Abstract Dielectric metasurfaces are two-dimensional structures composed of nano-scatterers that manipulate the phase and polarization of optical waves with subwavelength spatial resolution, thus enabling ultra-thin components for free-space optics. While high performance devices with various functionalities, including some that are difficult to achieve using conventional optical setups have been shown, most demonstrated components have fixed parameters. Here, we demonstrate highly tunable dielectric metasurface devices based on subwavelength thick silicon nano-posts encapsulated in a thin transparent elastic polymer. As proof of concept, we demonstrate a metasurface microlens operating at 915 nm, with focal distance tuning from 600 μm to 1400 μm (over 952 diopters change in optical power) through radial strain, while maintaining a diffraction limited focus and a focusing efficiency above 50%. The demonstrated tunable metasurface concept is highly versatile for developing ultra-slim, multi-functional and tunable optical devices with widespread applications ranging from consumer electronics to medical devices and optical communications.

Highly tunable elastic dielectric metasurface lenses

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1. Introduction

Metasurfaces are composed of a large number of discrete nano-scatterers (meta-atoms) that locally modify phase and polarization of light with subwavelength spatial resolution [1–15]. The meta-atoms can be defined lithographically, thus providing a way to mass-produce thin optical elements [1, 3–6] that could directly replace traditional bulk optical components or provide novel functionalities [6, 16]. The two dimensional nature and the subwavelength thickness of metasurfaces make them suitable for tunable and reconfigurable optical elements. Recent examples include frequency response tuning using substrate deformation [17, 18], refractive index tuning via thermo-optic effects [19,20], phase change materials [21,22], and electrically driven carrier accumulation [23, 24].

Stretchable substrates have also been used to demonstrate tunable diffractive and plasmonic metasurface components [25–28], but they suffer from limited efficiency and polarization dependent operation [28]. Here we present mechanically tunable dielectric metasurfaces based on elastic substrates, simultaneously enabling a large tuning range, polarization independent operation, and high transmission. As a proof of principle, we experimentally demonstrate a microlens with over 130% focal distance tuning (from 600 μm to 1400 μm) while keeping high efficiency and diffraction limited focusing.

2. Theory

Figure 1a shows a schematic of a metasurface microlens encapsulated in an elastic substrate with radius $r$ and focal distance $f$. The paraxial phase profile of the lens has the following form [29], and is drawn in Fig. 1c (solid blue curve):

$$ \phi(\rho, \lambda) \approx \frac{\pi \rho^2}{\lambda f}, $$

where $\rho$ is the distance to the center of the lens and $\lambda$ is the working wavelength.

Uniformly stretching the substrate with a stretch ratio of $1 + \varepsilon$, and assuming that the local phase transformation does not depend on the substrate deformation, the phase initially applied at radius $\rho$ is now applied at radius $\rho (1 + \varepsilon)$; therefore, the under strain phase profile becomes $\phi'(\rho, \lambda) = \pi \rho^2 / (\lambda (1 + \varepsilon)^2 f)$ (shown in Fig. 1c, solid red curve). This indicates that stretching the elastic metasurface microlens with stretching ratio of $1 + \varepsilon$ scales its focal length by a factor of $(1 + \varepsilon)^2$, as shown schematically in Fig. 1b.

For implementation, we used a metasurface platform based on high refractive index dielectric meta-atoms placed on a subwavelength periodic lattice in a low index medium. The building blocks of the metasurface are amorphous

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silicon (a-Si) square cross-section nano-posts on a thin layer of aluminum oxide encapsulated in Polydimethylsiloxane (PDMS) as a low index elastic membrane (Fig. 2a, inset).

