High resolution displacement measurement by a novel Michelson laser

Xiaomin Qin[1], Zijie Liu[1], Zhiyang Wang[1], Hangbo Shi[1], Tiantian Shi[2], Jingbiao Chen[1,3]
Email: xiaominqin@stu.pku.edu.cn tts@ pku.edu.cn jbchen@pku.edu.cn
1 State Key Laboratory of Advanced Optical Communication Systems and Networks, Institute of Quantum Electronics, School of Electronics, Peking University, Beijing, China
2 National Key Laboratory of Advanced Micro and Nano Manufacture Technology, School of Inte-grated Circuits, Peking University, Beijing, China
3 Hefei National Laboratory, Hefei 230088, China

***Abstract*—High-resolution displacement measurement is crucial in precision machining, biomedical sensing, and other fields. In this paper, we propose a novel displacement measurement scheme based on Michelson lasers, which obtains the cavity length variations from the laser frequency change, tracing displacement measurement to laser frequency measurement with high resolution. Furthermore, we present a Faraday-Michelson laser configuration utilizing the narrowband Faraday anomalous dispersion atomic filter as the frequency selection device, enabling simultaneous oscillation output of two laser beams. With frequency measurement achieving resolutions up to 12 digits, our scheme can theoretically reach a displacement measurement resolution in pm or even finer. It exceeds the current resolution of displacement measurement by laser interferometers, and can be used for precision displacement measurement and control of lithography machine and so on, paving the way for future advancements in high-resolution displacement measurement.**

Keywords—high resolution, displacement measurement, Michelson laser, laser interferometer, frequency measurement

I. Introduction

High-resolution displacement measurement techniques are widely used in gravitational wave detection [1], atomic force microscopy [2], and precision machining [3]. Laser interferometers with traceability to the definition of the meter are well-suited for displacement measurements. Among these, heterodyne interferometers exhibit high immunity to homodyne interference, and efforts have been made towards high-resolution measurements of 10 pm using fast phase detection methods [4,5]. However, the electronic and environmental noise pose challenges in measuring displacements of 10 pm or even finer.

Nowadays, frequency measurement has the highest measurement accuracy among all physical quantities. The systematic uncertainty of NIST's $^{27}Al^+$ optical clock reaches 9.4×10^{-19} [6], and JILA's Sr optical lattice clock achieves a stability of 4.8×10^{-17} at 1 s [7]. If we can trace displacement measurement to laser frequency measurement, the advantages of frequency measurement could enable higher-resolution displacement measurement.

Based on this, we propose a novel displacement measurement scheme: light emitted from a laser gain medium is split into two beams and directed into resonant cavity mirrors with high-reflectivity placed in each path. Since the laser frequency is related to the cavity length, any difference in length between the two paths can create a frequency difference between the two laser modes. By moving one of the cavity mirrors, we can deduce cavity length changes from the beat frequency change between the two laser modes. As the optical path structure is similar to a Michelson interferometer [8,9], we name it the Michelson laser. However, a fundamental distinction lies in the fact that we are implementing a laser with two laser modes rather than an interferometer. Given that commercial frequency counters already offer resolutions of up to 12 digits, our scheme could theoretically achieve a displacement measurement resolution in pm or even finer.

China Postdoctoral Science Foundation (BX2021020) and Innovation Program for Quantum Science and Technology (2021ZD0303200).

II. Experiment Setup

A. Michelson Laser

Figure 1(a) shows the schematic of the typical Michelson laser and its associated displacement measurement method. The light emitted from the laser gain medium (i.e., laser diode, gas, or other solid gain medium) is split into two beams by a beam splitter. One beam serves as the reference beam, reflected by a fixed cavity mirror, while the other acts as the measurement beam, reflected by a movable cavity mirror. After oscillation, we get two laser beams with different frequencies related to their cavity lengths. To facilitate oscillation, a highly reflective mirror is located behind the laser gain, and the output face of the laser gain is anti-reflected. What's more, to make sure the excellent immunity to mechanical vibrations, it is better to employ the corner-cube retroreflector as the cavity mirror, which can always reflect the injected light back to the source. There exists a relation between the laser cavity length (L) and frequency (ν),

$$\Delta\nu / \nu = -dl / L$$

where $\Delta\nu$ and dl indicate the change of ν and L, respectively. By employing a frequency counter to measure the change in the beat frequency between the two laser modes of Michelson laser, it is straightforward to calculate the displacement of the movable mirror. As the frequency measurement can achieve a high resolution of 12 digits, this scheme theoretically offers a displacement measurement resolution with an order of pm or less.

