Full-field macroscopic measurement of specular surfaces with SIM

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Micro SIM is able to measure specular objects in full field with a nanometer noise level [1], however with a field of smaller than 1 mm^2. A measurement of big objects without stitching is always desired. In this paper we present the first macroscopic SIM setup with a measurement field of 4.8 x 3.6 mm^2, which is implemented using commercial high-NA photo objectives and an OLED display.

1 Introduction

SIM (**S**tructured-**I**llumination **M**icroscopy) is an incoherent and non-interferometric height measuring principle. In [1] it was shown, that the implemented SIM setup in microscopic field (micro SIM) is capable of measuring the specular objects with a low hight uncertainty (down to 10nm) and a big angular dynamic of ±50°. However, its small measurement field (smaller than 1mm^2) doesn't allow measuring macroscopic object without stitching. For enlargement of the measurement field without minimizing the high depth resolution and angular dynamic, we need an objective that has to feature not only high NA and aberration free imaging quality but also a big field. Regarding the state of art in the lens design, there is no such perfect lens with affordable price. Typical high-NA photo objectives with a big field always suffer from considerable large aberrations. For us it is an interesting question, weather we can build a macroscopic SIM setup with these aberrated photo objectives that nevertheless deliver a submicron measurement uncertainty. In this paper, we will present the first implemented setup and discuss the achieved results.

2 Experimental setup

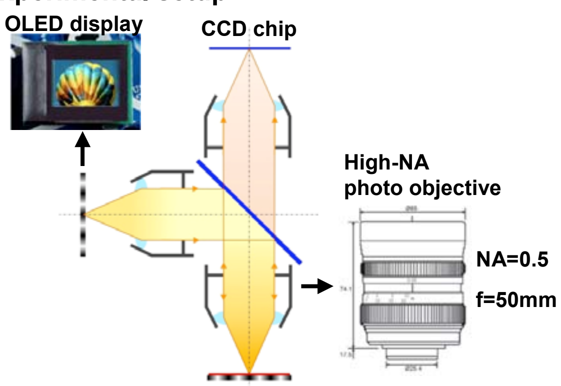

Fig. 1 Setup of the macro SIM equipped with an OLED display and three photo objectives (NA = 0.5, f = 50mm).

In micro SIM, a micro objective and tube lenses are used to demagnify the sinusoidal grating and project it incoherently into the focal plane of the wide field microscope. As the object is moved mechanically through the focal plane, every corresponding pixel will record a contrast curve that is calculated locally by doing phase shifting suggested in [2]. The peak of this curve displays the position where the corresponding object point is moved in the focus.

Due to the scanning mechanism, SIM doesn't suffer from depth of field (DOF) limitation, so we can apply high aperture imaging. In the aberration-free case, high NA gives rise to three advantages: high lateral resolution, high angular dynamic and low height uncertainty. To enlarge the measurement field without decreasing the NA, we have to substitute the micro objective and tube lens with high aperture photo objectives and choose the low magnification factor of 1. As illustrated in Fig. 1, three identical photo objectives with NA = 0.5 and f = 50mm are coaxially aligned with the infinite rays pointing to each other. An OLED display with a resolution of 800 x 600 pixels acts as the SLM in the illumination part and assures to fill out the entrance pupil (≈ 30°) with its intriguing feature of the self-illuminating. Combining employing a 1/3" CCD chip, the measurement field is increased to 4.8 x 3.6 mm^2 with an angular dynamic of ±20°.

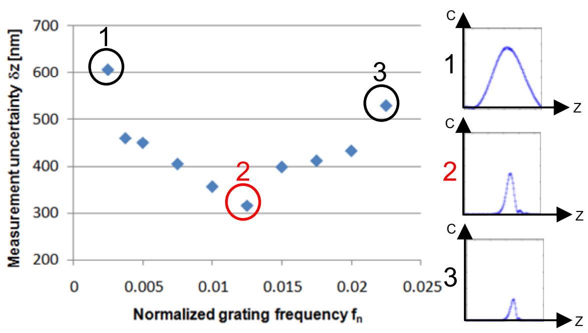

Fig. 2 *Standard deviation δz measured on a planar mirror and the contrast curve of three grating frequencies.*

Additionally, pattern frequency is another important parameter to set and has strong impact on the height uncertainty. While recording of contrast signal, setting higher fringe frequency will lead to narrower curve and simultaneously lower maximal contrast as shown in Fig. 2. If the noise level of the contrast curve and the number of sampling points used for evaluation are constant, the measurement uncertainty will be minimal as the ratio of curve width and maximal contrast is minimal. In practice the exact optimal frequency can be found out experimentally (as marked in Fig. 2).

