Frequency stabilization of Nd:YAG lasers with a most probable linewidth of 0.6 Hz

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Two Nd:YAG lasers at 1064 nm are independently frequency-stabilized to two separately located, vertically mounted ultrastable Fabry–Perot reference cavities. Measurements show that each laser system has achieved a most probable linewidth of 0.6 Hz and fractional frequency instability of $\sim 1.2 \times 10^{-15}$ between 1 and 40 s averaging time. Systematic evaluation shows that the performance of each laser system is limited by thermal noise of the reference cavity.

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1. INTRODUCTION

Narrow-linewidth lasers play a significant role in precision measurement and metrology, such as optical atomic clocks [1], low-phase-noise microwave generation [2], gravitational wave detection [3] and tests of fundamental physics [4]. In an optical clock, a laser with a spectral linewidth at the hertz or subhertz level is used as a local oscillator. Recent results have shown that improvements on the performance of narrow-linewidth lasers helped to improve the frequency stability of optical atomic clocks [5,6]. By using a femtosecond laser optical frequency comb [7,8], the super low phase noise and high frequency stability of a narrow-linewidth laser can be transferred to the microwave region to generate low-phase-noise oscillations.

By using the Pound–Drever–Hall (PDH) technique [9] to stabilize a laser frequency to the resonance of an ultrastable optical Fabry–Perot (FP) reference cavity, frequency noise of a laser can be largely reduced, and their original linewidth of several kilohertz or even megahertz can be narrowed to the hertz level or even lower [5,6,10–17]. In our previous work [16], two 1 Hz-linewidth Nd:YAG lasers at 1064 nm have been realized by stabilizing them independently to two separately located, vertically mounted ultrastable reference cavities. In this work, improvements on the two laser systems have been made to further optimize their performance: (1) homemade acoustic isolation chambers with temperature stabilizations; (2) zero-expansion temperature exploration for the reference cavities; (3) further reduction of residual amplitude modulation (RAM) [18–20]. With these efforts, measurements show that each laser system has achieved a most probable linewidth of 0.6 Hz [full width at half-maximum (FWHM)] and an averaging linewidth of 0.7 Hz. At short averaging times, the fractional frequency instability of each laser has approached 1.2×10^{-15}. The frequency drift rate of the beat note between two laser systems is within 0.1 Hz/s in 93% of measurement times over 7 days. Moreover, evaluations on the current laser systems show that the thermal noise [21] of the reference cavities dominates the whole noise budget.

2. EXPERIMENTAL SETUP

In this paper, two Nd:YAG lasers at 1064 nm are independently frequency-stabilized to the resonances of two ultrastable optical FP reference cavities (FP Cav1 and FP Cav2) by the PDH technique. The experimental setups for two laser systems are similar. Figure 1 shows the experimental setup for the laser system.

In the experiment, the reference cavity, as well as the experimental setup, for the PDH technique is on a passive vibration isolation platform (VIP) from Minus *K* Technology. The laser light is transferred to the VIP via a single-mode (SM) optical fiber employing fiber noise cancellation (FNC) to cancel the random phase noise induced by fiber length fluctuation [22]. The schematic diagram for FNC is also shown in Fig. 1, in which the fiber-induced random phase noise is measured by comparing the light reflected from the surface of the collimator at the far end of the fiber with that from the short reference arm, and canceled by tuning the frequency of an acousto-optic modulator (AOM_1) driver. The laser source and the experimental setup for FNC are put on a platform that is enclosed in a box to reduce the disturbance of air flow.

On the VIP, the output of the SM fiber is frequency-shifted by AOM_2. Then the first-order diffracted laser light is phase-modulated by an electro-optic modulator (EOM) at a radio frequency of ~3 MHz. A polarizer with high extinction ratio before the EOM is used to adjust the polarization of the laser light to get pure phase modulation in the EOM to reduce the effect of RAM. The EOM is temperature-stabilized above room temperature with a fluctuation within 4 mK. An optical isolator (Isol) with an isolation of more than 30 dB after the EOM is used to isolate the scattering light and reflected light. After that, the laser light is reflected on a beam splitter to the reference cavity (a reflectivity of ~20% for FP Cav1 and ~10% for

