Electron holography for vortex beams

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A combined technology of vortex beam technique and electron holography has been developed. A range about 10 times the diameter of the grating opening was irradiated and two-wave interference between a Bragg diffracted wave as a vortex beam and a transmitted wave from and around a fork-shaped grating was recorded as a hologram. Reconstruction by using the Fourier transform method was simultaneously performed for amplitude and phase distributions. Furthermore, by using a wave aberration function, the amplitude and phase distributions at various propagation positions were reconstructed numerically, resulting in the confirmation of vortex beam twists. © 2020 The Japan Society of Applied Physics

Electron vortex beams are considered to be novel electron probes that can use orbital angular momenta (OAMs) and can provide additional measuring functions and processing technologies for electron beam instruments such as electron microscopes.1–5 Generation methods of vortex beams and various characteristics of vortex beams have been discussed in the following fields: topological charges,6,7 detection of magnetic circular dichroism,8 trials of nanoscale magnetic field detection,9 and application of Bessel beams.10 Furthermore, interactions between vortex beams and materials have been analyzed extensively,11 and physical effects of vortex beams on materials have been studied.12 More recently, OAM sorters have been developed to detect OAMs interacting with specimen materials.13–15 In this way, vortex beams are getting close to practical use. Furthermore, understanding of the physics of vortex beams is being advanced by studies of their characteristics and performance.

Several studies have focused on the physical characteristics of vortex beam twists in reciprocal space.18–23 The existence of vortex beams can be confirmed from the formation of ring-shaped circular spots in the diffraction pattern: they make rotating structures along the rings. Vortex beams show a twisted profile during their propagation in reciprocal space. In these studies, however, the diffraction patterns of vortex beams were observed only in intensity distributions measured under through-focus conditions, and the intensity distributions were rotated. Although a few analyses of the phase distributions of vortex beams have been reported,5,24–26 it has not been clearly shown whether their amplitudes and/or phases are rotating or not during propagation.

In this study, we used electron holography to clarify the rotation properties of vortex beams systematically—for example, the amplitude and phase distributions of vortex beams were reconstructed separately and their propagations were numerically investigated. Very few holography studies in reciprocal space, however, have been performed because of the difficulty of reference waves not existing in reciprocal space in conventional electron holography. Even if we broaden our research target to other fields, only a few examples exist.27,28

In the present study, fork-shaped gratings were employed for generating vortex beams.2,3,21,23 Bragg diffraction waves generated by the grating were used as object waves and a transmitted wave around the grating was used as a reference wave. These waves were superimposed and interfered at displaced positions away from the reciprocal position. This is similar to Gabor’s original treatment for holography.29 Although this optical system does not use conventional electron biprisms for electron interferometers, it can generate two-wave interferograms as holograms. Therefore, this optical system is advantageous in experiments where in-line electron holography techniques cannot be used;30 for example, numerical analyses of vortex beam propagations in space can be realized by using the wave aberration function just as off-axis electron holography can.31,32

Figure 1 shows a schematic diagram of the electron holography optical system for the vortex beam experiment. A fork-shaped grating was irradiated using a convergent incident electron wave and vortex beams were observed and recorded using imaging optical systems not shown in the figure. Electron waves that passed around the fork-shaped grating were used as reference waves. The zeroth-order transmitted wave from and around the grating spread out along the propagation direction and then it was superimposed with the first-order Bragg diffraction waves. Two-wave interference patterns were recorded as holograms above and below the reciprocal plane. This indicates a holography system in reciprocal space in which diffraction waves correspond to object waves and the zeroth-order wave corresponds to a reference wave. In Fig. 1, convergent waves are used to irradiate the grating to form holograms; however, divergent irradiation waves can be used as well to form holograms.

