Site-controlled quantum dots coupled to a photonic crystal waveguide

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PHYSICS OF nanoSTRUCTURES

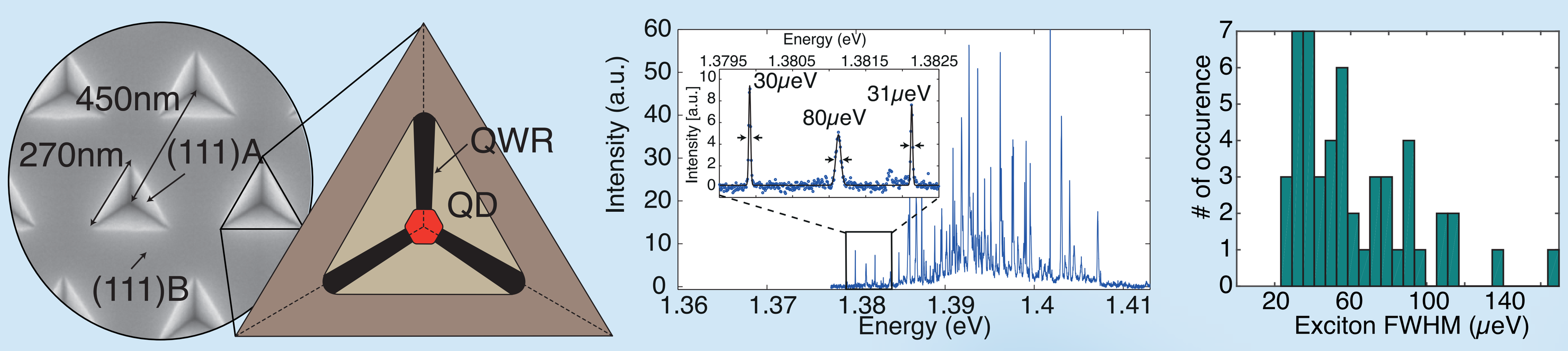
Motivations

- Emission, routing and measuring single photons on chip for quantum optics applications.
- Quantum dots (QDs) in photonic crystal circuits are a promising approach to achieve on chip reproducible[1] high $g^{(2)}$ [2], high indistinguishability, high brightness.
- Site-control of QDs is needed for reproducible and scalable photonic circuits.

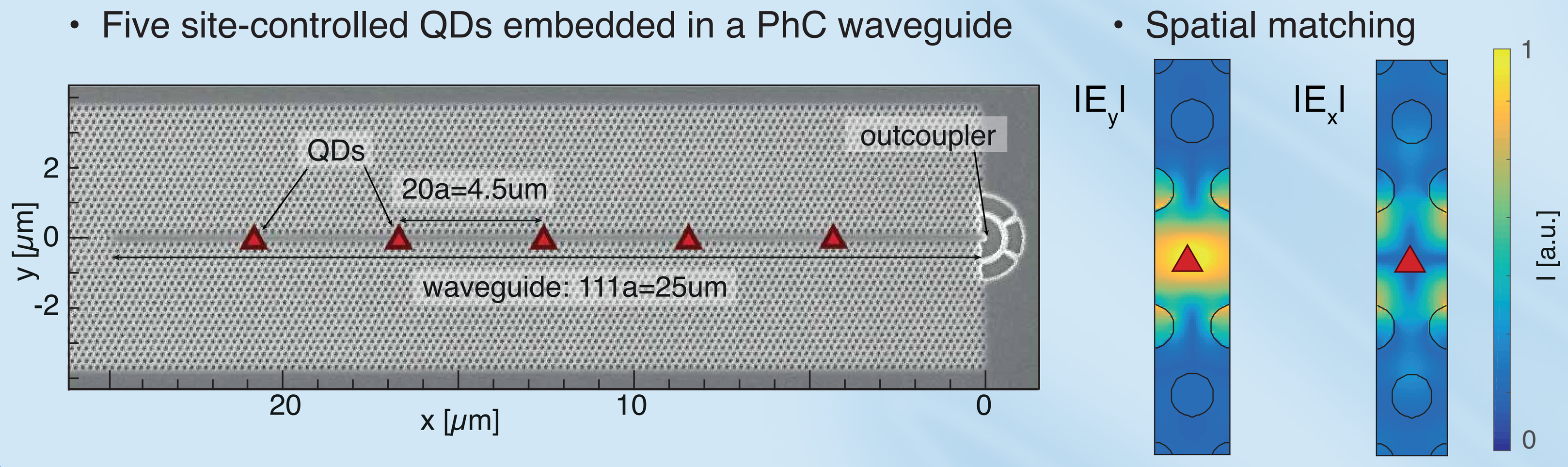
Objective: demonstrating a system of five QDs all coupled to a W_1 waveguide.

