Light transport in ordered and randomised photonic-plasmonic hybrid crystals

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Abstract

In this paper we investigate the disorder-driven transition from collective transport by Bloch waves and SPPs to single particle scattering in 2D hybrid plasmonic-photonic crystals. Where reflection and transmission of ordered structures appear to be highly correlated such strict relation is lost in the disordered case.

1. Introduction

Hybrid photonic-plasmonic crystals are characterized by a strong coupling between photonic and plasmonic excitations, which brings huge diversity to hybrid's optical properties. Our approach to hybrid crystals is to use all-dielectric photonic crystals (PhC) as templates for deposition of metal films [1]. In this case the 2-dimensional (2D) plasmonic crystal (PlC) adopts the topology of the template. Since structure and composition of the dielectric crystal are preserved, the hybrid appears as a sandwich of PlC and PhC possessing the same periodicity. This matching provides efficient interaction and hybridization of surface plasmon polaritons (SPP) of the PlC and Bloch modes of the PhC at the hetero-interface between the two crystals.

The properties of a PhC crucially depend on the order of its lattice. In the 2D ordered PhC Bloch waves propagate along the crystal plane. As far as those Bloch modes are situated in the light cone they are coupled to external radiation by diffraction at the 2D lattice of spheres. Oppositely, if the sphere array is randomised, light is coupled to localized Mie resonances of individual spheres and in-plane propagation is either absent or can only proceed via hopping of excitations from one sphere to another. Theoretical prediction of a co-existence of dispersive and non-dispersive bands in a 2D lattices of non-touching spheres [[2]] imply that preference can be given to one of these competing mechanisms of fast and slow light transport by choosing the topology of the sphere array.

The same scenario can be applied to the light transport in PlCs, for which guiding of SPPs along the metal surface is an intrinsic property. Extraordinary light transmission through the corrugated metal film as well as the observation of dispersive SPPs bands are manifestations of a band-like transport. Apparently, weak disorder in the PlC lattice leads to a localization of plasmon resonances. However, efficient coupling between PhC and PlC modes can postpone the degradation of the SPP band transport due to hybridization with less localized excitations in dielectric spheres. Whether this is the case or not, will be addressed in this report. To this end we evaluate angular dependent reflection and transmission spectra of samples with different degree of ordering. Changing the transport regime

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manifests itself in particular by a suppression of dispersive bands and as a domination of non-dispersive resonances in the transmission spectra.

2. Experimental technique

Ordered and disordered monolayers (ML) of 1063 nm polystyrene spheres were prepared using the Langmuir-Blodgett method. A progressive randomisation of the big spheres was achieved by using binary mixtures of 1063 nm and 303 nm spheres of different partial concentrations. Examples of the most ordered and the most disordered studied structures are shown in Fig.1. Finally hybrid metal-dielectric architectures were prepared by depositing a 30 nm Ag film on top of these samples.

Transmission and reflectance spectra were obtained under illumination with a collimated beam of white light in ss- and pp-polarization as a function of the incidence angle. Only 0^{th} diffraction order transmission and reflection were studied.

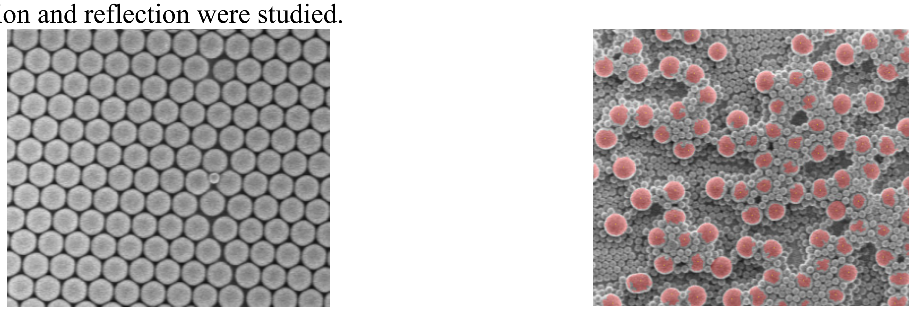

Fig.1. Scanning electron microscope images of the ordered 2D lattice of 1063 nm spheres (ML) and the disordered array composed from 1063 nm and 303 nm spheres (BML).

3. Results and discussion.

Transmission and reflectance spectra of samples shown in Fig.1 are presented in Figs.2 and 3. In the transmission spectra of regular ensembles minima correspond to diffractively excited Bloch modes, which propagate along the film. Because this is a collective effect its efficiency depends on the phase relation between the excitations of different spheres and therefore on the angle of incidence. In the hybrids the pool of modes is enriched by SPPs. In the case of a periodically corrugated and perforated thin metal film the coupling of SPP modes across the film results in the formation of bands of increased transmission and reduced reflection compared with a homogenous metal layer. The extraordinary transmission peak is seen at 1430nm at normal incidence in agreement with earlier works [3].

