

OPTICAL LENS AND METHOD OF FORMING THE SAME

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of priority of Singapore application No. 10201801855Y filed March 7, 2018, the contents of it being hereby incorporated by reference in its entirety for all purposes.

TECHNICAL FIELD

[0002] Various aspects of this disclosure relate to an optical lens. Various aspects of this disclosure relate to a method of forming an optical lens.

BACKGROUND

[0003] FIG. 1 illustrates the evolution of laser-transformed corneal surgery. Over the past two decades, laser assisted in situ keratomileusis (LASIK) has evolved from using a blade (the microkeratome), to 2nd generation of bladeless LASIK, i.e. involving two-step (femtosecond laser plus excimer laser), and now towards the next generation of bladeless and flapless, with one laser step (femtosecond laser only). This latest laser vision correction technique has been overall termed as refractive lenticular extraction (ReLEx), which has produced a $1\text{-}\mu\text{m}$ resolution laser spot to offer faster wound healing, less side effects, and higher accuracy correction for patients. However, this traditional optical method has a diffraction limit of $\sim 0.5\lambda/\text{NA}$, where NA is the numerical aperture of the objective lenses. The NA of objective lenses used in LASIK cannot be too large because a high-NA lens usually has a short working distance. In this case, the focused spot in a commercial LASIK is around $1\text{ }\mu\text{m}$. It therefore prevents the laser beam from being sharply focused beyond the barrier.

SUMMARY

[0004] Various embodiments may relate to an optical lens. The optical lens may include a substrate. The optical lens may further include a plurality of concentric rings on the substrate. The plurality of concentric rings may include a dielectric. The plurality of concentric rings may be configured to focus light onto a focal spot and may be further configured to decrease a size of the

focal spot to below a diffraction limit of the light by interference of the focused light at a focal length of at least $600\text{ }\mu\text{m}$.

[0005] Various embodiments may relate to a method of forming an optical lens according to various embodiments. The method may include forming a plurality of concentric rings on a substrate. The plurality of concentric rings may include a dielectric. The plurality of concentric rings may be configured to focus light onto a focal spot. The plurality of concentric rings may further be configured to decrease a size of the focal spot to below a diffraction limit of the light by interference of the focused light at a focal length of at least $600\text{ }\mu\text{m}$.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] The invention will be better understood with reference to the detailed description when considered in conjunction with the non-limiting examples and the accompanying drawings, in which:

FIG. 1 illustrates the evolution of laser-transformed corneal surgery.

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

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

FIG. 4A shows a meta-ring lens formed by integrating a focusing lens and a modulation lens together according to various embodiments.

FIG. 4B shows an image of a meta-ring lens according to various embodiments.

FIG. 4C is a plot of intensity as a function of radial distance, r (in λ or wavelength of light) showing the stimulated radial intensity profile of a focused spot at the focal plane of the lens according to various embodiments.

FIG. 4D shows another image of the meta-ring lens according to various embodiments under high magnification, while the inset is the image of the lens under low magnification.

FIG. 4E shows a schematic comparing a conventional objective lens and a Fresnel zone-plate (FZP) lens according to various embodiments.

FIG. 5A shows a scanning electron microscopy (SEM) image of a part of the optical lens according to various embodiments.

FIG. 5B shows an atomic force microscopy (AFM) image of the optical lens according to various embodiments.

FIG. 6A is a schematic showing a meta-ring lens 600 according to various embodiments focusing light into a super-resolution spot.

FIG. 6B shows the cross-sectional intensity profile generated by the lens according to various embodiments at the x-z plane (along the x-axis (in micrometres or μm) and along the z-axis (in micrometres or μm)).

FIG. 6C shows the transverse intensity profile generated by the lens according to various embodiments at the z-cut planes of z_A shown in FIG. 6B (at the x-y plane or along the y-axis (in micrometres or μm) and along the x-axis (in micrometres or μm)).

FIG. 6D is shows the transverse intensity profile generated by the lens according to various embodiments at the z-cut planes of z_B shown in FIG. 6B (at the x-y plane or along the y-axis (in micrometres or μm) and along the x-axis (in micrometres or μm)).

FIG. 6E shows the transverse intensity profile generated by the lens according to various embodiments at the z-cut planes of z_C shown in FIG. 6B (at the x-y plane or along the y-axis (in micrometres or μm) and along the x-axis (in micrometres or μm)).

