

DEVICE AND METHOD FOR FABRICATING DEVICE

TECHNICAL FIELD

[0001] The present disclosure generally relates to a device (e.g., an optical device, an electro-optic device) and a method of fabricating the device.

BACKGROUND

[0002] Metasurfaces are two-dimensional equivalents of metamaterials, composing subwavelength structures called meta-atoms. Different properties of the light such as amplitude, phase, dispersion, momentum, and polarization can be controlled by the metasurfaces. Metasurfaces have attracted enormous attention due to their versatile functionality, ultra-thin feature, and easiness of integration compared with conventional refractive optics. Active control of light propagation in the visible and near-infrared (near-IR) spectrum has practical and fundamental significance, especially for telecommunications and sensing applications. The ultimate goal of the active metasurfaces is the control over all unit cells separately, which gives the metasurfaces a variety of capabilities such as spatial light modulation (SLM), beam steering, tunable lens, and dynamic holography.

[0003] Currently, microelectromechanical system (MEMS) mirrors, electrically-addressed spatial light modulators (EASLM), and optically-addressed spatial light modulators (OASLM) are available in the form of commercial components. MEMS mirrors are only applicable in reflective modes and suffer from a short-range and small field of view due to their small mirror sizes and small deflection angles. EASLM and OASLMs use liquid crystals (LCs) as the tunable material in unit cells and suffer from low resolution and field of view (FOV) due to the cross-talk between the LCs in neighbor unit cells and also low speed limited by the rotation speed of LCs molecules.

[0004] Therefore, there exists a need to provide an improved device with tunable optical characteristics such as focal length, focal spot, etc.

SUMMARY

[0005] According to a first aspect of the present disclosure, a device is provided. The device may include a substrate; a tunable material formed on the substrate; and a plurality of electrodes formed on a top surface of the tunable material, wherein the tunable material comprises a plurality of unit cells, each unit cell is formed by a section of the tunable material between a

respective pair of neighbouring electrodes of the plurality of electrodes, wherein a respective refractive index of each unit cell is adjustable by changing a voltage applied between the respective pair of neighbouring electrodes, wherein an optical characteristic of the device is adjustable by changing a respective refractive index of each of at least one unit cell.

[0006] According to a second aspect of the present disclosure, a method of fabricating a device is provided. The method may include forming a tunable material on a substrate; and forming a plurality of electrodes on a top surface of the tunable material, wherein the tunable material comprises a plurality of unit cells, each unit cell is formed by a section of the tunable material between a respective pair of neighbouring electrodes of the plurality of electrodes, wherein a respective refractive index of each unit cell is adjustable by changing a voltage applied between the respective pair of neighbouring electrodes, wherein an optical characteristic of the device is adjustable by changing a respective refractive index of each of at least one unit cell.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] FIG. 1 shows a cross-section view of a device in accordance with some embodiments of the present disclosure;

[0008] FIG. 2 shows the optical properties of examples of 700 nm thick BST films deposited on STO substrate;

[0009] FIG. 3 shows an example of a unit cell of the plurality of unit cells included in the tunable material of the device with the corresponding neighbouring electrodes formed on the unit cell and the substrate on which the unit cell is formed;

[0010] FIG. 4 shows simulation results for the transmission amplitude and phase of the unit cell of FIG. 3;

[0011] FIG. 5A shows a device with lateral shift of the focal spot and tunable focal length according to some embodiments of the present disclosure.

[0012] FIG. 5B shows an enlarged view of the device of FIG. 5A;

[0013] FIG. 5C shows a front view of an exemplary zone arrangement of the device of FIG. 5A with the plurality of electrodes omitted;

[0014] FIG. 5D shows a schematic illustration of the first to N-th zones of the device in FIG. 5C;

[0015] FIG. 6A shows the simulation results of intensity as a function of the focal length for device with a tunable focal length of 400 μm , 500 μm , 600 μm , 700 μm and 800 μm respectively, in accordance with the zone patterns in Table I;

[0016] FIGS. 6B to 6D show the simulation results of the farfield electric field distribution of device with a tunable focal length of 400 μ m, 600 μ m and 800 μ m respectively, in accordance with the zone patterns in Table I;

[0017] FIGS. 7A to 7C show the simulation results of the focal spots of device with different lateral shifts of the spatial profile of the refractive index, as known as zone pattern of the device;

[0018] FIGS. 7D to 7F show a schematic illustration of the zone patterns of the device for achieving the focal shifting angle of 0°, 2.3°, and 4.6°, respectively as shown in FIGS 7A to 7C respectively;

[0019] FIG. 8A shows a device according to some embodiments of the present disclosure;

[0020] FIG. 8B shows the plurality of electrode rings included in the plurality of electrodes formed on a top surface of the tunable material;

[0021] FIG. 8C shows the dimensions of a central region, an outer region and an electrode fan-out region for the device;

[0022] FIGS. 9A to 9D show the optical microscope images of the fabricated device (e.g., electrically tunable circular FZP flat lens) with Au electrodes (electrode rings);

[0023] FIG. 10A shows the simulation results of intensity as a function of the focal length for a device with a tunable focal length of 400 μ m, 500 μ m, 600 μ m, 700 μ m and 800 μ m respectively;

[0024] FIG. 10B shows the tunability of focal length and performance of the device with tunable focal lengths;

[0025] FIG. 11 is a flow chart depicting a method of forming a device according to some embodiments of the present disclosure.

DETAILED DESCRIPTION

[0026] 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.

[0027] 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.

[0028] 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.

[0029] 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.

[0030] As used herein, the term “and/or” includes any and all combinations of one or more of the associated listed items.

[0031] 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.

[0032] The term “zone pattern” (or referred to as “refractive index profile” or “spatial profile of refractive index”) may be used herein to refer to a respective number of adjoining unit cells in each of a plurality of zones of a device and a respective zone refractive index (n_{zone}) of each of the plurality of zones. In other words, the term “zone pattern” may refer to an arrangements of individual zones including the number of adjoining unit cells in each individual zone.

[0033] The term “zone refractive index” may be used herein to refer a refractive index of adjoining unit cells in a zone. The zone refractive index (n_{zone}) of each individual zone may be determined by a voltage applied to that zone of unit cells.

[0034] The present disclosure provides new designs and platforms for achieving devices (e.g., electrically tunable flat lenses) with tunable focal lengths and lateral shift of focal spots for potential applications in LiDAR, dynamic holography, imaging, sensing, display, lithography, optical communication, and other consumer electronics. Ferroelectric material (e.g., BaSrTiO₃) is used as the active tunable material platform to obtain the electrically tunable flat lenses. The property of the material is characterized and an electrical tuning mechanism is introduced. The optical performance of the devices (e.g., electrically tunable flat lenses) is shown using simulations and is experimentally validated through the fabricated devices.

[0035] In the present disclosure, the BaSrTiO₃ (BST) is used as an electro-optically tunable material in designing the device (tunable flat lens). By using BST, a relaxer ferroelectric material, its large transparent window in the visible and near-IR spectrum, fast tuning speed, and all-solid-state device structure are utilised. Furthermore, with the innovative electrode and device structure, multi-functions of both focal length tuning in the light propagation direction and focal spot scanning (or referred to as focal spot shifting) in the lateral direction can be achieved.

[0036] A tunable lens using cylindrical or circular FZP structure for focal length tuning and/or focal spot lateral scanning (or referred to as lateral shifting of focal spot) are used as the electrically tunable device.

[0037] FZP structure is constructed by phase difference in tunable material (e.g., BST film) induced by different voltages applied to different sections of the tunable material by the lateral electrodes directly patterned on top of the tunable material (e.g., BST film). Lateral electrode pattern on top of tunable material (e.g., BST film) can achieve tunable unit cell.

[0038] Electrodes (e.g., electrode stripes, electrode lines or electrode rings) may be used to exert the required electric field pattern (or voltage pattern). Accordingly, a wide range of focal length tuning for the device can be achieved. The new electrode patterns make it possible to have a device (e.g., tunable flat lens) only using electrodes on top of tunable material (e.g., ferroelectric film). Moreover, the electric field is lateral by applying voltages between the neighbouring electrodes (e.g., electrode stripes, electrode lines or electrode rings) which are laterally spaced apart from one another. Different or similar voltages may be applied between the neighbouring electrodes as required by the phase profile (voltage profile or voltage pattern) for the device.

[0039] The design in the present disclosure applies the electric field between neighboring electrodes on one side of the tunable material (e.g., ferroelectric film). The new lateral electrode design would require a much smaller current to operate the device which reduces the power consumption.

[0040] In the present disclosure, thin tunable material (e.g., ferroelectric film) ($<6\mu\text{m}$) may be used. Such a thin tunable material (e.g., ferroelectric film) would be more suitable for deploying the electrode structure provided in the present disclosure. For example, a device with a thick substrate (e.g., a $300\mu\text{m}$ ceramic substrate) would be prohibited from deploying any electrode structure provided in the present disclosure due to the limitation on resolution and electrode width (minimum electrode width is $50\mu\text{m}$ for a device with a $300\mu\text{m}$ ceramic substrate). Moreover, a thick substrate (e.g., a $300\mu\text{m}$ ceramic substrate) would require a much higher voltage to operate (e.g., $\sim 300\text{V}$). In addition, the cost for the device 100/200/300 provided in the present disclosure would be cheap by depositing a very thin ferroelectric film directly on top of the substrate.

