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# Trapping light in resonant metasurfaces for plasmon lasing

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**Abstract.**
Mitigating radiative losses in resonant structures has been a target of extensive research in photonics, involving various concepts such as optical dark states, multipoles, anapoles, embedded eigenstates, as well as momentum- or symmetry-mismatched lattice resonances in periodic systems. Here, we explore the possibility of improving the quality factors of dispersive lattice resonances within the light cone of a plasmonic metasurface. In particular, we find that antisymmetric modes of a honeycomb lattice of isotropic metal nanoparticles have symmetry-protected degenerate band edges, whereas the same lattice composed of anisotropic nanoparticles has an off-normal bound state along one of the dispersive bands. In addition to theoretical calculations, we also present our preliminary experimental results on distributed feedback lasing in such systems.

## INTRODUCTION

Engineering the far-field radiation properties of photonic and plasmonic structures has been of vital interest for fundamental and applied optics. One of the main research targets has been to maximize the quality factors of resonant cavities by reducing their radiative losses, in order to improve the performance of lasers, sensors, and to enhance various light-matter interactions. Recently, it has been predicted [1] and demonstrated [2] that optical modes can be topologically protected against radiation losses inside polarization vortices emerging in the far-field patterns. In the centers of such vortices, the far-field radiation cancels out, giving rise to lossless bound states in the continuum (BIC). In recent years, several BIC-enabled lasing devices have been reported [3, 4].

In periodic arrays of resonant scatterers, hybridization between diffractive resonances (Rayleigh/Wood anomalies) and localized plasmonic/Mie resonances gives rise to lattice resonances [5], with quality factors much higher than those of individual scatterers [6]. These collective modes may extend beyond the light line and become guided modes. Inside the light cone, their band edges are routinely used as cavities for distributed feedback lasing and for outcoupling of emission towards free space [7]. Plasmonic nanostructures are particularly efficient in providing distributed feedback thanks to their giant scattering cross sections, which compensate for the deteriorating effect of Ohmic losses. Lasing can also benefit from symmetry-protected dark states, such as those occurring at the $\Gamma$ point. In such case, radiation normal to the lattice plane is prohibited due to polarization singularity in the momentum space, which shapes the emission in form of a donut [8, 9] or pair of separated spots [4]. In view of the above, one may expect that next generation of plasmonic lattice lasers would employ topological BIC-like strategies for eliminating radiation loss.

Here, we focus on the special case of honeycomb metasurfaces made of plasmonic nanoantennas. Honeycomb lattices are well known for their peculiar band topology (Dirac points, valley-Hall effect, exceptional rings, etc.), however, in this work we explore another feature of honeycomb metasurfaces, namely, their antisymmetric lattice resonances, which retain their narrow linewidths inside the light cone by relatively poor coupling with free-space radiation. We investigate the instances of symmetry- and topology-enforced cancellation of their radiative decay channels, yielding band edges and BICs with quality factors limited solely by intrinsic material loss.

## THEORY

Figure 1 shows examples of frequency-momentum maps of effective polarizability, transmissivity and reflectivity calculated using a dipolar Green function method with Ewald lattice summation [5, 10], for parameters specified in the caption. The top row shows results obtained for an array of in-plane isotropic nanoparticles, while the bottom row corresponds to an array of anisotropic nanoparticles. All band structures clearly show two main features: Rayleigh anomalies associated with diffraction, and dispersive lattice resonances, resulting from mixing of localized plasmon modes with Rayleigh anomalies. As can be seen in Fig. 1(a) and (d), lattice resonances become remarkably narrow not only outside the light cone (no coupling to free space), but also at certain isolated points inside the light cone, which coincide with vanishing transmission and reflection signatures in Fig. 1(b-c),(e-f).

