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Intensity modulation and polarization rotation of visible light by dielectric planar chiral metamaterials

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We have demonstrated how dielectric planar chiral surfaces can both modulate the intensity and change the polarization state of visible light diffracted from patterned surfaces. These effects are shown to be dependent on the sense of chirality of the surface and the input polarization state of the light. Individual diffracted beams can show variations of over 30% in their intensities for different input polarization states while opposite enantiomeric structures can exhibit differences of over 50%. The size of these effects could make these surfaces particularly promising candidates for the development of solid-state polarization-state detectors. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1944211]

Metallic planar chiral metamaterials with characteristic length-scales of a few microns have attracted significant interest recently in light of their novel and intriguing polarization properties.[1,2] Most notable of these is their ability to rotate and elliptize the polarization state of light. These effects were first observed for visible light diffracted in reflection from samples consisting of regular arrays of gammadion-shaped holes etched into thin metallic films[3] and were similar in form to effects that had been predicted for somewhat larger structures designed to operate in the microwave regime.[4] The underlying mechanism for these effects has previously been ascribed, at least in part, to the generation of induced currents or surface-plasmon-polaritons (SPP) in the walls of the metallic gammadions.[1,2] However, we will now demonstrate that similar effects are observable for visible light diffracted from patterned polymer films, suggesting that other mechanisms (such as electro-magnetic displacement currents or Fabry–Perot interference effects) may also play a significant role. More importantly, these results suggest that most patterned thin films that exhibit two-dimensional chirality[5] could be capable of exhibiting polarization sensitive effects, irrespective of the physical properties of the medium in which the chiral pattern is formed.

The global significance of these results is that they allude to the possibility of the creation of truly nonreciprocal optical structures from materials that are inherently nonmagnetic. Such effects have been predicted theoretically for a number of idealized physical structures subject to various preliminary assumptions and approximations,[4,6,7] but if they could be demonstrated experimentally for real structures they would undoubtedly prove crucial for the development of entirely new optical devices such as polarization sensitive detectors, manipulators, and other optical elements. Unfortunately, our attempts to realize such a device have so far failed to show any chirality-induced polarization change in the zero-order beam in either reflection or transmission when the sample is illuminated at either normal incidence or glazing incidence. However, other workers studying sub-wavelength structures (in which the average separation of the chiral elements, Λ, is less than the radiation wavelength, λ) have detected small rotations ($\sim 2°$) of the plane of polarization of the transmitted beam,[8] although the authors ascribed this effect to nonuniformities in the sample itself (such as in-plane birefringence or a small degree of nonorthogonality between the axes of the lattice structure) rather than being the result of two-dimensional (2D) chirality in the structures. More recent work on asymmetric L-shaped metallic nano-particles[9] has demonstrated significantly larger rotations together with evidence of second harmonic generation (SHG). Neither of these works though has so far reported a comparison of enantiomeric structures in order to fully test reciprocity or the influence of chirality.

We now believe that the strong rotations we see in higher order diffracted beams[1,3] could actually prove to be of more practical use than the relatively weak polarization changes seen in sub-wavelength samples, provided they could be incorporated into a suitably designed detection system. The key to their success would need to be a capability to modulate the intensities of the diffracted beams as well as the polarization states, and to do so in a manner that is dependent on the relative handedness of the chiral structures and the incident radiation. To this end, we have now studied the effect these chiral films exert on the relative power of the diffracted beams for different input polarization states.

The samples we used to demonstrate this capability all consisted of a 300 nm thick layer of UVIII resist on a double-polished highly resistive (110 Ω-cm) silicon wafer which was then patterned with regular square arrays of gammadion-shaped holes by electron beam lithography. This design was chosen in part for its fourfold symmetry, and hence lack of in-plane birefringence, and in part as a result of the previous theoretical work that existed in this area.[4] For each sample the pitch of the array (Λ) was set at 4.0 μm and the length of each of the two segments of each gammadion arm (ξ) was 1.4 μm. Two different enantiomeric (mirror-symmetric) designs were considered, a "right-handed" structure where the gammadions are characterized by a bending angle (α) of each arm of +45° [see Fig. 1(a)], and a "left-handed" structure where the bending angle is −45° [see Fig. 1(b)]. The optical properties of both samples were then char-

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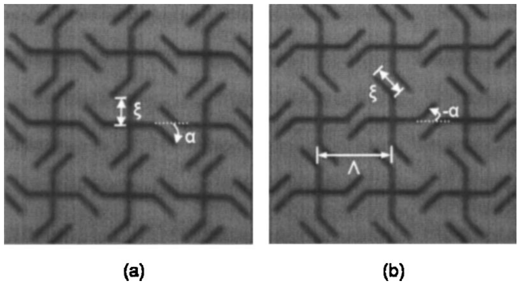

FIG. 1. Optical micrographs of arrays of (a) right-handed gammadions and (b) left-handed gammadions etched in a layer of UVIII resist deposited on a double polished silicon substrate.

acterized using the optical arrangements outlined in Figs. 2(a) and 2(b).

