Spiral phase contrast imaging offers an excellent opportunity to observe non-labeled biological samples with slight variations in refractive index or thickness. However, the overall system covering previous works is still complex and bulky, hindering miniaturization and compatibility with conventional systems. Furthermore, high-resolution imaging, particularly for observing biological specimens such as cellular structures, requires several refractive optical elements like objectives and relay optics which dramatically increases the system form factor. Here, it is demonstrated that a metalens, in which the phase profile is a sum of the hyperbolic phase and spiral phase with a topological charge of 1, performs 2D isotropic edge-enhanced imaging. The metalens achieves a submicrometer resolution of up to 0.78 \( \mu m \) operated under visible broadband range in conjunction with a compact form factor. Furthermore, experiments with biological samples can additionally prove the feasibility of practical usage. Capitalizing on compactness and high-resolution characteristics, it is believed that the scheme provides a stepping stone to biomedical imaging technologies and analog computing.

1. Introduction

Phase contrast imaging method was initially proposed by Frits Zernike in the early 1930s.[3] Light penetrating the structures of different refractive indexes results in different optical path lengths, establishing a phase contrast. Zernike found a way to transform the phase contrast into intensity variation, which is an observable physical quantity via conventional photographic devices or human vision systems. The phase contrast imaging method is significant in the field of biology dealing with transparent cellular structures that are invisible under bright field microscopy. Though staining the object allows visualization of the transparent object, this method diminishes the viability of the live specimen.[2,3] To resolve this issue, many phase contrast imaging methods such as differential interference contrast (DIC)[4] and spiral phase contrast imaging[5–7] microscopy have been implemented. Particularly, the spiral phase contrast imaging has been suggested as a promising methodology because of its ability to perform 2D field differentiation. This approach not only enables isotropic edge-enhancement of the amplitude or phase object, but also operates well even with a birefringent sample. However, the spatial light modulator (SLM), which generates a spiral phase filter at the Fourier plane, makes the overall system too bulky and limits the resolution.

Metasurfaces, which are planar optical elements consisting of artificially designed subwavelength structures, can manipulate the electromagnetic characteristics of light with a large degree of freedom.[8–11] Their unprecedented functionalities and ultra-compactness can overcome the limitations of conventional optical elements and systems.[12–21] Among diverse kinds of metasurfaces, a metasurface lens, usually referred to as a metalens, draws much attention under its subwavelength thickness, polarization-dependent multi-functionality, and high numerical aperture (NA) characteristics.[12–28] During the past few years, many efforts have been suggested to perform an edge-enhancement of the amplitude or phase object with metasurfaces. Deliberately engineered layer structures achieve spatial differentiation with a small form factor, which enables their compatibility with compact integrated systems.[19–36] However, because these layer structures modulate the transfer function by relying on the resonant phenomenon, a broadband operation is infeasible. Concerning this issue, utilizing metasurfaces with a conventional 4f Fourier filtering system is advantageous.[37,38] That being said, they require multiple lenses, which generates a complex and bulky optical system, thereby failing to exploit the compactness of metasurfaces. In regards to high-resolution imaging in microscopy, since the back focal plane (BFP) usually lies inside the objective lens,[39] additional relay optics to access the BFP are necessary. Hence the whole filtering system turns into bulkier, which especially poses a significant hurdle for practical implementation. Additionally, various methods based on oblique incidence have been proposed,[40–42] but their reflection-based system configuration hinders the miniaturization of the optical systems. These limitations are manifested clearly in Table 1, which sums up the representative breakthroughs with four key parameters; resolution, operation spectrum range, device type, and optical system.

To this end, we propose a compact single-layer spiral metalens of which a phase profile is a sum of a hyperbolic phase and spiral phase (spiral phase plate, SPP) with a topological
charge of 1, as shown in Figure 1a. Unlike the conventional 4f Fourier filtering system, our scheme compresses the imaging and edge-enhancement functionalities into single-layer metalens (see Figure 1b,c). Employing a high NA characteristic, the spiral metalens implements high-resolution imaging up to a submicrometer scale at broadband visible spectrum range, which is necessary to observe microscopic biological samples. Taking advantage of these innovations, we anticipate this approach opening new doors to biomedical imaging and analog optical processing.

