

OPTICAL SYSTEM AND METHOD OF FORMING THE SAME, METHOD OF FORMING A MULTI-COLOR IMAGE

TECHNICAL FIELD

[0001] Various embodiments of this disclosure may relate to an optical system. Various embodiments of this disclosure may relate to a method of forming an optical system. Various embodiments of this disclosure may relate to a method of forming a multi-color image.

BACKGROUND

[0002] Conventional refractive lenses are at the core of most imaging systems. However, high-end imaging systems are generally made of complex optical trains (i.e. assemblies of lenses and/or other optical elements that guide the incoming light towards a detector), in order to produce high resolution images with minimum optical aberrations, e.g. microscope objectives or photographic objectives. As a result, such imaging systems are overall bulky and heavy. On the other hand, for certain applications, it is highly desirable to have an imaging system as lightweight and compact as possible without compromising the imaging quality, e.g. for cell-phones cameras, drone cameras, satellites cameras, endoscopes camera. Recent developments in diffractive optics and flat optics hold the promise to replace traditional optical trains with only a few elements, or even a single one, having ultra-thin character (i.e. with thickness below or around the wavelength of incident light). This can be accomplished using diffractive lenses or flat lenses (the latter also called metalenses).

[0003] The role of a conventional refractive lens is to reshape the planar wavefront of an incoming light into a spherical wavefront, in order to focus light into a near diffraction-limited spot. The underlying physical mechanism involves a phase accumulation by light propagation through the material presenting a varying thickness in the propagation direction across the lens. A refractive lens is usually made of at least one hemispherical surface with a certain radius of curvature leading to a relatively thick device. Its diffractive counterparts, referred to as conventional diffractive lenses (CDL), restrict this phase modulation to its minimum, 2π , which allows to reduce considerably the thickness of the lens to, typically, a maximum thickness slightly larger than the wavelength of the light.

[0004] Diffractive lenses, however, suffer from severe chromatic aberrations due to their diffractive nature, i.e. they only focus a single wavelength (the design wavelength) at the

desired position, while the other wavelengths are not focused at the same position: the longer wavelengths are focused closer to the lens, and the shorter ones further away. The chromatic aberrations lead to blurred images and rainbow effects. This chromatic aberration of CDL, where the longer wavelengths are focused closer to the lens, and the shorter ones further away, is different than the usual chromatic aberration of refractive lenses, which is due to the material dispersion (i.e. change of the material refractive index with wavelength). One talks about positive chromatic dispersion for refractive lenses and negative chromatic dispersion for diffractive lenses. FIG. 1 provides an illustration of chromatic aberrations for (a) conventional refractive lenses and (b) diffractive lenses. Wavelengths $\lambda_1 > \lambda_2 > \lambda_3$ are focused at different places along the optical axis. Refractive lenses exhibit positive dispersion, while diffractive lenses exhibit negative.

[0005] More recently, with the advancements of nanofabrication techniques, other physical mechanisms for phase modulation have been explored and exploited. They are based on the interaction of light with nanostructures patterned on a flat surface, called meta-atoms, which impart locally a certain phase delay to the light. The main mechanisms are wave-guiding, geometrical phase and resonant interaction, and each of these mechanisms has different advantages and limitations. Typically, the meta-atoms restrict the phase modulation to 2π , and are smaller than the wavelength of interest in all directions (with the possible exception of the direction of light propagation, for which they might also have dimensions around the wavelength). Recent realization of extremely thin focusing surfaces based on this paradigm, called metalenses, demonstrated that they can outperform diffractive lenses in terms of numerical aperture (NA) and focusing efficiency, making them more promising candidates to replace refractive lenses.

[0006] However, there are mostly two impeding challenges that still limit the applicability of metalenses. Firstly, like diffractive lenses, they suffer from strong negative chromatic dispersion. Secondly, most of metalenses so far suffer from off-axis monochromatic aberrations (distortions on the focal spot when the angle of incidence is non-zero), namely coma and astigmatism, thereby considerably limiting the ability of the lens to focus the light to a good quality spot when the incoming light impinges with oblique incidence to the lens. The range of incidence angles for which the lens is able to produce good quality focusing is called the field-of-view (FOV). A large field of view is important for applications in imaging. These

two challenges prevent so far metalenses from being widely used and from replacing their refractive counterparts for multispectral and broadband imaging.

SUMMARY

[0007] Various embodiments may relate to an optical system. The optical system may include a plurality of color filters, a first color filter of the plurality of color filters configured to select light of a first wavelength range representing a first color channel, and a second color filter of the plurality of color filters configured to select light of a second wavelength range different from the first wavelength range, the light of the second wavelength range representing a second color channel, such that the plurality of color filters provide different color channels. The optical system may also include a plurality of metalenses, each of the plurality of metalenses associated with a respective color channel of the plurality of color channels. Each of the plurality of metalenses may have a focal length, the plurality of metalenses having equal focal lengths such that the different color channels are combined on a common focal plane to form a multi-color image. Each of the plurality of metalenses may include a plurality of nanostructures and may have a (FOV) field of view of more than 30 degrees. Each of the plurality of metalenses may have a desired working spectral bandwidth dependent on an extended depth of focus, a central wavelength of the associated color channel, and the focal length at the central wavelength.

[0008] Various embodiments may relate to a method of forming an optical system. The method may include providing a plurality of color filters, a first color filter of the plurality of color filters configured to select light of a first wavelength range representing a first color channel, and a second color filter of the plurality of color filters configured to select light of a second wavelength range different from the first wavelength range, the light of the second wavelength range representing a second color channel, such that the plurality of color filters provide different color channels. The method may also include providing a plurality of metalenses, each of the plurality of metalenses associated with a respective color channel of the plurality of color channels. Each of the plurality of metalenses has a focal length, the plurality of metalenses having equal focal lengths such that the different color channels are combined on a common focal plane to form a multi-color image. Each of the plurality of metalenses may include a plurality of nanostructures and may have a (FOV) field of view of more than 30 degrees. Each of the plurality of metalenses may have a desired working spectral

bandwidth dependent on an extended depth of focus, a central wavelength of the associated color channel, and the focal length at the central wavelength.

[0009] Various embodiments may provide a method of forming a multi-color image. The method may include in providing a broadband light to an optical system. The optical system may be any suitable optical system as described herein. The optical system may include a plurality of color filters, a first color filter of the plurality of color filters configured to select light of a first wavelength range representing a first color channel, and a second color filter of the plurality of color filters configured to select light of a second wavelength range different from the first wavelength range, the light of the second wavelength range representing a second color channel, such that the plurality of color filters provide different color channels. The optical system may also include a plurality of metalenses, each of the plurality of metalenses associated with a respective color channel of the plurality of color channels. Each of the plurality of metalenses may have a focal length, the plurality of metalenses having equal focal lengths such that the different color channels are combined on a common focal plane to form the multi-color image. Each of the plurality of metalenses may include a plurality of nanostructures and has a field of view of more than 30 degrees. Each of the plurality of metalenses may have a desired working spectral bandwidth dependent on an extended depth of focus, a central wavelength of the associated color channel, and the focal length at the central wavelength.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] In the drawings, like reference characters generally refer to the same parts throughout the different views. The drawings are not necessarily drawn to scale, emphasis instead generally being placed upon illustrating the principles of various embodiments. In the following description, various embodiments of the invention are described with reference to the following drawings.