FIG. 6F is a plot of spot size (in micrometres or μm) as a function of distance along z-axis (in micrometres or μm) showing the measured focal spot sizes generated by the lens according to various embodiments along z direction.

FIG. 7A shows an optical image of the sample (i.e. poly(methyl methacrylate) (PMMA) film positioned on a silicon (Si) wafer) being cut by the optical system according to various embodiments.

FIG. 7B shows an atomic force microscopy (AFM) image of the sample being cut by the optical system according to various embodiments.

FIG. 7C shows a plot of depth (in nanometre or nm) as a function of position (in micrometres or μm) showing the results of a one-dimensional scan of the sample being cut by the optical system according to various embodiments.

DETAILED DESCRIPTION

[0007] The following detailed description refers to the accompanying drawings that show, by way of illustration, specific details and embodiments in which the invention may be practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice the invention. Other embodiments may be utilized and structural, and logical changes may be made without departing from the scope of the invention. The various embodiments are not necessarily mutually exclusive, as some embodiments can be combined with one or more other embodiments to form new embodiments.

[0008] Embodiments described in the context of one of the methods or lenses/systems are analogously valid for the other methods or lenses/systems. Similarly, embodiments described in the context of a method are analogously valid for a lens/system, and vice versa.

[0009] Features that are described in the context of an embodiment may correspondingly be applicable to the same or similar features in the other embodiments. Features that are described in the context of an embodiment may correspondingly be applicable to the other embodiments, even if not explicitly described in these other embodiments. Furthermore, additions and/or combinations and/or alternatives as described for a feature in the context of an embodiment may correspondingly be applicable to the same or similar feature in the other embodiments.

[0010] In the context of various embodiments, the articles “a”, “an” and “the” as used with regard to a feature or element include a reference to one or more of the features or elements.

[0011] In the context of various embodiments, the term “about” or “approximately” as applied to a numeric value encompasses the exact value and a reasonable variance.

[0012] As used herein, the term “and/or” includes any and all combinations of one or more of the associated listed items.

[0013] Various embodiments may seek to address or mitigate the abovementioned issues. Various embodiments may provide an optical lens with a large focal length, and a small focal spot.

[0014] FIG. 2 is a general illustration of an optical lens according to various embodiments. The optical lens 200 may include a substrate 202. The optical lens 200 may further include a plurality of concentric rings 204 on the substrate 202. The plurality of concentric rings 204 may include a dielectric. The plurality of concentric rings 204 may be configured to focus light onto a focal spot and may be further configured to decrease a size of the focal spot to below a diffraction limit of the light by interference of the focused light at a focal length of at least 600 μm .

[0015] In other words, various embodiments may provide a lens 200 including a substrate 202, and a series of dielectric rings 204 around a point of the substrate 202. The lens 200 may be able to focus the light and reduce a size of the focal spot to below a diffraction limit of the light, while having a focal length of at least 600 μm .

[0016] For avoidance of doubt, FIG. 2 serves merely to illustrate the features of the lens 200 according to various embodiments, and does not indicate or limit, for instance, the sizes or relative sizes of the features, the arrangement or orientation of the features etc.

[0017] In the current context, the focal spot of the lens 200 may refer to a focus of the lens 200. The focal length of the lens 200 may refer to the distance between the lens 200 and the focus spot of the lens 200.

[0018] In the current context, the size of the focal spot may refer to the diameter of the spot at full width half maximum (FWHM).

[0019] In various embodiments, the focal spot may have a diameter of at most 0.515 of a ratio of a wavelength of the light to a numerical aperture of the optical lens (i.e. $0.515\lambda/\text{NA}$, where λ is the wavelength of the light and NA is the numerical aperture of the optical lens). In various embodiments, the focal spot may have a diameter of at most 0.45 of a wavelength of the light.

[0020] In various embodiments, the light may be visible light, ultraviolet light, or infrared light. In various embodiments, the light may be near infrared light, and may have a value or range of values from 0.75 μm to 1.4 μm . In various embodiments, the light may be a laser, such as a femtosecond laser.

[0021] The plurality of concentric rings 204 may be a number of annular rings around a spot on the substrate 202.

[0022] In various embodiments, the dielectric may be quartz or any other suitable dielectric, such as other forms of silicon dioxide (SiO_2), silicon nitride (Si_3N_4), silicon oxynitride (SiO_xN_y), titanium dioxide (TiO_2), niobium oxide (NbO), silicon (Si), aluminium oxide (Al_2O_3), gallium nitride (GaN), gallium phosphide (GaP) (for light at various wavelength ranges).

