Chiral and Spatially Tailored Quasi-Bound States in the Continuum

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Abstract: We show that two-layer photonic crystal slabs with chiral perturbations yield Fano resonances with controllable amplitude and phase, and demonstrate devices with spatially tailored dark modes that anomalously reflect light with controllable diffraction efficiency.

1. Introduction

Metasurfaces are quasi-two-dimensional structured materials that manipulate light, conventionally classifiable into two types. Type-I metasurfaces spatially manipulate optical wavefronts over a broad spectral range with diffractive dispersion. Examples include metasurface holograms, phase gradients, and lenses [1]. In contrast, Type-II metasurfaces spectrally manipulate light without shaping the wavefront. Examples include subwavelength gratings supporting guided mode resonances [2], photonic crystal slabs (PCSs) supporting Bound States in the Continuum (BICs) [3], and perturbed PCSs supporting quasi-BICs whose radiative lifetime is controlled by breaking a spatial symmetry [4]. Recently, the selection rules for quasi-BICs have been described, clarifying whether free-space excitation of a quasi-BIC is forbidden or allowed in the presence of a chosen planar (achiral) perturbation [5].

Here, we generalize PCSs with the $p2$ space group (which have only two-fold rotation symmetries) to include chiral perturbations. An achiral $p2$ perturbation enables simultaneous control of the Q-factor and orientation of the linear eigenpolarization [5]. The eigenpolarization is the free-space polarization state producing a resonance, whose Jones vector is unchanged upon reflection. Here, we show that by using two perturbed layers stacked atop one another, with a thickness of a quarter wavelength (imparting a 90° phase difference between the layers), the individually controlled linear eigenpolarizations of the layers determine an arbitrary elliptical eigenpolarization of the chiral device. We show that this enables PCSs fabricable by conventional nanofabrication methods to support optical Fano resonances reflecting light with arbitrarily controllable amplitude and phase when illuminated by circularly polarized light. When the amplitude is unity, the PCS supports a fully circularly dichroic Fano resonance (resonantly reflecting one spin while non-resonantly transmitting the opposite spin). By spatially varying the geometric phase, Fano resonances with spatially tailored dark modes may be realized in devices that anomalously reflect resonant light but specularly transmit non-resonant light. Exclusively shaping the wavefront of resonant light while leaving the remainder of the spectrum unaltered represents a Type-III functionality that fits neither the Type-I or Type-II category. In particular, our results show that Type-III metasurfaces employing chiral perturbations may achieve near-unity diffraction efficiency.

2. Results

We begin by studying the optical response of a PCS composed of two layers. Schematically shown in **Fig.1(a)**, the PCS sits on a substrate of silica and is made of two thin films of silicon (with a total thickness H), each with elliptical holes filled with the superstrate material (also silica). The elliptical holes are characterized by the in-plane orientation angle, α, of the ellipses in the first layer, and the difference in orientation angles $\Delta\alpha$ between the ellipses in the two layers (seen in **Fig.1(b)**). The dimensions of the ellipses control the Q-factor Q of the quasi-BIC [4,5]. Here, we choose the major and minor diameters to be $340nm$ and $80nm$ in a PCS with period $a = 400nm$ and $H = 500nm$, giving $Q \approx 500$. When $\alpha = 70°$ and $\Delta\alpha = 50°$, the eigenpolarization of the PCS is right hand circularly polarized (RCP) light. As depicted in **Fig.1(c)**, this device supports an optical Fano resonance with near-unity reflectance when illuminated by normally incident RCP light, but near-unity transmittance when illuminated by left hand circularly polarized (LCP) light. Naturally, for $\Delta\alpha = -50°$, it is RCP light that has near-unity transmittance.

A Fano resonance with any reflection amplitude for RCP light is therefore achievable by varying $\Delta\alpha$. This control corresponds to altering the eigenpolarization's latitude on the Poincaré sphere from one pole to the other; the reflected light is the projection of the incident polarization state onto the eigenpolarization. At the poles of the Poincaré sphere, there is a degeneracy in α: for any choice of α, a value of $\Delta\alpha$ may be found with equivalent spectra in **Fig. 1(c)**. Just off the poles of the Poincaré sphere, this degeneracy is seen to be the eigenpolarization's longitude, which has a well-known associated geometric phase for one of the constituent circularly polarized components. Here, as shown in **Fig.1(d)**, the geometric phase of the reflected RCP light varies as $\Phi \approx 4\alpha$, meaning that varying α and $\Delta\alpha$ simultaneously controls the amplitude and phase of the component of reflected light with preserved spin.