[0041] The device provided in the present disclosure can operate optimally at room temperature. The device provided in the present disclosure can achieve one of the highest electro-optically tunability at room temperature in the visible and near-infrared spectra.

[0042] Various embodiments of the present disclosure seek to provide a device, for example, a tunable lens. The device may include a substrate, a tunable material (e.g., ferroelectric material) formed on the substrate. The tunable material (e.g., ferroelectric material) may be divided into a plurality of unit cells, and a plurality of zones (e.g., groups) of unit cells. An individual refractive index of each unit cell may be adjustable by changing a voltage applied to that unit cell through a corresponding pair of electrodes formed on the tunable material (e.g., ferroelectric material). A zone refractive index of each zone of unit cells may be adjustable by changing a voltage applied to that zone of unit cells through a corresponding pair of electrodes formed on the tunable material (e.g., ferroelectric material). That is, a refractive index of the tunable material (or referred to as a refractive index profile) may be tunable/adjustable by tuning/adjusting the individual refractive indexes and/or the zone refractive index(es).

[0043] In various embodiments, an optical characteristic of the (optical) device may be tunable/adjustable by changing the voltage(s) applied to the tunable material (e.g., ferroelectric material). For example, the optical characteristic may include a focal spot, a focal length which may be tuned/adjusted in response to the refractive index profile. In other words, by tuning/adjusting the refractive index profile of the tunable material (e.g., ferroelectric material), the focal spot and/or the focal length of the device may be tuned/adjusted.

[0044] In various embodiments, the device may include a flat lens, or a Fresnel zone plate, a metasurface, or a combination of them. The tunable material (e.g., ferroelectric material) may be adaptively divided into a plurality of zones of unit cells in accordance with requirements, and each zone of unit cells may include a predetermined (different) number of unit cells so as to provide a desirable refractive index profile of the device. The plurality of zones of unit cells may be split into two symmetric regions, each symmetric region having a half number of the plurality of zones of unit cells.

[0045] In some embodiments, in each pair of (immediate) adjacent zones of unit cells, respective voltages may be respectively applied to obtain a higher zone refractive index and a lower zone refractive index. For example, a higher voltage may be applied to one (i.e., a first) of the pair of adjacent zones of unit cells to obtain a higher zone refractive index, and a lower voltage may be applied to the other (i.e., a second) of the pair of adjacent zones of unit cells to obtain a lower zone refractive index. In other words, higher voltages and lower voltages may be alternatively applied to the plurality of zones of unit cells so as to obtain alternative higher (equal) zone refractive indexes and lower (equal) refractive indexes in the plurality of zones.

[0046] The following examples pertain to various aspects of the present disclosure.

[0047] Example 1 is a device including: a substrate; a tunable material formed on the substrate; and a plurality of electrodes formed on a top surface of the tunable material, wherein the tunable material includes a plurality of unit cells, each unit cell is formed by a section of the tunable material between a respective pair of neighbouring electrodes of the plurality of electrodes, wherein a respective refractive index of each unit cell is adjustable by changing a voltage applied between the respective pair of neighbouring electrodes, wherein an optical characteristic of the device is adjustable by changing a respective refractive index of each of at least one unit cell.

[0048] In Example 2, the subject matter of Example 1 may optionally include that the optical characteristic of the device includes a focal length and/or a focal spot.

[0049] In Example 3, the subject matter of Example 1 may optionally include that the plurality of unit cells forms a plurality of zones including first to N-th zones, wherein N is an integer greater than or equal to 1, wherein each zone is formed by one or more adjoining unit cells configured to have a same refractive index by applying a same voltage between a respective pair of neighbouring electrodes corresponding to each adjoining unit cell in the zone, wherein an optical characteristic of the device is adjustable by changing a number of adjoining unit cells in at least one zone of the plurality of zones.

[0050] In Example 4, the subject matter of Example 3 may optionally include that the plurality of zones further includes first to N-th symmetric zones which are symmetric to the respective first to N-th zones about a central axis of the tunable material, wherein each zone of the first to N-th symmetric zones is formed by one or more adjoining unit cells configured to have a same refractive index by applying a same voltage between a respective pair of neighbouring electrodes corresponding to each adjoining unit cell in the zone, wherein a refractive index of the one or more adjoining unit cells in each of the first to N-th symmetric zones is the same as a refractive index of the one or more adjoining unit cells in the respective first to N-th zones.

[0051] In Example 5, the subject matter of Example 4 may optionally include that a number of adjoining unit cells in each of the first to N-th symmetric zones is the same as a number of adjoining unit cells in the respective first to N-th zones.

[0052] In Example 6, the subject matter of Example 3 may optionally include that a first voltage applied between a respective pair of neighbouring electrodes corresponding to each adjoining unit cell in the (2M-1)-th zone of the plurality of zones is configured to have a first value, and a second voltage applied between a respective pair of neighbouring electrodes corresponding to each adjoining unit cell in the 2M-th zone of the plurality of zones is configured to have a second value, wherein the second value is greater than the first value, where M is an integer greater than or equal to 1.

[0053] In Example 7, the subject matter of Example 3 may optionally include that different zones of the plurality of zones includes different numbers of adjoining unit cells.

[0054] In Example 8, the subject matter of Example 1 may optionally include that the plurality of electrodes includes electrodes that are linear and parallel to one another.

[0055] In Example 9, the subject matter of Example 1 may optionally include that the plurality of electrodes includes electrode rings that are concentric to each other.

[0056] In Example 10, the subject matter of Example 1 may optionally include that the plurality of electrodes includes a plurality of pairs of central neighbouring electrode rings, wherein the tunable material includes a central zone formed by a fixed number of adjoining unit cells configured to have a same refractive index by applying a same voltage between a respective pair of central neighbouring electrode rings corresponding to each adjoining unit cell in the central zone, wherein each adjoining unit cell in the central zone is formed by a tunable material between a respective pair of central neighbouring electrode rings of the plurality of pairs of central neighbouring electrode rings.

[0057] In Example 11, the subject matter of Example 10 may optionally include that one electrode ring of each pair of central neighbouring electrode rings is in electrical connection

with a first electrical line, and the other electrode ring of each pair of central neighbouring electrode rings is in electrical connection with a second electrical line, to apply a same voltage between each pair of central neighbouring electrode rings.

[0058] In Example 12, the subject matter of Example 11 may optionally include that an optical characteristic of the device is adjustable by changing a refractive index of the one or more adjoining unit cells in the central zone.

[0059] In Example 13, the subject matter of Example 10 may optionally include that the plurality of electrodes further includes a plurality of pairs of outer neighbouring electrode rings, wherein the tunable material further includes a plurality of outer zones, each outer zone being formed by one or more adjoining unit cells configured to have a same refractive index by applying a same voltage between a respective pair of outer neighbouring electrode rings corresponding to each adjoining unit cell in the outer zone, wherein each adjoining unit cell in an outer zone of the plurality of outer zones is formed by a tunable material between a respective pair of outer neighbouring electrode rings of the plurality of pairs of outer neighbouring electrode rings.

[0060] In Example 14, the subject matter of Example 13 may optionally include that each electrode ring of the plurality of pairs of outer neighbouring electrode rings are in electrical connection with a respective electrical line to apply a voltage between each pair of outer neighbouring electrode rings.

[0061] In Example 15, the subject matter of Example 14 may optionally include that an optical characteristic of the device is adjustable by changing a refractive index of the one or more adjoining unit cells in at least one outer zone of the plurality of outer zones.

[0062] In Example 16, the subject matter of Example 14 may optionally include that an optical characteristic of the device is adjustable by changing a number of adjoining unit cells in at least one outer zone of the plurality of outer zones.

[0063] In Example 17, the subject matter of Example 1 may optionally include that a thickness of the tunable material ranges from 40 nm to 2 μm .

[0064] In Example 18, the subject matter of Example 1 may optionally include that the tunable material includes barium titanate, strontium titanate, or barium strontium titanate.

[0065] In Example 19, the subject matter of Example 1 may optionally include that the substrate includes strontium titanate (SrTiO_3) or magnesium oxide (MgO).

[0066] In Example 20, the subject matter of Example 1 may optionally include that the tunable material or the substrate is transparent in visible light or near-infrared light.

[0067] In Example 21, the subject matter of Example 1 may optionally further include a printed circuit board, wherein the printed circuit board is wire-bonded to the plurality of electrodes for applying the voltage.

[0068] In Example 22, the subject matter of Example 1 may optionally include that a focal spot of the device is laterally shiftable by changing voltages applied to the plurality of electrodes to laterally shift a refractive index profile of the device.

[0069] In Example 23, the subject matter of Example 1 may optionally include that the tunable material includes ferroelectric material, transparent conductive oxide, phase change material, liquid crystal and/or elastomer.

[0070] Example 24 is a method of fabricating a device, the method including: forming a tunable material on a substrate; and forming a plurality of electrodes on a top surface of the tunable material, wherein the tunable material includes a plurality of unit cells, each unit cell is formed by a section of the tunable material between a respective pair of neighbouring electrodes of the plurality of electrodes, wherein a respective refractive index of each unit cell is adjustable by changing a voltage applied between the respective pair of neighbouring electrodes, wherein an optical characteristic of the device is adjustable by changing a respective refractive index of each of at least one unit cell.

