Phase correction in low coherence diffraction phase microscopy using the optical transfer function

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ABSTRACT

In this work, we experimentally determine the transfer function of our recently reported epi-illumination white light diffraction phase microscopy (epi-wDPM) system. The transfer function identifies how the low frequencies below k_0NA_{con} are modified due to the limited spatial coherence and how the high frequencies above k_0NA_{obj} are affected due to the limited objective numerical aperture. Using this transfer function, we perform deconvolution to remove the halo and obtain proper quantitative phase measurements without the need for excessive spatial filtering. The wDPM and epi-wDPM systems are now capable of obtaining halo-free images with proper topography at much higher speeds.

Keywords: diffraction phase microscopy, interferometric microscopy, quantitative phase imaging, optical inspection, coherence, optical transfer function, halo effect, halo removal.

1. INTRODUCTION

Over the past decade, quantitative phase imaging (QPI) has become a popular non-invasive imaging technique and has found applications in a plethora of fields including biology, neuroscience, photonics, nanotechnology, and even studies on image formation and coherence [1-3]. This class of techniques utilizes the phase of the imaging field, rather than its amplitude, in order to create nanoscale maps of a sample's surface. The structure of the specimen under investigation creates minute shifts in the phase front of the imaging field, which are in turn measured through interference and converted to relative changes in height.

Diffraction phase microscopy, or DPM, is a particular QPI method in which a compact Mach-Zehnder interferometer made up of a 4f lens system, diffraction grating, pinhole filter, and CCD is used to create the modulation [4-6]. The carrier frequency is created by the period of a diffraction grating, which is used to create multiple copies of the image at various angles. The first lens creates a Fourier transform. At the Fourier plane, the 0 and +1 order are kept, the +1 order is filtered down to DC using a small pinhole filter, and the two beams are then transformed again using the second lens and interfered at the CCD to create a spatially modulated signal where the phase information is readily available.

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2. COHERENCE ISSUES

A conventional light microscope even with the condenser aperture closed down to its minimum value does not provide sufficient spatial coherence for common-path QPI techniques to obtain quantitatively accurate phase images of all structures [7, 8]. While biological samples (which are optical thin, transparent, weakly scattering, and smooth) typical image well despite a small halo; materials science samples with larger area features and sharp edges tend to become problematic.

3. IMAGE FORMATION AND HALO EFFECT

Recently, our group developed a model for the image formation process in DPM based both on experimental measurements and theoretical derivations [7, 8]. This model uses an analytical closed-form expression which represents the image formation in common-path QPI as the true phase image minus a low-pass filtered version of itself. Therefore, the well-known halo effect [9] is a high-pass filtering phenomenon which makes the low spatial frequency content of the sample's structure unobtainable. The degree of high-pass filtering is dependent on two things: (1) the spatial coherence of the source which is represented by the mutual intensity function and (2) the filtering of the reference beam which should produce a uniform reference field at the CCD. If these two conditions are met, the technique will provide quantitatively accurate halo-free images with sub-nanometer height accuracy [7].

Unfortunately, excessive spatial filtering in both the condenser aperture plane and the DPM pinhole plane are required to meet these two conditions. This of course results in low-light conditions. In transmission mode where the sample are typically transparent and >90% of the incident light is recorded by the CCD, this is typically acceptable. In fact, simply increasing the gain of the camera has shown to be sufficient. In reflection mode however, at least for semiconductor samples, where only about 30% of the incident light is reflected, these low-light conditions result much longer exposure times, sometimes greater than 1 second [6, 7].

4. TRANSFER FUNCTION, SIMULATIONS, AND HALO REMOVAL

Based on experimental measurements of the illumination pattern at the condenser aperture (Gaussian distribution) as well as the effects of the microscope objective (circular aperture), the optical transfer function (OTF) was formed with low frequencies missing below k_0NA_{con} due to the limited spatial coherence and high frequencies above k_0NA_{obj} due to the limited numerical aperture of the objective. The OTF is shown in Fig. 1(a).

