Chiral light in single-handed Fabry-Perot resonators

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Abstract. Chirality is a universal phenomenon that is encountered on many different length scales in nature. Interaction of chiral matter with chiral light results in the effect of circular dichroism, which underlies many techniques of discriminating molecular enantiomers. Enhancing dichroic effects is typically achieved by interfacing chiral matter with various optical resonators. In this context it is important to understand how the eigenmodes of optical cavities relate to the field states with well-defined handedness. Here, we present the model of a single-handedness chiral optical cavity supporting only an eigenmode of a given handedness without the presence of modes of other helicity. Resonant excitation of the cavity with light of appropriate handedness enables formation of a helical standing wave with a uniform chirality density, while the opposite handedness does not cause any resonant effects. Our findings expand the set of tools for investigations of chiral matter and open the door towards studies of chiral electromagnetic vacuum states.

1. Introduction

Interaction of chiral electromagnetic field with chiral matter results in the well-known effect of circular dichroism, which underlies numerous techniques of discriminating molecular enantiomers [1]. Enhancing dichroic effects is typically achieved by interfacing chiral matter with various optical resonators [2,3]. For this reason, it is important to understand how the eigenmodes of optical cavities are projected onto the field states with well-defined handedness. Considering the classical type of an optical cavity - a Fabry-Perot (FP) resonator formed by two homogeneous metallic mirrors - one could expect that excitation of such a cavity with a circularly polarized light would result in excitation of a helical FP mode. In reality, eigenmodes of a FP cavity (at normal incidence) do not have any helicity [4] - helicity flipping of the wave travelling between the two mirrors creates a standing wave with exactly zero helicity, as sketched in Fig. 1(a). In the context, the concept of duality [5] plays an important role: dual structures preserve the handedness of incident light upon scattering, thus allowing existence of eigenmodes of well-defined helicity.

This poses a quest for optical cavities supporting eigenmodes of well-defined handedness [6]. An additional requirement that one could impose is that the structure supports an eigenmode of a certain handedness only, but not that of the opposite one (at least in the given spectral range). That would result in a single-handedness chiral optical cavity that would couple efficiently to emitters of a certain handedness, and considerably weaker to the opposite enantiomer. A progress has been made in design of helicity-preserving cavities that are based on excitation of large in-plane momentum modes [7]. However, such cavities possess mirror or inversion symmetry and therefore support eigenmodes of both helicities at the same time.
In this paper, we theoretically investigate a system fulfilling this requirement - an optical resonator supporting a single eigenmode of well-defined helicity, and lacking modes of opposite helicity in the appropriate spectral range. The proposed structure is a FP cavity formed by a stack of two photonic crystal slab mirrors [8]. The handedness preserving property of the mirrors allows resonant excitation of a standing helical wave of a certain handedness inside the cavity, while at the same time completely transmitting waves of the opposite handedness. The proposed system expands the set of tools available for investigations of chiral matter and opens the door to studies of chiral electromagnetic vacuum.

2. Results

In order to implement the desired modal spectrum of the cavity, we need to have at our disposal a reflecting structure that preserves handedness of the reflected wave, but is transparent to the opposite handedness, as sketched in Fig. 1(b,c). To that end, we utilize the geometry proposed in ref. [8]. The helicity-preserving mirror is a dielectric photonic crystal slab with a square lattice and its unit cell possessing only the mirror symmetry with respect to the horizontal plane $M_{xy}$ and two-fold rotational symmetry around the z-axis $C_{2,z}$, Fig. 1(d). $M_{xy}$ ensures that the single mirror itself is not chiral, while $C_{2,z}$ allows conversion between clockwise and counter-clockwise polarization in reflection, necessary for handedness preservation. At the same time, $C_{2,z}$ makes the effect slightly more robust with respect to the incidence angle.

We begin by designing a single mirror made of a dielectric with refractive index $n = 4$ in air featuring the desired spectral characteristics at a fixed wavelength of 800 nm. By optimizing the structure with the use of the particle swarm algorithm (and keeping sub-diffraction lattice periodicity), we find the set of unit cell dimensions yielding near-perfect polarization conversion for normally incident light of both helicities: thickness $H = 142$ nm, unit cell size $L = 366$ nm, $r_c = 90$ nm, $r_x = 89$ nm, $r_y = 34$ nm, $C_x = 59$ nm, $C_y = 104$ nm.

