Polarization-Independent Quasibound States in the Continuum

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A new property of the trapped mode (bound state in the continuum, BIC) supported by a dielectric resonant metasurface, which changes its lattice symmetry, is uncovered. The transformation of a metasurface composed of identical nanodisk resonators into a “diatomic” structure when one half of the nanodisks change their diameters is studied. The resulting folding of the Brillouin zone in the k-space transforms the trapped (BIC) mode to quasi-BIC resonances manifested in the polarization-independent response. This novel feature is verified experimentally in the transmission of the metasurfaces illuminated by light with both linear and circular polarizations.

1. Introduction

Strong light confinement resulting in enhanced light–matter interaction is critically important to enhance efficiency and improve performance of nanophotonic devices. As was recognized recently, enhanced light–matter interaction can be achieved using the physics of bound states in the continuum (BICs). The existence of such special resonant states originates from quantum mechanics but recently BICs have been predicted and observed in many photonic structures and they find important applications in diverse areas of physics ranging from low-threshold room-temperature lasing to efficient biological sensors.

BICs are unique states of light that are associated with the resonance having an infinite quality factor (Q factor) due to the vanishing linewidth (sometimes such modes are also referred to as the “trapped” or “dark” modes). Therefore, it is rather a mathematical concept that cannot be verified in a direct experiment. However, a quasi-BIC with a finite linewidth and a giant Q factor near a BIC can be found experimentally by symmetry breaking through small perturbation in photonic and plasmonic structures. Such examples are plentiful: photonic crystal slabs, gratings, coupled optical waveguides, and metasurfaces. Further increase in perturbation converts quasi-BIC to quasiguided mode resonance or leaky mode resonance. This is an extended state of the actual bound state, which always lies above the light line. It should be noted that losses in real systems also result in the transformation of BICs into resonant states with a finite lifetime. The scattering due to surface roughness and leakage into the substrate plays a vital role in such transformations.

Metasurfaces, made-up of high index dielectric resonators, have attracted huge attention in this decade as they allow loss-less control of incident light properties. Several interesting phenomena have been studied in metasurfaces composed of arrays of meta-atoms with broken in-plane inversion symmetry, which all show the excitation of high-Q resonances for the normal incidence of light. So far, tilted bars, dielectric nanodisks with asymmetric holes, plasmonic and dielectric split-rings, and notched cubes are used to make such metasurfaces with controllable perturbation through the geometry of the structure. The high-Q resonances observed in these metasurfaces are associated with the mechanism of BICs.

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Most of the previous structures exhibit polarization sensitivity having been excited with linearly polarized light. To realize a polarization-independent response, it is proposed to use cluster-based modifications of metasurfaces, although their practical realizations are rather rare. The characteristics of such metasurfaces are defined by the underlying symmetries of their clusters which can be analyzed involving group-theoretical methods.

In this article, we analyze the effect of the Brillouin zone folding on the existence of BICs and reveal polarization-independent response of the quasi-BIC states supported by the resulting “diatomic” dielectric metasurfaces. This novel feature is revealed from the analysis of the bandgap spectra, and it is associated directly with the folding of the Brillouin zone which occurs when we introduce a perturbation into the metasurface structure by changing the diameters of half of the nanodisks. We consider the metasurface composed of dielectric nanodisk resonators (meta-atoms) arranged in a square lattice. Such a configuration bears a degenerate BIC state which is characterized by two orthogonal eigenvectors existing at the same eigenfrequency.

2. Methodology

Although the degenerate symmetry-protected BIC does not exist in monatomic square lattices, the BIC can be realized in a dielectric metasurface from a trapped mode. In particular, an in-plane perturbation of the metasurface unit cell can transform the otherwise inaccessible trapped mode to a quasi-BIC state. The perturbation is introduced by modifying the radius of particular meta-atoms with respect to other ones, forming a diatomic unit cell. This quasi-BIC manifests itself in a high-Q resonance in the transmission spectra of the metasurface. Since the superposition of orthogonal x- and y-polarization components for the given trapped mode are present in the degenerate state, the quasi-BIC can be excited by light with any polarization mapped onto the Poincaré sphere. The Q factor, estimated from the eigen frequency data, is inversely proportional to the difference in radius between the two meta-atoms, confirming the quasi-BIC. Polarization-independence of the obtained quasi-BIC is checked against numerical simulations carried out with the rigorous coupled-wave analysis (RCWA) method and experimental measurements for the metasurface sample designed to operate in the visible range.

We consider a metasurface composed of the dielectric disk-shaped meta-atoms having the refractive index $n_t = 2.35$ and thickness $h = 80$ nm. These disks are distributed in the x-y plane, forming an infinitely large 2D array. To provide mechanical strength to the metasurface, the array is deposited on a glass substrate (refractive index $n_{st} = 1.52$ and thickness $h_{st} = 1.1$ mm) and is covered by poly(methyl methacrylate) (PMMA) as a superstrate (refractive index $n_s = 1.49$, height $h_s = 700$ nm).

