

COMPACT ABSOLUTE LENGTH MEASURING MACHINE BY COMBINING REGULAR CRYSTALLINE SURFACE AND LASER INTERFEROMETRY

Masato AKETAGAWA*, Pongpun RERKKUMSUP, Koji TAKADA,
Toshio TAKAGI, Tomonori WATANABE

Department of Mechanical Engineering, Nagaoka University of Technology
Kamitomioka 1603-1, Nagaoka, Niigata, 940-2188 JAPAN

1. Introduction

Since nanotechnology has progressed rapidly, new methods for length measurement applicable to the millimeter range with sub-nanometer resolution are required. Currently, the standard method for length measurement is laser interferometry. A heterodyne interferometer with a Zeeman laser¹⁾ or a homodyne interferometer using the bi-fringes counting method²⁾ is widely used in the industry. However, it is difficult to determine arbitrary length with the sub-nanometer accuracy using the interferometers, because they have the non-linearity problem of the fringe interpolation³⁾. A phase modulation homodyne interferometer, that can determine the optical path difference of wavelength times integer with the accuracy of 10 picometer or less, is proposed⁴⁾.

The lattice spacing of approximately 0.2 nanometer for some regular crystalline lattices is uniform and stable over a long range, when the crystals are stress free. These crystals can be used as reference scales with a sub-nanometer resolution instead of laser interferometry. X-ray interferometry (XRI) using silicon crystal has been developed to determine the lattice spacing of silicon at National Metrological Laboratories⁵⁾. Moreover, the combined optical and x-ray interferometer (COXI)⁶⁾ has been developed for absolute length measurement with sub-nanometer accuracy at European metrological laboratories. However, XRI is very delicate for an adjustment to obtain x-ray fringe, and not commonly used in the industry. On the other hand, a scanning tunneling microscope (STM)⁷⁾ and an atomic force microscope (AFM)⁷⁾ are becoming a powerful and popular tool in surface engineering fields and can be used to obtain “images of atoms” on a regular crystalline surface. Therefore, such crystalline lattice can be used as a “crystalline lattice scale” with sub-nanometer resolution by combining them with STM/AFM. We have shown the feasibility of the crystalline lattice scale using a graphite crystal (highly oriented pyrolytic graphite: HOPG) as the reference scale and a dual-tunneling-unit scanning tunneling microscope as the detector⁸⁾. In this article, we propose a compact absolute length measuring machine (ALMM) with sub-nanometer accuracy and sub-millimeter travel by combining “the crystalline lattice scale” as a fine scale and the phase modulation homodyne laser interferometry (= optical fringe) as a coarse scale.

2. Basic design and operation principle

Figure 1 and **2** illustrate the side and top views of the ALMM planned to construct. The sample of interest and reference crystal (HOPG) are set on piezo-driven stages A and B, respectively, which are just beneath AFM and STM heads with tips and YZ scanners. Both stages travel along 1-dimensional motion axes X_A and X_B . (A coarse motion mode with millimeter travel may also be added in stage A in Fig. 2.) The stage A and B are independently controlled and their motion

axes X_A and X_B are aligned to be parallel with the two arms of the Michelson interferometer. The interferometer can measure motion (= displacement) difference between the X_A and X_B axes. 3-dimensional images of the both samples can be obtained using the combined motions of the stages A/B and AFM/STM heads. The compact thermo-stabilized vacuum cell with a temperature stability of 1 mK and a vacuum of 10^{-5} torr is employed to remove thermal deformation and fluctuation of refractive index of air. The beam path of the interferometer is shown in Figure 2.