A key characteristic of this platform differentiating it from Huygens’ metasurfaces [12–14,18], is the weak optical coupling between the nano-posts, which simplifies the metasurface design by allowing local sampling of the phase profile using different widths for the nano-posts placed on the vertices of a square lattice. This weak coupling is due to the high index contrast between the nano-posts and their surrounding medium, and is manifested in the high localization of energy density inside the nano-posts [16, 30]. An important consequence of the weak coupling is that the phase transformation mainly depends on the nano-posts width and not on the distance between them, leading to the same local phase shift almost independent of the stretch factors of the substrate. Figures 2b and 2c show the simulated transmittance and phase of the transmission coefficient for a periodic square lattice of encapsulated nano-posts in PDMS with strain values from 0% to 50%. The nano-posts are assumed to be 690 nm tall, and the lattice constant at 0% strain is 380 nm. Nano-posts height must be chosen such that the whole 0 to 2\(\pi\) phase range is covered at all strains of interest by changing the nano-posts width, while keeping high transmission values. The lattice constant should be selected such that the lattice is subwavelength and satisfies the Nyquist sampling criterion simultaneously for all strain values (Supplementary Note 1 and Fig. S1 in Supplementary Materials). The simulation results are obtained assuming normal incidence at the wavelength of 915 nm (see Methods for simulation details). The weak dependence of the transmission of the nano-post array on different strain values, which can be seen in Figs. 2b and 2c, is another evidence for the weak coupling between the nano-posts.

Since the transmission coefficient is almost independent of the strain, we can design the metasurface at one specific strain. Figure 2d shows the intensity and phase of the transmission coefficient at the middle strain value (\(\epsilon = 25\%\)) as a function of the nano-post width, that is used for designing the tunable metasurface. Considering the desired phase profile \(\phi(\rho)\) at 25%, the corresponding nano-post width at each lattice site was found by minimizing the transmission error \(\Delta T = |e^{i\phi} - |t|e^{i\angle t}|\), where \(t\) is the complex transmission coefficient. An aspheric phase profile is assumed as the desired phase profile. Minimizing \(\Delta T\) at each lattice site results in selecting the nano-post with the closest complex transmission value to the desired one (\(e^{i\phi}\)) and automatically excludes the two high quality factor resonances observed in Fig. 2d around 171 nm and 214 nm nano-post widths. The nano-posts can be considered as truncated
square cross-section waveguides with multiple low quality factor Fabry-Perot resonant modes. These multiple resonances are excited and contribute to the scattered field with various strengths [16]. In addition, the high quality factor resonances observed in Fig. 2d are formed because of the extended lattice modes of the periodic arrangement of the nano-posts. Total transmission of the nano-posts array is determined by the superposition of the scattered fields of these resonant modes and the incident light, which results in high transmittance and a full 2π range for the phase shift of the transmission coefficient [16].

Using the proposed platform, a tunable metasurface microlens is designed to operate at the wavelength of 915 nm. The microlens has a diameter of 200 μm under no strain, and its focal distance changes from 600 μm to more than 1400 μm (optical power from 1667 to 714 diopters) when the strain value varies from 0% to 53%.

3. Methods

3.1. Design procedure

To find the transmittance and phase values (Fig. 2b-d), a periodic array of square nano-posts on a square lattice was simulated at 915 nm with a normally incident plane wave using rigorous coupled wave analysis (RCWA) [31]. Reflective indices of 3.56 and 1.41 were used for a-Si and PDMS. The lattice constant was chosen to be 380 nm at 0% strain and linearly scaled with the stretch ratio. It was chosen such that the array remains non-diffractive with enough sampling unit cells for reconstructing the wavefield at all the strain values of interest (Supplementary Note 1 in Supplementary Materials). The metasurface microlens was designed for the middle strain (25% strain), for which the lattice constant is 475 nm. The lattice constant was then scaled down to 380 nm for device fabrication.

3.2. Simulation

The intensity distributions shown in Supplementary Materials (Figs. S2 and S3) were found by modeling the microlens as a phase mask. The transmission coefficient of the phase mask was calculated through interpolation of the complex transmission coefficients of the nano-posts. The effect of the strain was considered in both the position and the transmission coefficient of the nano-posts. A plane wave was used to illuminate the phase mask. The fields after the phase mask were propagated through the top PDMS layer (~50 μm thick at zero strain) and air to the focal plane and beyond using plane wave expansion technique. For efficiency calculations, a Gaussian beam with more than 99% of its power inside the device was used. The Gaussian beam radius was linearly scaled with the stretch ratio. Intensity profiles in the focal plane for different strain values were found using the same plane wave expansion technique. The focusing efficiencies were calculated by dividing the power passing through a disk around the focal point to the total incident power. The diameter of the disk for each strain value was set to be ~3 times the analytical full width at half maximum (FWHM). In order to verify the accuracy of the described simulation method, a four times smaller version of the actual device (50 μm diameter, 150 μm focal distance in relaxed state) with the same NA was simulated at different strain values (0% to 50% with 10% steps) using the 3D finite difference time domain method [32]. Intensity distributions and the focusing efficiencies were in good agreements with the described simulation method based on the plane wave expansion technique.

