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REALIZATION OF THE HIGHEST LEVEL OF TRACEABILITY IN CROATIAN NATIONAL LABORATORY FOR LENGTH

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Summary

Traceability of length measurement to the SI unit meter is realized by means of interferometry, and primary interferometers are used at the highest accuracy levels to perform calibration of national gauge block standards. These devices are expensive, given the fact that they are manufactured on order and used almost exclusively by national measurement institutes. Therefore, The Croatian Metrology Institute/Faculty of Mechanical Engineering and Naval Architecture – Laboratory for Precise Measurements of Length (HMI/FSB-LPMD) decided to retrofit and modify its Zeiss gauge block interferometer. Measurements presented in this paper demonstrate substantial improvements in accuracy and ease of use. These improvements established the highest level of traceability in the Laboratory and enabled it to publish appropriate calibration and measurement capabilities (CMC) value in the BIPM (Bureau International des Poids et Mesures) key comparison database (KCDB) under the Mutual Recognition Arrangement (MRA).

Key words: *gauge block calibration, traceability, optical interferometry, interferogram analysis*

1. Introduction

For several decades, length (the meter) has been defined by wavelength of radiation sources in vacuum, first by the radiation of krypton 86 and currently by the radiation of an iodine-stabilized helium-neon laser. Since such definition is not “tangible” and is therefore very impractical to use in everyday measurements, the comparison of radiation source wavelength to physical length of an artefact has been done for many years by using the principles of interferometry. The use of interferometers to accomplish this task is in principle simple and well defined, but in order to perform the highest accuracy calibration a number of factors have to be carefully considered. Because of high cost and low availability of the highest level gauge block interferometers, The Croatian Metrology Institute / Faculty of Mechanical Engineering and Naval Architecture – Laboratory for Precise Measurements of Length (HMI/FSB-LPMD) decided to upgrade its Zeiss interferometer, which used krypton and helium spectral lamps; this approach is relatively common in national metrology institutes (NMIs) [1],[2]. The goal was to provide length calibration traceability up to the definition of a metre, as well as to improve the accuracy of interferometric measurement system.

1.1 Interferometric gauge block measurement

In order to measure the length of a gauge block interferometrically, its length has to be expressed in terms of the wavelength of source radiation [3] (Figure 1). What can be seen on an interferogram - what can actually be measured - is the fractional part of wavelength F that fits the actual length of the gauge block (Figure 2). The remaining integer number of full wavelengths N that span the length of the gauge block can be calculated by several methods.

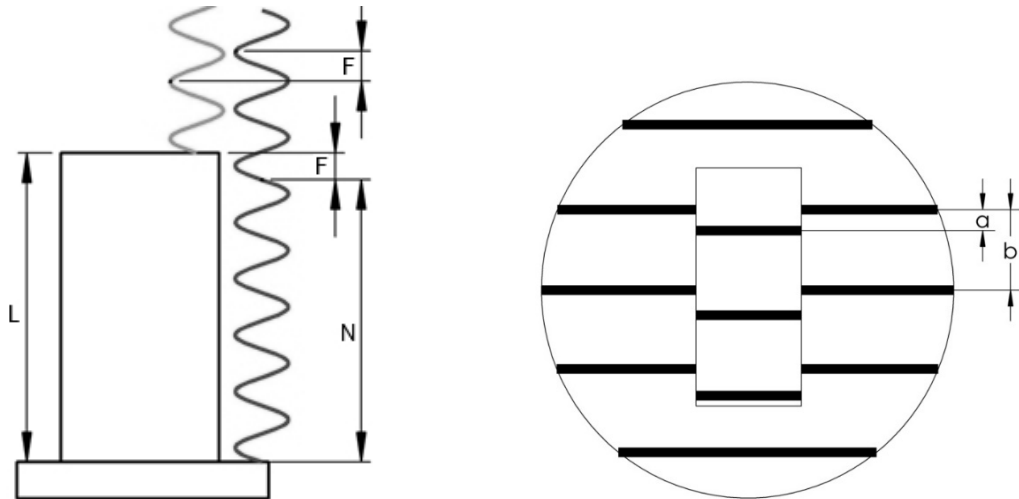


Fig. 1 Interferometric measurement of a gauge block **Fig. 2** Schematic interferogram of a gauge block

