Multilayer Noninteracting Dielectric Metasurfaces for Multiwavelength Metaoptics

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Supporting Information

ABSTRACT: Metasurfaces provide a versatile platform for manipulating the wavefront of light using planar nanostructured surfaces. Transmissive metasurfaces, with full 2π phase control, are a particularly attractive platform for replacing conventional optical elements due to their small footprint and broad functionality. However, the operational bandwidth of metasurfaces has been a critical limitation and is directly connected to either their resonant response or the diffractive dispersion of their lattice. While multiwavelength and continuous band operation have been demonstrated, the elements suffer from either low efficiency, reduced imaging quality, or limited element size. Here, we propose a platform that provides for multiwavelength operation by employing tightly spaced multilayer dielectric metasurfaces. As a proof of concept, we demonstrate a multiwavelength metalens doublet (NA = 0.42) with focusing efficiencies of 38% and 52% at wavelengths of 1180 and 1680 nm, respectively. We further show how this approach can be extended to three-wavelength metalenses as well as a spectral splitter. This approach could find applications in fluorescent microscopy, digital imaging, and color routing.

KEYWORDS: Multiwavelength metalens, polarization-insensitive, metasurface doublet, spectrum splitter

Optical metasurfaces, based on the resonant response of nanoantennas, have shown unprecedented flexibility to manipulate the wavefront of light, leading to the demonstration of numerous ultrathin optical elements, such as beam deflectors,1–3 holograms,4–7 Huygens’ surfaces,8–11 conformal optics,12 and lenses.13–17 Metasurfaces also provide the ability to create polarization18–21 and angle of incidence22 selective elements. However, chromatic aberration remains an intrinsic issue in resonance-based optical elements, making it challenging to create multiwavelength or achromatic metalenses, full-color holograms, and spectrally multiplexed metadevices. Researchers have demonstrated that the use of a reflective backplane23,24 or strongly resonant scatterers25,26 allows management of dispersion for achieving achromatic performance over limited bandwidths. However, these approaches are only applicable for relatively small phase delay (i.e., small lens diameter or low numerical aperture) due to the trade-off between achieving large dispersion, using resonances, and maintaining linear phase dispersion over a broadband.

Multiwavelength transmissive metadevices, while not ideal for broadband imaging systems, have many applications in fluorescent microscopy27 and digital displays, such as virtual reality headsets, and computer vision. One common approach to achieve multiwavelength operation is to spatially multiplex resonators on the same substrate, by either engineering multiple closely spaced resonators together using a super-cell,28–30 or interleaving lattices operating separately at each target wavelength.31–34 However, these methods have issues with cross-talk between meta-atoms and space filling limitations, leading to reduced efficiency, degraded holographic image quality, and unwanted diffractive orders. Ultimately, due to the limited engineering space using a single resonator layer, it is necessary to obtain an additional degree of freedom in the third dimension if one wants to design efficient elements for multiple wavelengths.

In this work, we demonstrate independent phase modulation at multiple wavelengths by closely stacking dielectric metasurfaces. This use of multilayer metasurfaces allows the realization of multiwavelength metadevices with an improved efficiency. As a proof of concept, we designed and demonstrated two and three-wavelength metalenses. A schematic of a metalens doublet along with its phase distribution is shown in Figure 1a. The phase response from...
each layer, added together, provides the required hyperbolic phase profile at two different wavelengths. The approach results in light passing through multiple resonator layers, which also relaxes the requirement to achieve 2π phase shift using a single resonator. In addition, the geometry of each layer is independent providing extra design space for achieving multiwavelength operation, avoiding the issues of coupling and reduced sampling resolution when using a single layer of resonators. By the same principle, a three-wavelength metalens can be designed by a metasurface triplet (Figure 1b). Multilayer metasurfaces have recently been investigated using vertically stacked plasmonic binary zone plates.36 However, the use of plasmonic resonators results in low efficiency, and multilayer lithography is generally not compatible with high index dielectrics, which often must be grown on a substrate. In past work on dielectric metasurface doublets designed for wide-angle corrected lenses and retroreflectors,37 the metasurfaces are separated as far as hundreds of microns. This large separation negates many of the advantages of using an ultrathin lens and causes many design and performance limitations for multiwavelength lenses and phase plates, as we show in this paper. Here, we develop techniques for realizing dielectric metasurfaces that are tightly spaced, allowing the utilization of ultrathin planar multiwavelength metadevices for a wide range of optical diameters.

