Noise quantitation of a home-made, rack-mounted ultra-stable laser

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***Abstract*—This paper presents a home-made rack-mounted ultra-stable laser. To analyze and optimize its performance, a noise model for the locking system was established. Various noise sources were tested and analyzed to determine their contributions to the overall system performance. The system achieved a frequency stability below 3.0×10^{-15} at the average time between 1 s and 10 s, approaching the thermal noise limit. This work provides a clear direction for further system optimization.**

Keywords—ultra-stable laser, noise quantitation, noise spectrum, Allan deviation

I. INTRODUCTION

With extremely high frequency stability and time coherence, ultra-stable laser plays essential roles in the fields of time-frequency transfer[1], optical atomic clocks[2], ultra-low phase noise microwave signal generation[3], gravitational wave detection[4] and fundamental physics experiments[5]. The performance of ultra-stable lasers is typically limited by the thermal noise of the optical reference cavity. Most research groups optimize their systems to approach the thermal noise limit[6-8]. However, system performance is influenced not only by thermal noise but also by other noises of cavity, residual amplitude modulation noise[9], detector noise, servo noise, and light source noise. Analyzing these noise sources provides deeper insights into the system, offering clear, direction-oriented guidance for system optimization. In this paper, we established a rack-mounted ultra-stable laser with all fiber-coupled devices before incidenting into the optical reference cavity. The cavity is designed to be a rigidly fixed cube with 5 cm length and cutted vertices. A noise model for the locking system was established, and various noise sources were tested and analyzed to determine their contributions to the system's performance.

II. METHODS/RESULTS

The actual Pound-Drever-Hall (PDH) laser locking system employs a dual-loop feedback control structure. The fast loop controls the acousto-optic modulator driver (VCO) and features a larger feedback bandwidth. The slow loop manages the piezoelectric transducer (PZT) port of the laser source, providing large-range slow frequency compensation to maintain the fast loop output average near zero. Because the slow loop control structure adds an additional low-frequency PI controller after the fast loop output, executed by the PZT and largely overlapping with the fast loop structure, its influence can be equivalently transferred into the laser source $N_l(f)$. This allows the system model to be simplified into a single-loop structure, as illustrated in Figure 1.

$S_{out}(f)$ denotes the total noise spectrum of the frequency-stabilized laser output, with units of Hz/$\sqrt{\text{Hz}}$. $N_{RAM}(f)$ represents the residual amplitude modulation noise spectrum, with units of Hz/$\sqrt{\text{Hz}}$. $N_{cav}(f)$ denotes the optical reference cavity noise spectrum, with units of Hz/$\sqrt{\text{Hz}}$. $N_{pd}(f)$ represents the photodetector noise spectrum, with units of V/$\sqrt{\text{Hz}}$. $N_d(f)$ denotes the demodulation unit noise and servo input noise spectrum, with units of V/$\sqrt{\text{Hz}}$. $N_s(f)$ represents the servo output noise spectrum, with units of V/$\sqrt{\text{Hz}}$. $N_l(f)$ denotes the laser free-running noise spectrum, which includes the PZT noise and slow loop output noise, with units of Hz/$\sqrt{\text{Hz}}$.

Given that the noise sources are independent of each other, the total noise spectrum of the stabilized laser output, according to control theory, is the incoherent sum of the contributions from each noise source at the output. This can be expressed as:

$$S_{out}(f)=\sqrt{\begin{array}{l}S_{cav}^2(f)+S_{RAM}^2(f)+S_{pd}^2(f)+\\ S_d^2(f)+S_s^2(f)+S_l^2(f)\end{array}} \tag{1}$$

Due to the system's loop gain $A_{loop}(f)$ being significantly greater than 1,

$$\begin{aligned}A_{loop}(f)&=D(f)\cdot R_v(f)\cdot L_1(f)\cdot G(f)\cdot K(f)\\ &=D_v(f)\cdot G(f)\cdot K(f)\end{aligned} \tag{2}$$

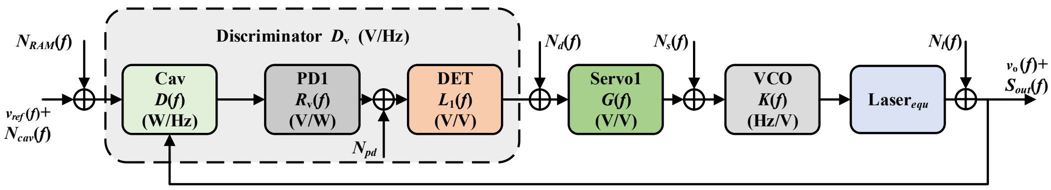

Fig.1 Noise model of the locking system

the total noise spectrum of the stabilized laser output can be described as

$$S_{out}(f) \approx [N_{cav}^2(f) + N_{RAM}^2(f) + \left(\frac{N_{pd}}{DR_v}\right)^2 (f) + \left(\frac{N_d}{D_v}\right)^2 (f) + \left(\frac{N_s}{D_v G}\right)^2 (f) + \left(\frac{N_l}{A_{loop}}\right)^2 (f)]^{\frac{1}{2}} \quad (3)$$

Similarly, for frequency stability analysis described by Allan deviation, due to its linear relationship with noise spectrum, the Allan deviation of the output laser is also the incoherent sum of Allan deviations contributed by each noise source. Additionally, the relationship between the Allan deviation of each noise source and its contribution at the output is consistent with the noise spectrum.

