

Ultrawide Field-Of-View, Large Depth-Of-Field Metasurface Assembly for Microendoscopy

CROSS-REFERENCE TO RELATED APPLICATION(S)

[0001] This application claims the priority benefit, under 35 U.S.C. 119(e), of U.S. Application No. 63/626,926, filed January 30, 2024, which is incorporated herein by reference in its entirety for all purposes.

BACKGROUND

[0002] Several narrow and/or tortuous anatomical structures throughout the human body are particularly challenging to reach and image using traditional endoscopes. Such structures include tissues and organs that may be monitored for early detection of cancer (such as lungs, ovaries, pancreas, *etc.*), cardiovascular risks (brain arteries), or the fetus (for pre-natal surgery). Optical probes that would allow the surgeon to better image and analyze problems *in-situ* would considerably improve the specificity and sensitivity of screening procedures (*e.g.*, screening for cancer) or guide surgical procedures (*e.g.*, treating a brain aneurysm).

[0003] A number of miniaturized endoscopes have been developed to ease access to such areas while minimizing trauma. Such endoscopes include fiber-bundles, spectrally-encoded endoscopes, scanning fiber endoscopes, and chip-on-tip endoscopes. However, with the exception of chip-on-tip endoscopes, these other endoscopes have not found wide-spread use by clinicians. Currently, many surgeons still rely on demanding *ex-situ* brightfield microscopy of biopsy samples for diagnosis.

SUMMARY

[0004] Due to sterility and cost considerations, disposable, miniature endoscopes that provide wide field-of-view (WFOV) imaging at high resolution would be beneficial to clinicians and researchers in the medical field. Described herein are microendoscopes that use a meta-optical imager (comprising two metasurfaces separated by a distance) and a deconvolution process to produce WFOV images (up to a 172-degree FOV) with high resolution (capable of resolving as fine as 115 line-pairs per mm). The depth-of-focus (DOF) for the meta-optical imager can be from 0.3 mm to at least 300 mm. The imaging optics may not include conventional lenses

(such as compound lenses) and instead comprise the two metasurfaces which can be formed on opposite sides of a flat substrate or on flat surfaces of two substrates using conventional lithography processes. Accordingly, the imaging optics can be low cost and disposable. Further, the size of the meta-optical imager can be no greater than 1 cubic millimeter in some implementations.

[0005] Some implementations relate to a microendoscope comprising: a wide field-of-view metalens comprising a first plurality of meta-atoms disposed on a first surface; an aperture comprising an opening in a light-blocking layer of material that is disposed on a second surface that is separated from the first surface, the aperture arranged to restrict a spatial extent of light received by the wide field-of-view metalens; and an extended depth-of-focus meta-optic comprising a second plurality of meta-atoms disposed on the second surface in the opening of the aperture, wherein the second plurality of meta-atoms is arranged to impart a phase profile across the opening to light passing through the opening and incident on the wide field-of-view metalens.

[0006] Some implementations relate to a method of imaging with a microendoscope. The method can include acts of: receiving light having a wavelength in a range from 450 nm to 1550 nm through an opening of an aperture from objects in a field of view subtending an angle of at least 160 degrees; imparting, with an extended depth-of-focus meta-optic disposed in the opening, a phase profile to the light; receiving, with a wide field-of-view metalens, the light from the extended depth-of-focus meta-optic; recording, with an imaging array, raw image data at an image plane of the wide field-of-view metalens; and deconvolving the raw image data with at least one point spread function (PSF) that corresponds to the phase profile imparted by the extended depth-of-focus meta-optic to produce an image of the objects in the field of view.

[0007] All combinations of the foregoing concepts and additional concepts discussed in greater detail below (provided such concepts are not mutually inconsistent) are part of the inventive subject matter disclosed herein. In particular, all combinations of subject matter appearing in this disclosure are part of the inventive subject matter disclosed herein. The terminology used herein that also may appear in any disclosure incorporated by reference should be accorded a meaning most consistent with the particular concepts disclosed herein.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] The skilled artisan will understand that the drawings primarily are for illustrative purposes and are not intended to limit the scope of the inventive subject matter described herein. The drawings are not necessarily to scale; in some instances, various aspects of the inventive subject matter disclosed herein may be shown exaggerated or enlarged in the drawings to facilitate an understanding of different features. In the drawings, like reference characters generally refer to like features (e.g., functionally and/or structurally similar elements).

[0009] **FIG. 1** depicts a portion of a metasurface having a plurality of meta-atoms disposed on the surface of a planar substrate.

[0010] **FIG. 2A** depicts an example structure for a meta-optical imager that can be implemented in a microendoscope.

[0011] **FIG. 2B** depicts an example implementation of an optical assembly comprising two meta-optics on a substrate for a microendoscope.

[0012] **FIG. 2C** depicts an example implementation of an optical assembly comprising two meta-optics on two substrates that can be bonded together for use in a microendoscope.

[0013] **FIG. 3A** plots a cubic phase map for an extended depth-of-focus meta-optic.

[0014] **FIG. 3B** plots several different point spread functions (PSFs) computed from numerical simulations for a cubic extended depth-of-focus meta-optic.

[0015] **FIG. 3C** shows results from measurements of PSFs produced by a cubic extended depth-of-focus meta-optic for comparison with the simulations of **FIG. 3B**. The grey scale has been inverted in the image.

[0016] **FIG. 4A** plots a PSF computed from a numerical simulation for a log-asphere extended depth-of-focus meta-optic.

[0017] **FIG. 4B** shows a measured PSF (inverted grey scale) produced by a log-asphere extended depth-of-focus meta-optic for comparison with the simulation of **FIG. 4A**.

[0018] **FIG. 5A** plots a shifted axicon phase map for an extended depth-of-focus meta-optic.

[0019] **FIG. 5B** plots a spiral phase map for an extended depth-of-focus meta-optic.

[0020] **FIG. 6** depicts steps of a design process for a meta-optic.

[0021] FIG. 7 is a photograph of a meta-optical imager (black rectangle at right) and indicates the size of the imager.

[0022] FIG. 8 plots deconvolution time as a function of number of pixels in an image frame for raw images acquired with a meta-optical imager of FIG. 2A.

[0023] FIG. 9A shows raw images obtained with a meta-optical imager having a cubic extended depth-of-focus meta-optic.

[0024] FIG. 9B shows deconvolved images produced from the raw images of FIG. 9A.

[0025] FIG. 10A shows deconvolved images (grey scale inverted) of different line-pair groupings of a reticle using a meta-optical imager having a log-asphere extended depth-of-focus meta-optic.

[0026] FIG. 10B shows raw images (grey scale inverted) of line pair groupings obtained at different object distances for the reticle of FIG. 10A.

[0027] FIG. 11 depicts components of a microendoscope with a meta-optical imager at the distal end.

DETAILED DESCRIPTION

[0028] 1. Introduction

[0029] The trade-off between different optical metrics (such as FOV, DOF, imaging resolution) and size of an imaging apparatus is particularly challenging when trying to make a small imaging device having a wide FOV, large DOF, and high imaging resolution. In colonoscopy, providing improved images of the entire colon can increase polyp and adenoma detection rates. A 1% increase in adenoma detection rate can result in a 3% decrease in the risk of interval cancer and a 5% decrease in the risk of a fatal interval colorectal cancer. As a consequence, wide FOV imaging systems are desirable for endoscopic imaging, with some conventional systems combining two independent optical assemblies to provide a FOV above 180°. Wide FOV ‘fisheye’ lenses (having a FOV near 180°) typically use at least 7 lenses in cascade to correct for aberrations. Such an assembly of lenses is hardly compatible with size requirements for microendoscopy. An axial extension of the imaging system places a lower bound on the endoscope’s bending radius, which limits capabilities in surgical settings. In addition, wide FOV imaging is commonly obtained with a large f-number, which precludes imaging at increased magnification and/or close to the endoscope’s tip.

