

Precise determination of characteristic laser frequencies by an Er-doped fiber optical frequency comb

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Precise determination of characteristic laser frequencies by an Er-doped fiber optical frequency comb

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Femtosecond optical frequency combs correlate the microwave and optical frequencies accurately and coherently. Therefore, any optical frequency in visible to near-infrared region can be directly traced to a microwave frequency. As a result, the length unit "meter" is directly related to the time unit "second". This paper validates the capability of the national wavelength standards based on a home-made Er-doped fiber femtosecond optical frequency comb to measure the laser frequencies ranging from visible to near-infrared region. Optical frequency conversion in the femtosecond optical frequency comb is achieved by combining spectral broadening in a highly nonlinear fiber with a single-point frequency-doubling scheme. The signal-to-noise ratio of the beat notes between the femtosecond optical frequency comb and the lasers at 633, 698, 729, 780, 1064, and 1542 nm is better than 30 dB. The frequency instability of the above lasers is evaluated by using a hydrogen clock signal with a instability of better than 1×10^{-13} at 1-s averaging time. The measurement is further validated by measuring the absolute optical frequency of an iodine-stabilized 532-nm laser and an acetylene-stabilized 1542-nm laser. The results are within the uncertainty range of the international recommended values. Our results demonstrate the accurate optical frequency measurement of lasers at different frequencies using the femtosecond optical frequency comb, which is not only important for the precise and accurate traceability and calibration of the laser frequencies, but also provides technical support for establishing the national wavelength standards based on the femtosecond optical frequency comb.

Keywords: optical frequency measurement, phase lock, Er-doped fiber laser, fiber optical frequency comb

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1. Introduction

National wavelength standards (NWSs) are the basis of the geometrical value transfer system. Their technical sophistication is closely related to national industrial development. In recent two decades, modern processing and technology have increased the number of requirements for improving measurement accuracy, precision, and uncertainty, which is a great challenge for the development of metrological standards. Faced with this requirement, on the one hand, researchers are constantly working to improve the performance of existing basic standard devices, and on the other hand, they are also constantly studying and developing new basic standard technologies with higher technical sophistication.

Iodine-stabilized 633-nm He–Ne laser radiation is the most popular in terms of application, influence, and contribution to the length measurement among the frequency-stabilized laser radiations recommended for defining the length unit "meter" by Bureau International des Poids et Mesures (BIPM).[1] Subsequently, a length measurement system based on 633-nm laser has been gradually formed. However, with the development of science and technology, social progress and industry, the iodine-stabilized 633-nm He–Ne laser is unable to meet the requirements of quantity transfer in some aspects.

Firstly, the iodine-stabilized 633-nm He–Ne laser wavelength standard needs to participate in international comparison to achieve quantity traceability.[2] The traceability of geometric values and the international mutual recognition of measurement results are only guaranteed if the NWSs pass international validation. Secondly, the iodine-stabilized 633-nm He–Ne laser wavelength standard can only transfer the quantity value at this single wavelength. Conversely, semiconductor lasers are small in size while solid-state lasers have a high output power with a good frequency instability. Meanwhile, fiber lasers are even more compact with a strong resistance to disturbance. All of these lasers are very popular as coherent light sources. For example, the iodine-stabilized 532-nm Nd:YAG laser without modulation output has more advantages for practical length measurement.[3] The absolute optical frequency and instability of the frequency-stabilized 780-nm laser used in the cold rubidium atomic gravimeter must be precisely addressed.[4] The parameters of these lasers cannot be traced by the iodine-stabilized 633-nm He–Ne laser. Thirdly, the uncertainty of the iodine-stabilized 633-nm He–Ne laser is limited to the order of 10^{-11}.[5] This laser wavelength standard can be used to measure the frequency instability, reproducibility and vacuum wavelength value of lasers including frequency-stabilized Lamb-dip He–Ne lasers, frequency-stabilized transverse Zeeman He–Ne

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lasers, frequency-stabilized dual longitudinal mode He–Ne lasers, and so on. However, the uncertainty of the order of 10^{-11} indicates that they can no longer fully meet the requirements due to technological advancement.

The limited performance of the iodine-stabilized 633-nm He–Ne laser in the quantity transfer necessitates developing new advanced laser wavelength standards with higher uncertainty. Establishment of NWSs based on a femtosecond optical frequency comb (FOFC) can effectively replace the iodine-stabilized 633-nm He–Ne laser while also adapting the progress of science and technology.

An FOFC can conduct absolute optical frequency, real-time international comparison, and equivalent mutual recognition.[6] An FOFC connects the microwave and optical frequencies precisely and simply.[7] Therefore, any optical frequency from visible to near-infrared region can be directly traced to a microwave frequency. Hence the length unit "meter" is directly traced to the time unit "second". Real-time international comparison and recognition is conducted especially, when FOFC is linked to the Coordinated Universal Time (UTC). An FOFC also has a wide wavelength measurement range, from visible to near-infrared region, and can transfer the quantity value across this range. An FOFC can effectively trace the optical frequency values of the 532-nm and 780-nm lasers as well as those of other optical clock lasers. The measurement uncertainty of an FOFC can reach the order of 10^{-16}.[8] For laser wavelength calibration, a relative uncertainty of the order of 10^{-12} is more than sufficient for practical applications. The uncertainty of several frequency-stabilized laser radiations used for the recommended reproducible meter definition is generally on the order of 10^{-10} to 10^{-13}. When an FOFC is connected with the time-frequency standard, the measurement uncertainty is of the order of 10^{-16}, which fully meets the requirements for wavelength calibration of those lasers and the improvement of uncertainty in the future

