Optical gauge block metrology in KRISS

Chu-Shik Kang, Jae Wan Kim, Jong-Ahn Kim, Ho Suhng Suh, and Won-Kyu Lee

Length/Time Metrology Group, Physical Metrology Division,
Korea Research Institute of Standards and Science, Daejeon 305-340, Korea

Gauge block measurement by using optical interferometry in Korea Research Institute of Standards and Science (KRISS) is described. A partially modified commercial Twyman-Green type gauge block interferometer equipped with three frequency stabilized lasers which are coupled into one single mode optical fiber, is used for the measurement of gauge blocks of nominal length up to 250 mm. Fringe scanning Fourier transform method is used to obtain the excess fraction value from the interference fringes. The temperature inside the interferometer is stabilized within ±4 mK for three hours. The standard uncertainty ($k = 1$) of measurement is 29 nm for a 250-mm gauge block.

OCIS codes: 120.3940, 120.3180, 070.2590, 120.5050.

Gauge blocks are the most precise and widely used artifacts in length metrology[1]. The gauge blocks are traceable to the definition of metre being calibrated by optical interferometry. Several techniques of optical calibration of gauge blocks have been reported. Some of them are multiple wavelength interferometry[2], white light scanning interferometry[3], and synthetic wavelength method[4]. In this paper, the overall aspects of the optical gauge block calibration being performed in Korea Research Institute of Standards and Science (KRISS) are described.

The measurement system is based on a commercial gauge block interferometer which has Twyman-Green configuration. It is capable of loading ten gauge blocks of nominal length up to 250 mm per one calibration round. At its 20th anniversary, some parts of the hardware were modified to upgrade the interferometer's measurement performance[5]. As a result, the automatic measurement of gauge blocks is achieved. The schematic diagram of the overall setup is shown in Fig. 1.

The interferometer uses three frequency stabilized lasers which are a Zeeman stabilized He-Ne laser at 633 nm, an iodine stabilized Nd:YAG laser at 532 nm, and a diode laser stabilized to rubidium's saturated absorption line at 780 nm. The Zeeman stabilized He-Ne laser is a commercial laser (HP 5517A), from which one of the two frequency components is selected for use. The frequency of the laser is calibrated by using the iodine stabilized He-Ne laser at a wavelength of 633 nm by measuring the beat frequency between the two lasers. The iodine stabilized Nd:YAG laser was introduced from VNIIM, Russia, and the a_{10} component is used for the measurement. The frequency (563 260 223 513 kHz) is adopted from the Mise en Pratique[6]. The diode laser stabilized at a wavelength of 780 nm is developed in-house. The frequency of an extended cavity laser diode was locked to one of the hyperfine absorption lines of rubidium atoms at 780 nm. We use the ^{87}Rb D_2 line $5S_{1/2} \rightarrow 5P_{3/2}$ ($F'' = 2 \rightarrow F' = 2/F'' = 2 \rightarrow F' = 3$ crossover resonance), the absolute frequency of which was reported to be 384 227 981.8773 MHz ±5.5 kHz[7]. Each laser beam is focused into a single mode optical fiber, whose cutoff wavelength is 410−450 nm, as shown in Fig. 2. Unlike the conventional case of using a multimode optical fiber for coupling several lasers, where a fiber vibrator is necessary to remove the speckle pattern, a single mode fiber generates a clean TEM_{00} mode only, and thus requires no fiber vibrator.

The output fiber end is placed exactly at the focal point of the collimating lens of the interferometer to produce