In the first of these, a 632 nm laser source is passed successively through a linear polarizer and a rhombic prism in order to generate circularly polarized light. A rotating second linear polarizer is then used to convert the monochromatic beam back into linear polarized light so that the polarization direction can be freely rotated about the direction of the beam without any appreciable variation in the final beam intensity. This linearly polarized monochromatic beam is then oriented perpendicular to the planar chiral sample, and focused onto one individual array using a long focal length lens ($f=20$ cm) that does not appreciably affect the polarization state of the incident beam. This chiral array is then aligned by rotation about the beam axis until one of its axes is parallel to the optical bench and the other perpendicular (as shown in Fig. 2). We then proceeded to analyze the intensity and the polarization states of the two first-order diffracted beams on either side of the zero-order beam, in the horizontal plane that contains the zero-order beam. We denote these diffracted beams as the $(-1,0)$ beam and the $(+1,0)$ beam, respectively, or for brevity −01 and +01. Note that in this configuration the zero-order beam is reflected back along the same axis as the incident beam, and as a consequence is difficult to measure.

Figure 3 shows the change in polarization state of the $(-1,0)$ and $(+1,0)$ diffracted beams relative to the polarization state of the incident beam (Φ) for both the left-hand and the right-handed gammadion array as Φ is varied. The state

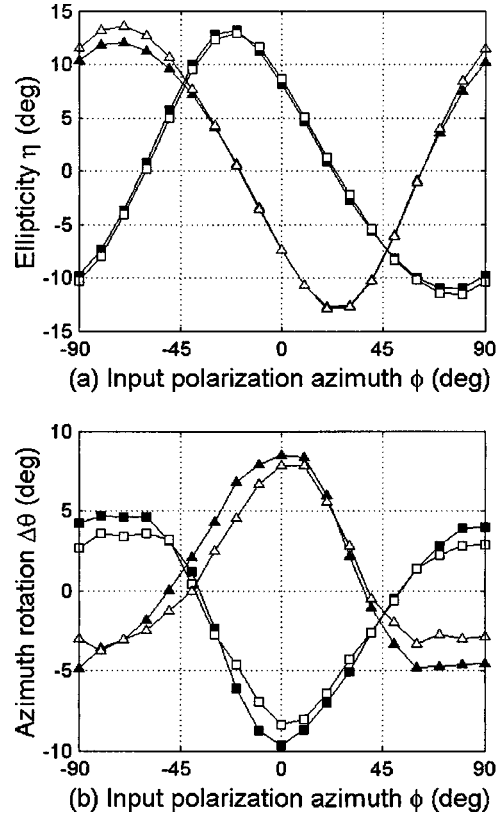

FIG. 3. The ellipticity (a) and polarization azimuth rotation (b) of visible light (632 nm) diffracted from arrays of left-(■ +01 order and □ −01 order), and right-(▲ +01 order and △ −01 order) handed gammadions etched in a UVIII polymeric layer, plotted as a function of the polarization azimuth of the linearly polarized incident wave.

$\Phi=0$ corresponds to the incident beam being vertically polarized. It can be seen that both chiral arrays induce large changes in the polarization states of the first-order beams. A comparison of opposite enantiomeric samples indicates that these polarization changes are opposite in sign for opposite input states (Φ) on opposite enantiomeric samples, while opposite diffraction orders from the same sample yield virtually identical results. The former result is a direct consequence of the invariance of the light–matter interaction for these structures under parity inversion (in accordance with the funda-

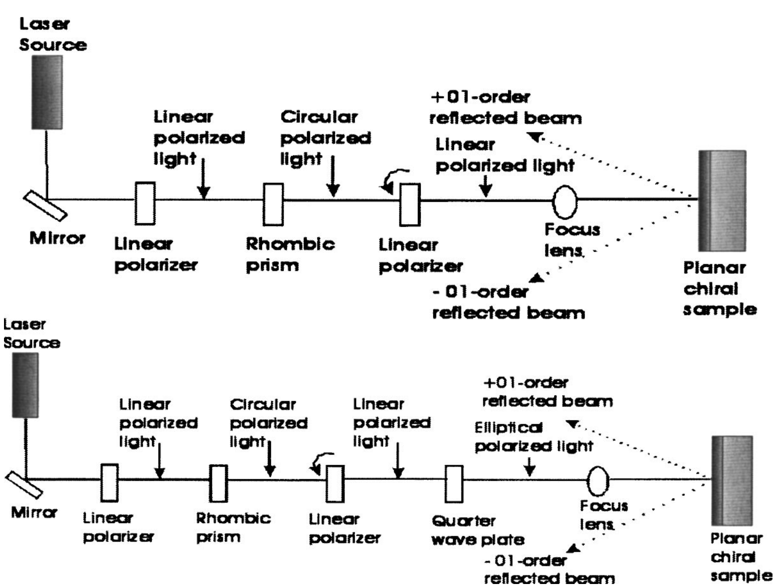

FIG. 2. Schematic diagrams of the optical arrangements used to characterize the optical properties of dielectric planar chiral metamaterials.

