PTB'S PROTOTYPE OF A DOUBLE ENDED INTERFEROMETER FOR MEASURING THE LENGTH OF GAUGE BLOCKS

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Abstract: A double ended interferometer (DEI) is an alternative design for traceable measurement of the absolute length of gauge block shaped bodies without the need of a platen to be wrung to one of the faces. In spite of this general advantage, until now it doesn't exist a well established DEI-system at any National Metrology Institute (NMI). PTB, as the NMI of Germany, plans to develop a dedicated DEI which is situated in a temperature stabilized vacuum chamber. A Prototype of DEI was built at PTB in order to study the measurement principle and potential challenges to be taken into consideration for the final design. This paper describes the experimental set-up and measurement procedures of the prototype. First results indicate that the current design is a good basis for the final version of DEI at PTB.

Keywords
gauge blocks, interferometery, absolute length, double ended interferometer

1. INTRODUCCION

Gauge blocks are the most important material standards to provide industry with reliable and traceable standards of length. When highest accuracy is required, the measurement of gauge blocks is performed by interferometry, i.e. the length of the gauge block is measured in terms of well known wavelengths.

In the first gauge block interferometers in the twenties of last century [1, 2] the interference systems were evaluated by visual estimation of the fringe separation between the patterns on gauge block and platen.

Many attempts have been made to improve the measurement and evaluation process. Significant progress has been made, since digital cameras and powerful computers are available and the technique of phase stepping interferometry was established and successfully implemented (see [3] and references therein).

As an alternative to the conventional design, a double ended gauge block interferometer was already patented and built by Dowell in 1943 [4]. In this setup two interfering beams traverse the same path in opposite directions. However, Dowell's DEI was made for measuring length differences between two gauges and not for measuring the absolute length of gauge blocks [5].
In 1972 Dorenwendt suggested a modified Michelson Interferometer in which the absolute length of gauge blocks could be measured without the need for wringing a platen onto one of the end faces [6]. This work, performed at PTB, was basically motivated by the assumed need to characterize a so called "wringing film" which thickness should be measured by comparison with the length obtained in the traditional design. Such wringing film thickness was later found to be negligible compared to other effects related to wringing inherent in most of the practical applications of gauge block length measurements by interferometry. For this reason the idea of DEI was put aside at PTB until recent years.

In 1983 Khavinson [7] also proposed a ring optical scheme as an alternative measurement method for measuring the absolute length of gauge blocks. Later Khavinson reported a variety of means to control the optical phase differences in this DEI [8]. In 1993 Lewis reported the set-up of a DEI at NPL which was part of NPL's Primary Length Bar Interferometer [9]. Similar designs have been suggested 1998 and 2003 [10, 11].

The technical progress in gauge block interferometers was combined with the idea of a double ended design by Kuriyama et al. in 2006 [12] building the first DEI which is equipped with CCD-cameras and phase stepping interferometry. This interferometer is situated in a laboratory of a gauge block manufacturer (Mitutoyo Co.) and is used for the purpose of quality control of the production process.

The present idea to establish a double ended interferometer at PTB is motivated by several measurement tasks in which the length or a dimensional change of a gauge block shaped sample body is to be studied highly accurately in a free state, i.e. in the absence of a platen.

This paper describes a prototype version of DEI at PTB which is built on a tabletop. This DEI is similar to that reported in [12]. However, more than one wavelength is used which makes this interferometer much more effective for the accurate extraction of the integer orders of interference. A special design for the light source had to be found to allow for the same adjustment states at the different wavelengths. All the knowledge and experience acquired from this prototype will be usedto build the final DEI set-up which will be situated in a temperature controlled vacuum chamber as other Precision Interferometers at PTB [13, 14].

2. EXPERIMENAL SET-UP AND METHODS

Figure 1 shows a schematic diagram of the experimental setup.

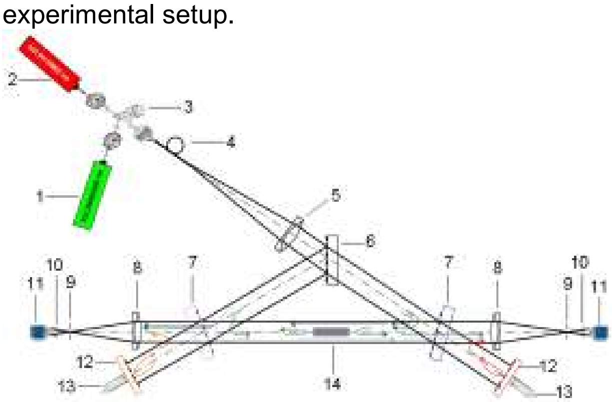

Figure 1 *Scheme of PTB's prototype DEI. 1- frequency-doubled Nd:YAG laser, iodine-stabilized, 2- He-Ne laser, iodine-stabilized, 3- beam combiner with shutters, 4- single mode fiber, 5- collimator, 6, 7- metal coated beam splitter plates, 8- achromatic lens, 9- output aperture, 10- output collimator, 11- CCD camera, 12- reference mirror, 13- piezo actuator and 14- gauge block*.

