

DEVICE AND METHOD FOR BEAM STEERING**TECHNICAL FIELD**

[0001] The present disclosure generally relates to a device for beam steering and a method for beam steering.

BACKGROUND

[0002] Beam steering technology refers to the control in the direction of a beam of energy, such as light or radio waves, and finds applications in fields like Lidar (Light Detection and Ranging), dynamic holography, imaging, sensing, display, lithography, optical communication, and various consumer electronics. Several beam steering methods have been developed, including mechanical scanning, MEMS mirrors, and acousto-optic beam steering.

[0003] Mechanical scanning utilizes moving components, such as rotating mirrors, prisms, or decentered lenses, to steer the beam. While this approach is straightforward and reliable, it is relatively slow and has a limited range of scanning directions. Acousto-optic beam steering, which employs sound waves to adjust the beam's direction, offers rapid and flexible control with the ability to steer the beam in multiple directions simultaneously. However, it tends to be more complex and costlier compared to other methods. MEMS mirrors, which are primarily used in reflective applications, have limitations in their range and field of view due to their small size and limited deflection angles.

[0004] Therefore, there exists a need to provide a device for improved beam steering and a method for improved beam steering.

SUMMARY

[0005] According to a first aspect of the present disclosure, a device for beam steering is provided. The device may include: a substrate; a first lens disposed on a first surface of the substrate; and a second lens disposed on a second surface of the substrate, the second surface being opposite to the first surface of the substrate, wherein at least one of the first lens and the second lens is a tunable lens having a tunable focal spot and the device is configured to steer a beam passing through the device by tuning the tunable focal spot of the tunable lens.

[0006] According to a second aspect of the present disclosure, a method for forming a device for beam steering is provided. The method may include: forming a first lens on a first

surface of a substrate; and forming a second lens on a second surface of the substrate, the second surface being parallel and opposite to the first surface of the substrate, wherein at least one of the first lens and the second lens is a tunable lens having a tunable focal spot.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] FIG. 1 is a block diagram showing a device for beam steering according to various embodiments of the present disclosure.

[0008] FIG. 2 and FIG. 3 are schematic diagrams showing examples of the device of FIG. 1 for beam steering.

[0009] FIG. 4A is a block diagram showing an example of the device of FIG. 1 for beam steering according to various embodiments of the present disclosure; and FIG. 4B is a schematic diagram showing the example of FIG. 4A for beam steering.

[0010] FIG. 5A shows a block diagram of a tunable lens according to various embodiments of the present disclosure; FIG. 5B shows simulated 2D far-field electric field distribution of the tunable lens of FIG. 5A; FIG. 5C shows transmission rate and phase change (phase change/ 2π) of the transmitted light beam by the tunable lens of FIG. 5A as a function of the tunable refractive index of the tunable lens of 5A; FIG. 5D shows the refractive index of the electrically tunable material plotted against the lateral axis (e.g. the x-axis) in which the entire profile of the refractive index has been laterally shifted to the right by 25 microns; FIG. 5E shows the transmitted light beam by the tunable lens of FIG. 5A is steered by 26.5° ; and FIG. 5F shows the radiation patterns of the transmitted light beam by the tunable lens of FIG. 5A.

[0011] FIG. 6A shows a block diagram of a tunable lens according to various embodiments of the present disclosure; FIG. 6B shows simulated 2D far-field electric field distribution of the tunable lens of FIG. 6A; FIG. 6C shows transmission rate and phase change (phase change/ 2π) of the transmitted light beam by the tunable lens of FIG. 6A as a function of the tunable refractive index of the tunable lens of FIG. 6A; FIG. 6D shows the refractive index of the electrically tunable material plotted against the lateral axis (e.g. the x-axis) in which the entire profile of the refractive index has been laterally shifted to the right by 15 microns; and FIG. 6E shows the radiation patterns of the transmitted light beam by the tunable lens of FIG. 6A.

[0012] FIG. 7 shows a block diagram of a unit cell of a metalens according to various embodiments of the present disclosure.

[00013] FIG. 8 shows transmission rate and phase change by a unit cell with respect to the width d of a nanobar of the unit cell according to various embodiments of the present disclosure.

[00014] FIG. 9 show simulation results of light beam intensity according to deflection angles by a device according to various embodiments of the present disclosure.

[00015] FIG. 10 shows a flow chart of a method 1000 for forming a device for beam steering according to various embodiments of the present disclosure.

DETAILED DESCRIPTION

[00016] Embodiments described below in the context of a method are analogously valid for the respective element, device, apparatus, or system, and *vice versa*. Furthermore, it will be understood that the embodiments described below may be combined, for example, a part of one embodiment may be combined with a part of another embodiment, and a part of one implementation may be combined with a part of another implementation.

[00017] It should be understood that the singular terms "a", "an", and "the" include plural references unless context clearly indicates otherwise. Similarly, the word "or" is intended to include "and" unless the context clearly indicates otherwise.

[00018] It will be further understood that the terms "comprise" (and any form of comprise, such as "comprises" and "comprising"), "have" (and any form of have, such as "has" and "having"), "include" (and any form of include, such as "includes" and "including"), and "contain" (and any form of contain, such as "contains" and "containing") are open-ended linking verbs. As a result, a method or device that "comprises," "has," "includes" or "contains" one or more steps or elements possesses those one or more steps or elements, but is not limited to possessing only those one or more steps or elements. Likewise, a step of a method or an element of a device that "comprises," "has," "includes" or "contains" one or more features possesses those one or more features, but is not limited to possessing only those one or more features. Furthermore, a device or structure that is configured in a certain way is configured in at least that way, but may also be configured in ways that are not listed.