The important role of the FOFC in the quantity transfer of laser wavelength has been recognized by BIPM and various national metrology institutes. The laser wavelength traceability of the iodine-stabilized 633-nm He–Ne laser was gradually abandoned a few years ago when the BIPM conducted an international comparison. Instead, an FOFC was used to directly measure and calibrate the wavelength of the iodine-stabilized 633-nm He–Ne laser. Since 2000, several metrology institutes worldwide have built self-traceable FOFCs to measure the optical frequencies of multiple optical radiations, including optical clocks based on trapped single ions and lattice-confined neutral atoms, as well as various frequency-stabilized lasers.[9–12] For example, since 2008, the National Institute of Standards and Technology (NIST) in the United States has used FOFCs, directly or indirectly, to calibrate all laser wavelengths, which are the framework of modern length metrology with calibrated laser interferometers.[13] The vacuum wavelength measurement using FOFCs effectively formed the top of the traceability chain of length measurements in the United States. In 2000, the National Institute of Metrology (NIM) in China started to develop FOFCs. Ti: sapphire FOFCs and Er-doped fiber FOFCs (Er-FOFCs) have been successfully developed.[14–16] Significant progress has been made in the key technology and a complete device has been constructed for developing traceable NWSs. In general, with the development of science and technology and the increasing demand, the establishment of NWSs based on an FOFC has become an inevitable trend in the development of the geometric value transfer systems.

In order to establish the NWSs, this paper demonstrates the ability to measure laser frequencies from visible to near-infrared region with a home-made Er-FOFC. The signal-to-noise ratio (SNR) of the beat notes between the Er-FOFC and the lasers at wavelengths of 633, 698, 729, 780, 1064, and 1542 nm, is better than 30 dB, after frequency conversion by the combination of spectral broadening in a highly nonlinear fiber (HNLF) with a single-point frequency-doubling (SPFD) scheme. The instability of the beat notes between the Er-FOFC and the afore-mentioned lasers is measured using a hydrogen clock signal as a reference, which has a frequency instability better than 1×10^{-13} at 1-s averaging time. Furthermore, the absolute optical frequencies of an iodine-stabilized 532-nm laser and an acetylene-stabilized 1542-nm laser are measured. The results are within the uncertainty range of the international recommended standards. In this paper, the frequency measurement of lasers with different frequencies by an Er-FOFC has been achieved with high technical sophistication, that meets the needs of various laser frequency traceability and calibration, thus providing technical support for the construction of FOFC-based NWSs.

2. Experimental setup

2.1. Er-doped fiber femtosecond optical frequency comb

The structure of the Er-FOFC is shown in Fig. 1. A detailed explanation of each module of the Er-FOFC can be found in a previous work.[17] The reference signal is a 10-MHz hydrogen maser (H-maser) signal, which is periodically calibrated by a caesium (Cs) atomic fountain clock (NIM5)[18] in NIM or traced to the International System of Units (SI) base unit of time. The former establishes independent traceability of the laser wavelength to the national time–frequency standard, and the latter establishes the traceability of the laser wavelength to the time unit "second". Both of them connect

the laser wavelength standard with the time-frequency standard. The 10-MHz standard frequency signal from the H-maser has a frequency instability better than 1×10^{-13} at 1-s averaging time. Once it is traceable to the SI base unit of time, the overall uncertainty of the traceability link is evaluated to be better than 5×10^{-16}.

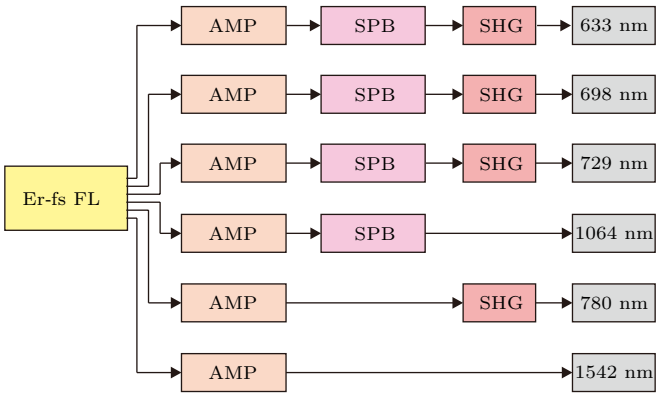


Fig. 1. Structure of the Er-FOFC. Er-fs FL is Er-doped femtosecond fiber laser, AMP is fiber amplifier, SPB is spectral broadening module, SHG is second harmonic generation module.

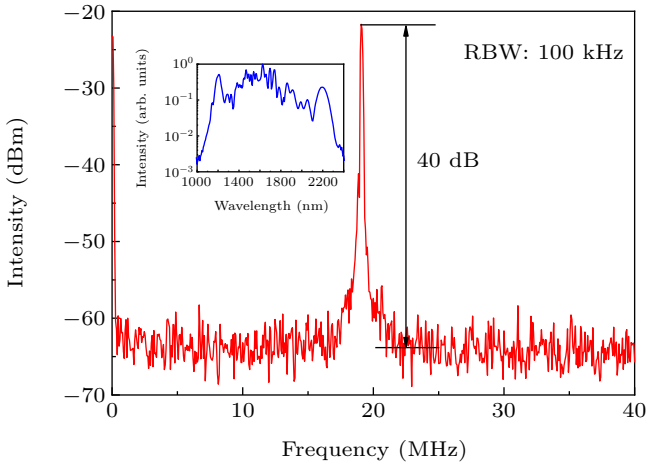


Fig. 2. Signal of the CEO frequency detected in the Er-FOFC with a resolution bandwidth (RBW) of 100 kHz. Inset is the broadened spectrum after the HNLF.

