Dual-wavelength ultra-stable laser operating at 780 nm and 852 nm

Tong Shen[1*], Jiyang Ma[1], Xiaobo Xue[1*], Yani Zuo[2], Weinan Zhao[1], Yabei Su[1], Zhiyang Wang[3], Honglei Yang[1], Tiantian Shi[4], Yige Lin[2], Jingbiao Chen[3,5], Shengkang Zhang[1]

[*]Email: tshen@pku.edu.cn, xbxue203@163.com

[1]Science and Technology on Metrology and Calibration Laboratory, Beijing Institute of Radio Metrology and Measurement, Beijing 100854, China

[2]Division of Time and Frequency, National Institute of Metrology, Beijing 102200, China

[3]State Key Laboratory of Advanced Optical Communication Systems and Networks, School of Electronics, Peking University, Beijing 100871, China

[4]National Key Laboratory of Advanced Micro and Nano Manufacture Technology,School of Integrated Circuits, Peking University, Beijing 100871, China

[5]Hefei National Laboratory, Hefei 230088, China

***Abstract*—We employed the Pound-Drever-Hall technique to independently stabilize the frequencies of two 780 nm semiconductor lasers and two 852 nm semiconductor lasers to 5 cm cube Fabry–Pérot optical cavities, with the finesse measured to be above 2.0×10^5 across the wavelengths from 780 nm to 852 nm. By comparing the two similar laser systems, we determined that each system exhibited a fractional frequency instability of 4.0×10^{-15}/1s at 780 nm and 4.2×10^{-15}/1s at 852 nm, respectively. The linewidth of each system is 2.5 Hz. This ultra-stable laser system can be used for precise spectroscopic measurements of clock lines of rubidium and cesium atoms.**

Keywords—Ultra-stable laser, Optical cavity, Rubidium, Cesium

I. INTRODUCTION

In the fields of precision measurement and atomic frequency standards, ultra-stable optical reference cavities are essential for achieving ultra-high frequency stability and narrow linewidth lasers. These stabilized lasers are critical light sources in the research and development of highly accurate optical clocks [1,2], gravitational wave detection [3], ultra-stable photo-generated microwave sources [4], and measurement of fundamental physical quantities [5,6]. Specifically, as clock transition detection lasers, their linewidth and stability have a direct impact on the frequency stability performance of optical clocks. The implementation of the Pound-Drever-Hall (PDH) frequency stabilization technique in ultra-stable laser systems involves the use of a reference cavity along with environmental isolation and active feedback control[7]. This methodology effectively locks the laser frequency to the optical length of the reference cavity, resulting in exceptional frequency stability [8-14].

Considering the practical requirements for portability and miniaturization, we employed the PDH technique to independently stabilize the frequencies of two 780 nm semiconductor lasers and two 852 nm semiconductor lasers to 5 cm cube ultra-stable cavities, with a broad wavelength mirror range from 780 nm to 852 nm. To approach the thermal noise limit as closely as possible, each cavity was operated at room temperature. Furthermore, we measured the time constants to ensure minimal impact of temperature fluctuations on the cavities. By comparing the two similar laser systems, we determined that each system exhibited a fractional frequency instability of 4.0×10^{-15}/1s at 780 nm and 4.2×10^{-15}/1s at 852 nm, respectively. The linewidth is 2.5 Hz. These advancements provide both theoretical and experimental foundations for the development of ultra-high frequency stability optical clocks and related products.

II. THEORETICAL ANALYSIS

In the implementation of frequency locking in a Fabry–Pérot (F-P) cavity, a critical aspect is the coupling and mode matching between the incident laser and the F-P cavity. This study covers a wavelength range of 780 nm to 852 nm, utilizing a plano-concave mirror configuration for the F-P cavity. Specifically, Mirror 1 is a planar mirror with an infinite radius of curvature, and Mirror 2 is a plano-concave mirror with a curvature radius of 0.5 m. For a cavity length of 5 cm, the calculated beam spot size is ~0.223 mm.

