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Flat Pathways to Maximum Optical Chirality

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Abstract – **Dielectric metasurfaces with eigenstates designed to selectively couple to circularly polarized light offer a game-changing platform for advanced chiral metaphotonics. Current designs rely on breaking the mirror symmetry by variable height, elevation or tilt of subwavelength meta-atoms, which complicates their fabrication. We discuss novel strategies for achieving maximum optical chirality with metasurfaces composed of flat layers processed with conventional two-dimensional lithography. Apart from extrinsic-chiral arrangements, which owe their broken mirror symmetry to a sample tilt, various single- and multi-layer designs are capable of maximizing intrinsic chirality at the normal incidence. We reveal specific conditions, when even weak symmetry-breaking effect of a transparent substrate can lead to maximum chirality.**

I. Introduction

Since optical chirality inherently requires the absence of a mirror symmetry, the chiral meta-optics, for decades, relied on complex meta-atoms resembling screws, springs, and spirals [1]. Recent rapid progress in the design and fabrication of dielectric metasurfaces has triggered pivotal changes as meta-structures of simpler shapes made of transparent materials with high refractive index can host eigenstates selectively coupled to circularly polarized light [2, 3]. Their transmission and reflection resonances can approach the ultimate limit of maximum optical chirality [4] enabling efficient filtering, emission, and detection of chiral light. The corresponding optical devices are desired for chiral sensing, for multiplexed telecommunication and quantum optics, and for chiral photochemistry [5].

Fabrication of optical dielectric metasurfaces relies on advanced nanotechnologies with all different lithographic steps perfected for producing precisely shaped holes and slits with vertical walls in layers of a constant thickness. Apparently, the resulting structures on their own retain a mirror symmetry plane passing through their middle, and the lack of geometric chirality substantially limits optical chirality. Known ways to break the mirror symmetry include relative shifting [2] or tilting [6] meta-atoms. Crafting silicon particles of different heights using the two-step nanolithography was recently implemented for the first demonstration of close-to-maximum optical chirality [7]. However, all such approaches require additional technological complications.

Clearly, feasibility of chiral metasurfaces for the fabrication by conventional one-step lithography will substantially facilitate their practical implementations. Here we compare different approaches to designing flat metasurfaces with strong optical chirality and illustrate them by numerical modeling of some examples.

II. Design strategies

Optical chirality of dielectric metasurfaces is determined by the chiral selectivity of excitation and irradiation of their eigenstates. For an eigenstate polarization current density $\mathbf{J}(\mathbf{r})$, the corresponding parameters $m_{R,L}$ of coupling to the right and left circularly polarized (RCP and LCP) waves are determined by the overlap integrals $m_{R,L} \propto \int_V e^{i\mathbf{kr}}\mathbf{J}(\mathbf{r}) \cdot \mathbf{e}_{R,L}\, dV$, where $\mathbf{k}$ is the wavevector of the incoming or outgoing RCP or LCP wave, and $\mathbf{e}_{R,L}$ are the electric field unit vectors, as, e.g., $\mathbf{e}_{R,L} = (\mathbf{e}_x \mp i\mathbf{e}_y)/\sqrt{2}$, when $\mathbf{k}$ is along the z-axis for a normally incident wave. Strong optical chirality requires m_R and m_L to be substantially different, and maximum chirality occurs, when one of them completely vanishes.

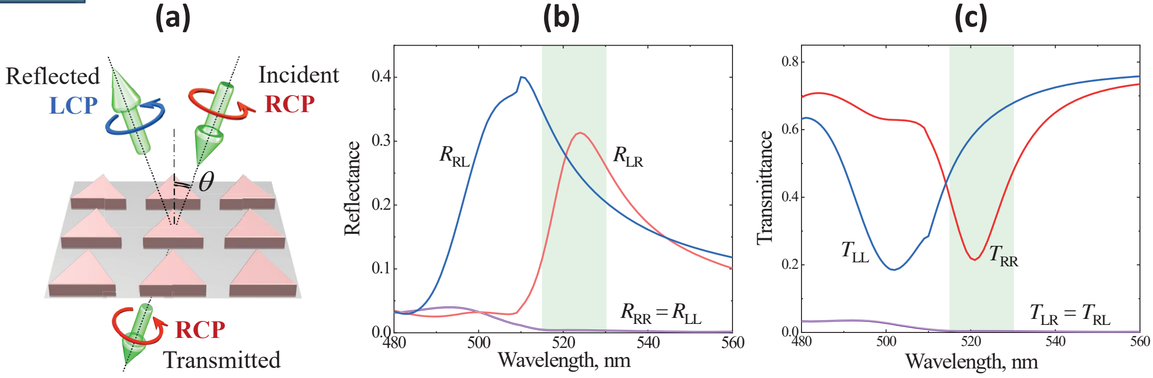

Fig. 1: Extrinsic chirality of an array of silicon triangular resonators illuminated at an angle $\theta = 12.5°$: (a) sketch of resonant transmission and reflection of RCP waves and simulated spectra of co-polarized and cross-polarized reflectance (b) and transmittance (c) for the metasurface as a part of electroluminescent chiral light source [8].

Symmetric arrays for extrinsic chirality. For highly symmetric metasurfaces, as the one in Fig. 1, optical chirality is forbidden at normal incidence, since $m_R = m_L$ due to the parity of eigenstate current. However, selective interaction with RCP/LCP waves is possible for oblique incidence. Notably, silicon particles of a basic triangular shape can be optimized to host eigenstates with a high chiral coupling selectivity. This allows employing such metasurface as a part of metacavity for chiral electroluminescence in a broad range of oblique directions [8].

