Collective mode excitation in clusters of semiconductor nanopillars with embedded quantum dots by azimuthally polarized vector beams

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All-dielectric nanostructures made of materials with high refractive indices have gained popularity recently in the scientific society thanks to low losses in the optical and near infrared ranges, high stability under intense laser radiation, CMOS-compatibility and tailorable magnetic and electric multipolar Mie-type resonances [1]. Such objects allow orders of magnitude increase of nonlinear optical effects such as optical harmonic generation on the nanoscale without phase matching [2], nonlinear absorption [3] and ultrafast optical modulation [4]. Such systems can also be used, for example, as unidirectional narrow-band nanoantennas [5], wavefront phase convertors [6] and ultra-thin polarizers [7].

The next step in the development of all-dielectric nanophotonic structures can be a combination of previously studied semiconductor systems with quantum-confined structures such as quantum dots (QDs). At the moment, only few experimental works have been done at the intersection of all-dielectric nanophotonics and quantum-confined systems. In these works QDs that were located near the surface [8] or inside the nanostructure [9] were excited by linearly polarized (LP) Gaussian beams, that in some cases limits operation of such hybrid systems. Contrary, the use of cylindrical vector beams with azimuthal polarizations (AP) [10] allows selective collective modes excitation [11] characterized by enhanced field localization factor [12], that may lead to more effective interaction of QDs with Mie-resonant oligomers.

In the presented work, we conducted a comprehensive numerical study of QDs photoluminescence (PL) in the case they were located in the volume of GaAs isolated quadrumers (Mie-resonant nanopillars located in the vertices of a square) and excited by LP and AP pump beams. As it was previously experimentally shown in the work of V. Rutckaia et al. [9] when the magnetic dipolar (MD) resonance of oligomer spectrally overlaps with QDs emission spectrum, several times enhancement of PL intensity is observed due to the Parcel effect. We numerically showed that utilizing collective optical modes excited by AP beams instead of MD resonance is a proper way for further PL enhancement. We demonstrated an order of magnitude QDs emission enhancement for AP illumination compared to the LP case, which was sensitive to point-sources positions and number, and also the size of the oligomers. We studied far-field diagrams of point-dipole emission coupled to the LP excited MD mode and AP excited collective optical modes that showed directivity enhancement for the second case. We also demonstrated the existence of described effect for random numbers and in-plane positions of QDs, which is closer to the real experimental situation.

For experimental investigation of QDs emission embedded to nanopillar clusters we fabricated sets of samples consisting of isolated Mie-resonant quadrumers made from GaAs films with embedded QDs made in Ioffe Institute in Saint-Petersburg (group of prof. S. Ivanov) by molecular-beam epitaxy. We characterized obtained sets of samples by scanning electron microscopy. For further optical characterization of fabricated hybrid systems we carried out dark-field spectroscopy of isolated oligomers in the reflection geometry for LP illumination on the home-made setup demonstrating overlap of MD resonance of some oligomers with QDs emission spectrum. We further plan experimental investigation of QDs PL under various excitation conditions at room and cryogen temperatures.

Development of hybrid quantum-confined structures may help to increase the efficiency of unidirectional nanoemitters, including single-photon sources with optical pumping. Hybrid systems can serve as an experimental basis for creating nanostructured materials with an artificial optical response for applied quantum optics on a chip.

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