Title: Resonant Wavefront-Shaping Flat Optics

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Abstract: Photonic devices rarely provide both elaborate spatial control and sharp spectral control over an incoming wavefront. In optical metasurfaces, for example, the localized modes of individual meta-units govern the wavefront shape over a broad bandwidth, while nonlocal lattice modes extended over many meta-units support high quality-factor resonances. We experimentally demonstrate dielectric metasurfaces that offer both spatial and spectral control of light, realizing a metalens focusing light only over a narrowband resonance while leaving off-resonant frequencies unaffected. Our devices realize such functionality by supporting a quasi-bound state in the continuum encoded with a spatially varying geometric phase. We also show that our resonant metasurfaces can be cascaded to realize hyperspectral wavefront shaping, which may prove useful for augmented reality glasses, transparent displays and high-capacity optical communications.
Main Text:

Metasurfaces—structured planarized optical devices with a thickness thinner than or comparable to the wavelength of light—typically support a “local” response, i.e., they tailor the optical wavefront through the independent response of each meta-unit. In contrast, “nonlocal” metasurfaces are characterized by an optical response dominated by collective modes over many meta-units (1, 2). Local metasurfaces have been widely explored to impart spatially varying phase distributions that shape the impinging optical wavefront to achieve functionalities such as lensing and holography (3, 4). However, these devices have typically limited spectral control: since the optical interactions with the meta-units are confined to deeply subwavelength structures, they are necessarily broadband, and the wavefront deformation is inevitably extended over a wide frequency range (Fig. 1a left panel). Areas of ongoing research efforts to extend the functionality of local metasurfaces include multifunctional (5, 6), stacked (7–9) and dynamically tunable metasurfaces (10, 11). There also is growing interest in local metasurfaces for display applications (12, 13), including augmented reality (AR) headsets (14, 15). In contrast, nonlocal metasurfaces, such as guided-mode resonance gratings (16, 17) and photonic crystal slabs (PCSs) (18, 19), can produce sharp spectral features (Fig. 1a middle panel), since they rely on high quality-factor (Q-factor) resonances extending transversely over many unit cells. These modes, however, cannot at the same time spatially tailor the optical wavefront. Nonlocal metasurfaces hold promise for applications such as sensing (20, 21), modulation (22, 23) and enhancement of nonlinear optical signals (24, 25).

In this work, we conceive, design and experimentally realize nonlocal metasurfaces that can shape the optical wavefront exclusively at selected wavelengths, leaving the optical wavefront impinging at other frequencies unchanged (Fig. 1a right panel). Our previous theoretical work
developed the theoretical framework of nonlocal metasurfaces that shape the wavefront only on resonance, including phase-gradient beam-steering metasurfaces and cylindrical metalenses (26, 27). This is achievable through a scalable rational design scheme previously only available to local metasurfaces, in which the configuration of scatterers across the surface is determined by reference to a pre-computed library of meta-units.

**Figure 1.** Functionality of resonant, wavefront-shaping metasurfaces. (a) Schematic illustrating the distinction between three types of metasurfaces. The nonlocal or resonant, wavefront-shaping metasurface demonstrated in this work provides spatial control exclusively across its sharp spectral features: It molds optical wavefronts only at the resonant frequency, while leaving the optical wavefronts impinging at other frequencies unchanged. (b) Schematic of cascaded meta-optics to realize hyperspectral wavefront shaping.

Since at non-resonant wavelengths the metasurface leaves the impinging beam undistorted, a stack of independently designed and operating nonlocal metasurfaces enables scalable systems exerting arbitrary control over spatial and spectral properties of light in a compact volume (Fig. 1b). Here, we experimentally demonstrate these principles with a nonlocal metalens focusing light at a selected wavelength, and a metalens doublet focusing two selected wavelengths. The
combination of broadband transparency and wavelength-exclusive wavefront shaping may prove particularly useful for see-through lenses in AR glasses that project contextual information into the eye only at narrowband wavelengths while simultaneously transmitting broadband light from the real world without distortion. If translated to active or nonlinear media, the enhanced light-matter interactions may expand the capabilities of meta-optics to include dynamic wavefront modulation (28) and signal-enhanced nonlinear wavefront shaping.