Using Gaussian beam optics transformation theory, the relationship between the waist radius and the waist position of a Gaussian beam is given by[15]:

$$\omega_{0out}^2 = \frac{f^2\omega_{0in}^2}{(f-d_{in})^2+\left(\frac{\pi\omega_{0in}^2}{\lambda}\right)^2} \tag{1}$$

$$d_{out} = f + \frac{f^2(d_{in}-f)}{(f-d_{in})^2+\left(\frac{\pi\omega_{0in}^2}{\lambda}\right)^2} \tag{2}$$

Here, d_{in} is the distance from the fiber endface to the lens, f is the focal length of the lens, and an aspheric lens with $f =$

7.5 mm is used here. The radius of the beam waist is half of the mode field diameter (MFD), i.e., $\omega_{0in} = 2.5$ μm.

Bringing the parameters into the formula, we can obtain the variation of the radius of the beam waist ω_{0out} and the position of the beam waist d_{out} of the Gaussian beam of the space light with the distance from the fiber endface of to the lens d_{in}, shown as Fig. 1.

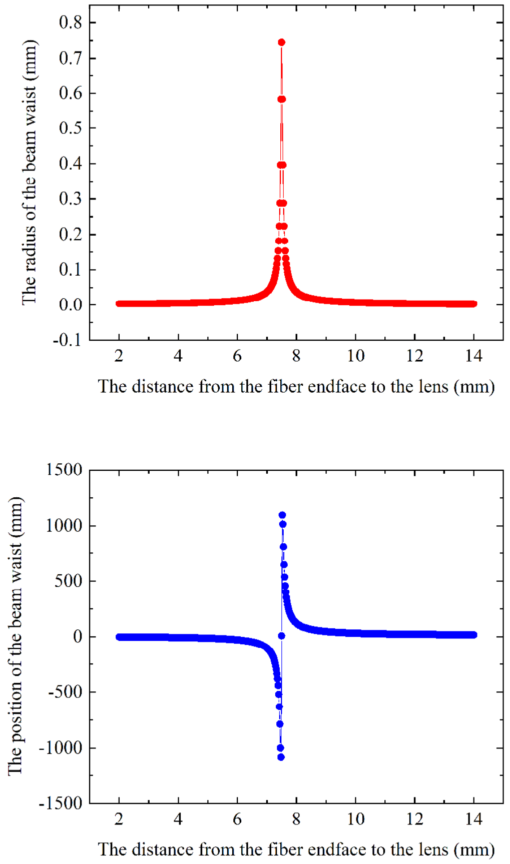

Fig. 1. Curve of the radius of the beam waist with the distance from the fiber endface to the lens (red) and variation curve of the position of the beam waist with the distance from the fiber endface to the lens (blue).

According to the calculation results, when the focal length *f*=7.5 mm, the waist of the Gaussian beam of the space light is 0.223 mm and the position is 647 mm. As shown in Fig. 2, The Gaussian radius of the spot we measured is 0.235 mm, which is in good agreement with the theoretical value.

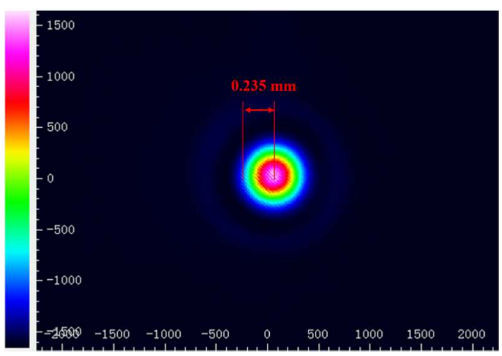

Fig. 2. The shape of the detected beam. The Gaussian radius of the beam spot is 0.235 mm

III. EXPERIMENTAL RESULTS

A. The finesse of the optical reference cavity

The finesse of an optical reference cavity are critical parameters that determine the frequency stability of a PDH stabilization system and the linewidth of the locked laser. For optical reference cavities with high finesse (on the order of hundreds of thousands), it is not feasible to directly measure the full width at half maximum (FWHM) of the transmission peak using an oscilloscope. Instead, cavity ring-down (CRD) spectroscopy is typically employed. This technique measures the decay curve of the transmitted beam through the resonant cavity. By fitting the decay curve, the photon lifetime within the optical cavity can be determined, which in turn allows for the calculation of the cavity's finesse.