The Er-FOFC can achieve long-term continuous phase locking and cover a broadband spectrum[17,19] from visible to near-infrared region. Once the Er-FOFC is stabilized in operation, the carrier-envelope offset (CEO) frequency (f_0) with an SNR of 40 dB is detected through subsequent amplification, spectral broadening and an f–$2f$ interferometer, as shown in Fig. 2. The output power of the fiber amplifier is 320 mW, and the pulse width after dispersion compression is less than 50 fs. A 35-cm section of an HNLF (NL-1550-Zero, YOFC) is used to broaden the spectrum. The attenuation of the HNLF at 1550 nm is 0.880 dB/km, and the cut-off wavelength is 1269 nm. The dispersion and dispersion slope are 0.993 ps/(nm·km) and 0.019 ps/(nm^2·km) at 1550 nm, respectively. The amplified optical pulses are coupled into the HNLF to generate a spectrum covering the wavelength from 1100 nm to 2200 nm, as shown in the inset of Fig. 2. The output power of the broadened spectrum is about 180 mW. Two wavelengths at 1100 nm and 2200 nm are used to detect the CEO frequency signal.

Through the phase-locking technique,[17] the repetition rate and CEO frequency of the Er-FOFC are continuously locked for more than one month. Figure 3 shows the frequency shift and relative Allan deviation of the repetition rate after 30 days of continuous phase-locking, where the averaging time is 1 s. The average value of the repetition rate after phase-locking is 200 MHz with a standard deviation of 0.327 mHz. Figure 4 shows the frequency shift and relative Allan deviation of the CEO frequency after 30 days of continuous phase-locking, where the averaging time is 1 s. After phase-locking, the average value of the CEO frequency is 20 MHz with a standard deviation of 0.568 mHz.

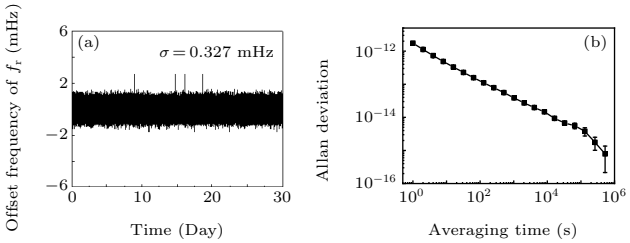


Fig. 3. Continuous phase-locking of the repetition rate of the Er-FOFC for 30 days. (a) Frequency shift of the repetition rate, and (b) relative Allan deviation.

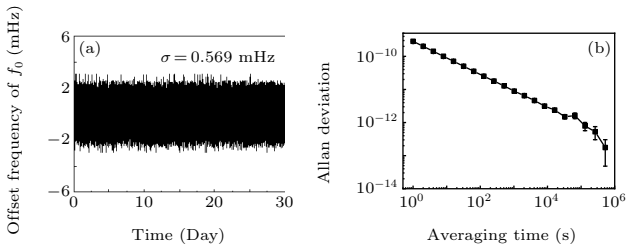


Fig. 4. Continuous phase-locking of the CEO frequency of the Er-FOFC for 30 days. (a) Frequency shift of the CEO frequency, and (b) relative Allan deviation.

2.2. Broadening spectrum to different wavelengths

The fundamental wavelength of the Er-FOFC is centred at 1550 nm with a spectral bandwidth of about 80 nm, depending on the net intra-cavity dispersion of the laser. Although a broadened spectrum covering from 1000 nm to 2200 nm can be achieved by the HNLF, it is in the infrared region, making it difficult to meet the measurement requirements of visible laser wavelengths. After the fiber amplifier and second harmonic generation, spectral broadening with a photonic crystal fiber, the output wavelength of the Er-FOFC can be extended to visible wavelength and ensures the acquisition of beat notes with an SNR of 30 dB between the comb and the laser to be measured.[17] However, in such a structure, the broadened spectrum still has the risk of drifting. This results in a decrease in the SNR of the beat notes, which is not beneficial for long-term frequency measurement.

The fundamental wavelengths of the iodine-stabilized 532-nm laser and the iodine-stabilized 633-nm laser are 1064 nm and 1266 nm, respectively. While the strontium atomic optical clock laser at 698 nm and the calcium ion optical clock laser at 729 nm correspond to 1396 nm and 1458 nm. The spectrum of the 1550-nm laser output from the Er-FOFC is easy to cover the fundamental wavelengths of those lasers, after spectral broadening by the HNLF.