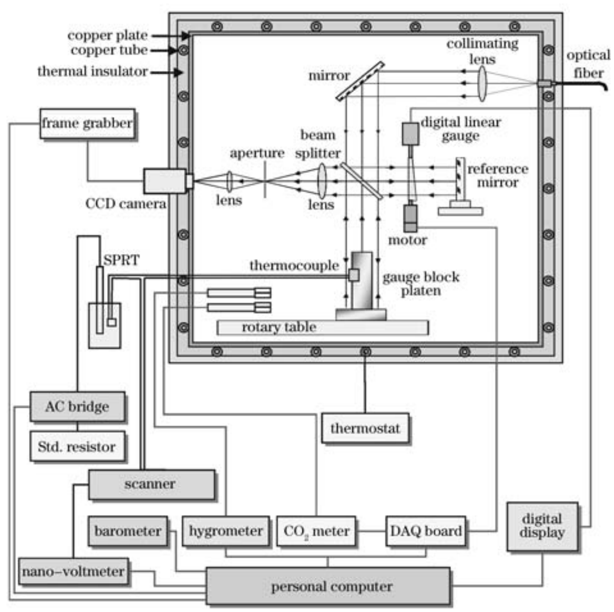

Fig. 1. Schematic of the KRISS gauge block interferometer.

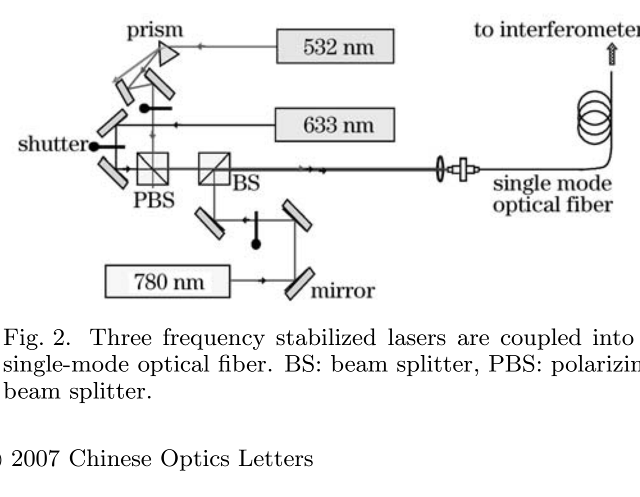

Fig. 2. Three frequency stabilized lasers are coupled into a single-mode optical fiber. BS: beam splitter, PBS: polarizing beam splitter.

1671-7694/2007/S1S237-03

collimated light into the interferometer. The collimation quality was confirmed by analyzing the laterally sheared interference fringes by using a shearing plate. During the measurement, each laser wavelength is selected one by one using three computer-controlled mechanical shutters placed in the laser beam paths.

The interferometer body is thermally stabilized by active cooling with water. All walls of the interferometer body are attached with copper plates where copper tubes are soldered. And then additional thermal insulator boards are covered over the copper walls. As shown in Fig. 3, copper tubes are aligned in the manner that the outlet tube follows back along the inlet tube, so that the temperature gradient is minimized over the copper plate. Thermally stabilized water from a thermostat is circulated through the copper tubes resulting in temperature stabilization within the interferometer body. Air temperature inside the interferometer is kept within 20.0 ± 0.1 °C with stability about 4 mK over 3 hours (see Fig. 4).

The length, l, of a gauge block is expressed as

$$l = (m_1+F_1)\frac{\lambda_1}{2n_1} = (m_2+F_2)\frac{\lambda_2}{2n_2} = (m_3+F_3)\frac{\lambda_3}{2n_3}, \quad (1)$$

where m_i ($i = 1, 2, 3$) and F_i denote the integer part and the fractional part of the interference order, and λ_i, n_i are the vacuum wavelengths of three lasers and the corresponding refractive indices of air, respectively. Refractive index of air is calculated by the modified Edlén's equation which requires the measured values of air temperature, air pressure, relative humidity, and carbon dioxide density in air[8]. Excess fractions are measured from the interference fringes by using the fringe scanning Fourier transform method (FSFTM)[5].

Unlike the conventional Fourier transforming fringe analysis, FSFTM does not use the spatial intensity profile of the static interferometric fringes. Instead, sinusoidal modulation of fringe intensity of a spatially fixed point is used for the analysis. The intensity modulation is introduced by linear translation of an optical wedge which is placed in the reference arm of the interferometer, by using a constant speed direct current (DC) motor. Three intensity modulation data, one from the central point at the gauge block's measuring face and the others from two points on the platen which are placed near the upper edge and the lower edge of the gauge block, respectively, are taken while translating the optical wedge. An example of the interference fringes and three intensity modulation data recorded from three fixed points depicted in Fig. 5 as p_1, g, and p_2, are shown in Fig. 6.