The metasurfaces demonstrated here are based on Si nanoposts with a high aspect ratio. The Si nanoposts, which can be modeled as truncated waveguides supporting Fabry–Perot resonances, are an ideal candidate for transmissive phase plates due to their high efficiency, localized resonances, and low angle of incidence sensitivity.36 Figure 2a shows a schematic of the Si nanopost unit cell embedded in a layer of polydimethylsiloxane (PDMS), where the nanopost height is set to be 750 nm with a period of 600 nm. As a proof of principle, target wavelengths of 1180 and 1680 nm were selected for designing a two-wavelength doublet metalens. The transmission and phase distributions at both wavelengths (Figure 2b,c) were first simulated as a function of nanopost radius. At each wavelength, nanoposts that sit in transmission dips are excluded from the design database. Figure 2d shows the schematic of the vertically stacked nanoposts embedded in PDMS. The resonators are designed to be closely spaced in the z-direction to minimize the effect of wavefront divergence after the first layer, but far enough to avoid coupling (Figure S1). Apart from the layer-to-layer separation, the fidelity of phase transfer from the first layer to the second also depends on the in-plane phase distribution. Abrupt in-plane phase variation leads to a greater wavefront divergence and deviation from a linear combination of the two layers’ phase distribution. To combat this issue, the lenses were designed with an appropriate numerical aperture so that each zone contains multiple nanoposts with the same size and phase delay. As a result, the transmission coefficient $t_1$ after the first layer is directly treated as the incident field to the second layer with the transmission coefficient $t_2$. The overall phase and transmission were calculated as the sum of the phase response ($\Delta \phi_{1} + \Delta \phi_{2}$) and product of the transmission ($t_1 t_2^* \text{t}$) from each layer. To obtain additional degrees of freedom for multiwavelength control, nanopost radii at each layer ($r_1$ on layer one and $r_2$ on layer two) were varied independently. The calculated transmission, considering all possible pairs of radii ($r_1, r_2$), are plotted at 1180 nm (Figure 2e) and 1680 nm (Figure 2g) and demonstrate that high transmission can be obtained over a wide range of design parameters. Figure 2f,h shows the calculated phase at the two wavelengths (1180 in Figure 2f and 1680 in Figure 2h). Note that the phase distributions are distinct at 1180 and 1680 nm and there are multiple choices of ($r_1, r_2$) available to provide the same phase change at one
wavelength but allowing for arbitrary phase modulation at the other wavelength, providing extra engineering space for multiwavelength operation. The design graphs of the structural parameters for achieving all possible phase combinations at the two wavelengths are provided in Figure S2. The radii of nanoposts on each layer are selected such that the required hyperbolic phase is achieved for both wavelengths (Figure S3). Details of optimization functions are presented in the Supporting Information.

To validate this approach experimentally, we first designed and fabricated a metalens doublet with a 500 μm diameter and a focal length of 540 μm, leading to a numerical aperture of 0.42. The fabrication involves semiconductor nanofabrication and material transfer techniques with the key steps of the processes summarized in Figure 3a. The first metalens was prepared using a 750 nm thick amorphous silicon (a-Si) layer grown by plasma-enhanced chemical vapor deposition (PECVD) on fused silica. The metalens along with alignment marks was defined using electron beam lithography and reactive ion etching (RIE). A thin layer of diluted PDMS was then spin coated to encapsulate the nanoposts and to form a thin spacer layer that allows close stacking of the second layer (Figure 3a, i). The second substrate was prepared by first depositing a 300 nm layer of germanium (Ge) on a Si handle wafer followed by 750 nm of a-Si growth on Ge via PECVD. The Si metalens was fabricated using the same procedures as the first, followed by embedding the lens in a thick layer (~50 μm) of PDMS using spin coating. The embedded nanoposts were released from the substrate by dissolving the Ge sacrificial layer (Figure 3a, ii). The transferred layer was then flipped.

