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The Origin and Limit of Asymmetric Transmission in Chiral Resonators

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Abstract: We develop a theoretical formalism which explains asymmetric transmission (AT) in chiral resonators from their eigenmodes. We derive a fundamental limit for AT and propose the design of a chiral photonic crystal offering 84% AT.

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A strong chiral response is essential for realizing devices that can manipulate the polarization of light. Natural chiral materials rely on bulk properties including birefringence and result in thick and bulky devices for polarization control. Much stronger chirality can be realized by exploiting the interaction of light with artificial nanostructures, for e.g., metasurfaces or photonic crystals. An extreme possible consequence of the chirality of a system is asymmetric transmission (AT), the difference in total transmittance when light with a certain polarization impinges from opposite sides of the system [1]. Notably, when an emitter is placed in asymmetrically transmitting systems, this strong chirality also implies a significant difference between the polarizations of the emitted light in opposite sides of the system. Realization of AT in nanostructures thus relates directly to potential functionalities such as polarization control of spontaneous emission, spin-dependent light emission and enantioselective sensing. To realize AT for linearly polarized light is significantly challenging, as it strictly requires broken mirror symmetry in the propagation direction [2]. Important open questions remain, like how to introduce an efficient symmetry breaking, what is the maximum AT that can be achieved, and how to design structures that can offer this maximum AT.

Here, we investigate in detail the AT for linearly polarized light in dielectric chiral resonators. We show that the quasinormal modes of the system can be used to predict the AT for any system. We develop a theoretical formalism to find structures that can offer very high AT. Comparing full-field simulations to original theory, the origin and limits of AT are explored in terms of the properties of the quasinormal modes of the system. We uncover an important relation between the AT, which is a resonant phenomenon, and the direct reflectivity, which is a non-resonant property of the system. This relation, derived from the principle of reciprocity, creates a fundamental limit for AT in any chiral resonator. Following an optimization strategy to conform to this result, an example design for a photonic crystal structure with subwavelength thickness that can offer AT as high as 84% is proposed.

Even though our conclusions and methodology apply to any general photonic systems, we illustrate them here with a specific example, a dielectric bilayer photonic crystal slab. We consider light that propagates perpendicular to the plane in which the structure is periodic. A unit cell of the 2-D periodic structure is shown in the inset of Fig. 1a. It is composed of two rectangular air holes stacked in mutually perpendicular fashion in a high-index ($n = 3.48$) material. The orthogonal arrangement of holes breaks mirror symmetry in the propagation direction. Dashed lines in Fig. 1a show the finite-element simulation results for forward and backward transmittances and AT. As evident from the figure, the AT has pronounced features around certain frequencies. The resonant nature of this chiral response hints at a connection between the response and resonant modes of the structure. We calculate the eigenfrequencies of the structure (orange triangles in Fig. 1a) for a parallel wavevector of zero. These simulations reveal that the resonances in the AT spectrum indeed coincide with the real parts of the eigenfrequencies of the structure, indicating a strong relation between the AT and the complex-frequency modes of the structure.

We use this understanding of the origin of AT to develop a theoretical formalism to predict AT from the properties of these eigenmodes. Building upon Ref. [3] and our recent work on quasi-normal mode expansion of scattering matrix [4], we develop a theoretical formalism to predict AT as well as the forward and backward transmittances. The predicted quantities are represented by solid lines in Fig. 1a and correspond very well with the simulation data. For isolated single modes, this theory can be simplified further and AT can be predicted as the first normalized Stokes parameter of the mode's polarization in the far-field. This very simple, yet powerful relation holds a huge potential for

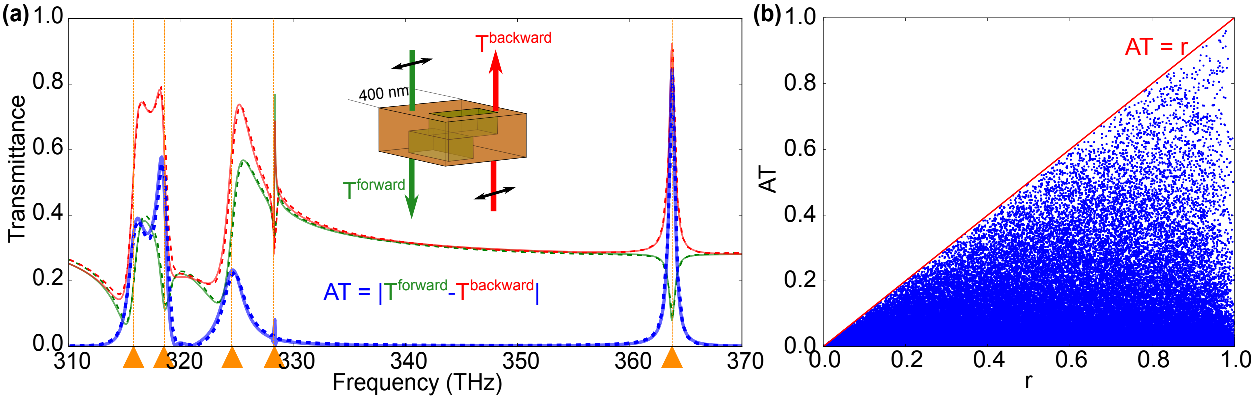

Fig. 1. (a) Forward (green) and backward (red) transmittances and AT (blue) as a function of frequency of the linearly polarized incident light. The dashed lines correspond to the FEM simulation data and solid lines feature transmittances predicted by our theoretical formalism. Orange triangles represent the calculated real parts of the eigenfrequencies of the structure for zero parallel wave vector. Inset shows a unit cell of the proposed structure. (b) Scatterplot of AT vs the non-resonant reflection coefficient r for 100,000 random eigenmode polarizations in a structure without any specific symmetry properties. Solid red line corresponds to AT = r.

obtaining the maximum possible AT for any structure by parametric optimization. AT can be maximum when an eigenmode is completely linearly polarized along the chosen input polarization direction. However, we find that a mode can be linearly polarized only if the corresponding non-resonant transmission coefficient t is zero. This constraint arises from the principle of reciprocity, which relates the polarization parameters of the resonant mode to the non-resonant scattering properties of the structure. Using the principle of reciprocity, we calculate the fundamental limit for AT in any system as the corresponding non-resonant, effective Fabry-Perot background reflection coefficient, r of the system. To illustrate the fundamental limit for the AT offered by any single-mode resonator regardless of its symmetry properties, in Fig. 1b we show the calculated AT for an isolated mode for 100,000 randomly chosen points in the polarization space as a function of r. It can be observed that all the values are below or at the predicted fundamental limit, r. It must also be noted that most of the random polarizations exhibit an AT significantly lower than the fundamental limit. Only very few combinations of polarization parameters can produce an AT close to the fundamental limit. With an educated choice of structural symmetry and a proper optimization of structural parameters, we can design structures that offer an AT near the fundamental limits. The proposed design shows a very high AT of 84% for an isolated mode.

In conclusion, we showed that the AT in chiral resonators depends strongly on the far-field properties of their eigenmodes. We developed a theoretical formalism that can predict AT offered by any system from its complex eigenmodes. We investigated the theoretical maximization of AT in chiral resonators. A fundamental limit for AT provided by a single mode is presented. We also proposed the design for a chiral photonic crystal that can offer AT as high as the fundamental limit, which is the non-resonant reflection amplitude of the system. The theoretical formalism presented here opens ways for designing and optimizing new structures for light manipulation.

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