3 Limits

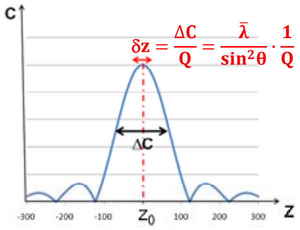

***Fig. 3** Relation between measurement uncertainty and the contrast curve. ΔC: curve width of the optimal grating frequency in an aberration free system.*

At the evaluation of the height data, the statistical height uncertainty δz at the optimal frequency is primarily determined by the contrast noise level and curve width ΔC. The resulting δz can be empirically expressed as the fraction of Rayleigh-DOF ($\bar{\lambda}/\sin^2\theta \cdot 1/Q$)). Since we use the curve width ΔC of the optimal grating frequency in an aberration free system as reference, and in this special case the ΔC is nearly as same as the Rayleigh-DOF (Fig. 3). The empirically introduced Q can present us as a quality factor of the whole system in the practice, how precise we can evaluate the real curve peak in unit of the Rayleigh-DOF.

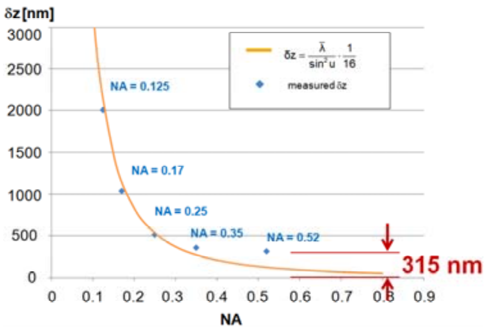

***Fig. 4** Standard deviation of measured height data on a planar mirror at different NAs with 25 camera integrations. Quality factor Q of diverse NAs: 16 (0.125); 16 (0.17); 16 (0.25); 11 (0.35); and 6 (0.52).*

The Fig. 4 shows the best reachable measurement uncertainty measured on a planar mirror respectively at different NAs after removing the photon- and camera noise. Despite the largest spherical aberration, the best δz of 315 nm is achieved at the highest NA. The reason for that is, the bad lateral resolution doesn't enable to project fine sinusoidal grating. Therefore, the curve width of the optimal frequency is mainly determined by NA other than the aberrations.

	micro SIM	macro SIM
NA	0.5	0.5
Q	100	6
ΔC	5.2 µm	110 µm
f_n [0-2]	0.2	0.0125
δz	20nm	315nm

***Tab. 1** Comparison between micro SIM and macro SIM at the same contrast noise level and same number of sampling points used for evaluation.*

The comparison in Tab. 1 between the two systems shows us, the δz in macro SIM is as 17 times worse as in micro SIM. As the quality factor Q implies, the height can only be evaluated with a height uncertainty of 1/6th of the Rayleigh-DOF. The fundamental cause for lower Q is the smaller optimal grating frequency due to the large amount of aberrations. That leads to a dramatically wide curve. The possible solution to improve the depth resolution is to buy better objectives with both good lateral resolution and big field. Thereby there will be potential to improve δz down to 20 nm.

4 Result and summary

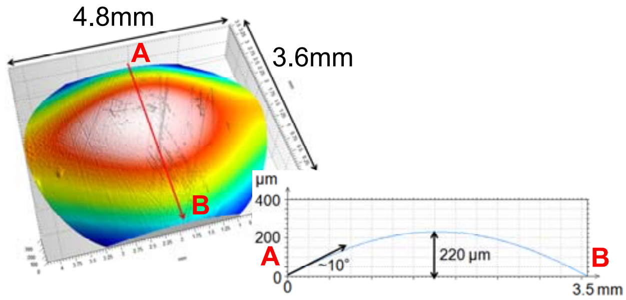

***Fig. 5** Measurement of a plastic freeform lens.*

By applying three high aperture photo objectives and a self-illuminating OLED display, we have built a Structured-Illumination macroscope, at which the measurement field is increased to 4.8 x 3.6 mm^2. A submicron measurement uncertainty on specular surface is possible in the first implemented setup, even using strong aberrated photo objectives. Thanks to the high NA of 0.5, specular surfaces with a maximal slope of ±20° can be measured. For further improvement, using better objectives will minimize the measurement uncertainty. Theoretically δz of 20nm is reachable.

References

[1] C. Kranitzky, C. Richter, C. Faber, M. C. Knauer, and G. Häusler: „3D-microscopy with large depth of field“ Proc. DGaO, p. A12 (2009).

[2] M. A. A. Neil, R. Juskaitis, and T. Wilson, „Method of obtaining optical sectioning by using structured light in a conventional microscpe,“ Opt. Lett. 22, 1905-1907 (1997)