**Vortex beam phases in real space studied by electron holography**

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Recently in electron-microscope studies on vortex beams (VBs), not only generation and control of VBs but also physical properties have been studied as a new electron probe [1]. They utilized intensity profiles of ring-shaped spots and orbital angular momenta of beams in the reciprocal space. Only a few attempts have been carried out to directly measure the phase distribution of the VBs. In the present study, we used electron interferometry in two waves, the first-order diffraction wave and the zeroth-order plane wave, to record phase distributions of VBs as holograms [2]. The principle of this experiment is the same as that of Gabor's original in-line holography.

Figure 1(a) shows an example of vortex beams in the reciprocal plane generated by fork-shaped gratings, zeroth-order centered diffraction spot and first- and second-order diffraction spots, which are all ring-shaped. Figure 1(b) shows over-focused diffraction spots as holograms of the first- and second-order diffraction waves. These interference fringes in vertical stripes at and around the ring-spots are clearly seen. These simple fringes were formed from two-wave interference. For convenience of explanations in the following, the right-side diffraction beams (VBs) are defined as direct waves and left-side diffraction beams (VBs), conjugate waves.

Since these holograms (Fig.1 (b)) are recorded in principle through two-wave interferometry, the conventional reconstruction procedure, i.e., the Fourier transform method, can be utilized. Furthermore, numerical compensation for defocusing distance from the fork-shapes grating to the recorded plane can also be carried out. Figures 2 shows reconstructed amplitude ((a) and (c)) and phase ((b) and (d)) images. The numerical compensation was determined for the conjugate waves in (a) and (b), and compensation for the reversed parameters was also determined for direct waves in (c) and (d) in the same way. The amplitude distribution of the conjugate wave (left-side) in (a) shows a uniform structure and the phase distribution of the conjugate wave in (b) shows a helical and plane structure, indicating the VB in real space. Similar features are shown in Figs. 2(c) and (d), even though numerical calculation parameters are reversed from those of the conjugate waves.

In conclusion, the amplitude and phase distributions of VBs in real space were successfully reconstructed through electron holography. We believe that this method for analyzing VBs, especially for analyzing phase distributions, will be effective in practical applications of VBs.

1. McMorran, B. J. *et al.*, *Phyl. Trans. R. Soc. A* **375** (2017) 20150434.
2. Harada, K. *et al.*, *Microsc. Microanal.* **23** (2017) 588; ibid. **21** (2015) 699; ibid. **20** (2014) 274.

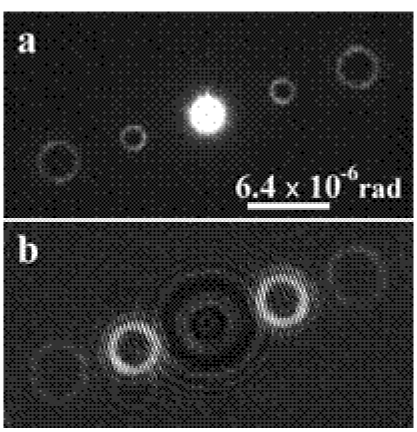


Fig. 1. (a) Vortex beams in diffraction mode, (b) over-focused hologram of the VBs. Left-side VBs are defined as conjugate waves and right-side VBs, direct waves.

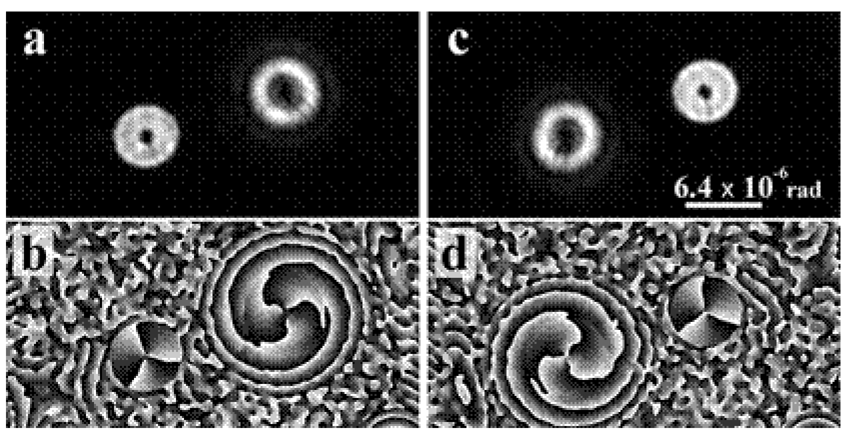


Fig. 2. Reconstructed images of the first-order VBs after compensation of defocus distance; (a) amplitude image of the conjugate VB, (b) phase image of the conjugate VB, (c) amplitude image of the direct VB, and (d) phase image of the direct VB.