Multifunctional Resonant Wavefront-Shaping Meta-Optics

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Abstract: We experimentally demonstrate systems of nonlocal optical metasurfaces that spatially shape the incident wavefront deliberately and distinctively for multiple independent resonances without altering the wavefront shape of non-resonant light.

1. Introduction

Optical metasurfaces typically support either a 'local' response where independent meta-units shape a wavefront spatially or a 'nonlocal' response where the collective effect of many meta-units results in spectrally sharp optical features. One realization of nonlocal metasurfaces is a symmetry-perturbed dielectric photonic crystal slab (PCS) supporting quasi-Bound States in the Continuum (q-BICs)—radiative states with Q-factor controllable by the perturbation strength. The in-plane symmetries of a perturbed PCS, a target mode, and the incident polarization, dictate whether excitation from normal incidence is forbidden or allowed [1]. In a PCS having a *p2* plane group (**Fig. 1a**), the incident linear polarization ϕ required to excite q-BICs corresponds directly with the in-plane orientation angle α of the perturbation as $\phi \approx 2\alpha$. Upon excitation by circularly polarized light, such a PCS will give a geometric phase of $\Phi = 2\phi \approx 4\alpha$ on resonance only to transmitted light of converted handedness or reflected light of preserved handedness [1, 2]. Meta-units with distinct α can be tiled to mold the wavefront shape exclusively at narrowband Fano resonances to theoretically [2] and experimentally [3] realize metasurfaces with both spatial and spectral control.

