Vector wavefront imaging using transport-of-intensity equation with a polarization camera

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ABSTRACT

Polarization and phase imaging is an important technique for characterizing material structures and molecular orientations. In this paper, we present a vector wavefront imaging technique based on the transport-of-intensity equation (TIE) combined with a polarization camera. In this method, the intensity distributions of different polarization components are acquired, and then the TIE is applied to calculate the complex amplitude of each orthogonal polarization component independently. The relative phase retardation between them is also estimated to determine the spatial distribution of the vector optical field. Experimental results are shown to demonstrate the effectiveness of the method.

Keywords: Transport-of-intensity equation, polarization imaging, vector wave, phase imaging, multimodal imaging

1. INTRODUCTION

The polarization state and phase distribution of an optical filed provides useful information for characterizing the optical and structural properties of materials, including biological tissues. It is thus important to develop multimodal techniques for measuring the polarization and phase. Polarization imaging [1] enables us to evaluate properties such as anisotropy and birefringence by analyzing changes in the state of polarization resulting from interactions with a sample. In polarization imaging, the Stokes or Muller matrix representation is generally used to express relative intensity ratios and phase retardation, which are related to the state of polarization. However, to obtain the spatial phase distribution of each polarization component, another measurement method should be combined. Although interferometry-based techniques, including holography, are useful in phase measurement, these techniques often require complicated system configurations and are susceptible to environmental perturbations. In addition, the maximum amount of phase to be measured is basically limited owing to phase wrapping, and it is difficult to simultaneously handle phase distributions across various states of polarization. For this reason, it is expected to develop a method to measure the spatial distribution of phase that exceeds 2π and polarization states simultaneously. In this study, we investigate a framework of multimodal imaging for complex amplitude and polarization. In this method, the spatial distributions of the amplitudes and phases for independent polarization components are measured by applying the TIE to the polarization images captured using a polarization camera, and the vector wavefront is reconstructed based on the relative phase difference between the orthogonal polarization. We show the concept of the method and some experimental results to demonstrate the effectiveness of the method.

2. METHOD

Figure 1 shows an overview of our method. The intensity distributions of linear polarization components in four directions are simultaneously acquired using a polarization camera (Fig. 1(a)). In addition, similar measurements are performed at positions $\pm\Delta z$ shifted in the optical axis direction. By applying the TIE to these intensity distributions, the phase distribution of each polarization component is calculated (Fig. 1(b)). Since these phase distributions are calculated independently, the phase retardation $\Delta\phi$ between each polarization is meaningless. A measurement using a quarter retarder is thus introduced to obtain a reference phase retardation $\Delta\phi_{ref}$ (Fig. 1(c)). This reference phase retardation is helpful to determine the real phase retardation $\Delta\phi'$ between the phase distributions previously obtained using the TIE for each polarization (Fig. 1(d)). Based on the spatial distributions of the intensity, phase, and phase retardation between each polarization, the vector wavefront can be reconstructed.

The electric field vector of a light wave at (x, y) on the plane perpendicular to the propagation direction can be expressed as Eq. (1).