[0030] The ability to image at close distances and/or at increased magnification is desirable in endoscopy. Magnification endoscopy is particularly relevant for early detection of minute lesions in patients with Barrett's esophagus and in patients undergoing colorectal cancer screening. Magnification endoscopy can be enhanced by topical application of stains (*e.g.*, magnification chromoscopy). Imaging at high numerical aperture (NA) is typically implemented with an extended depth of focus since endoscopes are often susceptible to undesired motion. Some commercial endoscopes include objective lenses with switchable focus to circumvent this issue. An example of such an endoscope is the EVIS X1™ available from Olympus™ Corporation of the Americas, Center Valley, PA. However, such endoscopes with extended DOF can have increased size and complexity. While a large DOF at low f-number theoretically provides the capability to zoom in on tissues without refocusing, current endoscopes have remained too limited in depth of focus to offer such seamless magnification.

[0031] **2. Overview of Metasurfaces and WFOV Metalens**

[0032] Metasurfaces are engineered optical surfaces comprising a plurality of sub-wavelength, three-dimensional structures (called "meta-atoms") patterned across the surface of a substrate. **FIG. 1** depicts a portion of a metasurface 110 having a plurality of meta-atoms 120 disposed on the surface 130 of a substrate. The meta-atoms can be formed on the surface 130 using microfabrication processes (*e.g.*, lithographic patterning, material deposition, etching, *etc.*) The substrate's surface 130 and resulting metasurface 110 can be flat for some applications, though they can be curved or non-planar in other applications. The meta-atoms 120 can have different shapes and orientations across the metasurface 110. The meta-atoms 120 can have any shape (*e.g.*, linear, curved, or bent lines, rectangles, cylinders, polygons, H shapes, *etc.*).

[0033] The portion of the metasurface 110 shown in **FIG. 1** is part of a WFOV fisheye lens. Rectangular and H-shaped meta-atoms were patterned in lead telluride and disposed on a flat calcium fluoride substrate. These materials were chosen for an operating wavelength of 5.2 microns. Other materials and shapes can be used for other operating wavelengths. The WFOV lens in combination with an aperture stop spaced apart from the WFOV lens on the same substrate provide diffraction-limited imaging over approximately 170° FOV for the operating wavelength of 5.2 microns. Further details of the WFOV fisheye lens can be found in "Single-Element Diffraction-Limited Fisheye Metalens," Shalaginov *et al.*, *Nano Lett.* 2020, 20, 7429–7437, which publication is herein incorporated by reference in its entirety.

[0034] There can be a large number of meta-atoms 120 on a metasurface. The periodicity of the meta-atoms 120 can be from approximately or exactly 150 nm to approximately or exactly 1 micron. In some implementations, larger periodicities are used. As such, there can be from approximately 10^6 to nearly 10^8 meta-atoms 120 per square millimeter on a metasurface. Typically, the fill ratio of a meta-atom 120 in its unit cell is no larger than 0.8. The height of the meta-atom 120 can be from approximately or exactly 100 nm to 3 microns. The meta-atoms 120 can be disposed in a rectangular array (which includes a square array) on the metasurface or in a hexagonal array, though other types of arrays are possible. A rectangular array is an array in which each meta-atom 120 is disposed in a rectangular unit cell. The rectangular meta-atom array of FIG. 1 is the special case where each unit cell is square. A hexagonal array is an array in which each meta-atom 120 is disposed in a hexagonal unit cell.

[0035] It will be appreciated that other materials can be used to form meta-atoms and meta-lenses. Other materials for the meta-atoms include, but are not limited to, amorphous silicon, silicon, silicon nitride, high-index polymers, and titanium oxide. Other meta-atom 120 materials include, but are not limited to different oxides (*e.g.*, tantalum oxide Ta₂O₅, hafnium oxide HfO₂, zirconium oxide ZrO₂), compound semiconductors (*e.g.*, gallium nitride, indium phosphide, *etc.*). Substrate materials include but are not limited to glasses, quartz, fused silica, sapphire, and transparent polymers.

[0036] The meta-atoms 120 scatter light incident on the metasurface 110 and are shaped and arranged in a predetermined pattern on the metasurface 110 to provide at least one desired optical function for the metasurface. Examples of desired optical functions include, but are not limited to, focusing the incident light over a wide field-of-view, filtering the incident light by wavelength, forming a desired pattern from the incident light, and polarizing or operating on the polarization of the incident light. In some cases, the metasurface can be designed to perform an optical function on only one selected polarization of the incident light and not on other polarizations of the incident light. Metasurfaces offer a new pathway to efficiently manipulate light and can replace bulky refractive optical assemblies with ultra-thin optical components that can be manufactured using microfabrication processes rather than grinding and polishing. Compared to diffractive optical elements, the reduced periodicities of meta-atoms 120 on metasurfaces 110 can provide large phase gradients, which is beneficial for implementing a lens with a large FOV. The so-called “flat optics” approach with metasurfaces can replace bulky lenses and optical fiber used in conventional endoscopes, while improving optical performance. Meta-optics for an endoscope can be engineered to provide aberration correction,

increased FOV, increased depth of field, *etc.*. Further, CMOS fabrication techniques can be used to make the metasurfaces at low cost compared to conventional bulk optical assemblies.

[0037] The inventors have recognized and appreciated that the fisheye lens approach described above that provides a WFOV of nearly 180° might be useful for endoscopy; however, the lens' performance has limited depth of field, particularly at higher numerical apertures. To image a point that is not located at or near infinity from the lens, a mechanical component would normally be used to adjust the spacing between focal plane and WFOV lens to bring the image into focus. As such, the WFOV fisheye lens and aperture combination would not be very suitable for high-NA imaging in endoscopic applications where imaged objects can be at or near infinity from the lens as well as close to the lens.

[0038] However, the inventors have also recognized and appreciated that point spread function (PSF) engineering, potentially coupled with image post-processing by deconvolution, can significantly extend the DOF of imaging systems such that moving parts need not be used to image objects at or near infinity from the lens as well as close to the lens (e.g., single-shot imaging). In PSF engineering, a desired phase profile is imparted to light that is focused by a lens to produce a raw image that has been manipulated by the desired phase profile. The raw image can then be deconvolved with a PSF corresponding to the phase profile to produce an image of objects (over an extended DOF) in the field of view of the system. In some implementations, the engineered PSF can be designed such that no deconvolution step is needed for imaging, ensuring faster imaging speed and reduced computational requirements. One example of such a PSF is the log-asphere PSF discussed further below in connection with **FIG. 4A** and **FIG. 4B**.

[0039] 3. Extended Depth of Field Meta-Optical Imager

[0040] The inventors have recognized and appreciated that the phase profile for PSF engineering to produce an extended depth of field can be combined with a focusing lens phase profile, and that both phase profiles can be imparted by flat metasurfaces that are separated from each other. The two metasurfaces comprise meta-atoms disposed on the flat surfaces. In some cases, the two metasurfaces can be disposed on opposite sides of the same substrate. In other implementations, the two metasurfaces can be patterned on two surfaces of separate substrates. The two substrates can be subsequently aligned and bonded together.

[0041] The inventors have further recognized and appreciated that placing a non-focusing or weakly focusing PSF phase-modulating meta-optic (which imparts the desired phase profile

for extending the depth of field) at the location of an aperture for the fisheye metalens, as depicted in **FIG. 2A**, can result in a desirable PSF-engineered phase wavefront imparted to light (referred to as “structured light”) passing through the PSF phase-modulating meta-optic that can significantly increase the depth of field for the meta-optic assembly and provide suitable imaging quality over a wide field of view. This PSF-engineered phase can be imparted at the location of the aperture identically or approximately identically across all angles of incident light on the fisheye metalens for a given wavelength. For each imaging angle, the engineered PSF can be invariant over a broad range of imaging depths. The inventors have also recognized and appreciated that this extended depth-of-focus (EDOF) phase profile can be imparted at the location of the aperture to obtain a large depth of field imager without introducing distortion to light impinging on the fisheye metalens, which distortion would occur if the EDOF meta-optic were located between the WFOV metalens and the aperture or in front of the aperture. Further, if there are residual angularly-dependent wavefront aberrations that can be predicted on the fisheye lens, then the resulting image can be deconvolved during postprocessing. For example, a proper image can be reconstructed despite residual angular-dependent meta-atom responses. The inventors have further recognized and appreciated that an extended depth-of-focus (EDOF) phase profile imparted by an EDOF meta-optic at the aperture can be used to extend the spectral bandwidth of the optical assembly, as compared to the aperture-only, WFOV assembly.

