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Modeling microcylinder-assisted conventional, interference and confocal microscopy

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Abstract. We present how to develop virtual microcylinder- or microsphere-assisted surface topography measurement instruments. As the most critical part, the interaction between light, microcylinder and measurement object is considered based on the finite element method (FEM). Results are obtained for microcylinder-assisted conventional, interference, and confocal microscopes without necessity to repeat the time-consuming FEM simulations for each sensor.

1 Introduction

As a promising technique to overcome the fundamental lateral resolution limit of a given microscope, microsphere and -cylinder-assisted microscopy (MAM) has grown to an intensively studied optical far-field measurement technique [1–3]. However, the physical mechanisms leading to resolution enhancement (for a detailed overview see e.g. [4]) and the extend of the improvement itself are still part of numerous debates. In addition, various configurations of MAM operating in transmission or reflection mode [1] as well as in combination with interference [5] or confocal microscopy [3] are examined and results generalized exciting further debates (see e.g. [6–8]). In order to shed light into this discussion, numerical models of the full measurement process including illumination, scattering and detection are developed.

In previous publications, we reproduced measurement results obtained by interference [9] and confocal microscopy [10] implementing an FEM-based simulation model. In more recent studies, the simulation model has been extended to microcylinder-assisted interference [11] and conventional [12] microscopy in order to analyze resolution enhancement. The results show that the achieved resolution improvement and corresponding mechanisms strongly depend on the measurement configuration. This observation probably explains different outcomes published in literature leading to the above mentioned debates. Further, we demonstrated that conventional, confocal and interference microscopes can be simply modeled based on the same theory with only slight adaptions to the respective measurement technique [13]. Based on these studies, we give a short introduction on how to develop virtual microcylinder-assisted microscopy techniques with focus on surface topography measurement.

2 Model

Since all of the required modeling aspects are documented in detail, but spread over several previous publications, we do not give equations here, but rather compile the relevant literature. Figure 1 sketches the considered measurement setups, where conventional and interference microscopy differ in the reference arm marked by the green rectangle in Fig. 1(a). It should be noted that we focus on microcylinders due to significantly less computational requirements compared to microspheres.

The interaction between light and the sample with microcylinder placed on is simulated using an FEM model generally described in [9], where no microcylinder is considered. The extension to a scattering geometry including microcylinder is shown elsewhere [11]. In [13] we explain how to model all of the three considered microscope setups using the same theory approximating the light surface interaction by Kirchhoff's diffraction theory. Here, we use exactly the same instrument modeling, simply exchanging the scattered field computation by FEM.

3 Results

For demonstration, simulations are performed for a microcylinder of radius $r = 3.5\,\mu\text{m}$ and refractive index $n = 1.4663$ placed on a rectangular silicon grating ($n_{\text{Si}} = 22.932 + 1.0731\text{i}$) of period length $l_x = 300\,\text{nm}$ and step height $h_0 = 140\,\text{nm}$, where the arrangement of microcylinder and grating is assumed to be periodic with period length $L_x = 13.2\,\mu\text{m}$. The illumination wavelength $\lambda = 440\,\text{nm}$ is considered to be monochromatic and the numerical aperture (NA) of the microscope objective lens is 0.9. Figure 2 shows cross-sections of image stacks obtained for conventional (2(a,b)), interference (2(c,d)) and confocal (2(e,f)) microscopy for TE as well as TM polarization. Note that more information on definition of the

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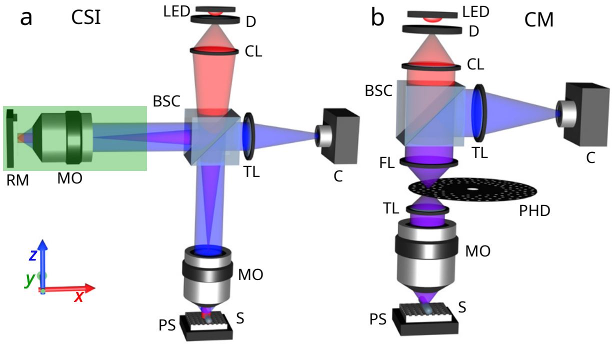

Figure 1. Schematic representation of microcylinder-assisted conventional, interference (a) and confocal microscopes (b). The area marked by the green rectangle corresponds to the reference arm, which is apparent in case of an interference microscope and replaced by an absorber for conventional microscopy. The illumination beam path is sketched in red, the imaging beam path in blue. D, diffuser; CL, condenser lens; RM, reference mirror; MO, microscope objective; BSC, beam splitter cube; FL, field lens; TL, tube lens; C, camera; PS, piezo stage; S, sample including microcylinder; and PHD, pinhole disk.

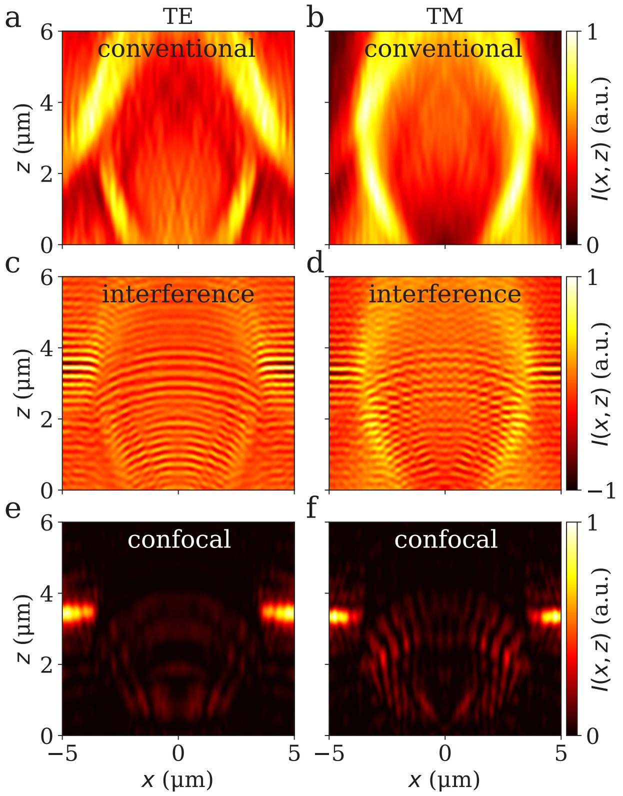

Figure 2. Image stacks simulated for conventional (a,b), interference (offset-reduced) (c,d) and confocal (e,f) microscopy assuming either TE (a,c,e) or TM (b,d,f) polarized light. The microcylinder extends from $x = -3.5$ µm to $x = 3.5$ µm.

polarization are provided in a previous publication [9]. In agreement with previous observations [12], the influence of the grating appears more significant for TM polarization in the area of the cylinder. Especially for interference and confocal microscopy with TM polarization (Figs. 2(d,f)), the grating can be recognized in the phase (interference) and contrast (confocal) of the image stacks. It should be noted that the grating considered as a measurement object more or less corresponds to a phase grating and hence only a weak influence on conventional microscope images is to be expected. For results of amplitude gratings we refer to [12]. In addition, it should be mentioned that the considered grating can be resolved by the measurement instruments without microcylinder as well due to the high NA. However, the grating corresponds to the smallest texture of the RS-N standard from Simetrics often considered in investigations and therefore used for demonstration here.

4 Conclusion

We introduce a method to simulate measurement results obtained by microcylinder-assisted conventional, interference and confocal microscopy as the most common optical profiling techniques. In future studies, simulations will be performed for these instruments to study resolution enhancement capabilities using e.g. approaches presented in literature [11, 12, 14] in order to elucidate the potential of MAM.

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