Table 1. Recent breakthroughs for field differentiation (or phase contrast imaging) mechanism.

| Resolution [µm] | Operation spectrum range [nm] | Device type | Optical system |
|-----------------|-------------------------------|-------------|----------------|
| Huo et al.[38]  | 3.11                          | Transmissive| 4f with filter |
| Zhou et al.[29] | ≈4                           | Transmissive| Single filter  |
| Zhu et al.[42]  | ≈5                           | Reflective  | Single filter  |
| This work       | 0.78                          | Transmissive| Single lens    |

Figure 1. Schematic illustration of the spiral metalens. a) The phase profile components of the spiral metalens. A sum of the hyperbolic and spiral phases with a topological charge of 1 results in the total phase profile. b) Simplified optical setup for the conventional spiral phase contrast imaging. The spiral phase plate (SPP) is placed at the Fourier plane of the 4f system. Field differentiation mechanism results in an edge-enhanced output image. c) The spiral metalens shows the same effect of edge-enhancement with a simplified optical system and higher resolution.
2. Results

2.1. Operating Principles

The phase profile of the spiral metalens is a sum of the hyperbolic phase and the spiral phase with a topological charge of 1 as follows:

$$\varphi(r, \theta) = \frac{2\pi}{\lambda} \left( f - \sqrt{r^2 + f^2} \right) + \theta$$

where $\varphi$ is the total phase profile, $(r, \theta)$ are the polar coordinates at the lens plane, $\lambda$ is a design wavelength, and $f$ is a focal length, respectively. Since being proportional to the Fourier transform of a pupil function, the point spread function (PSF) of the spiral metalens can be specified as:

$$\text{PSF} \propto \mathcal{F} \left[ \text{circ} \left( \frac{r}{R} \right) \exp(i\theta) \right] = \frac{\pi R}{2\rho} \left[ \mathcal{J}_0 \left( \frac{kR\rho}{f} \right) \mathcal{H}_0 \left( \frac{kR\rho}{f} \right) \exp(i\delta) \right]$$

where $\text{circ}$ is the circular mask function, $R$ is a radius of the lens, $\mathcal{J}_m$ is the $m$th-order Bessel function of the first kind, $\mathcal{H}_m$ is the $m$th-order Struve function, $k$ is the wave vector, and $f$ is a focal length, respectively.

Figure 2. Operating principles of the spiral metalens. a) Numerically calculated amplitude and phase distributions at the focal plane. Each of the distributions corresponds to doughnut and spiral shapes, respectively. The scale bars represent 250 nm. b) Horizontal cross-sections of the PSF for the spiral and hyperbolic metalenses, respectively. c) The input image and its Fourier Transform. Here, $k_0$ is the wave vector with a target wavelength of 580 nm. The scale bar represents 40 μm. d) Output image through the spiral metalens and its Fourier Transform. A convolution of the PSF and the input image results in the output image. The scale bar represents 40 μm. e) Schematic illustration of the hyperbolic metalens generating wave vectors ($k_r$) along the radial direction. f) Schematic illustration of the spatial frequency redistribution mechanism. The color bar represents the Fourier transform amplitude of the lens field. The final wave vector ($k'$) can be obtained by a vector sum of radial component ($k_r$) from the original hyperbolic phase and tangential component ($k_t$) from the spiral phase. Consequently, while the Fourier domain of the hyperbolic lens (left) is filled inside the NA line described as a dotted circumference, that of the spiral metalens has a small hole (right) near the origin by the spatial frequency redistribution mechanism.
(ρ, δ) are the polar coordinates at the focal plane, respectively. The amplitude and phase distributions of the PSF, as shown in Figure 2a, are numerically calculated through the angular spectrum method (ASM); each of them appears to be doughnut and spiral shapes having 1ℏ orbital angular momentum (OAM). In this case, arbitrary two points located in symmetric positions to the origin of the PSF have the same amplitude and are out of phase. When the light passing through the target object is convolved with this PSF, the monotonic phase (or amplitude) region is canceled by destructive interference, and only the high contrast region (edge of the object) survives.[43] Destructive interference in homogeneous areas redistributes the light energy into the areas with the high contrast of amplitude or phase without loss.[5,38,43] Section S2 in the Supporting Information explains more detailed theoretical derivation about the field differentiation mechanism. For comparison with conventional lenses, Figure 2b shows the horizontal cross-sections of the PSFs for the spiral and hyperbolic metalenses. Regarding an amplitude distribution of the PSF, the peak-to-peak (PTP) distance for the spiral metalens and the full width at half maximum (FWHM) for the hyperbolic metalens have nearly the same value (PTP/FWHM ≈ 1). There is a well-known relationship between a resolution and the FWHM of the PSF in a standard lens,[22] from which we can infer a similar correlation with the spiral metalens. Figure S3 (Supporting Information) reveals that the shorter the PTP distance is, the higher a resolution can be obtained, as expected.

