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## Recent Progress in Far-Field Optical Metalenses

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Additional information is available at the end of the chapter

<http://dx.doi.org/10.5772/66467>

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### Abstract

In this chapter, a review of the recent advances in optical metalenses is presented, with special emphasis in their experimental implementation. First, the Huygens' principle applied to ultrathin engineered metamaterials is introduced for the purpose of giving curvature to the wavefront of free-space wave fields. Primary designs based on metallic nanoslits and holey screens occasionally with variant width are first examined. Holographic plasmonic lenses are also explored offering a promising route to realize nanophotonic components. More recent metasurfaces based on nano-antenna resonators, either plasmonic or high-index dielectric, are analyzed in detail. Furthermore, 2D material lenses in the scale of a few nanometers enabling the thinnest lenses to date are here considered. Finally, dynamically reconfigurable focusing devices are reported for creating a scenario with new functionalities.

**Keywords:** metamaterials, optical lenses, subwavelength nanostructures

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### 1. Introduction

The advent of artificially structured media, coined as electromagnetic metamaterials, enables the observation of tailored properties not occurring in natural materials, opening up a new scenario in physics and technology [1]. For instance, negative-index metamaterials with simultaneously negative electric permittivity and magnetic permeability exhibit intriguing reversed electromagnetic properties like phase and energy velocity of opposite directions, leading to a reversed Snell's law. As a consequence, a thick planar slab made of this sort of novel materials, immersed in air, provides real images of an object set behind, which under some circumstances contains details with a resolution beyond the diffraction limit [2]. Furthermore, a concave negative-index lens would evidence a positive focal length and it might also bring an incident plane wave into a focus [3]. However, optimized structures with

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reduced losses have been mostly developed at microwave frequencies, dramatically reducing the above-mentioned applied possibilities in nanophotonics and optics [4].

For such spectral window, the well-known concept of lensing with Fresnel zone plates was efficiently materialized over ultrathin metallic films including nanoslits and holes with varying width (and occasionally shape) to achieve high transmission meta-screens with controlled phase distribution induced by elementary plasmonic modes with engineered effective index. As a stimulating alternative, metasurfaces with reduced dimensionality in the direction of light propagation confine the light-matter interaction into a surface thus drastically reducing the inherent losses of the constituting meta-atoms. Possibly the most revolutionary approach to metasurfaces-based focusing devices came to us soon consisting in the inclusion of optical nano-antennas arranged over transparent substrates and flat mirrors, thus achieving an abrupt phase change of the scattered field with controlled polarization pattern. By directly comparing with three-dimensional architectures, simpler fabrication processes through for instance electron beam lithography and its accessible implementation into optoelectronic devices establish the relevant features of these metasurfaces.

Although several reviews concerning plasmonic Fresnel-type lenses, hyperlenses and metalenses are present in the literature [5, 6], including an open-access book chapter published by InTechOpen [7], a continuous effort is necessary in order to provide the current state of the art of such fascinating and fast-evolving topic. Metalenses with applications in photonics (IR and visible wavelengths) are of our interest here, leaving to supplementary reviews the analysis of reflectarrays and array lenses for uses in low-frequency regimes [8]. Our purpose is then introducing the above-mentioned preliminary results but mainly focus on recent advances in the field, not thoroughly discussed yet. For instance, a revolutionary all-dielectric approach to plasmonic nano-antenna metasurfaces is presently being developed for applications in focusing and others where high-index nanoresonators are the constituents of the gradient nanostructure to provide a full control over the local amplitude, phase and polarization of the scattered field under minimal dissipation effects. On the other hand, two-dimensional materials such as graphene sheets and transition-metal dichalcogenide semiconductors have emerged as promising candidates for miniaturized optoelectronic devices and a few novel proposals enabling the thinnest optical lenses in the scale of a few nanometers. Furthermore, versatile platforms have experimentally been demonstrated for creating dynamically reconfigurable focusing devices. All these examples make the scene of new concepts and materials for the design and fabrication of the next generation metalenses.

Here, we present a review including the recent advances in the field of gradient-metasurfaces lenses. For that purpose, we first introduce the fundamental analysis enabling the control of the wavefront with metasurface structures. We then look into primary designs based on holey metallic screens and nanoslits with variant widths and more recent proposals based on nano-antenna resonators. Next we analyze in detail innovative assemblies including all-dielectric high-index nanoresonators as the constituents of the metasurface. A special emphasis will be set in atomically thin lenses enabling the thinnest lenses to date. Holographic lenses are also examined and we present the possibilities that they could offer in numerous useful applications. Finally, we consider reconfigurable lenses allowing the design of powerful new functionalities.

## 2. Fresnel zone plate metalenses

Conventional refractive lenses rely on gradual phase accumulation via light propagation through a bulk material polished to a specific surface topology to shape the incident beam. In general terms, metamaterial lenses will mold the phase front curvature of the light passing through the constituents of the photonic device. For the waves of individual building blocks to be in phase at the focal distance  $f$  from the lens, the phase delay as a function of distance  $x_t$  from the center of the lens, as predicted from the Huygens' principle, has to be

$$\phi(x_t) = \phi(0) + \frac{2\pi n}{\lambda} (\sqrt{f^2 + x_t^2} - f), \quad (1)$$

where  $n$  is the index of refraction of the medium propagating in either transmission or reflection and  $\lambda$  is the vacuum wavelength of the incident light. Note that for one-dimensional architectures,  $x_t = x$  represents the corresponding spatial coordinate, whereas for two-dimensional arrangements  $x_t = \sqrt{x^2 + y^2}$  stands for a radial coordinate. In this section we will analyze novel proposals for focusing wave fields based on the concept of diffraction. That is, modification of the complex amplitude of a given electromagnetic field by interacting with single-apertured or multiple-apertured opaque screens. We are mostly concerned on holey metallic films, though nanostructured metamaterials can be used to stop the contribution of light in the prescribed Fresnel zone plates.

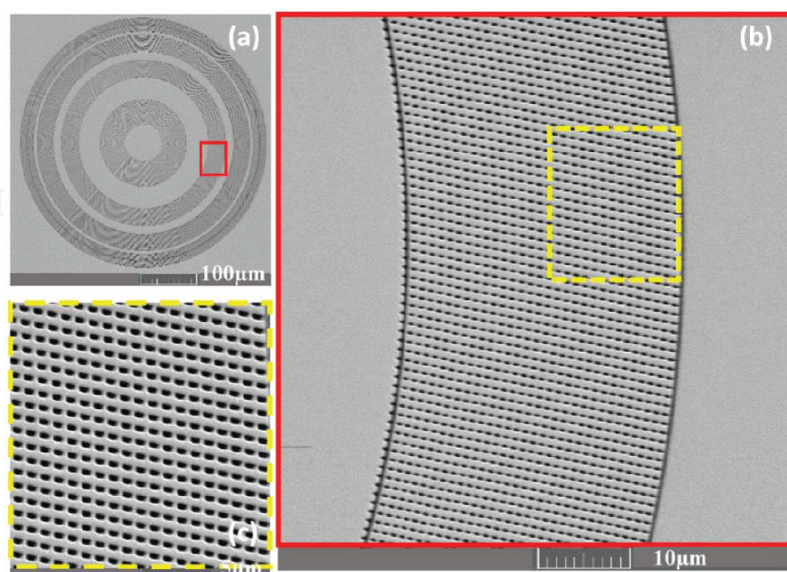
Fresnel zone plate lenses are practical energy collectors, which are currently in use in the electromagnetic spectrum spanning from the microwave to X-rays. The principle of operation of Fresnel zone plate lenses is based on the wave nature of light. The wavefront arriving at the lens is divided into sections, or zones. The specifications employed to characterize these zones are well established in the literature. For simplicity, let us first consider a central nanoslit and a set of off-axis nanoslits suitably placed in the metallic film. In the transmissive mode, the amplitude of the diffracted field is in practical terms zero in the plane immediately behind the zones where the metal is deposited. The phase difference between the light radiated from the  $m$ th surrounding slit and the light transmitted from the central nanoslit at the focusing spot position is about  $\Delta\phi(x_m) = \phi(x_m) - \phi(0)$ , where  $m = \pm 1, \pm 2, \pm 3 \dots$  and  $x_m$  is the center position of the  $m$ th slit. The constructive interference should occur when  $\Delta\phi$  is equal to a multiple of  $2\pi$  radians. In this case, the focusing intensity in the structure will be further improved due to the multiple-beam interference. The Fresnel zone plates are composed of concentric circles with their radii proportional to the square root of integers times the wavelength. The diffracted wave fields in the focal region can be accurately estimated by using for instance the Debye diffraction integral [9], provided that the focusing geometry is characterized by a high Fresnel number. From the practical point of view, by using nanoimprint lithography one can use molds to pattern PMMA on silicon substrates and PMMA patterns later being transferred to metals by lift-off, reaching a 20 nm minimum feature size [10].