[00019] Approximating language, as used herein throughout the specification and claims, may be applied to modify any quantitative representation that could permissibly vary without resulting in a change in the basic function to which it is related. Accordingly, a value modified by a term or terms, such as "about," "substantially", is not limited to the precise value specified but within tolerances that are acceptable for operation of the embodiment for an application for

which it is intended. In some instances, the approximating language may correspond to the precision of an instrument for measuring the value.

[00020] The term “optic element” may be used herein to mean any component or device that interacts with light for the purpose of manipulating or controlling its properties. Optic elements may be used in various fields, including optics, photonics, imaging, and telecommunications. An optic element may include a metalens, and/or a component of the metalens.

[00021] The term “tunable lens” may be used herein to refer to an optical element that allows for real-time adjustments to its optical properties, such as focal length or shape or focal spot. This dynamic capability may be achieved through various mechanisms, including electro-optic effects, liquid crystal adjustments, mechanical alterations, acousto-optic modulation, or microelectromechanical systems (MEMS). Tunable lenses may be highly versatile and find applications in imaging systems, augmented reality (AR), optical communication, and adaptive optics. They may offer significant advantages such as flexibility, compactness, and ease of integration into different devices, allowing for on-the-fly adjustments to meet varying conditions.

[00022] The term “metalens” may be used herein to mean a type of lens that uses nanoscale structures, often made of metamaterials or nanostructures, to control the phase and amplitude of light at the subwavelength scale. Unlike traditional lenses, which are made of bulk materials and rely on curved surfaces to refract light, metalenses may utilize engineered patterns at the nanoscale to achieve specific optical properties. Metalenses have gained significant attention in the field of optics and photonics due to their potential for compact size, lightweight design, and the ability to overcome some limitations of conventional lenses.

[00023] The term “refractive lens” may be used herein to refer to a lens using the principle of refraction to alter the direction of light rays, focusing or dispersing them to form clear images. Made from materials like glass or plastic, refractive lenses may bend light as it passes through, with convex lenses converging light to a focal spot and concave lenses spreading/diverging light rays apart.

[00024] Tunable metasurfaces, with their engineered structures that manipulate electromagnetic waves, may offer real-time and flexible beam control. Metasurfaces may refer to two-dimensional versions of metamaterials, consisting of subwavelength structures known as meta-atoms. Tunable metasurfaces may have garnered significant interest for beam steering applications due to their versatile capabilities, ultra-thin profile, and ease of integration

compared to traditional refractive optics. However, tunable metasurfaces that utilize liquid crystals (LCs) as the adjustable material may face challenges such as low resolution and limited field of view (FOV). These issues may arise from cross-talk between neighbouring LC cells and the inherently slow response times due to the rotation speed of LC molecules. Alternatively, transparent conductive oxides (TCOs) may be another material used in tunable metasurfaces, but they are restricted to reflective modes and suffer from high optical losses, reducing their efficiency to below 5%.

[00025] Various embodiments of what is described here seek to provide a device for beam steering. The device may include a substrate, a first lens and a second lens disposed on opposite sides of the substrate. In some embodiments, the (optical) device may include a substrate, a first metalens and a second metalens disposed on opposite (parallel) sides of the substrate. At least one of the first lens and the second lens may be a tunable lens having a tunable focal spot and the device may be configured to steer a beam passing through the device by tuning the tunable focal spot of the tunable lens. In other words, the displacement (e.g. distance, offset) of the focal spots of the first and second lenses may be adjustable by moving one or both focal spots of the first and second lens so as to steer the beam.

[00026] In various embodiments, a sum of a first focal length of the first lens and a second focal length of the second lens may be equal to a thickness of the substrate. In other words, the focal spots of the first and second lenses may be overlapped when the first and second lenses are aligned (i.e. their optical axes are coincident). The displacement (e.g. distance, offset) of the focal spots of the first and second lenses may be adjustable by parallelly moving one or both optical axes of the first and second lens so as to steer the beam. At least one of the first and second lenses may be a converging lens. Parallel rays of light are incident onto the first lens, which converges the light rays into either a virtual focal spot behind the second lens (if the second lens has a diverging phase profile), or into a real focal spot between the two lenses (if both lenses have converging phase profiles). The second lens transforms these light rays from the first lens, into parallel rays coming out from the second lens.

[00027] In various embodiments, the tunable lens may include a ferroelectric layer and a plurality of Distributed Bragg Reflector (DBR) layers disposed on each side of the ferroelectric layer. The refractive index of the tunable lens may be adjustable in response to multiple different voltages applied to the tunable lens (e.g. a respective voltage applied to a respective unit cell of the ferroelectric layer). The overall phase change of the entire stack may

be also adjustable in response to a number of layers of the DBR layers disposed on each side of the ferroelectric layer.

[00028] The following examples pertain to various aspects of the present disclosure.

[00029] Example 1 is a device for beam steering, including: a substrate; a first lens disposed on a first surface of the substrate; and a second lens disposed on a second surface of the substrate, the second surface being opposite to the first surface of the substrate, wherein at least one of the first lens and the second lens is a tunable lens having a tunable focal spot and the device is configured to steer a beam passing through the device by tuning the tunable focal spot of the tunable lens.

[00030] In Example 2, the subject matter of Example 1 may optionally include that a sum of a first focal length of the first lens and a second focal length of the second lens is equal to a thickness of the substrate.

[00031] In Example 3, the subject matter of Example 2 may optionally include that the tunable focal spot is tunable along a plane parallel to the first surface and/or the second surface of the substrate where the tunable lens is disposed.

[00032] In Example 4, the subject matter of Example 2 or Example 3 may optionally include that when the first surface is parallel to the second surface of the substrate, a deflection angle of the beam steered by the device is determined by the second focal length of the second lens and a displacement between a first focal spot of the first lens and a second focal spot of the second lens.