Since $D_v G$ is typically much greater than 1, the output noise from the servo and laser free-running noise in the loop will be sufficiently suppressed, allowing us to ignore their effects. Therefore, we only need to analyze the influence of cavity noise, RAM noise, photodetector noise, and servo input noise. Cavity noise is affected not only by thermal noise but also by optical power fluctuations, temperature fluctuations, air pressure fluctuations, and vibrations.

The noise spectra contributed by each noise source and the measurement results of Allan deviations are depicted in Figures 2 and 3, respectively. The photodetector noise is shown only in the power spectral density from 100 Hz to 100 kHz. This is because its measurement method aligns with RAM noise, and RAM noise dominates at frequencies below 100 Hz. Therefore, its contribution is not reflected in the Allan deviation curve.

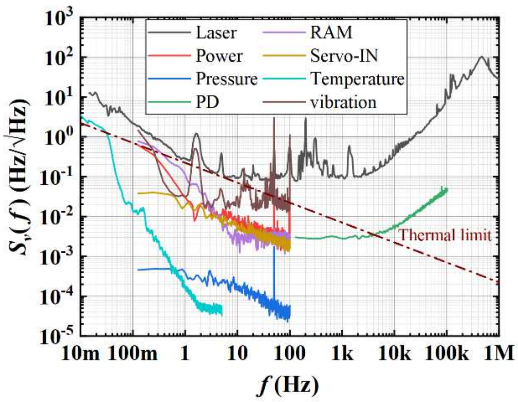

Fig.2 Frequency noise spectra of noise sources and stabilized laser beatnote.

As shown in figure 2, the grey curve represents the beatnote frequency noise spectrum between the stabilized laser and the reference laser. Above 10 Hz, the beatnote frequency noise spectrum is significantly higher than all other noise components. It exhibits a similar profile to the electronic noise (PD) of the photodetector, suggesting that this portion of the noise is limited by the electronic noise of the photodetector in the reference laser. Between 50 Hz and 2 kHz, there are some peaks primarily caused by mains power line noise and its harmonics, as well as spurious noise introduced due to insufficient circuit grounding. In the range of 0.7 Hz to 10 Hz, the noise is predominantly limited by the thermal noise of the optical reference cavity. There is a peak at 1.5 Hz attributed to horizontal vibrations, possibly caused by tidal-induced horizontal ground vibrations. Below 0.7 Hz, the laser frequency noise exceeds the thermal noise of the optical reference cavity, with a slope of approximately -0.8, steeper than the -0.5 slope of thermal noise. This region is primarily limited by low-frequency vibrations, residual amplitude modulation, and optical power fluctuations.

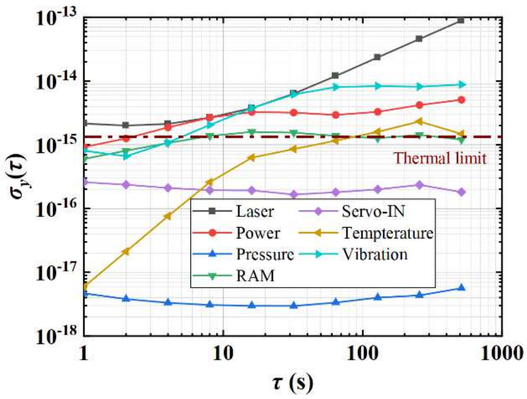

Fig.3 Allan deviation of noise sources and stabilized laser

Frequency stability, while less information-rich compared to frequency noise spectrum, remains a primary metric for assessing oscillator performance in the time-frequency domain. The frequency stability contributed by each noise source is depicted in Figure 3, where the grey curve represents the frequency stability of the stabilized laser minus a 70 mHz/s trend. Within the 1 s to 10 s range, the stability is consistently below 3.0×10^{-15}, approaching the thermal noise limit. Beyond this, there is an upward trend. Between 4 s and 10 s, performance is limited by optical power fluctuations, while from 10 s to 50 s, ground vibrations become the limiting factor. Beyond 50 s, performance deteriorates continuously due to aging drift in the optical reference cavity, leading to long-term performance degradation.

III. Conclusions

This paper established a noise model for the locking system and conducted tests to analyze the contributions of various noise sources. The frequency stabilization of the laser system is below 3.0×10^{-15} at the average time between 1 s and 10 s, which is approaching the thermal noise limit of 1.4×10^{-15}. The performance is limited by vibrations, power fluctuations and the aging of the cavity at the average time above 10 s. In this system, the vibration and intra-cavity power fluctuations can be optimized if the system performance is to be further improved, and the contribution of the other noises could be neglected.

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