Journal of Physical Science, Vol. 28(1), 87–98, 2017

Automated Contactless Gauge Block Interferometer

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Published online: 15 April 2017

To cite this article: Abdel-Maaboud, N. F. (2017). Automated contactless gauge block interferometer. *J. Phys. Sci.*, 28(1), 87–98, https://doi.org/10.21315/jps2017.28.1.7

To link to this article: https://doi.org/10.21315/jps2017.28.1.7

ABSTRACT: *The paper discusses the construction of the double-ended interferometer (DEI) at the National Institute for Standards (NIS) for contactless calibration of gauge blocks. The new measuring procedure avoids any contact to the working faces of the gauge block and maintains their quality from possible damage and scratches caused by repeated wringing during periodic calibration. The resulted uncertainty is reduced due to the absence of the auxiliary platen and the corresponding errors of wringing film and phase change. An optical technique based on polarised light is used to measure the surface roughness of the gauge block that influences the measured length. By using the principle angle of incidence, the polarised light technique can be used as an alternative to the stack method to measure the phase change correction with improved accuracy. The constructed interferometer uses multi-wavelength laser sources in illumination to produce a synthetic wavelength that can be suitable to measure the length of the gauge block of interest. The interferogram is analysed by dedicated software to extract the phase information. Optical set-up, alignment, measurement, and uncertainty are presented. The comparable calibration results for some gauge blocks of the new technique and the conventional Köster comparator confirm the reliability of the constructed double-ended interferometer.*

Keywords: Gauge blocks, DEI, contactless calibration, uncertainty, interferometer

1. INTRODUCTION

National measuring institutions (NMIs) pay special interest in improving the calibration methods of the gauge blocks as they act as an essential link in the traceability chain from the SI definition of the meter to the mechanical measurements in industry. To achieve the equivalence to the NMIs, it is necessary to reduce the uncertainty.

Köster comparator is used for short gauge blocks calibration at the National Institute for Standards (NIS). With this conventional system, the experimental work and the analysis consume long time, and the calibration becomes costly to the industrial sectors. This leads to many attempts of improvement for simplifying the calibration procedure and reducing the sources of errors. Recently, the femtosecond comb providing ultra-stable wavelengths was combined with the comparator in addition to modified software, and the uncertainty was reduced to 52 nm for 100 mm gauge block.[1]

The aim of the construction of the double-ended interferometer (DEI) is to realise the gauge block length with a comparable accuracy to the NMIs. It can eliminate restrictions with the conventional interferometic method for the gauge block calibration. One of the disadvantages of the conventional method is the need of wringing the gauge block to an auxiliary platen (i.e., mechanical contact). The corresponding errors induced by the wringing such as the wringing film and the change in the phase caused by the gauge block and the auxiliary platen of different materials are considerable and lead to significant uncertainty.[2–5] Moreover, the several wringing during the repeated calibration may affect the gauge block length.[6] The DEI avoids these difficulties and consumes the time of the calibration as it enables measuring both gauge block surfaces simultaneously.

NMIs have suggested different layout for the DEI.[7–9] The designed DEI at NIS uses multi-wavelength to avoid the ambiguity in phase measurement. The setup has less optical components as it combines the Michelson configuration with the reflecting mirrors at the measuring arm. The simplicity of the design allows extending the range of the measurement. Probing digital temperature sensors allow plotting the thermal stability of the gauge block during the calibration time. DEI setup, measurement, and uncertainty are explained in details.

2. NIS DOUBLE-ENDED INTERFEROMETER

The constructed technique uses a few optical and mechanical components (Figure 1). It aims to reduce the uncertainty in gauge block calibration by eliminating the influence of the wringing film and the phase change correction.