Multilayered structures. To achieve strong intrinsic chirality, the planar mirror symmetry can be lifted by splitting flat meta-atoms into layers with different refractive indexes. Then the eigenstate current density looses its parity, and one can optimize the state for full isolation from RCP or LCP waves. Especially intriguing is the possibility to engineer chiral quasi-bound states in the continuum (quasi-BICs) by combining an in-plane symmetry breaking perturbation, controlling the strength of eigenstate coupling to free-space waves, with the layering, giving rise to optical chirality. As an example, we show in Fig. 2 simulations of a metasurface made of layers of standard materials with tabulated properties. It lacks any point symmetry elements and hosts a non-degenerate chiral quasi-BIC underpinning a narrow RCP reflection resonance, while all LCP waves freely pass through. Naturally, the resonant wavelength can be adjusted within the transparency window of all materials.

Mirror symmetry broken by a substrate. The planar mirror symmetry of most lithographically cut metasurfaces is formally broken by substrates which refractive index is different from the environment. Although the related effects are typically subtle, it is possible to maximize the intrinsic optical chirality relying on peculiar hybridization of photonic eigenstates, which can be analyzed in terms of the resonant-state expansion theory [9]. In the absence of

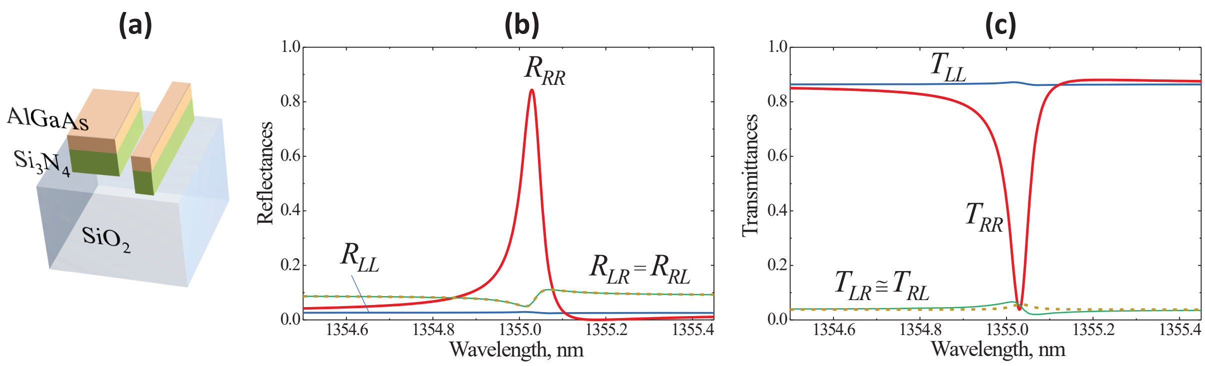

Fig. 2: Intrinsically chiral metasurface built as an array of rectangular particles cut from a bilayer of typical dielectric materials upon a glass substrate: (a) schematic of a square unit cell of the 900 nm periodic structure; and the simulated spectra of co-polarized and cross-polarized reflectance (b) and transmittance (c) in the vicinity of the resonance underpinned by the chiral quasi-BIC.

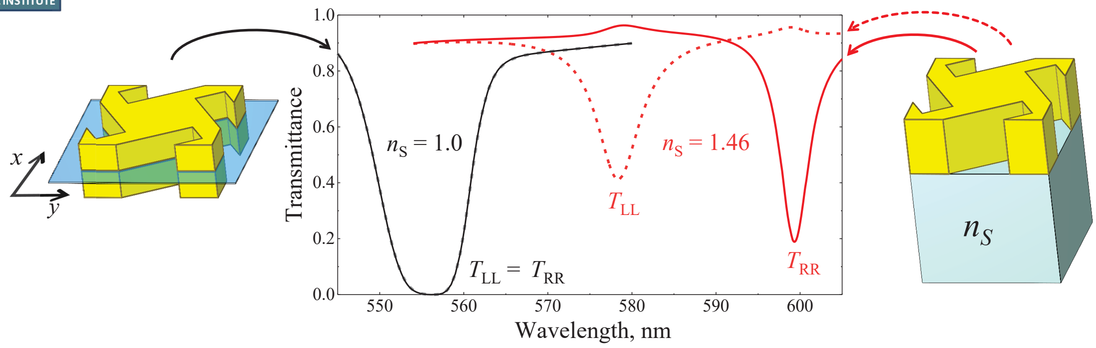

Fig. 3: Intrinsic chirality of a flat layer of material of a refractive index $n = 2.2 + 0.004i$ perforated with a C_4-symmetric array of holes. It remains optically achiral without the substrate (the substrate refractive index $n_S = 1.0$), and approaches maximum chirality when $n_S = 1.46$. The unit cells of the structures of a period of 380 nm are shown on the sides of the transmission spectra.

substrate, the states possess spatial parity, and the metasurface remains optically achiral. When a substrate is added, the states with close eigenfrequencies and opposite parity merge into hybrids with circularly polarized far-field asymptotics. In Fig. 3 we show simulated sharp close-to-maximum chiral transmission resonances underpinned by such states of a flat layer perforated with a C_4-symmetric array of holes. The rotation symmetry determines that the array resonantly absorbs blocked LCP and RCP waves.

III. Conclusion

The discussed pathways for maximizing optical chirality rely on high-quality photonic eigenstates selectively coupled to RCP or LCP waves. The illustrative examples show different approaches to break the out-of-plane mirror symmetry. The modeled metasurfaces also possess different in-plane point symmetry, which defines whether they perform as chiral reflectors or absorbers. Combining the optimal in-plane point symmetry with the convenient way of breaking the out-of-plane symmetry, one can meet the requirements of a particular application.

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