AN IMPROVEMENT OF INTERFEROMETER FOR GAUGE BLOCK CALIBRATION SYSTEM BY USING WAVELENGTH STABILIZED 532 NM, 633 NM AND 780 NM LASERS

Junichiro Kitta[1], Agustinus Winarno[1], Kazuo Tomiyama[1] and Tomizo Kurosawa[1]

1 Measurement and Calibration Center, Japan Quality Assurance Organization
21-25, Kinuta-1, Setagaya-ku Tokyo 157-8573 Japan
kitta-junichiro@jqa.jp

Abstract: (250 Words)

This paper aims at improving an optical interferometer for gauge block calibration. Gauge block calibration technique by using optical interferometric method is considered as an ultimate calibration method because of it enables absolute calibration, high accuracy and ensures direct traceability to the definition of length. Therefore, national institute of metrology, calibration laboratory organization or manufactures of gauge block often adopt this optical interferometric method.

We describe introducing iodine stabilized 532 nm Nd:YAG laser, rubidium stabilized 780 nm Nd:YLF laser and offset locked iodine stabilized 633 nm He-Ne laser into the interferometer of gauge block calibration system instead of a conventional standard wavelength lamp. These lasers have well coherent length and enough power to observe a well contrast interferometric fringe pattern for long gauge block.

As a result, we obtained the following three improvements. The first, because of the lasers have well coherent length, it allows us direct calibration procedure, and throughput of GB calibration became drastically shortening. The second, by the direct calibration procedure that independent from other comparison GBs, it allows us to determine a coefficient of thermal expansion of the GBs easily and exactly. The third, in this way, we can reduce the uncertainty in measurement of GB calibration approximately a half compare new improved interferometer and previous one.

Keywords: Gauge Block, Calibration Laser Interferometer, Wavelength Stabilized Laser, Coincidence Method.

1. INTRODUCTION

Gauge blocks (GB) are widely used for calibration of vernier calipers, micrometers, height-gauges and a lot of length measurement tools and apparatus as a standard of length. For calibration these GBs, there are two methods; one is comparison method that is a simple procedure by direct comparison with two GBs that are a standard GB and a under test GB, and the other is absolute method that is more complication procedure by using several standard wavelengths of light[1]. In general, calibration laboratories or calibration division of manufacturing firms use the former comparison method and a national measurement institute or the other high accuracy calibration laboratories or to calibrate the standard GBs for the comparison method calibration use the latter. For the latter absolute calibration methods, optical interfererometric method by using standard wavelength lamps or wavelength stabilized lasers are applied.

JQA is supplying a calibration service for the GBs (0.1 mm to 1000 mm) by this absolute calibration method. We have two interferometers apparatuses for absolute calibration of GB; one is for short-length (0.1 mm to 250 mm) calibration that has four standard wavelength of a mercury stable-isotope lamp (Hg [+198]), and the second is long length (250 mm to 1000 mm) calibration that has one standard laser (practical use stabilized 633 nm He-Ne laser) and two standard wavelength of a cadmium lamp. In this paper, we described about the improvement of the interferometer for the long length GB calibration.

Recent year, the technologies of lamp has come to be a so called “lost technology”, and LEDs are gaining power to widely use even in our home appliances instead of electric bulbs for the reasons of low-consumption energy, high efficiency, long lifetime and so on. The same movement comes to our standard wavelength lamps that are used in our interferometers for GB calibration, and continuously supplying this calibration service will consider to face to extinct because of the maintenance for these lamps becomes difficult by the lamp manufactures abandon their supplying. A standard lamp is a kind of vacuum tube. Manufacturing vacuum tube; a complicated construction that is consist of a lot of small metal or mica workmanships into a glass tube, and bottle it up during melting glass and make a umbilicus while keeping vacuum or a specific gas condition inside the glass, and keep such condition certainly for a long period of time is very specialized craftsmanship technique and it is difficult to continue.

Therefore, JQA attempted to change these lamps to laser diodes (LD) that are recently used laser to contiguously and stable supplying our calibration service of GB. In this paper, we have written about a first trial which we introduced two LDs (iodine stabilized 532 nm laser and rubidium stabilized 780 nm laser) and installed them into the long GB interferometer to replace the cadmium lamp to these LDs.

