Circularly polarized light generating optical forces between chiral metasurfaces

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Optical forces provide a reliable tool to trap and rearrange subwavelength objects such as nanospheres and nanowires. In recent years, the forces between stacked metasurfaces have attracted significant interest as a scalable mechanism to design nonlinear and tunable metamaterials. In this work, we investigate the optical forces that arise when chiral metasurfaces are illuminated by circularly polarized light. Using the Maxwell stress tensor formalism we calculate the momentum transfer based on full-wave numerical simulations. We observe a rich variety of optical forces, distinguishing scattering, gradient and chiral contributions. Our results pave the way for the development of nonlinear chiral metasurfaces.

Introduction

Metasurfaces make use of artificially structured layers to control a multitude of electromagnetic properties, manipulating the electromagnetic force [1-2], momentum [3], spin [4], polarization [5] and angular momentum [6] of electromagnetic waves. The separation distance between structured layers crucially determines the effect of metasurfaces on the incident light [2,7]. Because electromagnetic forces provide a reliable way to tune the separation distance in terms of the incident power, several research groups investigate the use of electromagnetic forces to design nonlinear metasurfaces [7-9]. In this contribution, we consider the optical forces arising due to circularly polarized electromagnetic radiation as they interact with chiral bilayer metasurfaces to develop a tunable chiral response.

Optical activity and dichroism in metamaterial bilayers

Following pioneering work of Jean-Baptiste Biot, it has been known for two centuries that the polarization of light in natural chiral materials such as quartz, sugars and DNA changes both in orientation (optical activity) and in kind (ellipticity) [10]. Experimental investigations by Pasteur (1860) led to the hypothesis that chiral media consist of elemental structures without inversion symmetry, allowing to distinguish left- and right-handed structures. When the number of left- and right-handed structures are imbalanced, the medium is chiral and treats circularly polarized eigenmodes, left (LCP) and right (RCP), in distinct ways. In particular, the eigenmodes propagate at different phase velocities and are subject to different attenuation coefficients, which is characterized by a complex chirality parameter κ.
Chiral metamaterials [10-11] make use of artificial building blocks such as gammadions [12], crossed wires [13] or rosettes [14] to enhance chiral effects [15] and to induce new electromagnetic behaviour such as circularly polarized waves with negative refractive indices [10-13,16-17]. Microscopically, the artificial building blocks impose (partially)

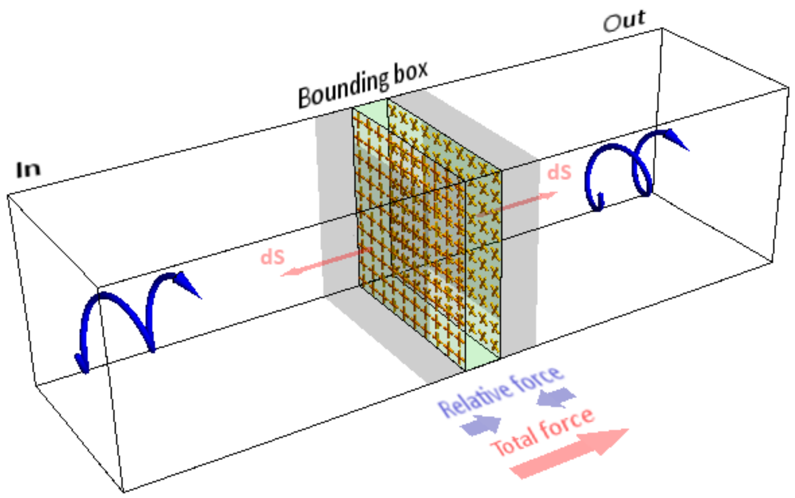

Figure 1: The optical force due to circularly polarized radiation on a bilayer metasurface decomposes into a relative force between individual sheets and a total repulsive force. The bounding box allows calculating the optical forces with the Maxwell stress tensor formalism.

parallel electric and magnetic dipole moments to realize large chirality parameters at the macroscopic level.

