Statistical evaluation process to measure step heights using multi-lambda shear interferometry

Corinna Krause*, Claas Falldorf*, Ralf B. Bergmann*,**

* BIAS - Bremer Institut für angewandte Strahltechnik GmbH, Klagenfurter Str. 5, 28359 Bremen, Germany
** University of Bremen, MAPEX Center for Materials and Processes and Faculty of Physics and Electrical Engineering, Otto-Hahn-Allee 1, 28359 Bremen, Germany

mailto: krause@bias.de

We demonstrate a statistical evaluation process for measuring step heights to overcome the limitations of the unambiguity range in multi-lambda interferometry by statistical averaging of the measured phase. Step heights larger than the synthetic wavelength can be measured with an accuracy of a few nanometers.

1 Introduction

Measuring step heights in the nm-range robust, accurate and over large distances is still a problem in industrial environments ranging from form measurement applications of comparatively small technical surfaces to such applications as wafer-level testing or even mirror phasing of large telescopes.

In common shear interferometry phase distributions are measured modulo 2π, therefore only surface steps smaller than half a wavelength can be measured unambiguously with single wavelength interferometry. Multi-lambda interferometry overcomes this limitation by introducing a larger synthetic wavelength as a combination of two or more wavelengths, but the measurement range is still limited by a half synthetic wavelength. Many experiments with extended range multi-lambda interferometry were already conducted with 2-wavelength approaches [1] or the method of excess fractions [2] just to name a few examples.

In the approach presented here, we make use of the foreknowledge that we measure no form, but only a step height. As a result, we found a new statistical method to measure step heights with an extended range larger than the synthetic wavelength.

2 Experimental setup

The experimental setup shown in figure 1 is a microscope-system with a 4f-setup. A λ/2-plate and a polarizer set the required polarisation. To produce two superposed wavefields we use a birefringent calcite wedge as a Wollaston prism with a 2° shearing angle in front of the camera and a second polarizer. Phase and amplitude of the interference pattern can be determined with the spatial carrier method in frequency space due to the tilt of the Wollaston prism. The object is a calibrated normal and a plane mirror as a reference. We measure with two lasers simultaneously ($\lambda_1 = 532$ nm, $\lambda_2 = 632.8$ nm), which are separated in Fourier space due to their wavelengths. For the evaluation two images for each wavelength are needed, one of the object and one of a plane reference mirror, to get a phase difference between the two, as shown in figure 2.

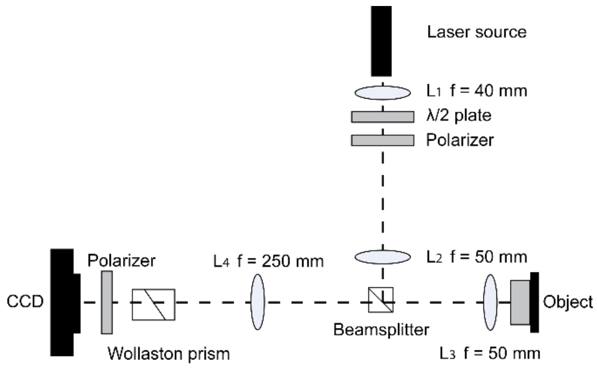

Fig. 1 *Microscope-system in a 4f-setup with 2 lasers for multi-lambda shear interferometry. The shearing is performed by a 2°-Wollaston prism in front of the camera. The object is a calibrated normal and is replaced by a plane reference mirror for the reference measurement.*

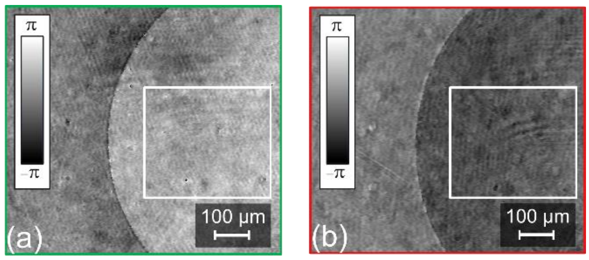

Fig. 2 *Phase difference between the object with a 1 µm-step and the reference object measured with a) a laser of $\lambda_1 = 532$ nm (green) (b) and a laser with $\lambda_2 = 632.8$ nm (red). The area marked by the white rectangle is the image section which is used for the evaluation process.*

3 Evaluation process

In this statistical evaluation approach the phase difference between target and reference measurement is relevant. Figure 3 shows a diagram of the space of phase values with the phase difference φ_1 for wavelength λ_1 and φ_2 for λ_2. The red dots are the phase values for each pixel in the image section in figure 2 (a) and (b). The yellow dot is a pair of phase difference values that marks the statistical average of the red dots. The phase diagram gives the possibility to convert the paired phase difference values into a step height. All valid data points will be located

DGaO Proceedings 2021 – http://www.dgao-proceedings.de – ISSN: 1614-8436 – urn:nbn:de:0287-2021-B022-9

submitted: 28.10.2021 published: 18.11.2021

on the black line, which represents the space of solutions

$$P(d) = |d \cdot \boldsymbol{g}| \bmod 2\pi, \quad (1)$$

which is spanned by

$$\boldsymbol{g} = \begin{pmatrix} k_1 \\ k_2 \end{pmatrix} \quad (2)$$

with the wave numbers k_1 for $\lambda_1 = 532$ nm and k_2 for $\lambda_2 = 632.8$ nm and starts at a distance of $d = 0$. The point where the yellow dot is projected onto the space of solutions corresponds to the step height. For a calibrated normal with a step height of 1 µm the yellow dot is projected onto the black line at 1005 nm.