2. INTERFEROMETER OF OPTICAL CALIBRATION FOR GAUGE BLOCKS

2.1 Gauge Block Calibration and Interferometer for Long Gauge Block

We will explain the outline of the interferometer for the long GB calibration that was shown in Fig. 1. It is a kind of simple Michelson type interferometer. There are two arms,

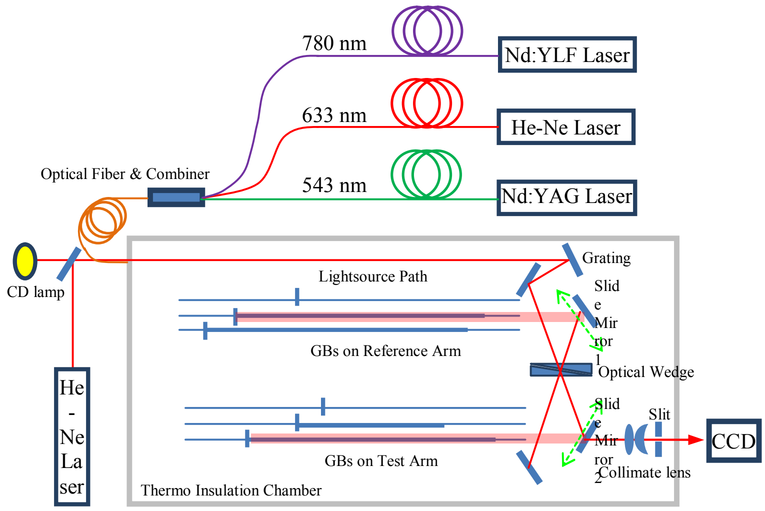

Fig. 1: Outline of interferometer for long GB calibration

one is for test GB and the other is for reference GB, and these two arms are corresponding to the two arms of Michelson type interferometer. Each arm has three slots, and each slot corresponds to one GB or a plane mirror. Lightsource comes from the upperpart of the interferometer. There is a grating on a rotating stage, and then we can select multiple wavelengths light on the same bean path. Mirrors reflect the beam and introduced it into the interferometer and a half-mirror splits the right down the middle, one is go for the test GB and the other is go for the reference GB.

GB is made by steel or zirconia and both surfaces are well polished to reflect the light. On away side of the edge is wringinged to a baseplate that is made by the same material of GB. The beam is reflected on the top surface of the GB and on the surface of the baseplate that is same as the bottom surface of the GB, so the reflected beam contains optical information of the total length of the GB exactly. The reflected beams from two arms test GB and reference GB are combined on the half-mirror, and put them together. Then we can observe the optical interference fringe pattern

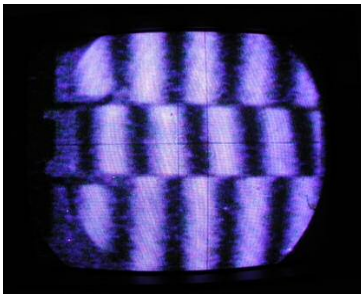

Fig. 2: Fringe pattern by optical interference of GB top surface and baseplate

that shows the difference length between test GB and reference GB shown as Fig. 2. The slide mirror 1 and 2 showed in Fig. 1 can select the each GB put on the slot, and make nine ways combination individually. If we select the reference GB arm to the plane mirror, we can observe test GB total length only directly.

