Modernization of Koesters interferometer and high accuracy calibration gauge blocks

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Abstract. The Optical Metrology Division (Diopt) of Inmetro is responsible for maintaining the national reference of the length unit according to International System of Units (SI) definitions. The length unit is realized by interferometric techniques and is disseminated to the dimensional community through calibrations of gauge blocks. Calibration of large gauge blocks from 100 mm to 1000 mm has been performed by Diopt with a Koesters interferometer with reference to spectral lines of a krypton discharge lamp. Replacement of this lamp by frequency stabilized lasers, traceable now to the time and frequency scale, is described and the first results are reported.

1. Introduction

In the early 1970s the team of John Hall of the NBS (renamed afterward as NIST) realized the first frequency chain connecting the microwave frequency of the cesium atomic clock to the frequency of a methane-stabilized helium-neon laser at 88.4 THz [1]. In the early 1980s it was possible to measure the frequency of some iodine stabilized He-Ne lasers allowing in 1983, during the 17th General Conference on Weights and Measures, a new definition of the meter, henceforth defined as “the path length traveled by light in vacuum during a time interval of 1/299 792 458 second” [2,3]. This definition fixes the speed of light to an exact value, thus requiring for the determination of the vacuum wavelength of a radiation through the measurement of its frequency [4]. Following this new definition of the meter, the International Committee of Weights and Measures (CIPM) published their *Mise en Pratique* with a list of radiations that can be used for its practical realization [5,6]. Among these there are a radiation of He-Ne laser, stabilized to the a_{16} component of the $^2I_{127}$ R(127) 11-5 hyperfine transition, which currently corresponds to the national primary length standard, and radiation transitions corresponding to $5d_5$-$2p_{10}$, $2p_8$-$5d_4$ and $1s_3$-$3p_{10}$ of the krypton spectral lamp (^{86}Kr), used as the working length standard in the interferometer Koesters. Since the 80s there were few spectral krypton lamps still in operation worldwide and with the advent of the stabilized lasers these lamps have been gradually replaced. In order to adapt the length measurements with traceability to current time and frequency standards the acquisition of a commercial frequency comb synthesizer [7] made it possible to equip the Koesters interferometer with three lasers stabilized at different frequencies, thus phasing out the now becoming obsolete spectral lamps.

With this substitution it is possible to further improve measurement capability, since the laser light provides sharper and more intense interference fringes for easier-viewing or image capture with digital cameras to carry out the reading of the fringe pattern. This also enables process automation, reducing measurement uncertainties and false operator judgments.

2. Materials and Methods

The materialization of the meter unit is carried out through artifacts known as gauge blocks, used by the industry for calibration of calipers, micrometers and performance verification of Coordinate Measuring Machines (CMMs). The traceability transfer between the length optical standards and the gauge blocks with nominal length between 100 mm and 1000 mm (long-blocks) is performed with a Koesters interferometer. The Koesters interferometer is a modified Michelson type interferometer, where the beam splitting and recombination is accomplished with a double prism [8] as shown in figure 1. In order to modernize length measurements with traceability to current time and frequency standards a femtosecond laser frequency comb was acquired and the interferometer equipped with three lasers, stabilized at different wavelengths, thus, phasing out now the becoming obsolete spectral discharge ^{86}Kr lamp.

For an unambiguous determination of the block deviation length value it is necessary to use at least three different wavelengths [9].

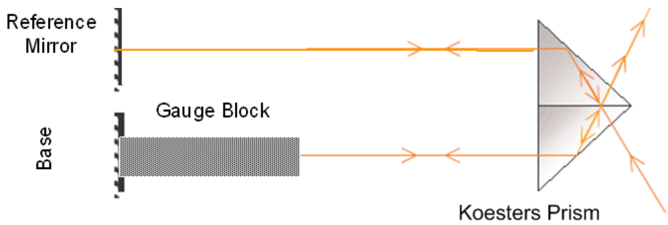

Figure 1. Simplified scheme of the optical layout of the Koesters interferometer.