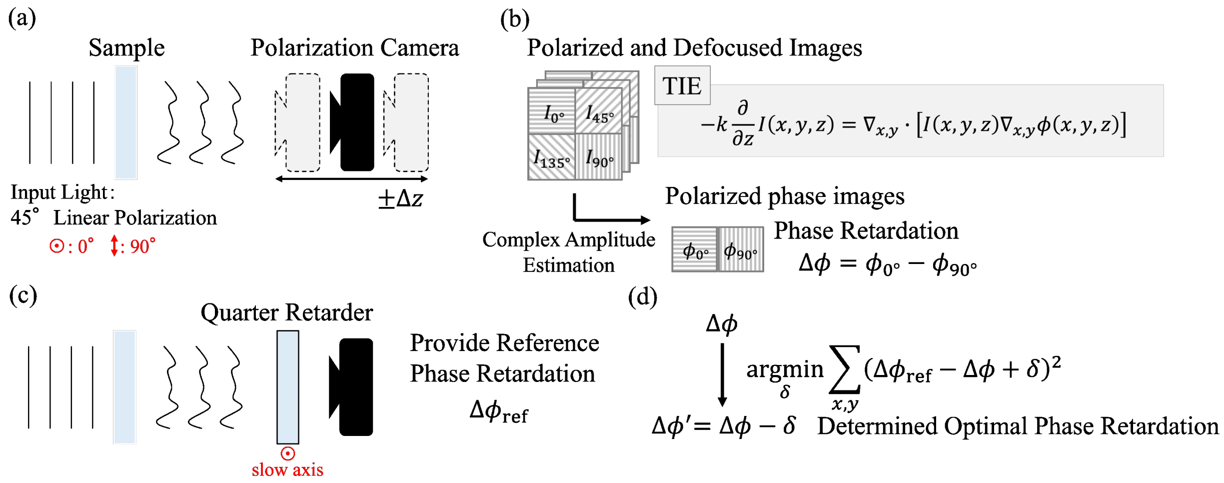

Figure 1. The overview of the multimodal imaging method. (a) Intensity distribution acquisition. (b) Phase retrieval by TIE. (c) Intensity acquisition with quarter retarder. (d) Estimation of phase retardation.

$$\mathbb{E}(x,y) = \begin{pmatrix} E_{0°}(x,y) \\ E_{90°}(x,y) \end{pmatrix} = \begin{pmatrix} \sqrt{I_{0°}(x,y)}\exp[-i\phi_{0°}(x,y)] \\ \sqrt{I_{90°}(x,y)}\exp[-i\phi_{90°}(x,y)] \end{pmatrix}, \tag{1}$$

where I and ϕ are the intensity and phase of the light wave, respectively, and the subscripts denote the polarization direction. 0° and 90° correspond to x and y directions, respectively. The state of polarization of the light wave is determined by the phase retardation $\Delta\phi = \phi_{0°} - \phi_{90°}$ between the two orthogonal axes. The TIE is a non-interferometric phase retrieval method that reconstructs the phase distribution of a light wave from the longitudinal variation of the intensity distribution. The phase is calculated by solving differential equations expressed in the following form:

$$-k\frac{\partial}{\partial z}I(x,y,z) = \nabla_{x,y} \cdot [I(x,y,z)\nabla_{x,y}\phi(x,y,z)], \tag{2}$$

where $\nabla_{x,y}$ is the transverse gradient operator. The intensity derivative $\frac{\partial I}{\partial z}$ is approximately calculated using the classical two-plane finite-difference method in Eq. (3).

$$\frac{\partial}{\partial z}I(x,y,z) = \frac{I(x,y,z+\delta z) - I(x,y,z-\delta z)}{2\delta z}. \tag{3}$$

As a solution method for TIE, the universal solution (US TIE) is employed in this study [2]. US TIE is a solver that can accommodate various experimental conditions through an iterative method with a direct measurement of boundary conditions using arbitrarily shaped apertures. We apply the US TIE to the intensity distribution for each polarization and obtain the spatial phase distribution for each polarization component independently.

The reference phase retardation ϕ_{ref} is calculated by:

$$\Delta\phi_{\mathrm{ref}} = \arctan\left(\frac{-2I'_{45°} + (I_{0°} + I_{90°})}{2I_{45°} - (I_{0°} + I_{90°})}\right), \tag{4}$$

where $I'_{45°}$represents the intensity for 45° linear polarization measured by inserting a quarter retarder whose slow axis is along the 0° direction. The reference phase retardation is determined as $\Delta\phi' = \Delta\phi - \delta$, where δ is obtained by:

$$\delta = \operatorname*{argmin}_{\delta} \sum_{x,y} (\Delta\phi_{\mathrm{ref}} - \Delta\phi + \delta)^2. \tag{5}$$

3. EXPERIMENTS

To demonstrate the effectiveness of the method, we designed and constructed the experimental system shown in Fig. 2. An optical wave from the He-Ne laser source is incident on a sample, and the vector wavefront just after the sample is measured. A linear polarizer is put at 45° before the sample, so that the intensities of the horizontal and vertical components of the illumination light is the same. The light passing through the sample was imaged using lenses L1 and L2 on a polarization camera (LUCID TRI050S1-PQ). The magnification of the imaging system is $f2/f1 = 2/3$. The defocused images required for the TIE were acquired by moving the polarization camera back and forward ±3cm using a motorized stage. The sample used consists of a lens (focal length: 400 mm) and quarter retarder plates. The ideal state of polarization just after the sample is 45° and 135° linear polarization in the left and right regions, and leftward circular polarization in the center region, as shown in the bottom right of Fig. 2.