The linear polarized beam (polarization angle : 45 degree) emitted from the frequency-stabilized He-Ne laser passes through the Pockels cell and the single-mode polarization preserving fiber. The Pockels cell is used to supply phase modulation and a phase bias shift between the two polarization components p and s. Removing the instability of beam

pointing and a heat source of the He-Ne laser can be attained using the fiber. The beam passes through the non-polarizing beam splitter 1 (NPBS1), and a part of the beam is split into the photodiode 1 (PD1) through polarizer 1 (P1: 45 degree) for the reference phase detection with the lock-in amplifier 1 (LIA1). The beam incident on the polarized beam splitter 1 (PBS1) is divided into two beams, s and p components. The two beams go along the two arms of the interferometer via PBS2 and 3, quarter wave plates 1 and 2 (QWP1/2), moving prism 1 and 2 (MP1/2) on the stages and trapezoid prism 1 and 2 (TP1/2). The beams travel back and fourth four times between MP1/2 and TP1/2. The two beams re-passed through QWP1/2 and the PBS2/3 are recombined at the PBS4. The recombined beam is divided at NPBS2 into two parts, one goes to PD2 via P2(45 degree) and the other to PD3 via QWP3 and P3 (45 degree), respectively. Output signals form the PD2 and 3 are fed into the LIA2 and 3 to determine the phase shift corresponding to the motion difference between the stage A and B using phase modulation and lock-in detection. The output signal of the LIA1 is used to control the bias phase shift of the Pockels cell so that amplitudes of the s and p components at the PBS1 should be the same. The output signals of LIA2 and 3 are the cosine and sine function of the optical path difference. The motion difference can be measured and controlled

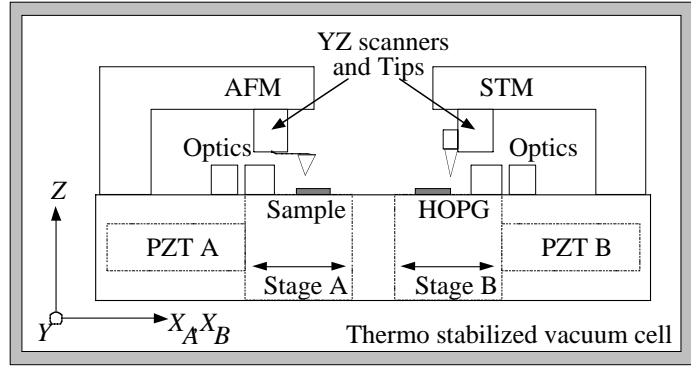


Figure 1. Side view of the absolute length measuring machine.

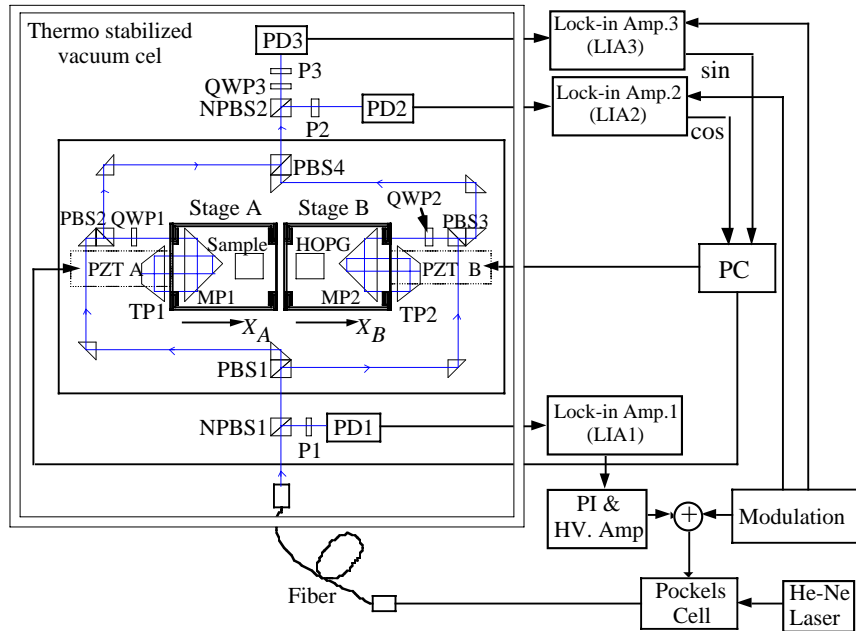


Figure 2. Top view of the absolute length measuring machine.

at the dark fringes points (= null points) with picometer resolution. In our design, the motion difference between the stages A and B, which is corresponding to 1 fringe should be (wavelength/8). The following steps represent the measurement procedure of the ALMM.