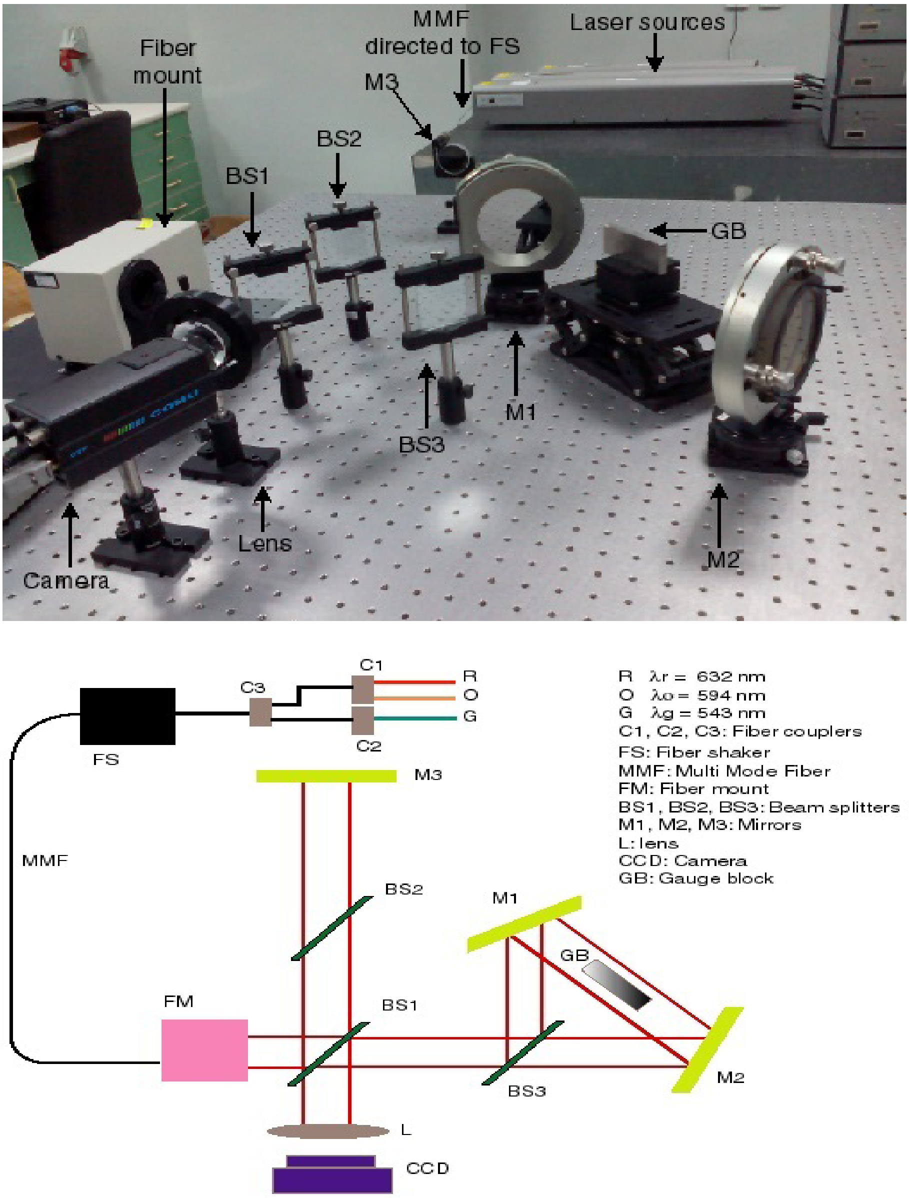

Figure 1: Optical system setup (above) and schematic diagram (below).

Tree laser sources (633 nm, 543 nm and 594 nm) illuminate the system to produce a synthetic wavelength suitable for any gauge block length. Fibre couplers gather the wavelengths emerged from the three lasers in a multi-mode fibre (MMF). Due to the signal transmission within the MMF, speckle noise results from the modal dispersion and a fibre shaker unit is used to remove the noise and improve the field of view. The signal is fed into a special fibre mount FM supplied with a beam expander which in turns provides a homogenous field of illumination to the interferometer entrance.

In the measuring arm, the DEI uses two opposite reflecting mirrors (M1 and M2), supported with tiling screws. Between M1 and M2, the gauge block of interest is placed on a mechanical mount that provides fine levelling, tilting and rotating as required. The reference arm has a plane mirror M3 mounted on a 3 micro screws precision mount. At the imaging arm, a collimating lens focuses the image onto a high resolution CCD sensor.

The beam splitter BS1 splits the beams into two parts. The first is directed to the reference mirror M3 through the compensating beam splitter BS2, and the second to BS3. Similarly, the beams at BS3 are divided and directed to M1 and M2 and reflected towards the gauge block surfaces in opposite directions. Total reflections of the reference mirror M1, opposite mirrors M2 and M3, and the gauge block surfaces are recombined by BS1 then collected by the lens and focused on the imaging sensor.

3. MEASUREMENTS

3.1 Gauge Block Length

First, the opposite mirrors M1 and M2 are adjusted such that the reflections can be seen by the sensor and superimposed, then the produced interference fringes can be reduced by the fine adjustment of the mirrors using the micro screws until fringes disappear or only one pattern is observed (Figure 2).