The phase distribution for each polarization was obtained by applying the TIE to the intensity distribution of each polarization acquired by the polarization camera. The phase distributions corresponding to 0° and 90° are shown in Fig. 3(a). The obtained phase distributions are consistent with the phase modulation of the light by the sample. Fig. 3(b) shows the reference phase retardation distribution obtained by measurement using a quarter retarder (upper) and the determined phase retardation distribution for the result of the TIE (lower). From the phase retardation distribution and the intensity distribution of each polarization component, the distribution of the polarization state shown in Fig. 3(c) was obtained. The polarization state is represented as an ellipse, and its shape and direction are visualized at each position. The result approximately agrees with the ideal polarization distribution estimated from the sample. In the left and right regions of the sample, linear polarization is dominant, but a small circular polarization component was detected. Also, some errors in the polarization state are observed in the lower part of the central region. These errors probably arise from a little inaccuracy in the phase retrieval in the TIE.

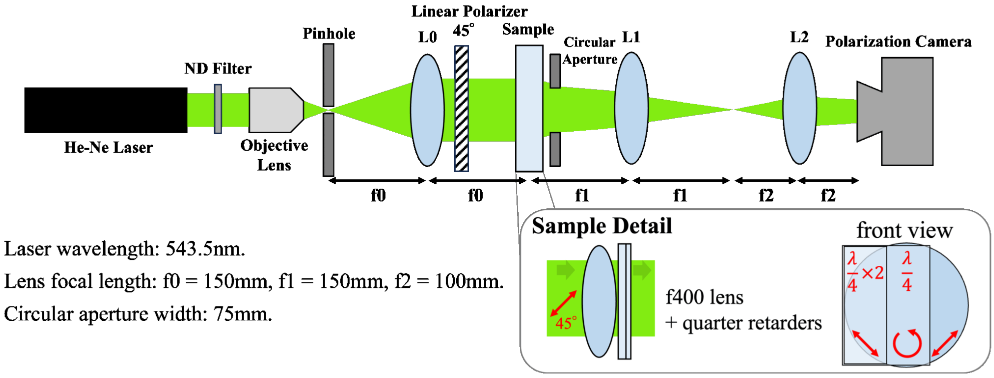

Figure 2. Experimental setup.

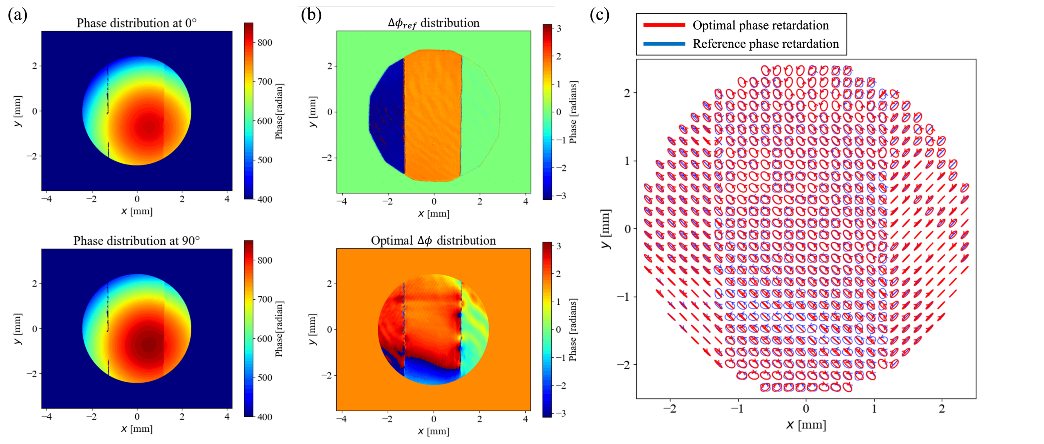

Figure 3. (a) Phase distribution for each polarization. (b) Reference and determined phase retardation. (c) Measurement result of vector optical field.

4. CONCLUSIONS

We presented a vector wavefront imaging technique that combines a polarization camera with the TIE for simultaneous measurement of different polarization components. The experimentally measured phase and polarization state distributions showed good agreement with the expected ones. The method will enable us to achieve multimodal imaging of phase and polarization state and it should be useful in investigation on material and/or biological samples.

Acknowledgements

This work was supported by JSPS KAKENHI Grant Number JP20H05886.

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