Fourier domain analysis explains the edge-enhancement characteristic of the spiral metalens more straightforwardly. Figure 2c shows the target input image and its Fourier transformed version, whereby most of the Fourier components are located near the origin of the frequency domain. Figure 2d shows the simulated output image obtained through the spiral metalens and its Fourier transform version. It is noteworthy that the Fourier components of the output image are more widely scattered over the high spatial frequency region. Since the total energy is conserved,[5,38,43] we can conclude that the edge-enhancement operation through the spiral metalens is enabled by redistributing the low spatial frequency component to a higher one. Generalized Snell’s law (GSL)[46] accounts for the spatial frequency redistribution mechanism. The spiral metalens has phase gradients along the radial and tangential direction at the same time, thereby generating the wave vector k along each direction. The magnitude of the k along each direction generated on the position (r,θ) can be calculated by GSL as following:

\[ k_\rho = \frac{d\rho}{dt} = \frac{2\pi}{\lambda} \frac{r}{\sqrt{r^2 + f^2}} = k_0 \frac{r}{\sqrt{r^2 + f^2}} \]  
\[ k_\theta = \frac{d\theta}{dt} = \frac{\lambda}{2\pi r} \]  

where k_0 = 2π/λ and dl is an infinitesimal displacement along tangential direction, respectively. Unlike conventional hyperbolic metalens only generates k_\rho as shown in Figure 2e, the spiral metalens produces the additional wave vector k_\theta according to Equation (4). Since the magnitude of the final wave vector \( k' = \sqrt{k_\rho^2 + k_\theta^2} \) is larger than \( k_\rho \), it can be assumed that the wave vector \( k_\rho \) at every position (r,θ) is redistributed to a higher one. Therefore the spatial frequency components are pushed outward because of the additional wave vector k_\theta as shown in Figure 2f, leading to an energy redistribution into a higher frequency region in the Fourier domain (see Section S4 in the Supporting Information for details). Inasmuch as the tangential component becomes smaller as the radial position gets farther away from the origin of the Fourier domain, the NA of the spiral metalens remains almost unchanged from that of the hyperbolic metalens. Thus, the theoretical description provided herein with both spatial and Fourier domain analysis supports that the spiral metalens can perform the edge-enhancement of the phase (or amplitude) object.

2.2. Experimental Results

As a proof of concept, the spiral metalens based on Equation (1) with a target wavelength of 580 nm is fabricated by the electron beam lithography technology (see Experimental Section for details). All the samples used in experiments are fabricated with hydrogenated silicon (a-Si:H) placed on a silicon dioxide (SiO_2) substrate, producing a diameter of 1 mm. The NA is determined as 0.8 at the target wavelength to provide submicrometer resolution (see Section S3 in the Supporting Information for details). A period of the unit cell structure is chosen to be 300 nm to avoid unwanted higher diffraction orders and satisfy the Nyquist sampling criterion considering the target NA.[45,46] The Pancharatnam-Berry (PB) phase method, also called geometric phase, is applied to impart the phase profile of the spiral metalens as shown in Figure 3a.[37,38,47] Figure 3b represents the polarization conversion efficiency over the visible spectrum range (480 to 680 nm) using the 3D electromagnetic wave simulations based on the finite difference time domain method (FDTD from Lumerical Inc.). Since the geometric phase method operates when the incident light is circularly polarized, some issues arise with polarization-sensitive specimens. A polarization-insensitive metasurface with multiwavelength or broadband achromatic characteristics can be a solution. However, it is challenging to achieve broadband and high NA characteristics simultaneously.[46,48] Figure 3c,d corresponds to optical image and scanning electron microscope (SEM) images of the fabricated metalens sample.

