Wavelength-Multiplexed Single-Shot Ptychography

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Abstract: We present multi-wavelength single-shot ptychography, a technique which is ideally suited for imaging dynamically evolving plasmas. Through improvements to single-shot ptychography and a novel probe constraint, wavelength-multiplexed single-shot ptychography was developed and experimentally realized. © 2020 The Author(s)

1. Introduction

Understanding fundamental properties of dynamically evolving plasmas is important for modelling plasma formation in techniques such as laser induced breakdown spectroscopy (LIBS). Current day plasma imaging techniques, such as Schlieren imaging and dual wavelength interferometry, however, are either not quantitative in nature, spatially resolved, or require an external reference and relatively weak plasma. In this paper, we introduce a novel computational imaging technique that is capable of probing the fundamental properties of dynamically evolving plasmas. The technique is built off of an advanced form of coherent diffractive imaging called ptychography. In ptychography, a sample is scanned with a laser beam across partially overlapped regions and the diffraction pattern intensities are collected on a camera. Sophisticated phase retrieval algorithms process the collected data and reconstruct the phase and amplitude for both the probe (laser beam) and object [1]. Scanning the object takes time and thus cannot be used for imaging non-reproducible transient phenomena outside of stroboscopic geometries. Ptychography can be performed in a single-shot through a setup such as the one shown in Figure 1 below. Single-shot ptychography (SSP) is performed by breaking up the laser beam into smaller beamlets with a diffractive optical element (DOE) [2]. The DOE is imaged to a detector with a two lens 4-f imaging system, where the beamlets cross at the focal plane of the first lens. By placing the object some distance away from the crossover point, the beamlets diffract through the object at partially overlapped regions. The diffraction patterns are then collected on the detector and thus the same data used in scanning ptychography is taken in a single shot. In order to probe the properties of dynamically evolving, partially-ionized plasmas, we want to distinguish the different density distributions of the neutral gas and the free electrons. This can be accomplished using SSP simultaneously with multiple wavelength probes, exploiting the strongly different dispersion of the two components. To do this, information multiplexed ptychography must be implemented in a single shot [3]. We have developed and experimentally verified this method.

2. Improvements to Single-Shot Ptychography

Through a number of modifications, we improve the robustness of the SSP method to expand it towards a wavelength-multiplexed approach. The first improvement was designing and implementing a DOE that maximizes the overlap uniformness of the probes on the object. In standard ptychography, scanning the probe across the object in a Fermat spiral pattern accomplishes this goal and has been shown to increase the fidelity of the reconstruction [4]. In designing our DOE, we took this into account and created a pattern of pinholes arranged in a Fermat spiral. The second

Figure 1 Top shows a schematic of a single-shot ptychography setup. Bottom shows a diagram of the same setup. This setup was also used in multi-wavelength single-shot ptychography.
improvement was optimization of the detector segmentation process for isolating diffraction patterns. Since all information on the detector is useful, we would like to chop out diffraction patterns such that all the space on the detector is most efficiently utilized. The optimal way of doing this is through a Voronoi tessellation where cells are created such that as much information as possible is used. Finally, we found that it is vital to know the offset distance between the beamlet crossing plane and the object. With our optical set up, the reconstructions were less reliable when this offset was not known to within 100um.

3. Multi-Wavelength Single-Shot Ptychography

In multi-wavelength single-shot ptychography, SSP is performed simultaneously with probes of different wavelength. A phase-retrieval algorithm deconvolves an image of both the probe and object for each wavelength. While this has been done for scanning ptychography, it has not been done in a single-shot configuration. We found that given the SSP setup shown in Figure 1 above, a novel probe constraint can be utilized to improve the reliability of wavelength-multiplexed SSP. Due to the fact that both the object space pixel size and the width of the probe are proportional to the wavelength, in pixel space the spatial profile of every different wavelength probes must be the same. The reliability of multi-wavelength SSP was enabled by exploiting the fact that different wavelengths must have the same probe structure in pixel units.

![Figure 2](image_url)

Figure 2 shows the setup and results from experimentally performed multi-wavelength single-shot ptychography. By illuminating a birefringent object with both a red and green laser beam that were orthogonally polarized and placing an analyzing polarizer after the object, an image of the non-birefringent sample was given by the red wavelength probe while an image of the birefringent sample was given by the green wavelength probe. Images a) and b) show the individual wavelength reconstructions and images c) and d) show the simultaneously illuminated wavelength reconstructions. Comparing images a) with c) and b) with d), multi-wavelength single-shot ptychography was experimentally realized. Experimental verification of multi-wavelength SSP (Fig. 2) was performed by imaging a micromachined birefringent sample with different wavelength probes that were orthogonally polarized. An analyzing polarizer was placed behind the birefringent object such that one wavelength reconstruction represents the non-birefringent part of the sample, while the other wavelength represents the birefringent part of the sample. Data was then collected for each wavelength individually illuminating the object and then, simultaneously illuminating the sample. The data from the individual wavelengths were then fed into a single-wavelength SSP reconstruction algorithm, while the simultaneously illuminated data was fed into the multi-wavelength SSP reconstruction algorithm with the novel probe constraint. As shown in Figure 2, the reconstructions of the object from the single-wavelength and multi-wavelength data compare favorably, verifying that the multi-wavelength SSP technique works. This novel imaging method is now ready to investigate fundamental properties of dynamically evolving refractive index profiles such as plasmas.

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References:

1. A. M. Maiden and J. M. Rodenburg, "An improved ptychographical phase retrieval algorithm for diffractive imaging," Ultramicroscopy 109, 1256–1262 (2009).  
2. P. Sidorenko and O. Cohen, "Single-shot ptychography," Optica 3, 9 (2016).  
3. D. Batye, D. Claus, J. Rodenburg, "Information Multiplexing in Ptychography," Ultramicroscopy 138, 13-21 (2014).  
4. Xiaojing Huang, Hanfei Yan, Ross Harder, Yeukuang Hwu, Ian K. Robinson, and Yong S. Chu, "Optimization of overlap uniformness for ptychography," Opt. Express 22, 12634-12644 (2014)