Near-field optical investigation of Hyperuniform Disordered photonic structures

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Abstract

Located in-between random structures and perfectly ordered photonic crystals, there is a special class of disordered heterostructures called hyperuniform disordered (HuD) photonic structures. These materials, due to the presence of a photonic bandgap, combine the advantages of disordered systems and ordered systems: here, we underline and experimentally prove all these advantages by means of the first near-field optical characterization of HuD photonic structures in the near IR.

1. Introduction

Disordered photonic nanostructures have attracted a lot of interest in the past decades, due to the fascinating, complex and elusive physics of random media, but also in addition to a wealth of interesting applications based on light-matter interaction and light controlling. Whereas periodic structures suffer from limited rotational symmetries, disordered and aperiodic geometries can be more isotropic, leading to superior optical functionalities such as scattering-induced light localization, light extraction from the light emitting diodes (LED), and omnidirectional absorption for solar applications. Located in-between random structures and perfectly ordered photonic crystals, there is a special class of disordered photonic heterostructures, called hyperuniform disordered (HuD) photonic structures [1,2]. These systems have recently been shown to display large isotropic band gaps (BG) as well as optical transparency, to mention two of the most fascinating an promising features. In particular, HuD systems may show BGs comparable in width to the ones found in photonic crystals, thanks to the underlying point-pattern template upon which the structures are built. In particular, a point pattern in real space is hyperuniform if, within a spherical sampling window of radius R (in d dimensions), the number variance $\sigma(R)^2$, for large R grows more slowly than the window volume (i.e. more slowly than R^d). This means that in Fourier space the structure factor, $S(\mathbf{k})$, approaches zero as $|\mathbf{k}|\rightarrow 0$, which is the reason of transparency at long wavelength. In addition, HuD systems share with disordered systems the presence of Anderson localization for light with quite small modal volumes for states at the borders of the BG. The additional advantages of HuD with respect to random systems is the prediction of resonances with low loss and relevant mode steadiness to external perturbation. It follows that, given the lack of periodicity in HuD solids, Bragg scattering is not a prerequisite for photonic band gaps; interactions between local resonances and multiple scattering are sufficient, provided that the disorder is constrained to be hyperuniform. Broadband k-space control, combined with rotational symmetry and with the possibility of systematically generate these patterns through a specific design rule via universal tessellation protocol, elevates HuD systems at the center of an innovative field of photonics applications, combining the advantages of both random and ordered structures. Pioneering experiments on photonic HuD systems have explored IR light diffraction in 3D dielectric structures [3], along with visible light scattering experiments from HuD plasmonic gold surfaces [4]. Here we report the first near-field optical mapping and spectroscopy of Anderson modes at telecom wavelengths in a HuD photonic system, consisting in a double membrane photonic structure.

2. Investigated structure and experimental setup

The investigated system is a HuD dielectric structure on two GaAs parallel membranes [5] with air circular holes following a specific pattern; the design is derived from a stealth hyperuniform point pattern with a stealthiness parameter χ = 0.5 (where χ is defined as the ratio between the number of **k** vectors for which the structure factor $S(k)$ is constrained to vanish and the total number of **k** vectors). The vertical etching assures that the holes patterns in the two parallel membranes have the same nominal design. Figure **1a** shows the top view scanning electron microscopy (SEM) image of one of the investigated samples, with lattice constant, a=360nm, and filling fraction ff=0.27%. From the SEM images, we measured both the slab thickness and the inter-membrane separation distance, that resulted to be respectively t=130nm and d=105nm. High density InAs quantum dots (QDs), whose ground state is centered at 1300nm, are embedded in the middle of the upper membrane, and act as optically active medium. A room temperature commercial SNOM Twinsnom, OMICRON is used in an illumination-collection geometry. The sample is excited with light from a diode laser (785 nm) coupled into a chemically etched optical fiber, which allows us to have a direct measurement of the LDOS of the system. Infact photoluminescence (PL) spectra from the sample are collected at each tip position through the same probe.