[00033] In Example 5, the subject matter of any of Example 1 to 4 may optionally include that the tunable lens has an electrically tunable refractive index.

[00034] In Example 6, the subject matter of Example 5 may optionally include that the tunable focal spot is tunable by changing voltages applied to the tunable lens to laterally shift a spatial profile of the tunable refractive index.

[00035] In Example 7, the subject matter of any of Examples 1 to 6 may optionally include that the tunable lens includes a tunable layer made of tunable materials including ferroelectric materials, transparent conductive oxides, phase change materials, liquid crystals, elastomers.

[00036] In Example 8, the subject matter of Example 7 may optionally include that the ferroelectric materials include Barium strontium titanate (BaSrTiO_3), barium titanate (BaTiO_3), strontium titanate (SrTiO_3), Lead Lanthanum Zirconate Titanate (PLZT), Lithium niobate (LiNbO_3), and ferroelectric liquid crystals (FLCs).

[00037] In Example 9, the subject matter of Example 8 may optionally include that Barium strontium titanate (BaSrTiO_3) includes $\text{Ba}_{0.7}\text{Sr}_{0.3}\text{TiO}_3$ or BST70/30.

[00038] In Example 10, the subject matter of Example 7 or Example 8 may optionally include that the tunable lens further includes a plurality of Distributed Bragg Reflector (DBR) layers.

[00039] In Example 11, the subject matter of any of Examples 7 to 10 may optionally include that the tunable layer includes an array of unit cells, and the tunable focal spot is tunable by a distance equal to an integer multiple of a dimension of the unit cell.

[00040] In Example 12, the subject matter of Example 11 may optionally include that each unit cell of the array of unit cells includes a respective pair of electrodes configured to receive a voltage for tuning the tunable focal spot.

[00041] In Example 13, the subject matter of any of Examples 1 to 12 may optionally include that the first lens is the tunable lens having a first focal spot being the tunable focal spot, and the second lens is a metalens having a second focal spot.

[00042] In Example 14, the subject matter of Example 13 may optionally include that the second lens includes a metalens.

[00043] In Example 15, the subject matter of Example 14 may optionally include that the metalens includes silicon nanobars.

[00044] In Example 16, the subject matter of any of Examples 1 to 15 may optionally include that the first lens is a flat lens, a Fresnel zone plate, a Fresnel lens, a meta-surface or any combination thereof, and wherein the second lens is a flat lens, a Fresnel zone plate, a Fresnel lens, a meta-surface or any combination thereof.

[00045] In Example 17, the subject matter of any of Examples 1 to 16 may optionally include that the beam includes visible light or near-infrared light.

[00046] In Example 18, the subject matter of any of Examples 1 to 17 may optionally include that the first lens and the second lens are configured to operate in transmission mode.

[00047] In Example 19, the subject matter of any of Examples 1 to 18 may optionally include that the substrate includes strontium titanate (SrTiO_3) or magnesium oxide (MgO).

[00048] Example 20 is a method for forming a device for beam steering, including: forming a first lens on a first surface of a substrate; and forming a second lens on a second surface of the substrate, the second surface being parallel and opposite to the first surface of the substrate, wherein at least one of the first lens and the second lens is a tunable lens having a tunable focal spot.

[00049] FIG. 1 is a block diagram showing a device 100 for beam steering. The device 100 may include a substrate 190; a first lens 110 disposed on a first surface 191 of the substrate 190; and a second lens 120 disposed on a second surface 192 of the substrate 190, the second surface 192 being opposite to the first surface 191 of the substrate 190. As least one of the first lens 110 and the second lens 120 may be a tunable lens having a tunable focal spot and the device 100 may be configured to steer a beam passing through the device 100 by tuning the tunable focal spot of the tunable lens.

[00050] According to various non-limiting embodiments, the substrate 190 may be transparent. The substrate may include strontium titanate (SrTiO_3) or magnesium oxide (MgO) or titanium dioxide (TiO_2) or barium titanate (BaTiO_3). According to various non-limiting embodiments, the device 100 may allow visible light or near-infrared light to pass through.

[00051] According to various non-limiting embodiments, the first lens 110 and the second lens 120 may be aligned with respect to the substrate 190 in a manner that the center line 101 of the first lens 110 is the center line 101 of the second lens 120. The tunable lens, being the first lens 110 and/or the second lens 120, may be configured to have the tunable focal spot tunable in a direction perpendicular to the center line 101. That is, the tunable focal spot may be tunable along a plane parallel to the first surface and/or the second surface of the substrate where the tunable lens is disposed. In an example, the tunable focal spot of the tunable lens, being the first lens 110 or the second lens 120, may be tuned off the center line 101, whereas a focal spot of the other lens, being the second lens 120 or the first lens 110, may be at the center line 101. In other words, the tunable focal spot of the tunable lens may be shifted from the focal spot of the other lens, that is, the tunable focal spot of the tunable lens is decentered from the focal spot of the other lens.

[00052] According to various non-limiting embodiments, the first lens 110 and/or the second lens 120 may be selected from a range of lens types, including a flat lens, a Fresnel zone plate, a Fresnel lens, a meta-surface or any combination thereof. Additionally, these lenses may be configured as either converging lenses, or diverging lenses.

[00053] According to various non-limiting embodiments, the tunable lens may include an electrically tunable lens having an electrically tunable refractive index. The tunable lens may include a tunable layer having an array of unit cells, and each unit cell of the array of unit cells may include a pair of electrodes configured to receive a voltage for tuning the tunable focal spot. Different voltages may be so applied to the pairs of electrodes to determine a respective refractive index of each unit cell and consequently the focal spot of the tunable lens. In other

words, a different voltage may be applied to each unit cell (or to different groups of unit cells) in a manner that the respective refractive index of each unit cell (or group of unit cells) varies accordingly, whereby the focal spot of the tunable lens is tuned by the different voltages. That is, the tunable focal spot of the tunable lens may be tunable by changing the voltages applied to the tunable lens.