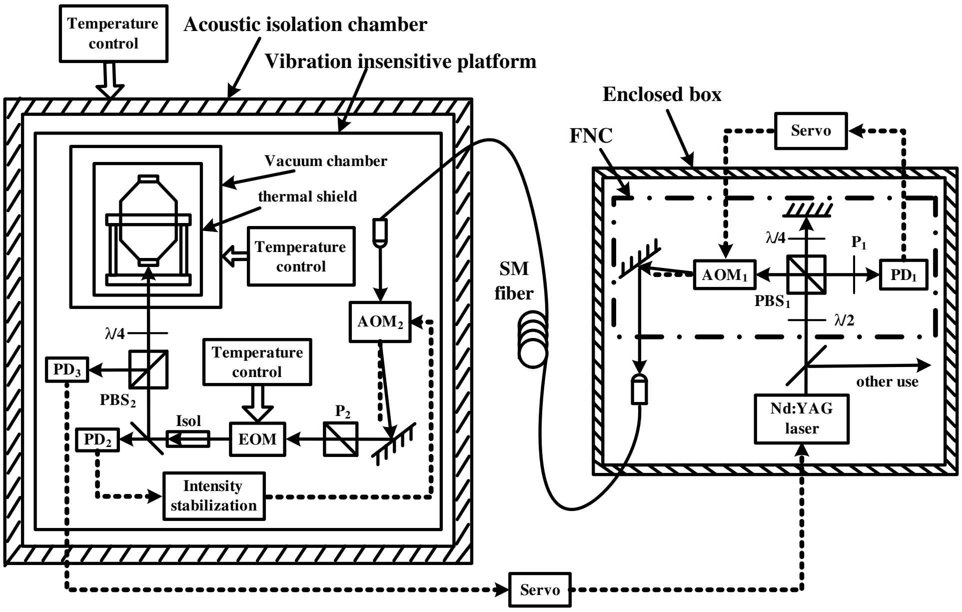

Fig. 1. Schematic diagram of the experimental setup for Nd:YAG laser frequency stabilization. AOM, acousto-optic modulator; P, polarizer; EOM, electro-optic modulator; Isol, optical isolator; PD, photodetector; PBS, polarization beam splitter; $\lambda/4$, quarter-wave plate; $\lambda/2$, half-wave plate; FNC, fiber noise cancellation; SM, single-mode.

FP Cav2), while the transmitted light is detected by a photodetector (PD_2) for intensity stabilization of the light beam to be coupled into the cavity by controlling the driving power of AOM_2. The reflected beam from the FP cavity is steered onto a photodetector (PD_3) and the output signal of PD_3 is sent to a mixer to demodulate against a phase-shifted reference signal that is also used to drive the EOM. After a low-pass filter, the frequency discrimination signal is used to control a piezoelectric transducer bonded on the monolithic Nd:YAG crystal of the laser to keep the laser frequency on resonance with the reference cavity.

The reference cavities, commercially available, are 7.75 cm long and have two mirrors with radii of curvature $R_1 = \infty$ and $R_2 = 0.5$ m. Both the spacer and the mirror substrates are made of ultra-low-expansion (ULE) glass to reduce thermal expansion. They are wider in the middle and tapered at the two ends. Each reference cavity is mounted vertically at its mid-plane by three Teflon posts to suppress cavity vibration sensitivity [12,14]. The cavity finesses are measured to be ~200,000 for FP Cav1 and ~230,000 for FP Cav2, corresponding to a cavity linewidth of ~8.5 kHz and ~7.7 kHz, respectively. And the cavity reflection contrasts are 67% for FP Cav1 and 75% for FP Cav2. Each cavity as well as its supporting posts are located in a gold-coated copper cylinder thermal shield, and are enclosed in a vacuum chamber ($\sim 1 \times 10^{-7}$ Torr) with temperature stabilization. As shown in Fig. 1, in each cavity-stabilized laser system, the vacuum and some optic components are placed on a VIP for vibration reduction. The VIP resides in a homemade acoustic isolation chamber with an attenuation of more than 20 dB. One of the acoustic isolation chambers is made of aluminum alloy for acoustic noise reflection while the other is made of wood. The surfaces of both acoustic isolation chambers are stuck with acoustic absorbing material. To reduce environmental temperature fluctuations, the acoustic isolation chambers are temperature-stabilized near room temperature with a fluctuation of <70 mK. With those improvements, the temperature instability of the vacuum chamber of FP Cav1 has been improved to be ~400 μK.