In recent years, metallic nanostructures based on surface plasmon polaritons (SPPs) and exhibiting extraordinary enhancement of transmission is appealing for researchers. The conversion from SPP waves, which can propagate inside slits and holes much smaller than the wavelength, to propagation waves in the quasi-far-field region takes place by diffraction

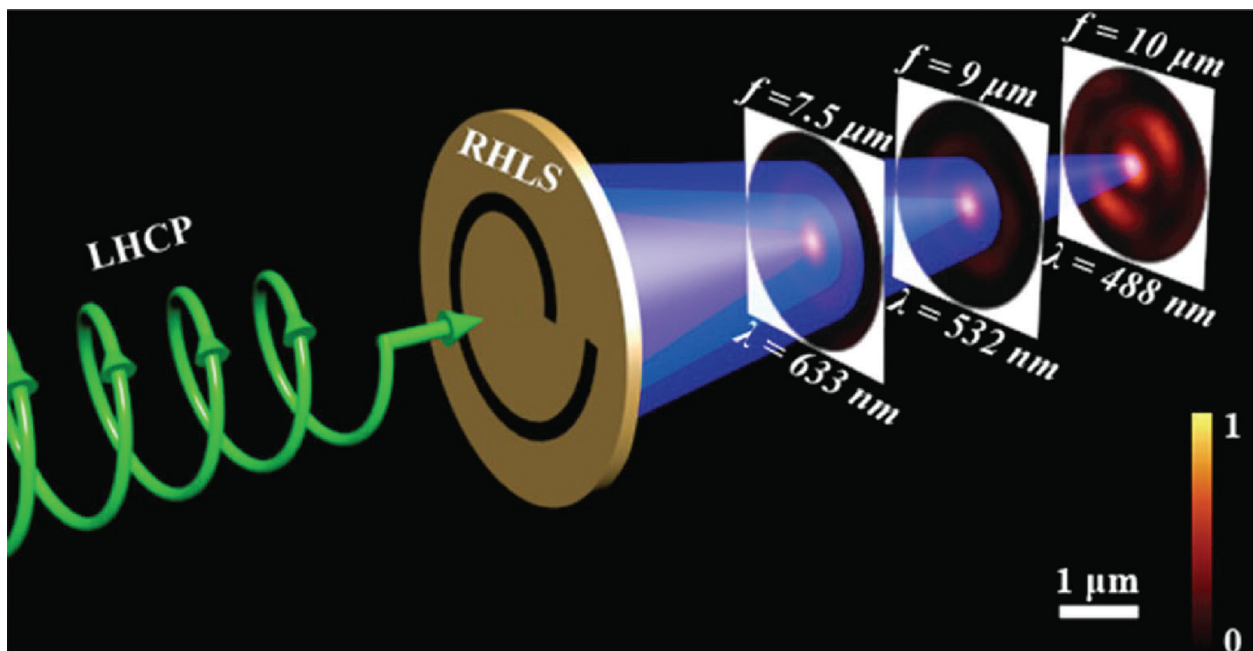
from the subwavelength zones of a given zone plate metalens. In this way, it was experimentally demonstrated that a Ag film-based microzone plate can combine such SPP wave effect and Fresnel zone plate focusing together [11]. Further noble metals such as gold can be used instead. In the cases given above, plasmonic waves do not contribute to far-field focusing. Importantly, the lens performance is significantly altered for the incidence in different polarization directions.

Following the basic proposal given above, a nano-focusing structure was experimentally demonstrated with high focusing efficiencies and easy fabrication by using a T-shape microslit surrounded by multislots in Au films [12]. In practical terms, it should be taken into account the propagation loss of SPPs owing to the Ohmic loss of Au and the fabrication roughness by focused ion beam (FIB). To realize the focusing, the T-shape microslit (microslit width of  $w = 1200$  nm and groove depth of  $d = 150$  nm) was suitably designed to be surrounded by multislots with the same slit width.

As a natural progress in the field, numerous types of Fresnel 2D zone metalenses subsequently appeared including for instance circular and elliptical nanopinhole. In Ref. [13], an optical nanosieve with circular symmetry was proposed, which is composed of 7240 subwavelength holes located at 22 concentric rings, where the holes in each ring are uniformly allocated and equally sized. However, more sophisticated designs can be found. For instance, light can concentrate into multiple, discrete spots by exploiting an evolutionary algorithm to optimize a structured optical material based on the discretization of a surface into a two-dimensional subwavelength lattice [14]. Polarization can be controlled by using the slits as antennas, as shown in **Figure 1**, acting as local linear polarizers. In such a way one may modulate an optical field in amplitude, binary phase and polarization for the cross-polarized component of the scattered field, for the generation of vectorial optical fields [15].



**Figure 1.** SEM image of a slot-antenna-based metalens with 450  $\mu\text{m}$  diameter. (a) Overall structure from top view. (b) Part of ring for the area enclosed with red solid line in (a). (c) Zoomed-in picture for the area enclosed with yellow-dashed line in (b). Reprinted with permission from [15] of copyright ©2015 Optical Society of America.



**Figure 2.** Right-hand logarithmic spiral exhibiting a broadband response under left-hand circularly polarized illumination. Reprinted with permission from [17] of copyright ©2015 WILEY-VCH Verlag GmbH & Co.

In some circumstances, the number of slits and any other kind of aperture mapping a metallic thin layer can be substantially reduced in order to generate a focused beam. One of the first experimental examples we found consists of a subwavelength annular aperture made on a silver film, where the transmitted light of a 442 nm incident laser was focused at several micrometers behind the silver structure at a tiny spot (354 nm), also exhibiting a remarkable depth of focus [16]. The resultant wave field is essentially a quasi-nondiffracting Bessel beam, whose depth of focus and transverse central spot can be tuned by changing the diameter of the subwavelength annular aperture. More recently, a logarithmic spiral nanoslit was proposed to converge an incident wave field of opposite handedness to that of the nanoslit into a subwavelength spot, a fact that is caused by a strong dependence on the incident photon spin [17]. By varying the nanoslit width, different incident wavelengths interfere constructively at different positions, thus configuring a sort of switchable and focus-tunable structure, as depicted in **Figure 2**. Anyhow, such inherent dispersive behavior attributed to diffraction can be corrected [18], enabling ultra-broadband achromatic focusing that is necessary for some applications. These kinds of lenses were recently fabricated using single-step grayscale lithography, where linear grooves with a designed height are set on a photoresist [19].

