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Near-field polarization conversion in planar chiral nanostructures

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Abstract

Enantiomeric-sensitive optical polarization conversion has been observed in the near-field above a planar chiral nanostructures consisting of an array of gammadions cut in a metal film. Formation of the far-field scattered light rotated with respect to the incident linear polarized light has been visualized.

1. Introduction

Optical chirality manifests itself in rotation of the polarization state of incident light that results in optical activity [1,2]. Three-dimensional molecular chirality is well understood and finding numerous applications in modern physics and technology. The concept of chirality is possible to adapt in two-dimensional case [2,3]. A planar object is chiral in two dimensions if it cannot be brought into congruence with its mirror image unless it is lifted from the plane. Planar chiral structures (PCSs) can offer unique potential in photonics applications ranging from polarization sensitive reflectors, beam splitters, spectral filters to direction-sensitive optical components. This provides a unique opportunity to control light and its polarization state in a very compact planar element integrated in nanoscale photonic devices.

Far-field optical measurements and calculations of optical properties of planar chiral structures consisting of gammadion arrays have recently demonstrated the influence of planar chirality on light scattering and diffraction [4,5]. Two types of planar enantiomorphism should be considered. The first one is due to the electromagnetic interaction

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between non-chiral objects arranged in an appropriate pattern on the surface [6]. The second one is associated with individual 2D chiral objects (e.g., gammadions) where the electromagnetic interaction between the structural elements of the object leads to the chirality effect [7]. When several such objects are placed on the surface, the effects of the electromagnetic coupling between them may additionally influence the observed optical properties.

In this paper, we have studied polarization dependencies of near-field distributions of light over metallic planar chiral nanostructures in order to understand the vectorial structure of the electromagnetic field over the chiral surface, the effects related to individual chiral objects, interaction between objects in a periodic array, and formation of the far-field scattered light over the surface. We show that PCSs are capable of manipulating the polarization state of light in the near-field, at immediate proximity to the structure, in addition to the far-field where the contributions of many chiral objects sums up [4].

2. Experiment

Metallic planar chiral structures were fabricated using a combination of electron beam lithography and ion milling techniques (Fig. 1(b)). A square lattice of 4-fold chiral gammadions was cut into a titanium/gold/titanium layer (20 nm/100 nm/20 nm thick) onto silicon substrate to produce an PCS of (442) wallpaper group symmetry. The array period was 10 μm in both directions. The total size of the arrays was approximately $1 \times 1\ mm^2$. Two types of samples were studied with different sizes of gammadions composed of elements of 2 and 4 μm length with 45° opening angle.

The electromagnetic field distribution over the samples and its polarization properties have been studied in the reflection configuration (Fig. 1(a)) using the polarization-resolution-capable scanning near-field microscope (SNOM). The quartz tuning fork based shear-force distance regulation allows the constant-distance operation mode providing simultaneous optical and topographic imaging as

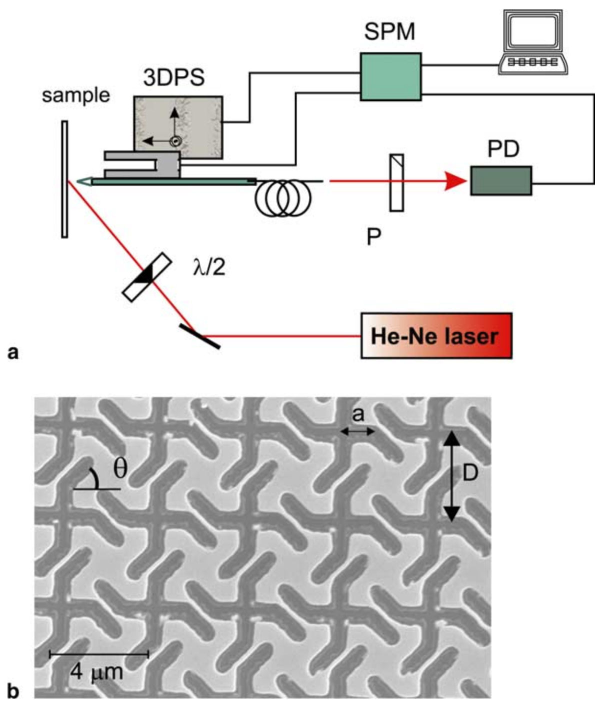

Fig. 1. (a) Schematic of the experimental set-up used for polarization-resolved near-field optical measurements. (b) Electron microscope image of the gammadion array. Main parameters of the gammadions are the length of the section a and the opening angle θ. D is the periodicity of the array.

well the constant-height mode at which a SNOM tip is scanned at a constant average distance from a surface without following a local topography. Since we are interested mainly in the electromagnetic field distribution over a smooth surface between individual gammadions, topographical artifacts are not important for interpretation of SNOM images.

