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Polarization dependency of the 3D transfer behavior in microsphere enhanced interferometry

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Abstract. Enhancing the lateral resolution limit in optical microscopy and interferometry is of great interest in recent research. In order to laterally resolve structures including feature dimensions below the resolution limit, microspheres applied in the optical near-field of the specimen are shown to locally improve the resolution of the imaging system. Experimental and simulated results following this approach obtained by a high NA Linnik interferometer are analyzed in this contribution. For further understanding of the transfer characteristics, measured interference data are compared with FEM (finite element method) based simulations with respect to the polarization dependency of the relevant image information.

1 Introduction

With the ongoing trend towards miniaturization overcoming Abbe's diffraction limit in optical metrology is of particular interest regarding research and industrial applications. Microsphere assistance as a near-field support is investigated as a technique to realize topographical interferometric [1–3] as well as microscopic [4–6] measurements of structures below the resolution limit. Photonic nanojets are mentioned frequently to be the decisive mechanism [7–9]. Also the role of evanescent waves and whispering gallery modes [10, 11] is discussed. It is also found that the polarization of the light source has an influence on the resolution capabilities using microspheres [6].

In this contribution the effects of the polarization of the illumination are examined with respect to interference microscopy. Thus, measured as well as rigorously simulated data sets are compared with respect to the polarization. Results are analyzed in the 3D spatial frequency domain in order to find out the transfer characteristics.

Experimental results are obtained by a high NA Linnik interferometer (100 x, NA = 0.9). The measurement process follows the principle of coherence scanning interferometry (CSI) and is described in further detail in [1]. Köhler illumination with an LED (royalblue, central wavelength: 440 nm) is used. A schematic representation of the experimental setup is shown in Fig. 1.

2 Analysis of the results in the 3D spatial frequency domain

The transfer characteristics of an interferometer can be obtained from the 3D spatial frequency domain representation [12, 13], which enables a profound understanding of the 3D measurement process. This method is applied to microsphere assisted interferometry to gain further insight into the mechanisms underlying the lateral resolution enhancement. Furthermore, Pahl et al. [14] developed a rigorous CSI simulation model based on FEM calculations of the electric field distribution close to the specimen and Fourier optics modeling of the imaging process. This model considers the conical 3D illumination in a microscope and has been extended by a microcylinder to approximate microsphere assisted interferometry.

For further analysis the data is transferred to the 3D spatial frequency domain also called $\mathbf{q}=\mathbf{k_s}-\mathbf{k_{in}}$ – space, with the incident wave vector $\mathbf{k_{in}}$ and the scattered wave vector $\mathbf{k_s}$. The resulting 3D spatial frequency distribution is limited by the Ewald-limiting-sphere which is shown

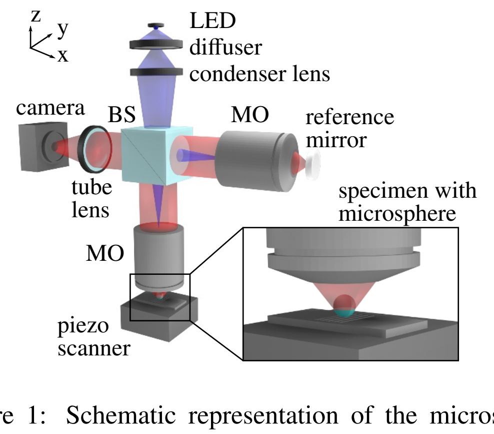

Figure 1: Schematic representation of the microsphere assisted Linnik interferometer containing two high NA microscope objectives (MO) and a beam splitter (BS). The illumination (blue) and imaging (red) beam paths are shown.

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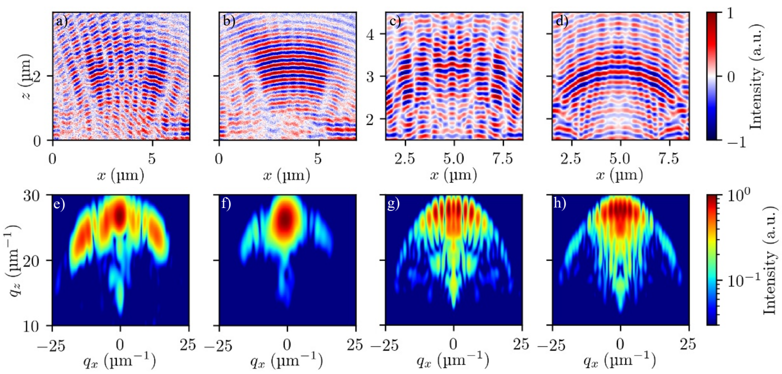

Figure 2: Interferometric measurement data obtained from a rectangular grating (SiMETRICS RS-N, Λ = 300 nm) using royalblue a) TM and b) TE polarized light through a microsphere (SiO_2, approx. 7 µm diam.), simulated data sets of a similar grating with c) TM and d) TE polarized light assuming a microcylinder of 5 µm diameter. The corresponding 3D spatial frequency representations are depicted in e) – h).

in further detail in [13]. Thus, the diffraction orders $q_{x,n} = \frac{2\pi n}{\Lambda}$ for a grating of period length Λ in x-direction appear as distinct vertical lines within the Ewald-limiting-sphere.

Figures 2a) – d) show measured and simulated interferometric data sets for a rectangular silicon grating (RS-N, SiMETRICS) with Λ = 300 nm and a nominal height of 140 nm. This phase grating evokes a phase modulation of the interference fringes along the x-axis, which is centered around the virtual image plane of the microsphere [1].

Comparing the different polarization configurations it can be observed that for TM polarized light the phase modulation induced by the grating is much stronger in both, measurement and simulation results. Besides, a qualitative correspondence of measured and simulated results can be seen. Therefore, the simulation approach in principle reproduces the transfer characteristics of microsphere assisted interferometry.

In Fig. 2e) – h) the 3D spatial frequency domain representations in the $q_x q_z$-plane of the different data sets are depicted. The diffraction orders for the measured data stacks are located at $q_x \approx \pm 15$ µm^{-1} (considering the additional magnification through the microsphere). Instead of distinct vertical lines the diffraction maxima appear blurred. This effect can be explained with the limited field of view while imaging through a microsphere. In Fourier optics the field of view corresponds to the area of integration for the Fourier integral leading to a convolution with an Airy-disc pattern in the Fourier domain leading to the blurring of the diffraction orders.

Comparing the frequency representations for the TM and TE case, the intensity maxima related to first order diffraction are lower for the TE case, which is in agreement with the weaker phase modulation visible in Fig. 2b). In comparison with the simulated results in the 3D spatial frequency domain, some effects occur differently. The magnification introduced by the microcylinder is higher (compare the extension in x-direction of the phase modulation in Fig. 2a) and c)), leading to slightly different positions of the diffraction orders. Furthermore, due to the use of a 2D microcylinder instead of a sphere in the simulation further effects appear [15]. Also slight differences in the diameter of the utilized microspheres influence the results.

3 Conclusion

Analyzing the polarization dependency of microsphere enhanced interferometry, TM orientation polarization should be preferred to obtain the relevant phase information of 2D topographies, which are shift invariant in y-direction. This is in agreement to previous results obtained for grating structures using an interference microscope without microsphere assistance and could be confirmed by rigorous simulations based on an FEM model [14].

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