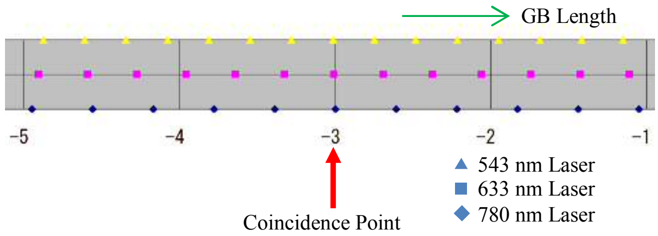

Fig. 3: Determination GB length by Coincidence method

To determine the GB length by using wavelength of light, coincidence method is applied. Equation (1) and Fig. 3 show the equation of coincidence method,

$$l = (n_i + \varepsilon_i)\frac{1}{2}\lambda_i \qquad (1)$$

where l is length of GB, λ is wavelength of the light, n is integer number that represent the length of GB and ε is fraction of the length of GB that was obtain from the fringe pattern of the interferometer. An issue of this coincidence method is how we determine the integer number n? So we change the wavelength of the light λ_i and search a point that all wavelength of the light are consistent to a same value nearby an approximately length or nominal length of the GB. These approximately lengths can be obtained by the other simple comparison method easily. Then we can determine the each integer number n_i, we can obtain the length of the GB from coincidence method by using wavelength of light.

The point of this coincidence method is using several wavelengths of light that are well stabilized and known the absolute value of the wavelength exactly. To satisfy as 1 µm accuracy at 1000 mm GB calibration, it needs the accuracy of wavelength at least 1×10^{-8}. In our interferometer for long GB calibration, there are a practical use stabilized He-Ne Laser (633 nm/Red), and a Cd lamp (509 nm/Green, 478 nm/Blue), so we have used three wavelengths as standards. From the reason which was shown the above, we explored another lightsource to replace the Cd lamp, and finally we took a decision to use an iodine stabilized 532 nm Nd:YAG laser and rubidium stabilized 780 nm Nd:YLF laser.

We also replace the practical use stabilized He-Ne laser to offset locked iodine stabilized 633 nm He-Ne laser from the following two reasons. The first is the wavelength accuracy. The uncertainty of our practical use stabilized He-Ne laser is approximately 5×10^{-9} that is merely adequate accuracy to satisfy the calibration accuracy of GBs. The second is laser power shortage was predicted by using an optical fiber and combiner. We will use another two lasers instead of the lamp, so it is difficult to keep three lasers beams alignment stationary for long time in space.

2.2 Iodine Stabilized 633 nm He-Ne Laser

This Iodine Stabilized 633 nm He-Ne laser shown in Fig. 4 has already installed in the interferometer and we have used it with CD lamp. This laser has iodine cell ([Kr] $4d^{10}$

$5s^2$ $5p^5$, Absorbing molecule $^{127}I_2$) and we can obtain the hyperfine component a_{16} (f = 473 612 353.604(10) MHz) in R(127) 11-5 transition that was defined in CIPM recommendation[2][3]. The laser is working under the variations of operational parameters that defined by CIPM recommendation and calibrated every three year by NMIJ which uses optical-comb as the national standards. We can use (λ = 632.991 212 579 (13) nm) as the standard wavelength while lock this laser to the component of a_{16}(f) absorption line. The combined relative uncertainty is u_c/y = 2.1×10^{-11}.

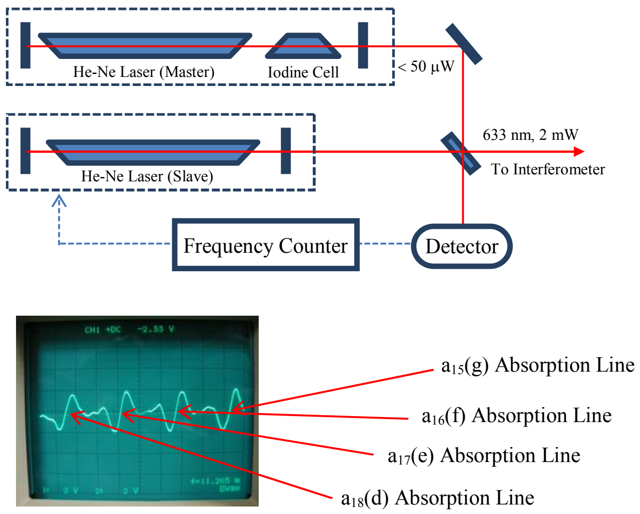

Fig. 4: Outline of iodine stabilized 633 nm He-Ne laser

In actual calibration, we use offset lock laser system which a slave laser that frequency shifted a few hundred MHz with this 633 nm laser uses as a master laser, because of iodine stabilized 633 He-Ne laser is very sensitive for the return beam by diffused reflection from outside, so it cause of the unexpected lock down, and the laser power is very weak to use the interferometer, it is only around a few ten µW.