3.3. Sample fabrication

Figure 3a schematically illustrates the key steps in fabricating a metasurface encapsulated in a thin elastic membrane. A germanium sacrificial layer (~300 nm) was evaporated on a silicon wafer, followed by a 690-nm-thick hydrocarbon PECVD (plasma enhanced chemical vapor deposition) a-Si layer (5% mixture of silane in argon at 200 °C). The refractive index of the a-Si layer was found to be 3.56 at the wavelength of 915 nm, using variable angle spectroscopic ellipsometry. A Vistec EBPG5000+ e-beam lithography system was used to define the pattern in ZEP-520A positive resist (~300 nm, spin coated at 5000 rpm for 1 min). A resist developer (ZED-N50 from Zeon Chemicals) was used to develop the pattern for 3 minutes. A ~100-nm-thick aluminum oxide layer was deposited on the sample by e-beam evaporation. The pattern was then transferred into aluminum oxide by lifting off the resist. The patterned aluminum oxide hard mask was used for dry etching the a-Si layer in a mixture of SF6 and C4F8 plasma (Fig. 3a, (i)). The PDMS (10:1 mixing ratio of Sylgard 184 base and curing agent) was diluted to toluene in a 2:3 weight ratio as a thinner. The diluted PDMS mixture was spin coated (at 3000 rpm for 1 min) on the fabricated metasurface to fill the gaps between the nano-posts and to form a thin PDMS film. The sample was then degassed and cured at 80 °C for more than 30 mins. The second layer of PDMS without a thinner (~50 μm, spin coated at 1000 rpm for 1 min) was likewise degassed and cured at 80 °C for more than 1 hr (Fig. 3a, (ii)). The sample was then immersed in a 1:1:30 mixture of ammonium hydroxide, hydrogen peroxide, and DI water at room temperature to remove the sacrificial germanium layer and release the embedded nano-posts in the PDMS substrate (Fig. 3a, (iii)). Another layer of PDMS without a thinner was then spin coated on the microlens side of the sample (at 1000 rpm for 1 min) to fully encapsulate the nano-posts in PDMS (Fig. 3a, (iv)). The sample was again degassed and cured at 80 °C for more than 1 hr. The total PDMS thickness was ~100 μm. Encapsulation of nano-posts in PDMS is a crucial step in preserving the metasurface shape and minimizing defects when the device is highly strained (see Fig. S4 in Supplementary Materials). A scanning electron micrograph of the nano-posts on germanium layer before spin coating the first PDMS.
Figure 3 Overview of the fabrication steps and images of the device at different steps. (a) Major steps involved in fabricating tunable metasurfaces: (i) a-Si nano-posts are patterned and dry etched using an aluminum oxide hard mask. The nano-posts rest on a germanium sacrificial layer on a silicon wafer. (ii) PDMS is spin coated on the metasurface structure. (iii) The sacrificial germanium layer is dissolved to release the nano-posts which are now embedded in the flexible and stretchable PDMS layer. (iv) A second PDMS layer is spin coated on the side containing the metasurface to provide a fully encapsulated microlens. (b) Scanning electron micrograph of the nano-posts before spin coating the first PDMS layer (step (i)). (c) Scanning electron micrograph of the nano-posts embedded in PDMS (step (iii)), taken at a tilt angle of 30 degrees. To dissipate the electric charge accumulated during scanning electron microscopy, a ~20-nm-thick gold layer was deposited on the sample prior to imaging. Small holes observed around the nano-posts are in the deposited gold layer. a-Si: amorphous silicon, PDMS: Polydimethylsiloxane.

layer is shown in Fig. 3b. The nano-post transfer process has a near unity yield in retaining almost all the nano-posts at their positions [16]. Void-free filling of the gaps between the nano-posts was confirmed by inspecting nano-posts embedded in PDMS before spin coating the PDMS cladding (Fig. 3c). To compensate for systematic fabrication errors, an array of devices with all the nano-post widths biased uniformly in steps of 3 nm was fabricated (Fig. 4b).

