

Capabilities and limitations of paraxial operator approach for modeling of nano-scale feature evaluation

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ABSTRACT

The interaction of light with nano-scale features is usually associated with rigorous vector modeling or other computation intensive method. It turns out, however, that several interesting cases can be analyzed by a model based on scalar, paraxial operators. Good correspondence was found between this theoretical model and experimental investigation. In our work, the capabilities of scalar, paraxial operator approach are discussed for the cases of Dark beam and Gaussian beam scanning microscopes. Fundamental limitations of the approach are outlined as well. The sensitivity of the Dark beam scanning microscope was compared for the real experimental procedure and the idealized theoretical model which indicated a potential of 1nm sensitivity.

Keywords: Dark beam, nano-scale, microscopy, modeling

1. INTRODUCTION

Progress in high-tech production, such as optical components, flat panel displays and semiconductor industry places increasingly stringent requirements on surface quality. As a result, there is a constantly growing demand for high-sensitivity and high-speed inspection systems operating in the production lines. Since traditional methods do not provide an adequate answer to industrial needs, other, more sophisticated methods were developed. Among these methods, Dark Beam (DB) microscopy was proposed¹⁻³ and preliminary investigations indicated high performance capabilities.

In Ref. 4 we have analyzed a generalized version of DB microscopy, Singular Beam (SB) microscopy, both experimentally and by numerical simulations, demonstrating nanoscale sensitivity. The simulations were carried out with the help of operator representation⁵ within the regime of paraxial optics approximation. The purpose of this paper is to discuss those simulations and estimate their validity for analyzing systems designed to investigate nanoscale features.

Choosing a particular method of analysis usually involves a tradeoff between the allowed errors and availability of computational resources and processing time. In this paper we demonstrate that the scalar paraxial approximation produces reasonably accurate results for optical systems with numerical apertures (NA) up to 0.4. The next section provides a general background on the SB microscopy and this is followed in Sect. 3 with a discussion of the DB microscopy as a particular case of the SB microscopy. Section 4 compares scalar, paraxial results with experiments and with rigorous vector calculations to estimate the introduced errors. Section 5 evaluates the implications of inaccuracies on the sensitivity of the microscopy approach. Finally, the conclusions are drawn in section 6.

2. SINGULAR BEAM MICROSCOPY

The main idea of SB microscopy can be outlined as follows. The space, containing the investigated object is scanned by a focused beam containing singularities. Light scattered by the object propagates in free space and/or through optical elements to a recording system where it is analyzed to evaluate required object features. Since SB microscopy does not deal with direct optical imaging, the classical diffraction limit is mitigated and system performance is constrained only by the Signal to Noise Ratio (SNR) of the measured data.

2.1 Singular beams and their generation

Optical singularities and their properties are subject for extensive study.⁶⁻¹⁰ A wide variety of optical singularities exists. These can be optical vortices, other kind of phase singularities or polarization singularities.¹¹⁻¹⁷ Our main interest here is in beams containing one or more phase singularities that generate spatial regions where the complex amplitude vanishes.