We can select another hyperfine component at a_8 to a_{21}. Each adopted values are defined in the CIPM recommendation respectively.

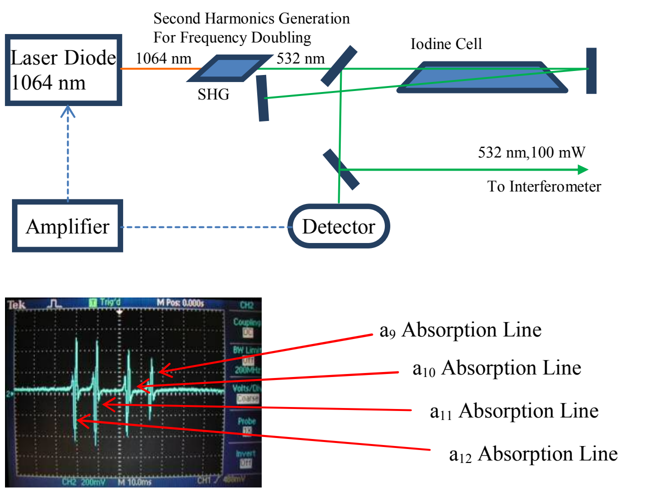

Fig. 5: Outline of Iodine Stabilized 532 nm Nd:YAG Laser

2.3 Iodine Stabilized 532 nm Nd:YAG Laser

Next, we installed a laser (INNOLIGHT/COHERENT, Inc. Prometheus & 3rd Harmonic Iodine Frequency Stabilization) that is shown in Fig. 5. This laser has iodine cell ([Kr] $4d^{10}$ $5s^2$ $5p^5$, Absorbing molecule $^{127}I_2$) and we can obtain the hyperfine component a10 (f = 563 260 223.513(5) MHz) in R(56) 32-0 transition that was defined in CIPM recommendation[2][3]. Fig. 5 also shows the absorbing signal arou nd hyperfine component at a_{10}. We can use (λ = 532.245 036 104 (5) nm) as the standard wavelength while lock this laser to a_{10}. The combined relative uncertainty is u_c/y = 8.9×10^{-12}.

Similarly to the 633 nm laser, we can select another hyperfine component at a_1 to a_{15}. Each adopted values are defined in the CIPM recommendation respectively.

