Production of electron vortex beams using fork-like gratings and spiral zone plates and their propagating properties

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After the first report of the production of an electron vortex beam using a spiral phase plate by Uchida and Tonomura [1], extensive studies on the production of electron vortex beams and their physical properties have been reported. Verbeeck showed that a grating mask with a fork dislocation generates electron vortex beams and an application of the vortex beams to energy-loss magnetic circular dichroism (EMCD) [2]. The grating mask produced a series of diffracted vortex beams aligned perpendicular to the propagation direction of the electron beam, where the *n*th order diffracted beam has an orbital angular momentum (OAM) *n* times larger than that of the 1st order beam. Another type of the binary mask producing electron vortex beams is a spiral zone plate [3,4]. In the present paper, we present the production of electron vortex beams using both fork-like gratings and spiral zone plates with different topological charges, and discuss the characteristic features of the formation and propagation of the vortex beams.

Fork-like gratings and spiral zone plates are designed by the holographic reconstruction. Figures 1(a), 1(b) and 1(c) show SIM images of masks designed by computer holograms using a vortex plane wave with an OAM of $1\hbar$ and $10\hbar$, and a spherical vortex waves wave with an OAM of $10\hbar$, respectively.

Figures 2(a) and 2(b) show schematic ray-path diagrams of the series of vortex beams, produced by a grating and a zone plate, respectively. A plane wave is illuminated these masks inserted in the condenser lens. The diffracted waves from the grating mask form a series of the plane waves whose wave vectors differ from each other in the transverse direction by the reciprocal lattice vector of the grating. On the other hand, the diffracted waves from the zone plate mask form a series of the spherical waves converging into the different points on the optical axis, or *z*-axis. The 0th order (transmitted) wave is focused by the condenser lens at $z = z_0$, where z_0 corresponds to the focal length of the condenser lens.

Figures 3(a) shows a series of diffracted beams produced by the fork-like grating mask shown in Fig. 1(a). The diffraction pattern shows vortex beams up to the 7th order wave with an OAM of $7\hbar$. The diameter of the 1st order beam is about 1 nm. The diameter of the donut intensity distributions linearly increases as the order *n* increases. Figures 4(a), 4(b), 4(c) and 4(d) show a series of propagating waves produced by the spiral zone plate shown in Fig. 1(b), observed at *z*-positions where the 0th, 1st, 3rd and 9th order waves are focused. The 0th order wave forms a sharp peak focused by the condenser lens. Figure 4(b) show a ring composed of 10 peaks as indicated by the arrow, which is the 1st order wave with an OAM of $10\hbar$. Figure 4(c) show a ring composed of 30 fine peaks whose diameter is 3 times larger than that of the ring of the OAM of $10\hbar$, indicating the 3rd order wave. In the present experiment, we could observe vortex beams up to the 9th order with an OAM of $90\hbar$.

References

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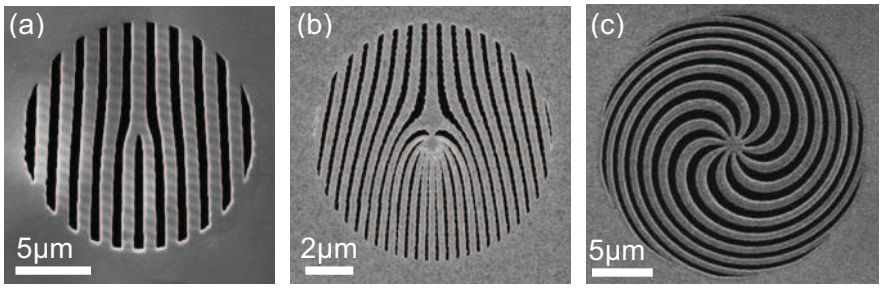

FIG. 1. SIM images of the masks fabricated by an focused-ion-beam instrument. Fork-like gratings with topological charges of 1 (a) and 10 (b), and a spiral zone-plate with a topological charge of 10 (c).

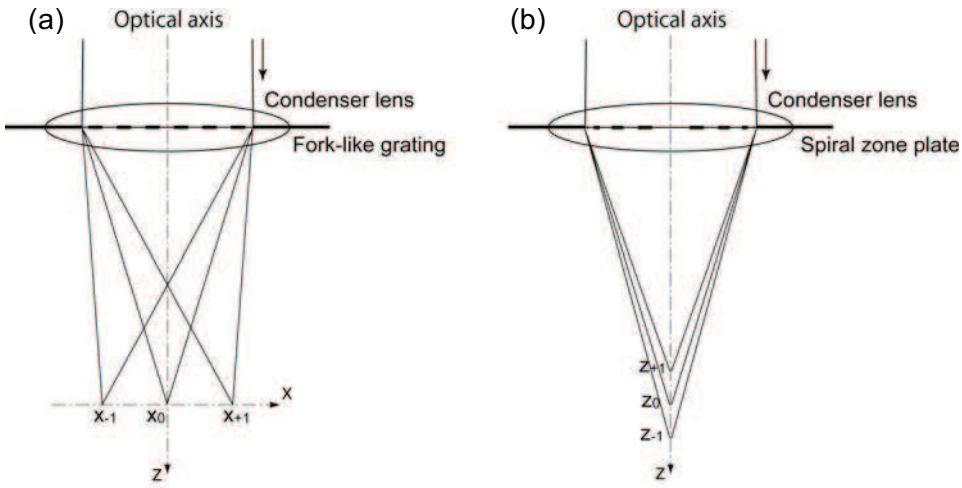

FIG. 2. Schematic raypath diagrams of diffracted waves produced by a fork-like grating (a) and spiral zone plate (b).

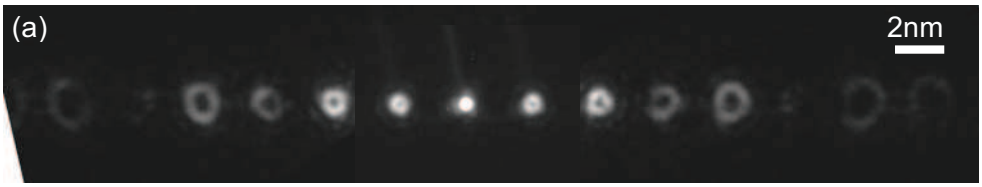

FIG. 3. A series of vortex beams produced by the fork-like grating shown in FIG.1(a).

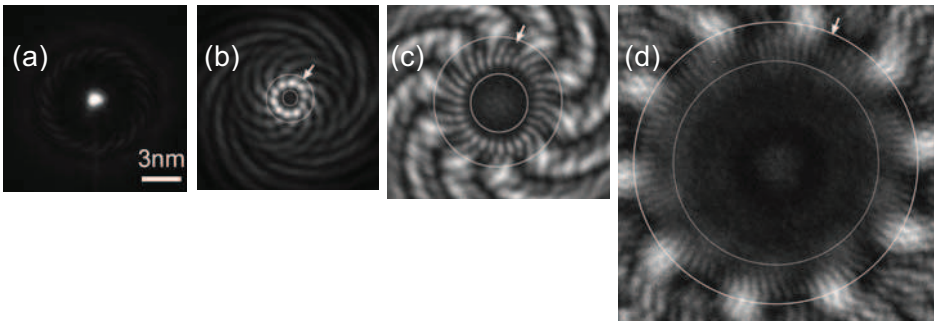

FIG. 4. A series of vortex waves focused at different z-positions, which are produced by the fork-like grating shown in FIG.1(b).