FIG. 1 provides an illustration of chromatic aberrations for (a) conventional refractive lenses and (b) diffractive lenses, in which $\lambda_1 > \lambda_2 > \lambda_3$ are focused at different places along the optical axis.

FIG. 2 is a general illustration of an optical system according to various embodiments.

FIG. 3 is a general illustration of a method of forming an optical system according to various embodiments.

FIG. 4 is a general illustration of a method of forming a multi-color image according to various embodiments.

FIG. 5A shows a schematic of an optical system according to various embodiments.

FIG. 5B shows a schematic of another optical system according to various embodiments.

FIG. 5C shows a schematic of yet another optical system according to various embodiments.

FIG. 5D shows a schematic of one particular embodiment of the optical system to achieve red-green-blue (RGB) imaging, where each metalens is optimized for corresponding central wavelengths in the red ($\lambda_R=620$ nm), green ($\lambda_G=530$ nm) and blue ($\lambda_B=460$ nm) regions.

FIG. 6 illustrates possible examples of nanoantennas according to various embodiments.

FIG. 7 shows an example of a lateral projection of metalenses collection according to various embodiments.

FIG. 8A is a plot of transmission as a function of duty cycle showing the simulated transmission values (obtained using the finite-difference time-domain (FDTD) method) of the metalenses including the nanopillars according to various embodiments.

FIG. 8B is a plot of transmission as a function of duty cycle showing the simulated phase values (obtained using the finite-difference time-domain (FDTD) method) of the metalenses including the nanopillars according to various embodiments.

FIG. 8C shows (above) the optical microscope images and (below) the scanning electron microscopy (SEM) images of the fabricated red (R), green (G) and blue (B) metalenses according to various embodiments.

FIG. 9 shows (a) – (c) plots of the modulation transfer function (MTF) as a function of spatial frequencies (cycles per millimetre or cycles/mm) showing the MTF simulation values of a red quadratic lens with ideal quadratic phase profile according to various embodiments designed to work in the red (R) region (central wavelength $\lambda_R = 620$ nm) for angles of incidence $\phi = 0^\circ$, 30° and 50° and bandwidths around the central wavelengths $\Delta\lambda = 10$ nm, 20 nm, 30 nm and 40 nm, and (d) – (f) the point spread function (PSF) corresponding to the conditions in (a) – (c) respectively.

FIG. 10 shows (a) – (c) plots of the modulation transfer function (MTF) as a function of spatial frequencies (cycles per millimetre or cycles/mm) showing the MTF measurements of a red quadratic lens with ideal quadratic phase profile according to various embodiments designed to work in the red (R) region (central wavelength $\lambda_R = 620$ nm) for angles of incidence $\phi = 0^\circ$, 30° and 50° and bandwidths around the central wavelengths $\Delta\lambda = 10$ nm,

20 nm, 30 nm and 40 nm, and (d) – (f) the point spread function (PSF) corresponding to the conditions in (a) – (c) respectively.

FIG. 11 shows (a) a schematic of an optical system including a plurality of apertures according to various embodiments; (b) a plot of the modulation transfer function (MTF) as a function of spatial frequencies (cycles per millimetre or cycles/mm) showing the MTF simulation values of a red quadratic metalens (central wavelength $\lambda_R = 620$ nm) with and without an aperture stop according to various embodiments for an angle of incidence $\phi = 0^\circ$; and (c) a plot of the modulation transfer function (MTF) as a function of spatial frequencies (cycles per millimetre or cycles/mm) showing the MTF simulation values of a red quadratic metalens (central wavelength $\lambda_R = 620$ nm) with and without an aperture stop according to various embodiments for an angle of incidence $\phi = 30^\circ$.

FIG. 12 shows the monochromatic imaging simulations for hyperbolic phase profile metalenses and quadratic phase profile metalenses according to various embodiments for angle of incidence $\phi = 0^\circ$.

FIG. 13 shows (a) the original standard ColorChecker test chart with 24 painted patches; (b) the result of red-green-blue (RGB) imaging by the optical system according to various embodiments for field of view (FOV) of $30^\circ \times 20^\circ$; and (c) the result of red-green-blue (RGB) imaging by the optical system according to various embodiments for field of view (FOV) of $100^\circ \times 67^\circ$.

FIG. 14 shows (a) the color ΔE for the ColorChecker red-green-blue (RGB) with field of view (FOV) of $30^\circ \times 20^\circ$ according to various embodiments; (b) the color ΔE for the ColorChecker red-green-blue (RGB) with field of view (FOV) of $100^\circ \times 67^\circ$ according to various embodiments; and (c) the color error (left) and the obtained red-green-blue (RGB) image (right) after the efficiency correction procedure for FOV of $100^\circ \times 67^\circ$ according to various embodiments.

FIG. 15 shows (a) a plot of efficiency (in percent or %) as a function of angle (in degrees) showing the angular dependence of the focusing efficiency at bandwidths around the central wavelengths ($\Delta\lambda$) of 10 nm, 20 nm, 30 nm and 40 nm for the red metalens according to various embodiments; (b) a plot of efficiency (in percent or %) as a function of angle (in degrees) showing the angular dependence of the focusing efficiency at bandwidths around the central wavelengths ($\Delta\lambda$) of 10 nm, 20 nm, 30 nm and 40 nm for the green metalens according to various embodiments; and (c) a plot of efficiency (in percent or %) as a function

of angle (in degrees) showing the angular dependence of the focusing efficiency at bandwidths around the central wavelengths ($\Delta\lambda$) of 10 nm, 20 nm, 30 nm and 40 nm for the blue metalens according to various embodiments.

FIG. 16 shows (a) an original still image; (b) the results of red-green-blue (RGB) imaging by an optical system with field of view (FOV) of $50^\circ \times 35^\circ$ according to various embodiments; and (c) the results of red-green-blue (RGB) imaging by an optical system with field of view (FOV) of $100^\circ \times 67^\circ$ according to various embodiments.

FIG. 17 is a table comparing an embodiment with a typical cellphone camera and a conventional diffractive lens.

DESCRIPTION

[0011] The following detailed description refers to the accompanying drawings that show, by way of illustration, specific details and embodiments in which the invention may be practised. These embodiments are described in sufficient detail to enable those skilled in the art to practise the invention. Other embodiments may be utilized and structural, logical, and electrical changes may be made without departing from the scope of the invention. The various embodiments are not necessarily mutually exclusive, as some embodiments can be combined with one or more other embodiments to form new embodiments.

[0012] Embodiments described in the context of one of the optical systems/methods are analogously valid for the other optical systems/methods. Similarly, embodiments described in the context of a method are analogously valid for an optical system/method, and vice versa.

[0013] Features that are described in the context of an embodiment may correspondingly be applicable to the same or similar features in the other embodiments. Features that are described in the context of an embodiment may correspondingly be applicable to the other embodiments, even if not explicitly described in these other embodiments. Furthermore, additions and/or combinations and/or alternatives as described for a feature in the context of an embodiment may correspondingly be applicable to the same or similar feature in the other embodiments.