Figure 2(a) shows a transmission electron microscope (TEM) image of the fork-shaped grating with a fifth-order edge dislocation at the center. The grating made of a Si3N4 membrane of 150 nm thickness was fabricated using a focused ion beam instrument (NB-5000). This grating was not an amplitude grating but a phase grating, whose intensity transmittance was about 44%. Figure 2(b) shows a micrograph of the grating at the center and the irradiated area. To superimpose the zeroth-order beam and the vortex beams on both sides of the zeroth-order beam, we irradiated a wide area 50 μm in diameter, 10 times the opening diameter of the grating. Figure 2(c) shows a small-angle electron diffraction (SmAED) pattern33 from the fork-shaped grating.
in Fig. 2(a) at a camera length of about 700 m. The vortex beams generated from the grating were observed with a 300 kV field-emission TEM (HF-3300S).

Figure 3 shows an example of electron interferograms of four vortex beams of the first- and second-order diffraction waves from the fifth-order fork-shaped grating shown in Fig. 2(a). Four ring-shaped circular diffraction waves generated by the vortex beams were interfered with the centered zeroth-order wave and recorded as holograms. Interference fringes inside the ring-shaped circular diffraction spots (see the lower-right inset in Fig. 3) were composed of edge dislocations whose shape was the same as that of the fork-shaped grating.

The upper-left inset in Fig. 3 shows the Fourier transform pattern of the hologram. This is the same as that of the SmAED pattern from the grating [Fig. 2(c)], because it corresponds to the reconstructed intensity in Fourier holography. We confirmed that the four holograms in Fig. 3 can be reconstructed separately by the Fourier transform reconstruction method. The pairs of positive and negative (right-side and left-side) diffraction rings, however, were constructed with the same spatial frequency, because they were recorded through the same relative propagation angles between the object and reference waves. Therefore, the positive and negative first- and second-order waves can be simultaneously reconstructed.

Figure 4 shows the amplitude and phase reconstructed distributions of the first- and second-order diffraction waves from Fig. 3; the amplitude distributions are given in Figs. 4(a) and 4(c), and the phase distributions are given in Figs. 4(b) and 4(d). The phase distributions are colored for better recognition. The phase distributions of the right- and left-side waves had vortex-like structures with the opposite rotation direction, while their phase gradient along the azimuth was the same. This was because the vortex-like structure in the opposite rotational direction depended on the distance from the grating position to the recorded position, while the phase gradient depended on the principle of the “twin image” characteristics of holography.

In electron holography, the defocusing factor \( \Delta f \)—the optical displacement distance from the recorded position to the grating position—can be compensated by the wave aberration function \( \chi(q) \) in the Scherzer equation,

\[
\chi(q) = \frac{2\pi}{\lambda} \left( \frac{1}{4C_s^2q^4} - \frac{1}{2Df^2q^2} \right),
\]

where \( q \) is the spatial frequency, \( \lambda \) is the wavelength of the electron wave, and \( C_s \) is the spherical aberration coefficient.

The present paper discusses only a very low spatial frequency region for SmAED patterns; thus the spherical aberration effect is negligibly small, and only the defocusing factor is taken into account.
account. The wave aberration function $\chi(q)$ is convoluted/deconvoluted during the reconstruction procedure. In this way, we can reconstruct any amplitude or phase distribution using $\Delta f$ as a parameter.

Figure 5 shows compensation examples of the defocusing factors in the first-order diffraction waves. To clarify the phase gradient along the azimuth, a fork grating with third-order edge dislocation was used. Figures 5(a), 5(c) and 5(e) are the amplitude distributions and Figs. 5(b), 5(d) and 5(f) are the phase distributions. Figures 5(c) and 5(d) are the reconstructed amplitude and phase distributions without compensation. In Figs. 5(a) and 5(b), the defocusing factor $\Delta f = -25$ mm under the over-focused condition has compensated the left-side waves. The amplitude distribution changed to a plane wave structure and the phase distribution changed from a vortex-like structure to a fan-like structure. On the other hand, in Figs. 5(e) and 5(f) the defocusing $\Delta f = +25$ mm under the under-focused condition has compensated the right-side waves. Since the core of the helical wavefront of the vortex beam was a singular point of the phase distribution, the amplitude as well as the intensity of the wave tended to zero; however, the phase distribution was well defined even near the core.

