X-ray microscope for discriminating spiral orientation of structures inside materials

A number of creatures in our world have spiral structures, such as DNAs and α-helices in proteins in biology, and in modern industrial materials. It is an important scientific theme to clarify an origin of such structures and to conceive elaborate novel devices.

In the present research, the spiral staircase structures inside materials was transferred to form distinguished X-ray vortices by the transmission of X-rays. This new X-ray microscope is useful for discriminating the spiral orientations and for deriving the two-dimensional map of spiral structures inside materials (Fig. 1).

An optical vortex (OV) has a wave front in a spiral form that is smoothly connected to neighboring wave front displaced by integer multiples of wavelength (Fig. 2(a)). This integer number is the winding number, corresponding to the number of phase rotation in unit of 2π, and is proportional to the orbital angular momentum (OAM) around the central axis. Presence of strong novel dichroic effects is predicted to be induced by X-ray beams carrying OAM [2].

Such an optical vortex has a distinct intensity zero at the central spot and is one form of structured light, which has promoted various revolutionary applications in science and technology, especially in the visible wavelength. Structured light is formed by introducing defects in the wave fronts and is analogous to phase defects on other waves observed in physical phenomena over a wide range of length scales, from astrophysics, condensed matter physics to elementary particle physics.

Our novel X-ray microscope uses so-called radial-Hilbert transform (RHT) principle. The RHT is generalization of the Hilbert transform developed for signal processing of complex-valued data, such as calculation of the temporal derivative of radio signals. The RHT microscope visualizes the 2D distribution of the derivative of the "phase and amplitude" of a wave passing through a sample. Using this property, the RHT microscope is known to provide edge-enhanced image of the sample. Our research showed that the RHT microscope, further, has the high sensitivity to phase gradient along both radial and azimuthal angle and can be elaborately used to characterize OV for determining its winding number downstream of objects containing spiral structures.

The verification of our finding was performed at SPring-8 **BL29XU** using 7.71 keV X-rays. Our microscope used the Spiral Fresnel zone plate (SFZP) as the objective lens to modify the wave front downstream of objects and to add vorticity, l times 2π phase shift per one rotation around the optical axis, where l denotes the winding number [1] (Fig. 2(a)). The utilized SFZP is composed of two axially-symmetrical spiral zones with the depth of zones, the outermost zone width and the diameter of SFZP of 1.84 μm, 0.18 μm and 648 μm, respectively (Fig. 2(b)). The depth was chosen to give destructive interference for the two spiral zones for 7.71 keV X-rays. The distance between sample and SFZP and between SFZP and detector were chosen to be around twice the focal length of SFZP, 0.73 m, to satisfy the lens formula.

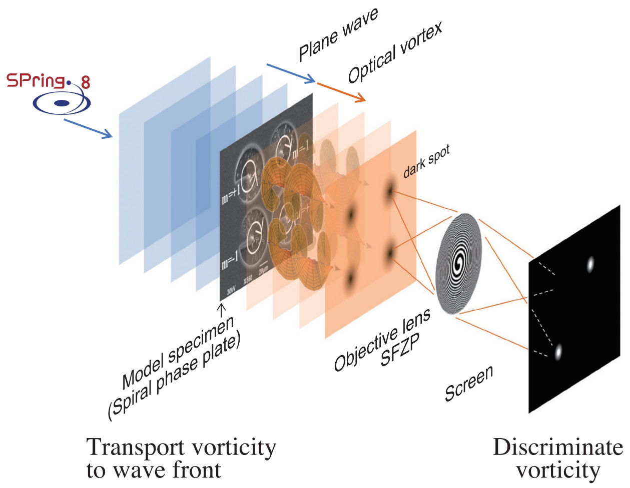

Fig.1. Schematics of the present research. Spiral staircase structure inside model specimen is transferred onto the X-ray wave front and form the distinguished X-ray vortex. Our new X-ray microscope using Spiral Fresnel Zone Plate (SFZP) as the objective lens is used to discriminate the spiral orientations and to derive the two-dimensional map of spiral structures in the model specimen.

