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Nonreciprocal Huygens' Metasurfaces Based on Bound States in the Continuum

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Abstract – **Magneto-optical effects are typically very weak in the optical spectrum, and therefore, nonreciprocal devices based on them are very bulky. We demonstrate that optical metasurfaces supporting quasi-bound states in the continuum provide a powerful way for achieving strong nonreciprocal responses in a sub-wavelength geometry. Using the multi-mode temporal coupled-mode theory, we synthesize and analyze a nonreciprocal metasurface with Huygens' meta-atoms based on conventional ferrite materials exhibiting nearly-unity contrast in transmission for circularly polarized light.**

I. Introduction

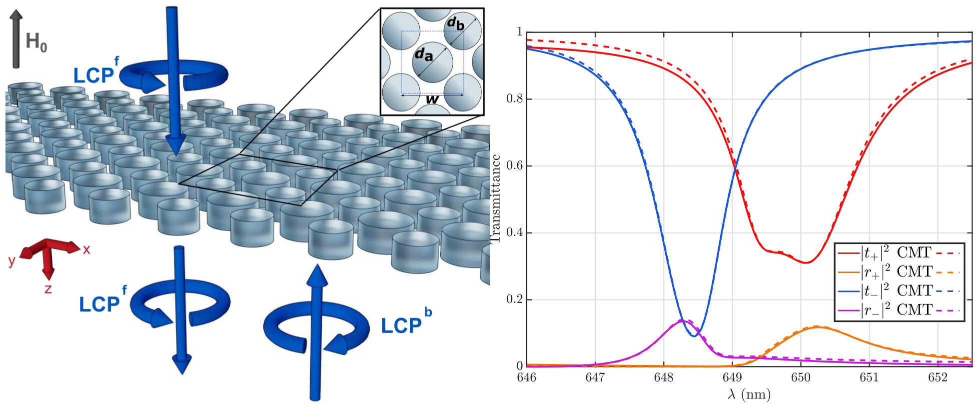
The development of nonreciprocal optical components is crucial for nanophotonic, optoelectronic, optomechanical, and quantum-optical applications. The traditional way of breaking reciprocity is based on magneto-optical (MO) effects in magnetized materials [1]. However, the MO effects are typically weak in the optical realm, and therefore, devices based on them must be very bulky (of the order of tens of centimetres – hundreds of thousands of wavelengths). There are different approaches to enhance the MO effects and reduce the size of a nonreciprocal device, such as exploiting the geometries of magnetic photonic crystals [2], coupled surface plasmon polaritons [3], or resonant metasurfaces [4]. 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 demonstrate that strong nonreciprocity in transmission can be achieved in magneto-optical metasurfaces supporting quasi-bound states in the continuum (quasi-BICs). BICs are states with theoretically unlimited quality factors [5]. We develop a coupled-mode theory (CMT) for the synthesis and analysis of the designed metasurface.

II. Geometry of the Problem

A geometrical description of the metasurface is presented in Fig. 1a. The metasurface consists of an array of dielectric nanodisks. The nanodisks diameters are defined as $d_{\text{a}} = d + \Delta/2$ and $d_{\text{b}} = d - \Delta/2$, where Δ is the parameter that accounts for the asymmetry [6]. The nanodisks support magnetic and electric dipole resonances at different wavelengths around $\lambda = 650$ nm, with the condition that neighbouring nanodisks support the same type of resonance but with opposite phase. These modes remain inaccessible without geometrical perturbation (i.e. $\Delta = 0$). They are known as symmetry-protected BICs. The most intuitive explanation of this phenomenon can be done in terms of induced dipoles. A checkerboarded array of nanodisks can be thought of as a superposition of two squared lattices, each holding a magnetic/electric dipole moment but with a π relative phase between lattices. In the unperturbed case, the superposition of both lattices cancels the far-field radiation and forms a symmetry-protected BIC.

In the perturbed case (i.e. $\Delta \neq 0$), a size difference between neighbours is introduced, and the electric/magnetic dipoles are not identical and do not resonate at the same exact wavelength. This geometrical mismatch induces a difference in amplitude and/or phase, enabling a non-perfect destructive superposition between squared lattices of dipoles in a narrow region of the spectrum, resulting in a high-Q resonance, i.e., a quasi-BIC. If losses are neglected, and no external magnetic field is applied, the symmetry point group of the structure (C_{4v}) ensures the two-fold degeneracy of the eigenmodes [7].



(a) (b)

Fig. 1: (a) Schematic of the metasurface topology. Light with circular polarization impinges on the metasurface at the normal incidence. The geometrical parameters are $d_a = d + \Delta/2$ for the diameter of type-a nanodisks, $d_b = d - \Delta/2$ for the diameter of type-b nanodisks, w for the squared lattice constant, h for the height of the nanodisks. The geometrical parameters are $d = 270$ nm, $\Delta = 20$ nm, $w = 430$ nm, and $h = 135.2$ nm. (b) Reflectances $|r|^2$ and transmittances $|t|^2$ of the magnetized metasurface in the circular-polarization basis. The solid and dashed lines represent results from full-wave simulations and coupled-mode theory, respectively.