5 QDs coupled to a waveguide

- Pyramidal site-controlled QDs[3]: narrow emission lines, low inhomogenous broadening.

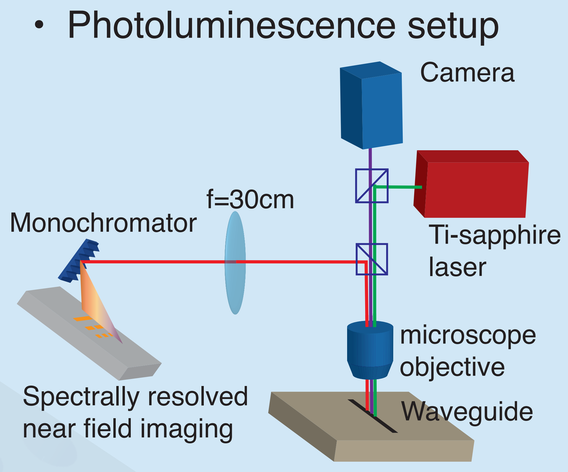


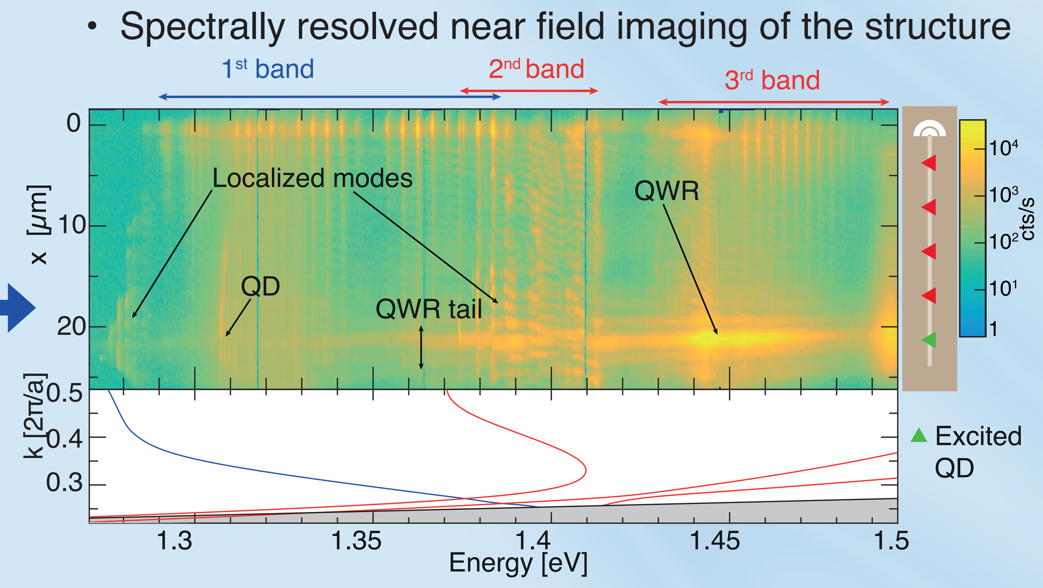
- Five site-controlled QDs embedded in a PhC waveguide
- Spatial matching