[0014] In the context of various embodiments, the articles “a”, “an” and “the” as used with regard to a feature or element include a reference to one or more of the features or elements.

[0015] In the context of various embodiments, the term “about” or “approximately” as applied to a numeric value encompasses the exact value and a reasonable variance.

[0016] As used herein, the term “and/or” includes any and all combinations of one or more of the associated listed items.

[0017] Diffractive lenses for chromatic compensation

[0018] In order to address the problem of the chromatic aberrations, different approaches have been considered. A so-called achromatic diffractive lens (ADL) can be used to operate at high diffraction orders and provide the same deflection angle for several discrete harmonic wavelengths. Though advanced numerical optimization can help to increase the focusing efficiency, a recent study demonstrated considerable limitation of the achievable Fresnel number (FN), which translates to a limited numerical aperture (NA) or lens size for a given focal length. Also, it should be noted that diffractive lenses suffer from parasitic interferences and shadowing effects inherent to their blazed profiles, which, in turn, limits their acceptable angles of incidence, i.e. their FOV.

[0019] Metalenses for chromatic compensation

[0020] Due to chromatic aberrations, and without further corrections, a single metalens cannot achieve imaging covering the whole visible range (white light imaging). Initially, the coverage of the visible spectrum was realized by using separate metasurfaces for each individual wavelength - red, green, blue (RGB) or even more additional colours. Another approach was adopted by cascading different metalenses (i.e. a stack of several metalenses) designed to operate at different wavelengths, which allows to compensate not only for chromatic aberrations but also for monochromatic one. These stacks of metalenses are however, difficult to design if inter-layer coupling and/or reflection is to be taken into account and/or minimized. Moreover, the required sophisticated fabrication and alignment processes present a serious challenge for their practical applications.

[0021] Further developments of metalens designs aimed at correcting this chromatic aberration within a single element, called a multispectral or broadband achromatic metalens, that focuses several discrete or a continuous range of wavelengths onto a single spot.

[0022] Different forward design approaches have been proposed:

[0023] (i) Spatial multiplexing of different meta-atoms inside a metalens “unit-cell”, each designed to manipulate a specific wavelength. In this case, however, interparticle coupling hinders the resolution and image quality. In addition to this, the associated efficiency drop as the number of wavelengths is increased translates into a low number of operational wavelengths and represents the main bottleneck of this solution.

[0024] (ii) Use of a single metalens with non-intuitive point spread function (PSF), typically leading to a largely extended depth of focus, enough to partially compensate for the chromatic focal shift. This needs to be followed by image processing techniques for image recovery, which introduces a delay time to process the image which can be problematic for real-time imaging applications.

[0025] (iii) Dispersion engineering of the individual meta-atoms, manipulating not only the imparted phase to the incident light, but also its group delay and group delay dispersion. Initial attempts to employ this approach used libraries of simple intuitive geometrical shapes. However, as these libraries typically cover only a part of the required phase and group delay variations, the success of this approach was limited to metalenses of very small sizes, efficiencies, NAs and FOVs.

[0026] Recently, computer algorithm-based optimization of meta-atoms and machine learning methods have somehow helped in designing multispectral and broadband achromatic metalenses with higher performances, using inverse design techniques. However, those methods often require high computational power and come at a cost of fabrication complexity, strong interparticle coupling and strong sensitivity to the polarization and angle of incidence of impinging light. Advancements in this area have allowed to overcome some of the mentioned issues in multispectral imaging, e.g. regarding relatively large metalens size and NA.

[0027] Metalenses for large field-of-view

[0028] With respect to the FOV, it should be noted that it explicitly depends on the type of phase profile encoded by the metalens. For example, the hyperbolic phase profile, a common standard for metalens design, produces an almost diffraction limited spot and high-NA when light impinges the metalens at normal incidence, while presenting strong coma and astigmatism aberrations for oblique incidence, which drastically limit their FOV to a few-degrees angle of incidence. Recently introduced quadratic phase profiles alleviate those limits on the FOV making this kind of metalenses a very attractive solution for imaging applications. Yet another alternative solution tackles the problem of limited FOV using doublets, introducing, however, a strong complexity in the fabrication.

[0029] The attempts mentioned above address the problems of achromatic imaging and wide FOV imaging separately, and there is no solution that perform both wide field-of-view (FOV) and multispectral or broadband achromatic imaging together.

[0030] Various embodiments may achieve compact wide field-of-view (FOV) and multispectral imaging, including white light imaging, simultaneously.

[0031] FIG. 2 is a general illustration of an optical system according to various embodiments. The optical system may include a plurality of color filters 202, a first color filter of the plurality of color filters 202 configured to select light of a first wavelength range representing a first color channel, and a second color filter of the plurality of color filters 202 configured to select light of a second wavelength range different from the first wavelength range, the light of the second wavelength range representing a second color channel, such that the plurality of color filters 202 provide different color channels. The optical system may also include a plurality of metalenses 204, each of the plurality of metalenses 204 associated with a respective color channel of the plurality of color channels. Each of the plurality of metalenses may have a focal length, the plurality of metalenses 204 having equal focal lengths such that the different color channels are combined on a common focal plane to form a multi-color image. Each of the plurality of metalenses 204 may include a plurality of nanostructures and may have a (FOV) field of view of more than 30 degrees. Each of the plurality of metalenses 204 may have a desired working spectral bandwidth dependent on an extended depth of focus, a central wavelength of the associated color channel, and the focal length at the central wavelength.

[0032] In other words, the plurality of color filters 202 are configured to filter light into different color channels, with each color channel having different range of wavelengths. The optical system may also include a plurality of metalenses 204 having equal focal lengths so that the different color channels are able to be focused onto a common focal plane to form a multi-color image.

[0033] For avoidance of doubt, FIG. 2 illustrates some of the features of an optical system according to various embodiments, and are not intended to limit the arrangement, orientation, shape, size etc. of the various features.

[0034] In various embodiments, the optical system may include one or more detectors defining the common focal plane.

[0035] In various embodiments, the plurality of color filters 202 may be internal bandpass filters of the one or more detectors. In other words, each color filter of the plurality of color filters 202 may be part of a respective detector of the one or more detectors.

[0036] In various other embodiments, the plurality of color filters 202 may be external to the one or more detectors. In other words, the plurality of color filters 202 may be separate from the one or more detectors.

[0037] In various embodiments, the plurality of metalenses 204 may be quadratic metalenses. In other words, the plurality of metalenses 204 may provide a quadratic phase profile. As mentioned above, each of the plurality of metalenses 204 may include a plurality of nanostructures. The specific arrangement of the plurality of nanostructures in each of the plurality of metalenses may provide a quadratic phase profile. Such a quadratic phase profile may intrinsically present a certain depth of focus (DOF), e.g. any value from about 5% to about 10% of the focal length (or focal distance) for red, green and blue (RGB) wavelengths according to various embodiments. For instance, for a focal length of 83 μm , the DOF may be any value from about 5 μm to about 7 μm for red, green and blue (RGB) wavelengths. In various other embodiments, the phase profile (i.e. the arrangement of nanostructures within each metalens of the plurality of metalenses 204) may be chosen differently, and such that the extended DOF is different, e.g. larger, than that provided by quadratic metalenses. In various embodiments, the DOF of the plurality of metalenses 204 may be engineered to provide a larger desired working spectral bandwidth.