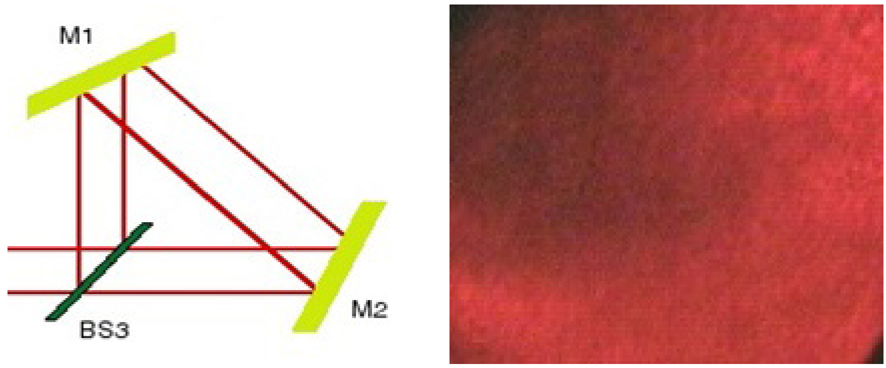

Figure 2: One pattern is observed in the interference region between the opposite mirrors at the measurement arm (M1, M2) in the absence of gauge block.

The gauge block is set on the mechanical mount and aligned such that the reflections from its surfaces interfere and interference fringes are seen on the gauge block surface. The formed fringes refer to angular error between the gauge block axis and the aside beams axis coming from the opposite mirrors M1 and M2. This error must be reduced by aligning the gauge block axis parallel to the aside beams axis using the micro screws of the gauge block mount. Once good alignment is achieved, the unwanted fringes disappear. When the reflection pairs of the opposite mirrors (M1 and M2) and the gauge block surfaces interfere with that of the reference mirror (M3) the desired interference patterns are observed as in Figure 3.

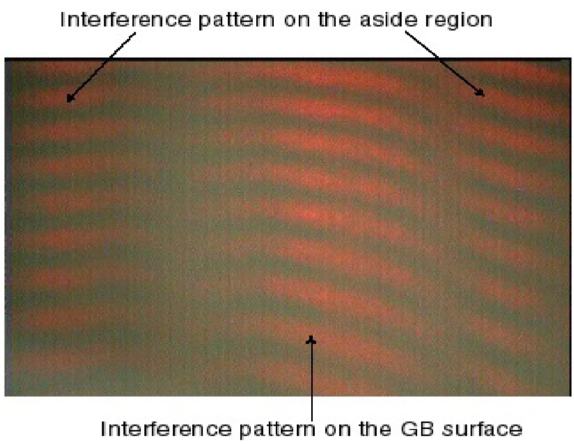

Figure 3: Interference fringes on gauge block surface and the aside region resulted from the superposition of the beams reflected from interferometer arms (measuring arm M1, M2, gauge block and reference arm M3).

The middle interference patterns are obtained from the reflection pairs on the gauge block surfaces while the surrounding patterns are formed by the reflection pairs passing aside. These interference fringes are used in measuring the gauge block length (Figure 4).

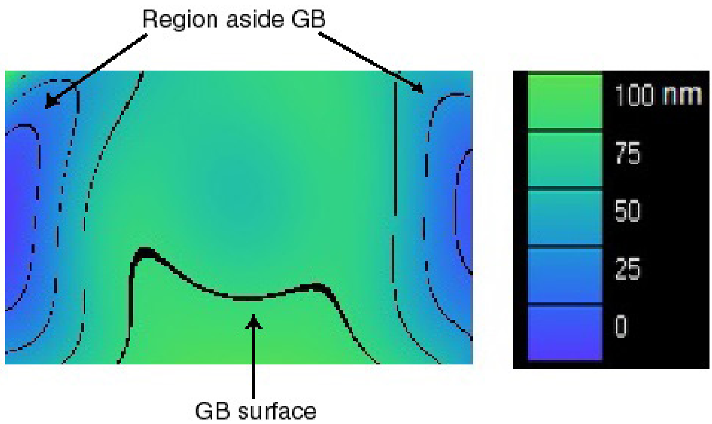

Figure 4: Surface mapping of gauge block and the aside region.

The gauge block is left in the interferometer for enough time until thermal stability is achieved before measurement (Figure 5). So the temperature sensor PT100 and the data logger PT104 monitor temperature fluctuations during the time of measurement.