Spatial coherence is a practical requirement when building a DEI because of the triangular geometry of the interferometer in which a residual shear between the interfering beams is typically existent. For this reason a single mode fiber is used as a light source in the focal point of the collimator. A reliable way for the extraction of integer interference orders requires at least two clearly separate wavelengths of the light [15]. However, the spectral transmittance of a single mode fiber is relatively narrow. Use of two separate fibers would require their mutual replacement during a measurement process. In order to overcome this problem a new concept of interferometer light source was developed that bases on beam combiners and a short fiber end designed to transmit the red and the green wavelength in the optimum mode (System designed by Schäfter + Kirchhoff, Germany). The two wavelengths of iodine stabilized lasers, a diode-pumped Yag-laser @ 532.290008382 nm and a He-Ne laser @ 632.99139822 nm (the same source as for the Precision Interferometer, [13]) are connected to a beam combiner equipped with a built in shutter to switch between them. After the beam is collimated, it is sent to the triangular shaped interferometer arrangement comprising three wedged beam splitters with flatness better than $\lambda/20$. One side of each plate is coated by chromium allowing about 50% transmission while the other side is anti-reflection coated to minimize potential parasitic interferences resulting from unwanted reflections. Two of the beam splitters can be adjusted by motorized screws (MICOS, Germany) to allow for optimum alignment with respect to vertical incidence of the light onto the faces (autocollimation adjustment). Each reference mirror is aligned by a three axes piezo actuator system (PI, Germany). The same system is used to establish phase stepping interferometry by simultaneously shifting the three axes by exactly the same steps.

On each side arm of the DEI interferograms are generated by interference of the beam from the reference mirror with either the reflected beam from the gauge block or, in the outer range, with the beam coming from the respective other arm. The imaging system involves the output collimators and an additional lens in from of each camera (12-bit low noise cameras from PCO, Germany). The distance between the lenses and the CCD chip can be adapted to the individual position of the end faces of a gauge block in order to handle different lengths.
A dedicated visual basic program was developed for the measurement control, interferogram analysis and length evaluation.

The temperature is measured by Pt-100 sensors. For the gauge block temperature, the sensors are integrated into a small copper plate of a clip, which is fixed to the gauge block so that good temperature contact is ensured. The air temperature sensors are located near the gauge block. The resolution of the temperature readings is 1 mK and the total standard measurement uncertainty of the calibrated system is

5 mK. To achieve temperature equilibrium, the gauge blocks have to be inserted into the interferometer in sufficient time before the measurements are taken. The computer records the sensors temperature readings each 10 seconds. The current DEI is able to measure gauge blocks length up to 300 mm.

Phase stepping interferometry is applied separately in the left and the right arm of the DEI. Each camera captures a set of shifted interferograms recorded at five defined z-positions of the reference mirror : $\{\mathbf{1}:-2\times\alpha, \mathbf{2}:-1\times\alpha, \mathbf{3}:0\times\alpha, \mathbf{4}:1\times\alpha, \mathbf{5}:2\times\alpha\}$, in which α is the step width. The corresponding phase maps are calculated by applying the Tang algorithm [16]:

$$\tan\ \phi\ = \frac{\sqrt{\left[2\left(I_4-I_2\right)+\left(I_5-I_1\right)\right]\ \left[2\left(I_4-I_2\right)+\left(I_5-I_1\right)\right]}}{I_1+I_5-2I_3} \quad (1)$$

in which I_1 to I_5 are the intensities of the respective interferograms at a certain pixel position. It is important to notice that phase evaluation in the double ended design strictly requires the step positions 3 ($0\times\alpha$) in the right arm when phase stepping is applied in the left arm and vice versa. Otherwise the relation of the phases in the interferometer (left to right) is lost which makes a proper length evaluation impossible.
Fig. 2 shows an example for a set of interferograms recorded in the right arm of the interferometer and the resulting phase map.

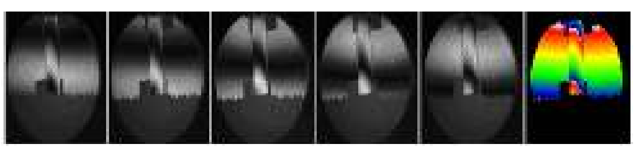

Figure 2 *Example of five interferograms and the resulting phase map measured in the right arm of the DEI for a 100 mm steel gauge block sample using the He-Ne laser iodine-stabilized*.