[0042] In view of the foregoing, the inventors have conceived a meta-optical imager for microendoscopy. **FIG. 2A** depicts an example of such a meta-optical imager 200 for a microendoscope. The meta-optical imager 200 comprises a meta-optical assembly 210 having two metasurfaces, though more metasurfaces could be used in some implementations. The meta-optical assembly 210 comprises an aperture 220, a WFOV metalens 240, and an EDOF meta-optic 230 located within the opening of the aperture 220. The meta-optical imager 200 can further comprise an imaging array 250 (*e.g.*, a CMOS imager) in optical communication with the meta-optical assembly 210 to acquire raw image data. The meta-optical imager 200 can be highly compact (*e.g.*, occupying a volume no larger than 25 mm^3 , no larger than 10 mm^3 in some cases, no larger than 5 mm^3 in some cases, and no larger than 1 mm^3 in some cases) and can be implemented on the tip or head of a microendoscope or larger endoscope, for example.

[0043] The aperture 220 comprises an opening 222 in an opaque layer 225, and can be formed using a thin layer of metal or other light-blocking material. The opening 222 in the light-

blocking material can be formed lithographically (*e.g.*, using photoresist, patterning of the resist, and etching). In some implementations, the aperture 220 can be disposed on the same surface of a substrate on which the EDOF meta-optic 230 is disposed, but can be formed on another surface in some cases. The aperture 220 restricts a spatial extent (in the x and y directions) of light received by the WFOV metalens 240. The light received by the WFOV metalens 240 passes through the opening 222 of the aperture 220.

[0044] According to some implementations, the WFOV metalens 240 can be implemented as a first metasurface disposed on an opposing surface of the same substrate 205 on which the EDOF meta-optic 230 and/or aperture 220 is disposed to space the aperture 220 and/or EDOF meta-optic 230 a desired distance d from the WFOV metalens 240. **FIG. 2B** depicts such an implementation. In some cases, the EDOF meta-optic 230 can be implemented as a second metasurface on the same substrate 205. The distance d between the WFOV metalens 240 and the EDOF meta-optic 230 can be from 0.05 mm to 5 mm. The working distance of the meta-optical imager 200 can span from sub-millimeter to infinity in some cases, or from 0.2 mm to 100 mm in some cases. Conventional commercial lens assemblies for endoscopes currently advertise working distances from 3 mm to 80 mm with a FOV limited to 120 degrees, but as discussed above comprise significantly larger optical assemblies and multiple bulky optical lenses compared to the meta-optical assembly of **FIG. 2A** and **FIG. 2B**.

[0045] **FIG. 2C** depicts an implementation in which the EDOF meta-optic 230 and aperture 220 are patterned on a first substrate 205-1 and the WFOV metalens 240 is patterned on a second substrate 205-2. The patterning and processing of the two meta-optics can be done separately and in parallel. Subsequently, the two meta-optics can be aligned to each other and their substrates 205-1, 205-2 bonded together. The thicknesses of the two substrates can be selected such that when bonded, the EDOF metasurface is separated from the WFOV metasurface by the desired distance d .

[0046] 4. EDOF Meta-Optics

[0047] As described above, the EDOF meta-optic 230 comprises meta-atoms disposed on a surface that is spaced a distance d from the surface on which the WFOV metalens 240 is disposed. Light passing through the EDOF meta-optic 230 is imparted a phase profile across the wavefront of the light passing through the aperture 220 and EDOF meta-optic 230, where the phase profile can be defined by the shapes and arrangement of the meta-atoms on the surface. At least four PSF-modulating phase profiles can be used for the EDOF meta-optic

230. The PSF-modulating phase profiles can offer accurate imaging in both near and far field. The first PSF-modulating phase profile considered by the inventors is a cubic phase profile (which is non-axisymmetric). **FIG. 3A** depicts a phase map for the EDOF meta-optic 230 that corresponds to the cubic phase profile. The transition from black to white in the image spans a range of 2π radians. The cubic phase EDOF meta-optic 230 is designed to impart such phase shifts to a plane wave over the area of the aperture 220. The cubic phase profile implemented in the meta-optical imager 200 can provide a near-180° FOV, an extended DOF from 1 mm to 300 mm, and resolution up to 50 lp/mm without refocusing. In some implementations, an efficient back-end deconvolution process can provide image acquisition frame rates suitable for video display.

[0048] The cubic phase profile imparts a phase profile across the opening of the aperture 220 according to **EQ. 1** below:

$$\phi(x, y) = \frac{\alpha}{R^3}(x^3 + y^3). \quad (1)$$

In this expression, $r = 0$ at the center of the aperture's opening 222, $r^2 = x^2 + y^2$, R is the radius of the opening in the aperture 220 where the EDOF meta-optic 230 is located, and $\alpha = 1000\pi$. The parameter α has a lower bound of π and can be adjusted to set a distance of the extended depth of focus from the meta-optical assembly 210. The upper bound is set by the Nyquist sampling criterion. Considering a unit cell size d and aperture radius R , the Nyquist sampling criterion requires that the phase change $\Delta\phi$ over two adjacent unit cells is smaller than π , such that $\Delta\phi < \pi$, which translates in an upper bound limit $\alpha < \frac{R}{d}\pi$. The cubic phase profile is an example of an aberration-based phase profile that introduces intentional phase aberrations to modify focus and extend the DOF.

[0049] The cubic PSF-modulating phase profile was evaluated numerically and experimentally across a wide range of incident angles. **FIG. 3B** plots several different PSFs computed from numerical simulations at two different depths of focus (3 mm and 10 mm) and different incident angles (0, 60, 80, and 89 degrees) for a point source located at infinity (producing a plane wave incident at the corresponding angle on the EDOF meta-optic 230). The PSFs are generated from light from the point source passing through the cubic EDOF meta-optic 230 followed by the WFOV metalens 240 and then forming an image on the image plane where the imaging array 250 would be located. The peak intensity is centered for each image. The plots show normalized intensity as a function of x and y directions across image planes located 3 mm and

10 mm behind the EDOF meta-optic 230. The plots indicate that the cubic-phase PSF is relatively stable across the incident angles and the 7 mm depth of focus. **FIG. 3C** shows results from measurements of the PSFs produced by the EDOF meta-optic 230 having the cubic PSF-modulating phase profile for comparison with the simulation in **FIG. 3B**. The recorded raw images are not shifted to center the peak intensity and are not plotted to the same lateral scale used for **FIG. 3B**. The recorded images show reasonable agreement with the numerical simulation (a stable PSF) for the variation in angle of incidence (AOI) up to 86 degrees and validates the numerical calculations.

[0050] A second phase profile considered for the EDOF meta-optic 230 by the inventors is the log-asphere phase profile (which is axisymmetric). The log-asphere phase profile imparts a phase profile across the aperture's opening according to **EQ. 2** below. The log-asphere phase profile can provide a uniform intensity distribution across a line of foci extending between the object locations s_1 and s_2 , considering a parallel incident beam.

$$\phi(r) = \frac{2\pi}{\lambda} \int_0^r \frac{r' dr'}{\left\{ r'^2 + \left[s_1 + (s_2 - s_1) \left(\frac{r'}{R} \right)^2 \right]^2 \right\}^{1/2}}. \quad (2)$$

In this expression, $r = 0$ at the center of the aperture's opening 222, $r'^2 = x^2 + y^2$, and R is the radius of the aperture's opening 222. To demonstrate extended depth of focus at high numerical aperture ($f/\#$ 1.5), the following values can be chosen: $s_1 = 300 \mu\text{m}$ and $s_2 = 1 \text{ mm}$. The log-asphere phase profile is an example of an axial redistribution phase profile that redistributes light intensity along the propagation axis while maintaining relatively high energy efficiency.

