OPTICAL METAMATERIALS WITH QUASICRYSTALLINE SYMMETRY: SYMMETRY-INDUCED OPTICAL ISOTROPY

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We compare, both experimentally and theoretically, metamaterials with three different symmetries: square lattice, hexagonal lattice, and quasicrystalline Penrose tiling. By relying on an advanced Jones calculus, we link the symmetry properties to the far-field optical response, such as ellipticity and circular dichroism, as the incident angle is varied. We show that hexagonal lattice metamaterials, when compared to the square ones, exhibit less circular dichroism and ellipticity due to their higher symmetry. Furthermore, we show that in contrast to periodic metamaterials, quasicrystalline metamaterials inhibit ellipticity and circular dichroism and open a new route to isotropy in metamaterials at oblique incidence.

Introduction

Metamaterials rely on the ability to design and fabricate nanoparticles with combined metallic and dielectric inclusions of various shapes – meta-atoms - and to place them in a user-defined arrangement. This allows for the creation of composite metamaterials optimized for a desired operation and functionality with respect to their interaction with electromagnetic radiation. The properties of metamaterials are commonly defined by the response of the individual meta-atoms, usually at normal incidence [1]. However, different types of meta-atom arrangements as well as different directions of excitation lead to different coupling conditions among meta-atoms, and as a result, to different optical responses [2]. Here we compare the optical properties of metamaterials with three different symmetries at oblique incidence.

Polarization Phenomena at Oblique Incidence

In our experiments, we study metal-dielectric-metal disks sustaining both electric and magnetic dipole excitations. Each meta-atom consists of two Au disks with a thickness of 25 nm separated by a 30 nm MgF_2 layer. The bottom diameter measures 180 nm and the meta-atoms show a weak taper angle of 10° (Fig. 1(a)). The samples are fabricated on an indium-tin-oxide (ITO) coated glass substrate by standard electron-beam lithography followed by the sequential evaporation of the Au/MgF_2/Au layers and a lift-off procedure in acetone.

Three different (two-dimensional) arrangements of meta-atoms have been fabricated: a square lattice (Fig. 1(b)), a hexagonal lattice (Fig. 1(c)), and a quasicrystalline Penrose tiling [3] (Fig. 1(d)) generated by the De Bruijn method [4]. The surface density of the nanoparticles is kept identical at one nanoparticle per 0.16 μm^2 for all three cases. The metamaterials under consideration have the

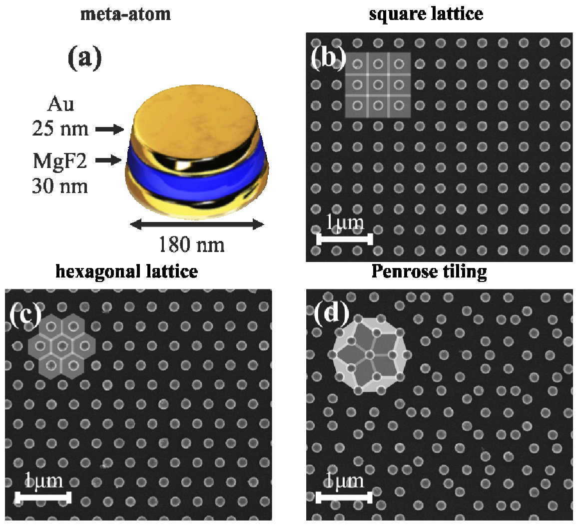

Fig. 1. Metamaterial symmetries. (a) Meta-atom and (b-d) scanning electron micrographs of square, quasicrystalline, and hexagonal arrangements of meta-atoms respectively

following point symmetry elements: the meta-atom by itself has the highest two-dimensional symmetry, the square lattice has 4 reflection-symmetry planes and correspondingly two 4-fold and two 2-fold rotation axes within each unit cell. The hexagonal lattice has one 6-fold rotation axis, two 3-fold rotation axes, and three 2-fold axes. It has also 6 reflection planes. The quasicrystalline metamaterial has local five-fold symmetry in specific high-symmetry spatial positions in real space whereas the structure exhibits ten-fold rotational symmetry in *k*-space

To emphasize the impact of symmetry, we extract the eigen-polarizations of the structures using the Jones matrix formalism [5]. Incident light with these eigen-polarizations preserve their polarization state upon propagation through the sample. We show that for arbitrary oblique illumination the Jones matrix has