Phase values of three points are calculated by using the fast Fourier transform (FFT) algorithm, the excess fraction is obtained as

$$F = \frac{1}{2\pi}\left\{\phi_g - \frac{\phi_{p_1} + \phi_{p_2}}{2}\right\}, \quad (2)$$

where ϕ_g denotes the phase of the fringes at the gauge block, and ϕ_{p_1} and ϕ_{p_2} denote the phase of the fringes at the platen located near the edges of the gauge block. Some of the main advantages of the FSFTM are: three intensity profiles have exactly the same carrier frequency regardless of the topography of the gauge block surface or the platen; all information on the phase is taken from the point of interest itself; the measurement result is not sensitive to nonlinearity of the charge coupled device (CCD) camera.

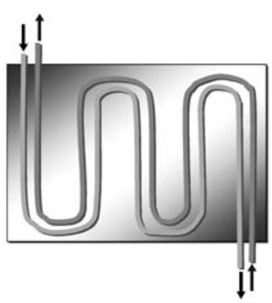

Fig. 3. Basic configuration of the copper tubes.

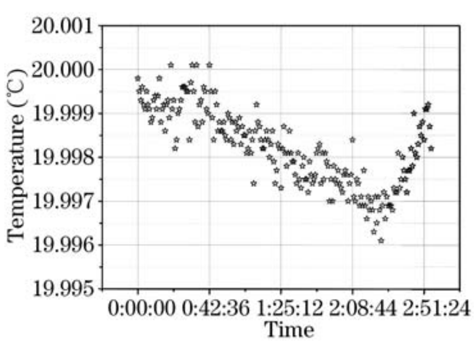

Fig. 4. Temperature stability inside the KRISS gauge block interferometer.

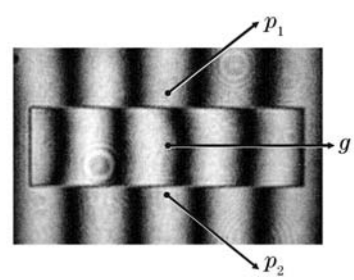

Fig. 5. Three points on the interference fringes from which the intensity modulation is measured.

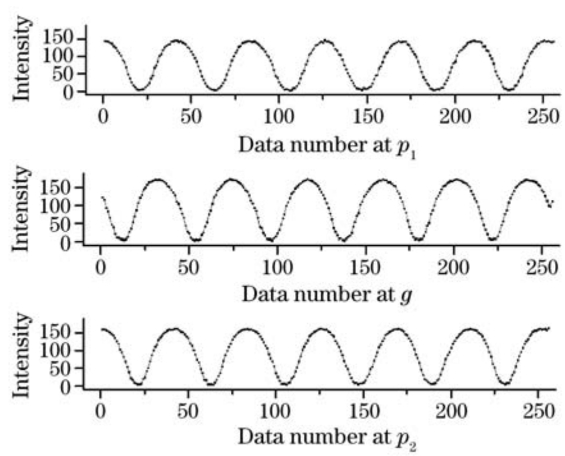

Fig. 6. Intensity modulation data from the three points shown in Fig. 5.

Integral orders, m_i, are determined by the exact fraction method by using Eq. (1).

The gauge block length such measured needs several corrections. The most important corrections are those for the thermal expansion and the phase shift due to dissimilar materials and/or surface textures of the gauge block and the platen.

The thermal expansion is corrected by applying

$$l_\mathrm{t} = -\alpha(t - 20)l_0, \quad (3)$$

where α is the linear thermal expansion coefficient of the gauge block material, l_0 is the nominal length of the gauge block, and t is the measured temperature of the gauge block which can be expressed as

$$t = t_\mathrm{s} + \Delta t, \quad (4)$$

where t_s is the temperature of the reference chamber measured by a standard platinum resistance thermometer, and Δt is the temperature difference between the reference chamber and the gauge block, measured by a thermocouple[9].