The PCSs were illuminated with 633 nm He–Ne laser light linearly polarized in the plane of the sample (s-polarized) in a way that the incident light electric field vector is directed parallel to the horizontal axes of gammadion grid on the images and that the incident light propagates in a vertical direction from top to bottom in all images. The incidence angle of the illuminating laser beam was about 45° to the normal to the sample.

Uncoated tapered silica fibre SNOM tips were used to minimize the electromagnetic disturbance of the vectorial structure of the field at the SNOM tip. The optical signal collected by the SNOM probe was decoupled from the fibre and passed through a polarizer *P*. Instrumental properties of the SNOM tips were checked prior to imaging by measuring the polarization contrast achieved by the fibre tips positioned above a smooth unstructured metal surface. Only SNOM tips that provided polarization extinction for "crossed" analyser better than 1:10 were used for imaging.

It should be noted that the interpretation of the polarized SNOM images is not always straightforward due to various effects related to the probe tip. Even for uncoated tip for which field enhancement effects in linear optical measurements can be neglected, the efficiency of the coupling to the guiding mode in the probe is different for different polarization components. The near-field distribution in the absence of a probe tip also significantly and non-trivially depends on the illuminating light polarization and illumination conditions [8].

3. Results and discussion

3.1. Near-field imaging of enantiomeric chiral structures

To simplify consideration of the near-field formation above a periodic arrangement of gammadions, we begin with studies of the separated gammadions to reduce the influence of the direct electromagnetic interaction between them. The near-field images of this type of structures exhibit complex intensity distributions (Fig. 2). The images are formed by light scattered on gammadion branches. This can be direct scattering with a wide spectrum of diffraction angles, including the components propagating at grazing angles along the surface as well as coupling to surface plasmon polaritons (SPPs) on the metal surface between gammadions. The excitation of SPPs is important since it can provide the coupling between different gammadions as well as the coupling between the branches of the same gammadion. The SPP excitation is non-resonant in this case due to the period of the structure but occurs due to diffraction on the grove edges [9]. The orientation of the polarization of the incident light with respect to the grooves determines the direction of the allowed SPP modes [10]. In addition to the SPPs on a metal surface in the gammadion plane, the SPPs can be excited inside the gammadion branches leading to strong polarization effects related to coupling between branches inside individual gammadions [5]. The

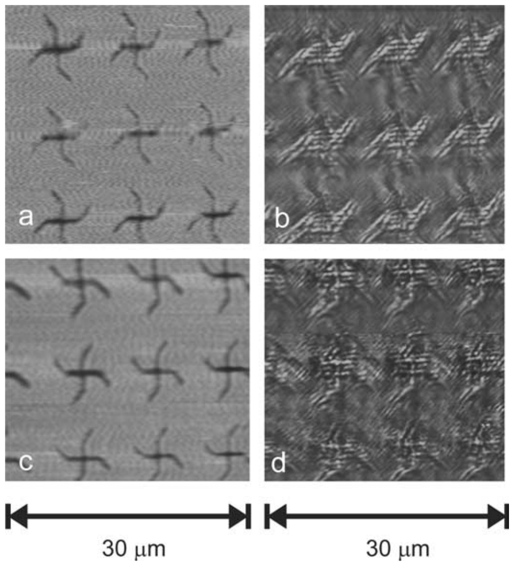

Fig. 2. (a,c) Topography and (b,d) near-field optical distributions above the chiral structures ($a = 2$ μm, (a,b) $\theta = 45°$, (c,d) $\theta = -45°$, $D = 10$ μm) for cross-polarization angle 0° ($A \perp P$). The grey-scale is the same for all optical images.

interference fringes between gammadion are probably related to the interference of SPP waves excited on a gold film and experiencing reflection on the gammadion edges.

The changes of polarization state of scattered light in comparison with the incident polarization state are observed in different places of the chiral structure. The change of the polarization state of reflected light from groves forming gammadion can be expected similar to the case of the deep groves in the metal film where SPP excitation provides for the conversion of the polarization state of light [11]. However, in the case of chiral objects, the polarization state of the reflected light depends on enantiometric orientation of the structure and different in the different branches (Fig. 2): for one type of the structure, the vertical branches of gammadions contribute to the polarization conversion while for the structure of opposite chirality the horizontal branches are dominating. One shall note that while the underling topography of the structure has a 4-fold axis of rotation, the near-field distribution does not and while the underlying topography of structures (a) and (c) are mirror images of one another, their polarized near-field images (b) and (d) are not, the same as was observed in the polarized far-field images [5].