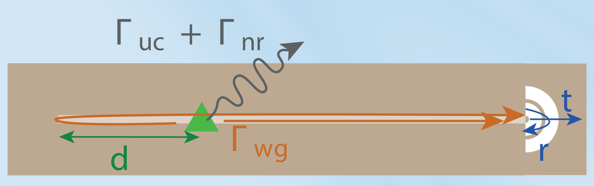
Site-controlled QDs: tool to probe the electric field

- Photoluminescence setup
- Spectrally resolved near field imaging of the structure





- In a waveguide: $\beta = \frac{\Gamma_{wg}}{\Gamma_{wg} + \Gamma_{uc} + \Gamma_{nr}}$



- A high β requires a high Purcell factor:

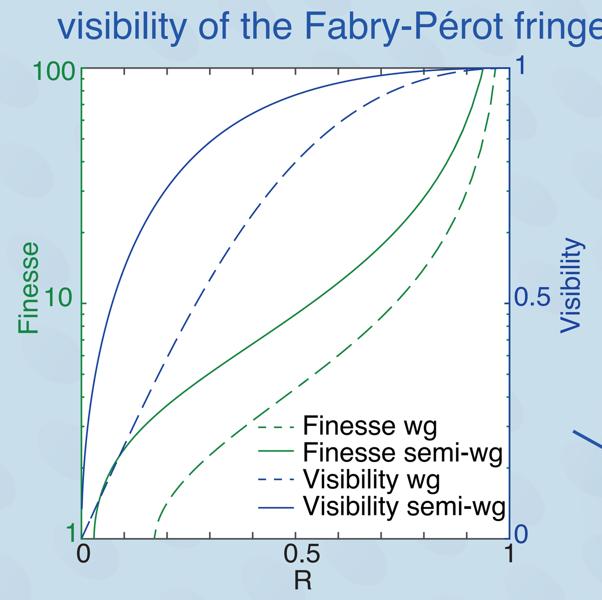
$$P_{sp,wg} = \frac{3\pi n_g}{n}\frac{c^2}{A\omega^2}\left|\vec{\nu}^*(r_d)\cdot\vec{u}_d\right|^2 \frac{t^2}{(1-r)^2}\frac{1}{1+4r/(1-r)^2\sin^2(\delta_l/2)}\cos(k_1 d)^2$$

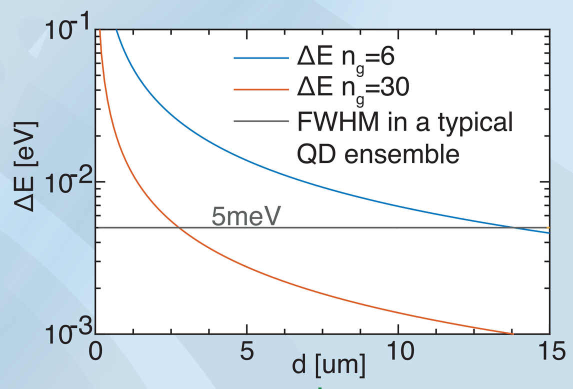
Overlap with the Bloch mode

Reflection from the outcoupler

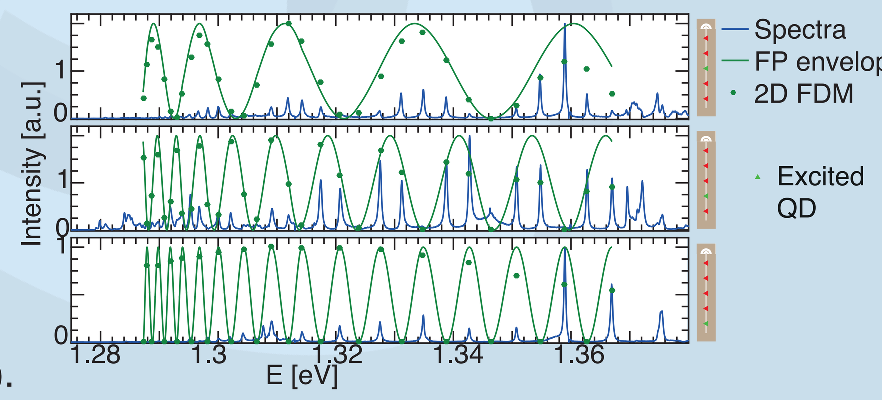
Reflection from the end of the semi-waveguide