Therefore, to avoid using a photonic crystal fiber, the fundamental wavelength of the iodine-stabilized 532-nm laser is measured directly. However, the iodine-stabilized 633-nm laser, the 698-nm laser, and the 729-nm laser used in optical clocks have no fundamental wavelength output, so the frequency measurement of the 633-, 698-, and 729-nm lasers adopts an SPFD scheme.[20] That is, the 1550-nm laser output from the Er-FOFC is amplified and spectrally broadened first, and then the three-wavelength points at 1266, 1396, and 1458 nm are selected for frequency doubling to achieve the laser outputs at the corresponding wavelengths of 633, 698, and 729 nm. For the frequency measurement of the 1064-nm laser, the laser output from the Er-FOFC is amplified and directly broadened to cover the wavelength of 1064 nm. In the case of the 1542-nm laser, the frequency measurement is realized by directly splitting the seed source of the Er-FOFC. For that of a 780-nm laser, the frequency measurement is realized by doubling the fundamental wavelength from the amplified laser of the Er-FOFC.

To achieve a broadened spectrum covering the visible light, the Er-FOFC is divided into multiple channels. Each channel is subjected to fiber amplification and frequency conversion to meet different requirements, as shown in Fig. 1. The structure and parameters of the fiber amplifiers are similar to those operated with two-stage power amplification. The two-stage amplifier adopts the backward pumping structure with maximum pump power of 750 mW for each amplifier. The gain fiber in the amplifier has an absorption rate of 80 dB/m at 1530 nm (Er80-4/125, LIEKKI). The length of the first-stage amplifier gain fiber is 50 cm, and that of the second-stage amplifier gain fiber is 85 cm. An incident optical power of 10 mW can be amplified to 111 mW and 356 mW after the first-stage and second-stage amplifier, respectively, with a pulse width of less than 50 fs after dispersion compensation.

The optical path of an SPFD scheme is shown in Fig. 5. The laser from fiber amplifier passes through the combination of the $\lambda/4$ and $\lambda/2$ wave plates to optimize the polarization state of the laser before being coupled into the HNLF. By optimizing the compensated dispersion and the polarization of the pulses, a broadened spectrum is obtained. A typical spectrum covering 1000 nm to 1700 nm after broadening is shown in Fig. 6. The output power is about 200 mW.

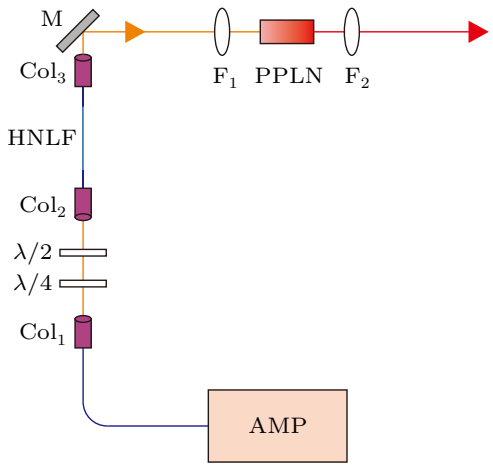


Fig. 5. Diagram of the SPFD scheme. AMP is fiber amplifier, Col_1–Col_3 are collimating mirrors, HNLF is a highly nonlinear fiber, M is a plane mirror, F_1 and F_2 are focusing lenses, PPLN is a frequency doubling crystal, and $\lambda/4$ and $\lambda/2$ are a quarter- and half-wave plate, respectively.

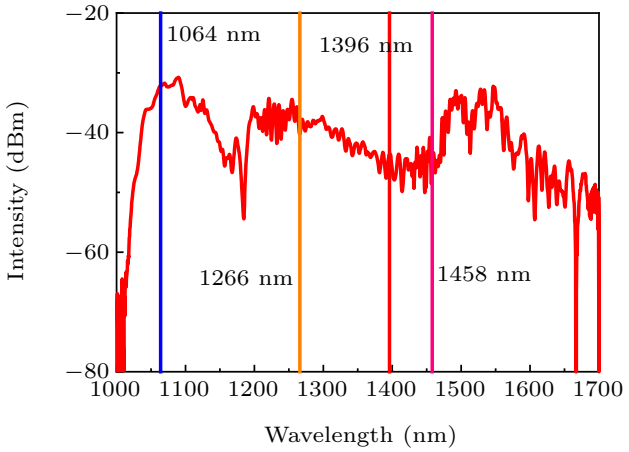


Fig. 6. The broadened spectrum after the HNLF.

An aspherical lens (A375TM-C, Thorlabs) is used to focus the laser onto the MgO-doped periodically poled lithium niobate (MgO: PPLN) crystal to realize frequency doubling of the laser at a certain wavelength. Another aspherical lens (A397TM-B, Thorlabs) after the crystal is used to collimate the frequency-doubled light. For the fundamental wavelengths of 1266-, 1396-, and 1458-nm light, the crystals used to achieve the laser output at 633, 698, and 729 nm, respectively, are listed in Table 1. The obtained spectra are shown in Fig. 7.

Table 1. The parameters of the PPLN crystals selected for frequency doubling at different wavelengths.