2.1. Radiation sources used

Until 2012 the Koesters interferometer used a krypton (^{86}Kr) spectral lamp for measurements of gauge blocks with nominal length between 100 mm and 1000 mm. The relevant wavelengths of interest are listed in table 1.

Table 1. Radiation emitted by the krypton lamp used for the calibrations of large gauge block.

Transition	λ(nm)	U (nm, k=3)
$5d_5$-$2p_{10}$	605.780 210 3	$2.4x10^{-6}$
$2p_8$-$5d_4$	642.280 060	$1.3x10^{-5}$
$1s_3$-$2p_{10}$	565.112 860	$1.1x10^{-5}$

In 2012 a 633 nm stabilized He-Ne laser operating in a single mode TEM00 was tested with the interferometer system. Other two stabilized He-Ne lasers, operating at 543 nm and 594 nm, were incorporated in 2014. Their respective wavelength stabilities are shown in table 2.

Table 2. Lasers coupled to the interferometer system.

Laser	λ(nm)	U (nm)
Red	632.991 372	$1.3x10^{-5}$ (k = 2)
Yellow	594.096 550 9	$1.8x10^{-6}$ (k = 1.65)
Green	543.515 310 0	$1.1x10^{-6}$ (k = 1.65)

The lasers and krypton lamp are arranged according to the optical layout, as shown in figure 2.

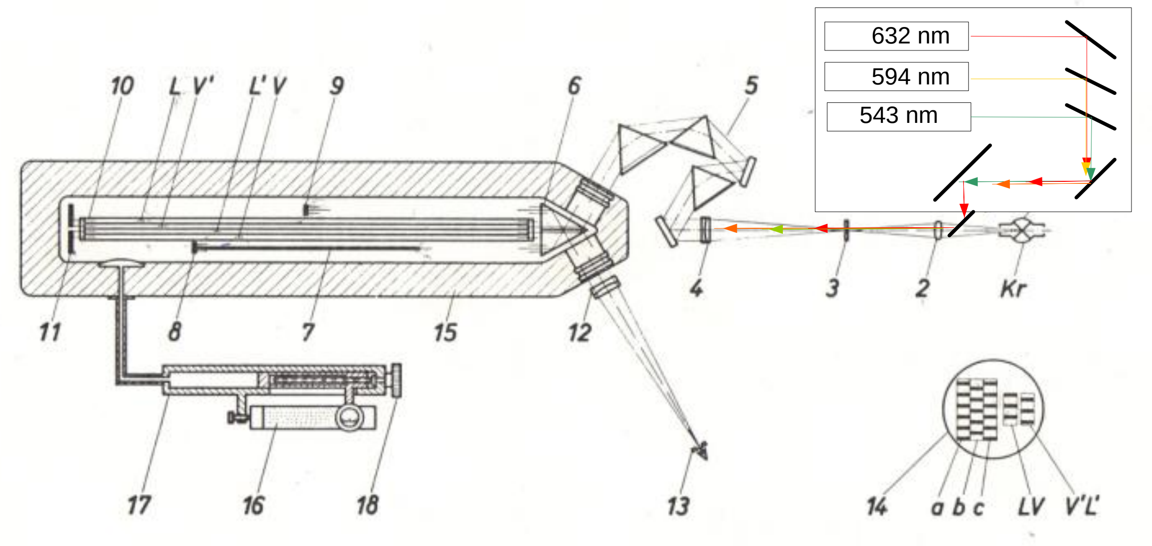

Figure 2. Graphic scheme of the Koesters interferometer with three different stabilized lasers.

In this figure also is shown the focusing optics (2), the collimating lens (4), the prism assembly used to select the wavelength (5), the Koesters prism (6), the reference mirror (9), the gauge block (7) and the wringing base (8). By means of the objective lens (12) and the circular diaphragm (13) the interference pattern is observed (14).

2.1.1. Traceability of Radiation Sources. The traceability of radiations emitted by the krypton spectral lamp as working length standard is ensured by an indirect and laborious calibration process, using a previously calibrated reference gauge block. With the use of lasers the traceability now is referenced to frequency measurements with an optical frequency comb synthesizer [10]. This equipment is located in a separated module of Optical Metrology Division, distant about 50 meters away from the Koesters interferometer. The laser beams are transmitted to the comb via optical fibers, as shown in figure 3. Thus, their calibration can be accomplished without removing the lasers from the system.