The data points of the detected transmission signals are represented as black dots in Fig. 3. The fitted decay curves, derived based on the attenuation law ($y = ae^{-\tau_c/b} + c$), are shown in red. The above panel displays the transmission decay signal at 780 nm, while the bottom panel shows the transmission decay signal at 852 nm.

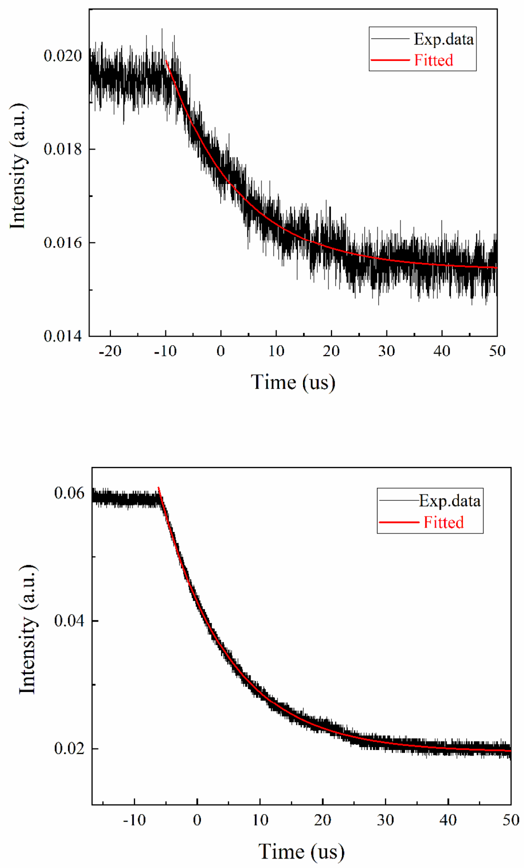

Fig. 3. Transmitted light attenuation signal (black) and fitting curve (red) of a resonator at 780 nm (above) and 852 nm (bottom), respectively.

The fitted decay time of the resonant cavity was determined to be 11.8 seconds and 10.8 seconds, respectively.

The finesse of the cavity is defined as the ratio of the free spectral range (FSR) to the intrinsic mode linewidth:

$$\mathcal{F} = \frac{\Delta\nu_{\mathrm{FSR}}}{\Delta\nu_{1/2}} = 2\pi\Delta\nu_{\mathrm{FSR}}\tau_c = \frac{\pi \cdot c \cdot \tau_c}{L} \quad (3)$$

where, c is the speed of light, τ_c is the photon lifetime, L is the cavity length.

Based on this formula, the finesse of the cavity is calculated to be 2.22×10^5 and 2.04×10^5 at 780 nm and 852 nm, respectively. The intrinsic mode linewidth ($\Delta\nu_{1/2}$) of the cavity is 13.5 kHz and 14.7 kHz, respectively.

B. Frequency stability

The beat frequency stability between two similar PDH-stabilized laser systems was measured to have a stability of 5.60×10^{-15}/1s at 780 nm and 5.99×10^{-15}/1s at 852 nm, shown as Fig. 4.

By assuming each laser system contributes equally to the measurement, each laser system has a frequency stability of 4.0×10^{-15}/1s at 780 nm and 4.2×10^{-15}/1s at 852 nm.

