Site-controlled quantum dots coupled to photonic crystal waveguides

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Abstract- We demonstrate selective optical coupling of multiple, site controlled semiconductor quantum dots (QDs) to photonic crystal waveguide structures. The impact of the exact position and emission spectrum of the QDs on the coupling efficiency is elucidated. The influence of optical disorder and end-reflections on photon transport in these systems are discussed.

The challenging goal of realizing on-chip quantum circuits in which spins are interfaced with photons that are then routed, processed and detected has triggered significant research efforts over the past decades [1]. InGaAs/GaAs quantum dots (QDs) integrated in photonic crystal (PhC) circuits are one of the most advanced technologies in this direction [2]. Most of the work has focused on Stranski-Krastanow QDs that nucleate at random positions [3], while achieving truly scalable quantum circuits requires a precise deterministic integration of an entire QD system in a photonic circuit. However, the inhomogeneous broadening inherent to QD systems makes the simultaneous efficient coupling of several QDs to a given photonic mode difficult to accomplish. On the contrary, the finite spectral bandwidth of photonic waveguides should facilitate the simultaneous optical coupling of QD systems. Such structures could be used, e.g., to increase the emission rate of single photon sources by efficiently coupling multiple QD single photon sources to the same optical channel.

In this work, we demonstrate the deterministic coupling of five site-controlled QDs placed at different positions within a W_1 semi-waveguide with a reflective termination and an out-coupler on its ends (see Fig. 1a). We study the spectra emitted by the s-states of each single QD and how they evolve during the propagation through the waveguide. In Fig. 1b) spectrally resolved near-field pattern in which light is emitted by a selectively excited QD positioned 20.5µm away from the out-coupler, propagates in the waveguide and is collected at the out-coupler. This constitutes the first direct observation of light emission by a site-controlled QD in a PhC waveguide.

Next, we analyze the fraction of light collected at the out-coupler relative to the intensity collected directly from the QD emission (by exciting each QD separately). We perform the same study on each QD of eleven structures with systematic variations in the PhC hole radii r such that the QDs s-states (with an energy around 1.31eV) were tuned into (r<72nm) and out of (r>72nm) resonance with the fundamental waveguide mode. As shown in Fig. 1c), the emission of QDs in the bandgap (r>72nm) is not efficiently channeled to the out-coupler. For QDs resonant with the waveguide photonic band (r<72nm), the fraction of light collected at the out-coupler I_{outc}/I_{QD} reaches values up to 10, evidencing an efficient coupling of the QDs with the waveguide modes. The intensity of the emission collected from the out-coupler for QDs in resonance with the waveguide band varies with the PhC hole radius. This is explained by the formation of Fabry Pérot-like modes in the waveguide due to the significant reflection at the out-coupler [4]. This effect is already observed in the QD spectra collected at the out-coupler in Fig. 1b: only QD lines near resonance with a Fabry Pérot line are efficiently channeled to the out-coupler. A minimal reflection at the out-coupler is thus required in this case to ensure a truly broadband coupling of the QD to the waveguide. This brings to light the need for alternative designs of out-couplers with very low reflection into the waveguide. Photon correlation measurements confirm the emission of single photons by the integrated QDs. The impact of PhC waveguide disorder on the propagation along the PhC channel will also be demonstrated and discussed. We show that mode localization can be avoided when propagation via modes of high enough frequency is used.

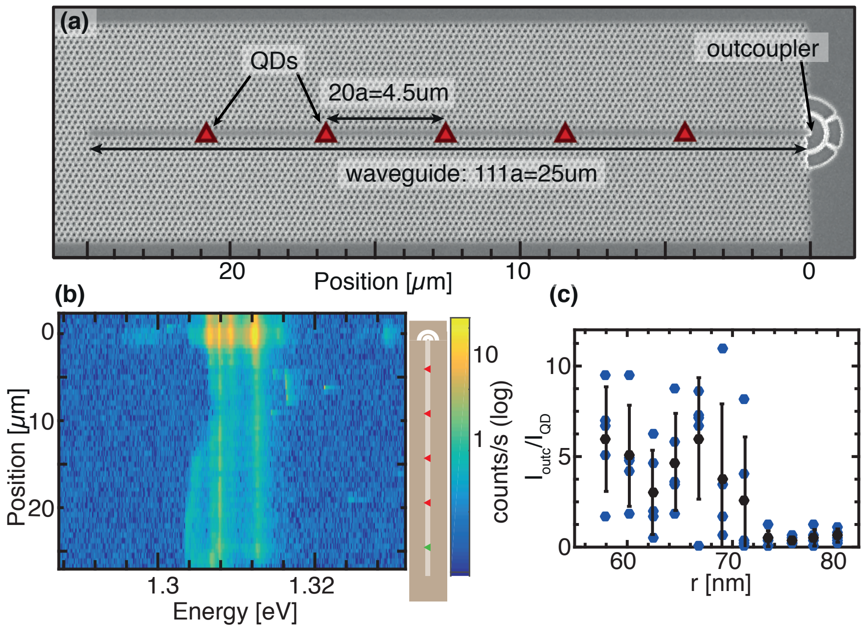

Figure 1: (a) SEM picture of a 25µm long semi-waveguide with indications of QD positions, (b) Spectrally-resolved near field pattern of the structure in (a) (Excitation power: P=5µW, T=10K, r=61nm), only one QD (shown in green) is excited. (c) Effect of tuning the QD emission through the bandgap: fraction of the intensity extracted from the outcoupler divided by the intensity collected directly from the QD s-states as a function of the PhC hole radius (Excitation power: P=5µW, T=10K, for each PhC hole radius, each data point corresponds to the emission of only one of the five QDs).

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