Spatial optical phase-modulating metadevice with subwavelength pixelation

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Abstract: Dynamic control over optical wavefronts enables focusing, diffraction and redirection of light on demand, however, sub-wavelength resolution is required to avoid unwanted diffracted beams that are present in commercial spatial light modulators. Here we propose a realistic metadevice that dynamically controls the optical phase of reflected beams with sub-wavelength pixelation in one dimension. Based on reconfigurable metamaterials and nanomembrane technology, it consists of individually moveable metallic nanowire actuators that control the phase of reflected light by modulating the optical path length. We demonstrate that the metadevice can provide on-demand optical wavefront shaping functionalities of diffraction gratings, beam splitters, phase-gradient metasurfaces, cylindrical mirrors and mirror arrays — with variable focal distance and numerical aperture — without unwanted diffraction.

OCIS codes: (240.0240) Optics at surfaces, (050.0050) Diffraction and gratings, (130.0130) Integrated optics, (160.3918) Metamaterials, (230.6120) Spatial light modulators.

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1. Introduction

The ability to control amplitude and phase of light at will with sub-wavelength spatial resolution would enable applications from dynamic focusing, diffraction and beam steering to video holography and programmable transformation optics. Sub-wavelength spatial control would allow effectively continuous variation of optical properties, avoiding unwanted diffracted beams that necessarily occur in established spatial light modulators based on liquid crystal or digital micromirror technology due to their pixelation on the order of 10 μm [1–3]. While deformable mirror technologies avoid diffraction, they suffer from even lower resolution determined by their typical actuator pitch of hundreds of microns. In this manuscript we define "resolution" as the smallest characteristic distance between points where the optical properties of the spatial light modulator can be independently controlled.

Technologies with the potential to achieve fast dynamic control over light with much higher spatial resolution are now emerging in the field of metamaterials and metasurfaces [4]. Metamaterials are media that obtain enhanced or unusual properties from artificial structuring on the sub-wavelength scale and therefore they do not suffer from unwanted diffraction, however, dynamic control over their optical properties with sub-wavelength resolution remains a challenge. In principle, dynamic control of light by a metamaterial can be achieved by (i) modification of constituent materials based on phase transitions [5, 6] or nonlinearities [7–9], (ii) coherent optical control of the light-matter interaction [10–13] or (iii) mechanical rearrangement of the metamaterial's structure [14–21]. While the spatial resolution of — optically induced — phase transitions, nonlinearities and coherent control can be far greater than that of conventional spatial light modulators, it is still diffraction limited. In contrast, the pixelation of nano-electromechanically actuated metamaterials is determined by nanofabrication technology, rather than light. Recently, nanomembrane technology emerged as a practical solution for such reconfigurable metamaterials [18–21] and similar optomechanical nanostructures [22–25] operating in the optical part of the spectrum: a dielectric membrane of nanoscale thickness (typically silicon nitride) serves as a flexible support for a thin film of plasmonic metal (typically gold) or high index dielectric (such as silicon), which is then structured by reactive ion etching and focused ion beam milling to selectively remove either one or both layers, creating both metamaterial resonators and moving parts. Electrical reconfiguration is most easily achieved by cutting a metal-coated nanomembrane into freestanding parallel nanowires, which may be actuated with microsecond scale response times by electrostatic forces [19], resistive heating or the magnetic Lorentz force [20, 21].

The scope of this paper is to propose a feasible design of a randomly addressable metadevice and to study the optical functionalities it can provide numerically. We propose a metasurface device that modulates the phase of light with sub-wavelength spatial resolution in one dimension. The metadevice consists of an array of plasmonic nanowires of sub-wavelength spacing, which can be actuated individually by electrical signals in order to control the phase of reflected waves and it is feasible based on recent advances in reconfigurable photonic metamaterials [26]. We demonstrate that such a metadevice can perform functionalities of gratings, phase-gradient metasurfaces and curved mirrors on demand and without unwanted diffracted beams that necessarily occur in conventional technology. Thus, this work illustrates the ultimate level of control over light that becomes possible when a metadevice becomes a spatial light modulator with one-dimensional subwavelength pixelation by studying the optical functionalities of a randomly addressable reconfigurable nanowire metamaterial for the first time. In contrast to previous reconfigurable nanowire metamaterials, the proposed device is non-resonant, broadband / wavelength tuneable, provides spatial light modulation in addition to temporal light modulation and manipulates reflected rather than transmitted light.