This effect may be related to several mechanisms. Among them, the interaction between the gammadions in the array due to surface polaritons (as discussed above) or due to localized surface plasmon which are important for larger gammadion sizes (see below). Another possibility is the interference effects of the light passed through the gammadion and received an additional phase difference with a some kind of "reference" wave (similar to the magneto-optical imaging [13]). The interference allows to discriminate the phase of the light wave transmitted in various places of a gammadion. The reference wave is always present due to direct scattering from the structured surface or the multiple reflection between a sample and a SNOM probe tip. In addition, one should generally consider the elliptically polarized light, presence of which could break the four-fold symmetry of the image. Elliptically polarized light may be present in the system due to imperfection of polarization components or appear through elliptization upon reflection from the substrate or SNOM tip or due to surface plasmon excitation and re-radiation.

3.2. Polarization properties of the near-field above chiral structures

The global changes of the polarization state of the reflected light have shown significant polarization conversion in the far-field depending on the diffraction order (far-field effect) of the scattered light [4]. The local polarization conversion is also seen in the near-field (Fig. 2) demonstrating a significant dependence on the location where it observed. Overall structure of the field is similar for all polarizations of the detected light, however, the local changes of the polarization state of the scattered light depend strongly on the point of observation and orientation of gammadion elements (Fig. 3). For example, light with significantly rotated polarization is related to the areas between gammadions in the direction of their

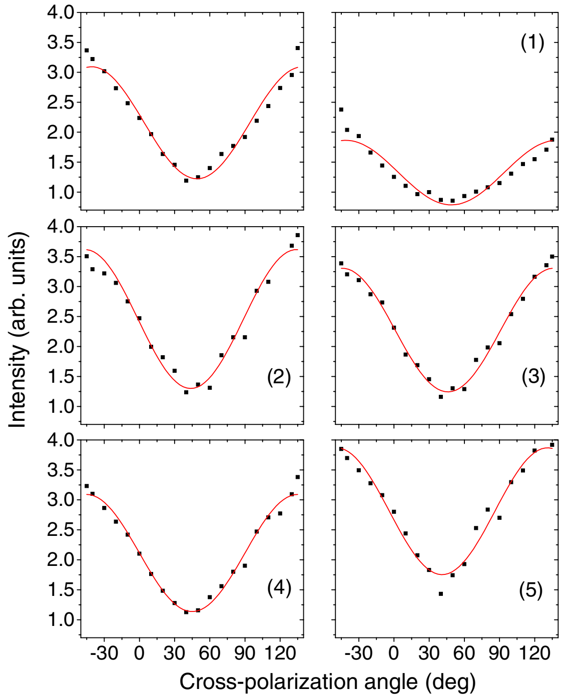

Fig. 3. Average and (1–5) local polarization dependencies above different areas of the structure measured from the series shown in Fig. 4. Curves (1–5) correspond to the areas 1–5 marked in Fig. 4(b).

vertical axes (area 4 in Fig. 4). At the same time, polarization conversion in the complementary areas 5 which have the same symmetry with respect to the overall structure but lie between the horizontal axes of the gammadions (the direction of the incident light polarization) is smaller. This corresponds well to the broken 4-fold symmetry of the polarized optical images observed above.

