Multi-fold Quantum Dot Luminescence Enhancement in a Plasmonic Metamaterial

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Abstract: We report that hybridizing quantum dots with plasmonic metamaterial leads to a multi-fold intensity increase and narrowing of their photoluminescence spectrum, which is linked to the Purcell effect and has crucial importance for gain metamaterials.

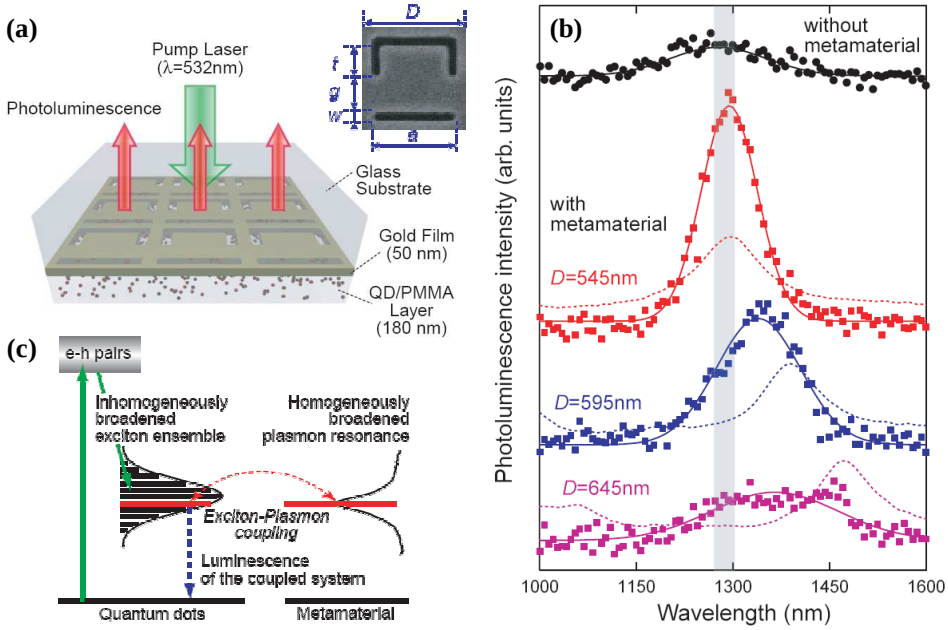

Fig.1: (a) Sketch of the experimental setup and SEM image of a metamaterial unit cell: D=545nm, a=470nm, t=g=170nm, w=65nm. (b) Photoluminescence spectra of the QDs without (top) and with metamaterial layer. A Gaussian fit is plotted with each spectrum (solid line). The dashed line indicates the metamaterial absorption spectrum. (c) Energy diagram of the QD-metamaterial coupled system.

Losses are the biggest challenge standing between countless proof-of-principle demonstrations of novel phenomena and the exploitation of metamaterials for practical applications. Combination of metamaterials with gain media is seen as a promising route to loss compensation and even metamaterial lasing.

Here we demonstrate that strong coupling between metamaterial resonators and semiconductor quantum dots (QDs) leads to dramatic intensity enhancement and spectral narrowing of the QD photoluminescence spectrum. We study photoluminescence of lead sulphide QDs dispersed in a 180 nm thick PMMA layer covering metamaterial arrays of asymmetrically split ring apertures cut by focused ion beam milling into a 50 nm thick gold film, see Fig. 1(a). As illustrated by Fig. 1(b), when the metamaterial absorption resonance (red dashed) is matched to the quantum dot photoluminescence peak (black data points), we observe an 800% increase of the photoluminescence intensity and spectral narrowing (FWHM) from 176 to about 100nm (red data points). On the other hand, a mismatch between the plasmonic absorption resonance and the quantum dot emission peak leads to rapid deterioration of the luminescence enhancement (blue, violet). This is clear evidence of plasmon-exciton coupling between QDs and metamaterial, see Fig. 1 (c) and may be understood in terms of the quantum electrodynamics Purcell effect. The quantum dot spontaneous emission decay rate is enhanced by the large density of photon states in the resonant metamaterial apertures. Purcell factor enhancement of about 100 is observed. We argue that the Purcell enhancement of luminescence has profound importance for the challenge of loss compensation in metamaterials.

[1] K. Tanaka, E. Plum, J. Y. Ou, T. Uchino, and N. I. Zheludev, "Multi-fold enhancement of quantum dot luminescence in a plasmonic metamaterial," arXiv.org:1008.4770 (2010).