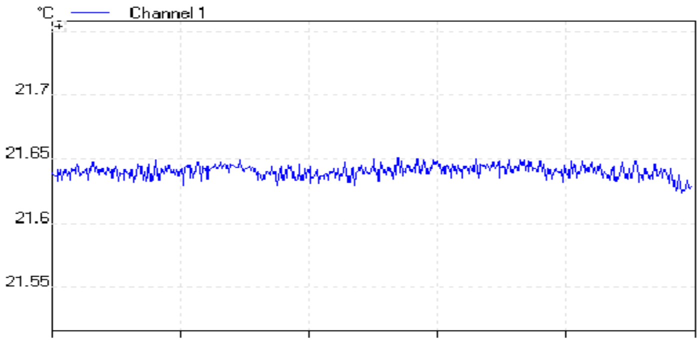

Figure 5: Gauge block's temperature display for 3 h shows good stability of the gauge block in the interferometer.

Synthetic wavelength is necessary for measuring the integer order of interference corresponding to the gauge block length. So at thermal stability, 3 interferograms are taken using the 3 different wavelengths (632 nm, 543 nm and 594 nm) and analysed by the software which determines the fringe fraction and calculates the gauge block's length according to the equation:

$$L + \Delta L = (\lambda/2)(n + \Delta n)$$

where L is the length corresponding to the integer number of order of interference n, and ΔL is the portion of length corresponding to the fractional part Δn. The integer order of interference is calculated according to Schodel.[10] The fractional part is determined based on the fringe analysis and phase reconstruction from a static interferogram using fast Fourier transform. The software considers the corrections of air refractive index using Edlen Formula[11] and the thermal expansion of the gauge block material.

3.2 Phase Change Correction

Since the constructed technique concerns the contactless calibration of the gauge block, the stack method is inconvenient for measuring the phase correction as it requires wringing of several gauge blocks together. Therefore, a polarised light technique is an alternative for measuring the phase correction using the optical constants of the gauge block material with the principal angle of incidence.[12] This method is suitable for the contactless method, and the uncertainty in measuring the change in phase angle is (± 2°).

3.3 Surface Roughness

The uncertainty due to gauge block surface roughness must be concerned. One of the widely used techniques for this purpose is the integrating sphere. In this technique, a photo detector measures the ratio between the diffused and the reflected light by the gauge block surface. This ratio is proportional to the roughness degree. A polarised light technique at NIS can study the surface roughness of the gauge block knowing its material optical constants with uncertainty ± 0.01 µm which is find to be suitable for the contactless calibration method.[13]

4. UNCERTAINTY IN MEASUREMENT

The uncertainty in measurement using the DEI is based on: light sources and fringe fraction; constructed interferometer; environment; gauge block parameters; and phase correction. These elements are explained in the following few sections.

4.1 Light Sources (l_λ) and Fringe Fraction (l_{fringe})

Lasers used in illumination are traceable to the primary laser at the National Physical Laboratory (NPL) and the expanded uncertainty in wavelength is ± 0.7 MHz. For accurate measurement of the gauge block length, the exact fringe fraction is determined by Fourier transformation with accuracy 0.01 fringe.

4.2 Constructed Interferometer $(l_{wavefront}, l_{alignment}, l_{sourse\ size})$

The optical components in use are of good quality and the surface finishing forms good interference fringes. This leads to uncertainty in wave-front error of 0.01 µm. Both alignment and the source size contribute to the total uncertainty with 0.12 L µm and 0.008 L µm respectively.

4.3 Environment $(l_{refractive\ index})$

Edlen's Formula evaluates the refractive index of the surrounding air. The uncertainty in this formula is 1×10^{-8}, and its contribution to the uncertainty in measurement is 0.01 L µm. The combined uncertainty relevant to readability, resolution, and calibration of the digital sensors used in recording air temperature, pressure, and humidity is 0.15 L µm.

4.4 Gauge Block Parameters (l_{GB})

Gauge block temperature and thermal expansion are of great concern in the uncertainty of gauge block calibration. The combined uncertainty of both factors is 0.12 L µm. Also, gauge blocks flatness and parallelism are determined by the fringe analysis software based on the quality and straightness of the interference fringes with uncertainty of 0.005 µm. The uncertainty in measuring the gauge block surface roughness using polarised light is 0.01 µm.

4.5 Phase Correction l_{phase}

The uncertainty in measuring the phase correction using the polarised light with the principle angle of incidence method is 0.002 µm.