[0038] In various embodiments, the plurality of color filters 202 may be arranged between the plurality of metalenses 204 and the common focal plane, such that each of the plurality of metalenses 204 is configured to direct a broadband light to an associated color filter of the plurality of color filters 202 to generate the respective associated color channel. Each metalens of the plurality of metalenses 204 associated with a particular color channel may direct a portion of the broadband light to the associated color filter of the plurality of color filters 202 to generate the respective associated color channel.

[0039] In various other embodiments, the plurality of metalenses 204 may be arranged between the plurality of color filters 202 and the common focal plane, such that each of the plurality of metalenses 204 is configured to direct the light of the respective associated color channel onto the common focal plane.

[0040] In various embodiments, each of the plurality of metalenses 204 may have a Fresnel number, the plurality of metalenses 204 having different Fresnel numbers, such that the plurality of metalenses 204 have equal focal lengths.

[0041] In various embodiments, the nanostructures of each of the plurality of metalenses 204 may be arranged in a periodic lattice having a predetermined period. In various embodiments, Fresnel numbers of different metalenses of the plurality of metalenses 204 may be different due to the different predetermined periods of the different metalenses (of the plurality of metalenses 204).

[0042] In various embodiments, the periodic lattice may be a square lattice, a rectangular lattice, a hexagonal lattice, or any other common periodic or quasi-periodic Bravais lattice.

[0043] In various embodiments, the optical system may further include a plurality of apertures arranged before the plurality of metalenses 204. Each of the plurality of apertures may be associated with a respective metalens of the plurality of metalenses 204. In various embodiments, the plurality of apertures may together with the plurality of metalenses 204 be arranged such that the plurality of color filters 202 may be arranged between the plurality of metalenses 204 (as well as the plurality of apertures) and the common focal plane. In such a case, the plurality of apertures may be arranged before the plurality of metalenses 204, while the plurality of color filters 202 may be arranged after the plurality of metalenses 204 (and before the common focal plane). In other words, the plurality of metalenses 204 may be arranged between the plurality of apertures and the plurality of color filters 202. In various other embodiments, the plurality of apertures may together with the plurality of metalenses 204 be arranged such that the plurality of metalenses 204 (as well as the plurality of apertures) is arranged between the plurality of color filters 202 and the common focal plane. In such a case, the plurality of apertures may be arranged before the plurality of metalenses 204 and after the plurality of color filters 202, i.e. between the plurality of color filters 202 and the plurality of metalenses 204.

[0044] In various embodiments, the plurality of metalenses 204 may be made of a material having a refractive index equal to or greater than 2.

[0045] In various embodiments, the plurality of metalenses 204 may include a suitable dielectric material or a suitable semiconductor material.

[0046] In various embodiments, the plurality of metalenses 204 may include silicon, gallium phosphide, hafnium oxide, gallium nitride, titanium dioxide, and silicon nitride, sapphire, diamond, silicon carbide, aluminium nitride, a III-V semiconductor (e.g. gallium arsenide or gallium phosphide), or a II-VI semiconductor (e.g. zinc oxide or magnesium oxide).

[0047] In various embodiments, heights or thicknesses of the plurality of metalenses 204 may be equal. The optical system may include a substrate. The plurality of metalenses 204 may be on the substrate. As the plurality of metalenses are formed on the same planar substrate, the top surfaces of the plurality of metalenses 204 may be of the same height level. The substrate may allow light to pass through.

[0048] In various embodiments, the plurality of nanostructures may be nanopillars. The nanopillars may have an arbitrary cross-section, such as circular, elliptical, rectangular, triangular, polygonal, freeform etc.

[0049] In various embodiments, the plurality of nanostructures 204 may be nanoantennas, i.e. able to support one or more optical resonances.

[0050] In various embodiments, the plurality of color channels may represent different spectral ranges of electromagnetic light.

[0051] In various embodiments, the plurality of color channels may be spectrally adjacent to one another or may be overlapping. In various embodiments, the plurality of color channels may collectively cover a continuous spectrum of wavelengths. In various embodiments, the plurality of color channels may be or may include a red (R) channel, a green (G) channel and a blue (B) channel. The bluechannel may have a central wavelength of about 460 nm, the green channel may have a central wavelength of about 530 nm, while the red channel may have a central wavelength of about 620 nm. The bandwidth of each channel may be about 40 nm.

[0052] FIG. 3 is a general illustration of a method of forming an optical system according to various embodiments. The method may include, in 302, providing a plurality of color filters, a first color filter of the plurality of color filters configured to select light of a first wavelength range representing a first color channel, and a second color filter of the plurality of color filters configured to select light of a second wavelength range different from the first wavelength range, the light of the second wavelength range representing a second color channel, such that the plurality of color filters provide different color channels. The method may also include, in 304, providing a plurality of metalenses, each of the plurality of metalenses associated with a respective color channel of the plurality of color channels. Each of the plurality of metalenses has a focal length, the plurality of metalenses having equal focal lengths such that the different color channels are combined on a common focal plane to form a multi-color image. Each of the plurality of metalenses may include a plurality of nanostructures and may have a (FOV) field of view of more than 30 degrees. Each of the plurality of metalenses may have a desired

working spectral bandwidth dependent on an extended depth of focus, a central wavelength of the associated color channel, and the focal length at the central wavelength.

[0053] For avoidance of doubt, FIG. 3 seeks to illustrate some of the steps in forming the optical system according to various embodiments, and is not intended to limit the sequences of the various steps. For instance, step 302 can occur before, after or at the same time as step 304.

[0054] In various embodiments, the method may also include forming or providing one or more detectors defining the common focal plane. In various embodiments, the plurality of color filters may be internal bandpass filters of the one or more detectors. In various other embodiments, the plurality of color filters may be external to the one or more detectors.

[0055] In various embodiments, the plurality of color filters may be arranged between the plurality of metalenses and the common focal plane, such that each of the plurality of metalenses is configured to direct a broadband light to an associated color filter of the plurality of color filters to generate the respective associated color channel. In various other embodiments, the plurality of metalenses may be arranged between the plurality of color filters and the common focal plane, such that each of the plurality of metalenses is configured to direct the light of the respective associated color channel onto the common focal plane.

[0056] In various embodiments, each of the plurality of metalenses may have a Fresnel number, the plurality of metalenses having different Fresnel numbers, such that the plurality of metalenses have equal focal lengths.

[0057] In various embodiments, the nanostructures of each of the plurality of metalenses may be arranged in a periodic lattice having a predetermined period. In various embodiments, Fresnel numbers of different metalenses of the plurality of metalenses may be different due to the different predetermined periods of the different metalenses (of the plurality of metalenses).

[0058] In various embodiments, the periodic lattice may be a square lattice, a rectangular lattice, a hexagonal lattice, or any other common periodic or quasi-periodic Bravais lattice.

[0059] In various embodiments, the method may further include providing or forming a plurality of apertures arranged before the plurality of metalenses.

[0060] In various embodiments, the plurality of metalenses may be made of a material having a refractive index equal to or greater than 2.

[0061] In various embodiments, the plurality of metalenses may include a suitable dielectric material or a suitable semiconductor material.

