A new interferometer for the absolute diameter determination of silicon spheres

Torsten Mai[1,#], Guido Bartl[1] and Arnold Nicolaus[1]

1 Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, 38116 Braunschweig, Germany
Corresponding Author / E-mail: torsten.mai@ptb.de, TEL: +49-531-592-5415, FAX: +49-531-592-69-5415

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As a part of the aimed redefinition of the SI unit kilogram on the base of a fundamental constant (i.e. the Avogadro constant N_A) the volume of a silicon sphere has to be determined with a relative uncertainty less than $1x10^{-8}$. For this task, a spherical interferometer has been developed, that makes it possible to measure absolute diameters of a 93.7 mm silicon sphere. By using spherical reference faces and a spherical beam with an aperture angle of about 52° measurements of spherical surface segments can be performed. Through positioning the sphere to 15-60 different orientations, depending on the overlap between the measured surface segments, the complete diameter topography of the sphere becomes available. In a first run with commercially available optical parts promising results with 1 nm uncertainty were achieved. To overcome technical limits a new interferometer for spheres was projected, designed and built up. In cooperation with Zeiss and Jenoptik a realization for the optical parts, Fizeau lenses and collimators, were found so that the best possible optical properties are reached. The demands were: operation in vacuum, reference surface < λ/30 and a wave front quality of the whole optical system better than λ/10. The new sphere interferometer will be introduced in detail.

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1. Introduction

The kilogram is the only SI-unit whose definition still bases on an artifact, the international kilogram prototype. Periodic verifications showed that it lost 50 µg in comparison to the mean of the official copies over the last century [1]. This result led to some doubts on the stability of the international kilogram prototype and suggests the necessity of a new definition basing on a fundamental natural constant.

One possible approach is a new definition of the kilogram via the Avogadro-Constant. It can be determined through measuring the molar mass, the cell unit volume, the mass and the volume of a nearly perfect crystal of 1 kilogram mass and around 93.7 mm diameter, in our case enriched silicon-28 mono-crystalline spheres with less than 100 nm deviation from a perfect sphere. This approach was followed by the International Avogadro Coordination [2].

For a new definition an overall relative uncertainty of $2x10^{-8}$ should be reached, which forces the volume measurement to achieve uncertainties less than $1x10^{-8}$, referred to the diameter of the sphere means 0.3 nm or λ/2000. In a first run with commercially available components $3x10^{-8}$ was reached [3]. The new sphere interferometer is meant to achieve a better thermal stability and is equipped with specially developed and processed high quality optical components to reduce the main uncertainty positions.

2. Measurement Principle

The measurement for the volume determination of the Avogadro spheres can be reduced to a measurement of a diameter distribution over the whole surface. The conditions of reliable speed and very low uncertainties are fulfilled best by interferometric techniques.

The diameter values to measure can be separated in integral multiples of the wavelength i and real multiples of the measurement wavelength r ($0 \leq r < 1$). The integral part can be determined with an accurate measurement of the mass and density. The real part is determined with the interferometer. The only demand on the sphere is that its deviations from a perfect sphere are less than λ/2, which is fulfilled for the Avogadro spheres.

Main idea of the sphere interferometer is to measure the distance D of a spherical etalon made up of two reference surfaces and then inserting the sphere in the center of this etalon and measure the distances between the reference surfaces and the sphere's surface d_1 and d_2 (see figure 1).

The sphere's diameter then is calculated as

$$d_{sphere} = D - d_1 - d_2 .$$

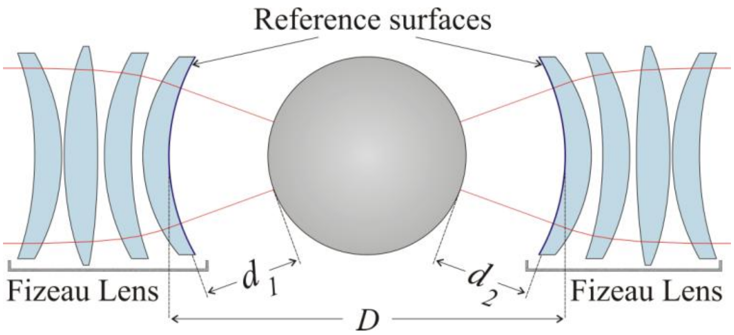

Fig. 1 Schematic drawing of the central parts of the interferometer for visualization of the measurement principle

For evaluation of the measurements the phase-step algorithm from Bönsch and Böhme [4] is applied. There for every diameter measurement five interferograms need to be taken with a phase step of $\pi/2$ between each. The phase steps are realized via a change of the laser wavelength used for measurement.

2.1 Measurement Setup

The sphere interferometer mainly consists of three parts, the temperature controlled vacuum chamber in the centre and the two opposing collimator arms which are fixed to it. In these arms light from a multimode fiber propagates 1.6 m in air and is then collimated by a plane-aspheric lens which also acts as the window of the vacuum chamber. The plane wave is focused by the Fizeau lenses whose focal points are accurately adjusted to the center of the silicon sphere. Since the inner surface of the Fizeau lenses is formed concentrically to the focused wavefront a spherical etalon is achieved with the sphere inserted between the inner Fizeau lens surface and the sphere or otherwise, without the sphere, between both inner Fizeau lens surfaces.

In the construction phase of the new sphere interferometer the attention was directed on reducing the main contributions to the uncertainty budget of the first try. Due to the influence of wavefront distortion through potential optical aberrations the number of optical surfaces was decreased and the optical quality improved. The beam shaping parts, the plane-aspheric lens and the Fizeau lens, deviate less than $\lambda/10$ and especially the reference surface less than $\lambda/30$ from the optimal shape. To increase the thermal stability of the spherical etalon temperated water flows through the vacuum chamber walls. Additionally the Fizeau lenses and the sphere to measure are housed in an inner interferometer block which rests on a three point support so that a temperature stability of only a few millikelvin can be reached. For lowering the dark current of the CCD and thus enabling a resolution of 512x512 pixels the cameras used are cooled to -80℃.

To achieve a complete measurement-coverage of the sphere without opening the vacuum chamber during the measurements a lifting and rotating mechanism is used. In the new sphere interferometer PiezoLEGS come into operation which enable high positioning accuracy and low heat emission.

3. Conclusion and Outlook

Basing on the experience and the research results gained with the first sphere interferometer the new one was designed and set up to reach the barrier in all significant details. After a long time of conception and manufacturing the measurement setup is completed and the adjustment procedure repeatedly checked and iteratively improved.

Comparative measurements between the two interferometers are object of current investigations.

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