B. Faraday-Michelson Laser

Additionally, we propose a specific scheme based on the narrow bandwidth Faraday anomalous dispersion optical

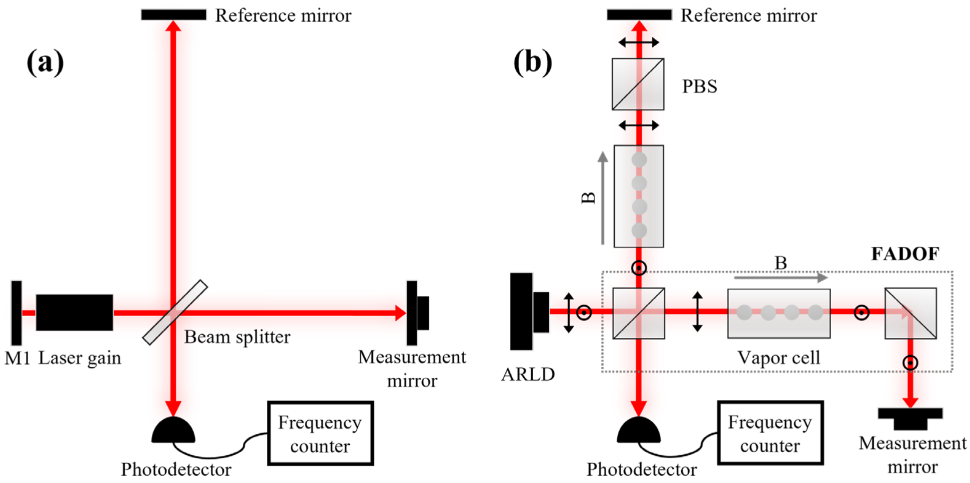

Fig.1 Schematic of the displacement measurement based on (a) typical Michelson laser and (b) Faraday-Michelson laser. (M1: mirror 1; ARLD anti-reflected laser diode; PBS: polarizing beam splitters. The polarization of two beams is indicated with black arrows, and the gray arrow represents the direction of the magnetic field.)

filter (FADOF), see Fig. 1(b). The anti-reflection coated laser diode (ARLD) serves as the gain medium only, preventing difficulties in oscillation for He-Ne tubes with a small gain. A polarizing beam splitter (PBS) divides the light into two beams, with polarization indicated in Fig. 1(b) by the black arrows. Two FADOFs with transmittance peaks differing by several GHz are placed in the two optical paths to generate two laser modes of the Michelson laser with different frequencies. The FADOF consists of a pair of PBSs for polarization selection and a vapor cell enriched with alkali metal gas. To achieve a specific frequency selection effect, the cell should be precisely temperature and magnetically controlled. Two cavity mirrors with a high reflectivity of 99.98% are placed after the FADOFs to enable oscillation. The measurement mirror is mounted with a piezoelectric transducer (PZT) to adjust the cavity length. A photodetector (PD) is positioned in one laser emitting port of the PBS to detect the two laser modes. The beat frequency is measured and analyzed using a frequency counter and spectrum analyzer. BY measuring the change in beat frequency of the two modes of the Michelson laser, we can calculate the displacement of the movable mirror.

III. Experimrntal Results

We constructed a Faraday-Michelson laser and tested its basic performance. A wavelength of around 852 nm anti-reflection coated laser diode (ARLD) is used as the gain medium only. Both FADOFs are enriched with pure Cs gas and have a magnetic field of 1000 Gauss. The temperature of the FADOF in the measurement optical path is 71°C, corresponding to the Cs $6^2S_{1/2}$ (F=4) → $6^2P_{3/2}$ transition. The temperature of the FADOF in the reference path is 79°C, with the transmission peak corresponding to the left side of Cs $6^2S_{1/2}$ (F=3) → $6^2P_{3/2}$ transition, having a lower frequency. By adjusting the position of the cavity mirrors, we achieved the simultaneous oscillation of the two beams. Under a diode current of 140 mA, the optical power of the measurement beam reached 3.23 mW with a wavelength of 852.336 nm, seeing Fig. 2(a), while the power of the reference beam was 2.71 mW with a wavelength of 852.368 nm, seeing Fig. 2(b).