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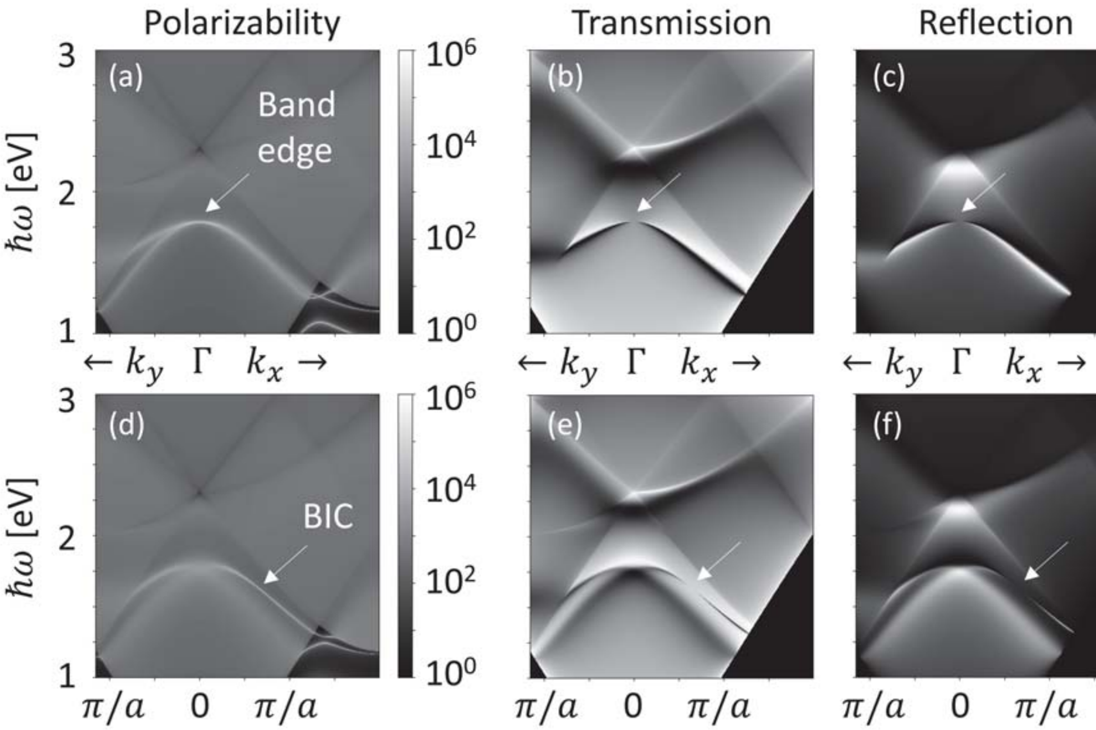

**FIGURE 1.** Calculated photonic band structures of a honeycomb lattice (pitch $a = 400$ nm) of silver nanoparticles (volume $V = 8\pi \times 10^{-22}$ m$^3$) embedded in a dispersive dielectric medium (refractive index from 1.51 to 1.58). (a-c) Isotropic nanoparticles; the arrows point at the symmetry-protected degenerate band edge, formed by antisymmetric lattice resonances. (d-f) Anisotropic nanoparticles; the arrows point at the BIC. (a,d) Effective polarizability (imaginary part of the sum of eigenpolarizabilities, multiplied by a factor $4\pi ka/V$). (b,e) Transmissivity. (c,f) Reflectivity. Incident light is assumed to be s-polarized. Calculations are based on theory presented in [5, 10].

In case of isotropic scatterers, Fig. 1 suggests the existence of two dipolar antisymmetric modes which have a symmetry-protected degeneracy at the Γ point. Engineering the geometry of individual plasmonic scatterers may destroy the symmetry protection against radiative loss at the Γ point, at the same time creating an off-Γ BIC at a singular $k$-$\omega$ point along one of the bands. We expect that detailed analysis of the polarization state of emitted light in the vicinity of these singularities should reveal a clear signature of their topology. From the application viewpoint, the first type of singularity could provide a high quality band edge for lasing, whereas the second type could be used for sensing and guiding light across the array with no radiative losses and with momentum that is matchable with free space radiation.

## EXPERIMENT

Our preliminary experimental results on arrays covered by gain media are shown in Fig. 2. In brief, the honeycomb metasurfaces are fabricated using electron beam lithography followed by evaporation of metal, removal of the polymer mask via lift-off, and spin-coating of SU8 doped with rhodamine 6G as the gain medium. Figure 2(a) shows an AFM image of one of the obtained nanostructures before coverage by the gain medium. A Fourier image (top) and a frequency-momentum map (bottom) of the emission from another metasurface above its lasing threshold is presented in Fig. 2(b). Both plots show that lasing occurs roughly at a single point coinciding with the Γ point, hence, it probably does not involve the symmetry-protected band edges discussed in the previous section.

Figure 2(c) presents the emission spectra near the lasing threshold. We find that this threshold is remarkably low, which is consistent with the recent report on plasmonic honeycomb lasers [11], where low-threshold lasing has been attributed to the presence of high-quality resonances resulting from hybridization of distinct multipolar modes near second Bragg condition. In our case, effective mode index of the gain medium layer is estimated at ∼1.53, yielding

