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Current trends and limitations in the primary realisation of the length

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Abstract
Interferometry is the most accurate measurement method for the realization of the SI-Unit for the length, the metre. In this way, the length of a distance refers to the time travelled by light waves. Many limiting factors have to be considered when interferometry is used for the primary realization of the length. In most of the applications the air refractive index limits the practically achievable measurement uncertainty. The availability of novel principles and optical sources, electronics and detectors opens unique possibilities for the primary realization of the metre. This contribution describes two of these new concepts, which are currently pursued by PTB. Latest results obtained at the newly developed systems are compared to those obtained at the traditional ones. Potential benefits and current limitations for the attainable measurement uncertainty in primary length calibrations of material measure and the measurement of distances are critically discussed.

Keywords: Realisation of the SI definition for the metre, imaging Interferometry, fs-frequency comb based interferometry, multi-wavelength Interferometry

1. Practical realization of the SI unit of length

Optical Interferometry is the most accurate method for the realisation of the SI unit “metre”. Thereby the length of a distance, l, is ascribed to the travel time Δt of light waves in vacuum: $l = c \cdot \Delta t$ in which c is the speed of the light. Within an interferometer, Δt is obtained from a measured interference phase difference $\Delta\varphi$, downscaled by the light frequency f. A length scale that is related to a variable position z can then be realized by: $l = \Delta z = \frac{1}{2}c \cdot \frac{1}{2\pi}\Delta\varphi \cdot {}^{1}/_{f}$. This relation can be rewritten into the more common format: $l = \frac{1}{2}\lambda \cdot \frac{1}{2\pi}\Delta\varphi$. Knowledge of f on a relative level better than 10^{-9} is a prerequisite for achieving sub-nanometre uncertainties in macroscopic length measurements. For the primary realisation of the length all influencing factors have to be considered in detail. Typically, length measurements are performed under air, i.e. not in vacuum. The air refractive index n downscales the speed of the light, and thus the wavelength. Under atmospheric conditions this effect is in the order of 0.3 mm per measured metre and is actually limiting the attainable accuracy. Moreover, there exist a variety of other influences onto the length measurement, not least the limited quality of the optical components of the interferometer causing wave front deformation of the light. In spite of these general limitations the attainable accuracy is related to the measurement principle. New interferometer concepts have been made to cope with the limitations in specific measurement tasks and PTB has established novel interferometer hardware, as we show for two examples.

2. Examples for new interferometer concepts pursued by PTB

2.1. Double ended imaging interferometer: a novel instrument for the realization of the length of material measures

Primary calibration of gauge blocks is a service offered by several of the worldwide National Metrology Institutes (NMIs) to distribute the SI-unit of the length to the industry. In this approach, one of the end faces of a gauge block is wrung onto a platen. Typically, large field imaging interferometers are used for this purpose. In the traditional design of a single ended interferometer (SEI), a large collimated light beam is reflected at the front face and at the platen, i.e. the gauge block length is measured as an optical step size from the platen to the front face. As an alternative to the traditional SEI, PTB started in 2006 building double ended interferometers (DEI) for realization of the gauge block length, beginning with a prototype [1]. The final type DEI, including all the surrounding equipment, was brought to completion in 2016. Two iodine stabilized lasers are used subsequently as light source (a He-Ne@633 nm and a 2f-Nd:YAG@532 nm). In a triangular configuration the collimated 80 mm beam is split several times so that the light waves reach the gauge block from both opposite directions (see figure 1). For each direction, part of the light is reflected at the gauge block's face, another part passes along the length that has to be measured. Both faces of the gauge block are imaged to separate CCD-cameras located at the opposite interferometer exits. In this setup a gauge block length can be measured interferometrically without wringing it onto a platen. Due to the more complex beam path, exceptional attention was paid to the optical quality of the wedged beamsplitter plates (λ/50 over 130 mm diameter, made by CMSE of CSIRO, Australia). This double phase-stepping interferometer is situated in a vacuum tight chamber whose temperature is stabilized and the gauge temperature can be measured on a sub-mK level around 20°C. Since in the DEI a gauge block is not need wrung onto a platen, the central length is free from any influence of deformation of the measuring faces due to interaction with the platen. This interaction can cause length deviations of several nanometres, shown by measurement results of the UPI with wringing on opposite gauge block faces in table 1. Moreover, an undistorted length topography of a gauge block can be determined by the DEI from the two separately measured phase topographies, allowing determination of unique values for local length deviations from the central length (e.g. the largest and smallest deviations f^{o} and f^{u}). On the other hand, surface effects onto the length are additive in such double ended interferometer design instead of being subtractive as for the single ended design. This affects the length of the gauge block to be measured too short by up to several ten nm (see results for DEI with and without correction in table 1). Restricted knowledge about the phase change correction (including roughness correction) is therefore today a major limiting aspect in this novel technique.

