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Engineering high Q/V photonic modes in correlated disordered systems

Nicoletta Granchi[1,*], *Richard* Spalding[2], *Kris* Stokkereit[2], *Matteo* Lodde[3], *Andrea* Fiore[3], *Riccardo* Sapienza[4], *Francesca* Intonti[1], *Marian* Florescu[2] and *Massimo* Gurioli[1]

[1]Department of Physics and Astronomy and LENS, University of Florence, Sesto Fiorentino (FI), Italy
[2]Advanced Technology Institute and Department of Physics, University of Surrey, Surrey, UK
[3]Department of Applied Physics and Institute for Photonic Integration, Eindhoven University of Technology, Eindhoven, NL
[4]The Blackett Laboratory, Department of Physics, Imperial College London, UK

Abstract. Hyperuniform disordered (HuD) photonic materials have recently been shown to display several localized states with relatively high Q factors. However, their spatial position is not predictable a priori. Here we experimentally benchmark through near-field spectroscopy the engineering of high Q/V resonant modes in a defect inside a HuD pattern. These deterministic modes, coexisting with Anderson-localized modes, are a valid candidate for implementations in optoelectronic devices due to the spatial isotropy of the HuD environment upon which they are built.

1 INTRODUCTION

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]. They have recently been shown to display large isotropic band gaps (BG) as well as optical transparency, to mention two of the most fascinating and promising features. Among the several experimental photonic realizations of HuD structures [3,4], also HuD systems on dielectric slabs have been recently proposed [5] and characterized as photonic materials capable of combining the small spatial footprint typical of random modes with Q/V ratios comparable with photonic crystal cavities for the Anderson-localized modes naturally occurring at the BG edges. These modes with relatively high Q, however do not have predictable spatial locations in the whole structure. Here, we take advantage of the same slab technology with embedded Quantum Dots, that act as internal light source, to engineer a defect inside the HuD luminescent pattern and deterministically control its spatial location in a correlated disordered environment and optimize the light confinement (as it has been recently proposed only theoretically in [6]).

2 STRUCTURE AND EXPERIMENT

The design of the structure is reported in Fig.1a; the central defect is designed in order to support several modes that are labelled accordingly with the Finite Element Methods (FEM) distributions of the magnetic field component Hz: dipole-like (D), hexapole-like (H), quadrupole-like (Q) and octupole-like (O) and so on [6]. By tuning the structural parameters such as the width of the dielectric veins in the HuD network and the radius of the central hole of the defect, we achieve a fine control over every spectral resonance to find the best condition that maximizes the Q factor for every mode. With the theoretical design, a GaAs membrane 180 nm thick, with InGaAs Quantum Dots embedded in the middle, is patterned through Electron Beam Lithography.

We experimentally benchmark this engineering through Scanning Near-field Optical Microscopy (SNOM), used in illumination-collection configuration and capable of subwavelength resolution in the near-IR range (upper right inset of Fig.1a). A room temperature commercial SNOM Twinsnom, OMICRON is used. 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 RESULTS AND DISCUSSION

The typical SNOM PL spectrum of the defect modes is shown in the bottom panel of Fig.1b, where D, H, Q and O are detected. The near-field PL map of mode H is reported in Fig.1c, and nicely agree with the FEM electric field intensity map. Thanks to the engineering of the structural parameters, we experimentally detect in a disordered system, modes with Q factors of the order of 6000. All the defect modes, being inside a correlated disordered system, will coexists with all the other localized modes supported by the HuD network.

* Corresponding author granchi@lens.unifi.it

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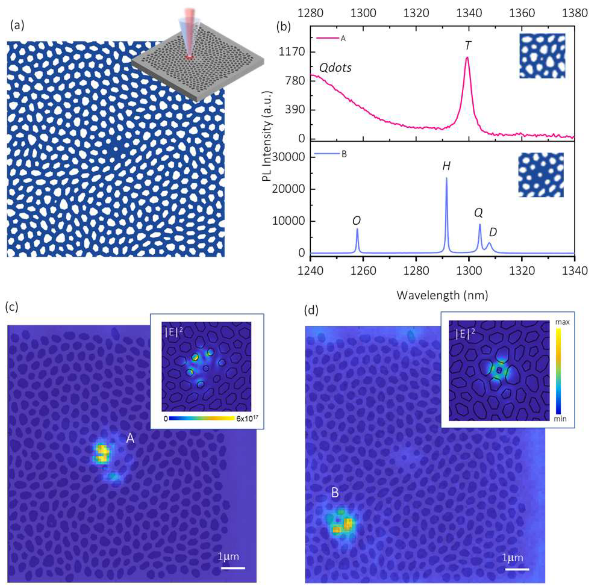

Fig. 1. (a) Design of the engineered defect in a HuD pattern and sketch of the SNOM probe used in illumination-collection configuration. **(b)** Bottom panel: SNOM PL spectrum acquired on the engineered defect displaying four modes D (dipole-like), Q (quadrupole-like), H (hexapole-like) and O (octupole-like). Upper panel: SNOM PL spectrum acquired on the accidental four-fold defect, called topological T. **(c)** SNOM PL map centered around 1326 nm, corresponding to mode H, whose FEM map of the electric field intensity is shown in the inset. **(d)** SNOM PL map centered amount 1339 nm, corresponding to the hyperuniform topological four-fold defect. The inset reports the relative FEM electric field intensity map.

A remarkable example of this innovative feature can be seen in the design (Fig.1a), where the central defect is spatially near to an accidental topological defect (here, a cell of the HuD network with four edges, rather than the average six), typical of stealthy HuD systems [5]. This is an unavoidable defect that depends on the tiling protocol employed to generate the pattern, and it is the first of many tightly localized modes occurring at the PB edge. The SNOM PL spectrum displaying the peak of this mode is shown in the upper panel of Fig.1b, and the correspondent PL map is reported in Fig.1d, again in a fairly good match with the FEM electric field intensity distribution.

The possibility of an experimental deterministic control of a defect inside a correlated disordered environment such as HuD therefore open the way to many applications for which guiding light through modes with different localization properties, a high spectral and spatial density of modes is required as well as a high Q/V ratio. The ability of optically characterizing localized modes of different symmetry and frequency in the same physical cavity can have a great impact on all-optical switching, implementations of linear-optical quantum information processors and single photon sources. Moreover, the average isotropy of HuD pattern in which the defects are placed makes them more adaptable in optoelectronic devices.

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