[0071] In Example 25, the subject matter of Example 24 may optionally include that the plurality of unit cells forms a plurality of zones including first to N-th zones, wherein N is an integer greater than or equal to 1, wherein each zone is formed by one or more adjoining unit cells configured to have a same refractive index by applying a same voltage between a respective pair of neighbouring electrodes corresponding to each adjoining unit cell in the zone, wherein an optical characteristic of the device is adjustable by changing a number of adjoining unit cells in at least one zone of the plurality of zones.

[0072] In Example 26, the subject matter of Example 24 may optionally further include wire-bonding a printed circuit board to the plurality of electrodes for applying the voltage.

[0073] FIG. 1 shows a cross-section view of a device 100 in accordance with some embodiments of the present disclosure. With reference to FIG. 1, the device 100 may include a substrate 110, a tunable material 120 formed on the substrate 110, and a plurality of electrodes 130 formed on a top surface of the tunable material 120. The tunable material may include ferroelectric material, transparent conductive oxide, phase change material, liquid crystal and/or elastomer. The plurality of electrodes 130 may be laterally spaced apart from each other. Tunable focal lengths and lateral shift of focal spot may be achieved by the device 100. In other

words, the device 100 may have tunable focal lengths and lateral shift of focal spot by applying various voltages to the tunable material 120 through the plurality of electrodes 130.

[0074] According to various non-limiting embodiments, the substrate 110 may include strontium titanate (SrTiO_3) or magnesium oxide (MgO). In some embodiments, the substrate 110 may be transparent in visible light or near-infrared light.

[0075] According to various non-limiting embodiments, the ferroelectric material 120 may include relaxer ferroelectric material. The relaxer ferroelectric material may exhibit high electrostriction. The ferroelectric material 120 may include barium titanate (BaTiO_3 or BTO), strontium titanate (SrTiO_3 or STO) or barium strontium titanate ($\text{Ba}_x\text{Sr}_{1-x}\text{TiO}_3$ or BST). The ferroelectric material 120 may include barium strontium titanate ($\text{Ba}_x\text{Sr}_{1-x}\text{TiO}_3$) with $0.5 \leq x \leq 1$. The ferroelectric material 120 may include a combination of barium titanate (BTO) and strontium titanate (STO). For example, the ferroelectric material 120 may include 70% barium titanate (BTO) and 30% strontium titanate (STO), 60% barium titanate (BTO) and 40% strontium titanate (STO), or 50% barium titanate (BTO) and 50% strontium titanate (STO). The ferroelectric material 120 may be of a thickness of less than 20 μm . A thickness of the ferroelectric material 120 may range from 40 nm to 2 μm . In some embodiments, the ferroelectric material 120 may be transparent in visible light or near-infrared light.

[0076] Barium strontium titanate (BST), barium titanate (BTO) and strontium titanate (STO) are tunable relaxer ferroelectric material that belong to the point group 4mm. The barium strontium titanate (BST) may have large Electro-optic (EO) coefficient and low loss in the visible spectrum. The electrical and optical properties of the barium strontium titanate (BST) may be controlled by changing the ratio of Ba and Sr in the crystal. The Curie temperature of the barium titanate (BTO) is 120°C meaning it is in the ferroelectric phase at room temperature (tetragonal 4mm crystal symmetry class) while strontium titanate (STO) is a paraelectric material at room temperature. If the content of Ba is smaller than 0.7 ($x > 0.3$), bulk barium strontium titanate (BST) ceramics may be at the desired paraelectric phase at room temperature.

[0077] BST 70/30 films with 70% BTO and 30% STO composition at the temperature of 700°C may be deposited on a substrate 110 (e.g., a STO substrate) using the Pulsed laser deposition (PLD) method. The crystal quality of the deposited films may be characterized by x-ray diffraction (XRD) to ensure large Electro-optic (EO) coefficients in ferroelectric and paraelectric materials.

[0078] According to various non-limiting embodiments, the plurality of electrodes 130 may be made of metal or transparent conductive oxide (TCO) material.

[0079] According to various non-limiting embodiments, the tunable material 120 may include a plurality of unit cells 122a, 122b, 122c, 122d, ..., collectively 122. In other words, the tunable material 120 may be divided into the plurality of adjoining unit cells 122. Each unit cell 122 may be formed by a section of the tunable material 120 between a respective pair of neighbouring electrodes of the plurality of electrodes 130. For example, a unit cell 122a may be formed by a section of the tunable material 120 between a pair of neighbouring electrodes 1301, 1302 of the plurality of electrodes 130. For example, a unit cell 122b may be formed by a section of the tunable material 120 between a pair of neighbouring electrodes 1302, 1303 of the plurality of electrodes 130. The widths of the plurality of unit cells 122 may be the same. A respective refractive index of each unit cell 122 may be adjustable by changing a voltage applied between the respective pair of neighbouring electrodes. For example, a refractive index of unit cell 122a may be adjustable by changing a voltage applied between the respective pair of neighbouring electrodes 1301, 1302. For example, a refractive index of unit cell 122b may be adjustable by changing a voltage applied between the respective pair of neighbouring electrodes 1302, 1303. In other words, the electrode 1302 may be shared between the adjacent unit cells 122a, 122b. An optical characteristic of the device 100 may be adjustable by changing a respective refractive index of each of at least one unit cell 122. The optical characteristic of the device 100 may include a focal length and/or a focal spot.

[0080] According to various non-limiting embodiments, the plurality of unit cells 122 may form a plurality of zones comprising first to N-th zones, wherein N is an integer greater than or equal to 1. Each zone may be formed by or include one or more adjoining unit cells 122 configured to have a same refractive index by applying a same voltage between a respective pair of neighbouring electrodes 130 corresponding to each adjoining unit cell 122 in the zone. For example, a first zone may be formed by or include adjoining unit cells 122a, 122b, 122c. The adjoining unit cells 122a, 122b, 122c may be configured to have a same refractive index by applying a same voltage between a respective pair (e.g., 1301/1302 pair, 1302/1303 pair, 1303/1304 pair) of neighbouring electrodes 130 corresponding to each of the adjoining unit cells 122a, 122b, 122c in the first zone. For example, a second zone may be formed by or include adjoining unit cells 122d, 122e. The adjoining unit cells 122d, 122e may be configured to have a same refractive index by applying a same voltage between a respective pair (e.g., 1304/1305 pair, 1305/1306 pair) of neighbouring electrodes 130 corresponding to each of the adjoining unit cells 122d, 122e in the second zone.

[0081] According to various non-limiting embodiments, a first voltage applied between a respective pair of neighbouring electrodes 130 corresponding to each adjoining unit cell 122 in

the (2M-1)-th zone of the first to N-th zones may be configured to have a first value. M may be an integer greater than or equals to 1. A second voltage applied between a respective pair of neighbouring electrodes 130 corresponding to each adjoining unit cell 122 in the 2M-th zone of the first to N-th zones may be configured to have a second value. The second value may be greater than the first value. Accordingly, a first refractive index (n_{Low}) of each adjoining unit cell 122 in the (2M-1)-th zone of the first to N-th zones may be lower than a second refractive index (n_{High}) of each adjoining unit cell 122 in the 2M-th zone of the first to N-th zones. M may be an integer greater than or equals to 1. In other words, a high voltage and a low voltage may be alternatively applied to neighbouring zones of the first to N-th zones. As a result, an high phase and low phase may be alternatively achieved in neighbouring zones of the first to N-th zones.

[0082] According to various non-limiting embodiments of the present disclosure, different zones of the first to N-th zones may include different numbers of adjoining unit cells 122. A number of adjoining unit cells 122 in different zones of the first to N-th zones may be different from one another. The numbers of adjoining unit cells 122 in the first to N-th zones may sequentially increase or decrease. An optical characteristic of the device 100 may be adjustable by changing a number of adjoining unit cells 122 in at least one zone of the first to N-th zones.

[0083] According to various non-limiting embodiments of the present disclosure, the plurality of zones may further include first to N-th symmetric zones which are symmetric to the respective first to N-th zones about a central axis (or referred to as a symmetric axis) of the tunable material 120. Each zone of the first to N-th symmetric zones may be formed by one or more adjoining unit cells 122 configured to have a same refractive index by applying a same voltage between a respective pair of neighbouring electrodes 130 corresponding to each adjoining unit cell 122 in the zone. A refractive index of the one or more adjoining unit cells 122 in each of the first to N-th symmetric zones may be the same as a refractive index of the one or more adjoining unit cells 122 in the respective first to N-th zones.

[0084] According to various non-limiting embodiments, a voltage applied to each of the first to N-th symmetric zones may be the same as a voltage applied to the respective first to N-th zones. Accordingly, a refractive index of the one or more adjoining unit cells in each of the first to N-th symmetric zones may be the same as a refractive index of the one or more adjoining unit cells in the respective first to N-th zones. According to various non-limiting embodiments of the present disclosure, a number of adjoining unit cells 122 in each of the first to N-th symmetric zones may be the same as a number of adjoining unit cells 122 in the respective first to N-th zones.