Fundamental wavelength (nm)	Period (μm)	Length (mm)	Temperature (°)	Spectrum after frequency doubling
1266	11.66	2	25	Fig. 7(a)
1396	15.10	2	25	Fig. 7(b)
1458	16.82	2	25	Fig. 7(c)

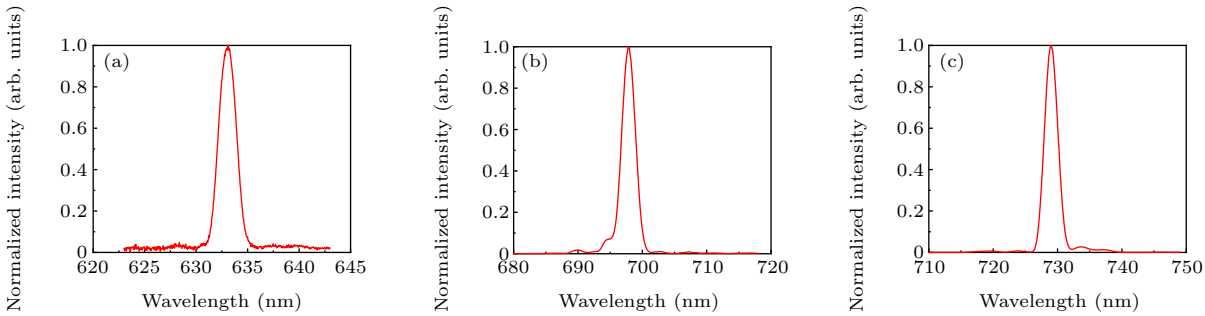


Fig. 7. The spectra obtained by SPFD at the fundamental wavelengths of (a) 1266 nm, (b) 1396 nm, and (c) 1458 nm.

To generate the spectrum at 780 nm, the light from the fiber amplifier is directly coupled into the frequency-doubling crystal without passing through the HNLF. First, it passes through the combination of the $\lambda/4$ and $\lambda/2$ wave plates to optimize the polarization of the fundamental wavelength. A short focal-length lens is used to focus the laser onto the PPLN crystal to double the frequency. The output power after frequency doubling is 150 mW with an efficiency of 35%. After frequency conversion, the wavelength of the spectrum is centred near 780 nm, as shown in Fig. 8.

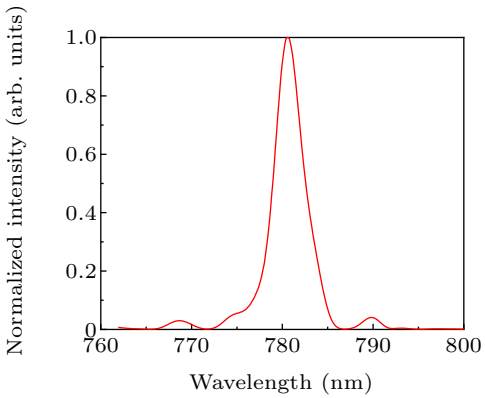


Fig. 8. The spectrum after direct frequency doubling of the light from the fiber amplifier.

2.3. Beat notes between Er-FOFC and lasers with different frequencies

To verify the measurement ability of the Er-FOFC and solve the "last mile" problem in optical frequency measurement, a module to detect the beat notes between the comb and the lasers is adopted. The beat note modules for visible light and near-infrared light are used in this system. The visible beat note module with a silicon photodiode (C5658, Hamamatsu) is used to generate the beat notes between the Er-FOFC and the lasers at 633, 698, 729, and 780 nm. In the near-infrared beat note module, an indium gallium arsenic (InGaAs) photodiode (ET3000A, EOT) is used to detect the beat notes between the Er-FOFC and the lasers at 1064 nm and 1542 nm.

The optical scheme and the photograph of the visible beat note module are shown in Fig. 9. The two light beams from the Er-FOFC and the measured laser pass through the half-wave plate to form orthogonally polarized states and then are combined by a polarization beam splitter (PBS). The light transmitted from the first PBS passes through another half-wave plate so that both beams have projections into the same polarization state. After passing through the second PBS, the two beams have an identical polarization state. A reflective holographic grating (2400/mm) is used to separate the spectral components, and only the frequency components of the laser to be measured are selected to be coupled into the detector (PD) by a high-reflection mirror. To achieve a small beam profile, the combined light passes through a focus lens (L) with a focal length of 100 mm before entering the detector. Since a grating filter is used in the beat note module, the grating angle needs to be fine-tuned for different wavelengths to ensure that the laser to be measured is accurately coupled into the detector.

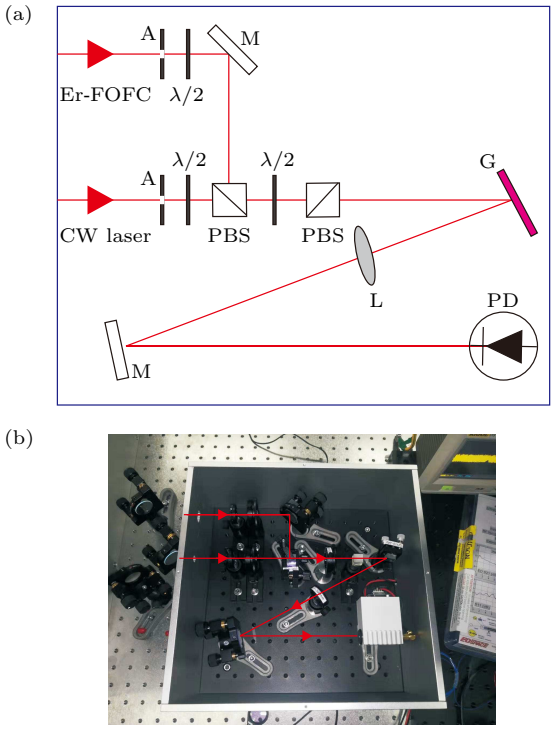


Fig. 9. The beat note module between the Er-FOFC and the laser to be measured. (a) Optical scheme of the module, where M is planar mirrors, A is an aperture, PBS is a polarization beam splitter, G is a grating, PD is a photodetector, L is a focusing lens and CW laser is the measured laser. (b) Photograph of the module.