2. Cascaded Resonant Metasurfaces

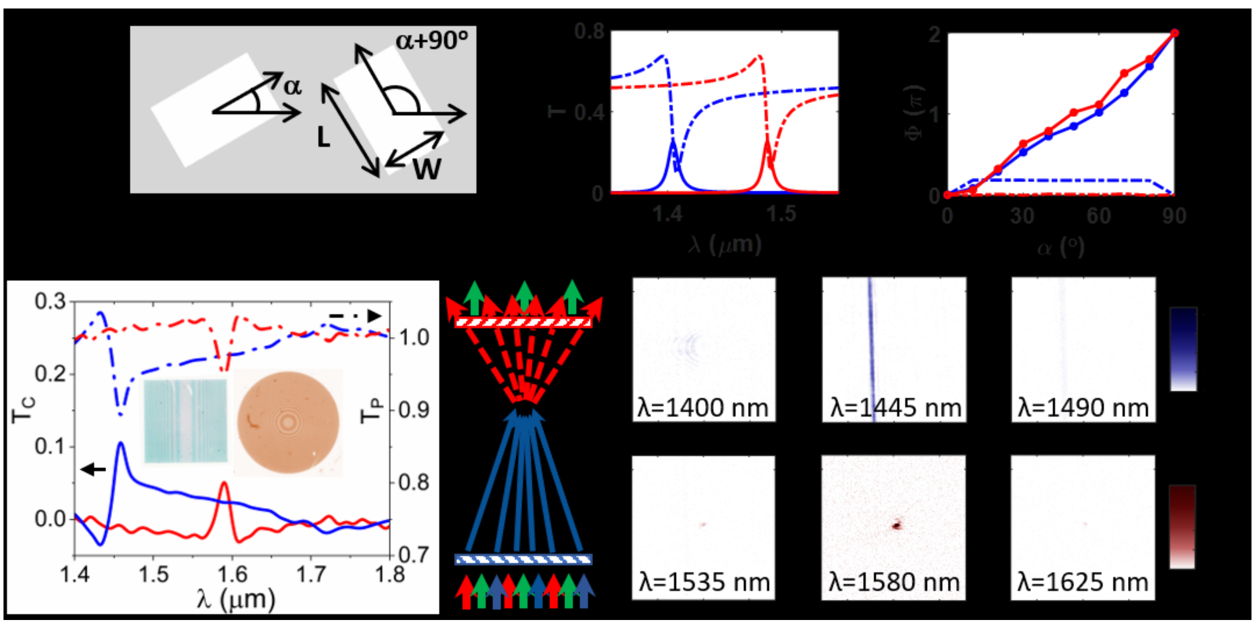

Figure 1: Design and experiments of cascaded resonant metasurfaces. (a) Schematic of a dimerized meta-unit. (b) Simulated circularly polarized transmission spectra of converted (solid line) and preserved (dashed line) handedness for two meta-units with α=30°. Dimensions of the 'blue' meta-unit library: A=410 nm, W=100 nm, L= 350 nm. Dimensions of the 'red' meta-unit library: A=450 nm, W=125 nm, L=375 nm. (c) Simulated geometric phase as a function of in-plane rotation angle α for the two meta-unit libraries for converted (solid line) and preserved (dashed line) handedness. (d) Measured circularly polarized transmission spectra (T_c for converted handedness and T_p for preserved handedness) for a NA=0.1 cylindrical metalens created from the 'blue' meta-unit library (blue curves) and a NA=0.2 radial metalens created from the 'red' meta-unit library (red curves). Insets: Optical microscope images of the cylindrical metalens (left) and radial metalens (right). (e) Schematic of cascaded metalenses setup. The convergent cylindrical metalens and the divergent radial metalens share the same focal plane. (f) Measured far-field intensity distributions of handedness-converted light on the focal plane. Both color scales are normalized to maximum at λ=1580 nm.

As our metasurfaces shape the wavefront only on resonance, multiple metasurfaces with distinct resonant wavelengths can be cascaded to achieve distinct functionalities at different wavelengths. We devise a cascaded nonlocal metasurface system for near-infrared light on a platform of rectangular apertures in 125-nm thick silicon thin films on glass (**Fig. 1a**). We design two spectrally separated meta-unit libraries by choosing different aperture dimensions and lattice constants for each library (**Fig. 1b**). At the respective resonant wavelength in each library, transmitted light of converted handedness experiences a relative geometric phase of approximately 4α (**Fig. 1c**). With electron beam lithography, we fabricate a cylindrical lens with a numerical aperture (NA) of 0.1 from the 'blue' library and a radial lens with NA of 0.2 from the 'red' library (**Fig. 1d**). The measured circularly polarized transmission spectrum of each device shows distinct resonances (**Fig. 1d**). We arrange these devices together as a doublet such that they share a focal plane (**Fig. 1e**). Imaging the handedness-converted intensity pattern on the focal plane reveals a focal line near the resonance of the cylindrical lens, a focal spot near the resonance of the radial lens, and minimal transmission of handedness-converted light at non-resonant wavelengths (**Fig. 1f**) [3]. More extensive multifunctionality can be realized on this platform by cascading either several metasurfaces or, more compactly, multifunctional metasurfaces.

3. Single-Layer Multifunctional Metasurfaces

Multifunctional wavefront-shaping nonlocal metasurfaces with up to four distinct functionalities can be achieved on a single planar device by adding orthogonal perturbations with each perturbation introducing a separately controllable geometric phase [2]. We design a metasurface with two distinct functionalities on a platform of rectangular apertures in a 200-nm thick silicon thin film on glass with a meta-unit geometry described in **Fig. 2a**. Each perturbation introduces a distinct q-BIC (**Fig. 2b**) whose geometric phase is controllable by the α of one set of apertures and not the other (**Fig. 2c**). As proof-of-principle, we fabricate a metasurface of two orthogonal cylindrical lenses with NA~0.05 such that each set of perturbations produces the phase profile for a distinct cylindrical lens (**Fig. 2d** and **2e**). Imaging handedness-converted light on the focal plane reveals a horizontal focal line at λ=1385 nm, a vertical focal line at λ=1460 nm, and mostly flat wavefronts at non-resonant wavelengths (**Fig. 2f**). As the resonant wavelength is dispersive with the deflection angle [2], new design schemes that maintain near-constant resonant wavelength across the device are required for radial lenses or higher NA cylindrical lenses. We envision that cascading multiple single-layer multifunctional nonlocal metasurfaces will enable highly multifunctional meta-optics systems. Active refractive index tuning of each metasurface would also result in a highly reconfigurable system [4].

