Enhanced spontaneous emission from single quantum dots inside short photonic crystal waveguides

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We present theoretical and experimental studies of quantum dots (QDs) integrated into short photonic crystal (PhC) waveguides (WGs). Our photoluminescence (PL) data reveals a combined effect of Fabry-Pérot (FP) and slow-light modes, resulting in an increased spontaneous emission rate of the QDs and an improved coupling efficiency to the guided mode. Therewith, our approach has great promise to funnel single photons efficiently (~80%) into PhC WGs and is thus very suitable for integrated quantum photonics applications.

I. INTRODUCTION

Single photon emitters are key building blocks for the implementation of integrated quantum information processing schemes [1]. QDs are perfectly suited for this purpose because they can be easily integrated into semiconductor devices. If embedded into PhC WGs, the QDs benefit from an enhancement of their spontaneous emission by the slow-light effect near the fringe of the WG dispersion. The broad spectral range of the slow-light mode and the large WG mode volume allow for large photon collection efficiencies even in the case of limited spectral and spatial matching.
In contrast to earlier work [2], we investigated short WGs (10-25 µm). WGs with reduced lengths still support slow light modes, but do not suffer under light localization induced by unavoidable fabrication disorder.

II. FABRICATION

The layer structures of our samples are fabricated by molecular beam epitaxy. On top of GaAs substrate a 1.5 µm thick AlGaAs sacrificial layer is grown, followed by a 320 nm GaAs membrane including InAs QDs which emit around 1300 nm. An intermediate SiO_2 etch mask is deposited on the surface before a resist is patterned by electron beam lithography. When the holes of the PhC lattice are defined, one line of holes is omitted in order to form a W1 WG. The pattern is transferred into SiO_2 by CHF_3/Ar reactive ion etching and into the substrate by Cl_2/Ar electron cyclotron resonance etching. Afterwards, the sample is cleaved and both the sacrificial layer and the residual SiO_2 are removed by hydrofluoric acid. Fig. 1 shows the suspended membrane of a fabricated device [3].

III. EXPERIMENTAL RESULTS

For optical characterization the QDs in the center of the WG are excited from the top and the PL is measured either from the top of the device or from the side at the cleaved facet.
In Fig. 2 the obtained spectra of a 17 µm long WG at room temperature are shown next to calculations of the corresponding band diagram [4]. When the PL is collected from above only the first-order guided mode is visible due to its polarization along the defect line of the WG. The fundamental mode on the other hand is polarized perpendicular to the WG and hence detected from the side. The intensity is higher near the cut-off at the low frequency side of the mode where the slow-light regime is prevalent. The FP modes which arise from the two WG end facets and appear only for the propagating fundamental mode, allow for an investigation of the slow-light effect. The spectral distances of the FP peaks is becoming smaller when the band edge is approached, which proves a strong increase in the photon group index. In addition, the Q-factor is increasing, giving evidence that the light is contained in the WG for a longer time owing to the slow-light effect.
Moreover, the expected decrease of the exciton decay time τ is confirmed by time-resolved measurements at low temperature. By comparing emission lines located away from (τ=1.6 ns) and in the slow light regime (τ=0.8 ns), we calculate an enhancement of the spontaneous emission by a factor of 1.7.

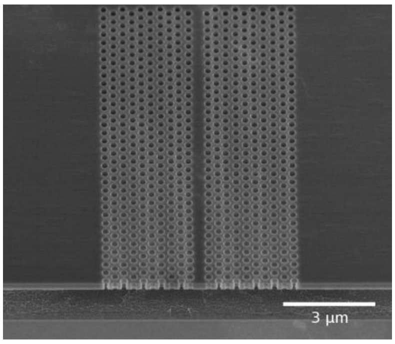

Figure 1.A scanning electron microscope image of a PhC WG.

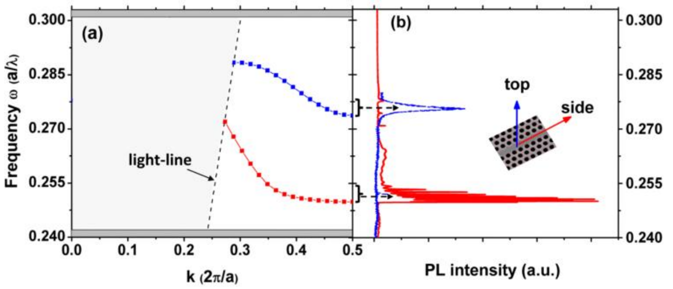

Figure 2.(a) Calculated band diagram and (b) PL data of a W1 PhC WG.

Furthermore, we determined the coupling efficiency into the slow-light mode to be ~80%.

The undoped GaAs membrane used for the devices presented here can also be replaced by a p-i-n diode structure, enabling Stark tuning of the quantum dot. This could be useful for a precise matching of the emission with the slow light mode and for applications where a control of the wavelength is required.

IV. CONCLUSION

We demonstrated that short PhC WGs can enhance the spontaneous emission rate of integrated QDs and the coupling efficiency into the slow-light mode, making this device schema a promising candidate as single photon source for future on-chip photonic circuits.

ACKNOWLEDGMENT

This work is supported by the European Commission within the FP7 project QUANTIP.

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