In addition, zero-expansion temperatures of both optical reference cavities are also explored by measuring the frequency of the beat note between two cavity-stabilized laser systems when the temperature of one of the cavities is changed. In the measurement, the temperature of the under-test cavity was changed by >1°C to make the resonance frequency change big enough to overwhelm residual frequency drift of the reference cavity. Figure 2 shows the frequency change of the beat note versus the temperature of FP Cav1 (dots) and FP Cav2 (square markers). The fitting curves show a zero-expansion temperature of $T_{01} = 22.9(2)$°C for FP Cav1 and $T_{02} = 10.6(2)$°C for FP Cav2. Possible explanations for the different zero-expansion temperatures observed for the ULE cavities are different coefficient of thermal expansion (CTE) properties of ULE glasses and some stress-induced issues [15]. The temperature sensitivities of the CTE of both cavities near the zero-expansion temperatures are 1.50 and 1.44 ppb/K^2, respectively. When both cavities are temperature-stabilized near their zero-expansion temperatures with an uncertainty of 0.2°C, the sensitivity of cavity resonance

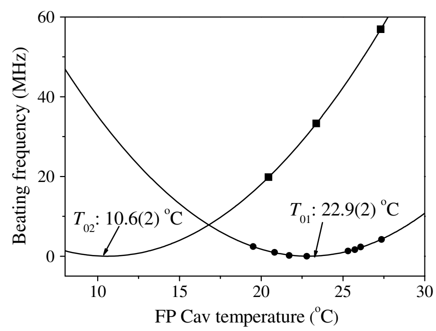

Fig. 2. Measurements of the zero-expansion temperatures of FP Cav1 (dots) and FP Cav2 (square markers) and the parabolic fits.

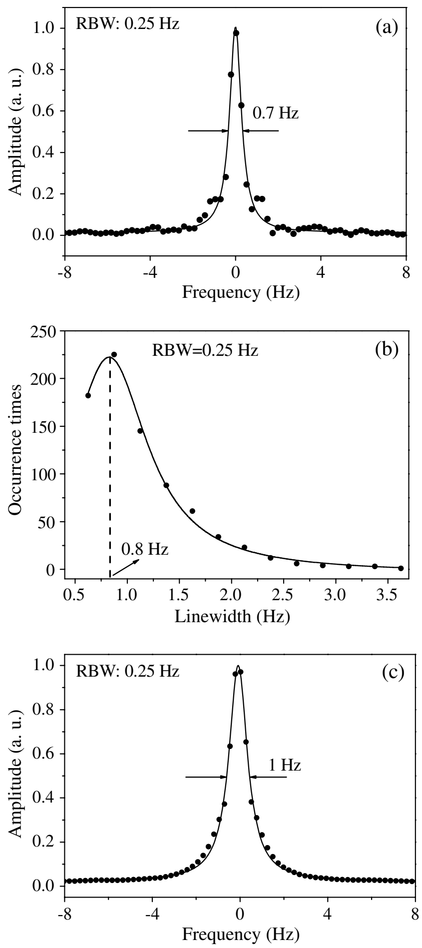

Fig. 3. Linewidth measurements when the RBW of the FFT spectrum analyzer is 0.25 Hz: (a) an example of the spectra of the beat note between two cavity-stabilized lasers (dots) and the Lorentzian fitting (solid curve), (b) linewidth distribution of approximately 800 groups of the spectra (dots) with 0.25 Hz step and the Lorentzian fitting (solid curve), and (c) an averaging spectrum of the beat note with center-overlapped (dots) and the Lorentzian fitting (solid curve).

frequency relative to temperature is ~96 Hz/mK for FP Cav1 and ~90 Hz/mK for FP Cav2. Since the vacuum chambers for the reference cavities are temperature-controlled only by heating, the vacuum chamber of FP Cav2 is temperature-controlled at ~22.9°C, where the temperature sensitivity is ~5 kHz/mK.

3. RESULTS AND DISCUSSION

Two laser systems are independently located on different platforms that are located at different corners of our laboratory, approximately 6 m away from each other. The laser light from one system is transferred to the other for frequency comparisons and measurements via a 10 m-long SM fiber with FNC.

A. The Most Probable and Averaging Linewidth at the Subhertz Level

To measure the laser linewidth, the beat note between two laser systems, without compensating any frequency drift, was down-converted to several tens of kilohertz and measured on a fast Fourier transform (FFT) spectrum analyzer with a resolution bandwidth (RBW) of 0.25 Hz. The spectra are recorded automatically by a computer. Figure 3(a) shows an example of the spectra with dots and its Lorentzian fitting (solid curve).