Figure 2. Metasurface building blocks and transmissive properties. (a) A schematic of a metalens building block made of an amorphous Si nanopost with a height $h = 750$ nm. The nanopost is embedded in a PDMS layer and arranged in a square lattice with a period $P = 600$ nm. (b, c) The calculated transmission and phase variations as a function of post radii at the wavelengths of 1180 nm (b) and 1680 nm (c). The radii that sit in transmission dips (highlighted by gray stripes) are excluded from the design database. (d) A schematic of a metasurface doublet unit cell. The radii $(r_1, r_2)$ at each layer were varied independently. The overall transmission and phase were calculated as the product of transmission $(|t_1t_2|^2)$ and sum of phase $(\angle t_1 + \angle t_2)$ from two layers, respectively. (e, f, g, h) The calculated overall transmission and phase for the metasurface doublet as a function of $(r_1, r_2)$ at wavelengths of 1180 nm (e, g) and 1680 nm (g, h).
over with the rod side facing the first layer, aligned using a 2D material transfer stage, and bonded by heating and curing the PDMS (Figure 3a,iii) (See the details of fabrication and alignment in Figure S4.) A scanning electron microscope (SEM) image of the Si nanoposts before PDMS spin coating. Scale bar: 300 nm. (c) An optical microscope image of the aligned metalens doublet. Scale bar: 100 μm. (d) An optical microscope (20× objective) image of the alignment marks from the two layers along with a schematic of cross section. Scale bar: 30 μm. (e) Simulated axial intensity profiles of the metalens doublet under the misalignment of δ = 1 and 3 and 6 μm at the two wavelengths.

The fabricated metalens doublet was characterized by illuminating the optic using a collimated and unpolarized supercontinuum laser, which was passed through a monochromator. (See the details of the optical systems in Methods and Figure S5.) To evaluate the performance of the metalens doublet, the full-wave simulations were carried out using a 3D finite difference time domain (FDTD) solver (MEEP).39 Due to limited computational resources, a lens with a diameter of 100 μm with 5 μm layer spacing and a numerical aperture of 0.42 was used in the simulation. (See the details of simulation in the Supporting Information.) The resulting focal spot profiles are presented in Figure 4a, indicating diffraction limited full-width at half-maximums (fwhms) of 1.43 and 2.05 μm at 1180 and 1680 nm, respectively. Figure 4b shows the measured focal spot profiles at 1180 and 1680 nm, and the

![Fabrication of metalens doublet and effect of misalignment.](image_url)
Figure 4. Optical characterization and imaging using the metasurface doublet. Simulated (a) and measured (b) focal spot profiles at the wavelengths of 1180 and 1680 nm. Scale bar: 3 μm. Simulated (c) and measured (d) axial intensity distributions. (e) Simulated focusing efficiency of the metalens doublet (diameter = 100 μm, NA = 0.42) as a function of layer spacing. (f) Simulated focusing efficiency as a function of numerical aperture. The diameter of the lens is 100 μm with 5 μm layer spacing. (g, h) Imaging results of the 1951 United State Air Force (USAF) test chart with the metalens doublet at the wavelengths of 1180 nm (g) and 1680 nm (h). The scale bars in the left column are 20 μm and 10 μm in the right column.
The fwhms are 1.74 and 2.57 μm at 1180 and 1680 nm, respectively. Figure 4c,d shows the simulated (Figure 4c) and measured (Figure 4d) axial intensity distributions along the propagation (z) direction, illustrating the same focal distance and diffraction limited focusing for the three wavelengths. Scale bar: 2 μm. (c) A schematic of a wavelength splitter using a metasurface doublet. The device is designed to focus three wavelengths (1180, 1400, and 1680 nm) separated by 100 μm on the same focal plane (600 μm). (d) An optical image of the spectral splitter. Scale bar: 100 μm. (e) Measured intensity distributions and focal spot profiles at the three wavelengths. Scale bar: 20 μm.