[0062] In various embodiments, the plurality of metalenses may include silicon, gallium phosphide, hafnium oxide, gallium nitride, titanium dioxide, and silicon nitride, sapphire, diamond, silicon carbide, aluminium nitride, a III-V semiconductor (e.g. gallium arsenide or gallium phosphide), or a II-VI semiconductor (e.g. zinc oxide or magnesium oxide).

[0063] In various embodiments, heights of the plurality of metalenses may be equal. The optical system may include a substrate. The plurality of metalenses may be on the substrate. The substrate may allow light to pass through.

[0064] In various embodiments, the plurality of nanostructures may be nanopillars. The nanopillars may have an arbitrary cross-section, such as circular, elliptical, rectangular, triangular, polygonal, freeform etc.

[0065] In various embodiments, the plurality of nanostructures may be nanoantennas, i.e. able to support one or more optical resonances.

[0066] In various embodiments, the plurality of color channels may represent different spectral ranges of electromagnetic light.

[0067] In various embodiments, the plurality of color channels may be spectrally adjacent to one another or may be overlapping. In various embodiments, the plurality of color channels may be or may include a red (R) channel, a green (G) channel and a blue (B) channel.

[0068] FIG. 4 is a general illustration of a method of forming a multi-color image according to various embodiments. The method may include in, 402, providing a broadband light to an optical system. The optical system may be any suitable optical system as described herein. The optical system may include a plurality of color filters, a first color filter of the plurality of color filters configured to select light of a first wavelength range representing a first color channel, and a second color filter of the plurality of color filters configured to select light of a second wavelength range different from the first wavelength range, the light of the second wavelength range representing a second color channel, such that the plurality of color filters provide different color channels. The optical system may also include a plurality of metalenses, each of the plurality of metalenses associated with a respective color channel of the plurality of color channels. Each of the plurality of metalenses may have a focal length, the plurality of metalenses having equal focal lengths such that the different color channels are combined on a common focal plane to form the multi-color image. Each of the plurality of metalenses may include a plurality of nanostructures and has a field of view of more than 30 degrees. Each of the plurality of metalenses may have a desired working spectral bandwidth dependent on an

extended depth of focus, a central wavelength of the associated color channel, and the focal length at the central wavelength.

[0069] In various embodiments, the multi-color image may be detected by one or more detectors defining the common focal plane.

[0070] FIG. 5A shows a schematic of an optical system according to various embodiments. The light coming from an object is focused on a pixelated color detector 506 by a collection of wide FOV metalenses 504 fabricated on the same substrate (chip) and having the same thickness. In various embodiments, metalenses 504 imparting a quadratic phase profile to the incoming light may be used. The collection of metalenses 504 may be arranged in one-dimensional (1D) or two-dimensional (2D) array of any arbitrary shape. Each metalens in the array may be optimized for operation at a particular color (central wavelength λ_c) and a corresponding frequency band with a certain bandwidth (i.e. color channel) that purposely matches the bandwidth of the color filters 502 in the system. In other words, each channel may provide a wide-FOV image with a certain bandwidth. Thus, corresponding images of each color channel may be formed and finally, the color channels may be merged to produce a multi-color image. The color filters 502 may be internal bandpass filters of the detector. The internal bandpass filter may limit the bandwidth of each channel.

[0071] FIG. 5B shows a schematic of another optical system according to various embodiments. The light coming from an object may be focused on a pixelated color detector 506 by a collection of metalenses 504 fabricated on the same chip. Each channel may produce a wide-FOV image with a certain bandwidth. The light may pass through the color filters 502 before reaching the metalenses 504. The images may be subsequently merged to produce a final multi-color image. In order to limit the bandwidth of each channel, external bandpass filters may be utilized.

[0072] For the ease of post-processing, the images may have the same magnification. This may be ensured by the same focal length f for all metalenses 504, which may also mean that all images are obtained in the same focal plane, corresponding to the detector plane (plane of the detector 506). In order to ensure good image quality over each bandwidth ($\Delta\lambda$), the depth of focus (DOF) of the quadratic metalenses 504 may have to be adjusted to work within the desired, non-zero bandwidth. In other words, the focal spot may need to intersect the detector plane and provide a good point spread function (PSF) for all wavelengths in the bandwidth range, which may be achieved by engineering an extended DOF.

[0073] Indeed, the chromatic shift of the focal distance of a metalens with the wavelength may be provided by $\Delta f/f_c \sim \Delta\lambda/\lambda_c$ where f_c represents the focal distance at the central wavelength λ_c of the range of interest. By considering that the maximum acceptable shift for the focal distance corresponds to the DOF, $\Delta f_{max} \sim DOF$, one may find the following relation between the working spectral bandwidth of the metalens $\Delta\lambda$ and the DOF:

$$\Delta\lambda \sim DOF \times \lambda_c / f_c$$

[0074] In various embodiments, a DOF of $\sim 5\%$ - 10% of the focal distance f_c may be engineered to cover a bandwidth of ~ 40 nm when the central wavelengths are red (R), green (G) or blue (B), which correspond to the bandwidth of typical filters used in commercial color sensors. Relying on this, each channel in the system may have a certain operational bandwidth and may bring multiple-hues into focus. The metalenses may form the image focusing light either at different detector locations of the detector 506, as in FIG. 5A, or at the same place, as in FIG. 5C.

[0075] FIG. 5C shows a schematic of yet another optical system according to various embodiments. The light coming from an object (passing through color filters 502) may be focused on a pixelated color detector 506 by a collection of metalenses 504 fabricated on the same chip. The metalenses 506 may form the image focusing light at the same place of the detector 502.

[0076] FIG. 5D shows a schematic of one particular embodiment of the optical system to achieve red-green-blue (RGB) imaging, where each metalens is optimized for corresponding central wavelengths in the red ($\lambda_R=620$ nm), green ($\lambda_G=530$ nm) and blue ($\lambda_B=460$ nm) regions.

[0077] The wide FOV metalenses may include a collection of nanostructures (often called nanoantennas or meta-atoms in the literature). In different embodiments, the meta-atoms may be: 1) nanopillars with circular, elliptical, rectangular or polygonal cross-section acting as waveguides; 2) nanofins, rotated in the metalens to exploit the Pancharatnam-Berry phase; 3) resonant nanoantennas, supporting one or more optical resonances, e.g. making up a Huygens metasurface, or any other type of meta-atoms commonly used to map the desired phase profile. The nanoantennas may or may not be embedded in a medium. FIG. 6 illustrates possible examples of nanoantennas according to various embodiments.

[0078] The material to generate the meta-atoms can include dielectric and semiconductor materials, such as silicon, gallium phosphide (GaP), hafnium oxide, gallium nitride, titanium

dioxide, silicon nitride, sapphire, diamond, silicon carbide (SiC), aluminium nitride (AlN) or other group IV, III-V or II-VI semiconductors or other oxides with moderate or high refractive index (typically $n > 2$) and that is relatively transparent in the wavelength range of interest ($k < 0.1$).