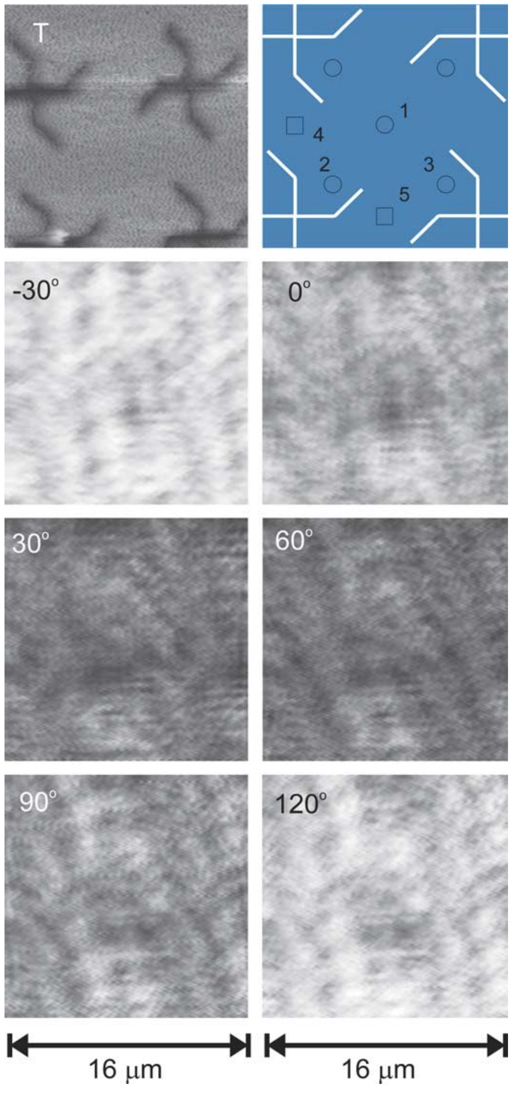

Fig. 4. Topography (T), the areas of the surface where the polarization dependencies are plotted in Fig. 3, and optical distributions measured at the distance ~5 μm from the surface of the chiral structure. Cross-polarization angle indicated on the images is measured with respect to a smooth metal surface. The grey-scale is the same for all optical images. Note a small shift between topographical and optical images.

In order to avoid influence of topography variations, we have studied local polarization conversion at the distance of about 5 μm from the surface using the constant-height scanning mode (Fig. 4). The polarized images reveal complex optical field distributions which can be understood taking into account the high number of interfering scattered beams which could be coupled into the SNOM probe. The nodes of the structure correspond to the Fresnel diffraction region intermediate between the near- and far-fields. However, the polarization dependencies associated with these distributions exhibit similar behaviour as in the near-field. The local intensities in different areas over the gammadion array follow the average intensity variations having minima and maxima at the same polarization angles. Nevertheless, the relative intensity changes are different in different areas. The area 1 which is a centro-symmetrical point of the chiral structure exhibits the smallest polarization conversion as well as smallest absolute intensity of the scattered light. At the same time, the area 5 which is mirror-symmetrical with a mirror plane in the direction of the incident light provides the strongest polarization conversion.

3.3. Strongly interacting chiral objects

With the increase of the gammadion size, the distance between the individual gammadions in the array becomes smaller fostering the (increased) electromagnetic interaction between them. The optical field distribution over the arrays of larger gammadions is even more complex than for weakly interacting gammadions (Fig. 5). The difference between structures consisted of separated (Fig. 2) and closely packed gammadions (Fig. 5) is immediately seen: in the closely packed structure the strongest polarization conversion is observed near the area corresponding to the gammadion pattern symmetry points (like the centro-symmetrical area 1 of the pattern in Fig. 4). The areas corresponding to mutually perpendicular mirror-symmetrical points of the structure can be identified in the optical distributions, however, in contrast to smaller gammadions discussed above, the relatively closed areas formed by the elements of four neighbouring

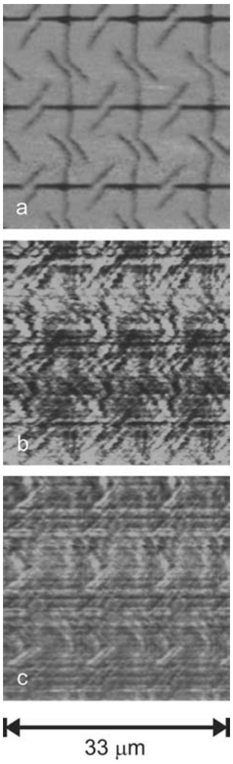

Fig. 5. Topography (a) and near-field optical distributions above a chiral structure ($a = 4$ μm, $\theta = 45°$, $D = 10$ μm) for 0° (b) and 90° (c) cross-polarization angles. The grey-scale is the same for all optical images.

gammadions contribute to all scattered light polarizations.

This effect is probably related to the electromagnetic coupling between the elements of different gammadions in the array, in particularly between the nearest sections where localized surface plasmons can be excited. This kind of surface plasmons localized on surface structures of complex geometries (e.g., self-affine structures) has been shown to contribute to the chiral effects [12]. The structure of the near-field image again reveals significant interference and/or localized surface plasmon patterns. However, in this case the fringes can be directly related to the gammadions branches. The same as for small gammadions, the contrast of the pattern and its periodicity are different in the direction of gammadion elements attached to vertical and horizontal branches, showing broken 4-fold symmetry of the polarized optical images.

4. Conclusion

Polarization properties of the scattered light in the near-field of the chiral nanostructures consisting of the periodic array of gammadions in a metal film have been studied. The polarization conversion reveals strong dependencies on position with respect to the individual gammadions and the enantiomeric state of the planar chiral structures, while the polarized near-field images fail symmetry of the underlying topography. The electromagnetic interaction between structures has been shown to play a significant role in the local polarization properties.

Acknowledgement

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