- Which determines the finesse and visibility of the Fabry-Pérot fringes.
- Which determines the FWHM of the envelope modulation in a semi-waveguide.





- The waveguide density of modes can be probed with site-controlled QDs showing the expected envelope modulation and Fabry-Pérot fringes:

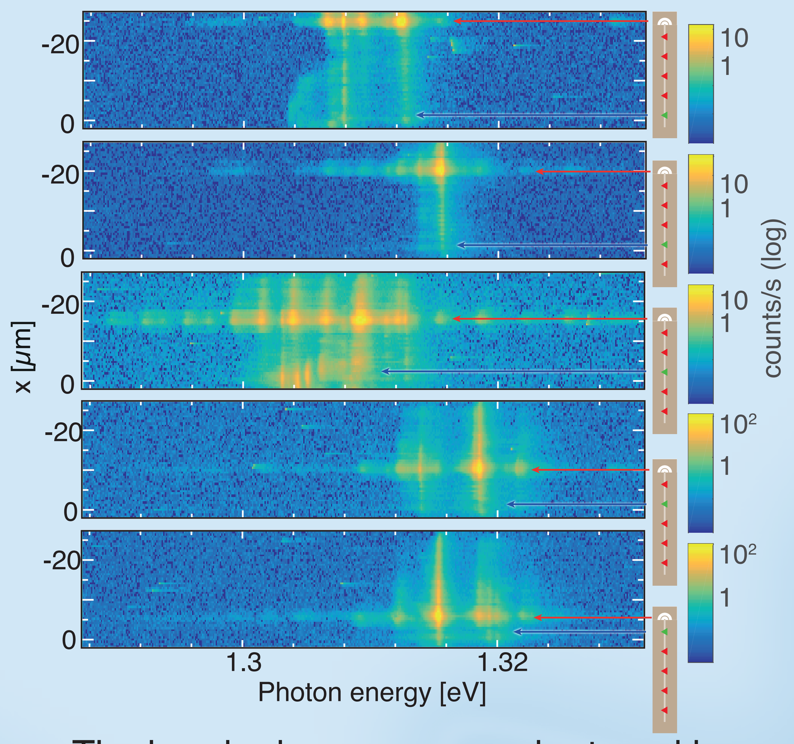


Conclusions:

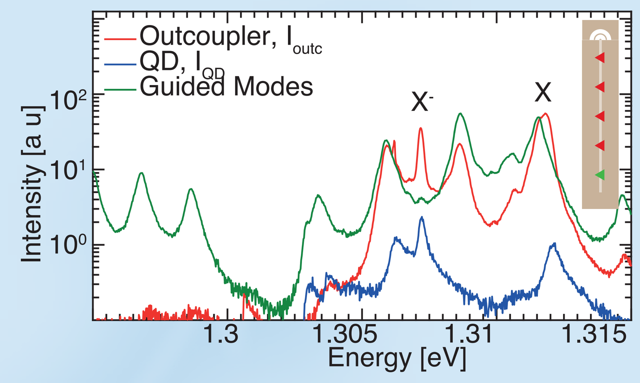
- Reflection from the outcoupler is detrimental to achieve a broadband coupling.
- In a semi-waveguide, the coupling is broadband only for QDs placed near the closed end of the waveguide (small d).