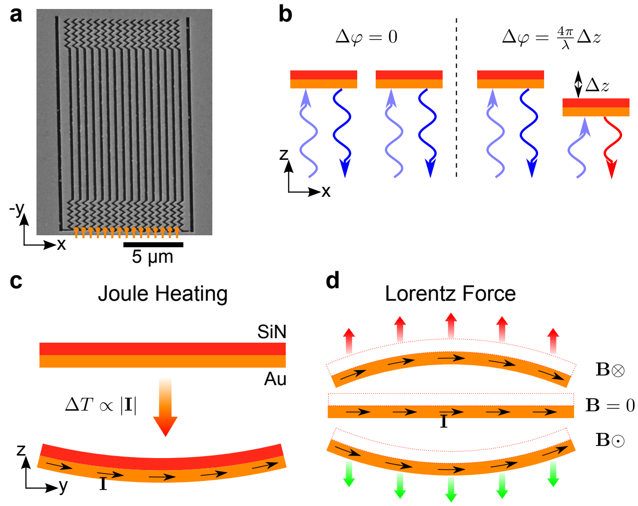

Fig. 1. Phase modulation by nanomechanical actuation. (a) Scanning electron microscope image of freestanding nanowires suitable for thermal and magnetic actuation. The nanowires consist of 50 nm of gold on 50 nm of silicon nitride, their overall length is 20 μm including 3 μm elastic springs at either end and their period is about 600 nm. (b) Out-of-plane nanowire displacement Δz changes the phase of the reflected wave by $\Delta\varphi = \frac{4\pi}{\lambda}\Delta z$. (c) Electrothermal actuation: resistive heating by electrical currents induces nanowire displacement by differential thermal expansion [20]. (d) Magnetic actuation: The magnetic Lorentz force displaces current-carrying wires placed in a magnetic field directed perpendicular to the current flow [21]. Magnetic actuation does not require the silicon nitride layer (red dotted line).

2. Results and Discussion

The nanomembrane device considered here can be made by focused ion beam milling and consists of 32 parallel nanowires of 300 nm width separated by 100 nm gaps, Fig. 1(a) shows a feasibility test with fewer nanowires of slightly larger period. The nanowires are fixed at both ends and consist of a gold layer of 50 nm thickness supported by a silicon nitride layer of the same thickness. One end of each nanowire is connected to a common ground, while the other is connected to one of 32 electrical control channels to allow independent actuation of each nanowire. The nanowires reflect electromagnetic waves that are linearly polarized with the electric field along the wire without polarization change and the phase of the reflected wave is controlled by displacing the nanowire in the direction normal to the device plane. As illustrated by Fig. 1(b), at normal incidence, a nanowire displacement of Δz changes the path of the reflected wave by $-2\Delta z$, resulting in a phase change $\Delta\varphi = \frac{4\pi}{\lambda}\Delta z$. As this is a non-resonant effect, the metadevice operates over the full wavelength range where its nanowire periodicity p_0 is smaller than the wavelength ($\lambda > p_0 = 400$ nm) — which avoids unwanted diffraction — and where the achievable maximum nanowire displacement is at least half a wavelength so that the full range of phases can be accessed ($\lambda \leq 2\Delta z_{\max}$). Therefore, our non-resonant plasmonic structure is a wavelength tuneable metadevice, making it very different from the resonant, and therefore narrow-band, functionalities offered by most metamaterials.

Electrical actuation of the nanowires can be achieved exploiting two mechanisms. As illustrated by Fig. 1(c), resistive heating of a gold/silicon nitride nanowire by an electrical current **I** will bend the nanowire due to differential thermal expansion as the thermal expansion coefficient of gold ($14.2 \times 10^{-6} K^{-1}$) exceeds that of silicon nitride ($2.8 \times 10^{-6} K^{-1}$) by a factor of 5. Neglecting the temperature variation along the wire for simplicity, the resulting nanowire displacement is proportional to $\Delta T \Delta\alpha L^2/t$, where ΔT is the temperature change (proportional to the applied current), $\Delta\alpha$ the difference in thermal expansion coefficients, L the nanowire length and t its thickness [27]. If the nanowire metadevice is placed in a magnetic field $\mathbf{B}$, then it can also be actuated by the magnetic Lorentz force $\mathbf{F} = L\mathbf{I} \times \mathbf{B}$ resulting in displacement of the nanowires of width w that is proportional to $\mathbf{F}L^3/(t^3 w)$. Such magnetic actuation can also be applied to electrically conductive nanowires consisting of a single material and it allows the actuation direction to be inverted by reversing the direction of either current or magnetic field, see Fig. 1(d). Electrothermal displacements of 100s of nm due to application of sub-mA currents to nanowires of 10s of μm length have been reported and similar magnetic displacements have been observed for magnetic fields of 100s of mT [20]. For such structures, electrothermal actuation is limited by the nanowire cooling timescale to 10s of kHz, while mechanical resonances limit magnetic actuation to 100s of kHz [21]. Here we present simulations of on-demand optical functionalities that can be expected from the metadevice.