[0051] The log-asphere PSF-modulating phase profile was also evaluated numerically and experimentally. **FIG. 4A** shows the normalized log-asphere PSF computed from a numerical simulation for a point source located at infinity and the optical wave passing through the EDOF meta-optic 230 and the WFOV metalens 240. The imparted log-asphere phase profile produces a PSF having an elongated focal spot across a distance defined at the design step, in this case defined from $400 \mu\text{m}$ (minimum measurable distance) up to 2 mm .

[0052] An EDOF meta-optic 230 was designed to impart a log-asphere phase profile at the aperture 220 to incident plane waves. The EDOF meta-optic was designed to have an elongated focal length over distances from $300 \mu\text{m}$ to 1 mm , similar to the simulated conditions for **FIG. 4A**. An experimentally measured PSF is shown in **FIG. 4B**. For the experimental measurement (and for the simulation of **FIG. 4A**), the imaging array was located $600 \mu\text{m}$

from the WFOV metalens 240, which in turn was located 500 microns from the EDOF meta-optic 230. The illumination wavelength was 940 nm. The measured PSF of **FIG. 4B** is in reasonable agreement with the simulated PSF of **FIG. 4A**.

[0053] More generally, the EDOF phase profile can integrate any of the following family of phase profiles, or any combination of the EDOF phase profiles described below and above. The listed phase profiles can increase the depth of focus (DOF). The following symbols (and their associated meanings) are used in the following expressions: r – radial distance (in polar coordinates); θ – azimuthal angle (in polar coordinates); k – wave number, defined as $k=2\pi/\lambda$, where λ is the wavelength of the light; A – a constant (amplitude or scaling factor), varying by the phase profile; m – topological charge or integer (for spiral phase profile), related to the number of phase twists; B – constant in the logarithmic phase profile, controlling the depth of field; x, y – Cartesian coordinates, $Z_n^m(r, \theta)$ – Zernike polynomial of radial order n and angular order m , describing wavefront aberrations; r_0 – a reference position in the shifted axicon phase profile, σ – parameter controlling the width of the apodization in the apodized phase profile; f – focal length (in the context of the FrFT phase profile); α – fractional order of the Fourier transform (in the FrFT phase profile).

[0054] 4.1. Axial Redistribution Phase Profiles

[0055] A first type of phase profile that can be introduced by the EDOF meta optic 230 is an axial redistribution phase profile. Such a phase profile redistributes light intensity along the propagation axis while maintaining relatively high energy efficiency. Examples of such phase profiles are given in this section.

[0056] Log-Asphere Phase Profile: This profile improves depth by modifying the phase logarithmically. The phase profile can also be expressed with an analytical formula of the following form, without being bound to a particular theory:

$$\Phi(r) = A \log(1 + Br^2). \quad (3)$$

[0057] Sinusoidal Phase Profiles: A sinusoidal phase modulation redistributes light axially, increasing the focal depth, with an analytical formula of the following form, without being bound to a particular theory:

$$\Phi(x, y) = Ax^4 \sin(kx) + Ay^4 \sin(ky) \quad (4)$$

[0058] Exponential Phase Profiles: An exponential phase modulation redistributes light axially increasing the focal depth, with an analytical formula of the following form, without being bound to a particular theory:

$$\Phi(x, y) = Ax \exp(kx^2) + Ay \exp(ky^2) \quad (5)$$

[0059] Tangent Phase Profiles: A tangent phase modulation redistributes light axially, increasing the focal depth, with an analytical formula of the following form, without being bound to a particular theory:

$$\Phi(x, y) = Ax^2 \tan(kx) + Ay^2 \tan(ky) \quad (6)$$

[0060] Square Root Phase Profiles: A square root phase modulation redistributes light axially, increasing the focal depth, with an analytical formula of the following form, without being bound to a particular theory:

$$\Phi(x, y) = Ax\sqrt{k - x^2} + Ay\sqrt{k - y^2} \quad (7)$$

[0061] Inverse Sinusoidal Phase Profiles: An inverse sinusoidal phase modulation redistributes light axially, increasing the focal depth, with an analytical formula of the following form, without being bound to a particular theory or coordinate basis:

$$\Phi(x, y) = Ax^2 \arcsin(kx) + Ay^2 \arcsin(ky) \quad (8)$$

[0062] Shifted Axicon Phase Profile: Axicons generate extended focal lines, and a shifted version allows for axial control. A shifted axicon phase profile can have an analytical formula of the following form, without being bound to a particular theory:

$$\Phi(r) = A |r - r_0|. \quad (9)$$

FIG. 5A depicts a phase map for a shifted axicon phase profile. The phase map depicts phase shifts that would be imparted to a plane wave incident on the EDOF meta-optic 230.

[0063] Apodized Phase Profile: Smooth apodization (e.g., gradual reduction of aperture transmission) extends focus by suppressing diffraction sidelobes, with an associated analytical formula of the following form, without being bound to a particular theory:

$$\Phi(r) = A e^{-\left(\frac{r}{\sigma}\right)^2}. \quad (10)$$

[0064] Jacobi/Fourier Polynomials Phase: Additional examples of axial redistribution phase profiles include the Jacobi/Fourier polynomials phase profiles of the following form, without being bound to a particular theory:

$$\Phi(r) = A \sum_{n=0}^{\infty} b_n \cos(n\pi r). \quad (11)$$

[0065] 4.2. Aberration-Based Phase Profiles

[0066] A second type of phase profile that can be introduced by the EDOF meta optic 230 is an aberration based phase profile. Such a phase profile introduces intentional aberrations to modify focus and extend the DOF. Examples of such phase profiles are given in this section.

[0067] Cubic Phase Profile: A cubic phase mask introduces a linear variation of defocus with depth, extending depth of focus. As described above, the cubic phase mask has an analytical formula of the following form, without being bound to a particular theory:

$$\Phi(x, y) = A(x^3 + y^3). \quad (12)$$

[0068] Quartic Phase Profile: A quartic phase mask extends DOF by introducing a higher-order aberration. The quartic phase profile can have an analytical formula of the following form, without being bound to a particular theory:

$$\Phi(r) = Ar^4. \quad (13)$$

[0069] Radial and Angular Zernike Phase Profiles: These phase profiles use Zernike polynomials to control higher-order aberrations, extending DOF, with an analytical formula of the following form, without being bound to a particular theory:

$$\Phi(r, \theta) = aZ_n^m(r, \theta). \quad (14)$$

[0070] 4.3. Angular Redistribution Phase Profiles

[0071] A third type of phase profile that can be introduced by the EDOF meta optic 230 is an angular redistribution phase profile. Such a phase profile introduces angular phase variation, leading to robust propagation and an extended focal region with unique beam shapes. Examples of such phase profiles are given in this section.

[0072] Annular or Ring-Based Phase Profiles: These profiles use annular structures to produce extended depth by redistributing the focus with an angular phase modulation, such as for example the Bessel-Gaussian phase profile, with an analytical formula of the following form, without being bound to a particular theory:

$$\Phi(r, \theta) = kr \sin(\theta). \quad (15)$$

[0073] Spiral Phase Profile: This phase profile introduces an azimuthal phase shift, resulting in a vortex beam with increased DOF. The spiral phase profile is designed to generate structured light carrying orbital angular momentum and can have an analytical formula of the following form, without being bound to a particular theory:

$$\Phi(r, \theta) \propto m(r, \theta) \cdot \theta. \quad (16)$$

The quantity $m(r, \theta)$ represents the topological charge. The topological charge may vary with the radial coordinate (r) or the azimuthal angle (θ), enabling dynamic control over the beam's properties. The target phase profile can involve a combination of multiple spiral phase profiles, either linearly or through other mathematical transformations, providing flexibility in tailoring the optical vortex characteristics to specific applications. **FIG. 5B** shows an example of a spiral phase map that can be implemented in an EDOF meta-optic 230.