In disordered samples the spectra show different patterns. Major features in transmission are non-dispersive bands, which match well with Mie resonances of large spheres. The deep transmission minimum is caused by the interference between light penetrating the sphere and light passing outside the sphere [4]. A similar structure is resolved in transmission of Ag-coated disordered MLs of spheres. However, the interference pattern seems to be shifted due to additional phase shifts acquired by the light being transmitted. The non-dispersive features in the transmission spectra suggest that in-plane light transport occurs via coupled Mie resonance modes of individual spheres.

In contrast reflectance spectra of the disordered ML show a much more pronounced angular structure, which is the result of interference between radiation directly reflected by the substrate and such backscattered by large spheres (Fig.3c). The reflection from the substrate has a weak angular dependence, where the Brewster angle around 50 degree is the most noticeable feature. In contrast backscattering appears in pronounced angular lobes, the number of which increases for decreasing wavelength. Here the angular dependence is not a signature of transverse transport, but of the directivity of scattering. Metal deposition has two effects: (i) both backscattering by the large spheres as well as the reflection by the metal film are enhanced thus increasing the contrast, (ii) the structure of background reflection is lost, in particular, the dip at the Brewster angle. All features of the reflectance of the Ag-coated disordered ML appear in counter-phase with those of its uncoated counterparts (compare Figs. 3c and d).

The features appearing in transmission and reflection spectra of disordered samples are partly correlated due to their different origin of major features. One can expect that in-plane light propagation occurs via scattering of the light captured by localized resonances.

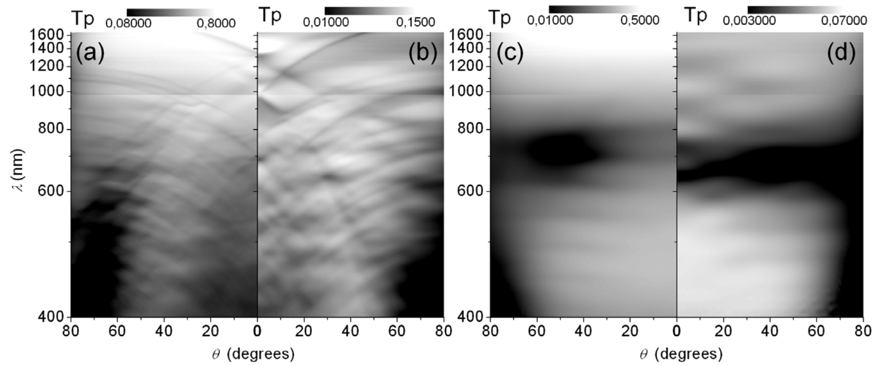

Fig.2. Transmission spectra of p-polarized light of regular (a) and disordered (c) MLs, and Ag-coated ordered (b) and disordered (d) MLs. The transmission is given in a logarithmic scale. The wavelength axis is transformed to display frequencies in linear units.

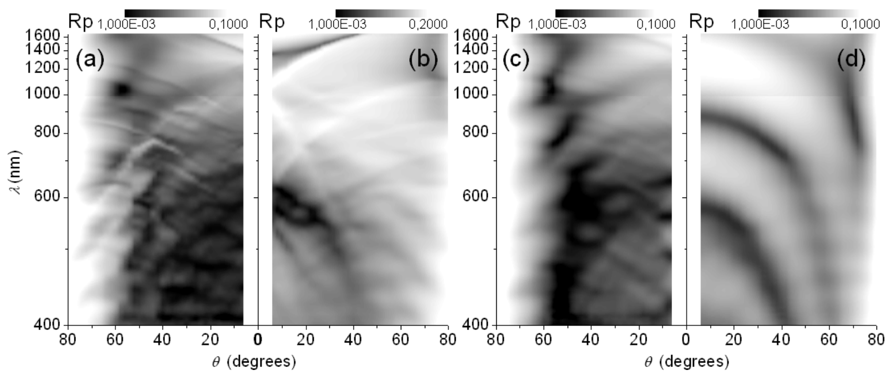

Fig.3. The same as Fig.2, but angular dependent reflectance spectra.

4. Conclusion

Disorder-driven suppression of ballistic transport and the transition from collective response to single particle scattering is demonstrated for both dielectric and silver covered PhCs. For ordered structures we observe bands with strong angular dispersion thus indicating light transport along the plane of the crystal. In contrast, transmission spectra of disordered sample lack the features of ballistic transport. The dominant influence of particle scattering resonances implies the hopping propagation of photons and plasmons in disordered arrays. Co-existence of both transport mechanisms in weakly disordered structures is observed. This intermediate transport regime can be characterized by the energy exchange between localized and propagating excitations.

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