Grating and mirror functionalities were simulated using finite element modelling (COMSOL Multiphysics 4.4), approximating the device with nanowires that have prescribed displacements and infinite length (Figs. 2-4). In order to minimize computational requirements, the field reflected from the grating structures (that require larger models due to diffracted beams, see Figs. 2 and 4) was extracted at a distance of 2 μm from the metadevice and propagated in free space by the beam propagation method using Matlab [28]. The gold side of the nanowire device is illuminated by a normally incident coherent plane wave of green light (wavelength $\lambda = 550$ nm) that is polarized with the electric field parallel to the wires. Gold and silicon nitride were modelled using electric permittivities of $\varepsilon_{\mathrm{Au}} = -5.8 + i1.6$ and $\varepsilon_{\mathrm{SiN}} = 4.0$, respectively [29]. All simulations presented here consider nanowires consisting of 50 nm of gold supported by 50 nm of silicon nitride. For gold-side illumination as discussed below, we note that simulations of the same nanowire arrangement with and without the silicon nitride layer yield almost identical results.

Grating functionalities result from displacing the nanowires periodically in space, see Fig. 2, where diffraction of order m at an angle θ from the normal is determined by the grating period p_g of the structure following $\sin\theta = m\lambda/p_g$. Thus, without nanowire displacement, the metadevice's period of 400 nm does not allow diffraction of visible light at normal incidence. Equal displacement of every second nanowire results in a diffraction grating of 800 nm period. It can be operated as a beam splitter or grating light valve [30, 31], where a displacement of $\lambda/4$ causes destructive interference of 0^{th} order reflection due to the π phase difference for waves reflected from neighboring nanowires and thus all reflected light is redirected into the 1^{st} diffraction order [panel (a)]. We note that only one of the nanowires at the device edges is displaced as the metadevice has an even number of nanowires, resulting in a small asymmetry that can be seen around $x = 0$. Equal displacement of every third nanowire switches the metadevice to a grating of 1200 nm period, resulting in diffraction up to the 2^{nd} order. Here, mirror-symmetric displacement results in equal intensities of diffraction orders $\pm m$ [panel (b)], while mirror-asymmetric displacement such as a sawtooth configuration corresponds to a blazed grating and allows light to be preferentially diffracted into selected diffraction orders [panel (c)]. A sawtooth configuration can also be used to create a constant phase gradient along the metadevice surface by displacing the nanowires in N steps of $\lambda/(2N)$, corresponding to phase steps of $2\pi/N$ and a phase gradient of $2\pi/(Np_0)$. In the phase-gradient configuration, the metadevice will reflect the incident light into a single 1^{st} diffraction order, for example, for $N = 4$ the phase gradient is $2\pi/(1600\text{ nm})$, resulting in (almost) complete reflection of the normally incident beam at 20° from the surface normal [panel (d)]. Arbitrary phase gradients can be realized by interpolation. In this way, the metadevice can provide anomalous reflection of phase-gradient