If the length of the gauge block is known to within one half wavelength, for example by making a mechanical comparison to another gauge block [4], then the integer number of wavelengths can be calculated from this measurement. If this is not the case, a common approach to determine the integer number of wavelengths, which was also used in our study, is the use of multiple wavelength interferometry [5] with the exact fractions method (Figure 3). This method uses several wavelengths to establish a system of equations with different fractional and integer wavelengths. These equations provide evenly spaced coincident solutions for the integer number of full wavelengths that span the measured length. If enough wavelengths are available, these solutions are spaced widely enough to determine the correct integer number of wavelengths. We used a stabilized helium-neon laser at 632.8 nm as the primary wavelength, and a tunable helium-neon laser at 612 nm and 543.5 nm as the source of additional wavelengths.

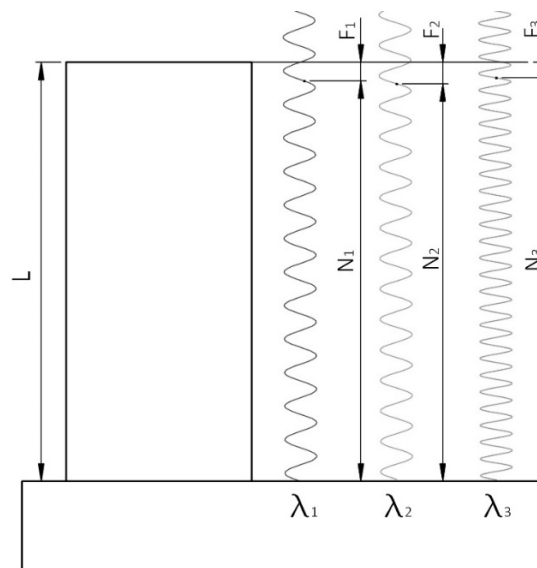


Fig. 3 Multiple wavelength interferometry

If the gauge block and platen are made of different materials, then a correction for a different phase change on reflection must be applied. A different phase change can also arise from differing surface roughness [6], and its amount is usually statistically determined from repeated measurements [7].

1.2 Zeiss interferometer

Zeiss interferometer (Figure 4) is based on the Kösters type of the Twyman-Green design, [8] which performs the amplitude splitting of source radiation using a beam splitter to divide the incoming beam into two beams – a reference and a measurement beam. These two beams are reflected and then recombined at the beam splitter, where they interfere. Zeiss interferometer features a monochromator, based on the Kösters prism, which is used to isolate certain frequencies of source radiation - originally hrypton and helium spectral lamps.

Prior to the study presented in this paper, this interferometer was equipped with a VGA black and white CCD camera, which was used to record interferograms. The interferograms were analysed visually by the operator.

