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Extreme nonreciprocity based on bound states in the continuum

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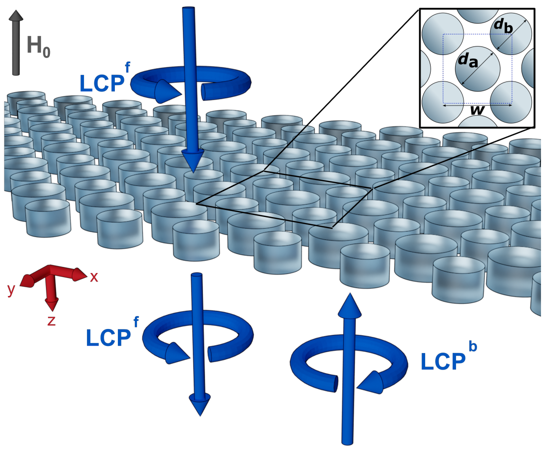
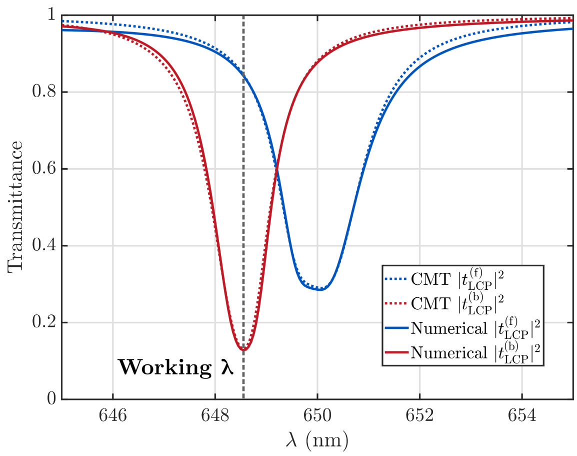
A common issue in developing nonreciprocal devices in the optical realm is the weak magneto-optical (MO) effects that ferrites present at the working wavelengths. There are different approaches to enhance the MO effect and reduce the size of a nonreciprocal device, such as exploiting the geometries of Mach-Zehnder interferometers, magnetic photonic crystals, coupled surface plasmon polaritons, or resonant metasurfaces. In the last few years, resonant metasurfaces have shown great potential due to their capacity to engineer propagating and evanescent fields that allow for enhancing the interaction between the incident waves and the constituent materials and control the scattering properties at will. In this presentation, we will demonstrate that strong nonreciprocity in transmission can be achieved in magneto-optical metasurfaces supporting quasi bound states in the continuum (quasi-BICs).

In order to design an optical isolator, the straightforward approach would be the creation of resonant Huygens meta-atoms made of low-loss ferrites to ensure full transmission and enhance the MO effect. Although it may seem like the way to go, the quality factors of conventional Huygens metasurfaces are insufficient to provide enough field enhancement, which leads to a weak overall MO effect in the metasurface.

In this work, we use quasi-BIC resonances that are able to produce Huygens pairs to achieve a greater enhancement of the electromagnetic (EM) field. By confining the EM fields into subwavelength meta-atoms, a greater nonreciprocal response is obtained. The metasurface topology used in this work [see Fig 1a] exploits the introduction of small asymmetries in the diameter of the nanodisks in the checker-board fashion [1, 2] to give rise to quasi-BIC states. The nanodisks diameters are defined as $d_\mathrm{a} = d + \Delta$ and $d_\mathrm{b} = d - \Delta$, where Δ is the parameter that accounts for the asymmetry. Both types of nanodisks are of the same height and are arranged in a square lattice of period w. The ferrite used, Bi3YIG [3], provides non-reciprocity to the structure. Furthermore, it also presents losses that allow the device to act as an isolator.



(a)



(b)

Figure 1. **(a)** Schematic of the ferrite-based metasurface supporting quasi-BICs and its geometrical parameters. The isolator working principle is shown. With a given fixed external magnetic field, at a certain working wavelength, the metasurface allows an LCP beam to pass through, but it absorbs the same beam in the opposite direction. **(b)** Scattering parameters of the device using the experimental data from Bi3YIG [3]. Energy transmission is depicted in the forward "f" direction and in the backwards "b" direction. The nonreciprocal behaviour is apparent in the obtained responses. The CMT fits are shown against the numerical results obtained using FEM analysis of the periodical structure.

We developed an optical metasurface isolator and a phenomenological explanation of it by using coupled-mode theory (CMT) and its mathematical formulation [4, 5]. The resulting equations can be fit to recreate the response obtained in the finite-element-method (FEM) simulations, depicted in Fig. 1b. Moreover, a simple eigenvalue study combined with the CMT results shows an approximate response of the device with a minimum computational effort. The discrepancies between CMT combined with an eigenvalue analysis and a full-wave simulation are due to the interference that happens between a continuous channel and a resonant state [6]. The theoretical model sheds light on the behavior of the system and thus serves as a guide in the design of metasurfaces with similar conditions. As it is shown in Fig. 1b, our design allows isolation for circularly polarized waves at 648.5 nm. On the one hand, left-handed circularly polarized (LCP) waves at the operation frequency will be transmitted in the forward direction with 85% efficiency and negligible reflection. On the other hand, the device absorbs the same polarization in the backward direction, allowing less than 15% of the energy to pass with reflections under 17%. The isolator mechanism works separately at different wavelengths with each handedness and can be switched by changing the direction of the external magnetic field.

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