Functional Comparison of Scalar and Vectorial Vortex Filtering for All-directional Edge-enhanced Microscopy

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Recently, a $4f$ system containing a vortex filter has been used to perform all-directional edge enhancement of phase-amplitude object (PAO) such as complex biological specimens[1]. The vortex filters are generally classified into two types, the scalar vortex filtering (SVF) and vectorial vortex filtering (VVF). SVF generates spiral phase $e^{i\theta}$ with azimuthal angle θ on beam cross section and VVF generates opposite directional spiral phase $e^{\pm i\theta}$ depending on direction of input circular polarization[2]. The edge-enhanced image of the biological specimens containing both phase object (PO) and amplitude object (AO) can be observed using SVF and VVF. However, few detailed studies have compared the functional differences between SVF and VVF experimentally. In this report, we will show that VVF has a significant advantage over SVF because of its potential to provide a separate and distinct edge for PO and AO in PAO while SVF contains interference on the edges of PO and AO in PAO. The general VVF output intensity is approximately given by spatial derivative of the PAO distribution $I_{\mathrm{VVF}}(\boldsymbol{r}_\perp) \approx |\boldsymbol{\nabla}_\perp f_{\mathrm{in}}(\boldsymbol{r}_\perp)|^2$, where $f_{\mathrm{in}}(\boldsymbol{r}_\perp)$ is complex amplitude distribution of PAO with $\boldsymbol{r}_\perp = (x, y)$ on beam cross section. Assuming PAO as $f_{\mathrm{in}}(\boldsymbol{r}_\perp) = A(\boldsymbol{r}_\perp)\mathrm{Exp}[\mathrm{i}B(\boldsymbol{r}_\perp)]$ with the amplitude function $A(\boldsymbol{r}_\perp)$ and the phase function $B(\boldsymbol{r}_\perp)$, the output intensity of PAO via VVF will be

$$I_{\mathrm{VVF}}(\boldsymbol{r}_\perp) = |\boldsymbol{\nabla}A(\boldsymbol{r}_\perp)|^2 + |A(\boldsymbol{r}_\perp)\boldsymbol{\nabla}B(\boldsymbol{r}_\perp)|^2, \tag{1}$$

which has distinct AO and PO edges. In the case of SVF, however, the output intensity consists of the same term with VVF and the interference term which is neither AO edge nor PO edge, and will spoil the AO and PO edges.

As shown in Fig. 1 (a), the experimental setup consists $4f$ system with q-plate (retardance π, and topological charge 1) followed by typical bright field microscopy. The system becomes SVF or VVF when quarter wave plate (QWP) is oriented at 45°or 0°. In order to verify the theoretical calculation, an onion cell containing a cell nucleus (PO) and an oblique cell wall (AO) was used as PAO sample. Figure 1 (b) shows the observation results of onion cells without a q-plate. The cell wall, which is an AO, can be seen without the q-plate, while the edge of the cell nucleus are difficult to see because it's transparent PO. However, from Figs. 1 (c) and (d), both the edges of the cell wall and cell nucleus can be seen after inserting the q-plate. In the portion wrapped with a white dashed square in Fig. 1 (c), the VVF image shows the edge of the cell nucleus as continuously connected circular shape, while the SVF image in Fig. 1 (d) shows discontinued arc shape because of interference between AO and PO edges.

Despite VVF provides distinct edge of AO and PO in PAO, the edges are enhanced equally, making it indistinguishable. Therefore, in our next research, we will carry out a proof-of-principle experiment on the isolation of the PO edge from the AO edge [3].

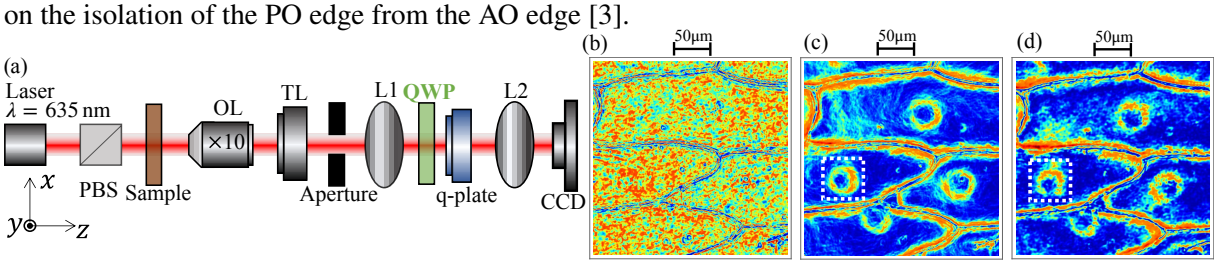

Figure 1: (a) The sketch of the experimental setup, (b) result of onion cell without q-plate, (c) VVF image, and (d) SVF image. PBS is Polarizing Beam Splitter; OL is objective lens; TL is tube lens; L1 and L2 are Fourier lenses; QWP is quarter wave plate; CCD is the charged coupled device camera. $f_{\mathrm{OB,TL,1,2}} = 18, 180, 300, 250$mm, where f_{OB} and f_{TL} are focal lengths of OL and TL. f_1 and f_2 are the focal lengths of L1 and L2.

References

[1] R. Gozali, et al., Rev. Sci. Instrum. **88**, 093701 (2017).
[2] Y. Zhou, et al., Appl. Opt. **56**, 2641 (2017).
[3] J. Zangpo, et al., *CLEO: Science and Innovation*, (Optica Publishing group, 2022), pp. JTh3B-7.