By optimizing the parameters systematically, including the polarization state, spectral shape, pulse power, and spatial coincidence of the light beams from the Er-FOFC and the measured laser, a beat note signal with an SNR of no less than 30 dB can be obtained at an RBW of 100 kHz. This SNR meets the requirements of continuous counting the beat note frequency for a long time

Figure 10 shows the beat notes between the Er-FOFC and the lasers at 633, 698, 729, 780, 1064, and 1542 nm. To facilitate the comparison, the background of the beat note of each wavelength is modified to form a common background. The frequency of the beat note is also adjusted at the same time.

Since the spatial optical path in the Er-FOFC is relatively short, the broadened spectrum is very stable, which results in the generation of the stable beat notes. That benefits the long-term continuous measurement of the optical frequency.

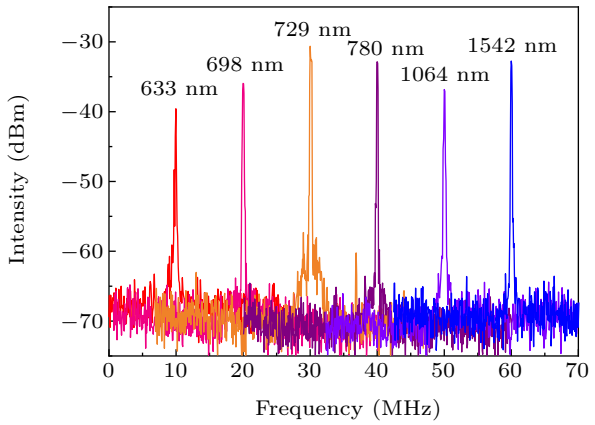


Fig. 10. The beat notes between the Er-FOFC and the lasers at different wavelengths.

3. Results and discussion

3.1. Instability measurement of lasers with different frequencies

Both the repetition frequency f_r and CEO frequency f_0 of the Er-FOFC are locked onto the reference frequency generated from an H-maser. The frequency instability of the standard frequency signal from the H-maser is better than 1×10^{-13} at 1-s averaging time, while the uncertainty of the signal traced to the SI second definition is better than 5×10^{-16}.

The 633-, 698-, 729-, 780-, 1064-, and 1542-nm lasers measured in the experiment are divided into two types. One type is that the laser is locked onto the spectral line with a fixed reference, and the absolute frequency can be measured by the Er-FOFC. In this case, the measured lasers include the 633-, 698-, 729-, 780-, and 1064-nm lasers, as well as the acetylene frequency-stabilized 1542-nm laser. The other type is to lock onto a Fabry–Perot cavity with a high Q value. The cavity length is deformed due to environmental interference, which causes the laser frequency to drift accordingly. Therefore, the Er-FOFC is used to directly measure the frequency drift. The narrow linewidth 1542-nm laser is measured in this case.

The lasers at 633, 698, 729, 780, 1064, and 1542 nm are separately beat with the nearest comb teeth of the Er-FOFC. The beat note (f_b) is measured with a frequency counter (53220A, Keysight) at 1-s averaging time. The relative Allan deviation used to describe the instability of the measured laser for different averaging times is given by the following equation:

$$\sigma_A(\tau) = \frac{1}{\nu}\sqrt{\frac{1}{2(n-1)}\sum_{i=1}^{n-1}[f_{i+1}(\tau) - f_i(\tau)]^2}, \tag{1}$$

where $\sigma_A(\tau)$ is the relative Allan deviation, τ is the averaging time, ν is the optical frequency of the measured laser, n is the number of sampling points, and $f_i(\tau)$ is the average frequency of the i-th measurement.

The beat note frequencies and their relative Allan deviation are shown in Fig. 11.

Since the instability of the reference is better than 1×10^{-13}, when the instability of the measured laser is better than that of the reference, the relative Allan deviation reflects the instability of the reference. In such a case, the measurement is limited to the instability of the reference and aims to obtain the absolute optical frequency of the laser or monitor the drift of the laser frequency. When the instability of the laser to be measured is lower than that of the reference, the relative Allan deviation reflects the instability of the laser. The measurement at this time can obtain the absolute optical frequency, frequency drift and instability of the laser.

For the thermal frequency-stabilized 633-nm laser, the frequency instability of the beat note is 7.01×10^{-10}. The instability of the laser is much lower than that of the reference, so it can be considered that the measurement results directly reflect the laser frequency instability. The 780-nm laser is locked onto a commercial Er-FOFC referenced to the rubidium clock with a frequency instability of 10^{-12}. Moreover, the frequency of the 780-nm laser is measured with the home-made Er-FOFC, and the result shows that the frequency instability of the 780-nm laser is 6.18×10^{-12}, which is limited to that of the referenced rubidium clock. For the fundamental wavelength of the iodine-stabilized 532-nm laser, the frequency instability is 1.93×10^{-13} at 1-s averaging time.