[0074] Fractional Fourier Transform (FrFT) Phase Profiles: FrFT phase masks modify the optical field to increase DOF through a fractional transformation. These phase profiles can have an analytical formula of the following form, without being bound to a particular theory:

$$\Phi(x, y) = -\frac{\pi}{f} (x^2 + y^2) \cot(\alpha). \quad (17)$$

[0075] 5. Design of a Meta-Optic

[0076] A meta-optic, such as the EDOF meta-optic 230 and WFOV metalens 240 can be designed using an iterative numerical process. **FIG. 6** provides an overview of steps involved in design process 600 for a meta-optic. The design process 600 can begin by identifying (step 605) the wavelength or wavelengths for which the meta-optic will be used. For the present application, the microendoscope can operate at one or more wavelengths in a range from approximately or exactly 450 nm to approximately or exactly 1550 nm. Once the wavelength(s) is(are) selected, materials can be selected (step 610) for the meta-optic. Generally, materials are selected that exhibit low loss and provide high index contrast for the operating wavelength(s). For visible wavelengths, example choices of materials for the meta-atoms include TiO₂, HfO₂, ZrO₂, GaN, crystalline silicon, silicon nitride. In the near IR, material choices for the meta-atoms include crystalline or amorphous silicon, or chalcogenides. As an example for visible radiation at 650 nm, a glass (*e.g.*, fused silica) may be selected for the meta-optic substrate 205 and crystalline silicon or another semiconductor material may be selected for the meta-atoms 120.

[0077] The phase profile(s) for the meta-optic can be selected (step 615) to obtain the desired optical functionality (or functionalities) for the meta-optic. For example, if an extended depth of field is desired, a cubic phase profile, a log-asphere phase profile, a spiral phase profile, or a shifted axicon phase profile can be chosen, examples of which are described above. The phase profile is essentially a phase pattern that is imparted to an optical wave passing through the meta-optic. If more than one functionality is desired for the meta-optic (*e.g.*, EDOF and weak focusing), then more than one phase profile can be selected and the phase profiles superposed for the meta-optic's phase profile. A weakly focusing phase profile could be a weakly focusing Fresnel lens providing a focusing power between 0.01 diopter and 1 diopter, for example. Such a weakly focusing phase profile can be combined with the EDOF phase profile in some cases.

[0078] The lattice type (*e.g.*, rectangular or hexagonal) can also be selected (step 620) by the designer. Either lattice type can work and other lattices may work. Rectangular lattices may be preferred since they conform better to lithographic patterning tools which typically generate patterns according to Cartesian coordinate systems.

[0079] The design process 600 can further include selecting the thickness (step 625) of the meta-atoms. Typically, because of microfabrication process constraints, all meta-atoms across a metasurface may have the same thickness. Having all meta-atoms be the same thickness can simplify the microfabrication process steps. However, gray-scale lithography can be used in some cases to have meta-atoms of different thicknesses across the metasurface. The thickness of meta-atoms can be chosen according to the phase profile and materials used. For example, if a maximum phase imparted by the phase profile is θ_{max} , then the thickness of meta-atoms can be chosen such that a wave propagating the shortest distance through the meta-atom material (normal incidence angle) receives a phase change equal to θ_{max} or a phase change greater than θ_{max} .

[0080] Once the materials, phase profile(s), lattice type, and meta-atom thickness have been selected, iterative design of the metasurface can begin. The design of the metasurface can be done region by region and even meta-atom by meta-atom. The design process 600 at this phase of design involves selecting a meta-atom shape (step 630) for a meta-atom located in a position $P(x,y)$ on the metasurface and then simulating the interaction of the meta-atom (surrounded by identical, nearest neighbor meta-atoms) with incident light at the design wavelength(s) and observing the response of the meta-atom in terms of amplitude and imparted phase.

[0081] The shape of the meta-atom 120 at the location can be drawn from a library of meta-atom shapes. A shape used for each meta-atom can be any of the following: cylinder, disk, disk with a center hole, rectangle, rectangle with a center hole, square, square with a center hole, crosses, H shapes, I shapes, L shapes, and an $n \times n$ grid of any of the foregoing shapes where n is an integer (*e.g.*, 2, 3 or larger). Fabrication limitations may limit the value of n , since the features of a grid in the unit cell would be smaller than features for a single meta-atom. The iterative design process can test each meta-atom shape from the library at each location on the metasurface.

[0082] Referring to **FIG. 3A**, the simulation of light interaction with the meta-atom is done for each selected location $P(x,y)$ in the metasurface. At the simulation location is a unit cell containing the i_{nth} , j_{nth} meta-atom in the meta-atom lattice. Each cell containing a meta-atom can be represented as $C(i_n, j_n)$. The size of the meta-atom and its neighbors used in the simulation can be varied (scaled down in size to occupy less of the unit cell or scaled up in size) and/or the shape can be changed to a different meta-atom shape and scaled until the desired phase value for that location is obtained. The periodicity of the lattice may also be varied. The height of the meta-atom may be varied cell-by-cell. If gray-scale lithography or nanoimprint lithography is being used to pattern the meta-atoms, different meta-atom heights can be fabricated. If the lithography process for patterning the meta-atoms does not permit cell-by-cell variations in meta-atom height, then a global height value can be picked from among the different heights simulated. The global height can be a height providing the smallest amount of phase error for considering all meta-atom responses in the array. The optical interaction of light with the meta-atom and its neighbors can be simulated using finite-difference time-domain (FDTD) electromagnetic field solving software and/or rigorous coupled-wave-analysis (RCWA) software.

[0083] When the desired phase response is achieved, the simulations are repeated for variations in the input wave (*e.g.*, changes in incidence angle, changes in wavelength, changes in polarization). An objective with the repeated simulations is to find a meta-atom shape that will provide a stable phase response and transmission value irrespective of variations in the input wave (step 640, step 650, step 660). The size and/or shape of the meta-atom (and its neighbors) can be gradually changed (step 660) during this iterative process. A shape and size providing the most stable phase response and transmission value can be selected for that location of the metasurface.

[0084] The iterative process can repeat until a meta-atom shape is obtained that provides a stable imparted phase and stable transmission value (*e.g.*, stable phase within ± 20 degrees, or within ± 10 degrees, or even within ± 5 degrees and stable transmission value within $\pm 10\%$, or within $\pm 5\%$, or even within $\pm 2\%$) for the range of input waves. Then, the design process advances (step 654) to a next meta-atom in the lattice (incrementing lattice index n in this example) and the iterative process repeats for the next meta-atom. The process repeats (*e.g.*, increments through each unit cell (row-by-row or column-by-column (steps 652, 654, 656, 658) until shapes and sizes for all meta-atoms in the lattice have been obtained after which the design process can finish (step 670) and may output a pattern of the meta-atoms and lattice suitable for lithography. The output pattern may be used for electron-beam lithography to pattern the metasurface on a substrate.

[0085] Design of the WFOV metalens 240 can involve determining the phase profile for the WFOV lens. Polynomials for the phase profile may be estimated from optical analysis (*e.g.*, from ray tracing analysis) based upon an intended location of the WFOV lens' focus and the acceptance angles of the WFOV lens. Once the polynomials are found, they can be used to determine the phase profile imparted by the WFOV metalens 240. The thickness of the substrate for the WFOV lens (or distance d in **FIG. 2A**) can be adjusted to provide telecentricity for the meta-optical imager 200, in which chief rays are incident perpendicular to the image plane. Interestingly, separating the EDOF meta-optic 230 and aperture 220 from the WFOV metalens 240 can relieve design pressure on the WFOV metalens 240. This is because the aperture reduces acceptance angles for the WFOV metalens 240. The larger acceptance angles are accommodated by the EDOF meta-optic 230, which does not need to focus strongly.

[0086] 6. Image Recovery

[0087] To recover a scene when using the meta-optical imager 200 and specific engineered PSFs, the raw image data produced by the meta-optical imager may be deconvolved with the PSF that was used to make the EDOF meta-optic 230. Because the PSF is stable across a very wide angular range for the system, a single PSF and single set of parameters can be used to deconvolve the raw images with acceptable accuracy. Using a single PSF can reduce post-processing latency and accelerate image acquisition rates.