### 2.1. Super-oscillatory metalenses

A new idea in optical imaging has emerged which exploits the recently predicted and observed effect of optical super-oscillations. The key element of this new super-resolution technique is a super-oscillatory lens, which is a nanostructured mask that creates a focus beyond the diffraction limit, in principle of any prescribed size, without the contribution of evanescent waves [20]. However, the subwavelength hotspot is created in a low-intensity

super-oscillatory region, thus only receiving a minimal fraction of the total power, with a simultaneous larger high-intensity halo, the latter limiting the field of view of this focusing device in imaging.

One of the first experimental demonstrations of super-oscillatory metalenses consisted of a quasicrystal array of nanoholes in a metal screen producing bright foci sparsely distributed in the focal plane [21]. Although nearly any array of small holes will create a diffraction pattern of foci when illuminated by a point source, a suitable choice of nanohole pattern is required for lensing applications [22]. Particularly, a Penrose array of 200 nm holes enables to generate an isolated hotspot of electromagnetic radiation at some distances [23]. Furthermore, a displacement of the point source leads to a linear shift of the image point, thus mimicking a function of the lens.

To design the binary mask, the radial coordinate can be divided into a number of concentric annuli, each of which had either unit or zero transmittance. In Ref. [24] 25 transparent regions of varying size was finally reached. Specifically, the ring pattern of the super-oscillatory lens with outer diameter of 40  $\mu\text{m}$  was manufactured by FIB milling of a 100-nm-thick aluminum film supported on a round glass substrate and mounted as a microscope illuminating lens. When illuminated with a laser at  $\lambda = 640 \text{ nm}$ , it generates a focal hotspot of 185 nm in diameter,  $\sim 25$  times the intensity of the incident light and located at a distance of 10.3  $\mu\text{m}$  from the film. The super-oscillation concept can be extended into the vectorial-field regime to work with circularly polarized light [25].

### 3. SPP-driven holographic metalenses

Surface plasmon polaritons cannot be used directly to focus light by free-space propagation since they propagate at the interface between a metal and a dielectric. SPPs and free-space beams are often coupled through periodic gratings. A metal grating with a period  $\Lambda$  on top of the metal layer provides an additional wave vector, in such a way that an incoming electromagnetic wave at an angle  $\theta$  will satisfy the condition of momentum conservation:

$$k_d \sin(\theta) + 2\pi m / \Lambda = \pm \text{Re}(k_{\text{SPP}}) \quad (2)$$

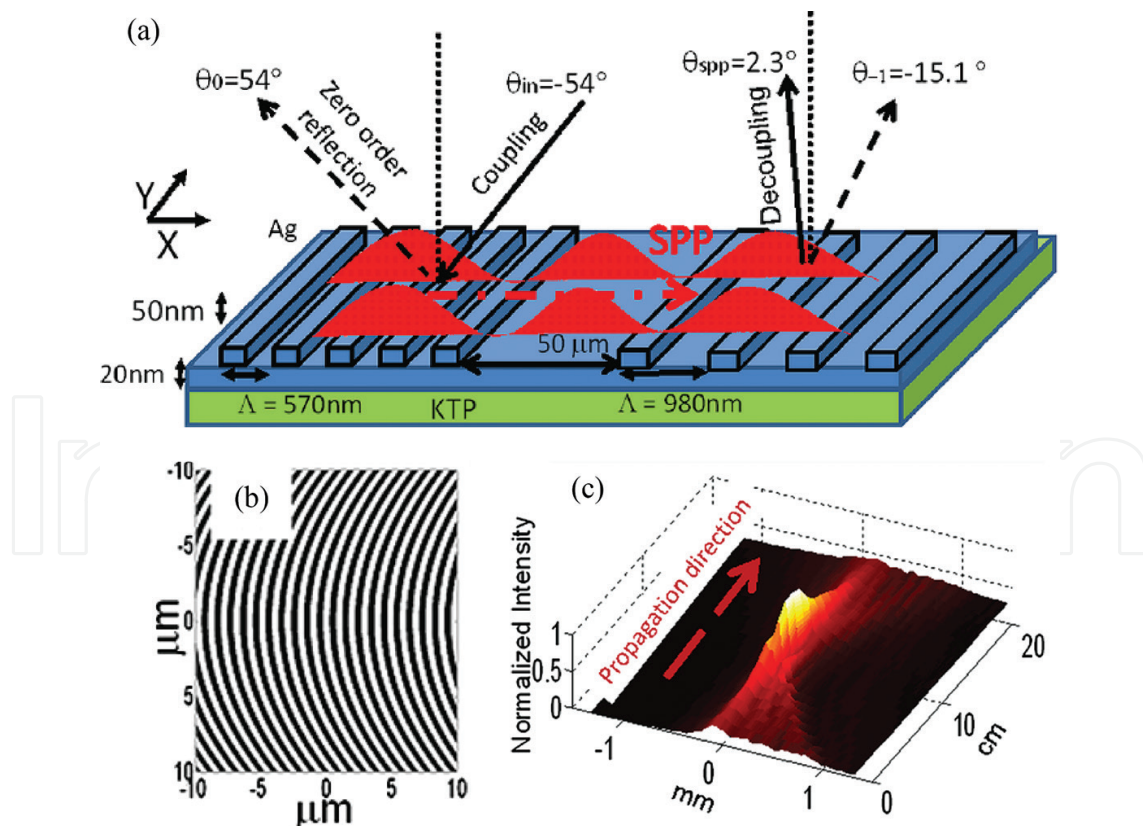
where  $k_d$  and  $k_{\text{SPP}}$  are the dielectric and SPP wave numbers, respectively and  $m$  stands for an integer.

By employing holographic-based techniques for modulating the grating, one can systematically control the amplitude and phase of the coupled free-space beam. Thus, a planar beam transformer can be obtained by means of gratings with different periods for the input and output coupling. Following such procedure, in Ref. [26] it was experimentally demonstrated the coupling of SPPs into focused free-space beams, as shown in **Figure 3**, as well as into accelerating airy beams and vortex beams.

Much earlier, it was theoretically shown how, by patterning the exit plane of an aperture in a metal film, the angular distribution of the transmitted light in the far-field region can

be shaped, producing highly focused beams at resonant wavelengths [27]. Since the diffracted beams are modulated by the nanometric grooves, through adjusting the parameters of the grooves such as their width, depth, period and number, the diffracted beams can be fully manipulated resulting in a tailored ultracompact lens [28]. The architecture can exhibit radial symmetry, so the plasmonic lens would consist of an annular slit and concentric grooves which, under radially polarized illumination, produces a focus spot. With a proper design, the inherent chromatic dispersion can be compensated and thus focusing dual-wavelength SPPs to the same focal plane [29]. Furthermore, the manipulation of plasmonic beaming fields can be based on the variation of dielectric surface gratings instead of using grooves. Plasmonic off-axis beaming and focusing of light by the use of asymmetric or nonperiodic dielectric gratings around a metallic slit has been experimentally demonstrated in Ref. [30].

Note that the present procedure based on plasmonics is suitable for terahertz beamforming. In this case, metallic grooves with a subwavelength spacing can couple to free-space propagating wave fields by means of spoof surface plasmon polaritons. Bullseye structures made of concentric scatterers periodically incorporated at a wavelength scale experimentally have demonstrated the launching of surface waves into free space to define a focal beam [31].



**Figure 3.** (a) Illustration of gratings enabling coupling and decoupling into SPPs. (b) 1D lens generated by output coupling of the SPP wave through a grating with quadratic phase. (c) Cross-section of the generated free-space beam. Adapted with permission from [26] of copyright ©2012 American Physical Society.



