Single-shot quantitative phase imaging facilitated by a bifunctional metasurface

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Abstract

A bifunctional metasurface was fabricated to facilitate quantitative phase imaging. The silicon-based metasurface is made of elliptical nanopillars and acts as a polarization splitter allowing for the recording of two images, where one is shifted from the other. The two images were then used in an iterative calculation to retrieve the phase information of technical samples like lenses.

1. Introduction

Current image detectors are sensitive only to the intensity of an incoming light. As such, while the phase contains more crucial information about the optical path of the incident light before reaching the detector, the phase cannot be readily detected. Information about optical path, in turn, can be related to structural or morphological components of biological or technical samples. Quantitative phase imaging (QPI) aims to recover the phase from available intensity recordings by numerical calculation using multiple images of the sample as constraints [1]. One such calculation is based on the transport-of-intensity equation (TIE), which relates the phase of the field to the intensity variation along the propagation direction. In actuality, TIE-based QPI is implemented by recording a focused and a defocused image of the sample by detector displacement. Single-shot TIE refers to the simultaneous recording of the two images without the need to mechanically displace the camera, allowing for the QPI of dynamic events.

In this work, we present a bifunctional metasurface to facilitate single-shot TIE [2]. Metasurfaces are composed of subwavelength unit components that can control different properties of light including its wavefront [3]. Dielectric metasurfaces are particularly interesting due to the possibility to achieve multifunctionality while maintaining sufficient device efficiency. By introducing structural anisotropy to the unit components, the properties of multiple polarization components of the incident beam can be modulated simultaneously and independently. We exploit this interesting property in fabricating a bifunctional metasurface that splits the two orthogonal polarization components of a beam and creates two images of the sample, where one is shifted from the other, for use in phase calculation via TIE. We demonstrate the effectiveness of the metasurface in the QPI of technical samples.

2. Metasurface design and fabrication

2.1. Optical system

The QPI system consists of a $4f$ optical setup, where the sample is placed at the front-focal plane of the first lens or the input of the $4f$ and illuminated by a 45°-plane polarized light. The Fourier components are then modulated by the metasurface placed at the back-focal plane of the first lens. Here, the transmitted beam is angularly split into the TE and TM-polarized components by the metasurface, and the TM component gains an additional propagation phase shift also introduced by the metasurface. After Fourier transformation by the second lens, the output of the $4f$ setup consists of two laterally separated images, one of which is axially shifted, of the sample. To achieve such a function, the following polarization-dependent phase profiles are introduced by the metasurface:

$$\phi_{\mathrm{TE}}(\eta,\nu) = \frac{2\pi}{\lambda}\eta\tan\theta \tag{1}$$

$$\begin{aligned}\phi_{\mathrm{TM}}(\eta,\nu) = &-\frac{2\pi}{\lambda}\eta\tan\theta \\ &+\frac{2\pi}{\lambda}\Delta z\sqrt{1-\frac{1}{f^2}\left(\eta^2+\nu^2\right)}\end{aligned} \tag{2}$$

where θ is the magnitude of the angular displacement introduced by the metasurface, Δz is the axial defocus of the TM relative to the TE component, λ is the illumination wavelength, f is the focal length of the lenses in the and (η,ν) are the spatial coordinates in the Fourier plane.

2.2. Metasurface design and fabrication

The bifunctional metasurface is designed for an operating wavelength $\lambda = 850$ nm and is composed of elliptical nanopillars made of amorphous silicon ($n_{\mathrm{Si}} = 4.07 + 0.02i$). The height of the nanopillars is $h = 411$ nm and they are arranged in a square lattice with spacing $a = 350$ nm. The structural parameters (i.e. elliptical diameters: D_x and D_y) of the nanopillars necessary to introduce certain combinations of phase shifts for both polarizations were first determined. This was done by FDTD calculations of

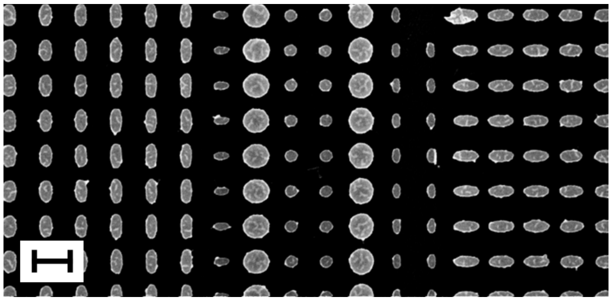

Figure 1: Scanning electron micrograph of the bifunctional metasurface based on elliptical nanopillars made of amorphous silicon. Scale bar: 400 nm.

periodically arranged uniform pillars, sweeping the diameters from 70-270 nm. The phase profiles in Eqns. 1 and 2 are then discretized by setting $\eta = ma$ and $\nu = na$, where m, n are the grid elements. In each grid, the phase value is converted to the optimal diameters of the nanopillar.