[0085] The device 100 may have a zone pattern defining the respective number of adjoining unit cells in each of the plurality of zones and the respective zone refractive index (n_{zone}) (i.e., a refractive index of each adjoining unit cell in a zone) of each of the plurality of zones. The focal length of the device 100 may be adjusted by changing the zone pattern of the device 100 by applying different arrays of voltages to the plurality of electrodes 130. To achieve a desired focal length of the device 100, the number of unit cells in each zone of the first to N-th zone of the device 100 may be governed/calculated by the Equation (2) as described in detail below and the width of each unit cell. When the device 100 further includes first to N-th symmetric zones which are symmetric to the respective first to N-th zones about a central axis (or referred to as a symmetric axis) of the tunable material 120, a number of unit cells in each of the first to N-th symmetric zones may be calculated as the same as the number of unit cells in the respective first to N-th zones. The device 100 may be a 2-phase FZP lens which is also known as a Fresnel Zone Plate lens having only 2 different phases: high phase and low phase. Table I shows examples of different zone patterns for a device 100 having different tunable focal lengths. The wavelength of the incoming light may be 633nm. The width of the unit cell may be 1 μ m. The N-th zone may be referred to as zone N hereinafter, The N-th symmetric zone may be referred to as sym zone N hereinafter, where N is an integer greater than or equal to 1. As seen from Table I, the focal length of the device 100 can be adjusted (i.e., different focal lengths of the device 100 ranging from 400 μ m to 800 μ m can be achieved) by changing the zone pattern of the device 100.

[0086] Table I. Examples of different zone patterns for a device 100 having different tunable focal lengths

	Focal Length (μ m)	400	500	600	700	800
n_{zone}		Number of unit cells	Number of unit cells	Number of unit cells	Number of unit cells	Number of unit cells
n_{Low}	zone 1/sym zone 1	16	18	19	21	22
n_{High}	zone 2/sym zone 2	7	7	8	9	9
n_{Low}	zone 3/sym zone 3	5	6	6	7	7
n_{High}	zone 4/sym zone 4	4	5	5	6	6
n_{Low}	zone 5/sym zone 5	4	4	5	5	5
n_{High}	zone 6/sym zone 6	3	4	4	4	5
n_{Low}	zone 7/sym zone 7	3	3	4	4	4

n _{High}	zone 8/sym zone 8	3	3	4	4	3
n _{Low}	zone 9/sym zone 9	3	3	3	1	
n _{High}	zone 10/sym zone 10	3	3	3		
n _{Low}	zone 11/sym zone 11	2	3			
n _{High}	zone 12/sym zone 12	2	2			
n _{Low}	zone 13/sym zone 13	2				
n _{High}	zone 14/sym zone 14	2				
n _{Low}	zone 15/sym zone 15	2				
	Total number of unit cells in the device	122	122	122	122	122

[0087] As shown in Table I, a focal length of 400 μ m may be achieved by a zone pattern where the tunable material 120 includes first to 15th zones (i.e., zone 1 to zone 15) and first to 15th symmetric zones (i.e., sym zone 1 to sym zone 15), where zone 1 to zone 15 are formed by or include 16, 7, 5, 4, 4, 3, 3, 3, 3, 3, 2, 2, 2, 2, 2 unit cells respectively, and the number of the adjoining unit cells in each of the first to 15th symmetric zones is the same as the number of adjoining unit cells in the respective first to 15th zones.

[0088] A focal length of 500 μ m may be achieved by a zone pattern where the tunable material 120 includes first to 12th zones (i.e., zone 1 to zone 12) and first to 12th symmetric zones (i.e., sym zone 1 to sym zone 12), where zone 1 to zone 12 are formed by or include 18, 7, 6, 5, 4, 4, 3, 3, 3, 3, 3, 2 unit cells respectively, and the number of the adjoining unit cells in each of the first to 12th symmetric zones is the same as the number of adjoining unit cells in the respective first to 12th zones.

[0089] A focal length of 600 μ m may be achieved by a zone pattern where the tunable material 120 includes first to 10th zones (i.e., zone 1 to zone 10) and first to 10th symmetric zones (i.e., sym zone 1 to sym zone 10), where zone 1 to zone 10 are formed by or include 19, 8, 6, 5, 5, 4, 4, 4, 3, 3 unit cells respectively, and the number of the adjoining unit cells in each of the first to 10th symmetric zones is the same as the number of adjoining unit cells in the respective first to 10th zones.

[0090] A focal length of 700 μ m may be achieved by a zone pattern where the tunable material 120 includes first to 9th zones (i.e., zone 1 to zone 9) and first to 9th symmetric zones (i.e., sym zone 1 to sym zone 9), where zone 1 to zone 9 are formed by or include 21, 9, 7, 6, 5, 4, 4, 4,

1 unit cells respectively, and the number of the adjoining unit cells in each of the first to 9th symmetric zones is the same as the number of adjoining unit cells in the respective first to 9th zones.

[0091] A focal length of 800 μm may be achieved by a zone pattern where the tunable material 120 includes first to 8th zones (i.e., zone 1 to zone 8) and first to 8th symmetric zones (i.e., sym zone 1 to sym zone 8), where zone 1 to zone 8 are formed by or include 22, 9, 7, 6, 5, 5, 4, 3 unit cells respectively, and the number of the adjoining unit cells in each of the first to 8th symmetric zones is the same as the number of adjoining unit cells in the respective first to 8th zones.

[0092] By arranging different zones with different numbers of unit cells, the device 100 may be tunable to have a focal length of 400 μm , 500 μm , 600 μm , 700 μm and 800 μm . The width of each unit cell of the device 100 may be 1 μm . In the above examples of the zone patterns of the device 100 shown in Table I, the one or more adjoining unit cells in the (2M-1)-th zone of the first to N-th zones and the (2M-1)-th symmetric zone of the first to N-th symmetric zones have a first refractive index (n_{Low}), and the one or more adjoining unit cells in the 2M-th zone of the first to N-th zones and the 2M-th symmetric zone of the first to N-th symmetric zones have a second refractive index (n_{High}), the first refractive index (n_{Low}) being lower than the second refractive index (n_{High}), where N is an integer greater than or equals to 1, and M is an integer greater than or equals to 1. In other words, the zone refractive index (n_{zone}) of the (2M-1)-th zone of the first to N-th zones and the (2M-1)-th symmetric zone of the first to N-th symmetric zones have the first refractive index (n_{Low}), the zone refractive index (n_{zone}) of the 2M-th zone of the first to N-th zones and the 2M-th symmetric zone of the first to N-th symmetric zones have the second refractive index (n_{High}). By applying different voltages to different zones and consequently obtaining different zone refractive indexes, the device 100 may refract and focus the light rays into different focal spots and accordingly have different focal lengths.

[0093] The first zone (i.e., zone 1) may have more than 16 unit cells to achieve a device 100 having a focal length above 400 μm .

[0094] The optical characteristic of the device 100 may be adjustable by changing a zone refractive index (i.e., refractive index of each adjoining unit cell 122 in a zone) of at least one zone of the plurality of zones. The refractive index of each adjoining unit cell 122 in the same zone may be the same. The zone refractive index of the at least one zone may be adjusted by changing a voltage applied to the zone (i.e., a voltage applied between the respective pair of neighbouring electrodes corresponding to each adjoining unit cell 122 in the zone).

[0095] Highly epitaxial crystalline BST films with different thickness (e.g., a thickness of 45nm and a thickness of 700nm) may be deposited on single-crystal STO substrates.

[0096] The thickness of the deposited films may range from 40 nm to 2 μ m. The thickness of the film may be measured by both a profilometer and variable angle spectroscopic ellipsometry. The ellipsometry may be carried out at 3 different angles of 65°, 70°, and 75° in the wavelength range of 400 nm to 1200 nm. A Tauc–Lorentz model may be used to model the STO substrate and BST films independently.

[0097] FIG. 2 shows the optical properties of examples of 700 nm thick BST films deposited on STO substrate. The Refractive index and extinction coefficient are shown in 411 and 412, respectively. The BST films have a high refractive index and are transparent in the visible and near-IR spectra.

[0098] The electrooptical tunability of the BST films may be measured using a birefringence measurement setup. The electrically induced birefringence change $\delta(\Delta n)$ of the BST films deposited at different conditions with different thicknesses may be measured. The optimum film may be evaluated to achieve the maximum value for total accumulated phase shift (Φ) from the electrically induced birefringence which is defined as:

$$\Phi = \delta(\Delta n) \cdot t \quad (1)$$

where t is the thickness of the BST films, measured using the Ellipsometry method.

[0099] Birefringence changes of $\delta(\Delta n)=0.466$ and $\delta(\Delta n)=0.087$ may be measured for a thin film sample (thickness ~ 45 nm) and a thick film sample (thickness ~ 700 nm), respectively.

[00100] FIG. 3 shows an example of a unit cell of the plurality of unit cells 122 included in the tunable material 120 of the device 100 with the corresponding neighbouring electrodes 130 formed on the unit cell and the substrate 110 on which the unit cell is formed.

[00101] In FIG. 3, the incoming light may come from within the substrate 110. The incoming light could also impinge from the tunable material (e.g., BST film) 120 on top of the substrate 110. As the voltage is applied between the electrodes, the refractive index of the tunable material (e.g., BST film) is changed due to electrically induced birefringence change, which would result in a change in the phase of transmitted light.

[00102] FIG. 4 shows simulation results for the transmission amplitude (421) and phase (422) of the unit cell of FIG. 3. The phase of the unit cell increases as the refractive index of the tunable material (e.g., ferroelectric material) increases. Accordingly, the phase of each unit cell is adjustable by changing a voltage applied between the respective pair of neighbouring electrodes corresponding to the unit cell. In some embodiments, the refractive index of the

tunable material can be changed by adjusting the voltage applied between the electrodes on top and below the tunable material. In some embodiments, the refractive index of the tunable material can be changed by adjusting the voltage applied between electrodes on the left and the right of the tunable material.