The 698-nm laser is locked onto the transition spectral line of strontium atom[21] with a systematic uncertainty of 2.9×10^{-17}. The 729-nm laser is locked onto the transition spectral line of calcium ions[22] with a systematic uncertainty of 1.3×10^{-17}. When using the Er-FOFC to measure the 698-nm and 729-nm optical clock laser frequencies, the frequency instabilities reach 7.71×10^{-14} and 9.85×10^{-14} at 1-s averaging time, respectively. Since the rough frequency instabilities

of the 698- and 729-nm lasers are higher than that of the reference source, the reference source determined the measured instabilities. The measurement of the afore-mentioned lasers is mainly focused on obtaining their absolute optical frequencies.

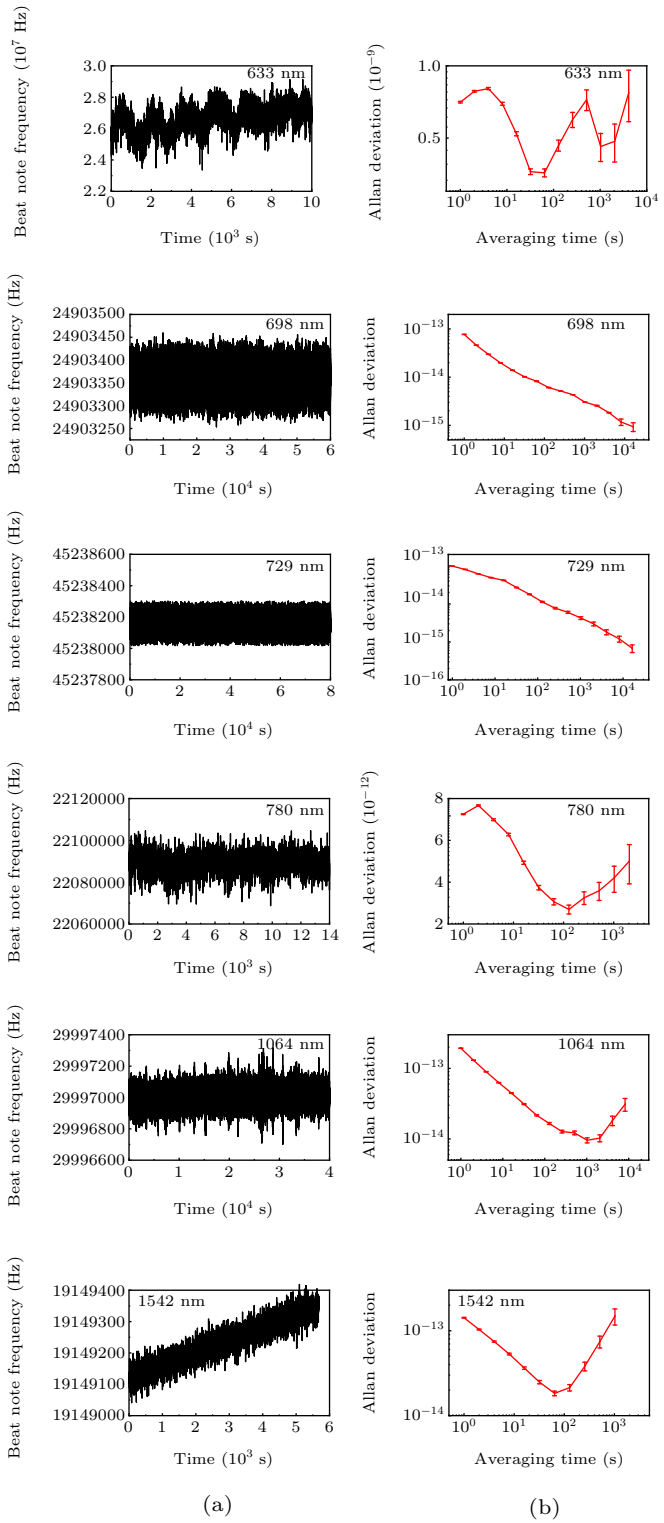


Fig. 11. Beat note frequency and its relative Allan deviation of each laser measured with the Er-FOFC. From top to bottom, the measured lasers are 633, 698, 729, 780, 1064, and 1542 nm, respectively. (a) Beat note frequency, and (b) its relative Allan deviation.

The 1542-nm laser is only locked onto the high-Q Fabry–Perot reference cavity. As the temperature control in the reference cavity of the 1542-nm laser has a variation, the laser frequency after locking has a large linear drift of about 0.05 Hz/s and a frequency instability of 1.42×10^{-13} at 1-s averaging time. Since the rough frequency instability of the measured laser is higher than that of the reference, the measurement result does not represent the true instability of the laser. The main purpose here is to use the Er-FOFC to monitor the frequency drift of the laser and provide a reference for the optimization of the cavity-locked laser and the evaluation of its operation performance.

3.2. Absolute optical frequency measurements of multiple lasers

Absolute optical frequency measurement is one of the important applications of the comb. For any continuous-wavelength laser, as long as its wavelength is within the output spectrum range of the comb, its absolute optical frequency, ν, can be calculated by the following formula:

$$\nu = N \cdot f_{\mathrm{r}} \pm f_0 \pm f_{\mathrm{b}}, \tag{2}$$

where, f_{b} is the beat note frequency between the laser and the adjacent comb tooth of the comb, and N is the ordinal number of the comb tooth closest to the laser frequency to be measured. Through the phase-locked loops, f_{r} and f_0 are locked onto the output frequency of the frequency synthesizer (SMB 100A, Rohde-Schwarz). They both are the displayed values from the frequency synthesizer.