The operating principles of our nonlocal, wavefront-shaping metasurfaces are rooted in the physics of periodic dielectric PCSs that support bound states in the continuum (BICs). BICs are bound modes with infinite radiative quality-factors (Q-factors) despite being momentum-matched to free space (29). Applying a dimerizing perturbation (i.e., a perturbation that doubles the period along a real-space dimension and halves the first Brillouin zone) to such PCSs results in a quasi-BIC mode that is leaky to an extent controlled by the magnitude of the perturbation \( \delta \), and excitable from free space with a finite radiative Q-factor that varies as \( Q \propto \frac{1}{\delta^2} \) (30, 31). There are many ways to dimerize a periodic structure, and the choice of symmetry-breaking perturbation dictates which modes are excitable from free space and with which polarization state. The selection rules governing whether excitation of a mode is forbidden (BICs) or allowed (quasi-BICs) according to the symmetries of the mode, perturbation and incident polarization, have recently been derived and catalogued for all crystallographic plane groups (26). One important finding in this context is that lattices belonging to the \( p2 \) plane groups (Fig. 2a) have two degrees of freedom: one controlling the Q-factor and the other controlling the linear polarization state to which the quasi-BIC leaks (27). Specifically, the in-plane orientation angle \( \alpha \) of the dimerizing perturbation prescribes that incident light linearly polarized along the \( \phi \sim 2\alpha \) direction can excite a quasi-BIC mode. When circularly polarized light is incident, this degree of freedom manipulates a geometric
phase. For example, for right-handed circularly polarized (RCP) incidence, the phases of transmitted left-handed circularly polarized (LCP) and reflected RCP light vary as $\Phi = 2\phi \sim 4\alpha$ (while the optical phase of RCP light in transmission and LCP light in reflection is invariant to $\alpha$). This ensures that varying $\alpha$ in a dimerized $p2$ lattice enables resonant, wavefront-shaping metasurfaces (26, 27). This $\Phi \sim 4\alpha$ geometric phase in nonlocal metasurfaces drastically differs from the $\Phi = 2\alpha$ geometric phase that has been widely used in broadband local metasurfaces (32–35), not only because it is a factor of two larger, but most importantly because it is only imparted onto light near a narrowband quasi-BIC resonance.

With finite-difference time-domain (FDTD) simulations (Lumerical Solutions), we design a library of meta-units that provides a geometric phase to resonant light and then construct a resonant phase-gradient metasurface configured by reference to this meta-unit library. Figure 2a shows that the meta-unit of a $p2$ plane group consists of two rectangular holes with in-plane rotation angles $\alpha$ and $\alpha + 90^\circ$, defined in a dielectric silicon thin film. The library consists of meta-units with different $\alpha$ but otherwise identical geometrical parameters (i.e., periods $A$ and $2A$ along $x$ and $y$ directions, respectively, and fixed dimensions for the rectangular apertures). Details of the meta-unit design considerations (Q-factor, resonant wavelength, and bandstructure) are shown in Supplementary Information Section 2. Our FDTD simulations confirm that the phase shift of converted light on resonance varies approximately linearly as a function of the in-plane orientation angle $\alpha$, following $\Phi \sim 4\alpha$ (Fig. 2b). We can readily arrange these meta-units to impart a constant phase gradient for anomalous refraction following the generalized Snell’s law (36) (Fig. 2c). The simulated transmission spectrum of the phase-gradient metasurface shows a resonant peak for light of converted handedness and a corresponding dip for light of unconverted handedness (Fig. 2d). Simulated optical wavefronts of the device show that only on resonance and only for light of
converted handedness is the outgoing wavefront tilted by the phase gradient (Fig. 2e). Notably, off resonance there is minimal transmission of converted light and high transmission of unconverted light.

Figure 2. Design of a meta-unit library for nonlocal, wavefront-shaping metasurfaces and a resonant phase-gradient metasurface. (a) Schematic of a meta-unit of a $p2$ plane group, generated by applying a dimerization perturbation of magnitude $\delta$ to a square lattice of square apertures. (b) Simulations showing that the geometric phase $\Phi$ of light of converted handedness of circular
polarization is approximately four times of the orientation angle $\alpha$ of the dimerizing perturbation. In this specific example, the meta-unit has a dimension of $A \times 2A = 450 \text{ nm} \times 900 \text{ nm}$; the rectangular apertures have a dimension of $(L-\delta) \times (L+\delta) = 125 \text{ nm} \times 375 \text{ nm}$ and are etched in a 125-nm silicon thin film on a glass substrate. (c) Schematic of a super-period of the resonant phase-gradient metasurface, consisting of 12 meta-units with spatially varying $\alpha$. (d) Simulated transmission spectra of the phase-gradient metasurface for light of the converted (red) and unconverted (black) handedness of circular polarization. The converted LCP light has a resonant peak with a Q-factor of ~130. (e) Simulated far-field electric-field profiles of the resonant phase-gradient metasurface, showing that beam steering (to a 33° angle) only occurs on resonance for light of converted handedness, and that the device remains largely transparent for non-resonant light.