3. Preliminary results and discussion

Figure **1** reports a summary of the data obtained by the SNOM experiment. In **fig.1b** we show a typical PL spectrum (in blue) of the HuD structure at a specific tip position, where several sharp resonances are clearly visible. These resonances are spectrally sparse over the full emission range of the QDs, (reported in the same graph in yellow), with quality factors (Q) ranging from 400 to 1000. We were able to calculate the PL enhancement spectrum at every tip position by dividing the recorded spectrum by the QDs PL spectrum. In this way it was possible to reconstruct the near-field spatial distribution of the PL enhancement over a broad range of wavelengths (1165-1280 nm), which reflects the distribution of the electric field intensity: this collective map, reported in **fig.1c**, allows us to visualize the high spatial density of modes that exhibit a very high PL enhancement (of the order of 15). Preliminary measurements show modes that, if located sufficiently far from the borders of the structure, can exhibit quite high Q factor if compared with the values of Q=100-200 found in randomly designed similar photonic structures [5]. Unperturbed HuD systems, similarly to other conventional disordered structures, display defect modes. These Anderson-like localized modes occur naturally at the PBG edges, extend over five to ten cells, and are easily distinguishable as below and above the PBG due to the electric field being concentrated in the dielectric and in air. Differently from defect modes arising from disorder, we found that the modes here investigated show steadiness features and resilience to fabrication imperfection. In **fig.1d** we report the spectra, obtained from two nominally identical structures, acquired in the position of maximum intensity of the electric field of a selected mode. The insets are the PL maps at the central wavelength of the two peaks. The two spectra (orange and red for the two replica) shows a spectral similarity that, combined with the almost identical spatial footprint visible in the corresponding PL maps, makes the effect of fabrication induced disorder almost negligible.

4. Conclusions

In this work we present the first near-field optical investigation in the near IR of a HuD photonic system. We show that these materials, due to the presence of a photonic bandgap, combine the advantages of disordered systems and ordered systems. Like random structures they exhibit a large plethora of photonic modes with high spatial density. However, while their statistical properties are robust against fabrication induced disorder, they are deterministic materials in the sense that it is possible, after theoretical calculations, to predict where light localization will take place experimentally, both spatially and spectrally. Moreover, the Q factors of the optical cavities arising from light localization that were experimentally detected are one order of magnitude larger than in the case of disordered systems.

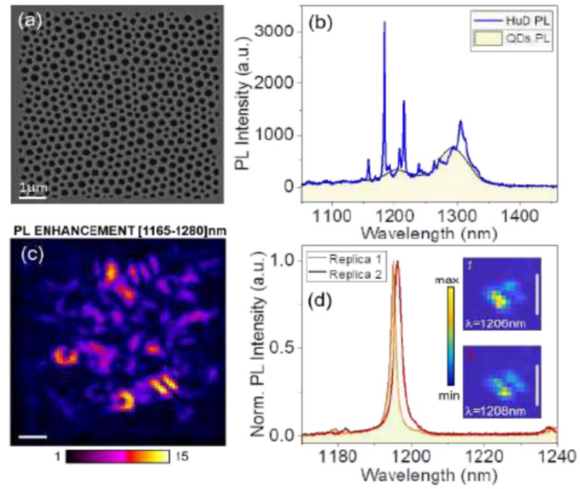

Fig.1:(a) SEM image of the HuD structure. **(b)** Typical PL spectrum of the structure acquired at a specific tip position (blue) and QDs PL spectrum (yellow). **(c)** Near-field PL enhancement map over a broad spectral range [1165-1280]nm. **(d)** PL spectrum of the same mode in two nominally identical replica (orange and red) and correspondent near-field PL maps at 1206nm (replica 1) and 1208nm (2). All the white scalebars are of 1μm.

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