To find out whether electron vortex beams as waves are twisted or not during propagation, we used vortex beams with a diamond-shaped opening as in our previous study. Figure 6(a) shows a fifth-order fork-shaped grating surrounded by a diamond-shaped opening and Fig. 6(b) shows its under-focused hologram. The experimental conditions were the same as those in the experiments described above.

Figure 7 shows reconstructed and defocus-controlled images of the amplitude and phase distributions. Figures 7(a), 7(c), 7(e), 7(g), 7(i), 7(k), 7(m), 7(o), and 7(q) are of the amplitude distributions and Figs. 7(b), 7(d), 7(f), 7(h), 7(j), 7(l), 7(n), 7(p), and 7(r) are of the phase distributions at different defocusing factors $\Delta f$ as parameters. The left-side phase distributions are colored in red for better recognition. The difference in propagation distance between two reconstructed waves of the left-side wave and the right-side wave was 48 mm. The reconstruction in Fig. 7 corresponds to measurement from $\Delta f = -96$ mm [right-side distributions of Figs. 7(a) and 7(b)] to $\Delta f = +96$ mm [left-side distributions of Figs. 7(q) and 7(r)]. The red arrowheads in the left-side phase distributions and the white arrowheads in the left-side amplitude distributions indicate the corner positions of the diamond opening of the fork-shaped grating. Both the amplitude and phase distributions were blurred by defocusing; however, for defocusing $-24 \text{ mm} \leq \Delta f \leq +24 \text{ mm}$, the corners of the diamond opening were clearly visible. It is confirmed from these results that electron vortex beams propagate with twists in both distributions due to their wave nature. This result is in accordance with previously reported vortex beam intensity twists.

In conclusion, we have developed a combined technology of electron holography and electron optical technique that can...
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(g) and (h) factor and phase (right-side panels) distributions depending on the defocusing

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were recorded as holograms at displaced positions away from the zeroth-order transmitted wave and Bragg diffraction waves

to control vortex beams. Two-wave interferences between the zeroth-order transmitted wave and Bragg diffraction waves

were recorded as holograms at displaced positions away from the reciprocal plane. Four Bragg diffraction waves of the first- and second-order diffraction waves were simultaneously recorded as holograms. Since the same-ordered holograms had the same spatial frequency in the interference fringes, reconstruction for the amplitude and phase distributions can be simultaneously performed using the Fourier transform method. Furthermore, we succeeded in separately reconstructing the amplitude and phase distributions of propagating electron vortex beams. Consequently, we have confirmed that electron vortex beams propagate while twisting in space.

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Fig. 7. (Color online) Reconstruction series of amplitude (left-side panels) and phase (right-side panels) distributions depending on the defocusing factor Δf: (a) and (b) Δf = −48 mm, (c) and (d) Δf = −36 mm, (e) and (f) Δf = −24 mm corresponding to the infocus condition for the left-side wave, (g) and (h) Δf = −12 mm, (i) and (j) Δf = 0 mm of non-compensated reconstructions, (k) and (l) Δf = +12 mm, (m) and (n) Δf = +24 mm corresponding to the infocus condition for the right-side wave, (o) and (p) Δf = +36 mm, and (q) and (r) Δf = +48 mm. Since two reconstruction waves on both sides had a conjugate relation with a 48 mm propagation distance, the left-side distribution in (e) is the same as the right-side distribution in (m) as indicated by the yellow arrow. Therefore, the total propagation distance from Δf = −96 mm to +96 mm is shown in the series. The white arrowheads in the left-side amplitude distributions and the red arrowheads in the right-side phase distributions indicate the corner position of the diamond opening of the fork-shaped grating.

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