論 文 内 容 の 要 旨

This Ph.D. thesis explores the edge-enhanced microscope of phase-amplitude objects, which is an essential technique in optical information processing that highlights object contours. It finds application in various fields, including image processing, microscopy, biological imaging, fingerprint recognition, and astronomy.

In the field of biological research, the traditional imaging technique is the bright-field microscope, which can observe opaque amplitude objects but yields low-contrast images for transparent phase objects. To address the limitations of the bright-field microscope, microscopist developed phase-contrast microscopes that enable the observation of transparent phase objects but do not enhance the objects' edges. As a more advanced microscope, the differential interference-contrast microscope can enhance the edges of both amplitude and phase objects, which was not possible with previous microscopes. Nevertheless, it still presents a constraint in terms of only one-directional edge enhancement. Recognizing this one-directional limitation, opticians and microscopists redirected their focus to the edge-enhanced microscope in which a vortex filter is used to alter the phase of light, providing all-directional edge enhancement and detailed information about transparent samples, such as biological cells. A vortex filter is placed on the Fourier plane of the 4f system to enhance the edges of objects in all-directions. Generally, the vortex filter is classified into two types: scalar and vectorial vortex filterings. When a spiral phase filter is generated by a spatial light modulator or a vortex phase plate in a 4f system, it exhibits scalar vortex filtering, whereas a q-plate or an s-wave plate, which is a spatially variable half-waveplate placed in a 4f system exhibits vectorial vortex filtering.

Recently, a 4f system containing a q-plate has been used to perform edge detection and enhancement of amplitude or phase objects. However, only a few studies have concentrated on edge enhancement of complex phase-amplitude objects and the details of edges present in phase-amplitude objects have not been analyzed so far. Moreover, despite the previous studies being promising on edge enhancement of the phase-amplitude objects, a detailed analysis of functional differences between scalar and vectorial vortex filterings has not been experimentally conducted so far. Therefore, in the first part of this study, we experimentally verified the functional differences between scalar and vectorial vortex filtering with the q-plate using an

onion cell, which contains the cell wall as amplitude object and cell nucleus as a phase object. The scalar vortex filtering image shows that the intensity of edges of the phase and amplitude objects was either reduced or increased due to their interference, while the vectorial vortex filtering image does not exhibit a change in the intensity of edges of the phase and amplitude objects. The intensity at the reduced edge in scalar vortex filtering image was three times lower compared to that of the vectorial vortex filtering image at the same position.

Our first part of the studies revealed that vectorial vortex filtering offers advantages over scalar vortex filtering and the vectorial vortex filtering successfully enhanced the edges of phase and amplitude objects in the phase-amplitude object. One problem, however, is the indistinguishability of the equally-enhanced edges of the phase and amplitude objects. In biological imaging, isolating phase object edges from an amplitude object is crucial for improving the visualization of phase-amplitude objects. As far as we are concerned, there are no studies on the isolation of edges of the phase object from the edges of the amplitude object. To address this issue, we propose a method to isolate phase object edges from the amplitude object edges using an off-axis vortex filter (q-plate) as our second part of the study. We used vectorial vortex filtering for this purpose because scalar vortex filtering cannot achieve the isolation of phase object edges. Herein, we combined off-axis q-plates with four different displacements to isolate the phase object edge from the amplitude object. To demonstrate the proposed method, we conducted experiments using two distinct samples: the first sample comprised a phase test target surrounded by an aperture and the second sample involved an overlap between the phase test target and a white hair with non-zero transmittance. In the samples, the isolated phase object edge agreed well with the requirements of theoretical expectations and the amplitude object edge was reduced by approximately 93%.

Since the previous work on the edge-enhanced microscope was conducted in the visible wavelength range, there arises a need to extend its applications to the invisible wavelength spectrum (near-infrared imaging), which would be important for near-infrared fluorescence and electronic circuit inspection through silicon semiconductor. However, digital cameras, such as silicon-based charge-coupled devices and complementary metal-oxide-semiconductors, tend to become expensive when operating in the invisible wavelength range. To address this issue, researchers have opted for a more cost-effective approach by utilizing single-pixel detectors with reconstruction of two-dimensional image by correlation calculation. Therefore, the third part of the study is dedicated to the implementation of a single-pixel edge

enhancement, thereby extending the capabilities and applications of our previous work on the edge-enhanced microscope.

Researchers attempted to integrate single-pixel imaging into an edge-enhanced microscope, where Fourier single-pixel imaging was adopted to capture the edges of the phase object using four or three-step phase shifting. While this method successfully detected and enhanced the edges of the phase object, the drawback is that due to the four or three-step phase shifting, resulting in four or three times single-pixel measurements are required for reconstruction. One advantage of their approach is the absence of a vortex filter; instead, they utilized a digital micromirror device to generate a reference wave and a vortex filter with the assistance of a super-pixel technique. Recognizing the need to minimize the number of single-pixel measurements, we propose a method, namely, a single-pixel edge- enhanced microscope via convolutional filtering. We conducted numerical simulations to validate this approach, achieving a 75% reduction in single-pixel measurements compared to previous studies. The simulation results shows that the correlation coefficient of edge enhancement of the object through our proposed method and ideal edge enhancement is 0.89, which indicates that the proposed method is indeed capable of effectively enhancing the edges of objects. We plan to demonstrate our proposed method experimentally using both visible and near-infrared light in the future. First, we will carry out experiments to enhance the edges of the object and then isolate the edges of the phase object from an amplitude object.