Thermal-Noise-Limited Transportable Ultra-stable laser

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***Summary*—We present the design and performance of rack-mounted transportable ultra-stable laser at 1542.44nm, which is built for non-laboratory environment. The fractional frequency instability reaches the thermal noise limit of the 5 cm cubic cavity of 2.1×10^{-15} at 1 s averaging time after 70 mHz/s linear drift removed, and the beatnote with commercial ultra-stable laser reveals a linewidth of 1.4 Hz.**

Keywords—Optical reference cavity; Laser stabilization; Laser Systems; Frequency standard; Rack-mount instrument

I. Introduction

Ultra-stable lasers have extremely high frequency stability and time coherence, and have important applications in the fields of time-frequency transfer [1], optical atomic clocks [2], ultra-stable microwave signal generation [3], gravitational wave detection [4] and fundamental physics experiments. The frequency instability of the current state-of-the-art ultra-stable lasers has entered the -17 order of magnitude, achieved by using 48-cm ultra-long cavities with operation in ultra-low temperature environments. These high performance ultra-stable lasers have very demanding environmental requirements and can only operate in laboratory environments with tightly controlled conditions, limiting their applications in geodesy [5], hydrology [6] and microwave reference signal generation [7] for radar systems, application scenarios that require lasers to operate in non-laboratory environments.

Here we show a rack-mounted small transportable ultra-stable laser with all optical paths connected by fiber optic devices before entering the cavity. A five-axis lens positioner with a focusable collimator is used to achieve laser beam coupling. The laser is locked using a digital servo with a frequency instability close to its thermal noise limit and a linewidth of 1.4 Hz. The laser can be easily moved and has no significant performance degradation after a distance of bumps.

II. Methods/Results

The optical reference cavity is designed as a cubic cavity based on the idea of transportability and minimizing vibration sensitivity. The optical reference cavity is rigidly fixed by squeezing four Teflon balls at the four truncated vertices. The cavity length is 5 cm, the spacer and substrate are ULE, the cavity mirror diameter is half inch, the thickness is 4 mm, the radius of curvature is 1 m, and the through-hole diameter is 6 mm. The finite element analysis simulation shows that the cavity length is insensitive to the compression force at the cutting depth of 5.9 mm, indicated in Fig.1, and the vibration sensitivity in all directions is less than 1×10^{-13}/g. The thermal noise limit is calculated to be 1.35×10^{-15}.

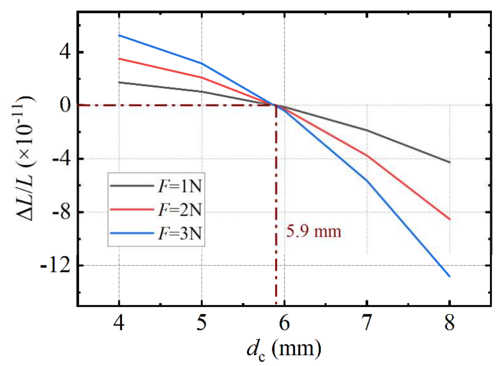

Fig.1. Simulation results of cutting depth and cavity length change.

The commercial fiber laser (NKT E15) is locked to the resonant frequency of the optical reference cavity using the PDH method. The optical path section is entirely fiber optic devices, which are directly coupled to the laser by a focusable collimator fixed to a five-axis adjustment frame. The cavity reflection signal is demodulated and fed to a digital servo for laser frequency locking.

To evaluate the performance of this ultra-stable laser, it was beated with a reference ultra-stable laser locked to a reference cavity with a 12 cm cylindrical all-ULE cavity. Since the two lasers are placed close together and both have a wavelength of 1542.44 nm, a 50 cm long fiber with a 10 cm long fiber coupler was used to merge the light to the photodetector and the beat frequency was measured with a counter (K+K FXE60).

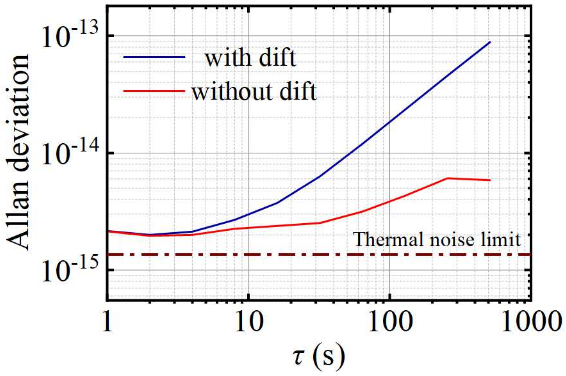

Fig.2. Fractional frequency instability of one stabilized laser. Wine-red dashed line: thermal-noise-limited frequency instability, 1.35×10^{-15}.

The fractional frequency instability of the reference laser is 2×10^{-15}/s with a linewidth of 1 Hz. The two lasers can be considered to have similar and uncorrelated noise performance, so the beat frequency instability is divided by a factor $\sqrt{2}$ to obtain the frequency instability of the test laser. As indicated in Fig.2, The fractional frequency instability is 2.1×10^{-15} at an integration time of 1 s. Without subtracting the frequency drift, the Allan deviation starts to lift upward after 4 s. After subtracting the linear drift of 70 mHz/s, the fractional frequency instability is less than 4×10^{-15} at the integration time of 0-100 s. The results are close to the thermal noise limit.

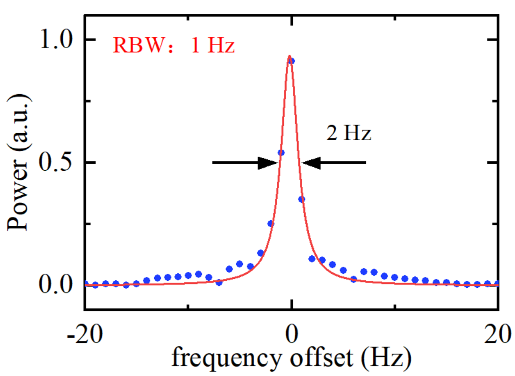

Fig.3. Linewidth of beatnote between two stabilized lasers. Blue dots: beatnote of two stabilized lasers, red thick line: Lorentz fit of two stabilized lasers.

To measure the laser linewidth, we mixed the beatnote to 400 Hz and measured the spectrum with an FFT analyzer (SR780) with an integration time of 1 s. Figure 3 demonstrates the linewidth of the laser beatnote at a resolution bandwidth (RBW) of 1 Hz. From the fit with the Lorentz line shape, the full-width at half-maximum (FWHM) is 2 Hz, divided by the factor $\sqrt{2}$ to obtain a linewidth of 1.4 Hz for the test laser.

III. Conclusions

In conclusion, we reported a rack-mounted transportable ultra-stable laser at 1542.44nm, based on a rigidly fixed cubic cavity made of ULE. The fractional frequency instability is measured to be less than 4×10^{-15} from 1 to 100 s, close to the thermal noise limit of the cavity. The beatnote with commercial ultra-stable laser system exhibits a linewidth of 1.4 Hz for our system. The cabinet can be rebooted and locked after pushing 500 m on a rough road without secondary commissioning alignment, and no significant performance changes were observed. Thus this ultra-stable laser has excellent robustness and can be flexibly moved without fear of performance degradation.

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