The general idea of length measurements by interferometry is to express the length as a multiple of the half wavelength of the light:

$$l_k = \frac{\lambda_k}{2}\ \left(i_k + q_k\right) \qquad k = 1,2 \quad (2)$$

in which l_k is the measured length, λ_k is the wavelength of the used light under air conditions, i_k is the large number of integer orders of interference and q_k is the fractional interference order.

λ_k is determined from the respective vacuum wavelength which is downscaled by the air refractive index n_k , i.e. $\lambda_k = \lambda_k^{vac} / n_k$. The refractive index of air around 20°C is determined by using an empirical equation [17] involving the environmental parameters for air pressure, air temperature, air humidity and CO_2 content which have to be measured precisely.

For the determination of the fractional order of interference, in each phase map (left and right arm) three regions of interest (ROIs) are defined (see Fig. 3). The central ROI is set to the position of the front face of the gauge block, while the two other ROIs, arranged symmetrically around the central ROI are set to positions in the outer pathway of the light beam. Before the fractional order is calculated it is necessary to ensure that there is no 2π discontinuity between the phases of these outer ROIs. This can be handled by processing the phase map in the same way as done for ROIs as explained in [15]. The fractional interference order can then be determined from.

$$q_k = \frac{1}{2\pi}\left\{\left[\frac{(\phi_{la}^1+\phi_{la}^2)}{2}-\phi_{la}^{GB}\right]+\left[\frac{(\phi_{ra}^1+\phi_{ra}^2)}{2}-\phi_{ra}^{GB}\right]\right\} \quad (3)$$

in which ϕ^1 and ϕ^2 indicate the average phases outside the gauge block and ϕ^{GB} at the front faces (indices: *la*: left arm, *ra*: right arm).

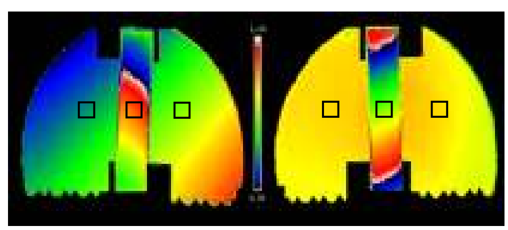

Figure 3 *Phase maps obtained for the left and the right arm obtained for green light. The regions of interest (ROIs) are indicated by squares. In this example a 30 mm steel gauge block was measured*.

The large number of integer orders is determined by the method of exact fractions as explained in [15]. Corrections must be applied to the length l_k of equation 2 measured in the DEI to take account of the phase change on reflection at the surfaces of the gauge block and their roughness [6]. This phase correction is larger than when the gauge block is wrung, since in the latter case the surfaces of the platen and the sample have the same direction and should have similar surface roughness so that only the difference between the corrections for the two surfaces is effective, whereas in the unwrung case, i.e. for the DEI, their sum is to be considered. At PTB the surface roughness correction for each individual surface of a gauge block is determined by applying an integrating sphere as described in [18]. In this technique, the roughness of the test surface is proportional to the square root of the ratio between the diffused light and the reflected light of the gauge block surface. The phase change on reflection is also dependent on the optical constants. Great care must be taken in order to account for the overall phase change correction in a double ended interferometer when the absolute length of gauge blocks is of primary interest. This is different when such interferometer is to be used for extracting drifts or thermal expansion coefficients.

3. ESTIMATION OF MEASUREMENT UNCERTAINTY

Table 1 summarizes all relevant contributions to the measurement uncertainty of the DEI prototype.

Table 1 *Summary of contributions to the measurement uncertainty of the DEI prototype used for length measurements under air conditions*

Influence Quantity x_i	Standard uncertainty $u(x_i)$	Sensitivity coefficient c_{x_i}	contribution to length uncertainty $c_{x_i}\,u(x_i)$
Wavelength of He-Ne laser	$5\times10^{-11}\lambda_1$	$L/2\lambda_1$	$2.5\times10^{-11}\mathrm{L}$
Wavelength of YAG laser	$7\times10^{-12}\lambda_2$	$L/2\lambda_2$	$3.5\times10^{-12}\mathrm{L}$
Fringe fraction	0.006 fringe	$(\lambda_1+\lambda_2)/4$	1.7 nm
GB temperature	4 mK	$\alpha\,\mathrm{L}$	$4.64\times10^{-08}\mathrm{L}$
Thermal Expansion Coefficient	$5\times10^{-07}\mathrm{K}^{-1}$	$(20-\mathrm{t})\mathrm{L}$	$1.5\times10^{-07}\mathrm{L}$
Wave front errors	4.3 nm	1	4.3 nm
Source size	2.7×10^{-13}	L	$2.7\times10^{-13}\mathrm{L}$
Alignment	2.76×10^{-09}	L	$2.76\times10^{-09}\mathrm{L}$
Edlèn equation	1.7×10^{-08}	L	$1.7\times10^{-08}\mathrm{L}$
Air temperature	5 mK	$9.6\times10^{-07}\mathrm{L/K}$	$4.8\times10^{-09}\mathrm{L}$
Air pressure	6 Pa	$2.7\times10^{-09}\mathrm{L/Pa}$	$1.62\times10^{-08}\mathrm{L}$
Air humidity	1.5 %	$9.7\times10^{-07}\mathrm{L}$	$1.46\times10^{-08}\mathrm{L}$
Co_2 contents	30 ppm	$1.4\times10^{-04}\mathrm{L}$	$4.2\times10^{-09}\mathrm{L}$
GB flatness and parallelism	7 nm	1	7 nm
Phase correction	8 nm	1	8 nm