[0079] As an example, in the particular embodiment as shown in FIG. 5D, GaP nanopillars with circular cross-section and with the same height ($H = 300$ nm) on glass substrate can be used to create the three metalenses composing the array. For operation at different spectral ranges, other materials, such as those given above, as well as other meta-atom shapes and heights may be used. As a rule of thumb, the meta-atoms may have a height of approximately the same length as the longest wavelength in the longest operating bandwidth or below. Importantly, to ease the fabrication for practical implementations, all the meta-atoms in all the metalenses can have the same height. FIG. 7 shows an example of a lateral projection of metalenses collection according to various embodiments. FIG. 7 illustrates the design rule described above. In various embodiments, the meta-atoms may be designed to act as local waveguides for the incident light. Owing to this, the meta-atoms may introduce a variable phase delay depending on their diameter. Importantly, the circular cross-section may ensure polarization-insensitive operation.

[0080] For each metalens, the meta-atoms may be arranged in a certain periodic lattice, such as a square lattice, a rectangular lattice, a hexagonal lattice or any other suitable two-dimensional lattice. The diameter of a meta-atom, placed at a certain lattice site situated at a distance r from the centre of the lens, is selected in such a way that it imparts a phase delay following a quadratic phase profile of the form $\varphi_i(r) = \varphi_i(0) - \frac{2\pi}{\lambda_i} \frac{r^2}{2f}$.

[0081] In this expression, $\varphi_i(r)$ is the desired phase delay at the meta-atom position, f is the focal length of the lens, $\varphi_i(0)$ is an arbitrary initial phase selected for the centre of the lens and λ_i is the central wavelength of the wavelength band or channel of interest (the subscript i explicitly denotes the particular channel within the selection of channels of the multispectral imaging system, e.g. $i = 1 \dots N$ in FIGS. 5A - C and $i = R, G, B$ in the embodiment shown in FIG. 5D).

[0082] In order to have the same metalens diameter D and focal length f for different λ_i , the Fresnel number FN of each metalens may be adjusted according to the formula $FN_i = D^2 / 4\lambda_i f$. This may be accomplished by scaling down the lattice period p_i for each metalens

operating at the central wavelength λ_i . In the RGB imaging embodiment, the GaP nanopillars on glass substrate are arranged in a hexagonal lattice with periods $p_R = 260$ nm, $p_G = 220$ nm and $p_B = 190$ nm, for the metalenses working at red (R), green (G) and blue (B) wavelengths, respectively.

[0083] FIGS. 8A - B show the simulated values (obtained using the finite-difference time-domain (FDTD) method) of the transmission and phase values for the nanopillars included in the R, G and B metalenses (depicted as solid line, dashed line and dashed-dotted line respectively), given as a function of the duty cycle, which is the ratio between the nanopillar diameters and the lattice constant. In order to demonstrate the feasibility of the disclosed technology, the RGB embodiment is realized experimentally.

[0084] FIG. 8C shows (above) the optical microscope images and (below) the scanning electron microscopy (SEM) images of the fabricated red (R), green (G) and blue (B) metalenses according to various embodiments. The metalenses may each have a diameter (D) of 200 μ m and a focal length (f) of 83 μ m. The scale bars in the optical microscope images correspond to 20 μ m, while the scale bars in the SEM images correspond to 200 nm. The parameters $p_R = 260$ nm, $p_G = 220$ nm and $p_B = 190$ nm denote the designed lattice periods.

[0085] In order to characterize the optical performance of the disclosed imaging system, the point spread function (PSF) and modulation transfer function (MTF) of the metalenses can be measured for different angles of incidence and frequency bandwidths around the central wavelength of each metalens. This can be done using a collimated laser beam, whose angle of incidence (ϕ) onto the metalens and bandwidth ($\Delta\lambda$) can be adjusted.

[0086] FIG. 9 shows (a) – (c) plots of the modulation transfer function (MTF) as a function of spatial frequencies (cycles per millimetre or cycles/mm) showing the MTF simulation values of a red quadratic lens with ideal quadratic phase profile according to various embodiments designed to work in the red (R) region (central wavelength $\lambda_R = 620$ nm) for angles of incidence $\phi = 0^\circ$, 30° and 50° and bandwidths around the central wavelengths $\Delta\lambda = 10$ nm, 20 nm, 30 nm and 40 nm, and (d) – (f) the point spread function (PSF) corresponding to the conditions in (a) – (c) respectively. The diffraction-limited MTF may be given for similar NA = 0.5 and $\Delta\lambda = 0$ nm. The scale bars in (d) – (f) correspond to 2 μ m.

[0087] FIG. 10 shows the same characteristics measured for the fabricated metalens. FIG. 10 shows (a) – (c) plots of the modulation transfer function (MTF) as a function of spatial frequencies (cycles per millimetre or cycles/mm) showing the MTF measurements of a red

quadratic lens with ideal quadratic phase profile according to various embodiments designed to work in the red (R) region (central wavelength $\lambda_R = 620$ nm) for angles of incidence $\varphi = 0^\circ$, 30° and 50° and bandwidths around the central wavelengths $\Delta\lambda = 10$ nm, 20 nm, 30 nm and 40 nm, and (d) – (f) the point spread function (PSF) corresponding to the conditions in (a) – (c) respectively. The diffraction-limited MTF may be given for similar NA = 0.5 and $\Delta\lambda = 0$ nm. The scale bars in (d) – (f) correspond to 2 μm .

[0088] Evidently, a good match with the simulations is observed. As can be seen, the MTFs are worse than that of a diffraction-limited lens of the similar NA = 0.5, due to spherical aberrations inherent to the phase profile of the metalenses. If necessary for applications, the MTF may be improved by putting an aperture stop in the front focal plane of the metalens. This embodiment together with MTF improvement are illustrated in FIG. 11. FIG. 11 shows (a) a schematic of an optical system including a plurality of apertures 1108 according to various embodiments; (b) a plot of the modulation transfer function (MTF) as a function of spatial frequencies (cycles per millimetre or cycles/mm) showing the MTF simulation values of a red quadratic metalens (central wavelength $\lambda_R = 620$ nm) with and without an aperture stop according to various embodiments for an angle of incidence $\varphi = 0^\circ$; and (c) a plot of the modulation transfer function (MTF) as a function of spatial frequencies (cycles per millimetre or cycles/mm) showing the MTF simulation values of a red quadratic metalens (central wavelength $\lambda_R = 620$ nm) with and without an aperture stop according to various embodiments for an angle of incidence $\varphi = 30^\circ$. Besides the plurality of apertures 1108, the optical system may also include a plurality of filters 1102, a plurality of metalenses 1104 and a detector 1106.

[0089] Importantly, as seen in FIGS. 9 - 10, the MTF may be almost insensitive to the bandwidth for $\varphi = 0^\circ$ and may degrade slowly for $\varphi = 30^\circ$ and $\varphi = 50^\circ$, following PSF broadening. This degradation, associated with chromatic aberrations, may only be slowly increasing with φ and $\Delta\lambda$ and, importantly, may be acceptable for the majority of applications for a certain metalens bandwidth (e.g. 40 nm).

[0090] The MTF data can be translated into the quality of imaging. To illustrate the uniformity of imaging over the bandwidth, monochromatic imaging simulations for $\varphi=0^\circ$ when the imaging wavelength is deviated from the designed one shown in FIG. 12.