Approximately 800 groups of spectra have been obtained in four different days covering 79 days and each group was fitted with a Lorentzian function to obtain the linewidth of the beat note. Figure 3(b) shows the linewidth distribution with 0.25 Hz step. When fitted with a Lorentzian function, the most probable linewidth of the beat note is ~0.8 Hz, corresponding to a most probable linewidth of 0.6 Hz for each laser system by assuming that each laser contributes the same to the linewidth measurements.

To characterize the linewidth of the beat note from another view, we center-overlapped all the spectra and averaged all the groups, as shown in Fig. 3(c) with dots. The Lorentzian fitting (solid curve) shows that an averaging linewidth is 1 Hz. Therefore, each laser has approached an averaging linewidth of 0.7 Hz.

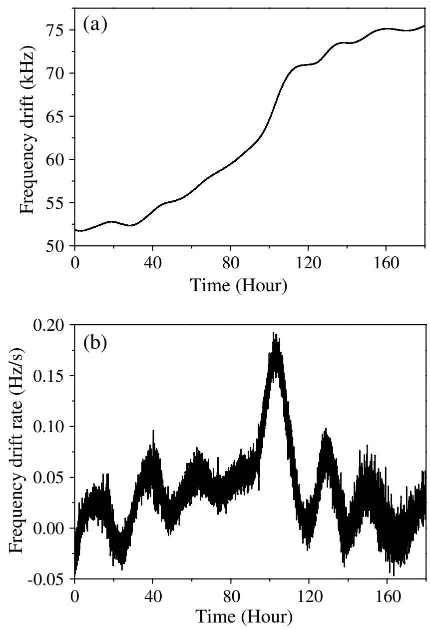

Fig. 4. (a) Relative frequency drift of the beat note between two cavity-stabilized lasers at 1064 nm over 7 days and (b) calculated relevant frequency drift rate.

B. Frequency Drift Rate and Allan Deviation

To explore the relative frequency drift between the two laser systems, we counted the frequency of the beat note over 7 days continuously, which is shown in Fig. 4(a). Figure 4(b) shows the calculated relevant frequency drift rate. During 180 h, the frequency drift rate was less than 0.2 Hz/s. Moreover, in 93% of the total measurement time, the frequency drift rate was within 0.1 Hz/s, largely improved from our early results.

The fractional frequency instability of one cavity-stabilized laser is shown with dots in Fig. 5 when a linear drift of 0.05 Hz/s was removed. At 1 and 40 s averaging times, the fractional frequency instability of one laser system has approached 1.2×10^{-15}, close to the thermal-noise-limited frequency instability of $\sim 1 \times 10^{-15}$.

C. Cavity Frequency Noise Measurement

The frequency of one laser was stabilized to FP Cav1 and at the same time, a small part of the laser light was sent to FP

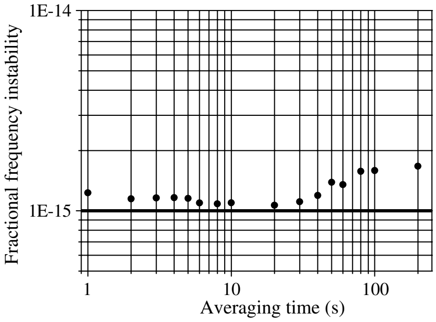

Fig. 5. Fractional frequency instability of one cavity-stabilized laser (dots). The solid line denotes the thermal-noise-limited frequency instability of approximate 1×10^{-15} for one cavity.

Table 1. Systematic Evaluation of the Frequency-Stabilized Nd:YAG Laser Systems

Noise Contribution	Frequency Noise at 1 Hz (Hz/$\sqrt{\text{Hz}}$)	Frequency Instability at 1 s for FP Cav1 ($\times 10^{-15}$)	Frequency Instability at 1 s for FP Cav2 ($\times 10^{-15}$)
Electronic noise	0.01	~0.1	<0.1
Error-signal noise	0.02	~0.2	0.1
Intensity fluctuation	0.02	0.2	0.2
Cavity vibration	~0.1		
Cavity temperature sensitivity		<96 Hz/mK	~5 kHz/mK
Cavity thermal noise	0.24	1	1
Measurement	0.26	1.2	

Cav2 to evaluate the laser frequency noise. By keeping the laser frequency sitting on resonance with FP Cav2 via an extra AOM frequency shifter, we used the PDH signal of FP Cav2 to recover the laser frequency variation information. Figure 6 shows the frequency noise spectrum for one cavity averaged 10^4 times. The dashed line shows the calculated thermal-noise-limited frequency noise spectrum of a cavity at $0.24\ \text{Hz}/\sqrt{f}$, where f is the Fourier frequency. The frequency noise spectrum of each cavity is close to the thermal noise limit at Fourier frequencies lower than 10 Hz. At above 10 Hz, it is limited by vibration noise.