2.4 Rubidium Stabilized 780 nm Nd:YAF laser

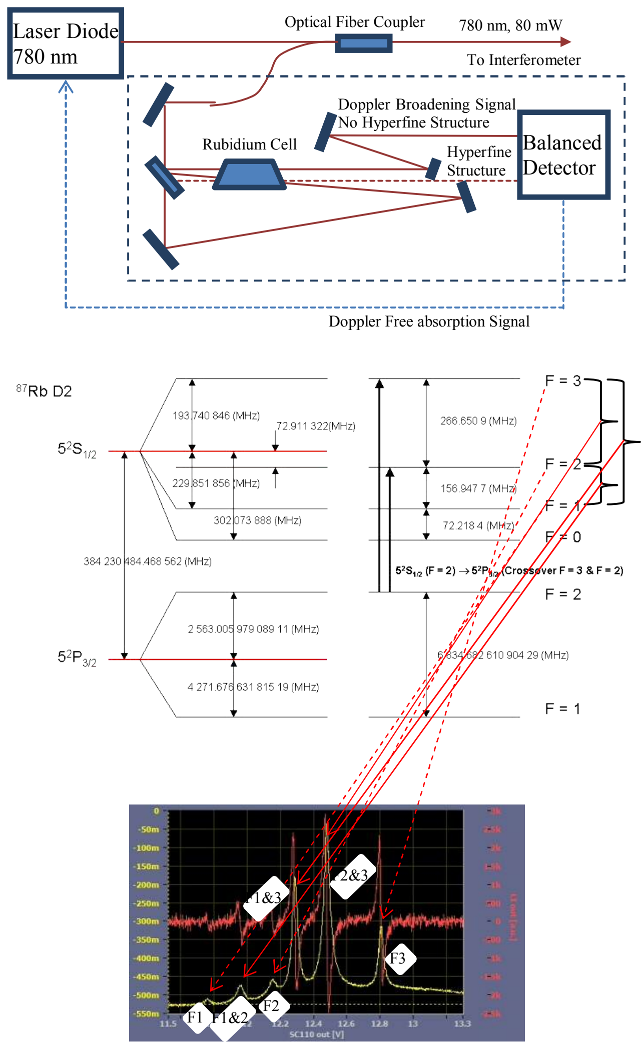

Fig. 6: Outline of Rubidium Stabilized 780 nm Nd:YLF laser

We need the third laser to determine the GB length certainly by using the coincidence method. Obviously, four or more standard wavelength lightsource make more surely to determine the GB length, however from the reason of cost of equipment and calibration throughput, we adopted to use three standard lasers.

We installed a laser (TOPTICA PHOTONICS AG, DL pro 780 & Rubidium Frequency Stabilization) that is shown in Fig. 6. This laser has rubidium cell ([Kr] $5s_1$, Absorbing molecule is mixture gas of ^{85}Rb (73 %) and ^{87}Rb (27%)). There are two absorbing lines (Line D1 ($5^2S_{1/2} - 5^2P_{1/2}$) and Line D2 ($5^2S_{1/2} - 5^2P_{3/2}$)), totally, there are four absorbing lines (^{85}Rb/D1, ^{85}Rb/D2, ^{87}Rb/D1 and ^{87}Rb/D2). We can obtain the hyperfine component (f = 384 227 981 877.3 kHz ± 5.5 kHz) in $5^2S_{1/2}$ (F = 2) → $5^2P_{3/2}$ (Crossover F = 3 & F = 2 on ^{85}Rb/D1) two molecular transition that was defined in Jun Ye et al. (1996)[2]. Fig. 6 also shows the absorption signal around this hyperfine component. Then we can use (λ = 780 246 291.623 389 nm) as the standard wavelength while lock this laser to the above the crossover of two molecular transition. The combined relative uncertainty is $u_c/y = 1.0\times10^{-10}$.

Similarly, we can select another absorbing molecular line and another hyperfine component or crossover combination. The standard wavelengths are defined in the same absorbing frequency table.

3. IMPROVEMENTS

3.1 Modifications of Interferometer

Thus, we have prepared well stabilized three wavelength lasers, 532 nm laser, 780 nm laser instead of the CD lamp that mentioned the above and 633 nm laser that we have already been used in this interferometer. All wavelengths of the lasers have enough low uncertainty to calibrate GBs.

All laser beams are introduced into an optical fiber individually and the three fibers are connected to an optical combiner to combine to one fiber that shown in Fig. 1. So three laser beams are all in one fiber and delivered to the interferometer.

A CCD camera that installed in the interferometer for observation the optical fringe pattern of GB was replaced to a new CCD camera that has more sensitivity over infrared area because of the application of 780 nm laser. The other part of the interferometer, we did not change anything, all optical parts and mechanisms are used as our previous interferometer. This interferometer has designed for wavelength of visible light. Although 780 Nd:YLF laser is infrared, there were no problem to determine the fringe patter of GBs without the matter of CCD sensitivity area that mentioned above.

3.2 Enable Direct Calibration

By installing these three lasers to replace the lamp, it brings us not only the continuously supplying GB calibration service, but enable us a direct calibration and a well contrast of fringe pattern cause by high coherency of wavelength of laser that has several ten meter or more. The direct calibration means to select a GB on the test arm and select a mirror that means a 0 mm GB with a baseplate on the reference arm, and then calibrate the GB directly (0 to GB's total length) at one time. This direct calibration brings us a great improvement of calibration throughput of GB. Previous interferometer had the CD lamp (509 nm/Green, 478 nm/Blue) which maximum coherent length is only approximately 100 mm, so it is difficult to create an optical fringe patter by this lightsource over 100 mm with well contrast, so we cannot measure more than 100 mm differential length of GBs at one time. Although, there is the 633 nm He-Ne laser that has well coherent length, only one laser does not contribute to the coincidence method to determine the GB length. Therefore, the limitation of the coherent length of the CD lamp was forced us to apply a replacement calibration method that was repeat calibration and replace every 100 mm step GBs on test arm and reference arm step by step. By this procedure, when we calibrate 1000 mm GB, it needs really ten times calibrations (0 to 100, 100 to 200, 200 to 300, – – –, 900 to 1000) for reach the 100 mm coherent length to the 1000 mm GB.