To fully characterize the spiral metalens conveying vortex information, the intensity distributions of the PSFs are measured at wavelengths of 497, 532, 580, and 633 nm using a microscope setup (see Section S5 in the Supporting Information for details). The output beam has 1ℏ OAM since the spiral phase with a topological charge of 1 is added to the conventional hyperbolic phase profile. Figure 3e,f portrays the numerical and experimental results of the intensity distributions of the PSFs at each wavelength. The doughnut-shaped intensity distributions of the PSFs declare that the transmitted light
Figure 3. Design and demonstration of the spiral metalens. a) Unit cell structure description with side and top views. The meta-atom consists of a-Si:H on a SiO₂ substrate. The height, length, and width of the meta-atom are \( H \), \( L \), and \( W \). The pixel period of the unit cell is \( P \). When circularly polarized light (\( \sigma \), +1 for the right circular polarization and -1 for the left circular polarization) is normally incident to the meta-atom with an orientation angle of \( \theta \), the cross-polarized component of transmitted light experiences a phase variation of \( 2\sigma \theta \). b) The simulated polarization conversion efficiency of the designed meta-atom over the whole visible spectrum from 480 to 680 nm. This conversion efficiency is defined as the transmitted optical power ratio with opposite helicity to the incident circularly polarized optical power. c) Optical image of the fabricated spiral metalens with a diameter of 1 mm. The scale bar represents 200 µm. d) SEM images with a top (left) and tilted view (right). The scale bars represent 500 nm. e) Numerically simulated PSFs for wavelengths of 497, 532, 580, and 633 nm, respectively. The scale bars represent 2 µm. f) Experimentally measured PSFs for wavelengths of 497, 532, 580, and 633 nm, respectively. The scale bars represent 2 µm.
passing through the spiral metalens has the OAM as expected. Since Equation (1) depends on the wavelength of the incident light while the geometric phase is constant for every single wavelength, the focal length changes from 462 to 312 μm as the wavelength of the incident light varies from 480 to 680 nm. The focal spot is defined as a position representing the maximum value in the normalized intensity distribution along the x-z plane (see Section S6 in the Supporting Information for details). The NA variation due to the change of focal length and a spherical aberration contribute to a non-uniform size of the PSFs over the visible broadband range. The measured focusing efficiencies are defined as the focused power ratio of the opposite helicity to the left circularly polarized light incident power, which are 16.34%, 20.83%, 35.03%, and 22.53% for blue, green, yellow, and red, respectively. The experimental setup for measuring the focusing efficiency is similar to that of measuring PSF. A ≈1 mm iris is placed right before the image plane (corresponding to a ≈36 μm pinhole at the focal plane, see Section S6 in the Supporting Information for details). The measured focusing efficiencies are 25.46%, 42.04%, 66.86%, and 53.91% for the corresponding wavelength, as shown in Figure 3b, which are lower than the numerically calculated polarization conversion efficiencies. Undersampling the phase profiles caused by the large NA and fabrication imperfection contributes to the difference between the simulation and the experiments. Reducing a lattice constant or developing a more precise fabrication process can decrease the discrepancy between the simulated and experimental results. In addition, fabrication with low-loss materials such as silicon nitride and titanium dioxide can improve the efficiency by reducing absorption, especially for the short-wavelength regime in the visible spectrum range. A slight asymmetry of the measured intensity profile is attributed to the slight misalignment of the experimental setup.