[0091] FIG. 12 shows the simulated quadratic phase profile images for the quadratic metalens according to various embodiments, in the particular case of red operation ($\lambda_R = 620$ nm), when the imaging wavelength is varied. For comparison, the simulations corresponding

to a hyperbolic phase profile as previously proposed in the literature are also presented. For the latter, the lens NA, diameter and designed wavelength are fixed to 0.5, 200 μm and 620 nm, similar to the quadratic phase profile. The focal length of the hyperbolic metalens has been changed to 173 μm to obtain the same NA as the quadratic metalens. This leads to a difference in demagnification, which can be seen by different sizes of the scale bars. The scale bars for the hyperbolic phase profile images is 10 μm , while the scale bars for the quadratic phase profile images is 5 μm . As can be seen, the images at different wavelengths for the quadratic phase profile remain virtually unchanged, exhibiting uniform imaging over 40 nm bandwidth. In contrast, the hyperbolic phase profile shows a high-resolution image only at the designed wavelength (620 nm), but a substantial degradation at 600 nm and 640 nm.

[0092] The stability of the MTF (and corresponding image quality) of the optical system according to various embodiments over a certain bandwidth may provide more balanced imaging and may reduce color distortions. More complex meta-atoms may be utilized to improve MTF stability via dispersion engineering. The nanopillars described here as examples may be simple in terms of the fabrication process.

[0093] Various embodiments may also allow for good colour reproduction. The colour reproduction of the optical system may be characterized by a standard ColorChecker test chart with 24 painted patches (often referred as Macbeth chart), as depicted in FIG. 13(a).

[0094] FIG. 13 shows (a) the original standard ColorChecker test chart with 24 painted patches; (b) the result of red-green-blue (RGB) imaging by the optical system according to various embodiments for field of view (FOV) of $30^\circ \times 20^\circ$; and (c) the result of red-green-blue (RGB) imaging by the optical system according to various embodiments for field of view (FOV) of $100^\circ \times 67^\circ$.

[0095] FIG. 13(b) – (c) show the images of the individual R, G and B color channels obtained by the R, G and B fabricated metalenses, respectively. The R, G and B color channels show raw images obtained by each metalens, while the RGB image is the resulting merged image after post-processing. The RGB images may be obtained by a post-processing merging process that includes a simple normalization procedure to account for minimum and maximum intensity values (color balance) in each channel.

[0096] The quality of the color reproduction can be assessed using the CIELAB metric. For this, RGB intensity values for both reference and measured images, may be converted to luminance (L^*), color relation in a red-green (a^*) and color relation in a yellow-blue (b^*). Then,

the color error ΔE is calculated as geometric difference in $L^*a^*b^*$ three-dimensional space: $\sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}$. FIG. 14 shows (a) the color ΔE for the ColorChecker red-green-blue (RGB) with field of view (FOV) of $30^\circ \times 20^\circ$ according to various embodiments; (b) the color ΔE for the ColorChecker red-green-blue (RGB) with field of view (FOV) of $100^\circ \times 67^\circ$ according to various embodiments; and (c) the color error (left) and the obtained red-green-blue (RGB) image (right) after the efficiency correction procedure for FOV of $100^\circ \times 67^\circ$ according to various embodiments.

[0097] For the RGB imaging, the color error ΔE is found to be in the range between 5 and 23 varied for different patches for FOV of $30^\circ \times 20^\circ$ (FIG. 14a), and between 5 and 57 for larger FOV of $100^\circ \times 67^\circ$ (FIG. 14b). The larger errors found for larger FOV can be associated with the angular dependent focusing efficiency of the metalenses. In order to implement the intensity correction procedure in each R, G and B channel, the focusing efficiency can be measured and used as a calibration curve. This procedure may allow reducing the color error (FIG. 14c shows the efficiency corrected RGB image with the corresponding color errors, FIG. 15 presents the measured metalenses focusing efficiency).

[0098] FIG. 15 shows (a) a plot of efficiency (in percent or %) as a function of angle (in degrees) showing the angular dependence of the focusing efficiency at bandwidths around the central wavelengths ($\Delta\lambda$) of 10 nm, 20 nm, 30 nm and 40 nm for the red metalens according to various embodiments; (b) a plot of efficiency (in percent or %) as a function of angle (in degrees) showing the angular dependence of the focusing efficiency at bandwidths around the central wavelengths ($\Delta\lambda$) of 10 nm, 20 nm, 30 nm and 40 nm for the green metalens according to various embodiments; and (c) a plot of efficiency (in percent or %) as a function of angle (in degrees) showing the angular dependence of the focusing efficiency at bandwidths around the central wavelengths ($\Delta\lambda$) of 10 nm, 20 nm, 30 nm and 40 nm for the blue metalens according to various embodiments.

[0099] For general imaging quality assessment, a multi-color detailed picture can be used. FIG. 16 shows (a) an original still image; (b) the results of red-green-blue (RGB) imaging by an optical system with field of view (FOV) of $50^\circ \times 35^\circ$ according to various embodiments; and (c) the results of red-green-blue (RGB) imaging by an optical system with field of view (FOV) of $100^\circ \times 67^\circ$ according to various embodiments. The red (R), green (G) and blue (B) channels show raw images, produced by each metalens, while the RGB image indicates the

results of the fusion of the different channels. The images denoted “Wiener filter” indicates that the images are reconstructed by deconvolution.

[00100] One may notice that the produced RGB images have lower contrast than the original one. This originates from the quadratic metalens MTF behavior, also known as the 'veiling glare' effect. However, MTF may still be preserved at higher spatial frequencies (see FIG. 9(a)-(c)), so that the image information is not lost. This property may allow the quality to be further improved by simple deconvolution algorithms based on widely utilized Wiener filtering. The reconstructed images (denoted as Wiener filter in FIG. 16(b)-(c)) may demonstrate greatly improved sharpness and good color consistency. From a practical point of view, it may be important that the filter is fast and not power hungry, making it suitable for portable and compact devices. Other filters, such as total variation regularizer, can further improve the image, albeit being more resource demanding and taking longer time to process. This may be a solution for other types of systems that are focused on better precision and color reproduction but may not require real-time updates.

[00101] FIG. 17 is a table comparing an embodiment with a typical cellphone camera and a conventional diffractive lens. “+” indicates presence of a particular trait while “-” indicates absence of a particular trait.

[00102] Various embodiments may include or provide an array of quadratic metalenses on a single chip and a color detector, each metalens designed to provide wide-FOV focusing of good quality over a certain angular range and realized using dielectric materials. The optical system may include additional bandpass color filters and/or apertures in the front focal plane of each metalens. Each metalens (color channel) may operate in a certain spectral bandwidth, defined by internal detector or external bandpass color filters. Each channel may provide a large FOV image. The final multispectral image may be produced by the channels fusion. The merging process may include intensity correction, color balance and deconvolution.

[00103] Various embodiments may involve usage of an array of quadratic phase profile metalenses providing wide field-of-view for multispectral and white light imaging. Various embodiments may relate to an approach to form the image in the same detector plane with detector filters bandwidths similar to metalenses operation bandwidths. Various embodiments may relate to the use of quadratic phase profile lenses having an extended depth of focus, thereby allowing for quality enhancement image processing techniques.

[00104] Various embodiments may have a great commercial potential in a number of applications where a full-color large FOV imaging is needed. Various embodiments may have applications in portable cameras, mobile phone cameras, security cameras, compact microscopes for medicine, agriculture and object identification, as well as general drone inspection.