The focusing efficiency is defined as the ratio between the transmitted power passing through a circular aperture at the focal plane and the total incident power on the lens.13,14 The focusing efficiencies were calculated to be 48% at 1180 nm and 56% at 1680 nm, while the fabricated lenses had measured efficiencies of 38% and 52% at 1180 and 1680 nm, respectively. (See the details of the measurement setup in Methods and Figure S5a). This can be compared with previous multi-
wavelength metalenses, which employ spatial multiplexing\textsuperscript{30,33} and suffer from either distorted focal spot profiles or low efficiencies, limiting their overall optical performance. However, the efficiency of our lenses remains lower than a singlet metalens\textsuperscript{11} (>80% with NA = 0.42) primarily due to our design strategy that assumes the overall phase delay is a simple sum of the phase at each lens. This strategy neglects wavefront divergence after the first layer, trading efficiency for lower computational overhead. Higher efficiencies can be achieved through smaller lens spacing, reducing the role of beam divergence between the layers, which is illustrated in Figure 4e. Our design strategy precludes the use of doublets with a macroscopic layer separation,\textsuperscript{36–38} as has been demonstrated in the past. The focusing efficiencies are also expected to be higher for lenses with a smaller numerical aperture, which is verified by examining the efficiency of a 100 μm lens with a 5 μm layer spacing as a function of numerical aperture (see Figure 4f). These issues could potentially be overcome by employing a more efficient design strategy, such as an optimization routine,\textsuperscript{40,41} where the layers are designed together.

To demonstrate imaging quality, the metalens doublet was used to image a standard 1951 United State Air Force (USAF) test chart (Thorlabs Inc.). The metalens was paired with a tube lens and positioned at a test chart (Thorlabs Inc.). The metalens was paired with a tube lens and positioned at a test chart (Thorlabs Inc.). Images at 1180 and 1680 nm are shown in Figure 4g,h, respectively. Images of group 6 and group 7 with line widths of 7.81 and 3.91 μm, respectively, are clearly resolved at both wavelengths. The slightly larger blur at 1180 nm can be attributed to a ghost image caused by the back reflection from lens surface, along with the secondary focal spot.

This approach can be extended by adding a third layer to form a metasurface triplet. As a proof of concept, a metalens triplet with a diameter of 120 μm and focal length of 200 μm (NA = 0.29) was designed at wavelengths of 1180, 1400, and 1680 nm. Figure 5b shows the FDTD simulation of the axial intensity distribution and focal spot profiles at the three wavelengths, which have the same focal distance and no secondary focusing. Diffraction limited fwhms of 2.22, 2.37, and 3.03 μm and focusing efficiencies of 34.5%, 30.7%, and 51.1% were obtained for 1180, 1400, and 1680 nm, respectively. These efficiencies surpass past work on three-wavelength transmissive metalenses\textsuperscript{18,25,35} but are lower than the doublet lens primarily due to increased interlayer scattering from the additional layer. Note that the use of three layers triples the group delay of the nanoposts while allowing for linear phase dispersion, which enables dispersion engineering over a continuous band. In past work on achromatic metalenses based on the geometric phase,\textsuperscript{25,26} the approach is only applicable for circularly polarized light and exhibits efficiency variations across the spectrum. Here, the use of low quality factor cylindrical resonators allows for flat transmission over a continuous band and a polarization-insensitive response. As a proof of concept, metalens triplets with a diameter of 200 μm and bandwidth of 100 nm are demonstrated for continuous and hyper-dispersion operations in the Supporting Information (Figure S8).