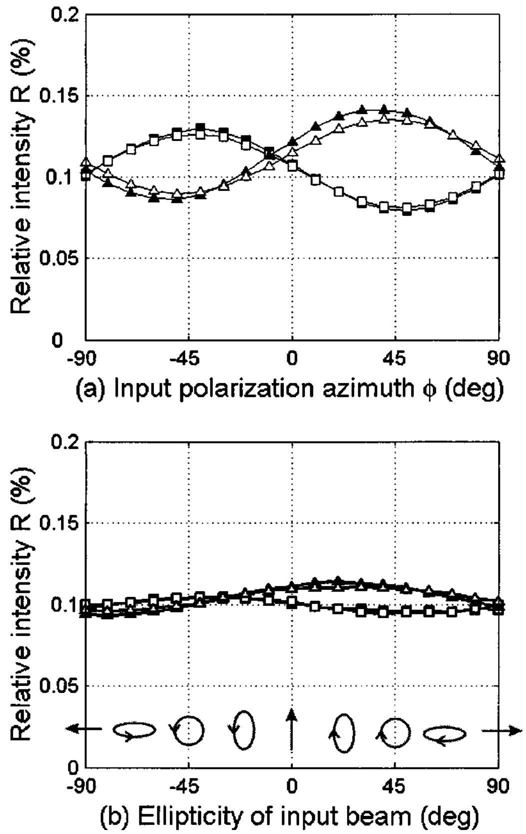

FIG. 4. Relative intensity of the first-order beams diffracted from arrays of left-(■ +01 order and □ −01 order) and right-(▲ +01 order and △ −01 order) handed gammadions etched in a 300 nm thick UVIII layer as a function of (a) azimuth angle of a linearly polarized incident beam, and (b) the ellipticity of the incident beam (with inset diagrams showing the evolution of the elliptical beam).

mental laws of classical electrodynamics) while the latter is a direct result of the twofold rotational symmetries of the chiral patterns and the input polarization states. A more complete explanation of these results can be found elsewhere,[10] but this pattern of behavior is similar to that previously observed for chirally patterned metallic films[1,3,11] only this time our results cannot be attributed to the presence of induced currents or SPP.

If we now consider the effect of variations in Φ on the relative intensities of the two first-order beams [see Fig. 4(a)] we see a similar oscillatory behavior to that displayed in Fig. 3. What is particularly surprising is the magnitude of this modulation of intensity with Φ. For each enantiomer this amounts to a peak-to-trough variation of ∼30% compared to the mean intensity, while the maximum difference between enantiomers can be almost 50% of the mean. These large variations in intensity immediately lend themselves to the possibility of facilitating the development of a new range of photo-detectors as they clearly allow opposing enantiomeric structures to be used to differentiate between orthogonal linear polarization states. The exception, however, is the case of horizontal and vertical states where the mirror anti-symmetry of the two enantiomeric structures results in the same anti-symmetry of their intensity response. This is in total contrast to the polarimetry measurements (see Fig. 3) where the optical responses of the two enantiomers are significantly different at each of $\Phi=-90°$, 0°, +90°.

If we now modify the input beam by including a quarter-wave plate [with its fast axis aligned vertically as shown in Fig. 2(b)], rotating the second linear polarizer as previously now changes the ellipticity of the input beam while leaving its polarization azimuth direction Φ unaffected. In contrast to changes in Φ, changes in the ellipticity angle, η, appear to have little effect on the relative intensities of the first-order beams, as shown in Fig. 4(b). The peak-to-trough modulation in both cases is barely 10% of the mean and the difference between enantiomers is significantly less than this. This suggests that the variation in diffracted power is significantly more sensitive to variations in the azimuth of the incident beam than it is to changes in its ellipticity.

In conclusion, we have shown that dielectric films patterned with two-dimensional chiral arrays not only alter the polarization state of diffracted light, but also modulate the intensity. This latter property could be of considerable value if these structures were to be incorporated into an appropriately designed detection system. In addition, because these chiral structures are constructed from transparent loss–less materials, they can be used in both reflection and transmission configurations, thus increasing their flexibility of application.

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