#### 4. Gradient-index metalenses

In this section we consider different proposals to locally modulate the effective index of refraction undergone by wave fields traversing the apertures that constitute a metalens. The basic degrees of freedom include changing the width of the slits, assuming a cylindrical holey lens, their relative positions and the shape of the entrance and exit surfaces. An early idea inspired in thick left-handed metamaterial lenses is based on creating metallic lenses with curved surfaces, resembling glass lenses in their shape, such that each nanoslit transmits light with a phase retardation which is controlled by the metal thickness [32]. However, efficient fabrication processes may benefit from keeping the film thickness fixed but tailoring alternate geometrical parameters of the holey metallic device. Shi et al. first proposed a lens design based on an array of nanoslits which have constant depth but variant widths [33]. The variation of the slit width is associated with a change in the effective index of the transmitted field mode. The latter principle of operation was massively followed by others.

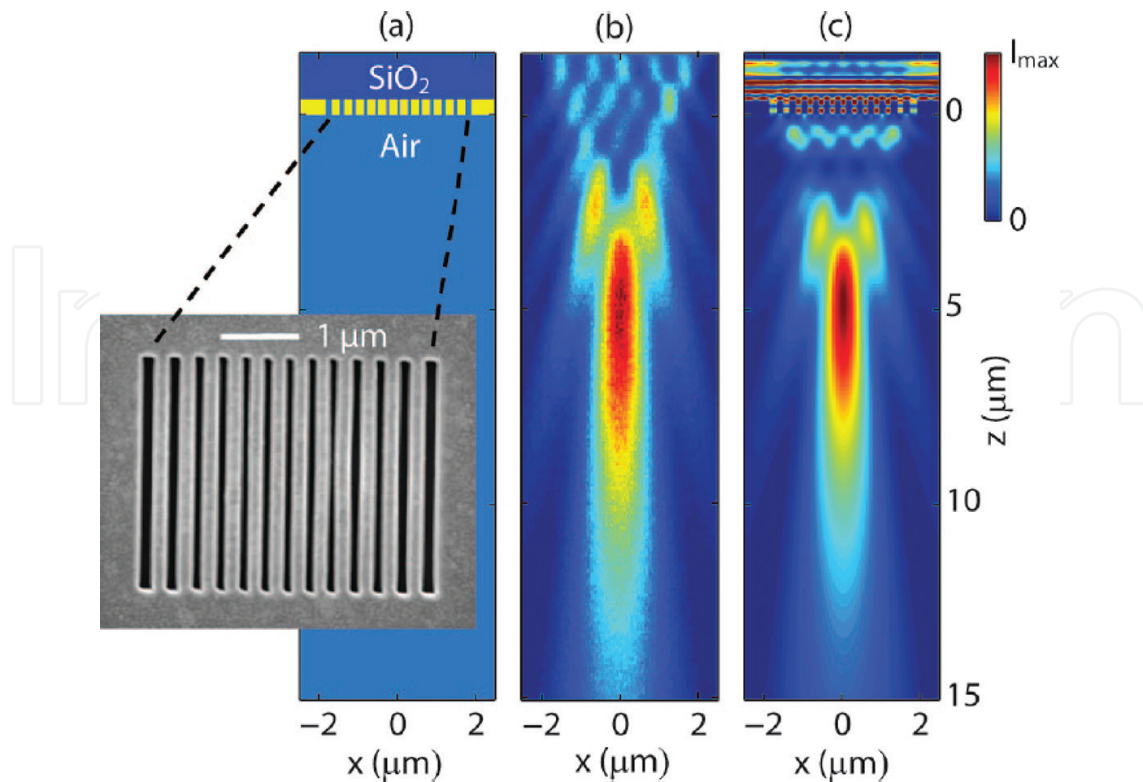
The basic building block of the patterned metallic lens is a narrow slit surrounded by metallic walls. By illuminating with a plane wave whose electric field is polarized perpendicularly to the orientation of the slits, the fundamental transverse magnetic (TM) mode is excited in the metal-insulator-metal structure following a dispersion relationship as

$$\tanh\left(\frac{w}{2} \sqrt{\beta^2 - k_0^2 \epsilon_d}\right) = - \frac{\epsilon_d \sqrt{\beta^2 - k_0^2 \epsilon_m}}{\epsilon_m \sqrt{\beta^2 - k_0^2 \epsilon_d}} \quad (3)$$

which relates the modal propagation constant  $\beta$  to the free space propagation constant  $k_0 = 2\pi/\lambda$ , the permittivity of the metal  $\epsilon_m$  and the dielectric  $\epsilon_d$  inside the slit and the slit width  $w$ . The real and imaginary parts of the effective refractive index  $n_{\text{eff}}$  calculated as  $\beta/k_0$ , determine the phase velocity and the propagation loss of the SPP modes, respectively. The phase delay introduced by a single pass in the nanoslit is estimated by  $\beta d$  and strongly depends on the slit width, where  $d$  represents the film thickness. The narrower slit introduces the larger phase delay. Thus, a structure that consists of slits with increasing width from the center to the side creates a curved wavefront. Simultaneously, the field at the exit surface of the film is also modulated since the transmission of each nanoslit varies as a function of slit width. Finally, the influence of the interaction between two adjacent nanoslits on the phase delay has been systematically investigated using the finite-difference time-domain method [34].

Verslegers et al. reported the first experimental demonstration of far-field lensing using this type of gradient-index nanoslit array [35, 36]. The fabricated planar lens consists of an array of nanoscale slits, with range in width from 80 nm at the center of the array to 150 nm on the side, in an optically thick gold film, as illustrated in **Figure 4**. The gold film is evaporated onto a fused silica substrate using electron beam evaporation, which is later patterned by milling through the film. After this exploratory finding, the interest for gradient-index metalens grew tremendously followed by a large number of experimental studies. For instance, Chen et al. [37] fabricated plasmonic lenses in the visible range using nanoslits in an aluminum film.

Flat metalenses offer some advantageous accessibility to manufacture and integrate in complex devices; however, they suffer from severe geometrical restrictions to attain extremely high numerical apertures. An alternative design relies on sculpturing a concave surface. In