[0023] In various embodiments, the substrate 202 may also include the dielectric. The substrate may also include quartz or any other suitable materials such as glass. For instance, the plurality of concentric rings may be directly formed from a quartz substrate. In various other embodiments, the substrate may include a dielectric different from a dielectric of the plurality of concentric rings.

For instance, the substrate may include a dielectric such as quartz, and a further dielectric such as silicon nitride may be deposited on the substrate to form the plurality of concentric rings.

[0024] In various embodiments, each of the plurality of concentric rings may form a binary phase element. Each of the plurality of concentric rings may provide a phase modulation of π (in radians), while a neighbouring gap may provide a phase modulation of 0 (in radians).

[0025] In various embodiments, a first group of the plurality of concentric rings may be a focusing arrangement configured to focus light onto the focal spot. In various embodiments, a second group of the plurality of concentric rings may be a modulation arrangement configured to decrease the size of the focal spot. The first group may include one or more focusing rings of the plurality of concentric rings 204. The second group may include one or more modulation rings of the plurality of concentric rings 204.

[0026] The substrate 202 and the plurality of concentric rings 204 may form a single integral structure. The plurality of concentric rings 204 may extend from the substrate.

[0027] The optical lens may have an efficiency of 40%.

[0028] The widths and/or gaps of the plurality of concentric rings may be different or may be the same.

[0029] In various embodiments, a width of a first ring of the plurality of concentric rings 204 may be different from a width of a second ring of the plurality of concentric rings 204. In various embodiments, the widths of the plurality of concentric rings 204 may be different. In various embodiments, a width of a first ring of the plurality of concentric rings 204 may be equal to a width of a second ring of the plurality of concentric rings 204. In various embodiments, the widths of the plurality of concentric rings 204 may be equal.

[0030] In various embodiments, a gap between a first pair of neighbouring rings of the plurality of concentric rings 204 may be different from a gap between a second pair of neighbouring rings of the plurality of concentric rings 204. In various embodiments, the gaps between the plurality of concentric rings may be different. In various embodiments, a gap between a first pair of neighbouring rings of the plurality of concentric rings 204 may be equal to a gap between a second pair of neighbouring rings of the plurality of concentric rings 204. In various embodiments, the gaps between the plurality of concentric rings may be equal.

[0031] The optical lens 200 may be referring to as a meta-ring lens.

[0032] In various embodiments, the lens 200 may have a high numerical aperture. Various embodiments may have a numerical aperture of more than 0.9, e.g. more than 0.95, e.g. 0.96. The plurality of concentric rings 204 may be more than 100.

[0033] The lens 200 may be micro structured. Each of the rings 204 may have a width of any value less than $100\text{ }\mu\text{m}$. Each of the gap between neighbouring rings may have a spacing of any value less than $100\text{ }\mu\text{m}$. Forming features in the micrometer range may facilitate and greatly ease the challenges and costs in mass production.

[0034] Various embodiments may relate to a dielectric lens composed of well-optimized meta-ring lens with superfocusing capability at near infrared (IR) range, which may enable sub-micron resolution for femto-second laser based corneal refractive surgery. In order to acquire superfocusing of near-infrared femtosecond laser beam, various embodiments may be used to form a focal spot of about 0.45 (FWHM) , less than half of the $1\text{-}\mu\text{m}$ resolution of existing corneal refractive surgery tool (VisuMax). Through rigorous design of the structural parameters in the meta-rings, the transmitted light may be controlled to realize constructively interference at a pre-definable focal length ($\geq 0.6\text{ millimetre}$) with a sub-diffraction limit focusing spot. The flat meta-ring lens may be tested using a femto-second laser system.

[0035] Various embodiments may achieve sub-diffraction-limit focusing with a super long focal length. Various embodiments may be able to focus light onto a spot with $0.45\lambda\text{ (FWHM)}$ at a distance $\geq 600\text{ }\mu\text{m}$ away from the lens surface. In contrast, traditional objective lenses typically have a focal spot of $0.56\lambda\text{ (FWHM)}$ and a focal length smaller than $400\text{ }\mu\text{m}$. Various embodiments may have a super-long focal length ($\sim 962\lambda$), which may be sufficient for the practical implementation of femtosecond laser based surgery.

