Giant Electrogyration in a Nanomechanical Metamaterial

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Abstract: Electrogyration is electric-field-dependent polarization state rotation in chiral media. We demonstrate a metamaterial with a quadratic electrogyration constant of 7.8×10^{-14} rad m^2 V^{-2}, which is a million times stronger than in natural materials.

1. Introduction

The linear (Pockels) and quadratic (Kerr) electro-optical effects, which describe how an external electric field changes *linear* birefringence and dichroism are of great technological importance. In the 1960s Aizu and Zheludev introduced electrogyration, the corresponding phenomenon for *circular* birefringence and dichroism. It describes how an external electric field influences the optical activity of a medium. Electrogyration has been observed in dielectrics, semiconductors and ferroelectrics, but the effect is small. This work demonstrates a nanostructured photonic metamaterial that exhibits quadratic electrogyration – proportional to the square of the applied electric field – six orders of magnitude stronger than in any natural medium. Giant quadratic electrogyration emerges as electrostatic forces acting against forces of elasticity change the chiral configuration of the metamaterial's nanoscale building blocks and consequently its polarization rotatory power. The observation of giant electrogyration turns this phenomenon into a functional part of the electro-optic toolkit with application potential.

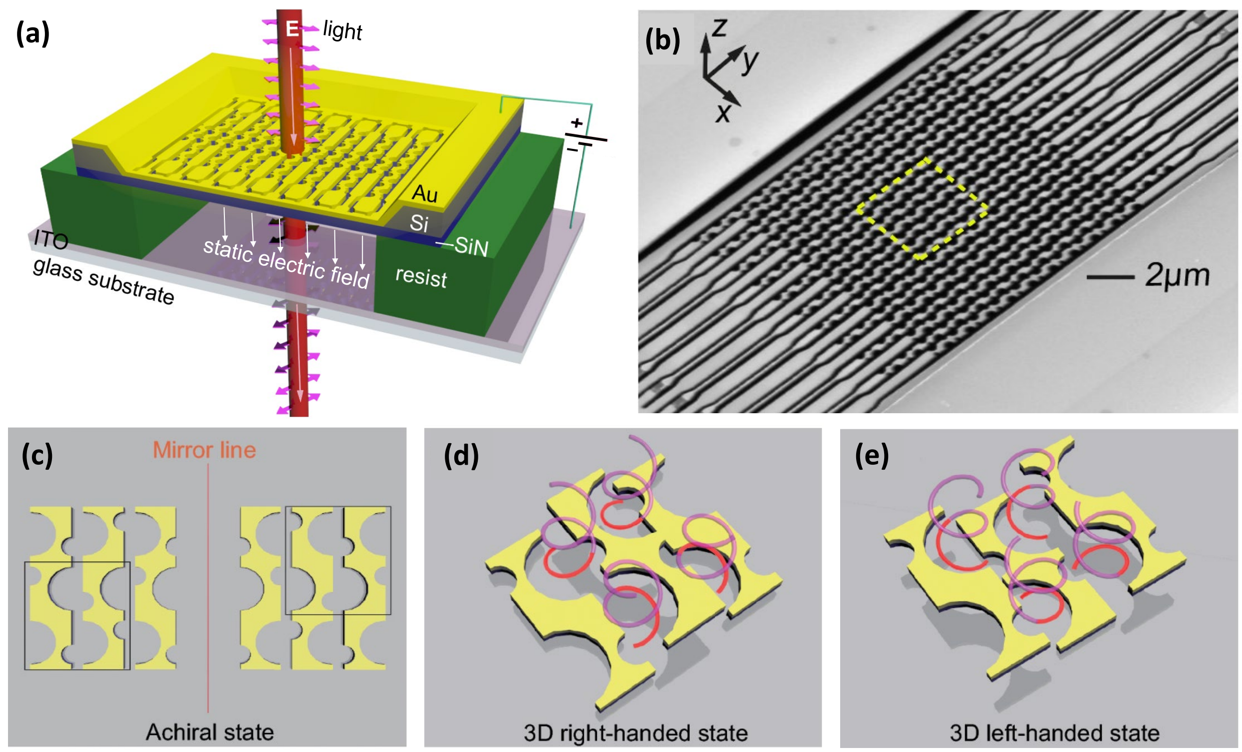

Fig. 1. Electrogyratory metamaterial. (a) Artistic impression of the metamaterial – a nanostructured gold-coated silicon nitride membrane – suspended above an ITO-coated glass back-plane. Static electric field actuates the nanomechanical material, changing its chirality and optical activity. (b) Scanning electron microscope image of the metamaterial. (c) The structure is achiral when the metamaterial beams all lie in the same plane: the metamaterial (left) and its mirror image (right) have identical unit cells (rectangular box). (d, e) With mutual out-of-plane displacement between alternate beams, either right-handed (d) or left-handed (e) chirality emerges, depending on the displacement direction: the semicircular notches all form simplified helix-like geometries of the same, left or right, handedness. Helices are superimposed to aid visualization.

2. Results

The metamaterial consists of a period array of patterned nanowires manufactured on a free-standing 100-nm-thick silicon nitride membrane coated with 50 nm of gold (Fig. 1a, b). Each nanowire is perforated with alternating small and large semicircular notches. Size and position of the notches on neighboring beams are chosen to form a simplified planar (2D) spiral-like hole, which can be deformed into a 3D helix-like geometry by their mutual out-of-plane displacement. To facilitate such movement, the ends of the beams are patterned to endow neighboring beams with alternating mechanical and electrical properties (Fig. 1b). The metamaterial is suspended above a grounded transparent indium tin oxide (ITO) back-plane at a distance of ~4 μm (Fig. 1a) such that a bias voltage applied between the gold and ITO electrode layers leads to electrostatic reconfiguration of the metamaterial's structure.