[00054] According to various non-limiting embodiments, the tunable lens may include a tunable layer made of tunable materials including ferroelectric materials, transparent conductive oxides, phase change materials, liquid crystals, elastomers. The ferroelectric materials may include Barium strontium titanate (BaSrTiO_3), barium titanate (BaTiO_3), strontium titanate (SrTiO_3), Lead Lanthanum Zirconate Titanate (PLZT), Lithium niobate (LiNbO_3), and ferroelectric liquid crystals (FLCs). In an example, Barium strontium titanate (BaSrTiO_3) may include $\text{Ba}_{0.7}\text{Sr}_{0.3}\text{TiO}_3$ or BST70/30.

[00055] FIG. 2 and FIG. 3 are schematic diagrams showing examples 200, 300 of the device 100 for beam steering.

[00056] According to various non-limiting embodiments, the device 200 may include a substrate 290; a first converging lens 210 disposed on a first surface 291 of the substrate 290; and a second converging lens 220 disposed on a second surface 292 of the substrate 290, the second surface 292 being opposite to the first surface 291 of the substrate 290. As least one of the first converging lens 210 and the second converging lens 220 may be a tunable lens having a tunable focal spot and the device 200 may be configured to steer a beam passing through the device 200 by tuning the tunable focal spot of the tunable lens.

[00057] According to various non-limiting embodiments, the substrate 290 may have a thickness d as denoted in FIG. 2. The first lens 210 may have a first focal length f_1 (i.e. positive) and the second lens 220 may have a second focal length f_2 (i.e. positive). A sum of the first focal length f_1 of the first lens 210 and the second focal length f_2 of the second lens 220 may be so designed to be equal to the thickness d of the substrate 290, that is, $f_1 + f_2 = d$. In some embodiments, the first focal length f_1 of the first lens 210 may be equal to the second focal length f_2 of the second lens 220. In other words, the thickness d of the substrate 290 may be two times of the first focal length f_1 of the first lens 210 or the second focal length f_2 of the second lens 220.

[00058] According to various non-limiting embodiments, the device 300 may include a substrate 390; a first converging lens 310 disposed on a first surface 391 of the substrate 390; and a second diverging lens 320 disposed on a second surface 392 of the substrate 390, the

second surface 392 being opposite to the first surface 391 of the substrate 390. As least one of the first converging lens 310 and the second diverging lens 320 may be a tunable lens having a tunable focal spot and the device 300 may be configured to steer a beam passing through the device 300 by tuning the tunable focal spot of the tunable lens.

[00059] According to various non-limiting embodiments, the substrate 390 may also have a thickness d as denoted in FIG. 3. The first lens 310 may have a first focal length f_1 (i.e. positive) and the second lens 320 may have a second focal length f_2 (i.e. negative). A sum of the first focal length f_1 of the first lens 310 and the second focal length f_2 of the second lens 320 may be so designed to be equal to the thickness d of the substrate 390, that is, $f_1 + f_2 = d$.

[00060] In FIG. 2, the first lens 210 and the second lens 220 are both shown as converging lenses. In FIG. 3, the first lens 310 is shown as a converging lens and the second lens 320 is shown as diverging lenses. For example, the first and second lenses 210, 220 and the first and second lenses 310, 320 may include optical convex lens, metalenses composed of nanostructures to manipulate light, Fresnel Zone Plate, or any other device that is capable of steering light (e.g. converging light or diverging light).

[00061] The devices 200, 300 may include similar features of the device 100 as described above in connection to FIG. 1, and therefore, features that are described in the context of the device 100 may correspondingly be applicable to the same or similar features in the devices 200, 300 and *vice versa*. Furthermore, additions and/or combinations and/or alternatives as described for a feature in the context of the device 100 may correspondingly be applicable to the same or similar feature in the devices 200, 300 and *vice versa*.

[00062] FIG. 4A is a block diagram showing an example 400 of the device 100 for beam steering. FIG. 4B is a schematic diagram showing the example 400 of the device 100 for beam steering.

[00063] According to various non-limiting embodiments, the device 400 may include a substrate 490; a first flat lens 410 disposed on a first surface 491 of the substrate 490; and a second flat lens 420 disposed on a second surface 492 of the substrate 490, the second surface 492 being opposite to the first surface 491 of the substrate 490. As least one of the first flat lens 410 and the second flat lens 420 may be a tunable lens having a tunable focal spot and the device 400 may be configured to steer a beam passing through the device 400 by tuning the tunable focal spot of the tunable lens. It shall be appreciated that although the first lens 410 and the second lens 420 are shown as converging lenses in FIGS. 4A and 4B, the first lens 410 and

the second lens 420 shall not be limited to converging lenses, either of them or both of them may include a diverging lens.

[00064] According to various non-limiting embodiments, the first lens 410 may have a first focal length f_1 (e.g. positive) and the second lens 420 may have a second focal length f_2 (e.g. positive). A sum of the first focal length f_1 of the first lens 410 and the second focal length f_2 of the second lens 420 may be so designed to be equal to a thickness d of the substrate 490, that is, $f_1 + f_2 = d$. The first focal spot 411 of the first lens 410 may be (laterally) shifted from the second focal spot 421 of the second lens 420 by a displacement Δ as denoted in FIGS. 4A and 4B, that is, the first focal spot of the first lens 410 is decentered from the second focal spot of the second lens 420. In some embodiments, when the first surface 491 is parallel to the second surface 492 of the substrate 490, a deflection angle θ of the light beam steered by the device 400 may be determined by the second focal length f_2 of the second lens 420 and the displacement Δ between the first focal spot 411 of the first lens 410 and the second focal spot 421 of the second lens 420 as described in more details with reference to FIG. 4B.

