Coherent Control of Birefringence and Optical Activity

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Abstract: Control of polarization of light with light is demonstrated in thin slabs of linear material promising ultrafast all-optical data processing at arbitrarily low intensities. In proof-of-principle experiments we access any polarization azimuth and any ellipticity.

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1. Introduction

Conventional electromagnetic materials are often used in bulk form, however, many useful functionalities can be realized with metamaterials of sub-wavelength thickness. Thin functional layers open up a new opportunity for control of light with light without nonlinear media [1-3]. As illustrated by Fig. 1, the metamaterial can be placed at an anti-node or node of the interference pattern formed by counter-propagating coherent electromagnetic waves leading to enhanced or zero electric excitation of the structure and control of any associated properties. Similarly, the magnetic excitation of thin materials can be controlled. By adjusting the phase difference between the incident "Signal" and "Control" beams, the material excitation and associated scattered fields can be continuously adjusted, providing opportunities for modulation of metamaterial functionalities as well as coherent spectroscopy.

Here we explore how interaction of two waves on a thin sheet of material can be used to control the polarization effects associated with linear birefringence and optical activity. Based on proof-of-principle experiments in the microwave part of the spectrum we demonstrate coherent polarization rotators and coherent ellipticity modulators.

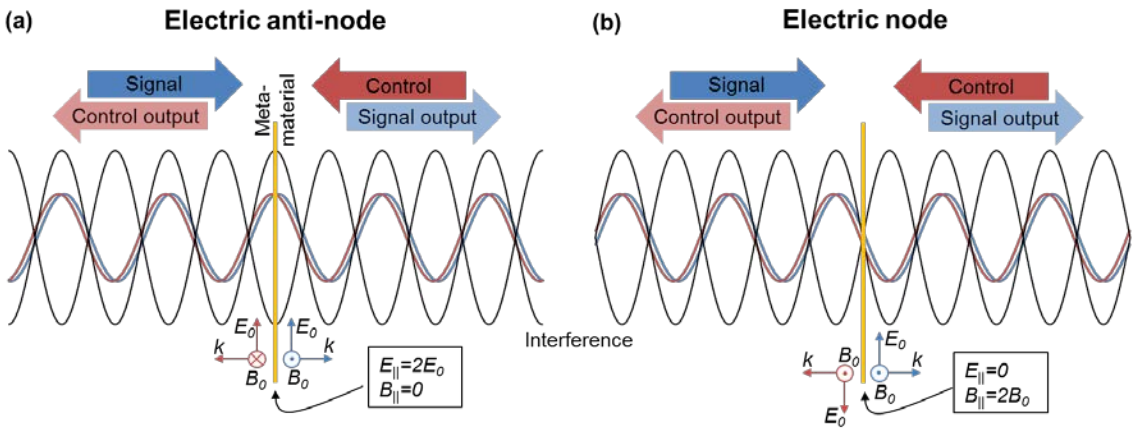

Fig. 1. Coherent control of metamaterial functionalities. Coherent counterpropagating beams "Signal" and "Control" form an interference pattern. A functional material of substantially subwavelength thickness can be placed at a position of (a) constructive interference or (b) destructive interference of the incident electric fields E_0 leading to enhanced or vanishing electric excitation of the material, respectively. Similarly, (a) destructive and (b) constructive interference of the incident magnetic fields B_0 leads to vanishing or enhanced magnetic material excitation.

2. Results

Linear birefringence and linear dichroism are the optical manifestations of anisotropy and lead to phase delays and differential transmission of the ordinary and extraordinary linear eigenpolarizations of anisotropic materials. One of the most well-known anisotropic planar metamaterials is an array of split rings, where the eigenpolarizations are oriented parallel and perpendicular to the pattern's line of mirror symmetry, see Fig. 2(a). As for linearly birefringent crystals, the ordinary and extraordinary polarizations will not be changed by the metamaterial, but the polarization effects associated with optical anisotropy can be easily studied for illumination with an intermediate polarization state. Therefore we study optical anisotropy for a split ring metamaterial by illuminating it with waves polarized at 45° to its line of mirror symmetry under quasi-normal incidence conditions. This is just like one would illuminate a linearly birefringent quarter wave plate to create circular polarization and experiments with a single illuminating signal beam show that the metamaterial acts as a quarter wave plate around 9 GHz.