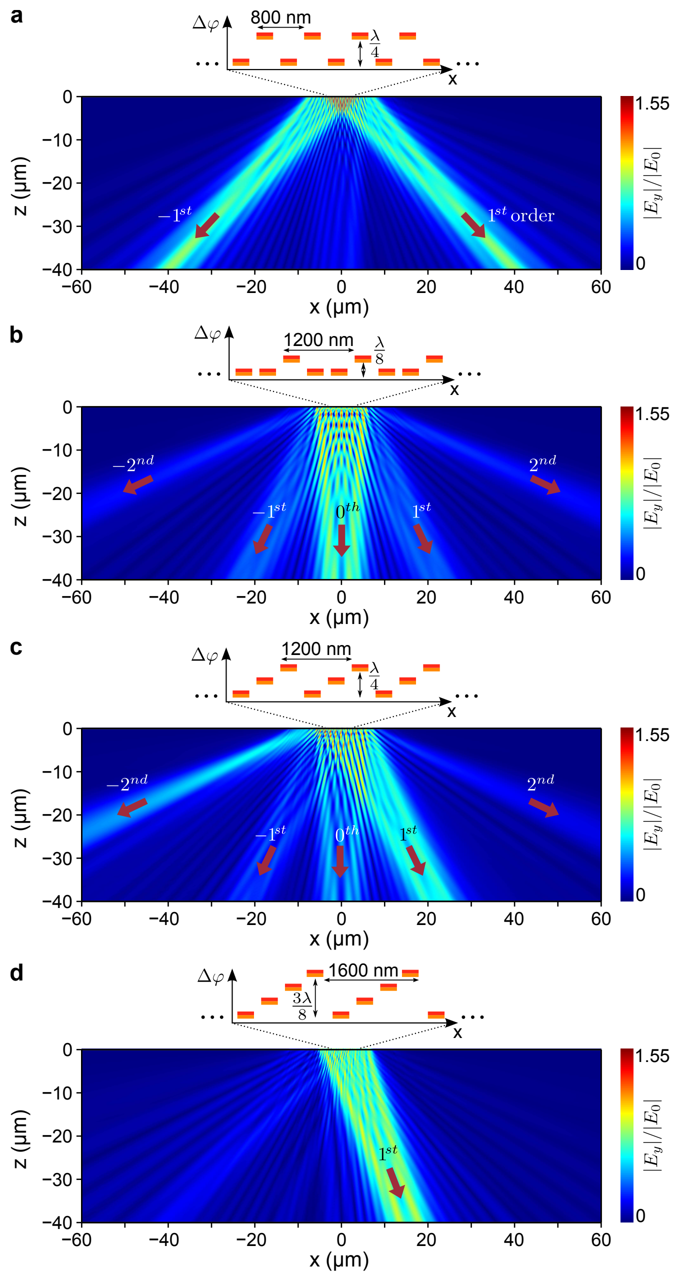

Fig. 2. Reconfigurable gratings are formed by spatially periodic vertical displacement of the nanowires. (a) Grating light valve (beam splitter) of period $p_g = 800$ nm realized by $\lambda/4$ actuation of every second nanowire. (b) Grating of period $p_g = 1200$ nm resulting from $\lambda/8$ displacement of every third nanowire. (c) Blazed grating ($p_g = 1200$ nm) and (d) phase-gradient surface ($p_g = 1600$ nm) based on a sawtooth configuration of the nanowires that are displaced in steps of $\lambda/8$. The magnitude of the only non-zero reflected electric field component $|E_y|$ is shown and the metadevice, that is located at $z = +2$ µm, is illuminated by a y-polarized plane wave of 550 nm wavelength and electric field amplitude $|E_0|$ propagating along the positive z-axis. The diffraction orders are labelled and marked by arrows.