[00065] According to various non-limiting embodiments, if the light beam 401 is impinging on the first lens 410 from the left side, the transmitted light 402 after passing through the second lens 420 may have a deflection angle of θ which may be calculated as:

$$\theta = \tan^{-1} \left(\frac{\Delta}{f_2} \right) \quad (1)$$

The refraction of the light beam in the substrate 490 is not considered in Equation (1).

[00066] According to Equation (1), as the second focal length f_2 of the second lens 420 decreases, the diverging angle θ increases. The transmitted light beam 402 may be kept as parallel rays, which is highly desirable for beam steering used in most applications. Moreover, in the embodiment shown in FIGS. 4A and 4B where the first and the second lenses 410, 420 are converging, if the displacement Δ between the first lens 410 and the second lens 420 is positive (i.e. $\Delta > 0$, e.g. the first lens 410 is tuning upward and/or the second lens 420 is tuning downward as shown in FIGS. 4A and 4B), the light beam 402 may be deflected downward with the angle $\theta > 0$, as shown in FIGS. 4A and 4B. On the other hand, if the displacement Δ between the first lens 410 and the second lens 420 is negative (i.e. $\Delta < 0$, e.g. the first lens 410 is tuning downward and/or the second lens 420 is tuning upward as shown in FIGS. 4A and 4B), the light beam may be deflected upward ($\theta < 0$). In other embodiments, where the second lens 420 is a diverging lens, $f_2 < 0$ may be used in Equation (1). Accordingly, if the displacement Δ between the first lens 410 and the second lens 420 is positive (i.e. $\Delta > 0$, e.g.

the first lens 410 is tuning upward and/or the second lens 420 is tuning downward as shown in FIGS. 4A and 4B), the light beam may be also deflected upward with the angle $\theta < 0$.

[00067] In an example, the first and second lenses 410, 420 are converging lenses as shown in FIGS. 4A and 4B. The thickness of the substrate 490 is set as $450\ \mu\text{m}$, and the first focal length f_1 of the first lens 410 and the second focal length f_2 are equal and are set as $225\ \mu\text{m}$. If the displacement Δ between the first lens 410 and the second lens 420 is tuned to $18\ \mu\text{m}$, according to Equation (1), the transmitted light 402 may be diverted to $\theta = \tan^{-1} (18/225) = 4.574^\circ$. If the first and second lenses 410, 420 are both electrically tunable and their focal spots are shifted laterally in opposite directions, e.g. $\Delta = 2 \times 18\ \mu\text{m}$, the transmitted light 402 may be diverted to $\theta = \tan^{-1} (36/225) = 9.090^\circ$.

[00068] In an example, the first and second lenses 410, 420 are also converging lenses as shown in FIGS. 4A and 4B. With the same thickness of the substrate 490 of $450\ \mu\text{m}$, if the first flat lens 410 has the first focal length of $f_1 = 400\ \mu\text{m}$ and the second flat lens 420 has the second focal length of $f_2 = 50\ \mu\text{m}$ and the first focal spot 411 of the first lens 410 is electrically shifted by $\Delta = 18\ \mu\text{m}$, the transmitted light beam 402 may be diverted by $\theta = \tan^{-1} (18/50) = 19.799^\circ$. If both lenses are electrically tunable and their focal spots are shifted laterally in opposite directions, e.g. $\Delta = 2 \times 18\ \mu\text{m}$, the transmitted light 402 may be diverted by $\theta = \tan^{-1} (36/50) = 35.754^\circ$.

[00069] In an example, the first lens 410 is a converging lens and the second lens 420 is a diverging lens (e.g. as shown in FIG. 3). With the same thickness of the substrate 490 of $450\ \mu\text{m}$, if the first flat lens 410 has the focal length of $f_1 = 500\ \mu\text{m}$ and the second flat lens 420 has the second focal length of $f_2 = -50\ \mu\text{m}$ and the displacement Δ between the first lens 410 and the second lens 420 is tuned to $18\ \mu\text{m}$, the transmitted light may be diverted by $\theta = \tan^{-1} (18/-50) = -19.799^\circ$. The negative angle may imply the opposite direction of the deflection angle compared to the above example. If both lenses are electrically tunable and their focal spots are shifted laterally in the opposite directions, e.g. $\Delta = 2 \times 18\ \mu\text{m}$, the output transmitted light may be diverted by $\theta = \tan^{-1} (36/-50) = -35.754^\circ$.

[00070] In some embodiments, the first lens 410 may be the tunable lens having a first focal spot being the tunable focal spot, and the second lens 420 may be a metalens having a second focal spot. The metalens may include silicon nanobars (e.g. see FIG. 7).

[00071] According to various non-limiting embodiments, the first lens 410 and the second lens 420 may be configured to operate in transmission mode.

[00072] According to various non-limiting embodiments, the tunable lens may be made of a Barium Strontium Titanate ($\text{Ba}_{0.7}\text{Sr}_{0.3}\text{TiO}_3$ or BST70/30, referred as BST) film, a uniaxial perovskite crystal. The crystal quality of the deposited BST film may be characterized and confirmed by x-ray diffraction (XRD), which is one of the most important factors in achieving large electro-optic coefficients in ferroelectric and paraelectric materials. The electrooptical tunability of BST films may be measured using a birefringence (also known as double refraction) measurement setup.