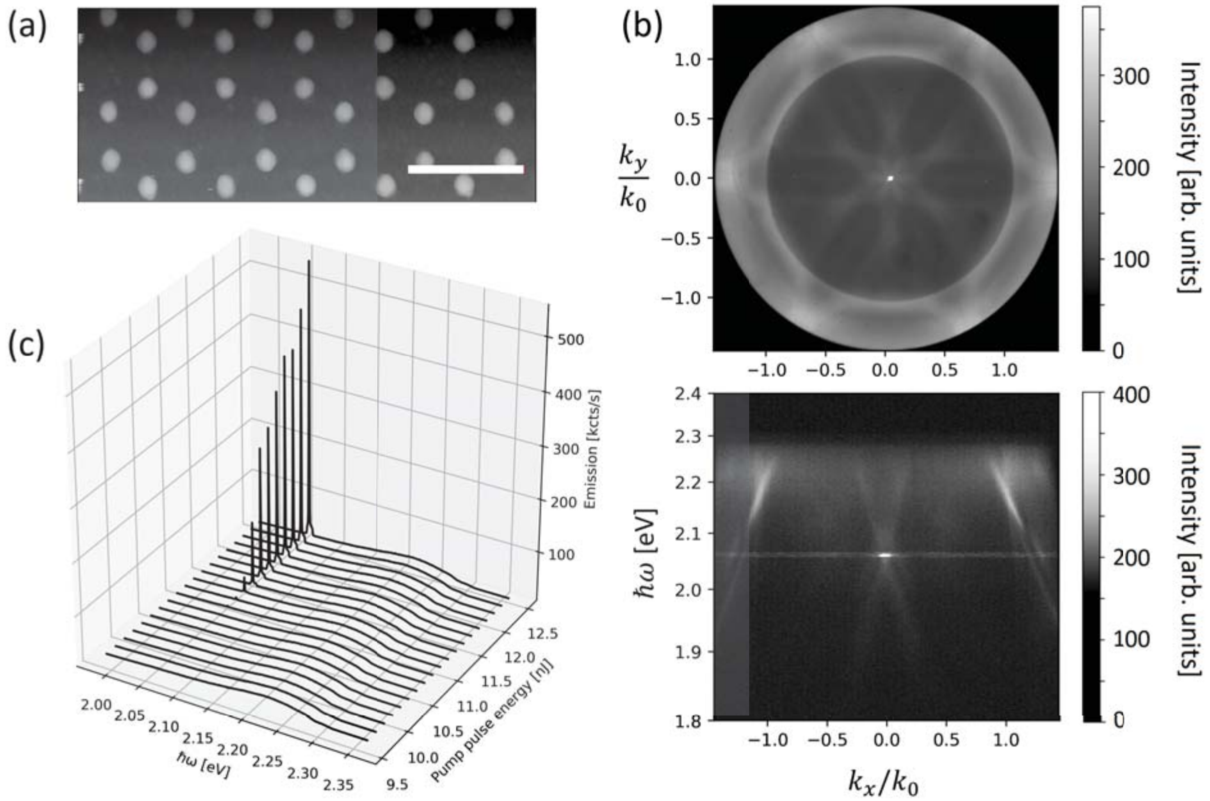

**FIGURE 2.** (a) AFM image of one of the studied silver nanoparticle arrays (before deposition of the gain medium layer). Scale bar: 500 nm. (b) Lasing at the Γ point in Fourier image (top) and photonic band structure (bottom) measured from another metasurface (pitch 450 nm) under 532 nm picosecond pumping above lasing threshold. (c) Emission spectra as a function of pump pulse energy.

second Bragg condition at ∼2.08 eV, which is consistent with the lasing peak observed in Fig. 2(b-c). Our current goal is to redesign the honeycomb metasurfaces, such that the gain band of the laser dye is kept away from the band edges near Bragg conditions and overlaps with the dipolar symmetry-protected band edges or with BICs. This could enable distributed feedback lasing and amplification at frequencies and angles not constrained by any Bragg condition.

## OUTLOOK

The majority of photonic systems studied to date in the context of BIC involved materials of practically real-valued $\varepsilon$, rendering them intrinsically lossless. Relatively little attention has been devoted to BIC-like scenarios involving media of non-negligible imaginary part of $\varepsilon$, i.e., having significant loss or gain. Apart from plasmon lattice lasers discussed above, this regime is of special relevance in the context of parity-time (PT) symmetry [12], involving resonant metasurfaces with spatially-patterned gain and loss as a promising platform for realization of PT symmetry breaking-induced phenomena [10, 13], which is another target of our ongoing research.

Recently, we have also discovered many interesting effects associated with phase singularities, embedded in parameter space spanned by frequency (as the first parameter) and either the in-plane momentum or a geometry parameter (as the second parameter). These singularities are distinct from polarization singularities of BIC, but they posses similar topological character. For instance, it has been shown [14] that plasmonic Salisbury screens (metasurface-mirror hybrids) may feature pairs of phase singularities with complete suppression of reflected light, enabling perfect absorption and full control over reflected phase around these singularities. On the other hand, we have recently predicted that similar phase vortices in gain-doped dielectric metasurfaces can yield "catastrophic singularities" – an opposite of perfect absorption – with scattered fields of divergent amplitude and undefined phase. Our findings offer new perspectives on singularity photonics based on resonant metasurfaces combining lossy scatterers with gain media.

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