Pyramidal QDs emitting through a PhC waveguide

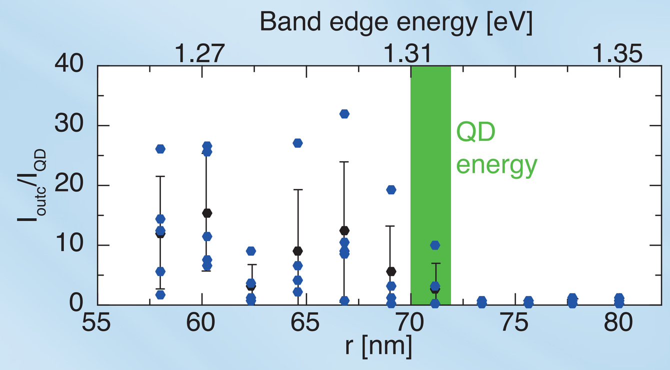
- Each QD can be excited separately, light propagation is observed.



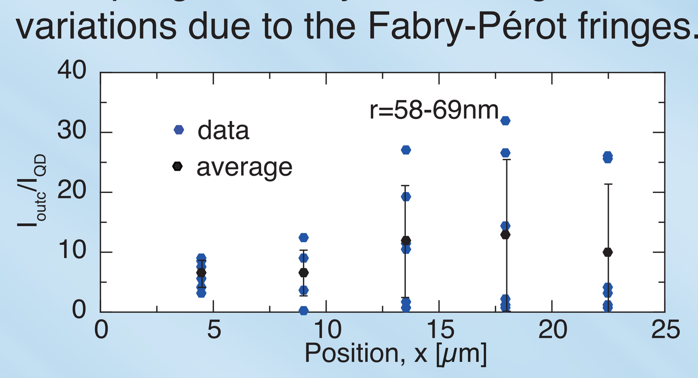
- We can then distinguish between the spectrum of the QD and the spectrum of light guided through the waveguide.



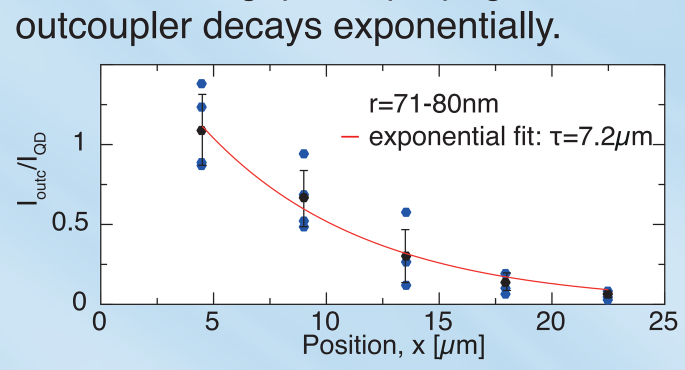
- The band edge energy can be tuned by hole size variations.



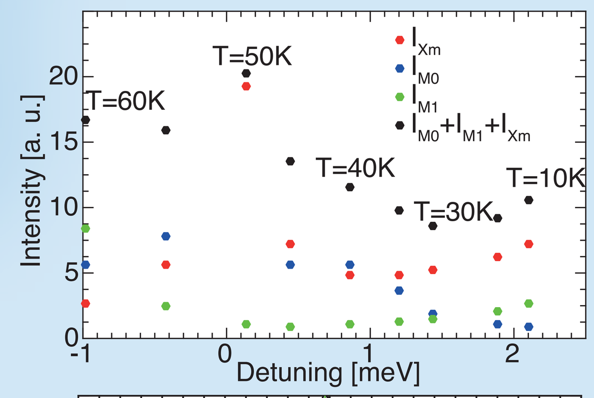
- coupling efficiency shows large variations due to the Fabry-Pérot fringes.