In what follows, we carry out a comparative study of resonant characteristics of two particular designs of the metasurface. For the first (monatomic) design, the metasurface is composed of identical (blue) disks with the radius $r_{st} = 110$ nm, whereas for the second (diatomic) design, two different disks (blue and red) with different radii are used where the radius difference $\Delta r = r_{st} - r_{st}$ is considered as a perturbation parameter. A unit cell of the given metasurface can be outlined in several ways. In particular, for the diatomic design, the unit cell with a lattice constant $a = 460$ nm consists of one red meta-atom at the center and four blue meta-atoms at the corners, as shown in Figure 1a. When $r_{st} = r_{st}$, we have a unit cell that is rotated by 45° with respect to the diatomic design. In this case, the array possesses a mirror symmetry along the plane passing between any two nearest meta-atoms and has the lattice constant $a = a/\sqrt{2}$.

The Brillouin zones for monatomic and diatomic designs are shown in Figure 1b, which are enclosed by the red and blue squares, respectively. The energy dispersion surfaces in the first Brillouin zone have inversion symmetry. Therefore, the eigenvalues are equivalent in the red and blue-colored areas, by time-reversal symmetry. This property can lead to the Brillouin zone folding resulting in the $\Gamma - X$ region of the band diagram for the diatomic design by folding the $\Gamma - M$ region of the monatomic structure into half.

The band diagrams of low-order transverse electric (TE) modes calculated by eigen frequency analysis are shown in Figure 1c,d for the monatomic and diatomic designs, respectively. Note that, the wavelength scale is provided on the right side of these diagrams to simplify their comparison with subsequent experimental data. For this calculation, the guided mode expansion method through the Legume python library is used. The obtained results are also verified in the COMSOL Multiphysics software.

From Figure 1c, one can conclude that the dispersion curve of the TE$_0$ mode (shown in blue with strong $H_z$ and $E_x$ components and negligible $E_y$, $E_z$, $H_x$, and $H_y$ components) crosses the dispersion curve of the TE$_1$ mode (shown in red has strong $H_z$ and $E_x$ components and negligible $E_y$, $E_z$, $H_x$, and $H_y$ components) at the $M$ point, which leads to the degeneracy of eigenvalue at this state. The corresponding eigenfrequency is a purely real quantity, which is a signature of the trapped mode (BIC). Moreover, Figure 1d shows that in the diatomic metasurface, the Brillouin zone folding leads to the coincidence of the $M$ point with the $\Gamma$ point. Therefore, the introduced perturbation transforms the BIC present above the light cone at the $M$ point to the quasi-BIC at the $\Gamma$ point. In particular, for the chosen structure parameters, the BIC is found to be at the wavelength of 704 nm. This resonant wavelength experiences some shift as the BIC transforms to quasi-BIC.

3. Results and discussion

To study characteristics of this transformation, we carried out calculations of the complex eigenfrequencies $\omega = \omega_0 + i\omega$ for different values of the perturbation parameter $\Delta r$ at the $\Gamma$ point. The calculated Q factor ($Q = \omega / \Delta \omega$) and the resonant wavelength as functions of $\Delta r$ are shown in Figure 2a. As expected, there is a BIC with an infinite Q factor at the wavelength of 704 nm for the degenerate TE$_0$ - TE$_1$ mode when $\Delta r = 0$. When a perturbation is introduced into the metasurface, the Q factor becomes finite, and the resonant wavelength red (blue) shifts as $\Delta r$ increases (decreases). Overall, this confirms that $\Delta r$ is having the same role as the distortion parameter of the previously reported trapped-mode metasurfaces.

The electric and magnetic near-field distribution in the plane corresponding to the half-height of the resonators is plotted for
both these modes in Figure 2b,c, respectively. The orthogonality of the two modes is apparent from the very similar field distributions that are rotated by 90°. The field flow (arrows) shows that the electric field magnitude is equal but is in opposite directions in the neighboring atoms of the unit cell. Thus, these currents are fully compensated and cannot be coupled to the continuum.

Nevertheless, these modes can be transferred to the Γ point by perturbation (Δr ≠ 0), where they act as the quasi-BIC. In this case, the electric near-field flow is no longer compensated since in the adjacent rows of the array there are disks with different parameters. It is noteworthy that this BIC to quasi-BIC transformation does not lift the polarization degeneracy, and the mode field profile remains the same.