[00103] This unit cell may be used to design an electrically tunable device using the Fresnel zone plates (FZP) lens concept.

[00104] In an FZP lens (or an electrically tunable device using the FZP lens concept), the radius of the m -th zone can be given by the following Equation (2):

$$r_m = \sqrt{m\lambda f + \frac{1}{4}m^2\lambda^2} \quad (2)$$

[00105]

[00106] Where λ is the wavelength of the incoming light, f is the focal length of the electrically tunable device, m is an integer number of zones, and r_m is the radius of the m -th zone, or a distance from a center point of a tunable material (e.g., ferroelectric material) of the electrically tunable device to a boundary between the m -th zone and the $(m+1)$ -th zone. The electrically tunable device may be a device 100/200/300 in the present disclosure. FIG. 5A shows a device 200 with lateral shift of the focal spot and tunable focal length according to some embodiments of the present disclosure. FIG. 5B shows an enlarged view of the device 200 of FIG. 5A. With reference to FIG. 5A and FIG. 5B, the device 200 may include a substrate 210, a tunable material 220 formed on the substrate 210, and a plurality of electrodes 230 formed on a top surface of the tunable material 220. The plurality of electrodes 230 of the device 200 may include electrodes that are linear and parallel to one another. For example, the electrodes in the plurality of electrodes 230 may be electrode lines, electrode strips, etc. The plurality of electrodes 230 may be laterally spaced apart from each other.

[00107] The tunable material 220 may include a plurality of unit cells 222a, 222b, 222c, 222d, ..., collectively 222. In other words, the tunable material 220 may be divided into the plurality of adjoining unit cells 222. Each unit cell 222 may be formed by a section of the tunable material 220 between a respective pair of neighbouring electrodes of the plurality of electrodes 230. For example, a unit cell 222a may be formed by a section of the tunable material 220 between a pair of neighbouring electrodes 2301, 2302 of the plurality of electrodes 230. For example, a unit cell 222b may be formed by a section of the tunable material 220 between a pair of neighbouring electrodes 2302, 2303 of the plurality of electrodes 230. The plurality of unit cells 222 may be linear and parallel to one another. The distance between each pair of the plurality of pairs of neighbouring electrode may determine a width of each unit cell as each

unit cell is formed by a section of the tunable material 220 between a respective pair of neighbouring electrodes of the plurality of electrodes 230. The widths of the plurality of unit cells 222 may be the same. A respective refractive index of each unit cell 222 may be adjustable by changing a voltage applied between the respective pair of neighbouring electrodes. For example, a refractive index of unit cell 222a may be adjustable by changing a voltage applied between the respective pair of neighbouring electrodes 2301, 2302. For example, a refractive index of unit cell 222b may be adjustable by changing a voltage applied between the respective pair of neighbouring electrodes 2302, 2303. In other words, the electrode 2302 may be shared between the adjacent unit cells 222a, 222b. An optical characteristic of the device 200 may be adjustable by changing a respective refractive index of each of at least one unit cell 222. The optical characteristic of the device 200 may include a focal length and/or a focal spot.

[00108] FIG. 5C shows a front view of an exemplary zone arrangement of the device 200 of FIG. 5A with the plurality of electrodes 230 omitted. As shown in FIG. 5C, the device 200 may include the substrate 210, the tunable material 220 formed on the substrate 210, and the plurality of electrodes 230 (not shown) formed on the top surface of the tunable material 220.

[00109] The plurality of unit cells 222 may form a plurality of zones comprising first to N-th zones (2201 to 220N respectively), wherein N is an integer greater than or equal to 1. In an example of the device 200 as shown in FIG. 5C, N is equal to 9. Each zone of the first to N-th zones (2201 to 220N respectively) may be formed by one or more adjoining unit cells 222 configured to have a same refractive index by applying a same voltage between a respective pair of neighbouring electrodes corresponding to each adjoining unit cell 222 in the zone. For example, a first zone may be formed by or include adjoining unit cells 222a, 222b. The adjoining unit cells 222a, 222b may be configured to have a first same refractive index by applying a first same voltage between a first respective pair (e.g., 2301/2302 pair, 2302/2303 pair) of neighbouring electrodes 230 corresponding to each of the adjoining unit cells 222a, 222b in the first zone. For example, a second zone may be formed by or include adjoining unit cells 222c, 222d, 222e. The adjoining unit cells 222c, 222d, 222e may be configured to have a second same refractive index by applying a second same voltage between a second respective pair (e.g., 2303/2304 pair, 2304/2305 pair, 2305/2306 pair) of neighbouring electrodes corresponding to each of the adjoining unit cells 222c, 222d, 222e in the second zone. According to some embodiments of the present disclosure, different zones of the first to N-th zones may include different numbers of adjoining unit cells 222. A number of adjoining unit cells 222 in different zones of the first to N-th zones may be different from one another.

[00110] According to various non-limiting embodiments of the present disclosure, the plurality of zones may further include first to N-th symmetric zones (2211 to 221N respectively) which are symmetric to the respective first to N-th zones about a central axis AA' (or referred to as a symmetric axis) of the tunable material 220. In the example of the device 200 as shown in FIG. 5C, N is equal to 9. Each zone of the first to N-th zones (2201 to 220N respectively) and the first to N-th symmetric zones (2211 to 221N respectively) may be formed by one or more adjoining unit cells 222 configured to have a first same refractive index by applying a first same voltage between a first respective pair of neighbouring electrodes corresponding to each of the one or more adjoining unit cells 222 in the zone. A refractive index of the one or more adjoining unit cells 222 in each of the first to N-th symmetric zones (2211 to 221N respectively) may be the same as a refractive index of the one or more adjoining unit cells 222 in the respective first to N-th zones (2201 to 220N respectively).

[00111] FIG. 5D shows a schematic illustration of the first to N-th zones (2201 to 220N respectively) of the device 200 in FIG. 5C. A first voltage (V1) applied between a respective pair of neighbouring electrodes corresponding to each adjoining unit cell 222 in the (2M-1)-th zone of first to N-th zones (2201 to 220N respectively) may be configured to have a first value. M may be an integer greater than or equals to 1. A second voltage (V2) applied between a respective pair of neighbouring electrodes corresponding to each adjoining unit cell 222 in the 2M-th zone of the first to N-th zones (2201 to 220N respectively) may be configured to have a second value. The second value may be greater than the first value. In other words, a high voltage and a low voltage may be alternatively applied to neighbouring zones of the first to N-th zones. Accordingly, a first refractive index (n_{Low}) of each adjoining unit cell 222 in the (2M-1)-th zone of the first to N-th zones may be lower than a second refractive index (n_{High}) of each adjoining unit cell 222 in the 2M-th zone of the first to N-th zones.

[00112] According to various non-limiting embodiments of the present disclosure, a voltage applied to each of the first to N-th symmetric zones may be the same as a voltage applied to the respective first to N-th zones. Accordingly, a refractive index of the one or more adjoining unit cells in each of the first to N-th symmetric zones may be the same as a refractive index of the one or more adjoining unit cells in the respective first to N-th zones. In other words, a zone refractive index of each of the first to N-th symmetric zone may be the same as a zone refractive index of the respective first to N-th zone.

[00113] According to various non-limiting embodiments of the present disclosure, a number of adjoining unit cells 220 in each of the first to N-th symmetric zones may be the same as a number of adjoining unit cells 220 in the respective first to N-th zones.

[00114] According to various non-limiting embodiments, the optical characteristic of the device 200 may be adjustable by changing a number of adjoining unit cells 222 in at least one zone of the first to N-th zone. A number of adjoining unit cells 220 in each of the first to N-th symmetric zones may be changed accordingly to be the same as a number of adjoining unit cells 220 in the respective first to N-th zones. Examples of different zone patterns for different focal length of the device 200 may be the same as the examples shown in Table I. The width of each unit cell of the device 200 may be 1 μ m.

[00115] According to various non-limiting embodiments, the optical characteristic of the device 200 may be adjustable by changing a zone refractive index (i.e., a refractive index of each adjoining unit cell 222 in a zone) of at least one zone of the plurality of zones. The refractive index of each adjoining unit cell in the same zone may be the same. The zone refractive index of the at least one zone may be adjusted by changing a voltage applied to the zone (i.e., a voltage applied between the respective pair of neighbouring electrodes corresponding to each adjoining unit cell in the zone).

[00116] The focal length of the device 200 may be adjusted by changing the zone pattern of the device 200 and by applying different arrays of voltages to the plurality of electrodes 230. To achieve a desired focal length of the device 200, the number of unit cells in each zone of the first to N-th zone of the device 200 may be governed/calculated by the Equation (2) as described above and the width of each unit cell. When the device 200 further includes first to N-th symmetric zones which are symmetric to the respective first to N-th zones about a central axis (or referred to as a symmetric axis) of the tunable material 220, a number of unit cells in each of the first to N-th symmetric zones may be calculated as the same as the number of unit cells in the respective first to N-th zones. The device 200 (e.g., an electrically tunable cylindrical FZP flat lens) with 122 unit cells and a width of 122 μ m may be optically simulated by adopting the zone patterns according to Table I as described above.