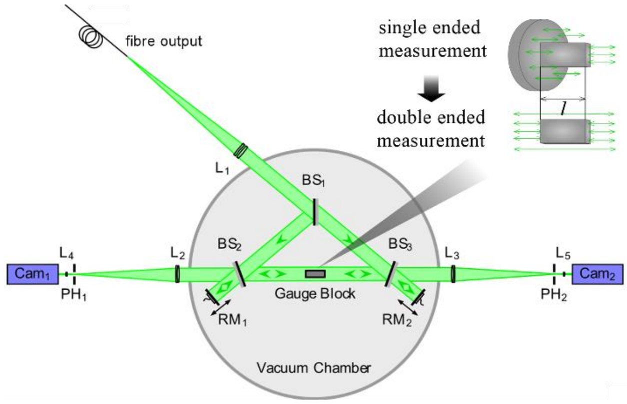

Figure 1. Scheme of PTB´s double-ended interferometer (L: lenses, BS: beamsplitters, RM: reference mirros, PH: pinholes, Cam: Cameras)

Table 1 Results of length measurements on a steel gauge block, wrung to a steel platen in single-ended interferometer, and in double-ended interferometer with and without phase change correction (PCC)

Interferometer	**Wringing, PCC yes/no**	**Measured length [µm]**	**Length differences to a) [nm]**
Single-ended interferometer (UPI, see [2])	left GB face a)	30000.0890	-
	right GB face, new wringing	30000.0867	-2.3
Double-ended interferometer (DEI, see [3])	none, no PCC	30000.0340	-55.0
	none, with PCC	30000.0882	-0.8

2.2. Frequency comb based multi-wavelength interferometry

For the primary calibration of macroscopic distances PTB uses two different reference baselines, 50 m and 600 m in length, respectively. While the 50 m baseline, situated in a temperature-controlled floor, uses the direct determination of the interference order ($\Delta\varphi/2\pi$) by traditional fringe counting, the 600 m baseline, situated outside, needs an alternative technique for reference measurements, namely multi-wavelength interferometry [4]. With this method the unambiguity range of the length measurements is considerably enlarged. However, thereby the uncertainty of the resulting length is upscaled. To overcome this limitation, a new measurement concept is suggested and pursued at PTB, comprising a heterodyne detection scheme in combination with the usage of two optical frequency combs. The dual comb interferometer was first built with cavity-enhanced electro-optic modulation [5, 6] as shown in Fig. 2a. Beating two combs of slightly different mode spacing, several interference phase signals can be detected simultaneously at the difference frequencies of the modes of interest. Fig. 2b depicts the benefit: a given synthetic wavelength can be realized by several equivalent combinations of different comb modes. Averaging these measurements leads to a substantial reduction of the measurement uncertainty, even below the “classical” limit of the uncertainty of the shortest synthetic wavelength. An expanded measurement uncertainty $U(l) = \sqrt{(10.4\ \mu\mathrm{m})^2 + (0.1\ \mu m/m)^2 l^2}$ could be demonstrated for lengths up to 10 m, mainly limited by the comb bandwidth of approx. 300 GHz. A considerably larger bandwidth of several THz is realized in a final approach in which frequency filtering is applied to a commercial seed fibre frequency comb in order to generate dual-combs [7]. Theoretically, with such an apparatus a measurement uncertainty of few nanometres could be realized. However, first experimental results indicate that low signal power of the individual modes and observed amplitude fluctuations seem to become a major limitation of this promising scheme.

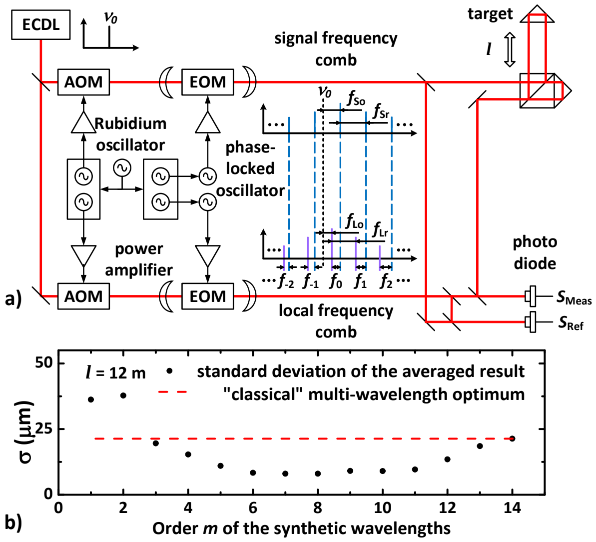

Figure 2. a) Heterodyne dual comb interferometer based on cavity-enhanced electro-optic frequency generators as presented in [5, 6]. (ECDL: external cavity diode laser; AOM: acoustooptic modulator; EOM: electrooptic modulator; S_{Meas}/ S_{Ref}: measurement and reference signals; ν_0: ECDL frequency; f_{Lr}/ f_{Sr}: repetition frequencies local oscillator/signal comb; f_{Lo}/ f_{So}: respective offset frequencies; f_{-2}, f_{-1},…: beat note frequencies.) b) Favourable uncertainty scaling due to averaging of synthetic wavelengths of equal order for a length l = 12 m.

3. Conclusions

Novel optical technologies open novel possibilities for interferometric length metrology. The realisation of the SI definition of the metre seems to become more straightforward, and spectral properties of novel sources may lead to exciting benefits for the length measurement. As the presented examples show, however, when targeting improved uncertainties multiple influence factors still have to be taken into account with great care. Even more attention is required to newly arising limitations before advantage can be taken from the new equipment.

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