Here we study how the anisotropic metamaterial response is affected by an additional coherent control beam of the same polarization as the signal beam. In general, the optical response of the metamaterial strongly depends on the phase difference α between the incidence signal and control beams. For a phase difference of α=180°, for which the electric material excitation vanishes, the metamaterial becomes essentially transparent with about 100% transmission of both input beams without polarization change, see Fig. 2(b). On the other hand, at the electric anti-node (α=0°), the enhanced electric material excitation leads to almost complete conversion of all incident intensity to the perpendicular linear polarization. The anisotropic polarization conversion and the associated polarization changes are non-resonant and therefore broadband and low loss. As a result, the metamaterial acts as a broadband coherent polarization rotator that uniquely maps phase onto polarization azimuth from 6.5 GHz to 11.5 GHz. This is illustrated in detail by Fig. 2(c) for 9.1 GHz where the ellipticity angle of the output polarization remains small (<15°). Similarly, the structure acts as a coherent ellipticity modulator between 6 and 7 GHz, which allows the output beam to be continuously tuned from right-handed circular polarization to left-handed circular polarization.

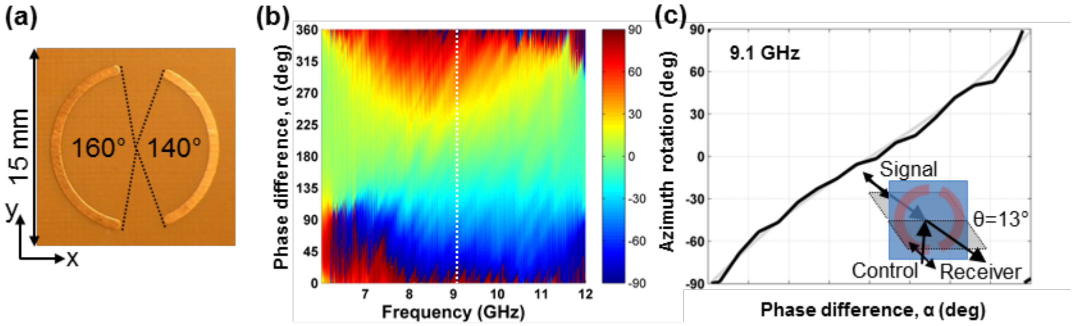

Fig. 2. A coherent polarization rotator. (a) Unit cell of the metamaterial array consisting of asymmetrically split wire rings. (b) Measured output polarization azimuth as a function of frequency and the phase difference α between the signal and control input beams. (c) Measured (black) and simulated (gray) output polarization azimuth for a selected frequency of 9.1 GHz. Both input beams are diagonally polarized and an incidence angle of incidence 13° results from having to place control antenna and receiver side by side, see inset.

Similar control of manifestations of optical activity (circular birefringence and circular dichroism) is observed for well-known examples of intrinsically 3D-chiral and extrinsically 3D-chiral metamaterials.

We investigate an intrinsically 3D-chiral negative index metamaterial consisting of mutually twisted metal patterns in parallel planes and show that it acts as a coherent polarization rotator at its optically active resonance. Exploiting selective electric and magnetic excitation of the layered metamaterial, we also experimentally identify electric and magnetic resonances of the structure, illustrating the principles of coherent spectroscopy.

Optical activity occurs not only in materials that are chiral by themselves, but also when the experimental arrangement consisting of material and direction of illumination cannot be superimposed with its mirror image. Extrinsic 3D chirality is known to lead to large optical activity in metamaterials and here we control the associated polarization phenomena coherently, demonstrating coherent polarization modulators based on extrinsic 3D chirality.

Furthermore, we also identify regimes of coherent intensity modulation, where the relative phase of the signal and control beams is mapped onto the intensity of the output beams.

3. Summary

In summary, we demonstrate for the first time coherent control of manifestations of optical anisotropy and optical activity. We report coherent control of polarization effects in anisotropic planar metamaterials and optically active, thin, intrinsically/extrinsically 3D-chiral metamaterials, demonstrating coherent polarization rotators and coherent ellipticity controllers. We also control intensity coherently and illustrate the concept of coherent spectroscopy.

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