[0036] Various embodiments may achieve structural and performance optimization via self-developed algorithm and code.

[0037] Various embodiments may relate to a fully constituted lens with microscale ring structures to achieve far field sub-diffraction-limited resolution. Various embodiments may alleviate manufacturing challenges.

[0038] Various embodiments may relate to a phase type of meta-ring lens could improve the efficiency up to 40%, which is higher than 10% in the amplitude-type lenses.

[0039] Various embodiments may relate to an optical system, such as a surgical laser system. The optical system may include a lens as described herein, and a light source configured to generate the light. The light source may be a laser source. The surgical laser system may be used for ophthalmic operations. In various embodiments, the system may also include a collimator or collimating lens configured to collimate light generated by the light source, thereby providing collimated light to the lens. In various other embodiments, the light generated by the light source may already be collimated.

[0040] FIG. 3 is a general illustration of a method of forming an optical lens according to various embodiments. The method may include, in 302, forming a plurality of concentric rings on a substrate. The plurality of concentric rings may include a dielectric. The plurality of concentric rings may be configured to focus light onto a focal spot. The plurality of concentric rings may further be configured to decrease a size of the focal spot to below a diffraction limit of the light by interference of the focused light at a focal length of at least 600 μm .

[0041] In other words, various embodiments may relate to a method of forming a lens with a series of concentric rings on a substrate.

[0042] In various embodiments, the method of forming the plurality of concentric rings may include or refer to etching or removing a portion of the substrate to define the plurality of concentric rings. The portion of the substrate to be etched or removed may be defined by a mask. For instance, resist may be deposited onto the substrate. Lithography may be carried out using the mask. The resist exposed by the masked may then be removed. The underlying portion of the substrate may then be etched or removed. By etching the substrate, e.g. a quartz substrate, various embodiments may require fewer processing steps compared to conventional lenses, and may also be more robust.

[0043] In various embodiments, the focal spot may have a diameter of at most 0.515 of a ratio of a wavelength of the light to a numerical aperture of the optical lens (i.e. $0.515\lambda/\text{NA}$, where λ is the wavelength of the light and NA is the numerical aperture of the optical lens). In various embodiments, the focal spot may have a diameter of at most 0.45 of a wavelength of the light.

[0044] The dielectric may be quartz or any other suitable dielectric.

[0045] In various embodiments, the substrate may also include the dielectric. The substrate may also include quartz.

[0046] Each of the plurality of concentric rings may form a binary phase element.

[0047] A first group of the plurality of concentric rings may be a focusing arrangement configured to focus light onto the focal spot. A second group of the plurality of concentric rings may be a modulation arrangement configured to decrease the size of the focal spot.

[0048] The first group may include one or more focusing rings of the plurality of concentric rings. The second group may include one or more modulation rings of the plurality of concentric rings.

[0049] The substrate and the plurality of concentric rings may form a single integral structure.

[0050] The optical lens may have an efficiency of 40%.

[0051] In various embodiments, the light may be visible light, ultraviolet light, or infrared light. In various embodiments, the light may be near infrared light, and may have a value or range of values from $0.75\ \mu\text{m}$ to $1.4\ \mu\text{m}$. In various embodiments, the light may be a laser, such as a femtosecond laser.

[0052] Various embodiments may relate to forming an optical system, such as a surgical laser system. The method may include forming the optical lens as described here. The method may also include forming or providing a light source, such as a laser source, configured to generate the light or laser. The method may also include forming or providing a collimator or collimating lens.

[0053] Various embodiments may provide an optical lens with sub-micron resolution and long focal length, which potentially may enable sub-micro resolution for a femtosecond laser based surgical system to bring in unique perspectives for laser corneal refractive surgery. The meta-rings lens may include or consist of concentric annular micro-structures fabricated on a flat transparent substrate. The lens may be able to focus a light beam with a sub-diffraction-limit resolution of about 0.45λ (0.45 of the wavelength of light) and a long focal length in the far field. Through sharper focusing with lower energy, safer photo disruption, higher accuracy, minimal tissue damage, eventually leading to smaller incision wounds as well as a faster healing time, laser-based corneal refractive surgery may be improved.