(1) Initial to zero calibration point: At the starting position x_{A0} of scan for stage A, displacement of stage B x_B is controlled and locked so that the fringe of the interferometer should be dark (null point). The stage B is then at position x_{B0} .

(2) Scanning of the stage A for the AFM: The stage A is then scanned for the AFM imaging to the ending position x_{A1} . The moving translation ($x_{A0} - x_{A1}$) will consist of integer part n of optical fringe $n*(\text{wavelength}/8)$ and fractional part f of an optical fringe $f*(\text{wavelength}/8)$. n is then determined from the output of the LIA2 and LIA3.

(3) Scanning of the stage B for the STM: The stage B is then scanned for the STM atomic imaging to position x_{B1} to shift the optical fringe to the next dark (null point). The translation ($x_{B0} - x_{B1}$) equals to the fractional part f of the optical fringe and it can be determined by counting the number m of atoms in the STM image, in which lattice spacing is d .

(4) Determination of total translation length: The total translation equals to $n*(\text{wavelength})/8 + md$.

3. Pre-experiments

In order to realize the ALMM project, a lattice spacing on crystalline surface must be determined. The lattice spacing of a bulk state may not be same as the one of a surface state. To research the problem, we preliminary made a measuring machine for lattice spacing on crystalline surface ⁹⁾, which consist of a flexure piezo-driven X axis-stage, a STM head with tip and a YZ-scanner and a phase modulation homodyne interferometer. In the interferometer, a differential-4-path configuration is used. **Figure 3** shows the outline of the machine, which are almost same as the ALMM, except an AFM head and another flexure stage. The stage is fabricated from low linear expansion cast iron whose linear expansion coefficient is less than $0.8*10^{-6} \text{ K}^{-1}$. A first resonance frequency of the stage is about 2 kHz. A maximum travel of the stage is about 10 micrometers. Pitch and yaw motion are less than 1.5 radian for maximum travel. We can obtain a good quality image of HOPG for counting the number of atomic array.

Figure 4 shows a part of atomic image of HOPG obtained using the machine, whose length is 1 micrometer.

Figure 5 shows a demonstration of the phase modulation homodyne interferometer used on the stage shown in Fig. 3. In Fig. 5, signals (A), (B) and (C) are from capacitive displacement sensor set on the stage, photodiode ended at the interferometer (PD2 in Fig. 2) and the lock-in am-

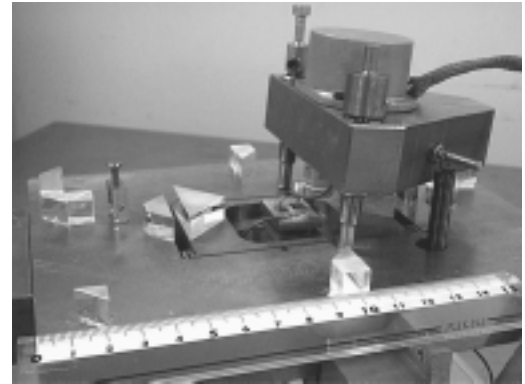


Figure 3. Photograph of the measuring machine for lattice spacing on crystalline surface.

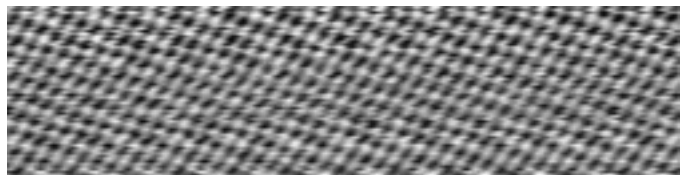


Figure 4. Part of a long atomic image of HOPG. The lateral axis was selected as the measurement and the fast scanning direction. The scanned area was 1 micrometer (lateral axis) * 2 nanometer (vertical axis). Tip speed was 2 micrometer/s. The scanned time for one line along the fast scanning axis and the scanning period of the complete image were 0.5 and 256 s, respectively.

plifier (LIA2 in Fig.2). In Fig. 5, the X axis stage moves with triangular motion. About $(2+1/4)$ fringes $(=(2+1/4)*(1/16)*\text{wavelength})$ from PD2 can be observed. The result almost agrees with the output of 90 nanometer from the displacement sensor. The LIA2 signal crosses null line when the PD2 signal reaches at bright and dark points. The S/N ratio for LIA2 signal is not sufficient in Fig. 5, because the modulation amplitude is not so high. We believe it is possible to improve the S/N ratio by tuning the modulation method. By combining the results from Fig. 4 and 5, we can report determination process for lattice spacing on HOPG crystalline surface in the near future, and we can also realize the ALMM project.