Experimental data

[00073] The electrically induced birefringence change $\delta(\Delta n)$ in the BST films deposited at different conditions with different thicknesses are measured. The optimum film is selected to achieve the maximum value for total accumulated phase shift (Φ) from the electrically induced birefringence, defined as $\Phi = \delta(\Delta n) \cdot t$, where t is the thickness of the BST films. Birefringence change of $\delta(\Delta n) = 0.466$ have been measured for a thick sample ($t_{\text{BST}} > 500 \text{ nm}$). It shall be appreciated that other types of tunable materials including but not limited to other ferroelectric materials such as BTO, PLZT, LiNbO_3 , and LC, transparent conductive oxides, phase change materials, liquid crystals, elastomers may be used in the design of electrically tunable metasurface. The thickness of the BST film is $t_{\text{BST}} = 5.6 \mu\text{m}$ and the length of the unit cell is $1.05 \mu\text{m}$. The higher thickness of the BST film may improve the focusing efficiency of the tunable metalens which is necessary to achieve higher diffraction efficiency in the decentered lens beam steering according to various embodiments.

[00074] The simulations are done at the wavelength of $\lambda = 940 \text{ nm}$. The first electrically tunable lens is designed to have a converging focal length of $f_1 = 500 \mu\text{m}$ and the second lens is a diverging Si metalens designed to have a focal length of $f_2 = -50 \mu\text{m}$. In these simulations, the thickness of the substrate is chosen to be $t_{\text{Sub}} = 450 \mu\text{m}$, which agrees with the condition $f_1 + f_2 = t_{\text{Sub}}$.

[00075] FIG. 5A shows a block diagram of a tunable lens 500 (e.g. the tunable lenses of lens 100, 200, 300, 400) according to various embodiments of the present disclosure.

[00076] According to various non-limiting embodiments, the tunable lens 500 may include a first Distributed Bragg Reflector (DBR) 504, a Barium strontium titanate (BaSrTiO_3 , referred as BST) layer 505, a second DBR 506 and a substrate 507, 508. In other words, the tunable lens 500 may include the BST layer 505 sandwiched by the first DBR 504 and the second DBR 506. That is, the tunable lens 500 may be a Fabry-Perot cavity using BST. An air Perfectly Matched Layer (PML) 51 and a substrate PML 59 are shown in FIG. 5A for computational

simulation purposes of a boundary that mimics an infinite space, so that waves can exit the simulation area without causing artificial reflections. The substrate 507, 508 may be set as port 1 and an air section 52, 53 may be set as port 2; the port 1 and port 2 are used in simulation through which light beam may enter or exit.

[00077] According to various non-limiting embodiments, the first DBR 504 may have a same structure as the second DBR 506, including a plurality (e.g. 7) of alternating layers of materials with high and low refractive indices. For example, the first DBR 504 may include Magnesium oxide (MgO) layers having a lower refractive index of 1.719 and Strontium Titanate (STO) layers having a high refractive index of 2.301. The number of layers and the thickness of these layers may be chosen such that they filter out specific wavelengths (by reflecting them) and allow other wavelengths to pass through. A higher number of layers may result in a sharper and more selective reflection band, which may in turn enhance the transmission of other wavelengths. The tunable lens 500 may provide a phase change of nearly π , for example, a phase change of 0.834π by having a tunable refractive index change of 0.087, which in turn steers beam from -26.5° to $+26.5^\circ$.

[00078] According to various non-limiting embodiments, the tunable lens 500 may include one layer DBR 510 which has a different thickness from the DBR layers 504, 506. This different thickness is optimized (e.g. adjusted) to enable the entire DBR to work as intended.

[00079] FIG. 5B shows simulated 2D far-field electric field distribution of the tunable lens 500 being a first lens, and a second lens is denoted as 530. The second lens may include silicon metalens having nanobars, set to be in air and infinitely long in out-of-screen direction. The port 1 is set as input (e.g. input 1 Watt of power) and the port 2 is set as output. The time-averaged power outflow is 0.047583 Watts. A total transmission rate of 4.76% is obtained and the transmission of the unit cell of the lens 500 which includes the entire DBR stack together with the BST layer 505, is 6%.

[00080] FIG. 5C shows transmission rate 541 and phase change 542 (phase change/ 2π) of the transmitted light beam by the tunable lens 500 as the tunable refractive index of the tunable lens 500 increases from 2.102 to 2.189.

[00081] FIG. 5D shows refractive index distribution across the tunable lens 500 (e.g the x-axis of FIG. 5B). In other words, the optical axis (i.e. the focal spot) has been tuned from 0 to approximately 2.5×10^{-5} m (25 μ m) as shown in FIG. 5B.

[00082] FIG. 5E shows the transmitted light beam (plotted as the square of the normalized far-field Electric field) by the tunable lens 500 is steered by 26.5° .

[00083] FIG. 5F shows the radiation patterns of the transmitted light beam by the tunable lens 500.

[00084] FIG. 6A shows a block diagram of a tunable lens 600 (e.g. the tunable lenses of lens 100, 200, 300, 400) according to various embodiments of the present disclosure.

[00085] According to various non-limiting embodiments, the tunable lens 600 may include a first Distributed Bragg Reflector (DBR) 604, a Barium strontium titanate (BaSrTiO_3 , referred as BST) layer 605, a second DBR 606 and a substrate 607, 608. In other words, the tunable lens 600 may include the BST layer 605 sandwiched by the first DBR 604 and the second DBR 606. That is, the tunable lens 600 may be a Fabry-Perot cavity using BST. An air Perfectly Matched Layer (PML) 61 and a substrate PML 69 are shown in FIG. 6A for computational simulation purposes. The substrate 607, 608 may be set as port 1 and an air section 62, 63 may be set as port 2; the port 1 and port 2 are used in simulation through which light beam may enter or exit.