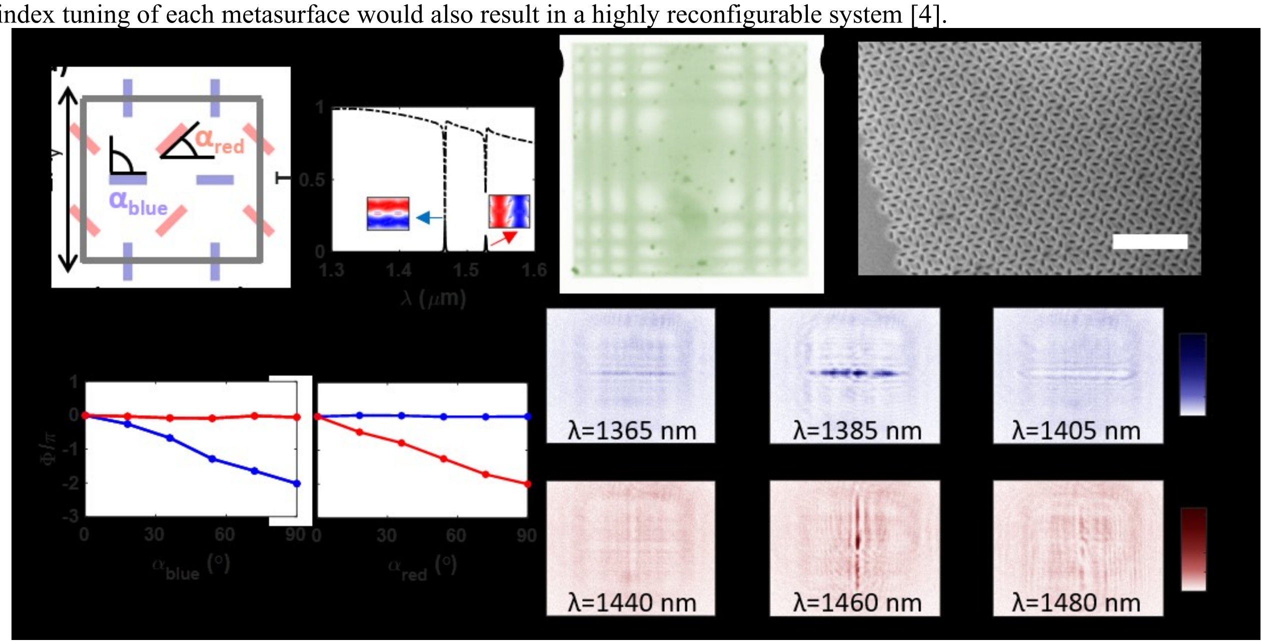

Figure 2: Design and experiments of single-layer multifunctional resonant metasurfaces. (a) Schematic of a meta-unit with two sets of perturbations giving independent geometric phases. (b) Simulated circularly polarized transmission of a meta-unit with dimensions Ax=460 nm, Ay=430 nm, W=200 nm, L=50 nm. Insets: Out of plane E-field mode profiles. (c) Simulated geometric phase at λ=1459 nm (blue) and λ=1527 nm (red) as a function of each set of in-plane rotation angles α_{blue} (left) and α_{red} (right). (d) Optical microscope image of a 505 μm × 505 μm device. (e) Scanning electron micrograph of a portion of the device (scale bar: 2 μm). (f) Measured far-field intensity distributions of handedness-converted light on the focal plane. Both color scales are normalized to maximum at λ=1385 nm.

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References

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