More sophisticated nonlocal metasurfaces with non-constant phase gradients, such as metalenses, may be envisioned by considering that the resonant wavelength is dispersive with the deflection angle, and therefore with the magnitude of the phase gradient (26). This represents a design constraint: the total shift in resonant frequency due to the phase-gradient variation across a device must be smaller than the full width at half maximum of the resonance. As such, there is a tradeoff between the Q-factor and the range of deflection angles across a device, commonly manifested as the numerical aperture (NA) of the resulting metalens (26, 27). For the meta-unit library in Fig. 2, the estimated maximum achievable NA for a radial metalens is ~0.26 (Fig. S1c). Supplementary Information Section 2 details the tradeoff and strategies for creating nonlocal metalenses with both high NA and high Q-factors.

Using the meta-unit library in Fig. 2, we fabricate a radial metalens with NA=0.2 and a diameter of 800 $\mu$m (Figs. 3a-c). This metalens has a resonance centered at $\lambda=1590 \text{ nm}$ with a Q-factor of ~86 and a maximum conversion efficiency of ~8% of the incident power, as indicated by
the transmission spectra in Fig. 3d. Note that this conversion efficiency is $\sim$32% of the theoretical maximum (which is 25% of the incident power) (27, 37). A series of transverse two-dimensional (2D) far-field scans shows that focusing is most efficient at the center of the resonance, $\lambda$=1590 nm, with the focusing efficiency dropping at the two shoulders of the resonance, $\lambda$=1575 nm and 1600 nm, and that the focal spots become almost undetectable at wavelengths tens of nanometers away from the center of the resonance (Fig. 3e). Longitudinal 2D far-field scans of the device (Fig. 3f) reveal that the focal spots at resonance ($\lambda$=1575-1600 nm) are orders of magnitude brighter than the focal spots off resonance, following a Lorentzian line shape. The device is functionally transparent off resonance: The background planewave is estimated to be three to four orders of magnitude stronger in power than the focal spots at off-resonance wavelengths. Notably, the focal spot at resonance is diffraction limited: vertical and horizontal linecuts of the focal spot at resonance (Fig. 3g) reveal Strehl ratios (estimated from the Airy disc and first ring of the intensity pattern) of 0.89 and 0.85 in the x and y directions, respectively.
Figure 3. Experimental results of a resonant radial metalens with NA=0.2. (a) Illustration showing the resonant operation of the metalens (‘blue’ light being focused, while the rest shown in white passing the lens without distortion). (b) Photograph of the metalens with a diameter of 800 μm. (c) Scanning electron microscope (SEM) image of a portion of the device. (d) Measured transmission spectra of the metalens for light of converted and unconverted handedness of circular polarization. (e) Measured transverse intensity distributions on the focal plane. (f) Measured longitudinal intensity distributions on a plane through the focal spot. The metalens is located at Z=0. (g) Measured (solid red curves) and theoretical (black dashed curves) linecuts of the focal spot at the center of the resonance, λ=1590 nm, along the x and y directions.
Cascading multiple nonlocal metalenses with distinct resonant wavelengths will enable multifunctional devices. The broadband transparency and independent design and operation of each constituent layer promise a scalable platform for hyperspectral wavefront shaping (Fig. 1b). We demonstrate a proof-of-principle implementation in the form of a resonant metalens doublet that focuses light at two selected wavelengths. This doublet consists of a converging cylindrical lens with NA=0.1 resonant at a shorter wavelength λ=1450 nm and a diverging radial lens with NA=0.2 resonant at a longer wavelength λ=1590 nm. They are arranged such that they share the same focal plane located between the two elements (Fig. 4a) but they may be rearranged as desired. Both elements are devised from meta-unit libraries of rectangular apertures etched in a 125-nm thick silicon film on glass for convenience, but each element could be based on a different material platform or with a different meta-unit motif for more advanced functionalities. The radial lens is the same device as Fig. 3, acting here as a diverging lens because the handedness of circularly polarized incident light has been switched. Compared to this design, the meta-unit library for the cylindrical lens, as detailed in Fig. S5, has smaller dimensions (i.e., A = 410 nm, \((L - \delta) \times (L + \delta)\) = 100 nm \times 350 nm) to blueshift the resonant wavelength to \(\lambda=1450\) nm with \(Q\sim65\) (Fig. 4b). Longitudinal far-field scans of the doublet in the region between its two elements (Figs. 4d and e) confirm the focusing behavior of the cylindrical lens at \(\lambda=1445\) nm and the radial lens at \(\lambda=1580\) nm. Multiwavelength transverse far-field scans at the focal plane (Fig. 4c) show that at \(\lambda=1450\) nm, one element of the doublet (the cylindrical lens) generates a focal line, while at \(\lambda=1600\) nm, the other element of the doublet (the radial lens) produces a focal spot. Off resonance, there is minimal transmission of handedness-converted light—a plane wave transmits through the doublet with no polarization conversion nor wavefront deformation.
Figure 4. Experimental results of a resonant metalens doublet composed of a cylindrical metalens (metalens #1) and a radial metalens (metalens #2). (a) Schematics showing the operation of the components of the doublet in isolation (left and middle panels) and combined (right panel). (b) Transmission spectra of light of converted handedness of circular polarization (LCP) and unconverted handedness of circular polarization (RCP). (c) Measured transverse intensity distributions of converted light of the doublet. (d) and (e) Measured longitudinal intensity distributions of converted light of the doublet. The cylindrical metalens is located at Z=0. (c), (d), and (e) share the same color bars.
Several possible combinations of nonlocal metasurfaces, each with distinct wavefront shaping capability, may be cascaded, as long as no elements share a common resonant wavelength. For example, Fig. S6 details another doublet consisting of the cylindrical lens with NA=0.1 and a quasi-radial lens with NA=0.2 arranged such that the two focal patterns lie on different focal planes at their respective resonances.