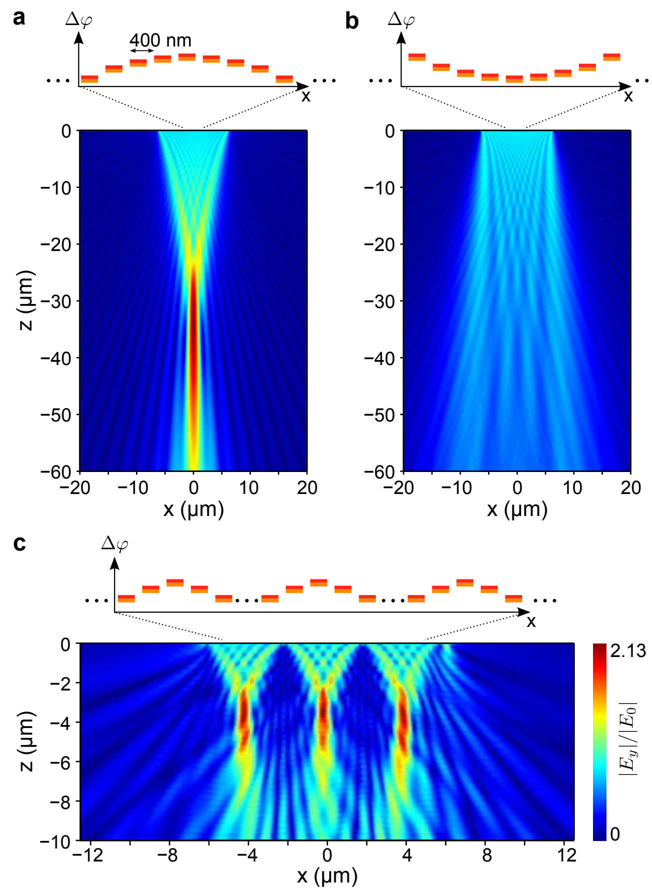

Fig. 3. Reconfigurable mirrors. (a) Focusing and (b) defocusing mirrors with 38.5 μm focal length formed by arranging the nanowires to form concave and convex cylindrical segments, respectively. (c) Multifocal mirror array, where each mirror of 3.3 μm focal length is formed by a concave cylindrical arrangement of 11 nanowires. The maximum nanowire displacement is 250 nm in all cases. The magnitude of the only non-zero reflected electric field component $|E_y|$ is shown and the metadevice, that is located at $z = 0$, is illuminated by a y-polarized plane wave of 550 nm wavelength and electric field amplitude $|E_0|$ propagating along the positive z-axis.

metasurfaces [32–35], but, crucially, the device is electrically controllable allowing on-demand beam steering.

Broadband focusing and defocusing cylindrical mirrors can be realized by displacing the nanowires to approximate a cylindrical segment, where the focal distance corresponds to half of the radius of curvature, see Fig. 3. Concave mirrors focus light [panel (a)], where a focal distance of 38.5 μm results from a maximum nanowire displacement of only 250 nm. A defocusing mirror is realized by a convex nanowire configuration [panel (b)], where the same maximum displacement results in reflection of the incident plane wave as if it originated from an imaginary focal point 38.5 μm behind the metadevice. Independent control of every nanowire can be used to create multifocal devices where the position and numerical aperture of every focus can be set independently, for example, a reflector with 3 focal points consisting of 3 concave cylindrical mirrors formed by 11 nanowires each [panel (c)]. We note that neighboring

