Transport of intensity imaging applied to quantitative optical phase tomography

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Abstract: A bulk phase object is imaged tomographically and reconstructed using transport of intensity principles. The resulting object reconstruction shows good agreement with the actual object.

OCIS codes: 110.6955, 100.5070, 100.3190

1. Introduction

Phase contrast microscopy is the traditional method for qualitative imaging of weak phase objects (those with indices of refraction close to that of their surrounding media). If quantitative results are desired, as is often true in the case of cell imaging within the fields of pathology and cell biology, then interferometric systems coupled with the use of phase unwrapping algorithms are usually employed to quantify the amplitude and phase of the field observed at a detector plane. If the complete three-dimensional (3D) structure of the phase object is desired, then the data is acquired tomographically and inversion algorithms are used to reconstruct the three-dimensional complex index distribution of the object.

Unfortunately, interferometric measurement systems are often bulky, expensive, and sensitive to small perturbations. Furthermore, phase unwrapping requires sophisticated post-processing that is generally unstable with noise, introducing reconstruction artifacts. Intensity-based phase retrieval techniques, in which both the amplitude and phase of a field are retrieved from defocused intensity measurements, offer an experimentally simple solution to determining phase quantitatively without the use of phase unwrapping algorithms.

Recently, it has been shown that transport of intensity can be used to image optical fibers (cylindrically symmetric) immersed in index-matching fluid [1]. In this paper, we apply transport of intensity principles to tomographically image and reconstruct an asymmetric bulk phase object (12 mm thick) in 3D. Our imaging system, which is capable of retrieving the complex index distribution of a phase object without use of interferometry, has wide applicability in fields such as underwater imaging, cell biology, pathology, and even x-ray imaging (e.g., for security or medicine). An added benefit is that our system is experimentally simple to set up and can be easily adapted to fit imaging geometries of conventional brightfield microscopy with minimal modifications.

2. Theory

Intensity-based methods of phase retrieval are based upon the principle of conservation of energy of a propagating wavefield. While one cannot determine phase from a single intensity measurement, the wave equation specifies uniquely how intensity will propagate through a homogenous medium (provided that there are no optical vortices present) [2,3]. If the propagation of the wavefront is paraxial, then the Transport of Intensity Equation (TIE) [3,4] provides a simple relationship between the derivative of the intensity in the direction of propagation and the lateral gradient of intensity (perpendicular to direction of propagation):

$$\frac{2\pi}{\lambda}\frac{\partial}{\partial z}I = -\nabla_{\perp}\cdot I\nabla_{\perp}\phi \qquad (1)$$

Where I is the intensity measured in a plane perpendicular to the axis of propagation, z, and the $\perp$ subscripts indicate the gradient operator acts in a plane perpendicular to the optical axis. λ is the spectrally-weighted mean wavelength of illumination, and ϕ is the phase. Equation 1 allows direct recovery of phase information and is valid in many practical cases for partially coherent illumination [5,6].

If the intensity upon the focal plane is approximated as constant, then Equation 1 reduces to a 2D Poisson Equation [5,7]

$$\frac{2\pi}{\lambda}\frac{\partial}{\partial z}I = -\nabla_{\perp}^{2}\phi \qquad (2)$$

and can be solved using an FFT-based Fast Poisson Solver or via iterative algorithms. If the intensity is not constant, then a substitution can be made and the Poisson Equation can be solved twice to retrieve both amplitude and phase [3,8].

If this process is repeated in a tomographic fashion (i.e., at multiple projection angles about the object), then the object's complex index distribution can reconstructed by following basic principles of tomography [9,10]. For our tomographic setup, we chose to rotate the object inside the imaging system rather than the system about the object for reasons of experimental simplicity.