The factors contributing to the uncertainty are combined in the model:

$$\Delta L = (l_\lambda + l_{fringe}) + (l_{wavefront} + l_{alignment} + l_{sourse\ size}) + l_{refractive\ index} + l_{GB} + l_{phase} - L_{nominal}$$

The thermal conditions are the major contributors in the uncertainty budget. For this reason, the system is placed in a temperature controlled room, and sensitive probing sensors are used in temperature recording with resolution 0.001 k. The expanded uncertainty at confidence level (95%) in the calibration of 75 mm gauge block is $U_{95} = \pm 0.065$ µm. In case of using the auxiliary platen, the total uncertainty would exceed 0.005 µm. Sources of the uncertainty are summarised in Table 1 for both Köster comparator and DEI where *L* is the nominal length of gauge block in meter. The results obtained by both interferometers are compared and show good agreement within the uncertainty range of both of them (Figure 6).

Table 1: Uncertainty budget for gauge block calibration on Köster and DEI.

Source x_i	Köster		DEI	
	Standard Unc. $U(x_i)_1$	Unc. Contribution $U(y_i)_1$ (µm)	Standard Unc. $U(x_i)_2$	Unc. Contribution $U(y_i)_2$ (µm)
Light sources		0.002+0.001*L*		0.002+0.001*L*
Wavelength				
λ_{red}	0.5×10^{-9} m		0.5×10^{-9} m	
λ_{orange}	0.5×10^{-9} m		0.5×10^{-9} m	
λ_{green}	0.5×10^{-9} m		0.5×10^{-9} m	
Excess fraction	0.01 fringe		0.01 fringe	
Interferometer				
Wave front error	0.008 µm	0.008	0.01 µm	0.01
Alignment	0.08 mm	0.11L	0.09 mm	0.12*L*
Source size	5 µm	0.008L	5 µm	0.008*L*
Environment				
Room temperature	0.008 k	0.1*L*	0.008 k	0.1*L*
Air pressure	20 Pa	0.1*L*	20 Pa	0.1*L*
Air humidity	0.5%	0.01*L*	0.5%	0.01*L*
Edlen Equation	1×10^{-8}	0.01*L*	1×10^{-8}	0.01*L*
Gauge block parameters				
Gauge block temperature	0.008 k	0.1*L*	0.008 k	0.1*L*
Thermal expansion	0.065×10^{-6}/k	0.06*L*	0.065×10^{-6}/k	0.06*L*
Flatness and parallelism	0.005 µm	0.005	0.005 µm	0.005
Roughness	0.007 µm	0.007	0.01 µm	0.01
Wringing	0.007 µm	0.007	–	–
Phase change	0.008 µm	0.008	0.002 µm	0.002

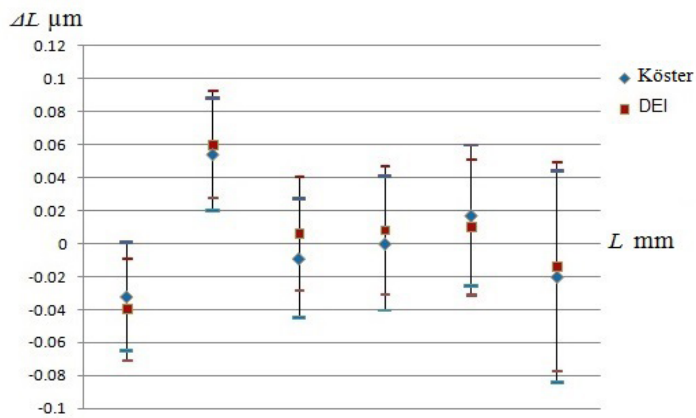

Figure 6: Results obtained by the DEI and Köster comparator for a set of 6 gauge blocks of length (2 mm, 5 mm, 10 mm, 20 mm, 25 mm, and 75 mm) show good agreement.

5. CONCLUSION

The DEI for gauge block contactless calibration is constructed using Michelson configuration with two opposite reflecting mirrors at the measuring arm. Multi-wavelengths are used in illumination to form a suitable synthetic wavelength to the gauge block of interest. The recorded interferogram is processed and analysed by Fourier transformation to determine the exact fringe fraction. The results obtained by both DEI and Köster comparator for a set of 6 gauge blocks are consistent and the small observed deviations are within the uncertainty limits. The constructed DEI can measure gauge block length up to 100 mm and the design allows extension for longer gauge block. The absence of the auxiliary platen and automation of the measurement provides the required simplicity in the calibration procedure without need to high skill level. Expanded uncertainty is evaluated as $U_{95} = \pm 0.065$ µm for 75 mm gauge block after eliminating the sources of errors induced by the auxiliary platen.

6. ACKNOWLEDGMENTS

This work is supported by the Joint Research Grant Under EG/SA Research Partnership Program Bilateral Agreement (EG:12-2-13). The optical and mechanical tools used in the set-up are funded by the Ministry of Scientific Research (Egypt) and the National Institute for Standards.

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