[0088] In one approach, the deconvolution process uses the Wiener filter algorithm, given by **EQ. (18)**:

$$G(u, v) = \frac{H^*(u, v)}{|H(u, v)|^2 + \frac{P_u(u, v)}{P_n(u, v)}} \quad (18)$$

where $G(u, v)$ is the Wiener filter, $H(u, v)$ is the Fourier transform of the PSF, $P_u(u, v)$ is the power spectrum of the signal process, and $P_n(u, v)$ is the power spectrum of the noise process. The ratio $\frac{P_u}{P_n}$ can be understood as the signal-to-noise ratio (SNR). Using the Wiener filter, one can reconstruct the scene $\hat{S}(u, v)$ from the measured data $X(u, v)$ using the following expression:

$$\hat{S}(u, v) = G(u, v)X(u, v). \quad (19)$$

[0089] Numerical simulations were carried out to compare deconvolution with a single PSF and deconvolution with multiple incident-angle-dependent PSFs. In the first image deconvolution, image data was deconvolved with a single PSF (derived for a point source at 0°) for all incident angles ranging from 0° to 80° . In the second image deconvolution, different PSFs (derived for point sources at 0° , 20° , 40° , 60° , and 80°) were used depending on incident angles of the light. Some segmentation appeared in the deconvolved image when different PSFs were used, but otherwise comparable imaging quality was observed for the two deconvolution processes.

[0090] 7. Example Meta-Optical Imager

[0091] Several images were acquired with a meta-optical imager 200 like that shown in FIG. 2A. FIG. 7 shows an example of one such meta-optical imager 200. The meta-optical imager 200 is a rectangular structure (the small black rectangle) having an aperture opening measuring 0.2 mm by 0.2 mm and an imaging plane measuring 1 mm by 1 mm.

[0092] For analysis of the meta-optical imager 200, the recovered images were obtained using a single PSF (corresponding to either the cubic phase EDOF meta-optic 230 or the log-asphere phase EDOF meta-optic 230). The signal-to-noise ratio (SNR) used for deconvolution of all the raw images was 0.003. Following deconvolution, the contrast of all images was rescaled with respect to their maximum contrast, so as to provide continuity in contrast for video imaging. The deconvolution and contrast-scaling post-processing took approximately 1.1 seconds for an image with 10^7 pixels (3664×2864 pixels) and approximately 44 milliseconds for an image with 2.5×10^5 pixels (500×500 pixels). Since state-of-the-art chip-on-tip cameras below 1 mm diameter currently integrate $\sim 2.5 \times 10^5$ pixels, the post-processing

pipeline for a microendoscope of the present embodiments is nearly compatible with video frame rate imaging (41 ms per image). Thus, the microendoscope having the components of **FIG. 2A** could offer live video to a clinician (assuming that there are no other significant latencies in data acquisition and image display).

[0093] **FIG. 8** plots latency due to postprocessing vs. resolution of the resulting image. A state-of-the-art 1 mm × 1 mm chip-on-tip endoscope camera has 2.5×10^5 pixels (indicated by upward pointing arrow) and can acquire and display images (over a much smaller FOV and DOF) within a latency typically allowed for video frame rate imaging (indicated by horizontal dashed line). The latency for an example microendoscope of the present embodiments (having the same number of pixels and a much larger FOV and DOF) is slightly over the currently-allowed latency (by less than 10%).

[0094] The inventors have recognized and appreciated that methods can be used to speed up and/or simplify the post-processing pipeline. Accordingly, there is room for improvement of a hybrid imaging approach that combines flat meta-optics with efficient image restoration techniques. The inventors have also recognized that some meta-optic designs do not require computational reconstruction for image recovery. Instead, the quality of the raw images can be sufficient for image analysis.

[0095] **FIG. 9A** shows a set of raw images (of line-pair groupings on a 1951 USAF reticle) acquired with a microendoscope of the present embodiments at different distances from the scope's aperture 220. The endoscope uses the cubic PSF-modulating phase EDOF meta-optic 230. **FIG. 9B** shows the deconvolved images corresponding to the images of **FIG. 9A**. The distance to the target is decreased from left to right, changing from 75 mm to 1 mm. The imaging resolution can be as fine as 50 line pairs/mm.

[0096] The inventors have found that the log-asphere PSF may have two advantages over the cubic PSF: (1) the log-asphere PSF is rotationally symmetric, which improves the SNR in the final image and (2) the final image is directly interpretable, before proceeding to deconvolution. The same advantages apply to the third and fourth embodiments of the PSF-modulating meta-optic, namely (1) a phase profile generating structured light that carries orbital angular momentum and (2) an inverse-design phase profiles that generates a PSF with an extended depth of focus).

[0097] **FIG. 10A** are imaging results with a microendoscope having the meta-optical imager 200 of **FIG. 2A** with a log-asphere EDOF meta-optic 230 and an aperture opening 222 of 200

μm diameter. The images were obtained using a CMOS sensor with a pixel size of $1.67\ \mu\text{m} \times 1.67\ \mu\text{m}$, such that only about 120×120 pixels were used to acquire the images. The imager is able to resolve lines separated by nearly $4\ \mu\text{m}$ (1951 USAF reticle, group 6, set 6), corresponding to an approximate resolution limit of 115 lp/mm. **FIG. 10B** shows that focusing remains stable over distances extending from $400\ \mu\text{m}$ to 1.5 mm. The images of **FIG. 10B** were obtained without any image post-processing, showing that the raw images are recognizable for the log-asphere phase profile without deconvolution. The resolution of the imager may be limited by the pixel size of the imaging array 250 rather than the meta-optical assembly 210.

[0098] Polarization multiplexing offers a way to embed, in a single imaging device, the two complementary approaches of **FIG. 9A** (PSF associated with a cubic phase profile) and **FIG. 10A** (PSF associated with a log-asphere phase profile) described above. For example, the meta-atoms of the EDOF meta-optic 230 can be engineered to provide a first phase profile (*e.g.*, cubic phase) to a first polarization state of light and to provide a second phase profile (*e.g.*, log asphere) to a second polarization state of the light incident on the EDOF meta-optic 230. In such a case, the EDOF could be increased further (by selecting polarization) without refocusing or changing optical elements in the endoscope.

[0099] Color imaging can make the endoscope more desirable for widespread use. Because of the variation in refractive index with wavelength, there can be chromatic aberrations from the meta-optic imager 200 when imaging over the full visible wavelength band. For example, there may be differences in image size and/or image location for the different color bands (red, green, blue). To compensate for chromatic aberrations when color imaging, different PSFs can be used for the different color bands (wavelength ranges) to deconvolve recorded images. For example, a first PSF can be used for deconvolving images obtained by red pixels (corresponding to red wavelengths), a second, different PSF can be used for deconvolving images obtained by green pixels (corresponding to green wavelengths), and a third, different PSF can be used for deconvolving images obtained by blue pixels (corresponding to blue wavelengths). The different PSFs can be computed or measured from the meta-optic assembly 210 for a central wavelength in each color band.

[00100] The inventors also recognize that the bilayer EDOF and WFOV telecentric architecture may be suitable for full color imaging applications. For example, during the design phase, phase stability can be investigated additionally for changes in wavelengths spanning

some or all of the visible region. If the meta-atoms produce stable phase profiles over a range of wavelengths, then deconvolution with different PSFs may not be needed.

[00101] FIG. 11 depicts a microendoscope system 900 that comprises the meta-optical imager 200 disposed in an endoscope head 910. The microendoscope system 900 comprises the endoscope head 910, a flexible cable 920, a controller 930, and a display 940 (*e.g.*, an LED display screen) for displaying images acquired by the system. The endoscope head 910 can comprise the aperture 220, the EDOF meta-optic 230, and the WFOV metalens 240, examples of which are described above. The opening of the aperture 220 can have a radius in a range from 50 μm to 500 μm in some cases, or in a range from 25 μm to 100 μm in some cases. The EDOF meta-optic 230 can be disposed in the opening of the aperture 220. In some cases, the WFOV metalens 240 can be disposed on a first surface of a substrate and the aperture 220 and EDOF meta-optic 230 can be disposed on a second surface of the same substrate that is on a side of the substrate opposite the first surface (*e.g.*, on two surfaces of an optical flat).