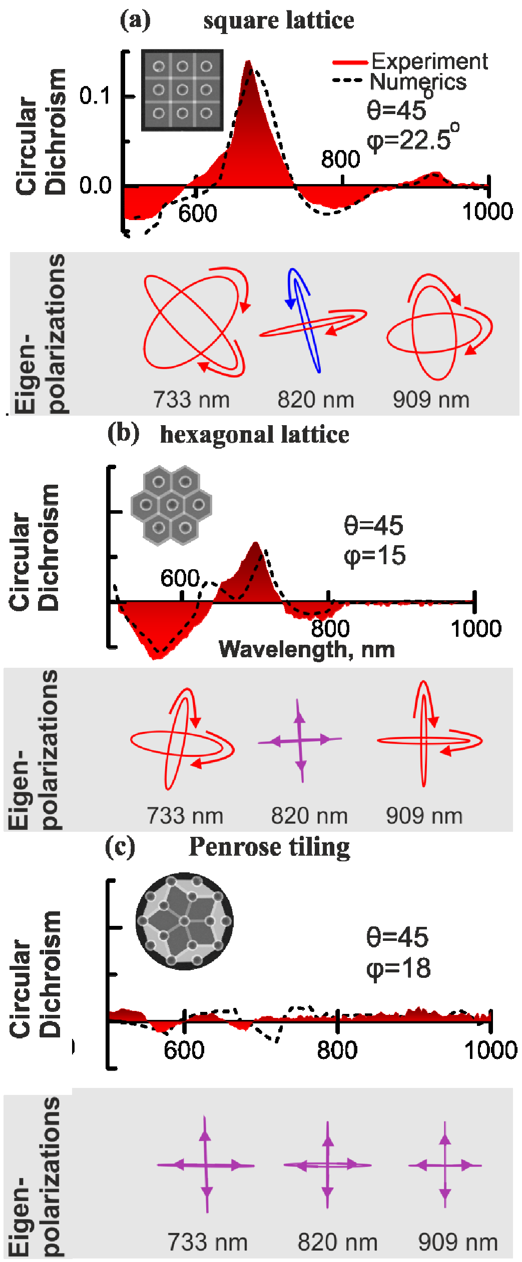

Fig. 2. Symmetry-dependant optical properties of metamaterials for the case (iii) oblique incidence. (a-c) Upper row: Circular dichroism of square, hexagonal, and quasicrystalline metamaterials, respectively. Lower row: The eigen-polarizations of the structures at indicated wavelengths. Angle φ is chosen such that the circular dichroism reaches its maximum

the most general from, which allows the observation of a large variety of polarisation phenomena, such as asymmetric transmission and circular dichroism [5]. We focus on circular dichroism, which can be measured as: $(T_{LL}-T_{RR})/(T_{LL}+T_{RR})$, where T_{LL} (T_{RR}) corresponds to the transmission of left- (right-) circular polarization through the system. The top part of Fig. 2 shows the experimentally measured and theoretically calculated circular dichroism for the three metamaterial arrangements at specific oblique illumination. In the measurements we used a devoted spectroscopic setup to characterize the fabricated samples. In the calculations we used a finite-difference time-domain method. We see that the square lattice has the highest dichroism at specific wavelengths as it has the lowest symmetry among these three metamaterials, and the Penrose tiling has a dramatically suppressed dichroism. The bottom part of Fig 2 shows the eigen-polarisations of the metamaterials for several wavelengths as extracted from the calculations. While the square and hexagonal lattices exhibit high ellipticity of their eigenvectors, the Penrose tiling preserves the linear eigen-polarisations within the accuracy of calculations. We attribute these linear eigen-polarizations (or negligibly small ellipticity) of the quasicrystalline metamaterial to the absence of translational symmetry. Thus, the collective response of the entire system exhibits an effective isotropy, preserving the Jones matrix in a simple diagonal form in the linear basis.

Conclusion

Taking advantage of symmetry considerations, we have analyzed the potential of various metamaterials to affect the polarization state of light upon oblique illumination. We have shown that depending on the angle of illumination, metamaterials are able to support specific polarization states. The presented methodology that using ellipticity and circular dichroism, provides an unambiguous language for discussing the impact of the inherent symmetry of the metamaterial lattices on their far-field response. Our findings allow the quantification analysis of the impact of inter-element coupling and lattice symmetry on the optical properties of metamaterials, and to separate this contribution from the response associated with a single meta-atom. In addition, we have studied the concept of optical quasicrystalline metamaterials, revealing that the absence of translational symmetry (periodicity) of quasicrystalline metamaterials causes an isotropic optical response, while the long-range positional order preserves the resonance properties. Our findings constitute an important step towards the design of optically isotropic metamaterials and metasurfaces.

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