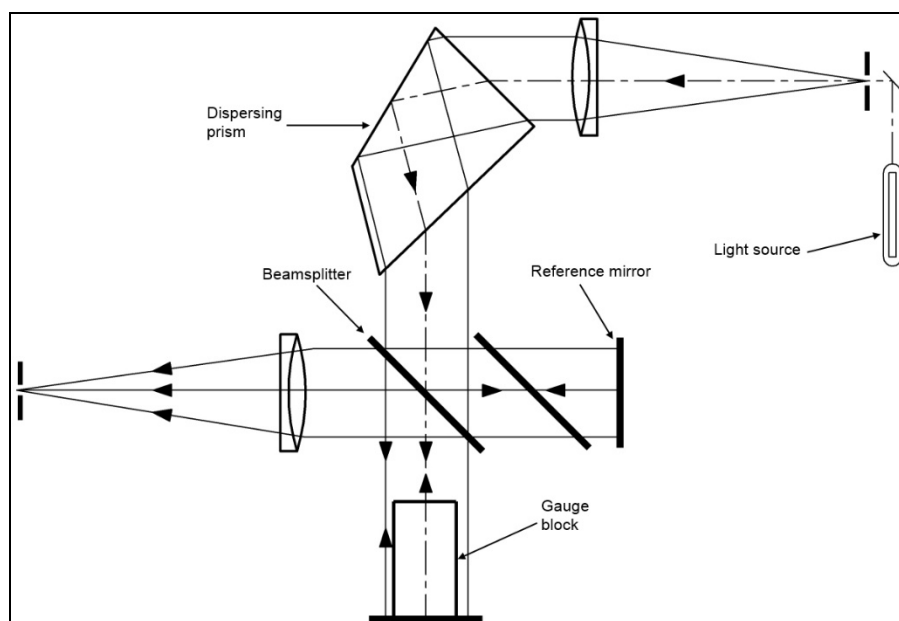


Fig. 4 Schematic representation of Zeiss interferometer

2. Modifications to Zeiss interferometer

In order to achieve current state-of-the-art in accuracy and measurement uncertainty, several modifications have been done to the previously described Zeiss interferometer. These modifications, described in the following sections, enable the use of lasers as sources of radiation; they also improve measurement of temperature, pressure and humidity and enable digital interferogram acquisition and evaluation. The internal optical system was not modified due to the extremely delicate alignment of optical components and sealed optical path.

2.1 Laser coupling

In order to use a laser as the source of radiation, an optical coupling system had to be designed. To achieve flexibility in the design, optical fibres were selected for laser light delivery rather than mirrors. The use of optical fibre requires a fibre launch system (Figure 5) to couple laser light into the fibre. The fibre launch system is comprised of a precision six axis alignment platform, a translation stage for focus adjustment, and a 50x microscope objective.

Since multiple wavelength interferometry is used, a multimode cable with a core diameter of 100 μm was chosen. In order to eliminate the speckle pattern at the output of the fibre, a rotating diffuser was used to reduce spatial coherence of the laser; the diffuser was produced by treating an ordinary glass disc with hydrofluoric (HF) acid.

An optical system for the interferometer input aperture was designed with an achromatic lens to allow for different source wavelengths. Since the focal length and the diameter of the collimating optics inside the interferometer were not known precisely, a telescope assembly was designed at the input aperture (Figure 6) in order to find the correct input numerical aperture.

All optical and mechanical components for these systems are standard products, made by either Thorlabs or Edmund Optics. Lens that were used are 25.4 mm (1 inch) achromatic doublets with antireflection coating for visible spectrum.

These modifications resulted in substantial reductions in necessary laser power, due to good coupling efficiency. Furthermore, better alignment of interferometer's optical axis is now possible, which has beneficial effects on measurement uncertainty.

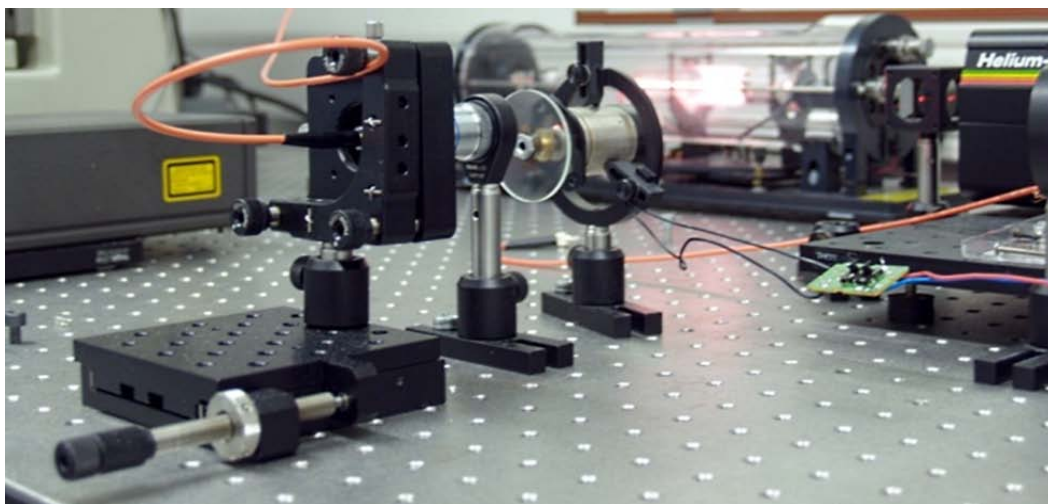


Fig. 5 Fibre launch system with rotating diffuser. Laser beam passes through a rotating diffuser, is then focused by a 50x microscope objective into a multimode optical fibre with core diameter of 100 μm and numerical aperture $\text{NA} = 0,22$.



Fig. 6 Telescope assembly at interferometer aperture. The beam exiting the optical fibre is first collimated and then focused onto input aperture of interferometer.

2.2 Interferogram acquisition and evaluation

The acquisition of interferograms was performed digitally with a color CMOS camera. An objective lens was chosen to match the decollimating optics of the interferometer. The camera has a resolution of 5 Megapixels, which provided more than adequate pixel density for the fringe fraction analysis; typical fringe spacing is >300 pixels.