3.3 Determine Thermal expansion coefficient of GB

Moreover, this direct calibration enables us a determination a thermal expansion coefficient of GB simply, certainly. The thermal expansion coefficient is the one of the most major component of uncertainty. Equation (2) shows the compensated GB length at 20 °C.

$$L = l\big(1 + \alpha(20 - t)\big) \tag{2}$$

Where L is actual length of GB, l is observed length of GB, α is thermal expansion coefficient of GB and t is temperature of GB. For example, when α is 11.5 μK^{-1} for conventional steel GB, t is 20.5 °C for room temperature that is even fine temperature controlled room within ± 0.5 °C and at l = 1000mm GB, the deviation value reaches really 5.8 μm which is approximately three times of maximum permissible error of K-grade GB. Therefore, it is necessary correct the effect of the thermal expansion which was given by combination of thermal expansion coefficient of GB and temperature of GB to determine the length of GB accurately. To correct the effect of the thermal expansion, it is important to know the thermal expansion coefficient of GB exactly.

To determine this coefficient, we measure a lot of GB length data with changing the environmental temperature nearby 20 °C, and obtain the coefficient from fit the characteristic of these lengths to temperature to normally linearly least-squares. The example of result when calibrated 1000 mm GB is shown in Fig. 7

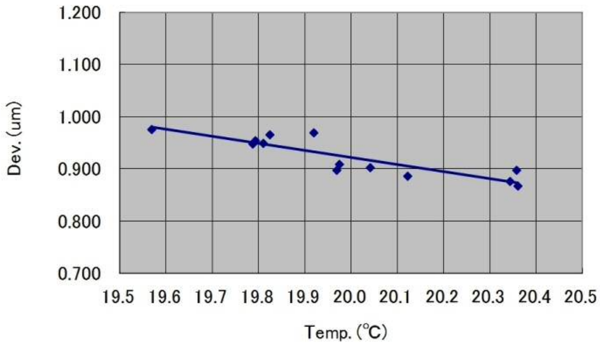

Fig. 7: A result of 1000 mm GB with changing temperature nearby 20 °C.

By previous replacement calibration procedure, it is difficult to determine the effect of thermal expansion coefficient separately, because two GBs are on test arm and reference arm, and two GBs have different thermal expansion coefficient and measurement is performed at same time, it is impossible to distinguish the effect of thermal expansion which one is. Even if we start this examination from 0 to 100 mm GB to determine the thermal expansion coefficient of GB, we cannot neglect the effect of accumulation of uncertainty for determination of thermal expansion coefficient of GB.

3.4 Reduce Uncertainties

The certainly determination of thermal expansion coefficient also contributes to reduce the uncertainty in measurement approximately a half. Table 1 shows the budget sheet of uncertainty in measurement for the interferometer at 1000 mm GB. We can obtain more accurate GB length at 20 °C exactly by compensation from exactly thermal expansion coefficient and GB temperature which are major component of uncertainty in measurement of GB.

For example, as 1000 mm GB, we estimated the effect of thermal expansion coefficient and temperature of GB as 30 mm by sum square of all residuals from normally linearly least-squares mentioned in Fig. 7. Expanded uncertainty in measurement is estimated approximately 180 nm when we apply the new determination for the thermal expansion coefficient of GB, instead of our estimated expanded uncertainty 340 nm in previous interferometer.