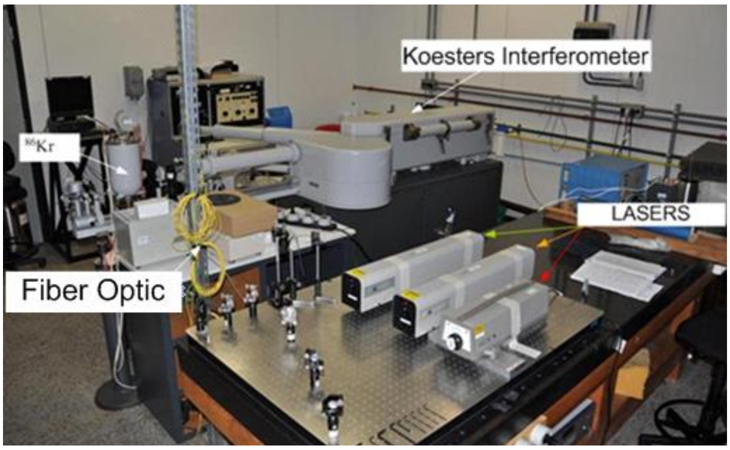

Figure 3. Koesters interferometer and lasers.

3. Results

The graph shown in figure 4 shows the monitoring measures of a gauge block used as a reference standard for over 17 years. Deviations from the nominal length were obtained until 2011 through measurements exclusively using three reference radiations emitted by the krypton spectral lamp.

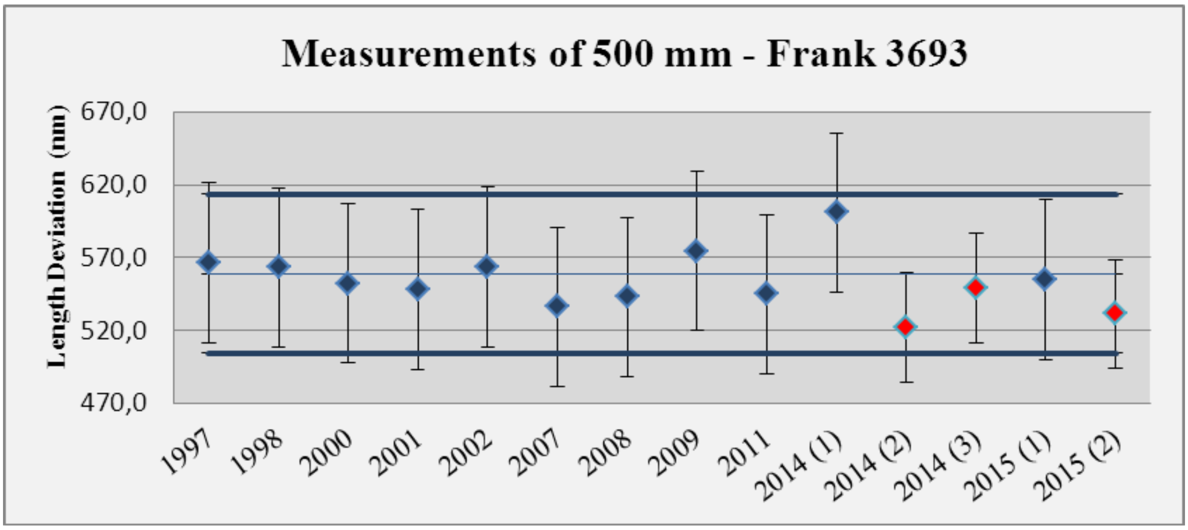

Figure 4. Evolution of length deviation measurements from a 500 mm reference block.