The interferometric gauge block measurement was previously performed by visual inspection of interferograms with approximately $\lambda/10$ (~ 60 nm) accuracy. To improve measurement accuracy, a software for interferogram acquisition and evaluation was developed (Figure 7).

This software was used to capture the interferogram from the camera, apply environmental corrections, evaluate fringe fractions automatically, and finally calculate the gauge block length and its deviation from nominal length. Measurements of gauge block temperature and air pressure, temperature and humidity were taken at the same time as the interferogram, having provided the most accurate information about these conditions at the time of the measurement.

Fringe fractions were determined by an edge detection algorithm developed at the HMI/FSB-LPMD, which transformed the captured color image into grayscale by applying adaptive thresholding based on several histogram traces. The image was then binarized and fringe centers were calculated by linear least squares fitting. This procedure was found to be accurate to more than $\lambda/1000$ (<1 nm), and it represented the largest single contribution to the improvement of measurement accuracy. Synchronous acquisition of environmental measurements further added to the achieved reduction in measurement uncertainty.

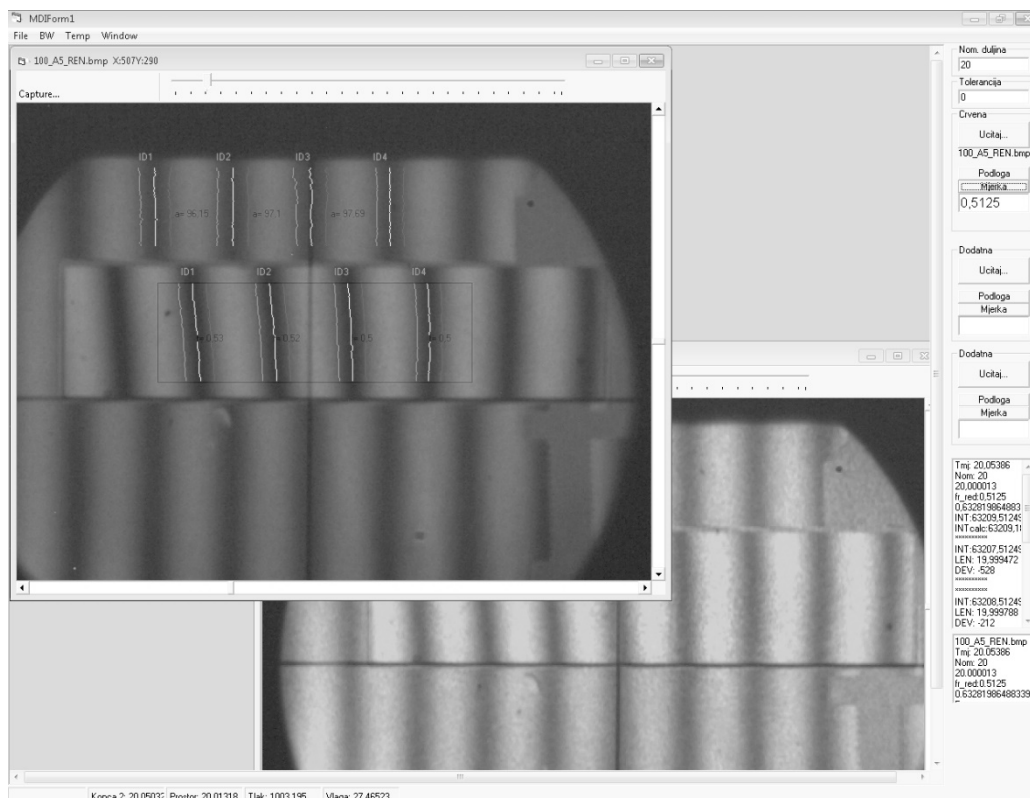


Fig. 7 Interferogram analysis software. Interferogram taken with red wavelength is analysed, and a part of the second interferogram taken with green wavelength is visible below. It can be seen that the fringe fractions are different for the wavelengths.