Table 1: Budget Sheet of uncertainty in measurement by the interferometer at 1000 mm GB

Uncertainty Component	$u_i(y)$, Uncertainty (nm) Previous Interferometer	New Interferometer
Wavelength of Lightsource	0.50	0.50
Fringe Reading Error	6.36	6.36
Refractive Index Number	81.99	81.99
Temperature of GB	115.0	---
Thermal expansion coefficient of GB	87.0	30.0
Optical Alignment Error	4.7	4.7
Optical Phase GB and Baseplate	5.0	5.0
Wringing Condition	5.7	5.7
Flatness of Baseplate	5.8	5.8
Combined Uncertainty	166.7	88.8
Expanded Uncertainty (k = 2)	340	180

4. RESULTS

The new improved interferometer with three lasers was examined by comparison of eight GBs (300 mm to 1000 mm) between previous interferometer. All GBs are TSUGAMI CORPORATION, steel material and thermal expansion coefficient is defined as (11.5 ± 1.0) ×10^{-6} K^{-1} by manufacturers.

Table 2 shows results of the comparison. All values of new interferometer agreed well with the previous one. The function of the interferometer with 532 nm and 780 nm laser and this compatibility to the previous interferometer was confirmed by the result of good agreements within expanded uncertainties.

Table 2: Comparison of GBs length with three lasers to one laser and CD lamp interferometer

Nominal length (mm)	Current Value (μm)	Previous Value (μm)	Difference (μm)	Expanded Uncertainty (k = 2) (μm)
300	+0.141	+0.215	−0.074	0.11
400	+0.010	+0.049	−0.039	0.14
500	+0.185	+0.243	−0.058	0.18
600	+0.336	+0.419	−0.083	0.21
700	−0.111	−0.023	−0.088	0.24
800	+0.549	+0.737	−0.188	0.27
900	+0.431	+0.640	−0.210	0.32
1000	+0.957	+0.776	+0.181	0.35

Table 3 shows the result of the estimated values of coefficient of thermal expansion of GBs that obtained by the new improved interferometer. It seems much smaller than its manufacture's value or value mentioned in ISO/DIS 3650 or JIS B 7506 that is defined as (11.5 ± 1.0) ×10^{-6} K^{-1}. Although results of GB length mentioned in Table 2 were within the expanded uncertainties, the cause of some deviations seems significancy in Table 2 was considered by this disagreement of thermal expansion coefficient. Improved interferometer gathered a lot of data around 20 °C and fitted to normally linearly least-squares to estimate the GB length at 20 °C exactly, however previous interferometer cannot obtain in such certainty procedure, from only simple average as assumes thermal expansion coefficient to (11.5 ± 1.0) ×10^{-6} K^{-1}.

Table 3: Estimated values of coefficient of thermal expansion of GBs

Nominal length (mm)	Manufacture's Value (ISO/DIS 3650, μ/K)	Estimated Value (μ/K)	Difference (μ/K)
300	11.5	10.734	−0.766
400	11.5	10.758	−0.742
500	11.5	10.661	−0.839
600	11.5	10.633	−0.867
700	11.5	10.646	−0.854
800	11.5	10.597	−0.903
900	11.5	10.595	−0.905
1000	11.5	10.541	−0.959

4. CONCLUSIONS

To corresponds to the matter of lamp extinction, iodine stabilized 532 nm Nd:YAG laser and rubidium stabilized

780 nm Nd:YLF laser were introduced into the interferometer of GB calibration system. As a result, not only we can completely change the lightsource to the future calibration, but we obtained the following three improvements. The first, because of the lasers have well coherent length, it allows us the direct calibration procedure, and throughput of GB calibration became drastically shortening a few weeks or months to a few days per one calibration lot (four GBs at one time). The second, by the direct calibration procedure that independent from other comparison GBs, it allows us to determine a coefficient of thermal expansion of the GBs easily and exactly. The third, in this way, we can reduce the uncertainty in measurement of GB calibration approximately a half compare new improved interferometer and previous one.

We are going to apply the lighsource of these three lasers into another short-length (0.1 mm to 250 mm) GB interferometer system with connecting another optical fiber coupler which split the lightsource to interferometer for long GB calibration and short-length GB calibration. We aim to obtain the same effects and getting the same improvements to interferometer for short-length GB calibration.

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