To experimentally demonstrate the edge-enhancement characteristic and quantify the resolution of the spiral metalens, we use the United States Air Force 1951 (USAF 1951) resolution test chart. Section S7 in the Supporting Information shows a schematic illustration of the experimental setup. Left circularly polarized (LCP) light from the supercontinuum source is focused on the resolution test chart by × 10 objective (NA = 0.3) for intense illumination. The scattered light from the test chart forms an edge-enhanced image through the magnification setup consisting of spiral metalens and tube lens. Figure 4a delineates the bright field image of the high-resolution part of the USAF1951 test chart illuminated at the target wavelength. We use a similar experimental setup to obtain a bright field image by replacing the spiral metalens with an objective lens (× 50 magnification, NA = 0.8) without using a polarizer. Segments (1), (2), and (3) in Figure 4a correspond to a resolution of 1.74, 1.23, and 0.78 μm, respectively. For the incident light with wavelengths of 497, 532, 580, and 633 nm, Figure 4b presents the bright field and edge-enhanced images of (1), (2), and (3) segments. Figure 4c shows the vertical and horizontal cross-sections of the segment (1) at the target wavelength displaying six peak points. Intensity inhomogeneity shown in Figure 4c is attributed to the amplitude ripples of the PSF; the adjacent phase distribution convolved with the amplitude ripples affects the output image (see Section S8 in the Supporting Information for details). It is noteworthy that the spiral metalens can perform 2D isotropic edge-enhancement with a maximum resolution of 0.78 μm at the target wavelength of 580 nm, while attaining 1.23 μm over the non-targeted wavelengths. Figure S9 (Supporting Information) shows the theoretical tendency of resolution over the entire visible spectrum. However, a side-lobe of amplitude distribution arising out of a spherical aberration at non-targeted wavelengths can affect the resolution, thereby challenging to conjecture the exact resolution analytically over the entire visible spectrum. The resolution surpasses the previously demonstrated spatial differentiation or phase contrast imaging methodologies by more than two times, to the best of our knowledge. Since the proposed metalens can resolve up to 0.42 μm theoretically (see Section S3 in the Supporting Information), there is much room for improvement. Some results slightly show the directionality and anisotropy of 2D edge-enhancement, called the shadow effect.

![Figure 4](image-url)

**Figure 4.** Experimental demonstration of the edge-enhancement characteristic and quantifying a resolution using the USAF 1951 test chart. a) Bright-field image of the USAF 1951 resolution test chart at the target wavelength of 580 nm. Element 2 of group 8, element 5 of group 8, and element 3 of group 9 in the dashed boxes are designated as segments (1) to (3) in order. The corresponding resolutions are 1.74, 1.23, and 0.78 μm, respectively. The scale bar represents 10 μm. b) Bright field and edge-enhanced images of the segments (1) to (3) at wavelengths of 497, 532, 580, and 633 nm. c) Vertical and horizontal cross-sections of the intensity distributions of the segment (1) output image at the target wavelength.
We believe that this effect is attributed to the high NA of the metalens being sensitive to a slight misalignment of the optical system.

The spiral phase contrast imaging is significant to observe biological samples such as living cells because it can directly detect live specimens having slight variations in refractive index or thickness. The biological sample experimented with are human erythrocytes (red blood cells). Figure 5a,b shows the bright field and edge-enhanced images at wavelengths of 497, 532, 580, and 633 nm, respectively. The erythrocyte boundaries are remarkably discernible at a high contrast than bright field imaging, leading to superior observable results of cellular structures. According to the results, the outer region of the edge-enhanced images appears to be darker and more shadowed than the center field of view. We believe the objective lens used for intense illumination generates a non-uniform brightness, affecting the intensity homogeneity of the output image. Nevertheless, we use the objective since our supercontinuum laser source has limited power at the high-frequency spectrum range. Also, the narrow field-of-view attributed to the high NA limits the isotropic edge-enhancement at the outer area. Doublet metalens or disorder-engineered metasurface have been explored to overcome problems associated with the field-of-view, which enables our spiral metalens to operate at a wider angle range. All the imaging experiments use target objects possessing a kind of abrupt phase (or amplitude) contrast. Section S10 in the Supporting Information shows that our scheme is still valid to some extent for a sample in which the phase changes slowly. However, the exact details about the phase (or amplitude) information for a specimen, including arbitrary and continuous phase (or amplitude) distribution, are difficult to be obtained. The quantitative phase imaging method can solve this issue. Among diverse kinds of quantitative phase imaging technologies, the spiral phase contrast imaging with varying the offset phase of the zeroth-order is a promising candidate to get the absolute phase information. This quantitative phase imaging method with our scheme exploiting a multi-functionality of the metasurface might be an interesting future study to deal with a sample having continuous phase (or amplitude) distribution.