[0054] Various embodiments may relate to a flat meta-ring lens including a focusing lens and a well-optimized modulation lens. FIG. 4A shows a meta-ring lens formed by integrating a focusing lens and a modulation lens together according to various embodiments. In various embodiments, the meta-ring lens may be formed by superimposing or integrating the focusing lens

and the modulation lens. In other words, the design of the meta-ring lens may be separated into the design of the focusing lens and the design of the modulation lens before integrating together or superimposing the focusing lens and the modulation lens. In this meta-ring lens, the focusing lens may be used to realize the focusing functionality while the modulation lens may decrease the size of the focused spot beyond the diffraction limit by carefully tuning the interference of focused light. Both lenses may be binary-phase elements with a phase of 0 or π , so that they can be integrated into a single device, as shown in FIG. 4A.

[0055] The focusing lens may be realized in modified Fresnel zone-plates (FZP). The ring structures of the focusing lens may be relate by the formula:

$$[0056] \quad r_n = \sqrt{Mn\lambda f + \left(\frac{nM\lambda}{2}\right)^2} \quad (1)$$

where r_n is the radius of the focusing lens, f is the focal length, λ is the wavelength, and n is the index of the ring. The parameter M determines that the smallest width of the rings in this focusing lens may be $M\lambda/2$, when n is infinitely large. In various embodiments, M may be chosen to be 3 so that the smallest ring width is $1.5*\lambda$ ($\sim 1.5\mu\text{m}$ at the wavelength of 1040 nm), which facilitates the fabrication of the meta-ring lens as compared to a lens with ring width in hundreds of nanometres.

[0057] The structures of the modulation lens may be obtained through the optimization algorithms such as genetic algorithms and particle swarm optimization. In order to avoid any mismatch of rings between the focusing lens and the modulation lens, the ring values of the binary phase elements may be chosen among the existing r_n of Fresnel zone-plate. Thus, after the combination of both phases, the meta-ring lens may still have the smallest ring width of $M\lambda/2$. In fact, the rings of modulation lens may be of any arbitrary value. However, it may lead to finer details (smaller than $M\lambda/2$) if any mismatch happens. In various embodiments, the modulation lens may have a much smaller ring number than the focusing lens, which therefore provides the sufficient degree of freedom for realizing a super-resolution spot.

[0058] In simulation, the Rayleigh-Sommerfeld diffraction integral may be used to model the meta-ring lens and simulate its optical properties such as spot size.

[0059] FIG. 4B shows an image of a meta-ring lens according to various embodiments. FIG. 4B shows the phase profile at the central part of this lens with a diameter of about 4mm. This lens may have a focal length of about 600 μ m, which indicates that its numerical aperture about 0.96.

[0060] FIG. 4C is a plot of intensity as a function of radial distance, r (in λ or wavelength of light) showing the stimulated radial intensity profile of a focused spot at the focal plane of the lens according to various embodiments. The spot has the lateral size of 0.45λ , which is smaller than the diffraction limit of $0.515\lambda/NA=0.54\lambda$. FIG. 4D shows another image of the meta-ring lens according to various embodiments under high magnification, while the inset is the image of the lens under low magnification.

[0061] FIG. 4E shows a schematic comparing a conventional objective lens and a Fresnel zone-plate (FZP) lens according to various embodiments.

[0062] The meta-ring lens may be directly fabricated on a quartz substrate by using dry etching with the help of a mask encoding the structure information of meta-ring lens. The etched parts may have a phase of 0 and the other parts may have the phase modulation of π . The etched depth on quartz Δh may be calculated by using:

$$[0063] \quad \Delta h = \lambda / [2 * (n - 1)] \quad (2)$$

where n is the refraction index of quartz and λ is the wavelength.

[0064] Considering that all the structures in this lens may be fabricated on a transparent quartz, the total efficiency of the lens may be enhanced by 4 times compared with an amplitude lens. In addition, as the direct fabrication on quartz cannot give the fine structures at the level of hundreds of nanometres, this has been taken into account in theoretical designs with the smallest ring width being of about 1500 nm.

[0065] FIG. 5A shows a scanning electron microscopy (SEM) image of a part of the optical lens according to various embodiments. The image shown in FIG. 5A is taken around the central part of the optical lens.

[0066] FIG. 5B shows an atomic force microscopy (AFM) image of the optical lens according to various embodiments. The AFM image may show the smoothness of the lens surface.