Hyperspectral wavefront-shaping is not readily attainable in stacks of conventional local metasurfaces, which mold wavefronts with limited spectral selectivity: Diffractive dispersion and large propagation lengths between elements are required to first spatially separate color components before manipulating each wavefront individually and then recombining the colors. Our cascaded metalenses have less stringent design constraints in terms of the number of wavelengths, wavelength spacing and material selection than previous works reporting multifunctional metasurface devices (7, 8, 38, 39). In our experiments, each of the cascaded metasurfaces has its own independent substrate, but future devices could be stacked into an integrated substrate with successive independently operating layers spaced only a few wavelengths apart, creating a meta-optical volume with unprecedented command of light. Furthermore, we have previously reported a scheme where multifunctional operation in a single metasurface can be realized by adding successive orthogonal perturbations, each uniquely controlling the optical wavefront at a set of resonant wavelengths (27) and offering additional compactification. We have also shown that resonant metasurfaces composed of two tightly stacked layers that introduces chiral perturbations are capable of controlling the polarization properties of the resonant light over the entire Poincare sphere, enabling vectoral wavefront shaping and resonant meta-optics with unity efficiency (40). Combined with the cascading functionality demonstrated here, we envision
cascaded nonlocal meta-optics as a next-generational optical platform for hyperspectral vectoral wavefront engineering in compact optical volumes.

In summary, we have experimentally demonstrated resonant metalenses in the near-infrared that focus light only on resonance and are otherwise transparent. This platform of stackable nonlocal metasurfaces readily allows for independent control of resonant wavelengths (via meta-unit geometry), Q-factors (via perturbation strength), resonant frequency dispersion (via bandstructure engineering), and wavefront (via spatial distribution of the geometric phase) at multiple wavelengths (via cascading and/or multiplexing distinct perturbations). These devices may expand the capabilities of multifunctional meta-optics to include active or nonlinear wavefront shaping by leveraging the increased light-matter interactions of the high Q-factor, wavefront-shaping resonances. Scaled to visible and shortwave infrared wavelengths, our resonant metasurfaces may prove useful for AR and transparent display applications as compact multi-color see-through optics, or for high-capacity, secure optical communications as volumetric metamaterials composed of rationally designed planarized layers that both spatially and spectrally encode information.
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