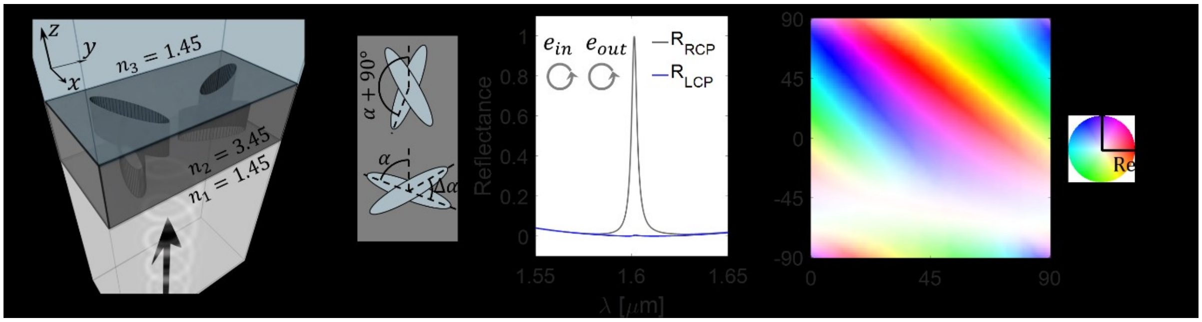

Fig. 1 (a) Schematic of a unit cell of a PCS with a chiral perturbation. (b) Top-view of a unit cell, defining the two in-plane orientation angles of the device (α and $\Delta\alpha$). (c) Reflectance spectra when RCP and LCP light is normally incident, showing a Fano resonance exhibiting full circular dichroism. The inset shows that the polarization state, e, is preserved for the eigenpolarization (RCP) on resonance. (d) Full control of the amplitude and phase of the electric field of reflected RCP light (E^r_{RCP}) by varying the chirality ($\Delta\alpha$) and geometric phase (4α).

Next, we select a subset of the structures in **Fig.1(d)** as a library of meta-units with near-unity reflection amplitude but phase varying over the 2π phase range (see **Fig.2(a)**). **Figure 2(b)** shows the values of $\Delta\alpha$ chosen for each α to maximize the amplitude, and shows that the meta-units have near-constant resonant wavelength, λ_{res}. By spatially varying the phase according to this library, a Type-III metasurface with a phase gradient is realized with near-unity diffraction efficiency for RCP light that is normally incident from the substrate. A superperiod of the metasurface and the field profile on resonance are depicted in **Fig.2(c)**, showing that a spatially tailored dark mode (a guided wave propagating in the x direction) is responsible for the Fano resonance. The far-field of the metasurface is depicted in **Fig.2(d)** for wavelengths near the resonance, showing specular transmission for all non-resonant wavelengths, but anomalous reflection to an angle of 20.1° with near-unity efficiency (96%) at the resonant wavelength.

The device in **Fig.2** is a Type-III metasurface that anomalously reflects light with large spectral and spin selectivity (LCP light is non-resonant, as in **Fig.1(c)**). We note that Type-III metasurface lenses are readily feasible, and that most generally, the library of meta-units in **Fig.1(d)** may enable highly spectrally selective phase-amplitude holography. Type-III metasurfaces based on chiral quasi-BICs are therefore promising for applications such as augmented reality (where narrowband anomalous reflection may deflect and focus contextual information overlaid on unaltered broadband external light) and optical modulators with extended functionality (where active control such as thermo-optic or electro-optic modulation may tune the resonant wavelength of anomalously reflected light).

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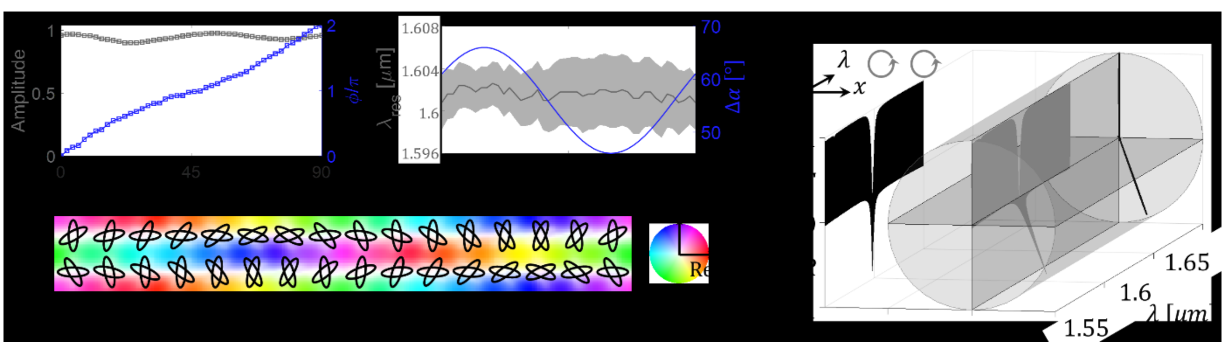

Fig. 2 (a) Sub-library of Fig.1(d) with near-unity amplitude but phase ϕ varying across 2π. (b) The resonant wavelength λ_{res} and linewidth (shaded area) for each meta-unit in (a), also showing the values of $\Delta\alpha$ chosen for each α to maximize amplitude. (c) Out-of-plane component of the magnetic field on resonance of a phase gradient metasurface made from the library in (a), with ellipses overlaid to show the geometry. (d) Far-field projection near the resonance of the device in (c), showing anomalous reflection with near-unity peak efficiency (96%) at the resonant wavelength, but simple specular transmission off the resonant wavelength. The polarization state is preserved, as shown in the inset depicting the polarization state, e, of input and output light, demonstrating that the eigenpolarization of the metasurface is RCP.

3. References

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