3. Conclusion

In summary, we have demonstrated the practical use of an ultra-compact phase contrast imaging lens that utilizes a high degree of freedom in wavefront modulation of metasurfaces. The spiral metalens attained the submicrometer resolution up to 0.78 μm. Furthermore, the PB phase method used here enables broadband operation in the entire visible spectrum. We gave two theoretical analyses of the operating principle in the spatial and frequency domain, respectively. Experiments with USAF 1951 resolution chart quantifies the phase contrast imaging performance and a resolution of the spiral metalens. Furthermore, we demonstrated practical application in the biomedical imaging field with experiments using human erythrocytes. By utilizing the super-thin form factor, submicrometer resolution, and broadband operation characteristics, we believe our scheme paves a new way for biomedical imaging, material surface examinations, optical analog computing, and image filtering.

4. Experimental Section

**Numerical Simulation:** The presented simulation results of Figure 2a–d and Figure 3e were carried out using commercial software, MATLAB R2020b. The amplitude, phase, and intensity distribution of PSF are calculated through the angular spectrum method, where incident light was modeled as a plane wave passing through the metalens. The dimensions of the meta-atom were designed by the FDTD method. For a unit cell structure, a nanopillar consisting of a-Si:H was placed upon the SiO2 substrate, and the periodic boundary conditions were applied along the x- and y-axis. The refractive index of a-Si:H was obtained using ellipsometry.

**Device Fabrication:** The metasurface was fabricated by a standard electron beam lithography process. First of all, a-Si:H was deposited with a thickness of 400 nm on the SiO2 substrate via plasma-enhanced chemical vapor deposition (HiDep-SC, BMR TECHNOLOGY). The flow rates were 10 sccm for silane (SiH4) gas and 75 sccm for hydrogen gas. Next, two layers of positive resists (PMMA, 495 A4 and 950 A2, MICROCHEM) were used to make a pattern transfer layer. The PMMA 495 A4 was spin-coated on the a-Si:H layer for 5 s at 500 rpm and 40 s at 2000 rpm in order. Then the sample was baked for 3 min at 180 °C on a hot plate. The PMMA 950 A2 was additionally spin-coated for 5 s at 700 rpm and baked for 1 min at 170 °C.
500 rpm and 40 s at 3000 rpm in order. Similar to the former step, the sample was baked for 3 min at 180 °C. Conducting polymer (ESPACER 300Z, SHOWA DENKO) was coated for 5 s at 500 rpm and 30 s at 2000 rpm in order, to avoid charge accumulation. The electron beam lithography (JBX-6300FS, JEOL) was used to draw the designed pattern. After the exposure, the layer of the E-spacer was removed by deionized water. The required pattern could be obtained via a development solution (MIBK:IPA = 13, MICROCHEM). Deposition of 20 nm-thick Chromium (Cr) by the electron beam evaporator (KVE-3004, KOREA VACUUM TECH.) was followed by the lift-off process with acetone. Finally, the etching process by the inductively coupled plasma reactive ion etching (ICP-RIE, VACUUM TECH.) was followed by the lift-off process with acetone.

Biological Sample Preparation: Erythrocytes are prepared for self-experiments by drawing a tiny drop of blood safely. Briefly, the skin of one fingertip was scrubbed with a cotton swab and rubbed with alcohol. Disinfected skin of the fingertip was punctured quickly by the disposable lancet. Then a small drop of blood was carefully squeezed on the cleaned slide glass. Before being dried, the small drop of blood was smeared with a coverslip placed on one edge of the blood drop and slowly moved away from it. Smeared blood was covered with a new coverslip. Informed consent was obtained from the volunteer (Y.K.) for their participation.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Keywords

flat optics, high resolution, metalens, metasurfaces, phase contrast imaging

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