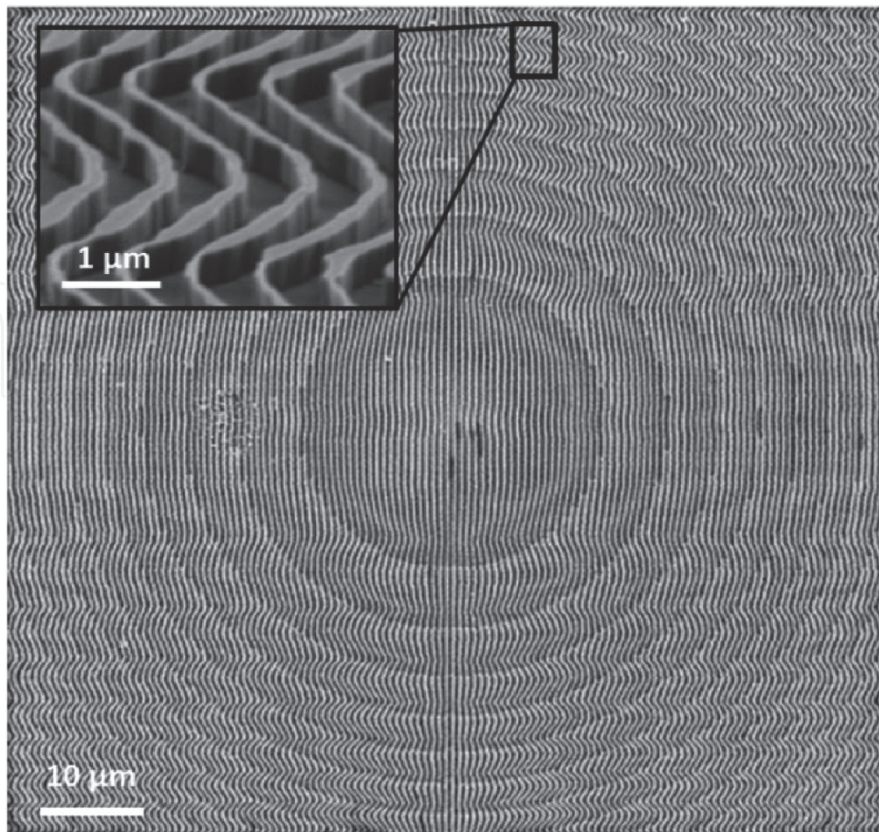


**Figure 4.** Planar lens based on nanoscale slit array in metallic film. (a) Geometry of the gradient-index lens. The inset shows a scanning electron micrograph of the structure as viewed from the air-side. (b) Focusing pattern measured by confocal scanning optical microscopy. (c) Finite-difference frequency-domain simulated focusing pattern of the field intensity through the center of the slits. Reprinted with permission from [35] of copyright ©2009 American Chemical Society.

such manner an aplanatic metasurface patterned on a spherical substrate has been proposed to focus light without coma and spherical aberrations [38]. Note that nonplanar metacoatings composed of subwavelength metal-dielectric arrays can not only focus an incoming light [39] but also let it accelerate in the near field [40]. Such basic concept can be utilized to engineer gradient-index ultrathin coatings, in a parallelizable assembly, as focusing elements with high efficiency [41, 42].

Differently from works conducted previously by other groups, it was investigated by numerical simulations and experiments the manipulation of an incident electric field that is parallel to the slits (TE-polarized plane wave) passing through arrays of nanometric spatially varying near-resonant slits perforated in a silver film [43]. Slits illuminated with the TE polarization exhibit a cut-off wavelength together with a resonance for transmission, enabling a fast phase modulation of the transmitted field, which is absent in the case of the TM polarization. Similarly, the dispersion of metal-dielectric-metal plasmonic waveguides is exploited to artificially mimic an epsilon-near-zero medium at optical wavelengths by working near the cut-off of the  $TE_1$  mode [44].

An important drawback of the nanoslit lens design is its polarization dependence, which can be eliminated by extending the concepts of gradient-index metalenses into two dimensions. For example, a planar, holey metal lens was experimentally made as a set of concentric



**Figure 5.** Scanning micrograph of the entire fabricated grating lens for  $f=100\ \mu\text{m}$  (top view). The inset emphasizes the region with two phase jumps. Reprinted with permission from [48] of copyright ©2013 Optical Society of America.

circular arrays of nanoscale holes milled in a subwavelength-thick metal film [45]. In this case, each nanohole used as a phase-shifting element acts as a finite-length, circular, single-mode waveguide with a radius-dependent mode index.

Note that laterally propagating SPPs excited by the periodic nanohole array play an important role in light transmission through a metal-dielectric hole array. Therefore, the novel idea is not exploiting propagating waves in a plasmonic waveguide but using resonances. An early experimental demonstration of two-dimensional focusing was based on planar plasmonic lenses formed by an array of subwavelength cross-shaped apertures in a thin metal film, where the apertures have dimensions that vary spatially across the device. In this case, the lenses utilize localized surface plasmon resonances occurring within the apertures that are accompanied by controlled phase shifts in the transmitted field by means of a modulation of the arm length of the crosses [46].

#### 4.1. Metalenses based on dielectric gratings

As an important category of the gradient-index metalenses, focusing elements based on semiconductor high-contrast gratings has been widely investigated. The basic geometry of the high-contrast grating consists of an array of nanoscale ridges completely surrounded by low refractive index materials (e.g., air). By using a nonperiodic design of the subwavelength grating pattern allows a dramatic control of the phase front of the reflected beam, without

affecting the high reflectivity of the mirror [47]. Note that wavefront-engineered diffraction gratings also enable high aperture three-dimensional focusing in free space. As an example, **Figure 5** shows a grating structure, made of amorphous silicon on a glass substrate, which is designed by locally modulating the period and duty cycle of the grating for a wavelength of 980 nm and optimized for operation in reflection, normal incidence and TM polarization [48]. In particular, a path-finding algorithm allows to find a path in the parameter space of the grating that continuously connects two points of the desired phase evolution.

In a complementary scheme, one may design a metalens by writing a space-variant nanograting which results in a space-variant effective birefringence. Then, by suitably engineering the local orientation of the nanograting, a Pancharatnam-Berry phase lens can be achieved [49]. In Ref. [50] it was reported a dielectric gradient metasurface optical element with a 120-nm-wide and 100-nm-high Si nanobeam as a basic building block. When the metalens is uniformly illuminated from the substrate side with right circularly polarized light at a wavelength of 550 nm, it concentrates light into a left circularly polarized focal spot.