The power difference is due to the different peak transmittances and the inconsistent optical powers of the ARLD light after passing through the PBS. This experimental result confirms the feasibility of the Michelson laser. However, due to the lack of a photodetector (PD) with a bandwidth exceeding 10 GHz in the laboratory, and the frequency difference between the two modes of the Michelson laser being approximately 13 GHz, the beat frequency has not been detected. Further experiments are

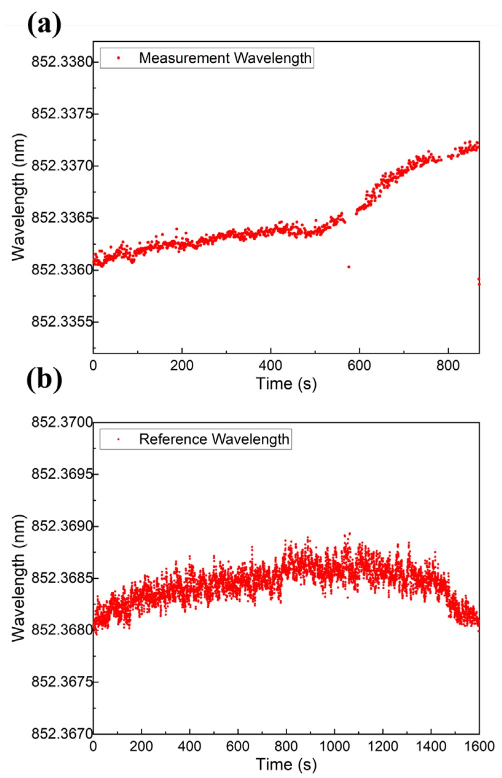

Fig.2 Free-running wavelength of the Michelson laser in (a) measurement and (b) reference optical path.

necessary for verification and optimization.

IV. Conclusions and Future Work

We propose a novel high-resolution displacement measurement scheme called Michelson laser, and experimentally verified the simultaneous oscillation of two laser modes of the Michelson laser for the first time. Unlike traditional heterodyne interferometry, which uses fine fringe counting or phase detection for displacement measurement, we trace displacement measurement back to laser frequency measurement. This approach allows us to fully utilize the high resolution of frequency measurement, breaking the 10 pm measurement limit and potentially achieving resolutions in pm or even finer. In the near future, we will focus on further frequency detection to validate the resolution of the proposed scheme. Additionally, the Michelson laser requires excellent mechanical and thermal stability to minimize the frequency drift of the laser itself, which is a crucial direction for future efforts. This scheme traces displacement measurement to laser frequency measurement, and offers a new approach for future high-resolution displacement measurement, with the potential to advance lithography machine, precision machining and other related fields.

Acknowledgment

This work is supported by China Postdoctoral Science Foundation (BX2021020) and Innovation Program for Quantum Science and Technology (2021ZD0303200).

References

[1] B. P. Abbott, R. Abbott, T. D. Abbott, M. R. Abernathy, F. Acernese et al., “LIGO Scientific Collaboration and Virgo Collaboration,” Phys. Rev. Lett., vol. 116, pp. 061102, February 2016.

[2] M. Sasaki, K. Hane, S. Okuma, M. Hino, and Y. Bessho, “Improved differential heterodyne interferometer for atomic force microscopy,” Rev. Sci. Instrum., vol. 65, pp. 3697-3701, 1994.

[3] H. N. Hansen, K. Carneiro, H. Haitjema and L. De Chiffre, “Dimensional Micro and Nano Metrology,” Ann. CIRP, vol. 55, pp. 721-743, 2006.

[4] T. D. Nguyen, M. Higuchi, T. T. Vu, D. Wei and M. Aketagawa, “10-pm-order mechanical displacement measurements using heterodyne interferometry,” Appl Opt. vol. 59, pp. 8478-8485, 2020.

[5] Magnus T. L. Hsu, Ian C. M. Littler, Daniel A. Shaddock, Jan Herrmann, Richard B. Warrington, and Malcolm B. Gray “Subpicometer length measurement using heterodyne laser interferometry and all-digital rf phase meters,” Opt. Lett., vol. 35, p. 4202-4204, 2010.

[6] S. M. Brewer, J.-S. Chen, A. M. Hankin, E. R. Clements, C.W. Chou, D. J. Wineland, “$^{27}Al^{+}$ Quantum-Logic Clock with a Systematic Uncertainty below 10^{-18},” Phy. Rev. Lett., vol. 123, pp. 033201, 2019.

[7] E. Oelker, R. B. Hutson, C. J. Kennedy, L. Sonderhouse, T. Bothwell, A. Goban, D. Kedar, C. Sanner, J. M. Robinson, G. E. Marti, D. G. Matei, T. Legero, M. Giunta, R. Holzwarth, F. Riehle, U. Sterr and J. Ye, “Demonstration of 4.8×10^{-17} stability at 1 s for two independent optical clocks,” Nat. Photon., vol. 13, pp. 714-719, 2019.

[8] A. A. Michelson and E. W. Morley, “On the relative motion of the Earth and the luminiferous ether,” Am. J. Sci. , vol. 34, pp. 333-345, 1887.

[9] A. A. Michelson, “On the application of interference methods to astronomical measurements,” Astrophys. J., vol. 51, pp. 257, 1920.