[00117] FIG. 6A shows the simulation results (431, 432, 433, 434, 435) of intensity as a function of the focal length for device 200 with a tunable focal length of 400 μ m, 500 μ m, 600 μ m, 700 μ m and 800 μ m respectively, in accordance with the zone patterns in Table I. The wavelength of the incoming light is set as 633nm. A large tuning range of focal lengths from 400 μ m to 800 μ m can be achieved. The focal length of the device 200 may be adjusted to 400 μ m, 500 μ m, 600 μ m, 700 μ m and 800 μ m by adopting the respective zone pattern according to Table I as described above. FIGS. 6B to 6D show the simulation results of the farfield electric field distribution of device 200 with a tunable focal length of 400 μ m, 600 μ m and 800 μ m

respectively, in accordance with the zone patterns in Table I. The wavelength of the incoming light is set as 633nm.

[00118] According to various non-limiting embodiments, the focal spot of the device 200 (e.g., an electrically tunable cylindrical FZP flat lens) may be laterally shifted by adopting different zone patterns as described with reference to FIGS 7A to 7F. In other words, focal spot lateral scanning may be achieved by adopting different zone patterns of the device 200.

[00119] FIGS. 7A to 7C show the simulation results of the focal spots of device 200 with different lateral shifts of the spatial profile of the refractive index, as known as zone pattern of the device 200. The device 200 may be an electrically tunable cylindrical FZP flat lens. FIGS. 7A to FIG. 7C show a simulated 2D far-field electric field distribution of the device 200 with a focal length of 400 μm , showing the lateral shifting of the focal spot (501, 502, 503 respectively) at a wavelength of 633 nm, for focal spot shifting angle of 0° , 2.3° , and 4.6° , respectively. FIGS. 7D to 7F show a schematic illustration of the zone patterns of the device 200 for achieving the focal shifting angle of 0° , 2.3° , and 4.6° , respectively as shown in FIGS 7A to 7C respectively. Focal spot shifting angle of 0° , 2.3° , and 4.6° corresponds to focal spot lateral shifting (LS) of $0\mu\text{m}$, $\pm 16\mu\text{m}$ and $\pm 32\mu\text{m}$. FIGS. 7D to 7F shows a refractive index (n_{BST}) of the tunable material as a function of the position of tunable material along a lateral direction (X-axis) in which the plurality of electrodes are spaced apart from one another. In FIGS. 7D to 7F, a high voltage and a low voltage are alternatively applied to neighbouring zones of the first to N-th zones. Each zone pattern in FIGS 7D to 7F indicates a respective width (and a respective number of adjoining unit cells is therefore determined, with the width of adjoining unit cell being set as a pre-determined value of $1\mu\text{m}$) of each of the plurality of zones and the respective zone refractive index (n_{zone}) of each of the plurality of zones. Table II shows the zone patterns of the device 200 in FIGS. 7D to 7F for achieving simulated 2D far-field electric field distribution as shown in FIGS 7A to FIG. 7C.

[00120] Table II. Zone patterns of the device 200 in FIGS. 7D to 7F for achieving simulated 2D far-field electric field distribution as shown in FIGS. 7A to 7C

Zone pattern	FIG. 7D	FIG. 7E	FIG. 7F
Focal Length (μm)	400	400	400

	zone	n _{zone}	No. of unit cells (UC)	zone	n _{zone}	No.of UC	zone	n _{zone}	No. of UC
	601	n _{Low}	2	631	n _{High}	3	661	n _{Low}	6
	602	n _{High}	2	632	n _{Low}	3	662	n _{High}	7
	603	n _{Low}	2	633	n _{High}	3	663	n _{Low}	16
	604	n _{High}	2	634	n _{Low}	4	664	n _{Low}	16
	605	n _{Low}	2	635	n _{High}	4	665	n _{High}	7
	606	n _{High}	3	636	n _{Low}	5	666	n _{Low}	5
	607	n _{Low}	3	637	n _{High}	7	667	n _{High}	4
	608	n _{High}	3	638	n _{Low}	16	668	n _{Low}	4
	609	n _{Low}	3	639	n _{Low}	16	669	n _{High}	3
	610	n _{High}	3	640	n _{High}	7	670	n _{Low}	3
	611	n _{Low}	4	641	n _{Low}	5	671	n _{High}	3
	612	n _{High}	4	642	n _{High}	4	672	n _{Low}	3
	613	n _{Low}	5	643	n _{Low}	4	673	n _{High}	3
	614	n _{High}	7	644	n _{High}	3	674	n _{Low}	2
	615	n _{Low}	16	645	n _{Low}	3	675	n _{High}	2
	616	n _{Low}	16	646	n _{High}	3	676	n _{Low}	2
	617	n _{High}	7	647	n _{Low}	3	677	n _{High}	2
	618	n _{Low}	5	648	n _{High}	3	678	n _{Low}	2
	619	n _{High}	4	649	n _{Low}	2	679	n _{High}	4
	620	n _{Low}	4	650	n _{High}	2	680	n _{Low}	4
	621	n _{High}	3	651	n _{Low}	2	681	n _{High}	3
	622	n _{Low}	3	652	n _{High}	2	682	n _{Low}	3
	623	n _{High}	3	653	n _{Low}	5	683	n _{High}	3
	624	n _{Low}	3	654	n _{High}	3	684	n _{Low}	3
	625	n _{High}	3	655	n _{Low}	2	685	n _{High}	3
	626	n _{Low}	2	656	n _{High}	2	686	n _{Low}	2
	627	n _{High}	2	657	n _{Low}	2	687	n _{High}	2
	628	n _{Low}	2	658	n _{High}	2	688	n _{Low}	2

	629	n_{High}	2	659	n_{Low}	2	689	n_{High}	2
	630	n_{Low}	2				690	n_{Low}	1
Total number of unit cells in the device	122			122			122		

[00121] As shown in Table II and FIGs. 7D to 7F, there are lateral shifts of zone pattern (or referred to as refractive index profile, spatial profile of the refractive index) of the device 200 from FIG. 7D to FIG. 7E, and from FIG. 7E to FIG. 7F. Lateral shift of zone pattern may include lateral shift of zone pattern of first to N-th zones (e.g., 691 in FIGs. 7D to 7F). The lateral shift of zone pattern of the device 200 may enable/cause/lead to lateral shifting of the focal spot. The lateral shift of zone pattern may enable/cause/lead to a lateral shift of the focal spot with a same distance and in a same direction of the lateral shift of zone pattern. For example, there is a lateral shift of zone pattern of a distance of 16 μm (i.e., $\text{LS}=16\mu\text{m}$) from the zone pattern of FIG. 7D to the zone pattern of FIG. 7E, causing/leading to a lateral shift of focal spot of the same distance (i.e., 16 μm) and in the same direction (i.e., to the left). For example, there is a further lateral shift of zone pattern of a distance of 16 μm (i.e., $\text{LS}=16\mu\text{m}$) from the zone pattern of FIG. 7E to the zone pattern of FIG. 7F, causing/leading to a further lateral shift of focal spot of the same distance (i.e., 16 μm) and in the same direction (i.e., to the left). There is a total lateral shift of zone pattern of a distance of 32 μm (i.e., $\text{LS}=32\mu\text{m}$) from the zone pattern of FIG. 7D to the zone pattern of FIG. 7F, causing/leading to a total lateral shift of zone pattern of the same distance (i.e., 32 μm) and in the same direction (i.e., to the left). The device 200 shows good performance with up to 16 μm lateral shift of focal spot at the focal length of 400 μm . The performance of the device 200 would degrade as the focal length or the lateral shift of focal spot is increased.

[00122] FIG. 8A shows a device 300 according to some embodiments of the present disclosure. The device 300 may be an electrically tunable circular FZP flat lens. With reference to FIG. 8A, the device 300 may include a substrate 310, a tunable material 320 formed on the substrate 310, and a plurality of electrodes 330 formed on a top surface of the tunable material 320. The plurality of electrodes 330 may include electrode rings that are concentric to each

other. The electrode rings included in the plurality of electrodes 330 may be spaced apart radially from each other.

[00123] FIG. 8B shows the plurality of electrode rings included in the plurality of electrodes formed on a top surface of the tunable material 320. The tunable material 320 may include a plurality of unit cells 322a, 322b, 322c, 322d, ..., collectively 322. In other words, the tunable material 320 may be divided into the plurality of adjoining unit cells 322. Each unit cell 322 may be formed by a section of the tunable material 320 between a respective pair of neighbouring electrode rings of the plurality of electrodes 330. For example, a unit cell 322a may be formed by a section of the tunable material 320 between a pair of neighbouring electrode rings 3301, 3302 of the plurality of electrodes 330. For example, a unit cell 322b may be formed by a section of the tunable material 320 between a pair of neighbouring electrode rings 3302, 3303 of the plurality of electrodes 330. The plurality of unit cells 322 may be a plurality of rings concentric to each other. In other words, an inner unit cell may have a smaller radius than an outer unit cell. The widths of the plurality of unit cells 322 may be the same. A respective refractive index of each unit cell 322 may be adjustable by changing a voltage applied between the respective pair of neighbouring electrode rings. For example, a refractive index of unit cell 322a may be adjustable by changing a voltage applied between the respective pair of neighbouring electrode rings 3301, 3302. For example, a refractive index of unit cell 322b may be adjustable by changing a voltage applied between the respective pair of neighbouring electrode rings 3302, 3303. In other words, the electrode 3302 may be shared between the adjacent unit cells 322a, 322b. An optical characteristic of the device 300 may be adjustable by changing a respective refractive index of each of at least one unit cell 322. The optical characteristic of the device 300 may include a focal length and/or a focal spot.