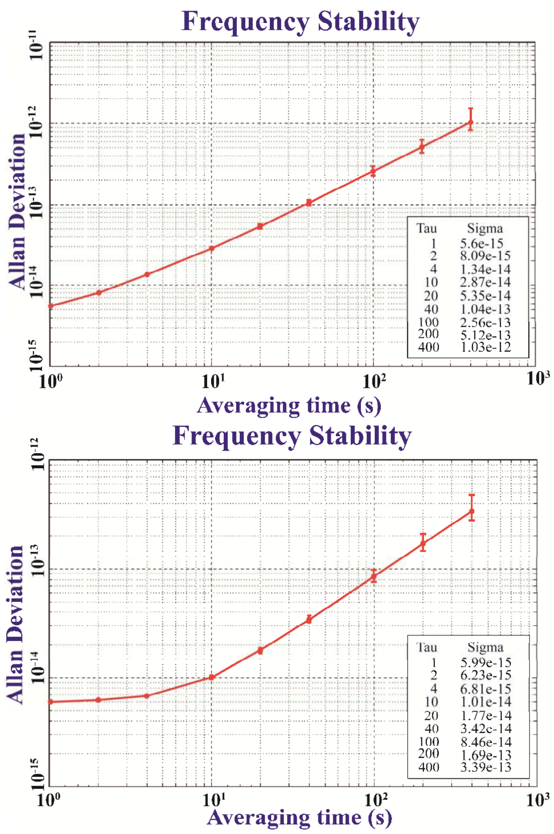

Fig. 4. Allan deviation for two similar systems at 780 nm (above) and 852 nm (bottom), respectively.

C. Laser linewidth

At the same time, the value of the linewidth was measured, shown as Fig. 5. The linewidth of the beat note between two cavity-stabilized lasers is around 3.6 Hz. By assuming each laser system contributes equally to the measurement, each laser system has a most probable linewidth of 2.5 Hz.

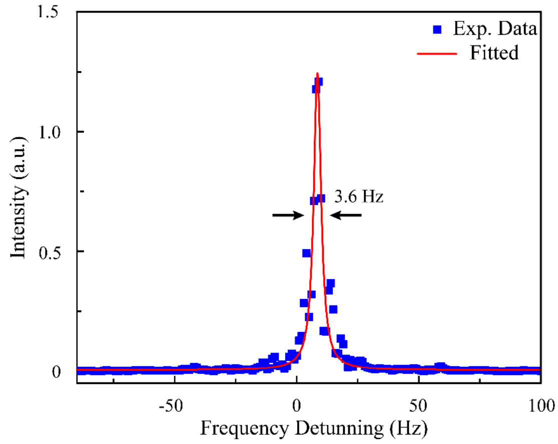

Fig. 5. The beat note between two cavity-stabilized lasers (blue squares) with 1 Hz resolution bandwidth (RBW) and its Lorentzian fitting curve (red solid line).

D. Time constants

We employed a dual-layer thermal shielding structure to reduce the rate of thermal exchange between the optical reference cavity and the external environment, thereby enhancing the precision of temperature control. The temperature transfer between the inner and outer layers of the thermal shield follows a relaxation process. A larger thermal exchange time constant for the designed thermal shield indicates slower temperature transfer, which consequently lowers the precision requirements for temperature control.

We measured the time constants of the ultra-stable cavity, shown as Fig. 6. It takes about 46 hours for the beat frequency to change to 1/e of the initial frequency. This implies that the required temperature control precision for the ultra-stable laser system is reduced to < 160 mK/s, which is easily achievable.

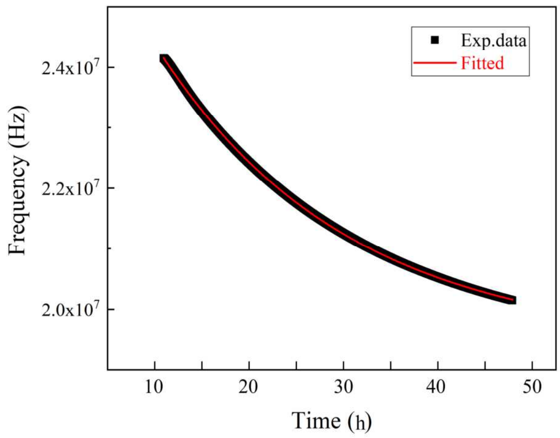

Fig. 6. The measured experimental data (black squares) and the fitted results (red solid line) of the time constants, from 305.15 K to 303.15 K.

Eventually, we put together the experimental data, as shown in Table 1.

TABLE I. EXPERIMENTAL DATA SUMMARY

Wavelength	Experimental data		
	Finesse	***Frequency stability***	***Linewidth***
780 nm	2.2×10^{5}	4.0×10^{-15} /1s	/
852 nm	2.0×10^{5}	4.2×10^{-15} /1s	2.5 Hz

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