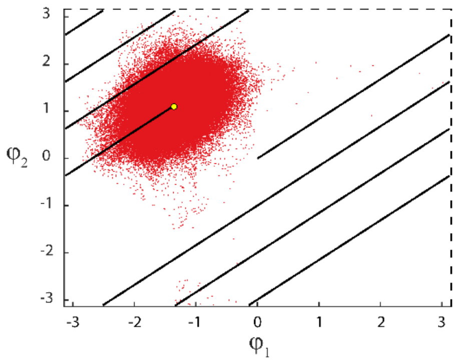

Fig. 3 *Plot of the space of phase values for a step height of 1 µm. φ_1 is the phase difference between object and reference image for wavelength $\lambda_1 = 532$ nm and φ_2 for $\lambda_2 = 632.8$ nm. The red dots are the phase values for each pixel in the section, the yellow dot is the average, and the black line denotes the space of solutions. The statistical average of the red phase values is projected onto the space of solutions at 1005 nm.*

To test this evaluation process with different step heights we conducted another series of experiments, where an adjustable mirror segment is shifted along the optical axis relative to a reference mirror. The space of phase values for a distance of 3 µm is exemplarily shown in figure 4. The statistical average gives us a value of 3035 nm for the step height. The accuracy of the measurement is limited by the adjustment of the piezo stage of the movable mirror, which has an uncertainty of 50 nm.

Figure 5 shows a diagram of the measured distance and the expected distance in these experiments. Many distances up to 5 µm were measured with a RMSE of 30 nm. For comparison purposes the synthetic wavelength of a measurement with $\lambda_1 = 532$ nm and $\lambda_2 = 632.8$ nm is

$$\Lambda = \frac{\lambda_1 \lambda_2}{|\Delta\lambda|} = 3339.8 \text{ nm}, \quad (3)$$

so the measured step height is much larger than the usual limit of $\Lambda/2 = 1669.9$ nm.

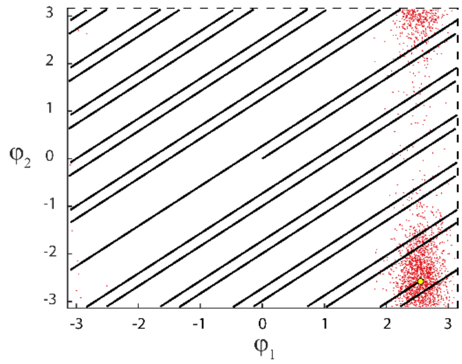

Fig. 4 *Plot of the space of phase values for two mirror segments with a distance of 3 µm. φ_1 is the phase difference between object and reference image for λ_1 and φ_2 for λ_2. The red dots are the values of each pixel in the phase difference image, the yellow dot is the average and the black line the space of solutions. The statistical average of the red phase values is projected onto the space of solutions at 3035 nm.*

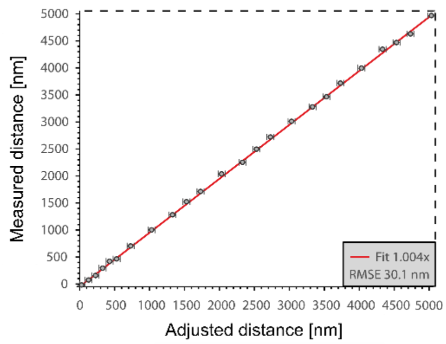

Fig. 5 *The measured distance of an adjustable mirror to the reference mirror vs. the expected distance, which was adjusted. Distances up to 5 µm even higher than the synthetic wavelength $\Lambda = 3339.8$ nm were measured. The fit of the values is a linear function with a slope of 1.004 and a standard deviation of $1\sigma = 30$ nm.*

4 Conclusion

This new evaluation process in multi-lambda shear interferometry with statistical averaging gives the opportunity to measure step heights larger than the synthetic wavelength. Even step heights of objects with a small tilt were measured with an accuracy of 30 nm.

5 Acknowledgment

The authors thank the Deutsche Forschungsgemeinschaft (DFG) for funding this research within the frame of project HyperCOMet (grant number 430572965).

References

[1] Y.-Y. Cheng, J.C. Wyant: “Two-wavelength phase shifting interferometry”, *Appl. Opt. 52,* 4539 (1984)

[2] C.E. Towers, D.E. Towers, K. Falaggis: “Extended range metrology: an age old problem”, *Optical Metrology* (2011)