[00124] The plurality of unit cells 322 may form a plurality of zones comprising first to N-th zones, wherein N is an integer greater than or equal to 1. Each zone may be formed by or include one or more adjoining unit cells 322 configured to have a same refractive index by applying a same voltage between a respective pair of neighbouring electrode rings corresponding to each adjoining unit cell 322 in the zone.

[00125] A first voltage applied between a respective pair of neighbouring electrode rings corresponding to each adjoining unit cell 322 in the (2M-1)-th zone of the first to N-th zones may be configured to have a first value. A second voltage applied between a respective pair of neighbouring electrode rings corresponding to each adjoining unit cell 322 in the 2M-th zone of the first to N-th zones may be configured to have a second value. The second value may be greater than the first value. M may be an integer greater than or equals to 1. In other words, a

high voltage and a low voltage may be alternatively applied to neighbouring zones of the first to N-th zones. Accordingly, a first refractive index (n_{Low}) of each adjoining unit cell 322 in the (2M-1)-th zone of the first to N-th zones may be lower than a second refractive index (n_{High}) of each adjoining unit cell 322 in the 2M-th zone of the first to N-th zones.

[00126] According to various non-limiting embodiments of the present disclosure, different zones of the plurality of zones may include different numbers of adjoining unit cells 322. A number of adjoining unit cells 322 in different zones may be different from one another.

[00127] According to various non-limiting embodiments, the optical characteristic of the device 300 may be adjustable by changing a number of adjoining unit cells 322 in at least one zone of the plurality of zones.

[00128] According to various non-limiting embodiments, the optical characteristic of the device 300 may be adjustable by changing a zone refractive index (i.e. a refractive index of each adjoining unit cell 322 in a zone) of at least one zone of the plurality of zones by changing a voltage applied to the zone.

[00129] The electrode rings of the device 300 may include a plurality of pairs of central neighbouring electrode rings. The tunable material 320 may include a central zone 3201 formed by or including a fixed number of adjoining unit cells 322 configured to have a same refractive index by applying a same voltage between a respective pair of central neighbouring electrode rings corresponding to each adjoining unit cell 322 in the central zone 3201. For example, the fixed number of adjoining unit cells 322 included in or forming the central zone 3201 may be 16. Each adjoining unit cell 322 in the central zone may be formed by a tunable material 320 between a respective pair of central neighbouring electrode rings of the plurality of pairs of central neighbouring electrode rings. An optical characteristic of the device 300 may be adjustable by changing a zone refractive index of the central zone (i.e., a refractive index of each adjoining unit cell 322 in the central zone). A zone refractive index of the central zone may be adjustable by changing a voltage applied to the central zone (i.e., a voltage applied between each pair of the plurality of pairs of central neighbouring electrode rings). In some embodiments, the voltage applied to the central zone may remain the same to achieve different optical characteristics (e.g., different focal lengths above 400 μ m) of the device 300.

[00130] One electrode ring of each pair of central neighbouring electrode rings may be in electrical connection with a first electrical line 30, and the other electrode ring of each pair of central neighbouring electrode rings may be in electrical connection with a second electrical line 32, to apply a same voltage between each pair of central neighbouring electrode rings.

[00131] The electrode rings of the device 300 may further include a plurality of pairs of outer neighbouring electrode rings. The tunable material 320 may further include a plurality of outer zones (e.g., a first outer zone 3202 and a second outer zone 3203). Each outer zone may be formed by or include one or more adjoining unit cells 322 configured to have a same refractive index by applying a same voltage between a respective pair of outer neighbouring electrode rings corresponding to each adjoining unit cell 322 in the outer zone. Each adjoining unit cell 322 in an outer zone of the plurality of outer zones may be formed by a tunable material 320 between a respective pair of outer neighbouring electrode rings of the plurality of pairs of outer neighbouring electrode rings. An optical characteristic of the device 300 may be adjustable by changing a zone refractive index (i.e., a refractive index of each adjoining unit cell 322 in the zone) of at least one outer zone of the plurality of outer zones. An optical characteristic of the device 300 may be adjustable by changing a number of adjoining unit cells 322 in at least one outer zone of the plurality of outer zones.

[00132] Each electrode ring of the plurality of pairs of outer neighbouring electrode rings may be in electrical connection with a respective electrical line of a plurality of electrical lines 34 to apply a voltage between each pair of outer neighbouring electrode rings.

[00133] FIG. 8C shows the dimensions of a central region 362, an outer region 364 and an electrode fan-out region 366 for the device 300. The central region 362 is a region where the central zone 3201 are arranged in or positioned in. The outer region 364 is a region where the plurality of outer zones (e.g. including the outer zones 3202, 3203) are arranged in or positioned in. The electrode fan-out region 366 is a region where the first electrical line 30, the second electrical line 32 and the plurality of electrical lines 34 are arranged in or positioned in. The two electrical lines (i.e., the first electrical line 30 and the second electrical line 32) would provide a required electric field (or voltage) for the plurality of pairs of central neighbouring electrode rings to reduce the total number of electrical lines, which would reduce the complexity of the control circuitry and the portion of the electrode fan-out region 366 of the device 300. The plurality of electrical lines 34 may come from different directions. The gap between the neighbouring electrode rings in the device 300 may determine the width of the unit cell 322. In some embodiments, the gap between the neighbouring electrode rings in the device 300 may be set to 1 μm for ease of fabrication.

[00134] The portion of the electrode fan-out region 366, which is undesired for the device operation (or lens operation), is calculated as follows:

$$\frac{\text{Undesired Electrodes Region}}{\text{Lens Region}} = \frac{\pi \times 46^2 \times \frac{53}{360}}{\pi \times 62^2} \times 100 = 8\%$$

[00135] (3)

[00136] The electrode fan-out region 366 occupies 8% of the total area of the device 300, which has a minor effect on the device performance (or lens performance) for many applications. The total area of the device 300 include the central region 362, the outer region 364 and the electrode fan-out region 366.

[00137] The device 300 (e.g., an electrically tunable circular FZP flat lens 300) may be fabricated and tested. FIGs. 9A to 9D show the optical microscope images of the fabricated device 300 (e.g., electrically tunable circular FZP flat lens) with Au electrodes (electrode rings). FIG. 9A shows the device 300 which is electrically connected and wire-bonded to a printed circuit board (PCB) for applying the voltage and optical testing, etc. FIG. 9B shows a zoom-in image of the area A1 of FIG. 9A. FIG. 9B shows the device 300 with electrical connection lines and some contact pads. Three devices 300 (i.e., active lenses in a butterfly shape) may be fabricated. Only the best among the three devices 300 (active lenses in a butterfly shape) may be selected, by inspection under a microscope, for electrical connection and wire bonding to the printed circuit board (PCB) for applying the voltage and optical testing, etc. FIG. 9C shows a zoom-in image of the area A2 of FIG. 9B. FIG. 9C shows a device 300 (active lens in a butterfly shape) consisting of an active zone region, an electrode fan-out region and an electrical connection region. The electrical lines in the electrical connection region may come from different directions. FIG. 9D shows a zoom-in image of the area A3 of FIG. 9C. FIG. 9D shows an active zone region consisting of a total of 75 unit cells 322 of the device 300.

[00138] The focal length of the device 300 may be adjusted by changing the zone pattern of the device 300 and by applying different arrays of voltages to the plurality of electrodes 330. To achieve a desired focal length of the device 300, the number of unit cells in each zone of the first to N-th zone of the device 300 may be governed/calculated by the Equation (2) as described above and the width of each unit cell. FIG. 10A shows the simulation results (451, 452, 453, 454, 455) of intensity as a function of the focal length for a device 300 with a tunable focal length of 400μm, 500μm, 600μm, 700μm and 800μm respectively. The wavelength of the incoming light is set as 633nm. A large tuning range of focal lengths from 400μm to 800μm can be achieved.

[00139] FIG. 10B shows the tunability of focal length and performance of the device 300 with tunable focal lengths. The device 300 uses different zone patterns to achieve different

focal lengths (i.e., 400 μm , 500 μm and 600 μm). The measurement of the focal length of the device 300 with the different zone patterns for the respective desired focal lengths of 400 μm , 500 μm and 600 μm is carried out at a wavelength of 633nm. The measured focal length of the device 300 with the different zone patterns for the respective desired focal length of 400 μm , 500 μm and 600 μm is 383 μm , 462 μm and 578 μm respectively. The measured focal lengths are close (or within an acceptable variation) to the corresponding desired focal lengths of the respective zone pattern. The results show that tuning a focal length of the device 300 by adjusting the zone pattern of the device 300 can be achieved. In other words, a desired focal length of the device can be achieved by way of controlling the zone pattern of the device 300. The focal length of the device 300 may be further adjusted by applying a different array of voltages to the electrodes of the device 300 using the control circuitry.