3.4. Measurement procedure

The device was measured using the setup shown schematically in Fig. 4a. A 915-nm fiber-coupled semiconductor laser was used for illumination and a fiber collimation package (Thorlabs F220APC-780) used to collimate the incident beam. A 50X objective lens (Olympus LMPanFL N, NA=0.5) and a tube lens (Thorlabs LB1945-B) with a focal distance of 20 cm were used to image intensity at different planes to a camera (CoolSNAP K4 from Photometrics). To adjust the light intensity and decrease the background noise captured by the camera, neutral density (ND) filters (Thorlabs ND filters, B coated) were used. A calibration sample with known feature sizes was also imaged with the setup to find the overall magnification. The sample was first mounted on a glass substrate, for characterization under no strain. The device with highest focusing efficiency (lowest systematic fabrication error) was found under no strain, because the current measurement setup does not enable translational movement of devices under strain. Then, for measurements under strain, it was manually clamped between two machined Teflon rings, such that the microlens of interest was stretched radially. To measure the focusing efficiencies under a specific strain, an additional lens with a focal length of 10 cm (Thorlabs LB1676-B) was used to partially focus the collimated beam. The beam radius was changed by adjusting the relative distance between the lens and the device under the test, such that more than 99% of the beam power falls inside the device under the test. A pinhole with a diameter ~3 times the measured FWHM was placed in the focal plane of the microlens to only let the light inside the pinhole pass through. This value is chosen because assuming a Gaussian beam profile, more than 99% of the beam power falls inside a pinhole with a diameter ~3 times the FWHM. The pinhole was fabricated by evaporating a thick layer of chrome on a fused silica substrate, and defining holes in it by wet etching. A power meter (Thorlabs PM100D) with a photodetector (Thorlabs S122C) was used to measure efficiencies at 915 nm. The focusing efficiency was calculated as the ratio of the power in focus (measured optical power after the pinhole) to the incident power (measured power before the sample). The focusing efficiency at 15% strain was measured in this manner. Focusing efficiencies at other strains were calculated relative to the focusing efficiency at 15% strain in the following manner: first, light intensity captured with the camera in the plane of focus was integrated inside a circle with a diameter ~3 times of the measured FWHM at each strain value including the 15% strain. Then, the integrated power for each strain was divided by the integrated power at 15% strain. Moreover, the ratio of the input power at 15% strain to the input power at other strains was calculated (the input power of the beam hitting the device increases as the device area increases). The focusing efficiency at other strains was then found by multiplying these two normalization factors by the directly measured efficiency at 15% strain. The measurement setup used for the efficiency characterization is shown in Supplementary Materials (Fig. S5).
4. Characterization of tunable metasurfaces