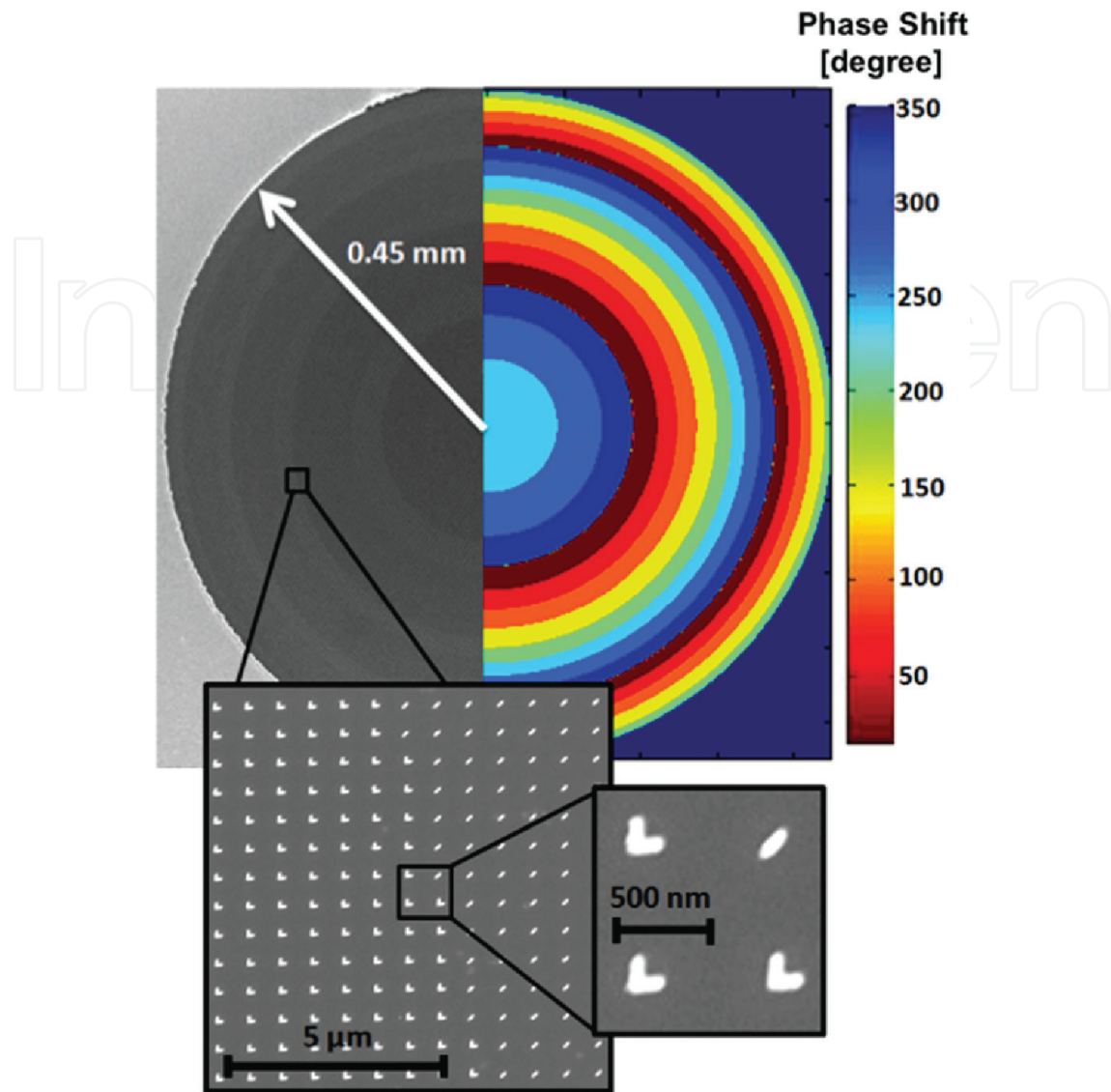
## 5. Focusing with nano-antennas

Metasurfaces have their conceptual roots in early works on subwavelength gratings. The concept of optical phase discontinuities provides a different path for designing flat lenses and has been used in the demonstration of metasurfaces capable of beaming light in directions characterized by generalized laws of reflection and refraction [51]. Under this approach, the control of the wavefront no longer relies on the phase shift accumulated during the propagation of light but is achieved by radiation as it scatters off the optically thin resonators comprising the metasurface.

### 5.1. Plasmonic metasurfaces

Light focusing was experimentally demonstrated in free space at telecom wavelength using a 60-nm-thick gold metasurface [52] as shown in **Figure 6**. In the fabricated metalens with 3 cm focal distance, eight different plasmonic V-shaped antennas were designed to scatter light in cross-polarization with relatively constant amplitudes and an incremental phase of  $\pi/4$  between neighbors. However, the variety in design of nanoresonators varying their shape and spatial distribution is certainly broad. For instance, a metal-insulator-metal configuration in which the top metal layer consists of a periodic arrangement of differently sized bricks, thus functioning as a metasurface in close vicinity of a metal film, was designed to work as a parabolic reflector [53].

Instead of molding linearly polarized wave fields, suitable designs of the elementary resonant nano-antennas and their spatial distribution can be used to manipulate the wavefronts and polarization of azimuthally polarized and radially polarized light. By means of elliptical optical antennas, which instead of converting one linear polarization to the other as in previous works, enable incident right-handed circularly polarized light to be almost converted into left-handed circularly polarized light [54]. In the latter case, the abrupt phase change occurs



**Figure 6.** SEM image of the fabricated lens (left). The corresponding phase shift profile is displayed on the right. Insets: close up of patterned antennas. Reprinted with permission from [52] of copyright ©2012 American Chemical Society.

for circularly polarized light that is converted to its opposite helicity, in such a way that the created focused light carries orbital angular momentum.

One can apply the same working principle by exploiting the shift of wave vector that results from the geometric Pancharatnam-Berry phase. For instance, a plasmonic bipolar lens consisting of dipole nano-antennas with controlled directional orientation was designed to exhibit helicity-controllable real and virtual focal planes, as well as magnified and demagnified imaging at visible and near-infrared wavelengths [55]. We point out that, also, gradient-rotation split-ring antenna metasurfaces were designed and experimentally demonstrated as spin-to-orbital angular momentum beam converters to simultaneously generate and separate pure optical vortices [56].

In contrast to conventional nano-antennas, it is possible to use an inverted design built on Babinet's principle. In this case, similarly shaped nano-voids (Babinet-inverted, or

complementary nano-antennas) have been milled in a thin metallic film, which provides a significantly higher signal-to-noise ratio [57]. More recently, helical devices composed of more than 121 thousands of spatially rotated nanosieves have been fabricated to achieve full manipulations of optical vortices by controlling the geometric phase of spin light, enabling for instance to create multifoci vortex lenses [58]. This approach has been also utilized in the development of innovative terahertz imaging systems.

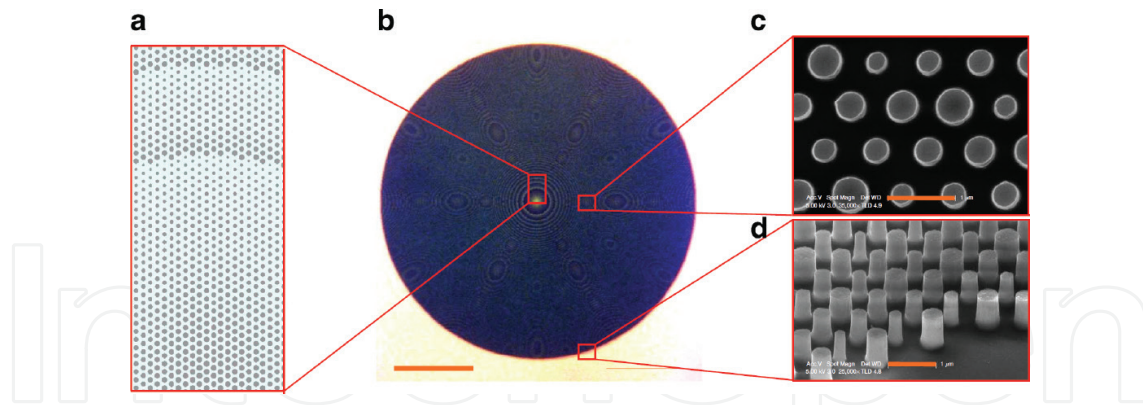
The metasurfaces demonstrated so far are conveniently designed to manipulate only the phase profile of the outgoing electromagnetic waves. A complete manipulation of the propagation of light, on the other hand, requires simultaneous control of amplitude and phase. To implement this approach for governing both phase and amplitude, a metasurface was designed that consists of C-shaped antennas. The scattered fields from both the symmetric and antisymmetric modes contribute to an orthogonally polarized output wave, whose phase and amplitude can be engineered by adjusting the shape parameters of the antenna [59]. By employing the designed C-shape split-ring resonators, a metasurface with a hyperboloidal phase profile is arranged to engineer the transmitted wavefront in the same way as a conventional lens. This architecture enabling scattered fields with controlled phase and amplitude distribution has also inspired the design of holographic-based multifocal metalenses [60].

In connection with Fresnel zone plates discussed in Section 2, it is worth noting that metasurfaces consisting of cross-shaped and rod-shaped optical nano-antennas can be used to construct diffractive lenses. Since the transmission function of the optical nano-antenna depends on its resonance, by creating metasurfaces out of wavelength and polarization selective optical nano-antennas, the total transmission function can be modulated and construct a metalens that operates as a binary-amplitude Fresnel zone plate.

## 5.2. Dielectric nanoresonators

A vast majority of previous designs based on plasmonic metasurfaces and gratings cannot provide a performance comparable to conventional curved lenses. The implementation of Huygens' sources at optical frequencies utilizing the strong electric and magnetic resonances of high-permittivity all-dielectric nanoparticles in the near-IR spectral range is currently a very active route. Using dielectric nanoresonators as phase shift elements, metasurfaces enable wavefront molding with experimental demonstrations of beam bending and lensing [61]. For instance, cylindrical converging wave fields can be produced by means of a lens consisting of an aperiodic arrangement of coupled rectangular dielectric resonators whose scattering phases are in addition engineered to achieve dispersion-free focusing at telecommunication wavelengths. The achromatic metalens can be fabricated by depositing 400 nm amorphous silicon on a fused silica substrate, where the rectangular dielectric resonators were defined by electron-beam lithography [62]. Such metalenses address an increased need for low-cost, lightweight and compact optical elements that can easily be assembled to electronic and mechanical components.