[0067] FIG. 6A is a schematic showing a meta-ring lens 600 according to various embodiments focusing light into a super-resolution spot. The fabricated meta-ring lens was tested using a scanning optical microscopy. A 1040nm laser light with linear polarization may be coupled to a

polarization maintaining single-mode fibre. A thin lens working as a collimator is located after the output terminal of the fibre, i.e. between the fibre and the meta-ring lens, in order to realize or provide the plane waves incident on the meta-ring lens. The collimated beam reflected by a mirror may be normally incident on the fabricated FZP lens 600 that is fixed on a stage. The optical field distribution in x-y plane may be measured by a 0.95-NA (Olympus) objective lens along the z direction around the focusing range.

[0068] FIG. 6B shows the cross-sectional intensity profile generated by the lens according to various embodiments at the x-z plane (along the x-axis (in micrometres or μm) and along the z-axis (in micrometres or μm)). FIG. 6C shows the transverse intensity profile generated by the lens according to various embodiments at the z-cut planes of z_A shown in FIG. 6B (at the x-y plane or along the y-axis (in micrometres or μm) and along the x-axis (in micrometres or μm)). FIG. 6D is shows the transverse intensity profile generated by the lens according to various embodiments at the z-cut planes of z_B shown in FIG. 6B (at the x-y plane or along the y-axis (in micrometres or μm) and along the x-axis (in micrometres or μm)). FIG. 6E shows the transverse intensity profile generated by the lens according to various embodiments at the z-cut planes of z_C shown in FIG. 6B (at the x-y plane or along the y-axis (in micrometres or μm) and along the x-axis (in micrometres or μm)). FIG. 6F is a plot of spot size (in micrometres or μm) as a function of distance along z-axis (in micrometres or μm) showing the measured focal spot sizes generated by the lens according to various embodiments along z direction.

[0069] From the measurement results showed in FIGS. 6B-F, it may be seen that the FZP lens has quite a quite long depth of focus. In the range of 530um to 600um, the focusing spot size may have a FWHM smaller than 0.5λ , below the diffraction limit. A focusing spot size of below 0.45λ or $\sim 0.48\mu\text{m}$ may be observed for a number of points below 550um in Z direction. It is important to notice that the focusing spot size is measured in the air ambient instead of normalizing the FWHM observed in dielectric ambient like those oil immersion high NA lenses. The results prove that phase type FZP lens may be suitable for sub diffraction limit focusing. In addition, it may also be shown that it is feasible to fabricate such lenses for practical applications.

[0070] In order to test the feasibility of the meta-ring lens in laser cutting, a nano-second laser (MOPA-DY- 20 pulsed fibre laser) with a centre wavelength of 1064 nm maximum peak power of 12 kW and pulse repetition rate of 12.5 MHz may be employed to illuminate the meta-ring lens.

The material being cut may be a 200 nm-thick poly(methyl methacrylate) (PMMA) film positioned on a silicon (Si) wafer, which is fixed on a three-dimensional stage. The stage may allow put the PMMA film to be positioned at the focal plane of this meta-ring lens.

[0071] FIG. 7A shows an optical image of the sample (i.e. poly(methyl methacrylate) (PMMA) film positioned on a silicon (Si) wafer) being cut by the optical system according to various embodiments. The smallest size of cut groove in the PMMA film is around 500 nm, which approaches the focal spot size showed in FIG. 6F. FIG. 7B shows an atomic force microscopy (AFM) image of the sample being cut by the optical system according to various embodiments. FIG. 7C shows a plot of depth (in nanometre or nm) as a function of position (in micrometres or μm) showing the results of a one-dimensional scan of the sample being cut by the optical system according to various embodiments. FIG. 7C shows that the smallest groove has the FWHM of 426 nm, which is also beyond the diffraction limit.

[0072] Various embodiments may relate to a dielectric lens including well-optimized meta-ring lens with superfocusing capability at near IR range. Various embodiments may achieve superfocusing of near-infrared laser beam to form a focal spot of about 0.45λ (FWHM, $\lambda=1040\text{nm}$), less than half of the 1- μm resolution of existing corneal refractive surgery tool. Various embodiments may have a long focal length of ≥ 0.6 millimetres.

[0073] Various embodiments may relate to a micro structured meta-ring lens for sub-diffraction-limited focusing with an ultra-long focal length. Various embodiments may relate to the use of the meta-ring lens in ophthalmic femtosecond laser. Various embodiments may make use of phase modulation in a transparent quartz.