![Fig. 1. (a-c). Concept of a single-handedness cavity. An ordinary achiral cavity, (a), does not support chiral eigenmodes due to handedness flipping of the standing wave inside the cavity. A single-handedness optical cavity supports a mode of a well-defined handedness, (b), and does not support a mode of the opposite handedness at the same wavelength, (c). (d) The unit cell of the photonic crystal slab mirror featuring handedness-preserving reflection at normal incidence. (e) Reflection and transmission coefficients of the optimized mirror in the circular polarization basis for the LH incidence exhibiting near-unity reflection with preserved handedness. (f) Reflection and transmission coefficients of the optimized mirror for the RH incidence exhibiting near-complete transmission.](image-url)
With these dimensions, LH light normally incident from top is nearly perfectly reflected with handedness preservation, $|\tau_{l}| \sim 1$, while a RH incident plane wave is nearly perfectly transmitted into the opposite handedness, $|\tau_{r}| \sim 1$, Fig. 1(e,f).

Now we stack two such mirrors to form a cavity. In order to find the optimal cavity thickness sustaining a chiral eigenmode, we simulate volume-average electric field enhancement in the region inside the cavity and sweep the distance between the mirrors $L$. For thickness $L=1724$ nm the field enhancement spectra demonstrate handedness-selective electric field enhancement for LH excitation at the wavelength of $\lambda_{res} = 798$ nm, and much weaker enhancement for RH excitation, Fig. 2(b).

Furthermore, the electric field intensity inside the cavity plotted at $\lambda_{res}$ demonstrates strikingly different spatial distributions for two incident polarizations. Field induced by the incident RH light features a typical standing wave pattern with alternating peaks and troughs caused by the non-zero reflection of the wave by each of the mirrors. The LH excitation, on the contrary, features a region of nearly uniform electric field intensity. Such a pattern is indicative of the helical standing wave, or so-called polarization standing wave formed by two counter-propagating plane waves of the same handedness.

![Fig. 2.](image)

(a) Illustration of the formation of a standing chiral wave in the region between two handedness-preserving mirrors. (b) Volume-average electric field enhancement in the region inside the cavity for the cavity thickness $L = 1724$ nm for RH and LH excitations at normal incidence. (c) Spatial distribution of electric field intensity inside the cavity induced by the LH incident wave at the resonant wavelength $\lambda_{res} = 798$ nm; the field is plotted in the two vertical middle planes of the unit cell. (d) The same as (c) for RH excitation. (e) Normalized optical chirality density $C$ for the LH illumination at $\lambda_{res} = 798$ nm indicating excitation of a pure RH cavity mode. (f) The same as (e) for the RH excitation.

In order to confirm the excitation of a chiral cavity mode by the LH incident light, we calculate the optical chirality density $C$ inside the cavity: $C = \frac{\alpha E_0}{\mu} \Im(\mathbf{E} \cdot \mathbf{B}^*)$. The resulting spatial distribution of $C$ (normalized by the absolute value of the chirality density of the incident circularly polarized wave $C_0$) at the resonant wavelength $\lambda_{res} = 798$ nm for a LH excitation clearly demonstrates a uniform region of largely enhanced positive chirality density inside the cavity, Fig. 2(e), suggesting excitation of RH fields. RH excitation, at the same time, results in a significantly lower magnitude of chirality density, which is also positive, indicating that the RH illumination also partially couples to the RH chiral mode.
3. Conclusions
To conclude, we have introduced the concept of a single-handedness chiral optical cavity. By utilizing the design of helicity-preserving photonic crystal mirrors, we engineered a Fabry-Perot cavity that supports an optical eigenmode of a well-defined handedness, and does not support the opposite handedness in the relevant wavelength range. Upon excitation, such a cavity features a uniform region of enhanced electromagnetic field intensity and chirality density. The concept of single-handedness optical cavity adds a new tool for investigations of chiral matter and opens the door towards studies of chiral electromagnetic vacuum states.

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