The phase shift in the interference fringes due to unlike materials or/and surface textures of the gauge block and the platen is corrected by using the pack (or stack) method[10]. The correction term is obtained from the equation

$$l_\phi = \frac{1}{k-1}\left(l_s - \sum_{i=1}^{k} l_i\right), \quad (5)$$

where l_i denotes the measured length of the ith gauge block, and l_s denotes the length of the gauge block pack which is formed by wringing these k gauge blocks on a platen.

The measurement software has been developed inhouse with Microsoft Visual Basic 6.0 Professional version. After the gauge block area within the interferogram is set by dragging the mouse cursor, 3 points where the intensity data are to be acquired are automatically recognized, and all processes to measure the gauge block length, including measuring the environmental data (air temperature, relative humidity, air pressure, and carbon dioxide density), scanning the fringes by translating the optical wedge, acquisition of the intensity variation, calculating the excess fraction value, and wavelength selection, performing the exact fraction method, and making necessary corrections, are done automatically.

Starting from the model equation

$$d = \frac{1}{3}\sum_{i=1}^{3}(m_i + F_i)\frac{\lambda_i}{2} - \frac{1}{3}\sum_{i=1}^{3}(n_i - 1)l_0 + l_\mathrm{t} + l_\phi - l_0, \quad (6)$$

where d is the deviation of gauge block length from its nominal length, the measurement uncertainty is evaluated according to the guide to the expression of uncertainty in measurement[11]. The uncertainty budget is shown in Table 1.

Table 1. Uncertainty Budget of Gauge Block Measurement

Source of Uncertainty	Uncertainty Contribution
Fringe Fraction	10.3 nm
Vacuum Wavelength	$9.0 \times 10^{-10} \times l_0$
Refractive Index of Air	$3.5 \times 10^{-8} \times l_0$
Thermal Expansion Coefficient	$2.9 \times 10^{-8} \times l_0$
Gauge Temperature	$8.8 \times 10^{-8} \times l_0$
Phase Shift Correction	10.2 nm
$u_c = \sqrt{(14.5\ \mathrm{nm})^2 + (0.1 \times 10^{-6} l_0)^2}\ (k = 1)$	

The uncertainty components contributed from the aperture effect, wave-front error, geometrical imperfection of the gauge block, and the variation of wringing layer, are all included in the uncertainty component for the fringe fraction.

The expanded uncertainty is evaluated to be $U = \sqrt{(29\ \mathrm{nm})^2 + (0.2 \times 10^{-6} l_0)^2}$ (coverage factor $k = 2$, level of confidence: approximately 95%), which amounts about 57 nm for a 250-mm gauge block.

This work was supported by the KRISS through the 'establishment and improvement of length standards' project. C.-S. Kang's e-mail address is cskang@kriss.re.kr.

References

1. ISO 3650:1998(E) GPS-Length standards-Gauge blocks (1998).
2. M. Born and E. Wolf, *Principles of Optics* (6th edn.) (Pergamon, New York, 1980).
3. E. Ikonen and K. Riski, Metrologia **30,** 95 (1993).
4. Y. Bitou and K. Seta, Jpn. J. Appl. Phys. **39,** 6084 (2000).
5. C.-S. Kang, J. W. Kim, H. S. Suh, and W.-K. Lee, Proc. SPIE **5879,** 5 (2005).
6. T. J. Quinn, Metrologia **36,** 211 (1999).
7. J. Ye, S. Swartz, P. Jungner, and J. L. Hall, Opt. Lett. **21,** 1280 (1996).
8. G. Boensch and E. Potulski, Proc. SPIE **3477,** 62 (1998).
9. C.-S. Kang, S. E. Lee, K. S. Gam, and M. J. Kim, Sae-Mulli **41,** 22 (2000).
10. J. Decker and J. Pekelsky, Gauge Block Calibration by Optical Interferometry at the National Research Council of Canada, NRC Doc. No. 40002 (1997).
11. Guide to the Expression of Uncertainty in Measurement, (1st edn.) ISO, Geneva (1993).