[00140] The performance of the device 300 with different zone patterns for the respective desired focal lengths of 400 μm , 500 μm , and 600 μm are measured. As shown in FIG. 10B, the focusing function of the device 300 may be achieved (from defocusing to focusing) after applying the voltages to the electrodes of the device 300 with different zone patterns for the respective desired focal lengths of 400 μm , 500 μm , and 600 μm . A high voltage and a low voltage may be alternatively applied to neighbouring zones of the first to N-th zones. For example, a high voltage (e.g., 45v) may be applied to the 2M-th zone of the first to N-th zones and a low voltage (e.g., 0v) may be applied to the (2M-1)-th zone of the first to N-th zones, where M an integer greater than or equals to 1. The results of the line profile across the focal spot for the device 300 with different zone patterns for the respective desired focal lengths of 400 μm , 500 μm , and 600 μm are also in alignment with the simulation results of the farfield electric field distribution of the device 300 with a zone pattern for a focal length of 400 μm , 500 μm and 600 μm respectively.

[00141] The maximum number of unit cells 122/222/322 may be limited by the dimension of the devices 100/200/300 (e.g., a width of the device 200 or a diameter of the device 300) and/or the number of electrodes controllable by the control circuitry. The width of each unit cell in the devices 100/200/300 may be 1 μm .

[00142] The present disclosure provides a method 800 of forming a device 100/200/300. FIG. 11 is a flow chart depicting a method 800 of forming a device 100/200/300 according to some embodiments of the present disclosure. The method 800 may include:

- (i) a step 810 of forming a tunable material on a substrate; and
- (ii) a step 820 of forming a plurality of electrodes on a top surface of the tunable material, wherein the tunable material may include a plurality of unit cells, each unit cell may

be formed by a section of the tunable material between a respective pair of neighbouring electrodes of the plurality of electrodes, wherein a respective refractive index of each unit cell may be adjustable by changing a voltage applied between the respective pair of neighbouring electrodes, wherein an optical characteristic of the device may be adjustable by changing a respective refractive index of each of at least one unit cell.

[00143] The tunable material may include ferroelectric material, transparent conductive oxide, phase change material, liquid crystal and/or elastomer.

[00144] The plurality of unit cells may form a plurality of zones comprising first to N-th zones, wherein N is an integer greater than or equal to 1, wherein each zone may be formed by one or more adjoining unit cells configured to have a same refractive index by applying a same voltage between a respective pair of neighbouring electrodes corresponding to each adjoining unit cell in the zone, wherein an optical characteristic of the device may be adjustable by changing a number of adjoining unit cells in at least one zone of the plurality of zones.

[00145] The plurality of electrodes (e.g., gold/ITO electrodes) may be deposited and patterned on the top surface of the tunable material (e.g., ferroelectric material) using Ebeam lithography.

[00146] The plurality of electrodes (e.g., gold electrodes) may be deposited and patterned on the top surface of the tunable material (e.g., ferroelectric material) using photolithography.

[00147] The method 800 may further include wire-bonding a printed circuit board to the plurality of electrodes for applying the voltage.

[00148] 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.

[00149] 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.

[00150] 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 comprising:

a substrate;

a tunable material formed on the substrate; and

a plurality of electrodes formed on a top surface of the tunable material,

wherein the tunable material comprises a plurality of unit cells, each unit cell is formed by a section of the tunable material between a respective pair of neighbouring electrodes of the plurality of electrodes,

wherein a respective refractive index of each unit cell is adjustable by changing a voltage applied between the respective pair of neighbouring electrodes,

wherein an optical characteristic of the device is adjustable by changing a respective refractive index of each of at least one unit cell.

2. The device of claim 1, wherein the optical characteristic of the device comprises a focal length and/or a focal spot.

3. The device of claim 1, wherein the plurality of unit cells forms a plurality of zones comprising first to N-th zones, wherein N is an integer greater than or equal to 1, wherein each zone is formed by one or more adjoining unit cells configured to have a same refractive index by applying a same voltage between a respective pair of neighbouring electrodes corresponding to each adjoining unit cell in the zone, wherein an optical characteristic of the device is adjustable by changing a number of adjoining unit cells in at least one zone of the plurality of zones.

4. The device of claim 3, wherein the plurality of zones further comprises first to N-th symmetric zones which are symmetric to the respective first to N-th zones about a central axis of the tunable material, wherein each zone of the first to N-th symmetric zones is formed by one or more adjoining unit cells configured to have a same refractive index by applying a same voltage between a respective pair of neighbouring electrodes corresponding to each adjoining unit cell in the zone, wherein a refractive index of the one or more adjoining unit cells in each of the first to N-th symmetric zones is the same as a refractive index of the one or more adjoining unit cells in the respective first to N-th zones.

5. The device of claim 4, wherein a number of adjoining unit cells in each of the first to N-th symmetric zones is the same as a number of adjoining unit cells in the respective first to N-th zones.

6. The device of claim 3, wherein a first voltage applied between a respective pair of neighbouring electrodes corresponding to each adjoining unit cell in the (2M-1)-th zone of the plurality of zones is configured to have a first value, and a second voltage applied between a respective pair of neighbouring electrodes corresponding to each adjoining unit cell in the 2M-th zone of the plurality of zones is configured to have a second value, wherein the second value is greater than the first value, where M is an integer greater than or equal to 1.

7. The device of claim 3, wherein different zones of the plurality of zones comprises different numbers of adjoining unit cells.

8. The device of claim 1, wherein the plurality of electrodes comprises electrodes that are linear and parallel to one another.

9. The device of claim 1, wherein the plurality of electrodes comprises electrode rings that are concentric to each other.

10. The device of claim 1, wherein the plurality of electrodes comprises a plurality of pairs of central neighbouring electrode rings, wherein the tunable material comprises a central zone formed by a fixed number of adjoining unit cells configured to have a same refractive index by applying a same voltage between a respective pair of central neighbouring electrode rings corresponding to each adjoining unit cell in the central zone, wherein each adjoining unit cell in the central zone is formed by a tunable material between a respective pair of central neighbouring electrode rings of the plurality of pairs of central neighbouring electrode rings.

11. The device of claim 10, wherein one electrode ring of each pair of central neighbouring electrode rings is in electrical connection with a first electrical line, and the other electrode ring of each pair of central neighbouring electrode rings is in electrical connection with a second electrical line, to apply a same voltage between each pair of central neighbouring electrode rings.

12. The device of claim 11, wherein an optical characteristic of the device is adjustable by changing a refractive index of the one or more adjoining unit cells in the central zone.

13. The device of claim 10, wherein the plurality of electrodes further comprises a plurality of pairs of outer neighbouring electrode rings, wherein the tunable material further comprises a plurality of outer zones, each outer zone being formed by one or more adjoining unit cells configured to have a same refractive index by applying a same voltage between a respective pair of outer neighbouring electrode rings corresponding to each adjoining unit cell in the outer zone, wherein each adjoining unit cell in an outer zone of the plurality of outer zones is formed by a tunable material between a respective pair of outer neighbouring electrode rings of the plurality of pairs of outer neighbouring electrode rings.

14. The device of claim 13, wherein each electrode ring of the plurality of pairs of outer neighbouring electrode rings are in electrical connection with a respective electrical line to apply a voltage between each pair of outer neighbouring electrode rings.

15. The device of claim 14, wherein an optical characteristic of the device is adjustable by changing a refractive index of the one or more adjoining unit cells in at least one outer zone of the plurality of outer zones.

16. The device of claim 14, wherein an optical characteristic of the device is adjustable by changing a number of adjoining unit cells in at least one outer zone of the plurality of outer zones.

17. The device of claim 1, wherein a thickness of the tunable material ranges from 40 nm to 2 μm .

18. The device of claim 1, wherein the tunable material comprises barium titanate, strontium titanate, or barium strontium titanate.

19. The device of claim 1, wherein the substrate comprises strontium titanate (SrTiO_3) or magnesium oxide (MgO).

20. The device of claim 1, wherein the tunable material or the substrate is transparent in visible light or near-infrared light.

21. The device of claim 1, further comprising a printed circuit board, wherein the printed circuit board is wire-bonded to the plurality of electrodes for applying the voltage.

22. The device of claim 1, wherein a focal spot of the device is laterally shiftable by changing voltages applied to the plurality of electrodes to laterally shift a refractive index profile of the device.

23. The device of claim 1, wherein the tunable material comprises ferroelectric material, transparent conductive oxide, phase change material, liquid crystal and/or elastomer.

24. A method of fabricating a device, the method comprising:

forming a tunable material on a substrate; and

forming a plurality of electrodes on a top surface of the tunable material,

wherein the tunable material comprises a plurality of unit cells, each unit cell is formed by a section of the tunable material between a respective pair of neighbouring electrodes of the plurality of electrodes,

wherein a respective refractive index of each unit cell is adjustable by changing a voltage applied between the respective pair of neighbouring electrodes,

wherein an optical characteristic of the device is adjustable by changing a respective refractive index of each of at least one unit cell.

25. The method of claim 24, wherein the plurality of unit cells forms a plurality of zones comprising first to N-th zones, wherein N is an integer greater than or equal to 1, wherein each zone is formed by one or more adjoining unit cells configured to have a same refractive index by applying a same voltage between a respective pair of neighbouring electrodes corresponding to each adjoining unit cell in the zone, wherein an optical characteristic of the device is adjustable by changing a number of adjoining unit cells in at least one zone of the plurality of zones.

26. The method of claim 24, further comprising wire-bonding a printed circuit board to the plurality of electrodes for applying the voltage.