We prepared a silicon demonstration specimen which contained multiple spiral phase plates (SPPs) with the thickness decrement in the clockwise and in the anti-clockwise orientations (Fig. 3(a)). The maximum depth of SPPs was set to 19.5 μm corresponding to the phase shift of 2π for 7.71 keV X-rays and the radii of SPPs were set to 34 μm. When X-ray transmitted through this specimen, X-ray vortices with reversed winding numbers, $m = -1$ and +1,were formed on its wave front. To prove our finding that the vorticity of the wave front will vanish when the vorticity given by the specimen and by the SFZP, objective lens, are canceled, we flipped SFZP to reverse the winding number l from $l = -1$ to +1. The observed microscope image manifested bright spots at the center of SPPs only when the winding numbers of OV formed by SPPs, m, and that of the SFZP, l, are canceled for (l, m) = (–1, +1) or (+1, –1), just as our theory predicted (Fig. 3(b) bottom panels). It is also important to note that the RHT microscope enables us to derive the two-dimensional map of spiral structures.

Our result manifested a high sensitivity of X-ray RHT microscope to detect X-ray vortices in the transmitted wave front downstream of spiral structures. We have already confirmed that X-ray vortices are formed by atomic spiral dislocations formed on crystals. X-ray RHT microscope will be a powerful tool for investigating such atomic spiral dislocations in Bragg reflection geometry. This method will be a new alternative to electron microscopes that need mapping of atoms to find such dislocations. Furthermore, our method will play a key role in investigating how the spiral and edge dislocations affect the quality of the functional materials, such as next-generation semiconductor power devices, light-emitting devices and high-rigidity metals. Special note is added here that the measured winding number or OAM is proportional to a quasi-magnetic field. Quasi-magnetic field represents the twist of the phase of the wave function and was the cause of another amazing effect, named the X-ray translation effect inside deformed crystal, which was first theoretically predicted [3] and was verified recently using SPring-8 [4,5].

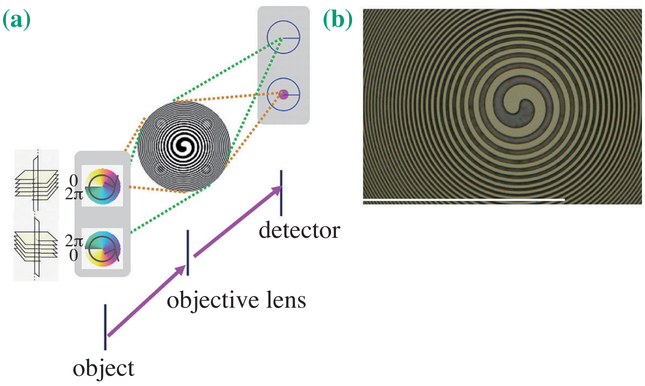

Fig.2. **(a)** Schematic diagram of experiment. At the object plane, spiral phase plates were set which gave the 2π phase jump to produce X-ray vortices with two inverse orientations as shown at the left. Due to the cancellation of vorticity, bright spots at the center of the spiral phase plates are observed in the microscope image plane only when the winding numbers of the spiral phase plates m and that of the SFZP l are canceled for (l, m) = (–1, +1), or (+1, –1) [see orange dotted lines]. Otherwise, dark spots are observed at the center [see green dotted lines]. **(b)** Visible light microscope image of SFZP. The scale bar is 100 μm.

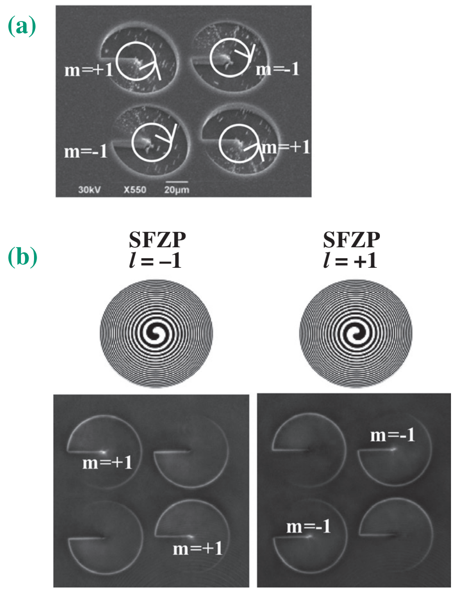

Fig.3. **(a)** Scanning electron microscope image of sample containing four spiral phase plates on silicon substrate with the thickness decrement in the clockwise and in the anti-clockwise orientations. The values of $m = -1, +1$ correspond to the winding number of the optical vortex when X-ray transmits through the spiral phase plates. **(b)** Middle panels show the orientations of the SFZP objective lens, which generates vorticity with the winding number $l = -1, +1$ to the wave front. The bottom panels show the X-ray radial-Hilbert transform microscope image of sample (a) with the corresponding settings of $l = -1, +1$. Bright spots were observed at the center of the spiral plates only for the cases of (l, m) = (–1, +1), or (+1, –1).

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