The metasurface is fabricated by first depositing amorphous silicon on a fused silica substrate by low power chemical vapor deposition. The patterning is then implemented using electron-beam lithography, followed by dry etch based on the Bosch process. For the complete details, interested readers are referred to the supplementary information of [2]. Figure 1 shows a scanning electron micrograph of the fabricated metasurface.

3. Results and Discussion

The overall transmission efficiency of the fabricated metasurface was found to be 68% and 65% for the TE- and TM-polarized incident beams, respectively, for $\lambda = 850$ nm. From k-space measurements, the angular deflections were verified to be as designed $\theta_{\mathrm{TE/TM,meas}} = 0.071$ rad, corresponding to a lateral separation of $d = 7.0$ mm between the centers of the two beams.

After the single-shot recording of the two laterally diplaced images, numerical post-processing was implemented to crop and center the two intensities. These were then used in an iterative calculation of the TIE [4], which is given by

$$-k\frac{\partial I(x,y)}{\partial z} = \nabla_{\perp} \cdot [I(x,y)\nabla_{\perp}\varphi(x,y)] \tag{3}$$

where φ is the phase information to be recovered, $k = 2\pi/\lambda$, $\nabla_{\perp}$ is the gradient operator over the x and y coordinates and $\frac{\partial I}{\partial z}$ is the axial intensity gradient that is estimated by the finite difference of the two intensity recordings: $\frac{\partial I}{\partial z} = \frac{I_{\mathrm{TM}} - I_{\mathrm{TE}}}{\Delta z}$. The axial displacement was $\Delta z = 5$ mm.

The metasurface-based single-shot TIE is demonstrated in the QPI of a convex lens, $f = 250$ mm. Figure 2 (a) shows the analytic phase profile of such a technical sample. The phase map in Figure 2 obtained from our proposed technique show similarity with the analytic phase. We benchmarked our proposed technique with two other similar and established techniques: conventional TIE (C-TIE) and multiple-plane phase retrieval (MPPR). Qualitative comparisons show correspondence between our metasurface-based technique, and C-TIE and MPPR. Quantitatively, the root-mean-squared errors (RMSE) between the experimental reconstructions and the analytic were calculated as $\mathrm{RMSE}_{\mathrm{MS-TIE}} = 0.7804$, $\mathrm{RMSE}_{\mathrm{C-TIE}} = 0.6632$ and $\mathrm{RMSE}_{\mathrm{MPPR}} = 0.7772$. These comparisons demonstrate the viability of the metasurface-based TIE as an alternative for QPI.

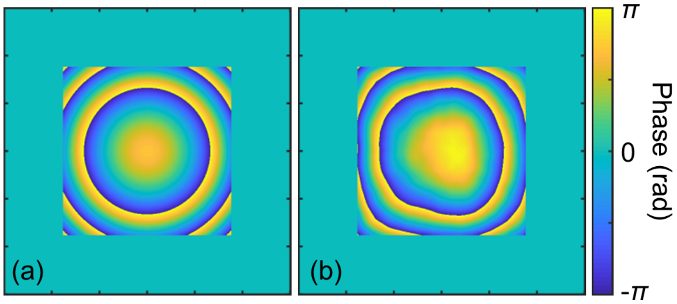

Figure 2: (a) Analytic phase profile of a convex lens, $f = 250$ mm. (b) Reconstructed phase profile from the metasurface-based single-shot TIE.

4. Conclusions

In conclusion, we proposed a compact optical configuration for single-shot quantitative phase imaging. The system is based on a 4f optical setup integrated with a bifunctional dielectric metasurface at the Fourier plane. We demonstrated the effectiveness of our proposed technique in the wavefront reconstruction of technical samples. This represents a first important step towards rapid quantitative phase imaging of dynamic samples.

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