[00105] By “comprising” it is meant including, but not limited to, whatever follows the word “comprising”. Thus, use of the term “comprising” indicates that the listed elements are required or mandatory, but that other elements are optional and may or may not be present.

[00106] By “consisting of” is meant including, and limited to, whatever follows the phrase “consisting of”. Thus, the phrase “consisting of” indicates that the listed elements are required or mandatory, and that no other elements may be present.

[00107] The inventions illustratively described herein may suitably be practiced in the absence of any element or elements, limitation or limitations, not specifically disclosed herein. Thus, for example, the terms “comprising”, “including”, “containing”, etc. shall be read expansively and without limitation. Additionally, the terms and expressions employed herein have been used as terms of description and not of limitation, and there is no intention in the use of such terms and expressions of excluding any equivalents of the features shown and described or portions thereof, but it is recognized that various modifications are possible within the scope of the invention claimed. Thus, it should be understood that although the present invention has been specifically disclosed by preferred embodiments and optional features, modification and variation of the inventions embodied therein herein disclosed may be resorted to by those skilled in the art, and that such modifications and variations are considered to be within the scope of this invention.

[00108] By “about” in relation to a given numerical value, such as for focal length, it is meant to include numerical values within 10% of the specified value.

[00109] The invention has been described broadly and generically herein. Each of the narrower species and sub-generic groupings falling within the generic disclosure also form part of the invention. This includes the generic description of the invention with a proviso or negative limitation removing any subject matter from the genus, regardless of whether or not the excised material is specifically recited herein.

[00110] Other embodiments are within the following claims and non-limiting examples. In addition, where features or aspects of the invention are described in terms of Markush groups,

those skilled in the art will recognize that the invention is also thereby described in terms of any individual member or subgroup of members of the Markush group.

Claims

1. An optical system comprising:
 - a plurality of color filters, a first color filter of the plurality of color filters configured to select light of a first wavelength range representing a first color channel, and a second color filter of the plurality of color filters configured to select light of a second wavelength range different from the first wavelength range, the light of the second wavelength range representing a second color channel, such that the plurality of color filters provide different color channels; and
 - a plurality of metalenses, each of the plurality of metalenses associated with a respective color channel of the plurality of color channels;
 - wherein each of the plurality of metalenses has a focal length, the plurality of metalenses having equal focal lengths such that the different color channels are combined on a common focal plane to form a multi-color image;
 - wherein each of the plurality of metalenses comprises a plurality of nanostructures and has a field of view of more than 30 degrees; and
 - wherein each of the plurality of metalenses has a desired working spectral bandwidth dependent on an extended depth of focus, a central wavelength of the associated color channel, and the focal length at the central wavelength.
2. The optical system according to claim 1, further comprising:
 - one or more detectors defining the common focal plane.
3. The optical system according to claim 2,
 - wherein the plurality of color filters are internal bandpass filters of the one or more detectors.
4. The optical system according to claim 2,
 - wherein the plurality of color filters are external to the one or more detectors.
5. The optical system according to claim 1,
 - wherein the plurality of color filters are arranged between the plurality of metalenses and the common focal plane, such that each of the plurality of metalenses is configured to direct a broadband light to an associated color filter of the plurality of color filters to generate the respective associated color channel.

6. The optical system according to claim 1,
wherein the plurality of metalenses are arranged between the plurality of color filters and the common focal plane, such that each of the plurality of metalenses is configured to direct the light of the respective associated color channel onto the common focal plane.
7. The optical system according to claim 1,
wherein each of the plurality of metalenses has a Fresnel number, the plurality of metalenses having different Fresnel numbers, such that the plurality of metalenses have equal focal lengths.
8. The optical system according to claim 1,
wherein the nanostructures of each of the plurality of metalenses are arranged in a periodic lattice having a predetermined period;
wherein Fresnel numbers of different metalenses of the plurality of metalenses are different due to the different predetermined periods of the different metalenses.
9. The optical system according to claim 8,
wherein the periodic lattice is a square lattice, a rectangular lattice, a hexagonal lattice, or any other common periodic or quasi-periodic Bravais lattice.
10. The optical system according to claim 1, further comprising:
a plurality of apertures arranged before the plurality of metalenses.
11. The optical system according to claim 1,
wherein the plurality of metalenses is made of a material having a refractive index equal to or greater than 2.
12. The optical system according to claim 1,
wherein the plurality of metalenses comprise a suitable dielectric material or a suitable semiconductor material.
13. The optical system according to claim 1,
wherein the plurality of metalenses comprises silicon, gallium phosphide, hafnium oxide, gallium nitride, titanium dioxide, silicon nitride, sapphire, diamond, silicon carbide, aluminium nitride, a III-V semiconductor, or a II-VI semiconductor.
14. The optical system according to claim 1,

wherein heights of the plurality of metalenses are equal; and

wherein the optical system comprises a substrate, the plurality of metalenses on the substrate.

15. The optical system according to claim 1,
wherein the plurality of nanostructures are nanopillars with any suitable cross-section.
16. The optical system according to claim 1,
wherein the plurality of nanostructures are nanoantennas.
17. The optical system according to claim 1,
wherein the plurality of color channels represent different spectral ranges of electromagnetic light.
18. The optical system according to claim 1,
wherein the plurality of color channels are spectrally adjacent to one another or are overlapping.
19. A method of forming an optical system, the method comprising:
providing a plurality of color filters, a first color filter of the plurality of color filters configured to select light of a first wavelength range representing a first color channel, and a second color filter of the plurality of color filters configured to select light of a second wavelength range different from the first wavelength range, the light of the second wavelength range representing a second color channel, such that the plurality of color filters provide different color channels; and
providing a plurality of metalenses, each of the plurality of metalenses associated with a respective color channel of the plurality of color channels;
wherein each of the plurality of metalenses has a focal length, the plurality of metalenses having equal focal lengths such that the different color channels are combined on a common focal plane to form a multi-color image;
wherein each of the plurality of metalenses comprises a plurality of nanostructures and has a field of view of more than 30 degrees; and
wherein each of the plurality of metalenses has a desired working spectral bandwidth dependent on an extended depth of focus, a central wavelength of the associated color channel, and the focal length at the central wavelength.

20. A method of forming a multi-color image, the method comprising:

providing a broadband light to an optical system, the optical system comprising:

a plurality of color filters, a first color filter of the plurality of color filters configured to select light of a first wavelength range representing a first color channel, and a second color filter of the plurality of color filters configured to select light of a second wavelength range different from the first wavelength range, the light of the second wavelength range representing a second color channel based on the broadband light, such that the plurality of color filters provide different color channels; and

a plurality of metalenses, each of the plurality of metalenses associated with a respective color channel of the plurality of color channels;

wherein each of the plurality of metalenses has a focal length, the plurality of metalenses having equal focal lengths such that the different color channels are combined on a common focal plane to form the multi-color image;

wherein each of the plurality of metalenses comprises a plurality of nanostructures and has a field of view of more than 30 degrees; and

wherein each of the plurality of metalenses has a desired working spectral bandwidth dependent on an extended depth of focus, a central wavelength of the associated color channel, and the focal length at the central wavelength.