[00086] According to various non-limiting embodiments, the first DBR 604 may have a same structure as the second DBR 606, including a plurality (e.g. 5) of alternating layers of materials with high and low refractive indices. For example, the first DBR 604 may include Magnesium oxide (MgO) layers having a lower refractive index of 1.719 and Strontium Titanate (STO) layers having a high refractive index of 2.301.

[00087] According to various non-limiting embodiments, the tunable lens 600 may include one layer DBR 610 which has a different thickness from the DBR layers 604, 606. This different thickness is optimized (e.g. adjusted) to enable the entire DBR to work as intended.

[00088] FIG. 6B shows simulated 2D far-field electric field distribution of the tunable lens 600 being a first lens (with a first focal length of $307\text{ }\mu\text{m}$), and a second lens (with a second focal length of $-50\text{ }\mu\text{m}$) is denoted as 630. The second lens may include silicon metalens having nanobars. The port 1 is set as input (e.g. input 1 Watt of power) and the port 2 is set as output. The time-averaged power outflow is 0.27866 Watts. A total transmission rate of 27.9% is obtained and the transmission of the unit cell is 37%.

[00089] FIG. 6C shows transmission rate 641 and phase change 642 (phase change/ 2π) of the transmitted light beam by the tunable lens 600 as the tunable refractive index of the tunable lens 600 increases from 2.102 to 2.189. The tunable lens 600 provides a phase change of up to 0.55π .

[00090] FIG. 6D shows refractive index distribution across the tunable lens 600 (e.g. the x-axis of FIG. 6B). In other words, the optical axis (i.e. the focal spot) has been tuned from 0 to approximately 1.5×10^{-5} m (15 μ m) as shown in FIG. 6B.

[00091] FIG. 6E shows the radiation patterns of the transmitted light beam by the tunable lens 600.

[00092] FIG. 7 shows a block diagram of a unit cell 700 of a metalens according to various embodiments of the present disclosure. The metalens may be included in the devices 100, 200, 300, 400, being the first lens when the second lens is the tunable lens, or being the second lens when the first lens is the tunable lens.

[00093] According to various non-limiting embodiments, the unit cell 700 may include a substrate 790 (e.g. made of strontium titanate (SrTiO_3)), and a nanobar 721 (e.g. made of silicon or titanium dioxide) disposed on the substrate 790. The nanobar 721 may have a height h and a width d . A pitch p of the unit cell 700 is also denoted in FIG. 7. The metalens may consist of periodically repeating unit cells 700.

[00094] FIG. 8 shows transmission rate 701 and phase change 702 by the unit cell 700 with respect to the width d of the nanobar 721. The light beam may enter from the substrate 790 and exit from the nanobar 721 into an air medium. The phase of the transmitted light beam may be controlled by changing the width d of the nanobar 721. In some embodiments, the passive metalens may be so designed by choosing the width d and/or height h of the nanobar 721 to achieve a parabolic phase profile, which allows the metalens to disperse light as a diverging lens with a specific focal length (e.g. -50 μ m). In some embodiments, the device may be so designed by combining a plurality of unit cells 500 or a plurality of unit cells 600 together to form a complete tunable converging lens. In other embodiments, the tunable lens may just include a single active tunable layer (e.g. BST) patterned with many individual electrodes.

[00095] FIG. 9 show simulation results of light beam intensity according to deflection angles by a device (e.g. devices 100, 200, 300, 400) according to various embodiments of the present disclosure, wherein the first lens is a flat tunable converging lens including repeating unit cells, the second lens is a converging metalens and the substrate is made of strontium titanate (SrTiO_3). The thickness of the substrate is 5.6 μ m. Graph 901 illustrates the light beam intensity when the displacement between the first lens and the second lens is equal to six unit cells (i.e. 6.3 μ m) of the flat tunable lens; Graph 902 illustrates the light beam intensity when the displacement between the first lens and the second lens is equal to twelve unit cells (i.e. 12.6 μ m) of the flat tunable lens; and Graph 903 illustrates the light beam intensity when the

displacement between the first lens and the second lens is equal to eighteen unit cells (i.e. 18.9 μm) of the flat tunable lens. That is, by increasing the displacement between the first lens and the second lens, the deflection angles changes from approximately -7.3° to approximately -21.6° . In other words, the tunable focal spot of the tunable lens may be tunable by a distance equal to an integer multiple of a dimension of the unit cell.

[00096] Table I summarizes the simulated performance of the device. The theoretical deflection angle from Equation (1) is compared to the simulation results. The slight difference between the resulting values may be from the uncertainties in the design of the two flat lenses on both sides of the substrate and also the refraction of the light when exiting the high refractive index substrate, which is not considered in Equation (1). The diffraction efficiency (%) at different angles is also shown in the table.

TABLE I. Summary of device performance

Lateral shift (unit cell)	Lateral shift (μm)	Theoretical Output angle ($^\circ$)	Simulated Output angle ($^\circ$)	Diffraction efficiency (%)
6	6.3	7.18	7.3	42
12	12.6	13.5	14	38
18	18.9	19.8	21.6	25

[00097] FIG. 10 shows a flow chart of a method 1000 for forming a device (e.g. devices 100, 200, 300, 400) for beam steering. The method 1000 may include: forming a first lens on a first surface of a substrate (at step 102); and forming a second lens on a second surface of the substrate, the second surface being parallel and opposite to the first surface of the substrate (at step 104). At least one of the first lens and the second lens may be a tunable lens having a tunable focal spot. The first and second lenses may include metalenses.