[00102] The endoscope head 910 can further comprise an imaging array 250, described above in connection with FIG. 2A. The imaging array 250 can be located at an image plane of the WFOV metalens 240 to record a raw image of objects in a field of view of the endoscope head. The field of view can subtend an angle of at least 160 degrees. In some implementations, the aperture 220, the EDOF meta-optic 230, and the WFOV metalens 240 can be arranged within a volume no larger than 5 mm^3 within the endoscope head 910. The endoscope head 910 can be located at a distal end of the flexible cable 920, away from the controller 930. Data from the imaging array 250 can be transmitted via the flexible cable 920 to the controller 930.

[00103] The flexible cable 920 can comprise one or more conductive wires for powering the imaging array 250 and communicating with the imaging array 250 (*e.g.*, receiving image data from the imaging array). The endoscope head 910 can be mounted on a distal end of the flexible cable 920 and the flexible cable 920 can have an outer polymer sheath.

[00104] The flexible cable 920 can connect to the controller 930 which receives and processes data from the imaging array 250 in the endoscope head 910. The controller 930 can comprise processing circuitry that is used, at least in part, to deconvolve the raw images and generate resulting images for display on the display 940. Examples of components that could be included in the processing circuitry of the controller 930 include, but are not limited to, a microprocessor, a microcontroller, a field-programmable gate array (FPGA), a digital signal processor (DSP), discrete analog circuit components, digital logic chips, *etc.*

[00105] A microendoscope can be implemented in various configuration and operated in various ways, some of which are listed below.

- (1) A microendoscope comprising: a wide field-of-view metalens comprising a first plurality of meta-atoms disposed on a first surface; an aperture comprising an opening in a light-blocking layer of material that is disposed on a second surface that is separated by a distance d from the first surface, the aperture arranged to restrict a spatial extent of light received by the wide field-of-view metalens; and an extended depth-of-focus (EDOF) meta-optic comprising a second plurality of meta-atoms disposed on the second surface in the opening of the aperture, wherein the second plurality of meta-atoms is arranged to impart a phase profile across the opening to light passing through the opening and incident on the wide field-of-view metalens.
- (2) The microendoscope of configuration (1), wherein the phase profile imparted by the extended depth-of-focus meta-optic to light passing through the opening of the aperture to the wide field-of-view metalens comprises an axial redistribution phase profile.
- (3) The microendoscope of configuration (1), wherein the phase profile imparted by the extended depth-of-focus meta-optic to light passed through the opening of the aperture to the wide field-of-view metalens comprises an aberration-based phase profile.
- (4) The microendoscope of configuration (1), wherein the phase profile imparted by the extended depth-of-focus meta-optic to light passed through the opening of the aperture to the wide field-of-view metalens comprises an angular redistribution phase profile.
- (5) The microendoscope of configuration (1), wherein the phase profile imparted by the extended depth-of-focus meta-optic to light passed through the opening of the aperture to the wide field-of-view metalens is an inverse-design phase profile that generates a point spread function (PSF) with an extended depth of field.
- (6) The microendoscope of any one of configurations (1) through (5), further comprising: an imaging array arranged at an image plane of the wide field-of-view metalens to record a raw image produced by the wide field-of-view metalens and the extended depth-of-focus meta-optic at the image plane; and a controller communicatively coupled to the imaging array to deconvolve the raw image with a point spread function corresponding to the phase profile imparted by the extended depth-of-focus meta-optic.

- (7) The microendoscope of configuration (6), further comprising: a cable to connect the controller to the imaging array; and an endoscope head disposed at a distal end of the cable away from the controller, wherein the wide field-of-view metalens, the aperture, the extended depth-of-focus meta-optic, and the imaging array are disposed in the endoscope head.
- (8) The microendoscope of any one of configurations (1) through (7), wherein the first surface is located on a first side of a substrate and the second surface is located on a second side of the substrate that is opposite the first side.
- (9) The microendoscope of any one of configurations (1) through (8), wherein the wide field-of-view metalens, the aperture, and the extended depth-of-focus meta-optic are arranged within a volume that is no larger than 25 mm³.
- (10) The microendoscope of any one of configurations (1) through (9), wherein the opening of the aperture has a radius less than 500 microns.
- (11) The microendoscope of any one of configurations (1) through (10), wherein the second plurality of meta-atoms is configured to: impart a first phase profile to a first polarization state of the light passing through the opening; and impart a second phase profile to a second polarization state of the light passing through the opening.
- (12) The microendoscope of configuration (11), wherein the first phase profile is a cubic phase profile and the second phase profile is a log-asphere phase profile.
- (13) A method of imaging with a microendoscope, the method comprising: receiving light having a wavelength in a range from 450 nm to 1550 nm through an opening of an aperture from objects in a field of view subtending an angle of at least 160 degrees; imparting, with an extended depth-of-focus meta-optic disposed in the opening, a phase profile to the light; receiving, with a wide field-of-view metalens, the light from the extended depth-of-focus meta-optic; recording, with an imaging array, raw image data at an image plane of the wide field-of-view metalens; and deconvolving the raw image data with at least one point spread function (PSF) that corresponds to the phase profile imparted by the extended depth-of-focus meta-optic to produce an image of the objects in the field of view.
- (14) The method of (13), wherein imparting the phase profile comprises imparting a cubic phase profile to the light.

- (15) The method of (13), wherein imparting the phase profile comprises imparting a log-asphere phase profile to the light.
- (16) The method of (13), wherein imparting the phase profile comprises imparting a phase profile generating structured light that carries orbital angular momentum.
- (17) The method of (13), wherein imparting the phase profile comprises imparting an inverse-design phase profiles that generates a PSF with an extended depth of field.
- (18) The method of any one of (13) through (17), wherein deconvolving the raw image data comprises deconvolving the raw image data with only one PSF.
- (19) The method of any one of (13) through (17), wherein deconvolving the raw image data comprises: deconvolving the raw image data with a first PSF corresponding to a red wavelength range; deconvolving the raw image data with a second PSF corresponding to a green wavelength range; and deconvolving the raw image data with a third PSF corresponding to a blue wavelength range.
- (20) The method of any one of (13) through (19), wherein imparting the phase profile to the light with the extended depth-of-focus meta-optic comprises: imparting a first phase profile to a first polarization state of the light passing through the opening; and impart a second phase profile, different from the first phase profile, to a second polarization state of the light passing through the opening.

[00106] 8. Conclusion

[00107] While various inventive embodiments have been described and illustrated herein, those of ordinary skill in the art will readily envision a variety of other means and/or structures for performing the function and/or obtaining the results and/or one or more of the advantages described herein, and each of such variations and/or modifications is deemed to be within the scope of the inventive embodiments described herein. More generally, those skilled in the art will readily appreciate that all parameters, dimensions, materials, and configurations described herein are meant to be exemplary and that the actual parameters, dimensions, materials, and/or configurations will depend upon the specific application or applications for which the inventive teachings is/are used. Those skilled in the art will recognize or be able to ascertain, using no more than routine experimentation, many equivalents to the specific

inventive embodiments described herein. It is, therefore, to be understood that the foregoing embodiments are presented by way of example only and that inventive embodiments may be practiced otherwise than as specifically described. Inventive embodiments of the present disclosure are directed to each individual feature, system, article, material, kit, and/or method described herein. In addition, any combination of two or more such features, systems, articles, materials, kits, and/or methods, if such features, systems, articles, materials, kits, and/or methods are not mutually inconsistent, is included within the inventive scope of the present disclosure.

[00108] Also, various inventive concepts may be embodied as one or more methods, of which an example has been provided. The acts performed as part of the method may be ordered in any suitable way. Accordingly, embodiments may be constructed in which acts are performed in an order different than illustrated, which may include performing some acts simultaneously, even though shown as sequential acts in illustrative embodiments.

[00109] All definitions, as defined and used herein, should be understood to control over dictionary definitions, definitions in documents incorporated by reference, and/or ordinary meanings of the defined terms.