Optical forces to position small nanostructures and surfaces

The seminal work of Arthur Ashkin and coworkers demonstrated that electromagnetic forces due to laser radiation can be sufficiently large to manipulate the position of small dielectric particles [18] or atomic-sized objects [19] to high precision with optical traps. In classical electrodynamics [20], the incident momentum of laser radiation indeed yields two contributions to the overall optical force that are crucial to optical traps: the gradient force can be used to move objects orthogonally to the direction of the beam propagation, whereas the scattering force only acts along the direction of propagation [21-22].

Electromagnetic forces between metasurfaces are both determined by the elementary properties of subwavelength objects and the properties of the incident light. On the one hand, the frequency-dependent electric and magnetic dipole resonances on metasurfaces provide a playground for observing optical forces. Nanowire metamaterial sheets, for example, either repel or attract each other depending on the strength of their magnetic and electric dipole resonances [2]. Chiral objects also display interesting dynamic behaviour, as they can be pulled by Bessel beams [23] and discriminated by gradient forces [24]. On the other hand, structured light [25-27] transfers spin or orbital angular momentum to the metasurface, adding new contributions to the force equations.

With incident circularly polarized light, we will explore the frequency-dependent transfer of linear and angular momentum on chiral metasurfaces.

A numerical approach: the Maxwell stress tensor formalism

In Fig. 1 we introduce our numerical setup for investigating electromagnetic forces between cross-wire metasurfaces due to incident circularly polarized light. To extract the forces from full wave numerical simulations, we rely on the Maxwell stress tensor formalism [20]. Indeed, due to conservation of total linear momentum, the time-averaged force on a metamaterial sheet

$$\langle F_i \rangle = \oint \langle T_{ij} \rangle dS_j \ , \qquad (1)$$

can be calculated as the flux integral of the Maxwell stress tensor T_{ij} along an arbitrary surface enclosing the object of interest with

$$\langle T_{ij} \rangle = \frac{1}{2} \mathrm{Re}\left[\varepsilon_0 \left(E_i E_j^* - \frac{1}{2} \delta_{ij} \sum E_k E_k^* \right) + \mu_0 \left(H_i H_j^* - \frac{1}{2} \delta_{ij} \sum H_k H_k^* \right) \right]. \qquad (2)$$

Equations (1)-(2) are a consequence of the conservation of total linear momentum and, therefore, contain all scattering and gradient contributions to the electromagnetic force. We emphasize that the momentum inside an arbitrary box, which contains the metamaterial sheet, either changes because of a mechanical force F_i or because of flows in energy-momentum T_{ij} through surfaces of the box with normal *j*. In this way, the Stokes theorem allows evaluating the optical force on a metamaterial sheet by calculating a surface integral, Eq. (1), on the bounding box. In summary, the Maxwell stress tensor formalism allows calculating the relative forces between the rightmost and leftmost layer with numerical surface integrals, providing valuable information about the relative distance between the sheets and the associated electromagnetic properties.

Results

The scattering force on both layers of the bilayer metasurface is decomposed into two contributions: the total force acting on the centre of mass (F_R + F_L) and the relative force determining the separation distance (F_R-F_L). Although both contributions do not change with the incident polarization, the electromagnetic force does depend on changes in polarization. Indeed, the frequency dependence of the reflectance component that preserves the initial polarization is clearly followed by the total force, whereas the frequency dependence of the reflectance leading to an opposite circular polarization state is followed by the relative force.

The total scattering force is quite small, having maxima of 6 nN/W at two resonance frequencies. Luckily, only the relative force is relevant for changes in separation distance. The relative force is largely repulsive in the resonance frequency window of the metasurface, obtaining maxima from 100 nN/W to 1000 nN/W as separation distances decrease from 2.4 mm to 0.4 mm for initial wavelengths surrounding 2.7 mm. We notice that, for this range of separation distances, the optical activity of the metasurface changes drastically due to electromagnetic coupling between both sheets as they approach each other, as modelled by the Born-Kuhn model [15]. Therefore, when balanced by a restoring force due to an elastic substrate, relative optical forces are sufficiently large to tailor the electromagnetic properties of chiral metasurfaces in a nonlinear way.

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