Many more proposals based on all-dielectric metasurfaces can be found in the literature to produce spherical wavefronts. Full-phase coverage combined with high efficiency in transmission are experimentally confirmed using for instance silicon nanodisks and square silicon



**Figure 7.** (a) Schematic illustration of the aperiodic high-contrast transmitarray used to realize a high-NA dielectric microlens. (b) Optical microscope image of the fabricated metalens with large NA. Scale bar, 100  $\mu\text{m}$ . (c and d) SEM images of the silicon posts forming the microlens. Scale bars, 1  $\mu\text{m}$ . Reprinted with permission from [64] of copyright ©2015 Macmillan Publishers Limited.

ridges [63]. Utilizing lithographically patterned arrays of elliptical silicon nanowires enables in addition to control the birefringence of the material and thus to create dynamically reconfigurable lenses in response to the polarization of the illumination.

Particularly interesting is the reported high-NA lens illustrated in **Figure 7**, which is composed of dielectric nanoposts that are fabricated in an amorphous silicon film [64]. Such polarization-insensitive, micron-thick, high-contrast transmitarray microlens produces a focal spot as small as  $0.57 \lambda$  with a measured focusing efficiency of 82%. Furthermore, complete control of polarization and phase can be attained using high-contrast dielectric elliptical nanoposts [65]. This novel metasurface platform achieves a measured efficiency of up to 97%, enabling the realization of free-space transmissive optical lenses for the simultaneous generation and focusing of radially and azimuthally polarized light from linearly polarized beams, even separating  $x$ - and  $y$ -polarized light and focusing them to two different points. Note that these lenses provide the high NA required for collimation of mid-IR quantum cascade lasers.

Silicon can be replaced by new high-index dielectric materials for the assembly of efficient focusing metasurfaces. For example, a metalens that consists of  $\text{TiO}_2$  nanofins on a glass substrate has been designed and fabricated, with a  $\text{NA} = 0.8$  and an efficiency as high as 86% in the visible range [66]. In this case, the required phase is conferred by rotation of the nanofin according to the geometric Pancharatnam-Berry phase, showing that they are able to provide diffraction-limited focal spots at arbitrary design wavelengths. Note that these sort of planar metalenses exhibit super-dispersive characteristics, enabling for instance to simultaneously form two images with opposite helicity of an object within the same field-of-view.

## 6. Reconfigurable metalenses

The inclusion of active tunability in static plasmonic devices greatly enhances their functionality. Index-variable materials are often incorporated in plasmonic devices and optical metasurfaces, including liquid crystals, vanadium dioxide, silicon and other materials. Thus, one

may manipulate the optical phase of the guided modes excited in graded-index metalenses in order to achieve a certain degree of tunability in the focusing behavior of the photonic device. Perhaps one of the first proposals consisted of embedding nonlinear media in the slit region of metallic nano-optic lens in such a way that the focal length can be easily controlled by means of the intensity of incident light in the structures [67].

As mentioned above, the slits of a holey metalens can be filled with liquid crystals to take advantage of their index changing property. In this case, the focal length can be easily controlled by exposing the plasmonic metalens to a constant external electric field, where the change in refractive index is directly converted into a locally modulated phase shift for the incident light. Ishii et al. experimentally showed that the irradiance as well as the transmission profile are altered provided that the liquid crystals change their phase from the nematic state to the isotropic state [68]. Such approach also allows electric and magnetic resonances to be spectrally tuned in all-dielectric metasurfaces as well as switching of the anisotropy (temperature-dependent) of the optical response of the device [69].

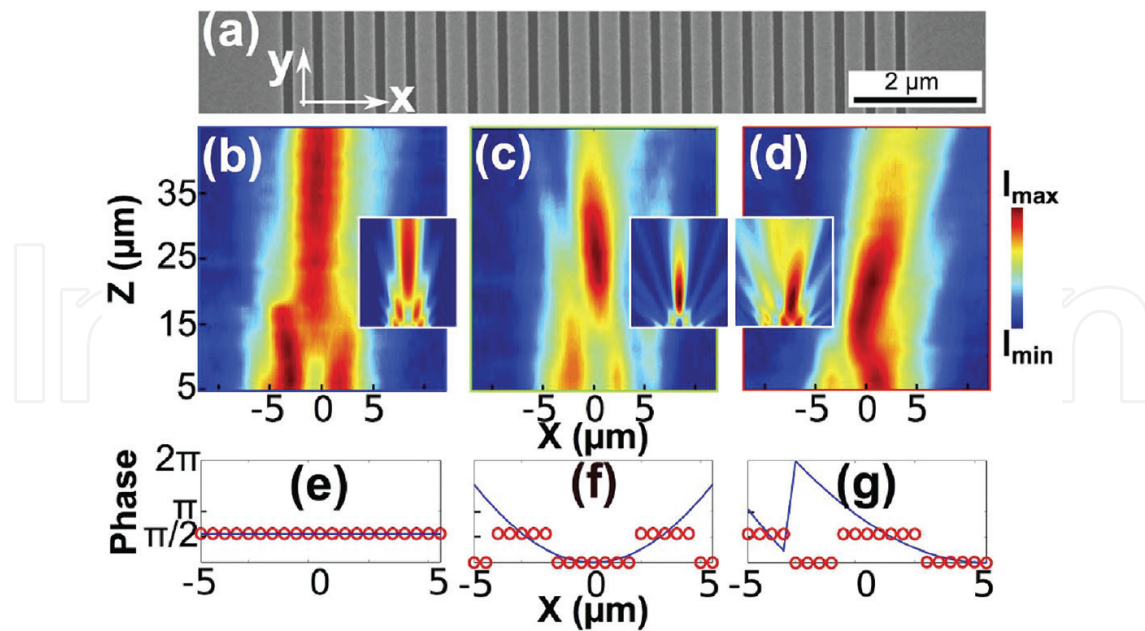
A novel planar metalens shown in **Figure 8**, which consists of an array of slits that are filled with phase-change material  $\text{Ge}_2\text{SB}_2\text{Te}_5$  (GST), has also been proposed to engineer the far-field focusing patterns [70]. By varying the crystallization level of GST from 0 to 90%, the transmitted electromagnetic phase modulation supported inside each slit can be as large as  $0.56 \pi$  at the working wavelength  $1.55 \mu\text{m}$ . In fact, this geometrically fixed platform can be applied to a variety of devices such as visible-range reconfigurable bichromatic lenses, multifocus Fresnel zone plates and super-oscillatory lenses [71].

In the terahertz regime one may fill the slit array with InSb to create a plasmonic lens with tunable focal length by simply controlling the temperature. When an external magnetic field is applied, the cyclotron frequency of high electron mobility semiconductors such as InSb locates also in THz frequencies, enabling to tune the dielectric properties of the magneto-optical material. Based on the magneto-optical effect, a tunable metal/magneto-optic plasmonic lens for terahertz isolator was introduced which, in addition, exhibits the nonreciprocal transmission property [72].

Planar diffractive microfluidic lenses with switchable properties have also been reported, in particular integrating controlled dielectrophoresis for trapping suspended silicon and tungsten oxide nanoparticles [73]. These nanomaterials can be trapped to produce alternating opaque and transparent rings using the dielectrophoresis forces, thus suitably forming diffractive Fresnel zone plates capable to focus the incident light. The Fresnel zone plate is tuned for the visible light region and the lens can be turned on (dielectrophoresis applied) or off (dielectrophoresis removed) in a controlled manner.