Apart from correcting chromatic aberration at specific wavelengths, the proposed multilayer metasurface platform can also be used to realize different functions at each wavelength. Such elements could be used for color routing,\textsuperscript{21} multispectral imaging,\textsuperscript{21} and wavelength division multiplexing. To validate this concept, we designed a multiband spectral splitter based on a metasurface doublet that can split three wavelengths separately on the same focal plane, a schematic of which is shown in Figure 5c. Here, we have added a third wavelength to the doublet resulting in less demanding fabrication, compared to three layers, at the expense of phase optimization. Based on full-wave simulations, a device with a 100 μm diameter, 120 μm focal length, and 20 μm focal plane separation was found to have focusing efficiencies of 25%, 22%, and 40% at 1180, 1400, and 1680 nm, respectively. Experimentally, we fabricated a scaled device with a 500 μm diameter, 100 μm focal plane separation, and focal length of 600 μm. An optical image of the device is presented in Figure Sd. Figure 5e shows the measured intensity distribution at the focal plane. The measurement shows intensity peaks at –100, 0, and 100 μm with measured focusing efficiencies of 5.1%, 12.8%, and 22% at 1180, 1400, and 1680 nm, respectively. We attribute the lower measured efficiencies to greater misalignment sensitivity due to an irregular arrangement of nanoposts. This was verified by adding a 2 μm misalignment to the simulation resulting in efficiencies being reduced to 5.4%, 8.8%, and 18.4% at 1180, 1400, and 1680 nm, respectively. However, since the size of the focal spot is generally not as critical in spectral splitting applications, the designs could be further optimized by designing supercells containing multiple resonators of the same size to enhance misalignment tolerance at the expense of phase sampling resolution. A higher efficiency is also achievable for splitters with a longer focal distance.

In conclusion, we have developed a multilayer transmissive metasurface platform to perform multiwavelength functions and thus address chromatic aberration at discrete wavelengths for diffractive metadevices such as metalenses and metagratings. The complete and independent control over phase at multiple wavelengths also enables integrated functionalities on a single planar device for applications such as full-color holograms and encoded optical information storage. Such integration can be further extended by superimposing polarization\textsuperscript{18} or angle\textsuperscript{22} response for increased functionality. Apart from phase modulation, the multilayer fabrication technique outlined here can be used to implement complex monochromatic functionalities, which are hard to embed on a single metasurface, such as biaxialotropic metasurfaces,\textsuperscript{43,44} topology optimized meta-optics,\textsuperscript{61} and metaholograms with depth cues.\textsuperscript{45}

**Methods. Design and Simulation.** The transmission coefficient of the nanoposts was retrieved using a rigorous coupled wave analysis (RCWA) solver.\textsuperscript{46} A 750 nm tall Si nanopost was arranged in a square lattice with a period of 600 nm, embedded in PDMS. The refractive index of the Si was 3.547, 3.5, and 3.47 at 1180, 1400, and 1680 nm, respectively. The transmission coefficients were assumed to be the same for both layers. The details of the metalens design and simulation are presented in the Supporting Information.

**Measurement.** A customized imaging system was built up by a 50× objective (Mitutoyo Plan Apo, NA = 0.42) paired
with a tube lens. To ensure achromaticity of the characterization system, a 5X objective (Mitutoyo Plan Apo, NA = 0.14) was used as a tube lens. The focal spot profiles were characterized by illuminating the sample with a collimated supercontinuum laser (Fianium WhiteLase) that passed through a monochromator (Cornerstone 130 1/8m), and the image intensity was recorded by a NIR camera (Xeva-1.7-640). The metatals were driven continuously on a motorized stage (Throlabs PT1-28) along the propagation direction for 0.3 mm, while 267 slices of images around the focal plane were subsequently captured by the camera corresponding to 1.13 um between each slice. The images were then stacked together to form the axial intensity distributions shown in Figure 4d. A schematic of the characterization system is shown in Figure S5a. The focusing efficiency was calculated by taking the ratio between the focusing power and the total incident power on the lens. To ensure that most of the power was incident on the device, a lens (AC254-200-C-ML, f = 200 mm) was placed in the front to form a ~200 μm diameter beam illumination. The focusing power was measured by passing the beam through an iris placed at the conjugate plane opened at a diameter corresponding to eight times the fwhm of the focal spot on the image plane. The total incident power was measured by removing the sample and opening the iris completely.

To perform the imaging, the test chart was illuminated using a 20X objective (Mitutoyo Plan Apo, NA = 0.40) as a condenser. The metatals was placed at a fixed position (~one focal length) away from the chart for imaging at both wavelengths. A tube lens (Mitutoyo Plan Apo, NA = 0.14) was used to form an image on the camera. Meanwhile, the condenser was slightly adjusted to reduce the noise and ghost images. A schematic of the imaging system is shown in Figure S5b.

**REFERENCES**


