be 2 parts in 10^{13} and it was inversely proportional to the counter gate time, which implies that the signal is of white phase noise. This result is reasonable because we are comparing the frequency of two types of OFS's, whose phases are stabilized to a common hydrogen maser. By taking the weighted mean of the total measurement data with a total acquisition time of 6027 s, the frequency difference between the OFS1, which was stabilized using the DLM, and the OFS2, which was stabilized using a conventional PLL method is estimated to be 0.10 Hz with the uncertainty of 0.17 Hz. The relative uncertainty is

4.8×10^{-16} as the optical frequency was compared at 352 THz. This result means that the optical frequency of the newly demonstrated OFS with zero-offset frequency by the DLM coincides with that of the conventional OFS using a PLL method. Accordingly, the OFS with zero-offset by the DLM is proved to have as good capability as a conventional one by the PLL method and expected to be successfully applied 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 ($^{13}\text{C}_2\text{H}_2$). 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. 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.

CONCLUSION

We demonstrated a new method for the construction of an optical frequency synthesizer based on a femtosecond mode-locked laser with 0 Hz carrier-envelope-offset frequency. Simple and inexpensive DLM technique was adopted to make the offset frequency 0 Hz, while the repetition frequency is stabilized with the well known PLL method. We verified that this new type of OFS with zero-offset frequency shows as good performance as a conventional OFS, of which f_{ceo} was stabilized by the PLL method. We also measured the absolute frequency of an acetylene-stabilized laser as an example of practical application of the OFS and the result agree well with the recommended frequency value. When combined with the comb injection technique [21-23] to select out a single comb mode, we expect that this OFS with zero-offset frequency will be utilized as a frequency-standard light source for the optical communication, as the frequency grid of the channels for the dense wavelength-division multiplexing has been recommended to be a multiples of a specified spacing, such as 100 GHz, 50 GHz, 25 GHz or 12.5 GHz, around 193.1 THz [8], which is easily realized if the f_{ceo} is zero.

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