Simulations of the DPM image formation process were conducted based on both the previously derived analytical equation as well as the OTF approach. Results from the new transfer function approach are shown in Fig. 1. Figure 1(b-d) show the ideal square pillar image, the simulated image using the OTF approach which shows halo and phase reductions, and the deconvolved image respectively. Figure 1(e) then shows a comparison between an experimentally measured pillar, the simulation, and the ground truth (obtained via Alpha Step). The cross-sections show excellent agreement.

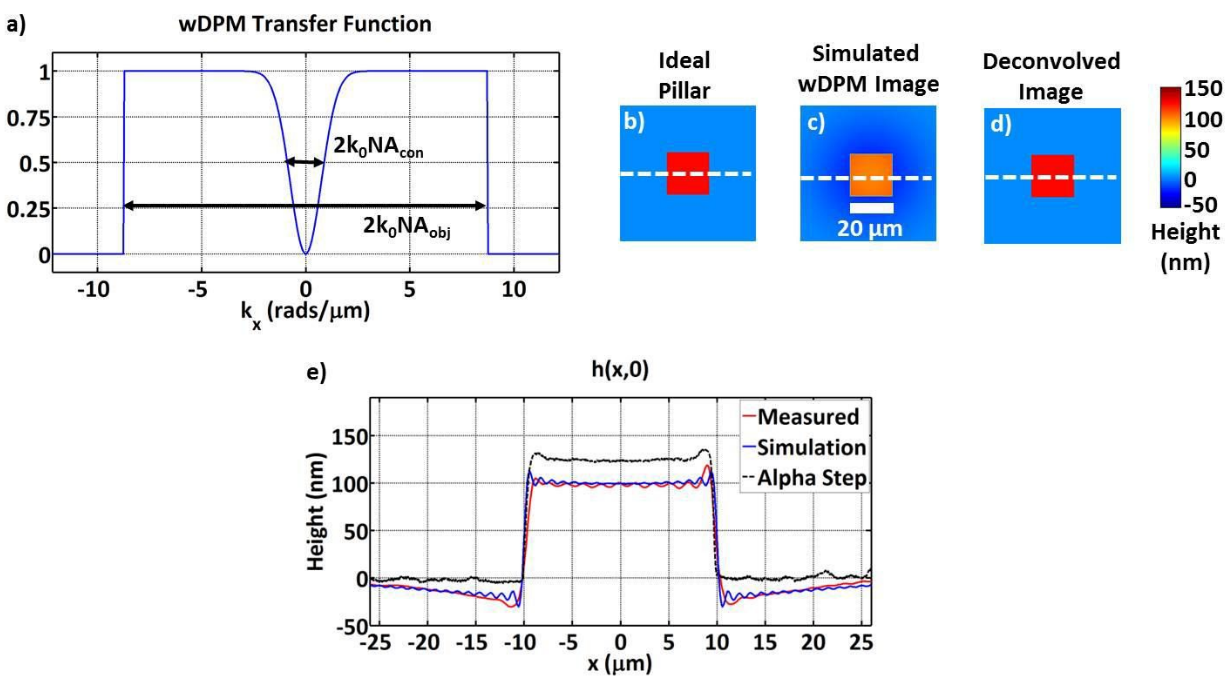

Figure 1: Simulation of DPM image formation using the optical transfer function.

Figure 2(a) shows a comparison of the simulated cross-sections using the previously verified analytical model and the new OTF approach. Figure 2(b) then shows a comparison of the two approaches for different width micropillars where the recorded height is simulated at various numerical apertures. Note that the spatial coherence decreases and the NA_{con} increases, resulting in reduced phase and halos. Also, larger width structures require a large degree of spatial coherence. Overall, the simplified transfer function approach seems to provide almost identical results.