[00110] Unless stated otherwise, the terms “approximately” and “about” are used to mean within $\pm 20\%$ of a target (*e.g.*, dimension or orientation) in some embodiments, within $\pm 10\%$ of a target in some embodiments, within $\pm 5\%$ of a target in some embodiments, and yet within $\pm 2\%$ of a target in some embodiments. The terms “approximately” and “about” can include the target. The term “essentially” is used to mean within $\pm 3\%$ of a target.

[00111] The indefinite articles “a” and “an,” as used herein, unless clearly indicated to the contrary, should be understood to mean “at least one.”

[00112] The phrase “and/or,” as used herein, should be understood to mean “either or both” of the elements so conjoined, *i.e.*, elements that are conjunctively present in some cases and disjunctively present in other cases. Multiple elements listed with “and/or” should be construed in the same fashion, *i.e.*, “one or more” of the elements so conjoined. Other elements may optionally be present other than the elements specifically identified by the “and/or” clause, whether related or unrelated to those elements specifically identified. Thus, as a non-limiting example, a reference to “A and/or B”, when used in conjunction with open-ended language such as “comprising” can refer, in one embodiment, to A only (optionally including elements

other than B); in another embodiment, to B only (optionally including elements other than A); in yet another embodiment, to both A and B (optionally including other elements); etc.

[00113] As used herein, “or” should be understood to have the same meaning as “and/or” as defined above. For example, when separating items in a list, “or” or “and/or” shall be interpreted as being inclusive, i.e., the inclusion of at least one, but also including more than one, of a number or list of elements, and, optionally, additional unlisted items. Only terms clearly indicated to the contrary, such as “only one of” or “exactly one of” or “consisting of,” will refer to the inclusion of exactly one element of a number or list of elements. In general, the term “or” as used herein shall only be interpreted as indicating exclusive alternatives (i.e., “one or the other but not both”) when preceded by terms of exclusivity, such as “either,” “one of,” “only one of,” or “exactly one of.” “Consisting essentially of,” shall have its ordinary meaning as used in the field of patent law.

[00114] As used herein, the phrase “at least one,” in reference to a list of one or more elements, should be understood to mean at least one element selected from any one or more of the elements in the list of elements, but not necessarily including at least one of each and every element specifically listed within the list of elements and not excluding any combinations of elements in the list of elements. This definition also allows that elements may optionally be present other than the elements specifically identified within the list of elements to which the phrase “at least one” refers, whether related or unrelated to those elements specifically identified. Thus, as a non-limiting example, “at least one of A and B” (or, equivalently, “at least one of A or B,” or, equivalently “at least one of A and/or B”) can refer, in one embodiment, to at least one, optionally including more than one, A, with no B present (and optionally including elements other than B); in another embodiment, to at least one, optionally including more than one, B, with no A present (and optionally including elements other than A); in yet another embodiment, to at least one, optionally including more than one, A, and at least one, optionally including more than one, B (and optionally including other elements); etc.

[00115] In the specification above, all transitional phrases such as “comprising,” “including,” “carrying,” “having,” “containing,” “involving,” “holding,” “composed of,” and the like are to be understood to be open-ended, i.e., to mean including but not limited to. Only the transitional phrases “consisting of” and “consisting essentially of” shall be closed or semi-closed transitional phrases, respectively, as set forth in the United States Patent Office Manual of Patent Examining Procedures, Section 2111.03.

CLAIMS

1. A microendoscope comprising:
 - a wide field-of-view metalens comprising a first plurality of meta-atoms disposed on a first surface;
 - an aperture comprising an opening in a light-blocking layer of material that is disposed on a second surface that is separated by a distance d from the first surface, the aperture arranged to restrict a spatial extent of light received by the wide field-of-view metalens; and
 - an extended depth-of-focus (EDOF) meta-optic comprising a second plurality of meta-atoms disposed on the second surface in the opening of the aperture, wherein the second plurality of meta-atoms is arranged to impart a phase profile across the opening to light passing through the opening and incident on the wide field-of-view metalens.
2. The microendoscope of claim 1, wherein the phase profile imparted by the extended depth-of-focus meta-optic to light passing through the opening of the aperture to the wide field-of-view metalens comprises an axial redistribution phase profile.
3. The microendoscope of claim 1, wherein the phase profile imparted by the extended depth-of-focus meta-optic to light passed through the opening of the aperture to the wide field-of-view metalens comprises an aberration-based phase profile.
4. The microendoscope of claim 1, wherein the phase profile imparted by the extended depth-of-focus meta-optic to light passed through the opening of the aperture to the wide field-of-view metalens comprises an angular redistribution phase profile.
5. The microendoscope of claim 1, wherein the phase profile imparted by the extended depth-of-focus meta-optic to light passed through the opening of the aperture to the wide field-of-view metalens is an inverse-design phase profile that generates a point spread function (PSF) with an extended depth of field.
6. The microendoscope of any one of claims 2 through 5, further comprising:
 - an imaging array arranged at an image plane of the wide field-of-view metalens to record a raw image produced by the wide field-of-view metalens and the extended depth-of-focus meta-optic at the image plane; and

a controller communicatively coupled to the imaging array to deconvolve the raw image with a point spread function corresponding to the phase profile imparted by the extended depth-of-focus meta-optic.

7. The microendoscope of claim 6, further comprising:
 - a cable to connect the controller to the imaging array; and
 - an endoscope head disposed at a distal end of the cable away from the controller, wherein the wide field-of-view metalens, the aperture, the extended depth-of-focus meta-optic, and the imaging array are disposed in the endoscope head.
8. The microendoscope of claim 1, wherein the first surface is located on a first side of a substrate and the second surface is located on a second side of the substrate that is opposite the first side.
9. The microendoscope of claim 1, wherein the wide field-of-view metalens, the aperture, and the extended depth-of-focus meta-optic are arranged within a volume that is no larger than 25 mm³.
10. The microendoscope of claim 1, wherein the opening of the aperture has a radius less than 500 microns.
11. The microendoscope of claim 1, wherein the second plurality of meta-atoms is configured to:
 - impart a first phase profile to a first polarization state of the light passing through the opening; and
 - impart a second phase profile to a second polarization state of the light passing through the opening.
12. The microendoscope of claim 11, wherein the first phase profile is a cubic phase profile and the second phase profile is a log-asphere phase profile.
13. A method of imaging with a microendoscope, the method comprising:
 - receiving light having a wavelength in a range from 450 nm to 1550 nm through an opening of an aperture from objects in a field of view subtending an angle of at least 160 degrees;
 - imparting, with an extended depth-of-focus meta-optic disposed in the opening, a

phase profile to the light;

receiving, with a wide field-of-view metalens, the light from the extended depth-of-focus meta-optic;

recording, with an imaging array, raw image data at an image plane of the wide field-of-view metalens; and

deconvolving the raw image data with at least one point spread function (PSF) that corresponds to the phase profile imparted by the extended depth-of-focus meta-optic to produce an image of the objects in the field of view.

14. The method of claim 13, wherein imparting the phase profile comprises imparting a cubic phase profile to the light.

15. The method of claim 13, wherein imparting the phase profile comprises imparting a log-asphere phase profile to the light.

16. The method of claim 13, wherein imparting the phase profile comprises imparting a phase profile generating structured light that carries orbital angular momentum.

17. The method of claim 13, wherein imparting the phase profile comprises imparting an inverse-design phase profiles that generates a PSF with an extended depth of field.

18. The method of claim 13, wherein deconvolving the raw image data comprises deconvolving the raw image data with only one PSF.

19. The method of claim 13, wherein deconvolving the raw image data comprises:
deconvolving the raw image data with a first PSF corresponding to a red wavelength range;

deconvolving the raw image data with a second PSF corresponding to a green wavelength range; and

deconvolving the raw image data with a third PSF corresponding to a blue wavelength range.

20. The method of claim 13, wherein imparting the phase profile to the light with the extended depth-of-focus meta-optic comprises:

imparting a first phase profile to a first polarization state of the light passing through the opening; and

impart a second phase profile, different from the first phase profile, to a second polarization state of the light passing through the opening.