Using a MO material to introduce nonreciprocity will affect the behaviour of the structure and its quasi-BICs. The simplest permittivity tensor, restricted to linear MO effects with the magnetic bias aligned with the z-axis has the form

$$\bar{\bar{\varepsilon}}(\omega, \mathbf{H}_0) = \begin{pmatrix} \varepsilon_{xx}(\omega) & j\varepsilon_{xy}(\omega, \mathbf{H}_0) & 0 \\ -j\varepsilon_{xy}(\omega, \mathbf{H}_0) & \varepsilon_{xx}(\omega) & 0 \\ 0 & 0 & \varepsilon_{xx}(\omega) \end{pmatrix}, \tag{1}$$

where ε_{xx} and ε_{xy} are complex permittivity functions and $\mathbf{H}_0$ is the external magnetic field along the z-axis. This permittivity tensor is not symmetric and consequently leads to a nonreciprocal behaviour [1]. We choose $\mathrm{Bi_3Fe_5O_{12}}$ (Bi3YIG [8]) as the material of the nanodisks. For such material, the ratio between the real parts of ε_{xy} and ε_{xx} is of the order of 0.05 in the considered frequency range. With the introduction of the external magnetic field, the point group symmetry of the metasurface is downgraded to C_4, and the degeneracy of the eigenmodes is lost. The magnetic and electric dipole resonances split. By exploiting this broken degeneracy, two pairs of electric and magnetic dipoles can be formed by tweaking the geometrical parameters. The electric dipoles radiate symmetrically with respect to the z-axis, while the magnetic dipoles radiate anti-symmetrically. Furthermore, the dipole pairs are orthogonal, making them Huygens pairs [9].

III. Results

We develop a multi-mode temporal coupled-mode theory [10] for the design and description of the nonreciprocal metasurface. The model allows us to explain and understand the scattering mechanism of the metasurface as well as how to optimize its nonreciprocal response. The dynamic equations for the nondegenerate resonant modes are given by

$$\frac{d\boldsymbol{\alpha}}{dt} = (j\Omega - \Gamma)\boldsymbol{\alpha} + K^T|a\rangle, \quad |b\rangle = C|a\rangle + D\boldsymbol{\alpha}, \tag{2}$$

where D is the output coupling $m \times n$ matrix, n is the number of resonant nondegenerate orthogonal modes, and m is the number of ports ($n = m = 4$ in the present case). Furthermore, C is the direct pathway scattering matrix of $m \times m$ size, K is the input coupling matrix of $m \times n$ size, Γ and Ω are $n \times n$ matrices which correspond to the decay rates and the resonance frequencies, respectively. In Eq. (2), $\boldsymbol{\alpha}$ vector contains the amplitudes for each resonant mode, while $|b\rangle$ and $|a\rangle$ vectors account for the output and input waves. The system properties of nonreciprocity and C_4 symmetry restrict the scattering matrix to have the form:

$$\mathbf{S}^{(xy)} = \begin{pmatrix} r & t & r_{xy} & t_{xy} \\ t & r & t_{xy} & r_{xy} \\ -r_{xy} & -t_{xy} & r & t \\ -t_{xy} & -r_{xy} & t & r \end{pmatrix}, \mathbf{S}^{(+-)} = \begin{pmatrix} r_+ & t_+ & 0 & 0 \\ t_+ & r_+ & 0 & 0 \\ 0 & 0 & r_- & t_- \\ 0 & 0 & t_- & r_- \end{pmatrix} = \begin{pmatrix} r^{\text{f}}_{\text{R-L}} & t^{\text{b}}_{\text{L-L}} & 0 & 0 \\ t^{\text{f}}_{\text{R-R}} & r^{\text{b}}_{\text{L-R}} & 0 & 0 \\ 0 & 0 & r^{\text{f}}_{\text{L-R}} & t^{\text{b}}_{\text{R-R}} \\ 0 & 0 & t^{\text{f}}_{\text{L-L}} & r^{\text{b}}_{\text{R-L}} \end{pmatrix}, \quad (3)$$

where $\mathbf{S}^{(+-)}$ is the scattering matrix in the circular-polarization basis with basis vectors $\mathbf{e}_\pm = (\mathbf{e}_x \mp j\mathbf{e}_y)/\sqrt{2}$. The elements of this matrix are $t_+ = t + jt_{xy}$, $r_+ = r + jr_{xy}$, $t_- = t - jt_{xy}$ and $r_- = r - jr_{xy}$. In the right equation in (3), the superscripts "f" and "b" indicate forward ($+z$) or backward propagation ($-z$), and the subscripts "L" and "R" indicate the left and right handedness, respectively. On a circular basis, nonreciprocity doesn't lead to a nonsymmetric scattering matrix, as discussed in [11].

By tuning the metasurface geometric parameters, we are able to maximize the contrast between transmittances $|t^{\text{f}}_{\text{L-L}}|^2$ and $|t^{\text{b}}_{\text{L-L}}|^2$. The maximal contrast of unity would imply that light with left-handed circular polarization transmits only in one direction through the metasurface, and nonreciprocity is maximized. Figure 1b plots these transmittances versus wavelength in free space λ. The theoretical results from the coupled-mode theory are in excellent agreement with the results obtained through full-wave simulations. While nearly 89% of incident left-handed circularly polarized light is transmitted for the forward illumination, only 9% of light energy passes through the metasurface for the backward illumination. Most of the light energy is absorbed in the latter scenario. Remarkably, such high transmittance ratio is achieved despite the subwavelength ($h = 0.2\lambda = 135.2$ nm) thickness of the metasurface.

IV. Conclusion

We have developed a nonreciprocal metasurface exhibiting handedness-selective one-way transmission empowered by quasi-BICs arranged in Huygens pairs. A phenomenological coupled-mode theory model was constructed to reproduce the nonreciprocal behaviour of the metasurface, showing great agreement with the finite-element-method simulations. Moreover, the model demonstrates that a strong nonreciprocal optical response can be achieved in a subwavelength setting with conventional magneto-optical materials. The proposed metasurface when combined with other reciprocal components (such as polarizers) can operate as a narrow-band optical isolator for arbitrary polarization of light.

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