Placing quantum dots in 3D photonic crystals and finding them back

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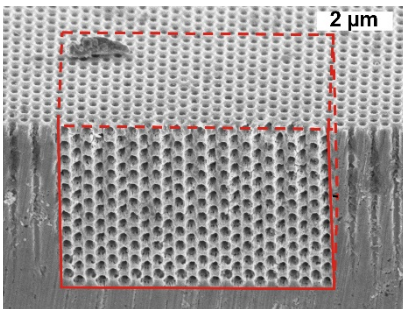
It is a major outstanding goal in Nanophotonics to precisely place quantum emitters inside a three-dimensional (3D) metamaterial. This offers control over cavity QED, spontaneous and stimulated emission, and non-linear optics [1]. Theory says that emission (e.g. from quantum dot) varies spatially on 100s nm scale [2]. Thus, we want to place emitters with a precision $\Delta x < 100$ nm. We developed a chemical toolbox to position quantum dots on 10 nm thick polymer brush layers inside 3D Si nanostructures [3]. Our photonic crystals have the 3D inverse woodpile structure (Fig. 1(A)) that exhibits a broad 3D band gap. The crystal are made by CMOS-compatible methods using deep reactive ion-etching through tailored masks. Here we want to learn if the quantum dots are at the right place?

Since nanophotonic materials are necessarily opaque, optical microscopy has insufficient penetration depth and limited resolution. SEM has plenty spatial resolution, but only the surface is viewed (Fig. 1(A)). Thus X-ray tools are ideal, especially X-ray fluorescence tomography, done at the ESRF beamline ID-16NI. We collect data while rotating the crystals from 0 to 180°. Projection maps are obtained at every angle followed by standard tomographic reconstruction to obtain the 3D atom density distribution with 50 nm spatial 3D resolution for each chemical element.

Fig. 1(B) shows a projection map of the lead atoms (PbS quantum dots) in one crystal. The 3D volume after reconstruction reveals two sets of pores running in Z and X-directions, matching the design (Fig. 1(A). The structure is periodic with lattice parameters that match the design. Quantum dots are located throughout the whole crystal volume. Their position correlates well with elements characteristic of the polymer brush layer. We conclude that X-ray fluorescence tomography is superb to solve many questions on 3D optical metamaterials, including cavity superlattices, physically unclonable keys, and precise positioning of emitters as qubits and for enhanced lighting efficiency. We look forward to the novel opportunities presented by speckle and coherent X-rays in the new ESRF!

(A)



(B)

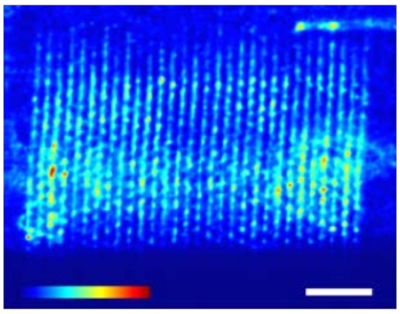


Fig. 1. (A) SEM image of the surface of a 3D Si inverse woodpile photonic crystal. The estimated extent is shown by dashed lines. The 3D crystal is surrounded by a large 2D array of pores that is first etched in the Z-direction. **(B)** Projection map of the number of Pb atoms per pixel (50 x 50 nm^2) integrated along the propagation direction of the beam, for an orientation as in (A). The color scale is the areal atomic density ranging from 0 to 420000 Pb atoms per pixel. The scale bar is 2 μm.

References

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