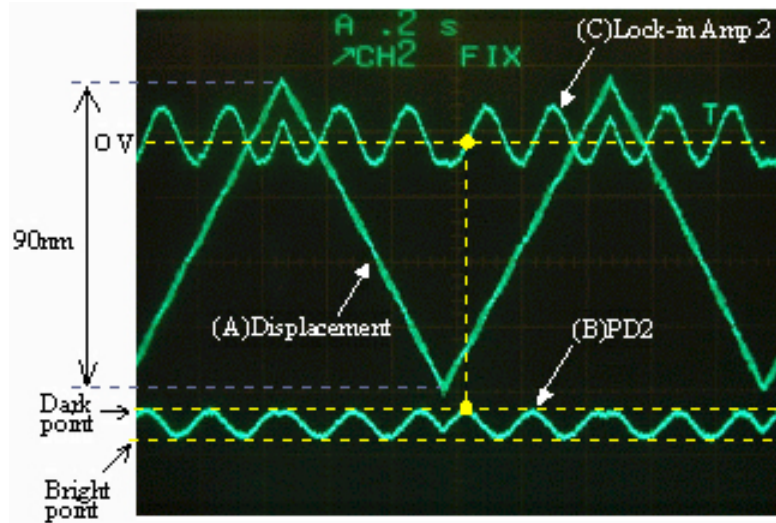


Figure 5. A demonstration of the phase modulation homodyne interferometer set on the stage shown in Fig. 3. Signals (A), (B) and (C) are from capacitive displacement sensor set on the stage, photodiode ended at the interferometer (PD2 in Fig. 2) and the lock-in amplifier (LIA2 in Fig.2). A differential-4-path configuration is used in the interferometer. With the configuration, optical one fringe equals $(1/16)*\text{wavelength}$. In the interferometer, two LiNbO_3 crystals ($5 * 5 * 30$ millimeters*2 piece) was used for the Pockels cell. A half-wavelength voltage for the cell is about 180 V. Modulation amplitude and frequency applied to the cell were 10 V and 10 kHz, respectively. Amplitude of LIA2 signal (C) is about 0.5 V.

Acknowledgment

The partial financial supports of the Saneyoshi Scholarship Foundation and the Mitutoyo Association for Science and Technology are gratefully acknowledged.

References

- 1) For example, Agilent Technologies, Model 10897B; 2001.
- 2) For example, Gonda S et al.. Real-time, interferometrically measuring atomic force microscope for direct calibration of standards. *Rev. of Sci. Instrum.* 1999; **70**: 3362.
- 3) Thalmann R, Hou W. Limitations of interpolation accuracy in heterodyne interferometry. *Proc. of the 7th International Precision Engineering Seminar*; May 1993; Kobe, Japan: 11.
- 4) Basile G, Bergamin A, Cavagnero G, Mana G. Phase modulation in high-resolution optical interferometry. *Metrologia* 1991-2; **28**: 455.
- 5) NIST, PTB, NPL, IMGCC, NRLM et al..
- 6) Basile G, Becker P, Bergamin A et al.. Combined optical and X-ray interferometry for high-precision dimensional metrology. *Proc. Royal Society Lond. A* 2000; 456: 701
- 7) Binnig G, Rohrer H.
- 8) Aketagawa M, Takada K et al.. Long atomic imaging over a 5-um-long region using an ultralow thermally drifted DTU-STM. *Rev. of Sci. Instrum.* 1999; **70**: 133.
- 9) Hashida T et al., *Proc. Spring meeting of JSPE*; 2000 March 22-24; Tokyo: 589. [in Japanese]