[0074] Various embodiments may have a high numerical aperture ($\text{NA}=0.96$) close to unity (1), i.e. the maximal in air. Various embodiments may have sub-diffraction-limit focusing with a super long focal length. Various embodiments may be able to focus light into a spot with 0.45λ (FWHM) at a distance of $\geq 600 \mu\text{m}$ away from the lens surface. In contrast, the traditional objective lenses have the focal spot of 0.56λ (FWHM) and the focal length is smaller than $400 \mu\text{m}$.

[0075] Various embodiments may include microscale ring structures to achieve far field sub-diffraction-limit focusing by structural and performance optimization via self-developed algorithm and code, which may ease manufacturing challenges. Various embodiments may relate to phase

type of meta-ring lens that may improve the efficiency up to 40%, which is higher than 10% of amplitude-type lenses. Various embodiments may achieve phase modulation in transparent quartz.

[0076] Various embodiments may have applications in laser surgery, laser machining, and/or laser scanning microscopy

[0077] While the invention has been particularly shown and described with reference to specific embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the appended claims. The scope of the invention is thus indicated by the appended claims and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced.

CLAIMS

1. An optical lens comprising:
 - a substrate; and
 - a plurality of concentric rings on the substrate, the plurality of concentric rings comprising a dielectric;
 - wherein the plurality of concentric rings is configured to focus light onto a focal spot and further configured to decrease a size of the focal spot to below a diffraction limit of the light by interference of the focused light at a focal length of at least 600 μm .
2. The optical lens according to claim 1,
 - wherein the focal spot has a diameter of at most 0.515 of a ratio of a wavelength of the light to a numerical aperture of the optical lens.
3. The optical lens according to claim 1,
 - wherein the focal spot has a diameter of at most 0.45 of a wavelength of the light.
4. The optical lens according to any one of claims 1 to 3,
 - wherein the dielectric is quartz.
5. The optical lens according to any one of claims 1 to 4,
 - wherein the substrate also comprises the dielectric.
6. The optical lens according to any one of claims 1 to 5,
 - wherein each of the plurality of concentric rings forms a binary phase element.
7. The optical lens according to any one of claims 1 to 6,
 - wherein a first group of the plurality of concentric rings comprises a focusing arrangement configured to focus light onto the focal spot; and

wherein a second group of the plurality of concentric rings comprises a modulation arrangement configured to decrease the size of the focal spot.

8. The optical lens according to any one of claims 1 to 7,
wherein the first group comprises one or more focusing rings of the plurality of concentric rings; and
wherein the second group comprises one or more modulation rings of the plurality of concentric rings.
9. The optical lens according to any one of claims 1 to 8,
wherein the substrate and the plurality of concentric rings form a single integral structure.
10. The optical lens according to any one of claims 1 to 9,
wherein the optical lens has an efficiency of 40%.
11. A method of forming an optical lens, the method comprising:
forming a plurality of concentric rings on a substrate, the plurality of concentric rings comprising a dielectric;
wherein the plurality of concentric rings is configured to focus light onto a focal spot and further configured to decrease a size of the focal spot to below a diffraction limit of the light by interference of the focused light at a focal length of at least 600 μm .
12. The method according to claim 11,
wherein the focal spot has a diameter of at most 0.515 of a ratio of a wavelength of the light to a numerical aperture of the optical lens.
13. The method according to claim 11,
wherein the focal spot has a diameter of at most 0.45 of a wavelength of the light.

14. The method according to any one of claims 11 to 13,
wherein the dielectric is quartz.
15. The method according to any one of claims 11 to 14,
wherein the substrate also comprises the dielectric.
16. The method according to any one of claims 11 to 15,
wherein each of the plurality of concentric rings forms a binary phase element.
17. The method according to any one of claims 11 to 16,
wherein a first group of the plurality of concentric rings comprises a focusing arrangement configured to focus light onto the focal spot; and
wherein a second group of the plurality of concentric rings comprises a modulation arrangement configured to decrease the size of the focal spot.
18. The method according to any one of claims 11 to 17,
wherein the first group comprises one or more focusing rings of the plurality of concentric rings; and
wherein the second group comprises one or more modulation rings of the plurality of concentric rings.
19. The method according to any one of claims 11 to 18,
wherein the substrate and the plurality of concentric rings form a single integral structure.
20. The method according to any one of claims 11 to 19,
wherein the optical lens has an efficiency of 40%.