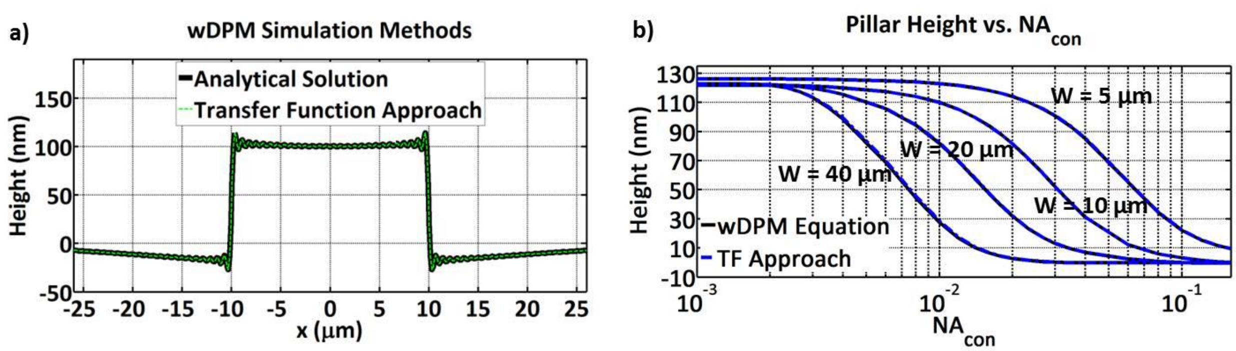

Figure 2: Comparison of new OTF approach with recently developed analytical equation.

Figure 3(a) contains an actual micropillar image obtained via wDPM with insufficient spatial coherence (NA_{con} = 0.0072). Deconvolution was then performed using a Weiner filter with the OTF. The results are shown in Fig. 3(b) and a comparison of the cross-sections is shown in Fig. 3(c). For this case, the halo was completely removed and the correct topography was obtained. Work is currently being done to develop a more rigorous and robust method capable of removing the halo on a wider range of images. However, these initial results are very promising.

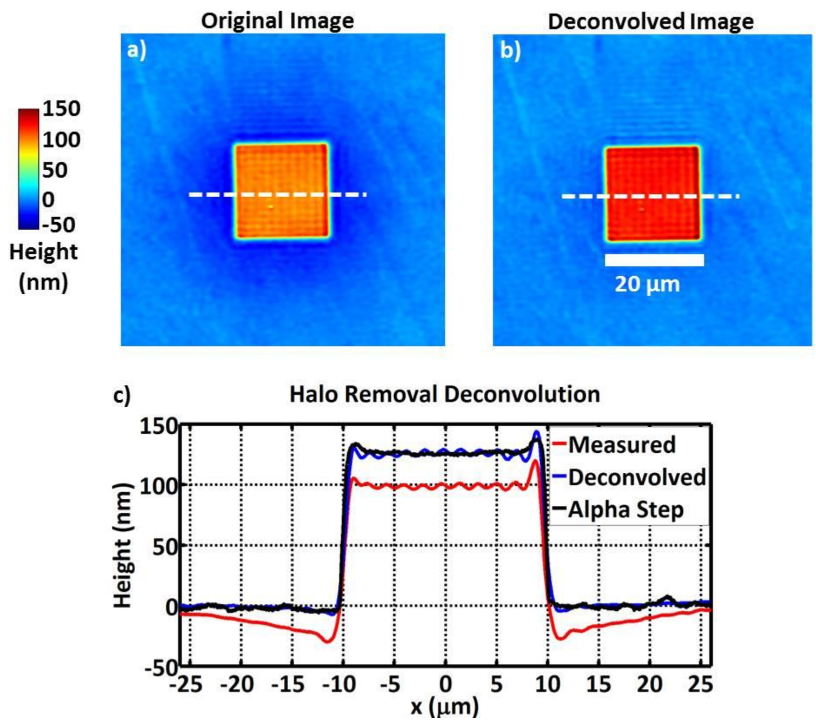

Figure 3: Halo removal using deconvolution with the OTF.

5. CONCLUSIONS

We introduced a new model for image formation in diffraction phase microscopy based on the optical transfer function. This approach is simpler than using the analytical equation and provides nearly identical results in simulation. The transfer function was used successfully to remove the halo from experimentally measured micropillar control structures. This approach will allow the wDPM and epi-wDPM systems to obtain halo-free images with proper topography without the need for excessive spatial filtering.

6. ACKNOWLEDGMENTS

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