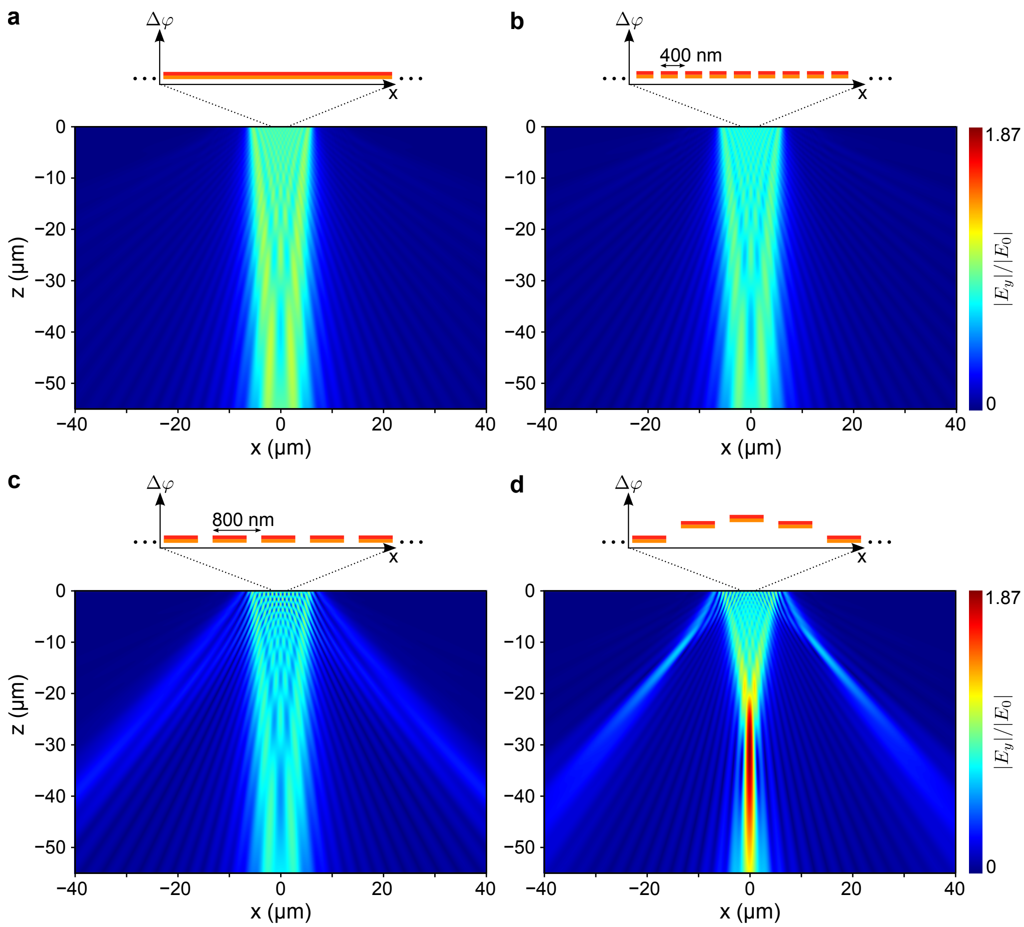

Fig. 4. Metadevices with and without sub-wavelength nanowire actuator pitch. (a) Flat continuous mirror of 12.7 µm width. (b) Flat mirror configuration of the nanowire metadevice with sub-wavelength period of 400 nm and overall width of 12.7 µm. (c) Flat mirror configuration of a coarser metadevice, where the period is doubled to 800 nm. (d) The metadevice with 800 nm periodicity in the same focusing mirror configuration as presented in Fig. 3(a) for the metadevice of period 400 nm. The magnitude of the only non-zero reflected electric field component $|E_y|$ is shown and the structures, that are located at $z = +2$ µm, are illuminated by a y-polarized plane wave of 550 nm wavelength and electric field amplitude $|E_0|$ propagating along the positive z-axis.

concave mirrors have one nanowire in common, leaving an extra nanowire at one edge of the 32-nanowire-metadevice that causes a small asymmetry. Such mirrors are broadband, suitable for illumination wavelengths that are larger than the nanowire periodicity p_0 while being small compared to the size of each individual cylindrical mirror.

In contrast to established spatial light modulators, the proposed metadevice offers sub-wavelength pixelation and Fig. 4 illustrates the importance of this. Without actuation, the metadevice reflects the incident visible light without diffracted beams like a flat mirror [compare panels (a) and (b)]. The microstructure that can be seen in the field distribution originates from diffraction of the incident plane wave on the device edges in the same way as it does for the flat continuous mirror of the same size and it vanishes during propagation to the far field.

In contrast, a coarser structure with a period that is larger than the wavelength of the incident wave will have diffracted beams [panel (c)] and these unwanted beams will be present in any applications [such as focusing, panel (d)], just as they are present in the case of commercial spatial light modulators. As such potentially dangerous stray beams remove intensity from the intended application, their absence in case of our metadevice increases both safety and energy efficiency.

With respect to the realization of a functional device, we demonstrate that the fabrication of a suitable nanowire structure is possible. Indeed, similar metadevices are being developed and individual electrical actuation of several selected nanowires was recently demonstrated [36]. We note that aluminum and silver (with a protective coating to prevent oxidation) may be more suitable alternatives to gold, due to their higher reflectivity in the blue part of the spectrum. Here, we consider gold as both electrothermal and magnetic actuation of gold-based nanowire structures has been demonstrated experimentally [20, 21]. Furthermore, the actuated nanowires will be flat only at their center, but curved towards their ends. Therefore, optical illumination should be limited to the central part of the nanowires in order to ensure a homogeneous optical response. While independent and simultaneous addressing of 32 nanowires remains an engineering challenge, such devices are feasible using existing fabrication techniques, and should be realisable in the near future. All required ingredients are available, the challenge is one of design, optimization and engineering in order to ensure reliable and simultaneous independent actuation of all nanowires.

3. Summary

In summary, we propose a metadevice providing dynamic spatial modulation of optical phase with sub-wavelength pixelation in one dimension. We show that the realization of such a device is feasible and demonstrate based on numerical modelling that it can focus and redirect light by providing optical functionalities of various types of gratings, beam splitters, phase-gradient surfaces and curved mirrors on demand. In contrast to existing spatial light modulator technologies, our proposed device does not create unwanted diffracted beams, making it safer and more optically efficient than current solutions in addition to allowing higher resolution modulation.

Acknowledgments

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