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The resulting overall uncertainty can be written as:

$$u=\sqrt{(11.6\,\mathrm{nm})^2+(1.6\times10^{-07}\,\mathrm{L})^2}$$

and the expanded uncertainty (k=2) is:

$$U=2\sqrt{(11.6\,\mathrm{nm})^2+(1.6\times10^{-07}\,\mathrm{L})^2}$$

4. RESULTS

The first measurements indicate consistent results for the length measurements using PTB's prototype of DEI. Figure 4 shows that, for a first set of samples, the coincidence between the results obtained with the two different laser wavelengths is typically better than 3 nm.

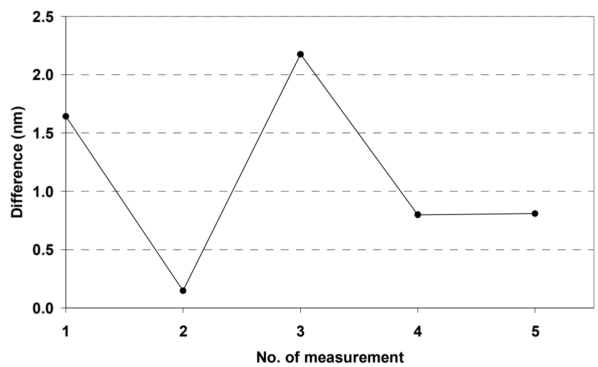

Figure 4 *Difference in the measured length obtained with the two different wavelengths for a 40 mm steel gauge block.*

For different steel gauge blocks, a comparison between the DEI measurements and that of the PTB interference comparator (INKO5) is made. Figure 5 shows a very good agreement between the results of the two interferometers. The maximum difference between the two interferometers, 26 nm, is within the uncertainty value. The repeatability using DEI is less than 2 nm as shown in Figure 6.

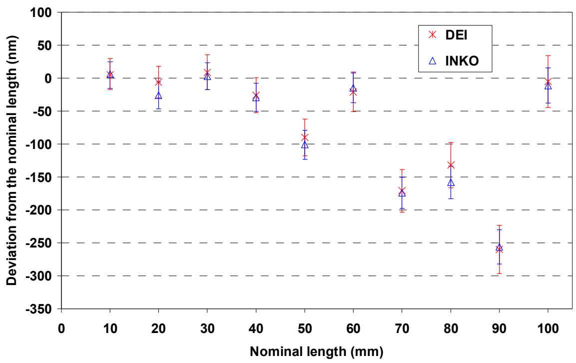

Figure 5 *Length measurements and individual uncertainties for both instruments INKO5 and DEI (prototype).*

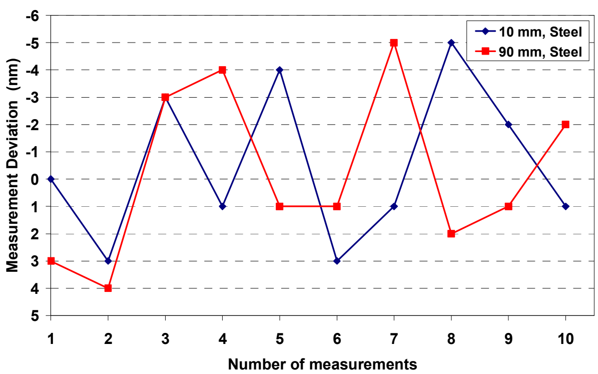

Figure 6 *Repeatability of DEI for two steel samples, 10 mm and 90 mm.*

5. Conclusion

The PTB-DEI prototype shows consistent results and good agreement with a well established gauge block interferometer (INKO5) within 26 nm. Its current uncertainty is limited by the length correction taking into account for the temperature deviation from 20°C and by the fact that measurements are performed in air.

6. Acknowledgments

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