To verify this polarization-independent excitation of the quasi-BIC resonance in the metasurface, the polarization characteristics of the transmitted field is carried out. We carried out the RCWA calculations of transmission spectra of the idealized
(lossless) and actual (lossy) metasurfaces. The electric field vector $\vec{E}$ of the incident wave is defined by components $E_x = [0.5(P + 1)]^{1/2}$ and $E_y = [0.5(P - 1)]^{1/2} \exp(i\beta)$, where $P \in [-1, 1]$ and $\beta \in [-\pi, \pi]$. The transmission coefficient of the metasurface irradiated by the $x$-polarized wave is shown in Figure 3a for both lossless and lossy cases. Although the losses increase the resonance line width, the resonance wavelength remains the same.

Figure 2. a) Calculated quality factor (shown on the logarithmic scale) and resonance wavelength as functions of perturbation (the radius difference $\Delta r$), and the normalized b) electric and c) magnetic near-field patterns and flow of the TE$_x^+$ and TE$_y^+$ of the purely real eigen modes ($\Delta r = 0$).

Figure 3. a) RCWA simulated transmission spectra, b) transmission $|T|$ coefficient mapped on the surface of a Poincaré sphere related to the polarization states of the incident wave, and c) normalized electric near-field patterns and flow at the wavelength of the quasi-BIC resonance. The radius difference $\Delta r$ is 10 nm. The states 1–3 correspond to linear $x$-, diagonal-, and $y$-polarization, and 4 and 5 are right-handed and left-handed circular polarizations, respectively.
Figure 3c. The appearance of the electric near-field corresponds to those of the BIC eigenmodes, which unambiguously classifies the quasi-BIC resonance as polarization independent. The experimental data confirm the manifestation of the quasi-BIC resonance is polarization independent. Our results can be useful for applications in polarization-independent filters and white light biosensors.

The scanning electron microscope images of a) side and b) top views of the actual metasurface. c) Experimental transmission spectra supplemented by the Fano fit for the metasurface irradiated by light with different polarization states 1–5 which can be defined as follows, the states 1–3 correspond to linear x-, diagonal-, and y-polarization, and 4 and 5 are right-handed and left-handed circular polarizations, respectively.

5. Experimental Section

Fabrication: We fabricated the diatomic metasurface having TiO2 nanocylinders with radius 100 and 90 nm (Δr = 10 nm) using an electron beam lithography technique. Due to the adhesion issue of TiO2 on the glass substrate, an ITO-coated quartz substrate is used. First, e-beam resist PMMA 632.12 is spin coated at 2000 rpm and soft baked at 160 °C for 5 min. Later, another e-beam resist PMMA 495 A4 is spin-coated at 2000 rpm and soft baked at 180 °C for 2 min. Using Raith eLine, our desired metasurface mask is written on the spin-coated bilayer PMMA on an electron high tension (EHT) voltage 20 keV with dose ~200 μC A–1. The final structure is developed in a solution of methyl isobutyl ketone (MIBK) and isopropyl alcohol (IPA) (1:3 ratio) for 90 s followed by rinsing in stopper (IPA) for 60 s. Then TiO2 is deposited using radio frequency (RF) sputtering with RF power 80 W for 26 min to get 80 nm thickness. To realize the pattern by lift-off, sample was sonicated in acetone for 10 min. The PMMA 632.12 (νi = 1.49) having a refractive index close to that of the substrate is deposited on the TiO2 nanocylinder array to form a superstrate layer. The scanning electron microscope images of the final structure are shown in Figure 4a,b.

Transmission Measurement: The transmission spectral studies are carried out on the fabricated metasurfaces (500 × 500 μm2) using home-made measurement setup. It consists of a white light source (halogen lamp) and Acton SP-500 spectrometer along with a combination of lenses to form near-collimated white light beam on the sample. A 50 μm diameter pin-hole is used to cut down higher k vectors. With a combination of polarizer, half-wave plate, and quarter-wave plate, various incident polarization states are generated and transmission spectra are measured. Due to different waveplates used to generate linear and circular polarization states, there is a small difference (0.03) in transmission measurement for these states.

4. Conclusions

In conclusion, we have suggested and demonstrated polarization-independent resonant dielectric metasurfaces based on the BIC physics and explained by the relocation of the BIC state due to the Brillouin zone folding. The study of the band structure has revealed that the BIC state in the guided region zone folded to the continuum to form a quasi-BIC state. In experiment, we have confirmed the existence of high-Q resonances and their polarization independence. Our results can be useful for applications in polarization-independent filters and white light biosensors.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

P.V. and V.G.A. conceived the original idea. P.V. wrote the RCWA code to design the structure. P.V. and V.R.T. carried out eigenvalue calculations to study the polarization response. H.G. and A.K. fabricated the samples. P.V. did the optical measurements. P.V., V.G.A., S.O.G., V.R.T., and Y.K. analyzed the data, interpreted the results, and wrote the manuscript. All authors discussed the manuscript.

Data Availability Statement

Research data are not shared.

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