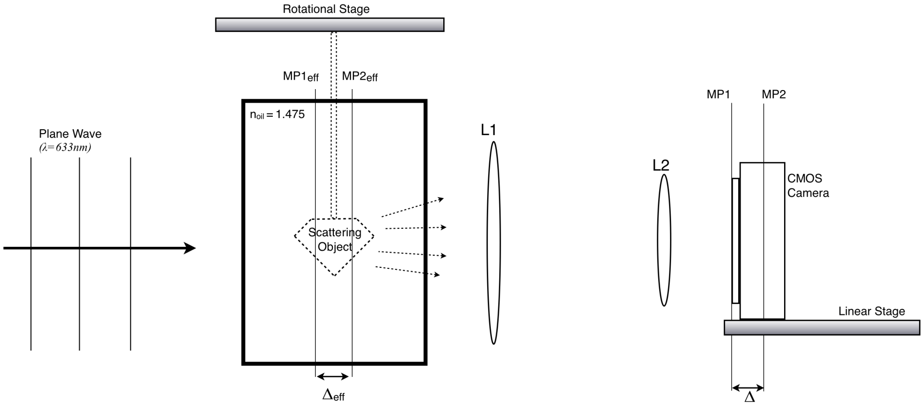

Fig. 1. Experimental Setup. An incident plane wave passes through a weakly scattering phase object (index-matched to surrounding medium), and images at various focal planes are collected on a CMOS camera. The camera is defocused by a moving it along a linear stage by a distance Δ, (resulting in defocus of the imaging plane by $\Delta_{\text{effective}}$), and an image is acquired at each location. The object is rotated between each pair of image captures for tomographic acquisition.

3. Experiment and Results

A transparent object (Pyrex diamond) was placed in index-matching fluid and imaged using the system in Fig. 1. The object was illuminated with a collimated plane wave from a 632.8nm HeNe laser. Intensity measurements were taken from 90 independent and equally spaced angles through a total of 180° of rotation (Fig. 2). The object was rotated by 2° between each set of image captures. At each angle, three images were taken: one corresponding to the in-focus image of the object, one corresponding to an over-focused image of the object via movement of the linear stage by +10µm, and one corresponding to under-focused images of the object obtained from movement of the linear stage by -10µm. These images were used to reconstruct maps of phase depth for each projection angle (Figure 3). The resultant phase maps were then used in a filtered backpropagation algorithm and volumetrically rendered for verification (no attempt was made to account for diffraction). The results show good agreement with the features and dimensions of imaged object.

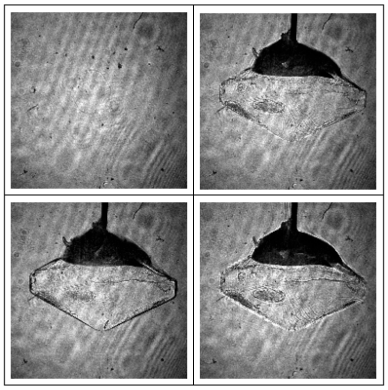

Figure 3. Sample images clockwise from top-left: background, in-focus, overfocused, and underfocused diamond. Background subtraction was applied via pixel-wise division by the background image before processing.

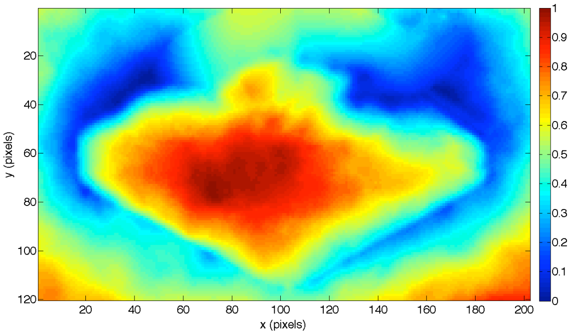

Figure 4. Phase map generated from transport of intensity-based phase retrieval (normalized for display). Areas of higher intensity denote greater phase delay (estimated to linearly correlate with the depth of the object).

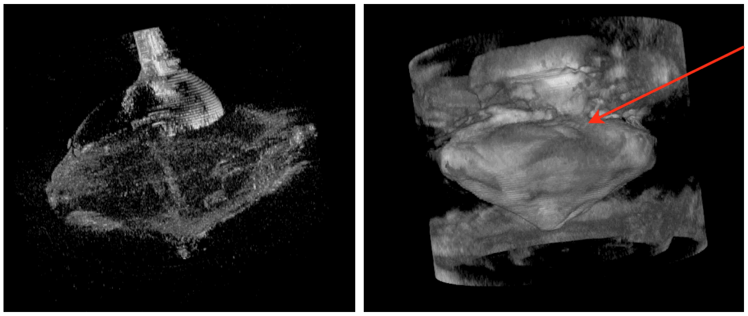

Figure 5. Volumetric reconstruction of the phase object. (Left) Reconstruction from amplitude information alone (without use of the TIE). (Right) Reconstruction results from transport of intensity-retrieved phase. The reconstruction results were found to agree with actual dimensions of the diamond to within 0.1mm. Additionally, the number of edges and ridges (red arrow) present in the diamond reconstruction is in agreement with the actual number of edges/ridges on the diamond.

4. References

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