https://doi.org/10.1051/epjconf/202226609001

Polarization singularities and optical chirality in dielectric metasurfaces

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Abstract. We theoretically study the relation between polarization singularities and optical properties in dielectric metasurfaces, or photonic crystal slabs. We focus on nondegenerate photonic bands leading to symmetry-protected Bound States in a Continuum (BICs). First, we discuss how BICs lead to polarization singularities in the far field, whose winding numbers – or topological charges – follows from the symmetry of the lattice. Then, we determine the polarization properties via the Stokes parameters, focusing on the conditions for the occurrence of a nonvanishing circular polarization. Finally, we calculate the optical response in reflection and the degree of circular dichroism. The results shed light on the role of polarization singularities and symmetry in determining the optical chirality.

1 Introduction

Photonic crystal slabs (PCS), or periodic dielectric metasurfaces, support Bound States in a Continuum (BICs) that lie in the spectral region of the quasi-guided modes, but have infinite quality factor and no coupling to the radiation field. Such BICs lead to vortex centers in the far-field polarization, or topological singularities, which are characterized by a winding number or topological charge [1]. Polarization singularities have attracted much interest in recent years within the area of topological photonics, as they lead to a number of processes that involve the topological charge [2], and they can be used to tailor the polarization properties in the far field.

Another research field of current interest in metasurfaces involves the chiral properties of the electromagnetic field, i.e., the differences in optical properties between states with right- and left circular polarization. Chiral effects like circular dichroism have been thoroughly studied [3], often with the goal of enhancing the sensitivity of chiroptical sensing, i.e., sensing of chiral molecules.

In this work, we present an extensive study of photonic crystal slabs that sheds light on the relation between polarization singularities and chiral optical properties in the far field.

2 Topological singularities and polarization

We calculate the photonic band dispersion and losses above the light cone in photonic crystal slabs by means of two complementary methods, namely Guided-Mode Dispersion (GME) [4,5] and finite-difference time domain (FDTD Lumerical-Ansys) simulations. Both methods lead to the k-space coefficients of the polarization d_x, d_y that allow to identify the topological singularities and the far-field behaviour of the polarization. Moreover, we develop simple models that implement the symmetry properties of the lattice, which are crucial in determining the topological invariants.

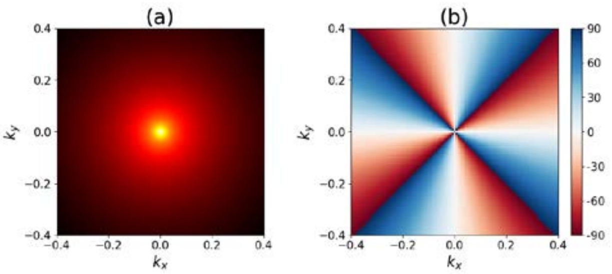

Fig. 1. (a) Q-factor and (b) phase of the polarization field in a PCS with hexagonal symmetry.

As an example, we show in Fig. 1 the quality factor and the phase of the polarization in a hexagonal PCS. The second photonic band has B-symmetry at the Γ point, leading to a BIC with infinite Q-factor. The polarization winds around the BIC with a topological charge $q = -2$.

For this kind of structures, we determine the degree of polarization in the far field by means of the Stokes parameters. The full Brillouin zone is mapped through GME and FDTD simulations. The normalized S_3 parameter is especially interesting as it determines the degree of circular polarization, which is nonvanishing only when the ratio d_y/d_x has a finite imaginary part. The conditions for the occurrence of a finite circular polarization, depending on the symmetry of the lattice and on the directions in k-space, are discussed.

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3 Optical reflection and circular dichroism

Optical spectra like reflection and transmission are well suited to excite the photonic modes of the PCS and to probe the far-field properties of the polarization. Here, we study reflection spectra for linear and circular polarizations, and focus on the Circular Dichroism (CD) in reflection as a measure of chirality of the metasurface. This quantity is defined as

$$\mathrm{CD}=\frac{R_{lcp}-R_{rcp}}{R_{lcp}+R_{rcp}}, \quad (1)$$

where R_{lcp} (R_{rcp}) is the reflectance for left- (right-) circular polarization. The CD can be nonvanishing at normal incidence for a chiral lattice (intrinsic chirality), or at oblique incidence along non-symmetry directions of the lattice (extrinsic chirality).

We calculate reflectance and CD spectra by a generalized scattering matrix method that relies on Bloch-mode expansion in each layer of a stratified medium, implemented in the EMUstack code [6]. Considering extrinsic chirality in nonchiral lattices, the CD has a nontrivial dependence on the incidence angle and on the azimuthal orientation. Importantly, the CD is correlated to the degree of circular polarization of the PCS resonances via the S_3 Stokes parameter. This relation, which was introduced recently by means of temporal coupled-mode theory [7], is here determined in a systematic way.

4 Conclusions

Topological singularities in dielectric metasurfaces bear a subtle relation to chiral optical properties in PCS. Such relation is analysized in this work by means of various symmetry-based and numerical approaches.

Acknowledgements

This work is partially supported from the Italian Ministry of University and Research (MUR) through 2017 PRIN project 2017MP7F8F-004 “NOMEN”.

References

1. B. Zhen et al., Phys. Rev. Lett. 113, 257401 (2014).
2. T. Yoda and M. Notomi, Phys. Rev. Lett. 125, 053902 (2020).
3. J.T. Collins et al., Adv. Opt. Mater. 5, 1700182 (2017).
4. L.C. Andreani and D. Gerace, Phys. Rev. B 73, 235114 (2006).
5. M. Minkov et al., ACS Photonics 7, 1729 (2020).
6. K.B. Dossou et al: J. Opt. Soc. Am. A 29, 817 (2012).
7. W. Chen et al., Phys. Rev. Lett. 126, 253901 (2021).