Graphene, indium tin oxide and vanadium dioxide have been frequently employed, owing to their large optical tunability as a function of either voltage or temperature. For instance, the Fermi level of graphene can be easily tuned by applying bias voltage, which, in turn, affects the resonance of nearby plasmonic structures. As a result, active metasurfaces capable of delivering efficient real-time control and complex-amplitude manipulation have been proposed, as we will also analyze in the next section devoted to atomically thin metalenses.





**Figure 8.** (a) SEM image of the fabricated planar lens before sputtering GST. (b, c and d) Focusing pattern by confocal scanning optical microscopy for amorphous GST in all slits without crystallization and GST being crystallized in the selected slits; insets show numerical simulations. (e, f and g) The calculated phase fronts (blue curves) and the binarized discrete phase distributions (red circles) which are anticipated from the samples in (b), (c) and (d), respectively. Reprinted with permission from [70].

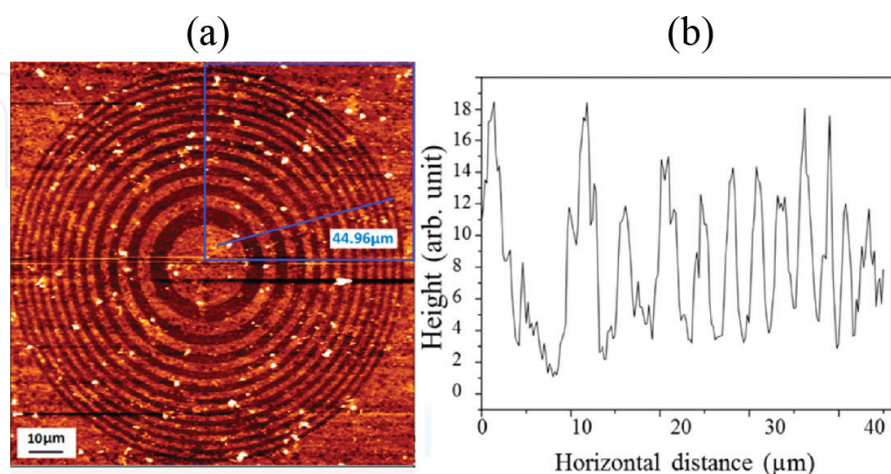
Active tunability can also exploit the benefits of microelectromechanical systems (MEMS). In these techniques, the substrate supporting for the metallic structures itself moves and shifts the plasmonic resonances. As an example, the active plasmon lens shown in Ref. [74] combines a MEMS structure with a metallic width-variant nanoslit lens. The active lens has five movable nanoslits whose widths can be controlled by an external bias, allowing focusing or defocusing of the diffracted light via controlling the phase front. In the reported experiments, a 5-V bias can modify the slit widths initially fixed at  $d_1 = 80$  nm,  $d_2 = 120$  nm and  $d_3 = 150$  nm, thereby changing the metalens transmission profile. Also, a mechanically tunable metasurface that includes a stretchable polydimethylsiloxane substrate has been proposed to change the relative position of arrayed plasmonic gold nanorods deposited above, thus controlling the local refraction angle continuously and thus the optical wavefront of the scattered field [75]. Following this method, a flat  $1.7\times$  zoom metalens was realized whose focal length can gradually be changed from 150 to 250  $\mu\text{m}$ . Direct applications in all cases include optical trapping, optical routing and beam stirring at the micron scale.

## 7. Atomically thin lenses

The ultrathin metalens fabricated by Capasso et al. [52], which is based on plasmonic nanoresonators with a thickness of only 60 nm, was considered to be a milestone in the current photonic nanotechnology. As graphene is one of the thinnest and probably most promising materials nowadays, it was used for the design of atomically thin Fresnel zone plates,

where in addition the lens performance can be tuned by adjusting the Fermi level of graphene and the number of layers. Early experimental demonstrations of graphene-based metalenses appeared soon after. Monolayers and multilayers of graphene were fabricated and giving form to Fresnel zones in order to produce diffractive lenses, allowing to operate in the visible and near-infrared frequency range [76]. In the reflection mode, the focusing efficiency increases with an increasing number of graphene layers. **Figure 9** shows a graphene Fresnel zone plate with a radius of about 50  $\mu\text{m}$  and containing 24 zones, where the average surface roughness was measured as 3.47 nm, which corresponds to approximately 10 layers of graphene. In order to demonstrate the thinnest possible metalens, a single layer of graphene was also successfully patterned lithographically onto a thick glass. The graphene lenses were found to be thinner and easier to fabricate compared to the metasurface-based lenses, having the potential to revolutionize the design of compact optical systems, such as laser focusing for optical storage and fiber optic communication.

Graphene has been demonstrated to support surface plasmon polaritons and, thereby, represents an attractive alternative to metals for the design of plasmonic metasurfaces. Furthermore, graphene conductivity can be dynamically controlled by an external stimulus such as electric and/or magnetic field, voltage, or temperature and therefore the optical response of the meta-material device potentially exhibits a versatile tunability. Metasurfaces based on 1D graphene nanoribbons, periodically patterned graphene nanocrosses, or alternatively nano-antenna plasmonic metasurfaces integrating single-layer graphene, have experimentally evidenced their capability to manipulate the wavefront of light, thereby used to create ultrathin lenses [77–79]. Moreover, a graphene cut-wire layer introducing a discontinuous Pancharatnam-Berry phase profile has been proposed as integrated in a metal-dielectric-graphene three-layer structure to improve the interaction of graphene nanostructures with incident waves [80]. By arranging two different graphene cut-wire resonators in one unit cell, one can excite two resonances and, as a result,  $2\pi$  phase modulation with efficiency approaching 50% can be achieved in a wide range of frequencies.



**Figure 9.** (a) AFM image of single graphene Fresnel zone plate. (b) Roughness distribution along the blue line. Reprinted with permission from [76] of copyright ©2015 American Chemical Society.

2D materials other than graphene can offer a superior performance for some specific applications and frequency ranges. For instance, a single-layer molybdenum disulfide provides an extremely high optical path length, which is roughly one order of magnitude larger in comparison with that experienced from a single layer of graphene. Such a giant optical path length has been exploited to design and fabricate probably the world's thinnest optical lens, enabling to curve the plane phase front of an optical beam within less than 6.3 nm thick that constitute a few layers of MoS<sub>2</sub> [81]. The bowl-shaped structure is 20 μm in diameter, where the MoS<sub>2</sub> thickness is gradually changed by using a FIB, thus serving as an atomically thin reflective concave lens. In addition, the refractive index of the layered MoS<sub>2</sub> can be largely tuned by applying an electric field, allowing the fabrication of microlenses with electrically tunable focal lengths.

## 8. Summary

In summary, we have reviewed and discussed the significant recent progress in the field of far-field metalenses in optical applications. The devices analyzed here exhibit important features directed toward solving the main objections related to conventional metamaterial lenses, such as transmission losses and fabrication. Some of the greatest achievements in this area are the staggering progress of current nanofabrication techniques, which have a higher capacity of resolution at the nanometer scale, the development of new materials enabling an increased performance in optical and IR metalenses and the design of novel subwavelength nanostructures with improved functionality. A number of proposals include tunability which allows the dynamic manipulation of complex wave fields, commonly on the diffraction limit and the versatile reconfiguration of metalenses. Owing to its countless advantages in terms of size, manufacturing simplicity and the wide range of applications, the metalenses may be considered indispensable elements conducting future optical devices such as integrated photonics, super-resolving imaging, optical trapping and quantum optics, to mention a few.

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