D. Systematic Evaluation

For further improvements, we systematically evaluated two cavity-stabilized laser systems. Table 1 lists noise contributions of the systems.

Similar to the cavity frequency noise measurement, we evaluated the error-signal noise for each laser system to be $0.02\ \text{Hz}/\sqrt{\text{Hz}}$ at a Fourier frequency of 1 Hz, when the laser frequency is off resonance with FP Cav2. The error-signal noise is a combination of electronic noise ($0.01\ \text{Hz}/\sqrt{\text{Hz}}$), shot noise and RAM. With further efforts on the reduction of the RAM in this paper, the fractional frequency instability induced by the error-signal noise for each laser system has been reduced to $(1\text{–}2) \times 10^{-16}$ level at 1 s averaging time.

Light intensity fluctuation in the reference cavity may act on the cavity length instability due to heating effect. The sensitivity of cavity resonance frequency to cavity input light power in our systems is measured to be ~25 Hz/μW at the input power of 6.4 μW for FP Cav1 and ~33 Hz/μW at 2.7 μW for FP Cav2. By directly measuring the light power before the FP cavity with a PIN photodiode, the laser frequency instability induced by the intensity fluctuation for both systems was estimated to be about 2×10^{-16} at 1 s and the laser frequency noise was evaluated to be $0.02\ \text{Hz}/\sqrt{\text{Hz}}$ at 1 Hz.

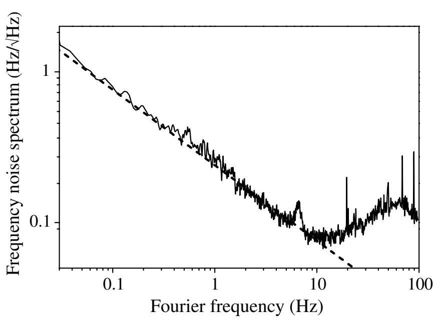

Fig. 6. Frequency noise spectrum of one cavity-stabilized laser system. The dashed line shows the calculated thermal-noise-limited frequency noise spectrum of one cavity at $0.24\ \text{Hz}/\sqrt{f}$.

From the spikes in the laser frequency noise spectrum for one reference cavity at the Fourier frequency frequencies above 10 Hz and the measured vertical vibration on the VIP, the vertical acceleration sensitivity for one of the cavities is estimated to be ~10 kHz/(m/s^2), resulting in a laser frequency noise of $\sim 0.1\ \text{Hz}/\sqrt{\text{Hz}}$ at a Fourier frequency of 1 Hz.

As for the laser frequency drift, since the temperature stabilization of FP Cav2 is far above the zero-expansion temperature, FP Cav2 contributes more to the relative frequency drift. From the laser frequency instability, we evaluated the temperature fluctuation of the reference cavities is $\sim 1 \times 10^{-7}$ K at 1 s averaging time.

Theoretical thermal noise of each cavity contributes $0.24\ \text{Hz}/\sqrt{\text{Hz}}$ to the cavity frequency noise at a Fourier frequency of 1 Hz and approximate 1×10^{-15} to the fractional frequency instability at 1 s averaging time.

From Table 1, we can find that the thermal noise of the cavities contributes the most to the present systems. For further improvements, cavities with lower thermal noise might be constructed [5,6,17,21,23]. Furthermore the temperature fluctuation of FP Cav2 and vibration noise of both cavities are the second largest noise contributors. In the near future, several steps might be taken to improve the systems. Peltier elements can be used to cool the vacuum chamber of FP Cav2 to the zero expansion temperature at 10.6°C to minimize its sensitivity to temperature fluctuation [15]. Better supporting configurations for the reference cavities can be designed to reduce the cavity vibration sensitivity.

4. CONCLUSION

In this paper, two Nd:YAG lasers operating at 1064 nm are independently frequency-stabilized to two optical reference cavities. With the several efforts discussed above in this work, each of the laser systems has achieved a most probable linewidth of 0.6 Hz, an averaging linewidth of 0.7 Hz, and a fractional frequency instability of 1.2×10^{-15} at the averaging time between 1 and 40 s. The laser systems have been working continuously for more than 10 days. Systematic evaluations of the current laser systems show that cavity thermal noise is the dominant limit. In the near future, constructions of transportable reference cavities and compactable narrow-linewidth laser systems will be in progress.

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