To verify its accuracy and precision, the system is used to measure the absolute optical frequencies of lasers locked onto the internationally recommended molecular or atomic absorption lines. For instance, the international recommended value of the $P(16)(\nu_1+\nu_3)$ absorption line of acetylene ($^{13}C_2H_2$) is 194369569384 kHz with a relative standard uncertainty of 2.6×10^{-11}. The international recommended value of the a_{10} component of the R(56) 32–0 transition line of iodine ($^{127}I_2$) is 563260223513 kHz with a relative standard uncertainty of 8.9×10^{-12}. An iodine-stabilized 532-nm laser[23] and an acetylene-stabilized 1542-nm laser (Stabiλaser 1542$^{\varepsilon}$, DFM) are chosen for verification. The iodine-stabilized 532-nm laser is a frequency-doubled Nd: YAG laser with a dual output of the fundamental wavelength at 1064 nm and the doubled frequency at 532 nm. In the frequency stabilization system, the frequency of the acousto–optic modulator in the iodine-stabilized 532-nm laser is shifted by 40 MHz. The acetylene-stabilized 1542 nm laser is shifted by 80 MHz. After the signs of f_0 and f_{b} are determined with the recorded value of f_{b}, the absolute optical frequency of the laser can be obtained from the formula (2). The $P(16)(\nu_1+\nu_3)$ absorption line of acetylene and the a_{10} component of the R(56) 32–0 transition line

from $^{127}I_2$ can be obtained once the frequency shift from the acousto-optic modulator is removed.

For the iodine-stabilized 532-nm laser, the fundamental wavelength of 1064 nm is measured by recording the beat note frequency at 1-s averaging time and a total sampling time of 7200 s. The repetition rate of the Er-FOFC, f_r, is 200001.036 kHz, the CEO frequency, f_0, is 20000 kHz, and the average value of the beat note frequency, f_b, is 12919.096691 kHz. From the international recommended frequency of the iodine-stabilized 532-nm laser, the ordinal number of the comb, N, is determined to be 1408143. The calculated frequency of the a_{10} component of the R(56) 32–0 absorption line of $^{127}I_2$ is 563260223510.489 kHz. The measurement is repeated six times within a certain period, and the average value of the measurement results is 563260223510.472 kHz with a standard deviation of 0.03 kHz, as shown in Fig. 12(a). The measured result meets the uncertainty range of the international recommended value of 563260223513 ± 5 kHz.

For the acetylene frequency-stabilized 1542-nm laser, the beat note frequency is collected at 1-s averaging time and a total sampling time of 10000 s. The repetition rate of the Er-FOFC, f_r, is 199972.8788 kHz. The CEO frequency, f_0, is 20000 kHz and the average value of the beat note frequency, f_b, is 70623.40832 kHz. From the international recommended frequency value of the acetylene stabilized 1542-nm laser, the ordinal number of the comb, N, is calculated to be 971979. It can be concluded that the frequency of the $P(16)(\nu_1+\nu_3)$ absorption line of $^{13}C_2H_2$ is 194369569386.554 kHz. On this basis, the measurement is repeated ten times within a certain period. The average value of the measurement results is 194369569386.497 kHz with a standard deviation of 0.021 kHz, as shown in Fig. 12(b). The measured result meets the uncertainty range of the international recommended value of 194369569384 ± 5 kHz.

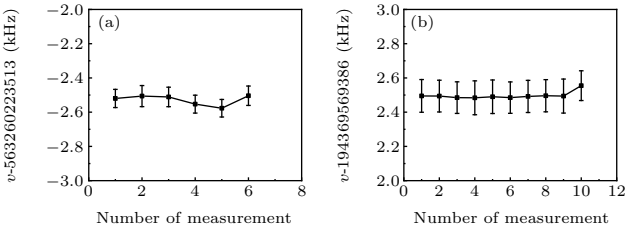


Fig. 12. Frequency measurement with the Er-FOFC: (a) a_{10} component of the R(56) 32–0 absorption line frequency of $^{127}I_2$, and (b) $P(16)(\nu_1+\nu_3)$ absorption line frequency of $^{13}C_2H_2$.

4. Conclusions and perspectives

In this paper, the capability of the Er-FOFC to measure the laser frequencies from visible to near-infrared region was verified. By combining spectral broadening in an HNLF and the SPFD scheme, the beat notes between the Er-FOFC and the lasers at 633, 698, 729, 780, 1064, and 1542 nm were determined, with an SNR better than 30 dB. The frequency instability of the above lasers was evaluated by using a hydrogen clock signal with a frequency instability better than 1×10^{-13} at 1-s averaging time. The measurement was further validated by measuring the absolute optical frequencies of an iodine-stabilized 532-nm laser and an acetylene-stabilized 1542-nm laser. The results were within the uncertainty range of the international recommended values. Our results demonstrate the accurate optical frequency measurement of lasers at different frequencies using an FOFC, which is not only important for precise and accurate traceability and calibration of the laser frequency, but also provides technical support for establishing NWSs based on an FOFC.

For lasers that are not locked onto the transition spectral lines of atoms or ions, only the frequency instability and frequency drift of these lasers are measured. The measurement system established in this paper will be used to measure the absolute optical frequencies of lasers with higher instability and accuracy in the future. Also, the frequency range will be extended to the mid-infrared region to measure the absolute optical frequencies of mid-infrared lasers. The Er-FOFC will be used at that time to truly realize the measurement of visible, near-infrared, and mid-infrared laser frequencies.

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