The metamaterial is achiral when flat, with all beams in the same plane: a unit cell of the metamaterial can be superimposed on its mirror image by a half-period translation along *x* and *y* (Fig. 1c). The pairs of large and small semicircular notches on adjacent beams form flat spirals with alternating senses of twist (two left- and two right-handed spirals per unit cell). However, mutual *z*-displacement of alternate beams transforms all of these planar spirals into 3D helices of equal handedness, i.e. either four left- or four right-handed helices per unit cell, depending upon the displacement direction (Fig. 1d,e). The applied voltage (electrostatic force) controls the beam displacement, which is proportional to the helix pitch, and will therefore control the magnitude of optical activity.

Propagation of light through a chiral medium rotates its polarization state and changes its ellipticity. Fig. 2a shows the measured voltage-dependence of azimuth rotation for transmission of *x*-polarized incident light through the metamaterial. Without applied field (at 0 V) the metamaterial exhibits moderate azimuth rotation of <6° as the structure is not perfectly flat in its zero bias state. The polarization rotation increases to 23° as the applied voltage increases to 18 V, reaching maxima at 1520 and 1600 nm wavelength. As chirality co-exists with anisotropy in low-symmetry media, we determined the true optical activity by averaging out anisotropic contributions, i.e. averaging polarization changes for different incident polarizations (Fig. 2c,d). Due to initial nanowire displacement, we observe a small level of optical activity at 0 V. The optical activity vanishes at 8 V, indicating that the field-induced deformation compensates the initial nanowire displacement, resulting in a flat structure as in Fig. 1c. The optical activity reverses above 8 V, indicating chirality reversal of the nanostructure. At 1600 nm wavelength, the observed quadratic electrogyration coefficient is 7.8×10^{-14} rad m^2 V^{-2}, which is a million times stronger than in natural materials known to exhibit the effect (e.g. quartz 4.5×10^{-20} and tellurium dioxide 6.6×10^{-20} rad m^2 V^{-2} [1]).

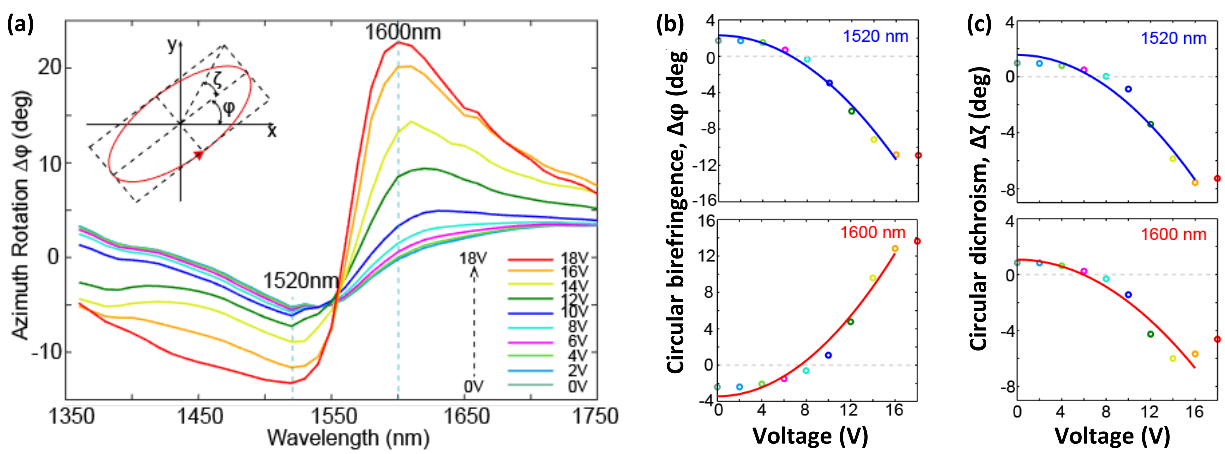

Fig. 2. Giant electrogyration. (a) Spectral dispersion of azimuth rotation for incident *x*-polarized light at 0 to 18 V static bias. (b, c) Bias-dependence of the metamaterial's (b) circular birefringence in terms of average polarization azimuth rotation and (c) circular dichroism in terms of average ellipticity angle for transmission of linearly polarized incident light at 1520 and 1600 nm wavelength. Data points are experimental results and lines show quadratic fits from 0 V to 16 V.

3. Summary

In summary, we demonstrate a metamaterial where optical activity is controlled by electric field. We observe quadratic electrogyration that is more than 6 orders of magnitude larger than has been observed in natural materials. This optical phenomenon is achieved by engineering the chiral properties of a nanomechanical metamaterial, which is actuated by electrostatic forces. Dynamic ranges of 16° azimuth rotation and 9° ellipticity angle in a metamaterial of nanoscale thickness transform electrogyration from being an obscure effect of only academic interest into a phenomenon with potential for practical application. Metamaterial nanomechanical chirality modulators could find applications in integrated photonic chips, compact dichroic spectrometers and other nanophotonic devices.

[1] O. G. Vlokh, R. O. Vlokh, "The electrogyration effect," Opt. Photon. News **20**, 34–39 (2009).