3. Results

The primary goal of our study was to introduce a laser as the wavelength source and to keep the laser-interferometer coupling system flexible enough to allow the use of the laser in other systems. Secondly, interferogram acquisition was substantially improved by the use of a high resolution digital camera and a quality objective. The software that was developed to acquire and analyse interferograms resulted in a significant increase in measurement resolution and consequently in improved measurement accuracy. The fact that environmental corrections are performed simultaneously with the interferogram acquisition allows further reduction in the associated measurement uncertainty. All of the factors stated above have a measurable contribution to the measurement uncertainty of calibration of gauge blocks. For that reason we decided to quantify the performance of the modified Zeiss interferometer by performing a complete evaluation of its measurement uncertainty according to the ISO Guide to the Expression of Uncertainty in Measurement (GUM). Table 1 shows the complete measurement uncertainty budget together with the expanded measurement uncertainty. The measurement uncertainty obtained in the study presented in this paper places the HMI/FSB-LPMD among the top European national laboratories in the field of short gauge block calibration. For example, if a 100 mm gauge block is measured, the expanded measurement uncertainty is just 25 nanometres.

The performance of the modified interferometer was evaluated in a European Association of National Metrology Institutes (EURAMET) key comparison in 2012, with slightly larger uncertainty and excellent results [9]. This enabled the HMI/FSB-LPMD to publish its *calibration and measurement capabilities* (CMC) value in the BIPM MRA KCDB in 2012. The Laboratory is currently participating in another EURAMET key comparison, in which the goal will be to formally confirm the improved uncertainty stated in Table 1. A detailed discussion of the uncertainty budget components would exceed the scope of this paper and will be presented later.

Table 1 Uncertainty budget for modified Zeiss interferometer.

Contribution to measurement uncertainty x_i	Source of measurement uncertainty	$u(x_i)$	$c_i = \partial l / \partial x_i$	$u_i(L)$ in nm, for L in mm
$u_c(l_{\text{fit}})$	Method of exact fractions:			
$u(\lambda_i)$	Vacuum wavelength	$0,01 \cdot 10^{-6} \lambda$	L/λ	$0,01L$
$u(F_i)$	Fringe fraction	0,005	$\lambda/2$	1,583
	Temperature influence:			
$u_c(\Delta\vartheta)$	Gauge block temperature	7 mK	$\alpha \cdot L$	$0,08L$
$u(\alpha)$	CTE	$0,66 \cdot 10^{-6} \text{ K}^{-1}$	$(20 - t_g)L = 50L \text{ mK}$	$0,033L$
$u_c(\Delta\vartheta)u(\alpha)$	Second order temperature influences	—	—	$0,007L$
$u(l_w)$	Wringing	6 nm		

(continue **Table 1**)

Contribution to measurement uncertainty x_i	Source of measurement uncertainty	$u(x_i)$	$c_i = \partial l / \partial x_i$	$u_i(L)$ in nm, for L in mm
Interferometer optics:				
$u_c(l_A)$	Imperfect optical surfaces	3 nm		
$u_c(l_\Omega)$	Imperfect collimation	–	–	0,003L
Refractive index of air:				
$u(E)$	Edlen equation	10^{-8}	L	0,01L
$u_c(t_z)$	Measurement of air temperature	2 mK	$-9,5 \cdot 10^{-7} L / K$	0,002L
$u_c(p)$	Measurement of air pressure	10 Pa	$2,7 \cdot 10^{-9} L / Pa$	0,027L
$u_c(R)$	Measurement of relative humidity of air	0,2 %	$-8,5 \cdot 10^{-9} L$	0,002L
$u_c(\lambda)$	Vacuum wavelength		$-1,2 \cdot 10^{-5} L$	
$u_c(l_G)$	Gauge block geometry	3 nm		
$u_c(l_\phi)$	Phase correction	4 nm		
Expanded uncertainty $U(L)$, $k = 2$, $P = 95\%$		$Q[17; 0, 18 L]$ nm, for L in mm		

4. Conclusion

Extensive modifications were performed on a Zeiss interference comparator and presented in this paper in detail, including the laser-to-interferometer coupling with speckle elimination, the optical system for acquisition of interferograms and the software for interferogram evaluation. The performance of the modified interferometer was confirmed by extensive measurements and by intercomparison with other European NMIs, which resulted in the acceptance and publishing of the CMC value in the MRA KCDB. It was shown that it is possible to realize competitive performance levels by using widely available parts and at a relatively low cost. Furthermore, these modifications also enable easy implementation of the phase shifting interferometry (PSI), this project is being developed and will be presented in future publications.

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