The blue indexed results 2014(1) and 2015(1) were performed using three spectral lamp radiations plus the radiation of a 632 nm red laser. The red indexed results 2014(2), 2014(3) and 2015(2), were obtained exclusively using the radiation emitted by three He-Ne stabilized lasers. Using the information presented in table 3 it can be concluded that the introduction of lasers in the system contributes to a global reduction of uncertainty of the final measurement of the gauge block. This reduction is due to the component associated with clearer interferometric fringe readings, and from the smaller contribution of the emitted laser radiation wavelengths as the emitted by the spectral lamp. The deviation values obtained with the introduction of lasers clearly converge in the graph with those obtained previously with the historical measurements made with the spectral lamp.

Table 3. Uncertainty components of interference fringe reading and radiation wavelengths (k=1).

L-independent terms		u_f	c_i	u_L (nm)
Fraction measurement	*^{86}Kr lamp*	3.3E-02	3.3E-02	2.9
	Laser	2.0E-02	2.0E-02	1.7
L-dependent terms (L=500 mm)		u_λ (nm)	c_i	u_L (nm)
Lamp wavelengths (^{86}Kr lamp)	*red*	4.5E-05	2.6E+05	11.7
	orange	4.0E-05	2.8E+05	11.0
	yellow-green	4.0E-05	3.0E+05	11.8
Laser wavelengths	*red*	6.5E-06	2.6E+05	1.7
	yellow	1.1E-06	2.7E+05	0.3
	green	6.6E-07	3.0E+05	0.2

The graph shown in figure 5 is the set of recorded values, over 12 hours, of the beat signal between the green laser and the laser comb. The average rate value calculated from the chart is used to calculate the laser frequency. Thus, it is shown that the maintenance of chain traceability of the Koesters interferometer can be performed more simply and directly, without intermediary standards and more laborious processes.

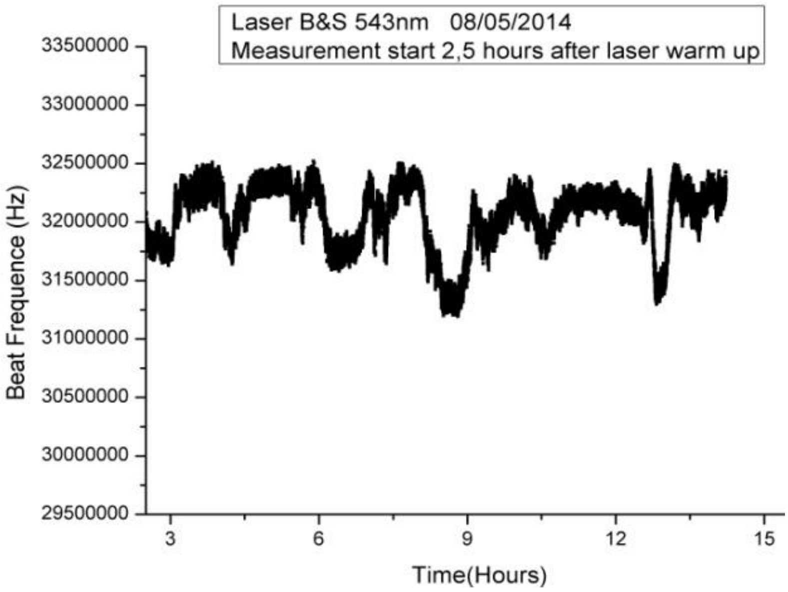

Figure 5. Beat frequency of the green He-Ne laser with the laser frequency comb.

4. Conclusions

Preliminary results indicate that using radiations emitted by stabilized He-Ne lasers has the following advantages compared to radiations emitted by the krypton spectral lamp.

Higher intensity and larger coherence length causes the formation of sharper and more intense fringes. Therefore they are easier to measure, and reducing in this way the final measurement uncertainty. Furthermore, a digital camera can be used to perform automatic fringe readings, which are currently still done by visual estimation.

Smaller wavelength uncertainties values with laser radiations are obtained in comparison with those emitted by the spectral ^{86}Kr lamp. This has a direct impact on reducing the final measurement uncertainty using the interferometer. The calibration of the lasers using an optical frequency synthesizer has been achieved.

As a next step for modernizing the Koesters interferometer one considers the incorporation of a CCD camera for image acquisition together with an automated fringe reading capability, thus, allowing for the automation of the entire calibration process and elimination of the need for visual observations.

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