Resonant Wavefront-Shaping Metasurfaces Based on Quasi-Bound States in the Continuum

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Abstract: We experimentally demonstrate dielectric metasurfaces that support spatially tailored dark modes (quasi-Bound States in the Continuum) and mold optical wavefronts only at narrowband Fano resonances, while leaving the rest of the spectrum unaffected.

1. Introduction

Conventional metasurfaces either spatially manipulate an optical wavefront with limited spectral control (Type-I) or spectrally manipulate incident light without spatial control (Type-II). Examples of Type-I metasurfaces include metasurface lenses, vortex beam plates, and holograms [1]. Type-II metasurface are typically periodic dielectric photonic crystal slabs (PCSs). Much recent progress in Type-II metasurfaces has focused on Bound States in the Continuum (BICs)—states that are momentum-matched to free space but have an infinite radiative Q-factor. One method to access symmetry protected BICs is to apply a dimerizing perturbation to a PCS, resulting in radiative modes with Q-factors varying inversely with the squared strength of the perturbation [2].

We have developed an exhaustive catalog of the selection rules for dimerized PCSs, prescribing which free-space polarization couples to which modes for each crystallographic plane group of the dimerized PCS [3]. This catalog suggests a three-step design process: (1) select the mode profile in real space, (2) choose the Q-factor by tuning the perturbation strength, and (3) adjust other geometrical parameters to engineer the angular dispersion in *k*-space. One key insight of the catalog is that the *p2* space groups impart a geometric phase to the optical Fano resonance that is tunable through an in-plane orientation angle. Meta-units of the *p2* space groups can then be tiled to create a metasurface that, mediated by a supermode (a spatially tailored dark mode), spatially shapes the wavefront only on resonance while leaving the rest of the spectrum unchanged. This resonant (Type-III) metasurface behavior is a departure from Type-I and II metasurfaces, with promising applications for augmented reality and multifunctional optical modulators.

2. Theory

In a dimerized structure with a *p2* space group (**Fig. 1(a)**), the in-plane rotation angle α dictates which incident polarization angle ϕ couples into the mode. As α varies from 0° to 90°, ϕ varies from 0° to 180°. For circularly polarized incident light (light with a unity value of spin), this structure imparts two factors of the geometric phase for transmitted light of the opposite spin and reflected light of the same spin on resonance. One factor of the geometric phase comes from the change of basis describing the coupling of circularly polarized light into a localized mode that can only be excited by ϕ-polarized light. The second factor of the geometric phase comes from decomposing the ϕ-polarized radiation of the mode into left and right handed circularly polarized light. So, the geometric phase on resonance varies approximately as 4α. Through finite-difference time-domain (FDTD) simulations, we develop a library of dimerized meta-units comprised of rectangular holes in a platform of 500 nm thick TiO_2 on quartz at near-visible wavelengths. The transmission spectra of a meta-unit in **Fig. 1(b)** shows a peak for the converted circular polarization (LCP) and a dip in the unconverted circular polarization (RCP) at the resonance. Varying the in-plane rotation angle α from 0° to 90° confirms an approximate 4α dependence for the phase of the transmitted LCP light (**Fig. 1(c)**).

We devise a Type-III metasurface by arranging meta-units with spatially varying α to create a desired phase profile. **Figure 1(d)** depicts the spatial distribution of in-plane rotation angles for creating one period of a phase gradient Type-III metasurface to deflect the transmitted portion of the converted light to ~30°. Examination of the simulated transmitted wavefront of this device (**Fig. 1(e)**) reveals an angled wavefront for converted LCP light on resonance, but no deflection off resonance or for unconverted RCP light. In this example, the phase gradient is orthogonal to the direction of the dimerization, but it is also possible to arrange the phase gradient along the direction of the dimerization. The resonant frequency is usually less dispersive to incident angle and, by reciprocity, deflection angle if the phase gradient is not in the same direction as the dimerization. Type-III metasurfaces also enable more complex functionalities such as resonant lenses where the achievable numerical aperture is dictated by the Q-factor and the angular dispersion of the resonant frequency [3]. Additionally, adding successive orthogonal perturbations allows for independent spatial control of the wavefront for up to four narrowband wavelengths [3].