For characterization of the fabricated tunable metasurface microlens, a custom built microscope was used to image the transmitted light intensity at different distances from the metasurface (Fig. 4a). First, the sample was mounted on a flat glass substrate and was characterized in the relaxed mode, and then it was clamped between two Teflon rings. A radial force was applied by pushing another Teflon tube from the backside and stretching the metasurface (see Fig. S6 in Supplementary Materials). An array of microlenses mounted between the rings and under \( \sim 30\% \) strain is shown in Fig. 4b. (see Methods for measurement details). Measured optical intensities in the axial plane (Fig. 4c, left) and the focal plane (Fig. 4c, right) at 6 different strain values (0% to 50%) show a large focal distance tunability while keeping a nearly diffraction limited focus at all strains. For comparison, and to investigate the effect of the weak dependence of the transmission coefficients on the lattice size, the performance of the metasurface at different strains is simulated in two different cases. First, we use the actual intensity and phase of the transmission coefficients shown in Figs. 2b and 2c, which take into account the effect of lattice constant changing with strain (see Methods for simulation details and Supplementary Fig. S2 for results). Second, neglecting the strain dependence, we use the transmission coefficients calculated at 25% strain (plotted in Fig. 2d), for all strain values. Simulated intensity profiles for this case are plotted in Supplementary Fig. S3. In both cases, the simulated intensity profiles and the corresponding focal distances and FWHMs are in good agreement with their measured counterparts. This confirms that the weak dependence on lattice constant does not affect the functionality and the diffraction limited performance of the device. Figure 4d shows a good agreement between the measured and the analytically predicted focal distances, which are plotted versus \((1 + \epsilon)^2\). Measured FWHM of the focal spots for different strains and their corresponding diffraction limited values are shown in Fig. 4e as a function of the numerical aperture (NA) of the microlens. The results show nearly diffraction limited operation of the microlens under strain values up to above 50%. As expected, NA decreases and the focal spot enlarges as strain is increased.

Focusing efficiency is defined as the ratio of the optical power focused by the device to the incident power, and is measured and plotted in Fig. 4f for various strains (see Methods for measurement details). The measured 75% focusing efficiency in the relaxed state, shows the high optical quality of the device. The efficiency decreases gradually
with increasing the strain; however, it remains above 50% for strain values up to 50%. To further understand the effect of the weak dependence of the transmission coefficients on the lattice strain, focusing efficiencies are calculated in two different cases considering and neglecting this dependence. In the first case, we have used the actual transmission coefficients for each strain value (plotted in Figs. 2b and 2c), and in the second case we have used the transmission coefficients calculated at 25% strain (Fig. 2d). These two simulated focusing efficiencies are plotted in Fig. 4f along with the measured values. It is observed that the small dependence of the transmission coefficients on strain results in a reduction of the focusing efficiency at strains other than the design value. At small strains, the measured focusing efficiencies agree well with their simulated values, but the measured efficiencies are lower at large strain values. We attribute the lower measured efficiency to possible mechanical deformations and misalignments of the nano-posts under strain, and the non-uniformity of the strain across the microlens. In addition, device characterizations were performed on the lens with the highest efficiency at 0% strain among the fabricated set (several lenses with all nano-post widths biased at different values were fabricated in order to compensate for the systematic fabrication errors, see Methods for details). Therefore, the measured focusing efficiencies in the relaxed state and at small strains could be higher than the simulated values for the lens designed for optimal performance at 25% strain. Also, the measured values are lower than the simulated focusing efficiencies obtained using ideal strain-independent transmission coefficients (Fig. 4f).

The reliability of the tuning process was tested by measuring the focal spot and focusing efficiency of the tunable metasurface microlens after multiple straining cycles. No changes in the focusing efficiency and focal spot shape of the microlens was observed after more than 10 cycles of stretching and releasing the device (see Fig. S7 in Supplementary Materials).

The demonstrated metasurface lenses are transmissive over a broad wavelength range (see Fig. S8 for simulated transmittance and reflection spectra). Although they suffer from chromatic aberrations similar to the other diffractive meta-lenses on rigid substrates [30, 33], multiwavelength tunable operation can readily be achieved by combining the current platform with the multiwavelength metasurface concept [33–36].

5. Conclusion

In conclusion, we demonstrated highly tunable dielectric metasurfaces based on elastic substrates. As proof of concept, a microlens with more than 952 diopters change in optical power was demonstrated. The proposed platform can be applied to other devices based on metasurfaces thus adding tunability over a thin layer without increasing the complexity of the system. For instance, it can be integrated with the recently demonstrated lithographically staked metasurfaces for correcting large angle aberrations [37] to enable ultra-compact wide field adjustable NA tunable objectives. Tunable metasurfaces can also be fabricated on high speed electrically tunable elastomers in order to decrease their response time to less than a millisecond [38]. Moreover, integration of the proposed platform with flexible and wearable electronics [39] can also lead to versatile tunable optoelectronic technologies.

Supporting Information

Additional supporting information may be found in the online version of this article at the publisher's website.

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