[00098] According to non-limiting various embodiment, the manufacture of the first and second lenses may employ several fabrication techniques to create nanostructures for light manipulation, including electron beam lithography (e-beam lithography), which uses a focused electron beam to pattern a resist material with high resolution; nanoimprint lithography (NIL), where a mold with nanoscale features is pressed into a resist-coated substrate to imprint the desired pattern; and photolithography, which projects light through a photomask onto a photosensitive resist to create larger-area patterns. Chemical Vapor Deposition (CVD) and Physical Vapor Deposition (PVD) may be used to deposit thin films of materials that are then patterned through etching techniques like Reactive Ion Etching (RIE). Stamping and embossing methods may involve pressing patterned stamps onto substrates, while laser

lithography uses focused laser beams to directly write patterns onto materials. Each of these techniques may be selected based on the required precision, material properties, and specific design needs of the lenses.

[00099] While the method described above is illustrated and described as a series of steps or events, it will be appreciated that any ordering of such steps or events are not to be interpreted in a limiting sense. For example, some steps may occur in different orders and/or concurrently with other steps or events apart from those illustrated and/or described herein. In addition, not all illustrated steps may be required to implement one or more aspects or embodiments described herein. Also, one or more of the steps depicted herein may be carried out in one or more separate acts and/or phases.

[000100] While this specification contains many details, these should not be understood as limitations on the scope of what may be claimed, but rather as descriptions of features specific to particular examples. Certain features that are described in this specification or shown in the drawings in the context of separate implementations can also be combined. Conversely, various features that are described or shown in the context of a single implementation can also be implemented in multiple implementations separately or in any suitable sub-combination.

[000101] Similarly, while operations are depicted in the drawings in a particular order, this should not be understood as requiring that such operations be performed in the particular order shown or in sequential order, or that all illustrated operations be performed, to achieve desirable results. In certain circumstances, multitasking and parallel processing may be advantageous. Moreover, the separation of various system components in the implementations described above should not be understood as requiring such separation in all implementations, and it should be understood that the described program components and systems can generally be integrated together in a single product or packaged into multiple products.

[000102] A number of implementations have been described. Nevertheless, it will be understood that various modifications can be made. Accordingly, other implementations are within the scope of the following claims.

CLAIMS

1. A device for beam steering, comprising:
a substrate;
a first lens disposed on a first surface of the substrate; and
a second lens disposed on a second surface of the substrate, the second surface being opposite to the first surface of the substrate,
wherein at least one of the first lens and the second lens is a tunable lens having a tunable focal spot and the device is configured to steer a beam passing through the device by tuning the tunable focal spot of the tunable lens.
2. The device of claim 1, wherein a sum of a first focal length of the first lens and a second focal length of the second lens is equal to a thickness of the substrate.
3. The device of claim 2, wherein the tunable focal spot is tunable along a plane parallel to the first surface and/or the second surface of the substrate where the tunable lens is disposed.
4. The device of claim 2 or claim 3, wherein when the first surface is parallel to the second surface of the substrate, a deflection angle of the beam steered by the device is determined by the second focal length of the second lens and a displacement between a first focal spot of the first lens and a second focal spot of the second lens.
5. The device of any of claims 1 to 4, wherein the tunable lens has an electrically tunable refractive index.
6. The device of claim 5, wherein the tunable focal spot is tunable by changing voltages applied to the tunable lens to laterally shift a spatial profile of the tunable refractive index.
7. The device of any of claims 1 to 6, wherein the tunable lens comprises a tunable layer made of tunable materials including ferroelectric materials, transparent conductive oxides, phase change materials, liquid crystals, elastomers.

8. The device of claim 7, wherein the ferroelectric materials comprise Barium strontium titanate (BaSrTiO_3), barium titanate (BaTiO_3), strontium titanate (SrTiO_3), Lead Lanthanum Zirconate Titanate (PLZT), Lithium niobate (LiNbO_3), and ferroelectric liquid crystals (FLCs).
9. The device of claim 8, wherein Barium strontium titanate (BaSrTiO_3) comprises $\text{Ba}_{0.7}\text{Sr}_{0.3}\text{TiO}_3$ or BST70/30.
10. The device of claim 7 or claim 8, wherein the tunable lens further comprises a plurality of Distributed Bragg Reflector (DBR) layers.
11. The device of any of claims 7 to 10, wherein the tunable layer comprises an array of unit cells, and the tunable focal spot is tunable by a distance equal to an integer multiple of a dimension of the unit cell.
12. The device of claim 11, wherein each unit cell of the array of unit cells comprises a respective pair of electrodes configured to receive a voltage for tuning the tunable focal spot.
13. The device of any of claims 1 to 12, wherein the first lens is the tunable lens having a first focal spot being the tunable focal spot, and the second lens is a metalens having a second focal spot.
14. The device of claim 13, wherein the second lens comprises a metalens.
15. The device of claim 14, wherein the metalens comprises silicon nanobars.
16. The device of any of claims 1 to 15, wherein the first lens is a flat lens, a Fresnel zone plate, a Fresnel lens, a meta-surface or any combination thereof, and wherein the second lens is a flat lens, a Fresnel zone plate, a Fresnel lens, a meta-surface or any combination thereof.

17. The device of any of claims 1 to 16, wherein the beam comprises visible light or near-infrared light.
18. The device of any of claims 1 to 17, wherein the first lens and the second lens are configured to operate in transmission mode.
19. The device of any of claims 1 to 18, wherein the substrate includes strontium titanate (SrTiO_3) or magnesium oxide (MgO).
20. A method for forming a device for beam steering, comprising:
forming a first lens on a first surface of a substrate; and
forming a second lens on a second surface of the substrate, the second surface being parallel and opposite to the first surface of the substrate,
wherein at least one of the first lens and the second lens is a tunable lens having a tunable focal spot.