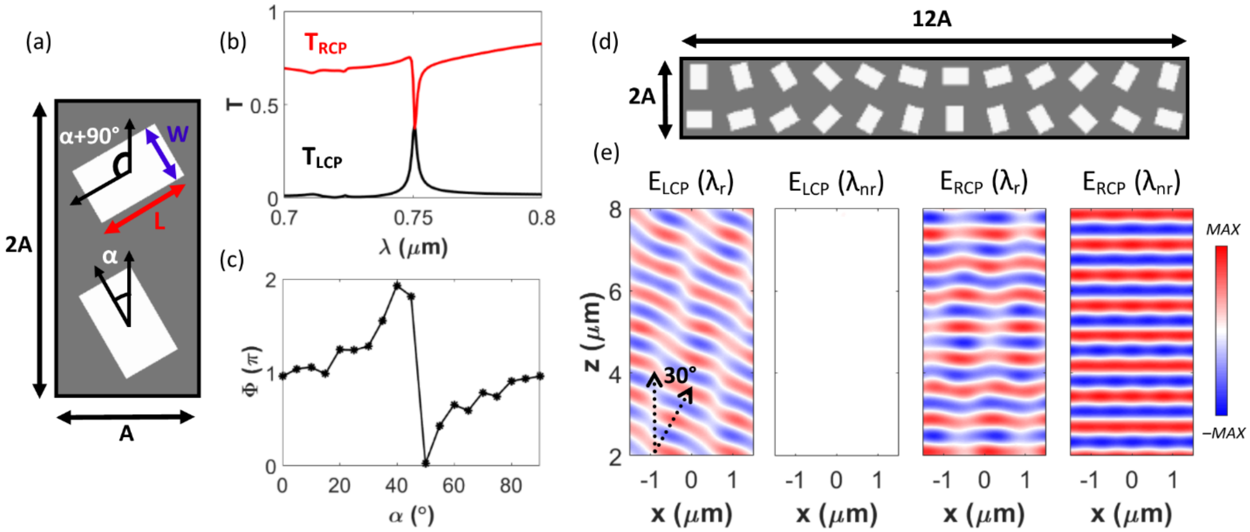

Fig. 1 (a) Schematic of a meta-unit of the *p2* space group of holes in TiO_2 with dimensions A=250 nm, W=100 nm, L=160 nm, and α=30°. (b) Simulated transmission for RCP incident light for the meta-unit in (a). (c) Geometric phase on resonance of transmitted LCP light as a function of in-plane rotation angle α. (d) Schematic of one period (covering 4π phase across 3 μm) of a phase gradient metasurface consisting of meta-units in (a) with varying rotation angles, α. (e) Transmitted electric field (real part) for the structure shown in (d) for incident RCP light both on and off the resonance (λ_r=0.758 μm and λ_{nr}=0.738 μm, respectively) for both the converted (LCP) and unconverted (RCP) transmitted light.

3. Experimental Results

We realize a resonant metasurface at near-infrared wavelengths by fabricating a 750 μm × 750 μm cylindrical lens (*NA≈0.16*) with 800 nm tall a-Si pillar meta-units on a silica substrate (**Fig. 2(a)**). We characterize the device by measuring the intensity at different *z* distances from the metasurface for incident light both on and off a resonance and for detected light of both converted and unconverted spin. **Figure 2(b)** shows that the metasurface acts as a lens only on resonance and only for transmitted light of converted circular polarization. Off a resonance or for light of unconverted circular polarization, the wavefront is unaffected. We expect that improved nanofabrication and engineering of the angular dispersion of the resonance will enable experimental demonstration of resonant radial lenses with moderate NA.

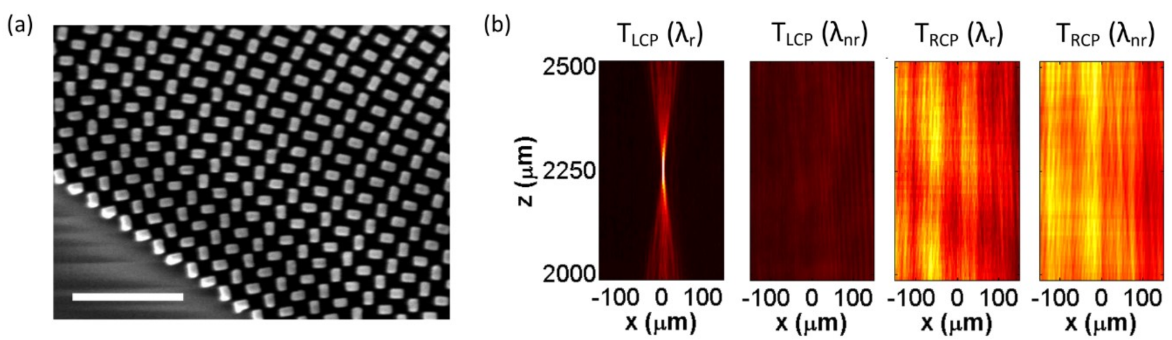

Fig. 2 (a) Scanning electron micrograph of a cylindrical resonant metasurface lens. Meta-unit dimensions: A=450 nm, L=300 nm, W=200 nm. Scale bar: 2 μm. (b) Measured far-field transmission intensity distributions for incident RCP light both on and off a resonance (λ_r=1.35 μm and λ_{nr}=1.55 μm, respectively) for both the converted (LCP) and unconverted (RCP) transmitted light.

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4. References

[1] P. Genevet., F. Capasso, F. Aieta, M. Khorasaninejad, and R. Devlin. Recent advances in planar optics: from plasmonic to dielectric metasurfaces. *Optica,* **4**, 139–152 (2017).
[2] K. Koshelev, S. Lepeshov, M. Liu, A. Bogdanov,and Y. Kivshar, Asymmetric metasurfaces with high-Q resonances governed by bound states in the continuum, *Physical Review Letters* **121**, 193903 (2018).
[3] A. C. Overvig, S. C. Malek, M. J. Carter, S. Shrestha, and N. Yu, Selection Rules for Symmetry-Protected Bound States in the Continuum, arXiv:1903.11125 [physics], arXiv: 1903.11125 (2019).