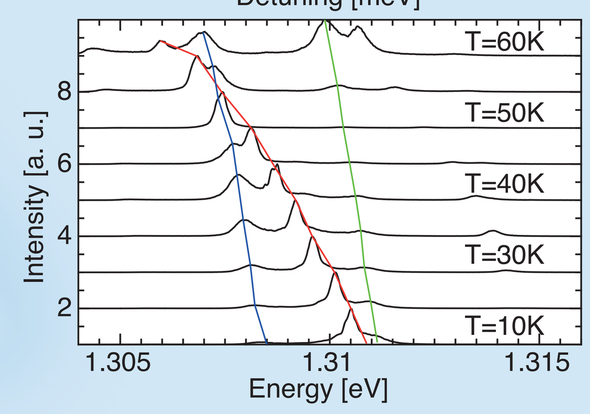


- In the bandgap, the propagation to the outcoupler decays exponentially.



- QD modes are tuned in and out of resonance with waveguide modes, showing large intensity variations.



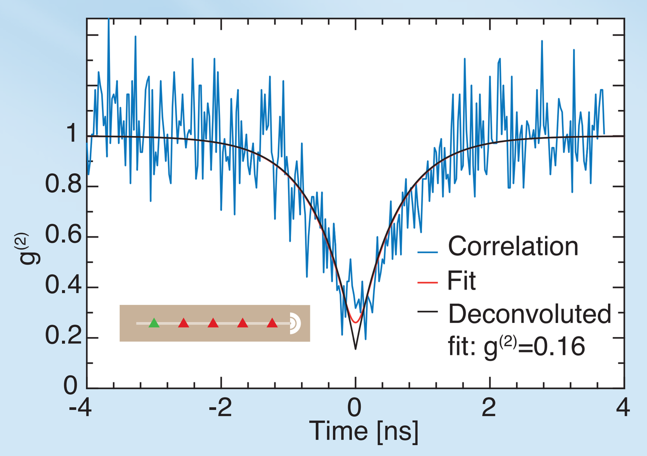


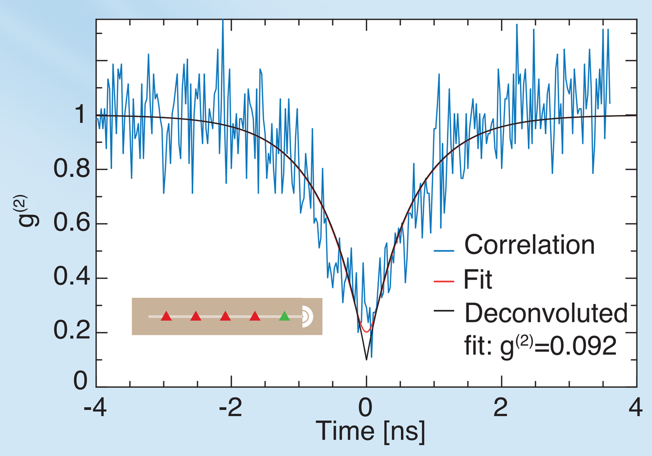
Conclusions:

- We can observe the propagation of light emitted by QDs along the waveguide.
- Fabry-Pérot fringes have a noticable impact on coupling efficiency.
- A coupling cutoff is observed when QDs energy is below the band edge of the PhC waveguide.

Single photon emission

- 22.5μm propagation: $g^{(2)}$=0.16
- 4.5μm propagation: $g^{(2)}$=0.092





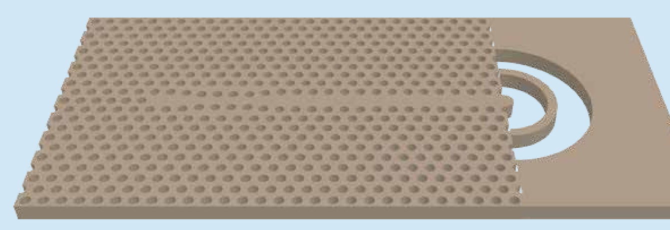
Conclusion and outlook

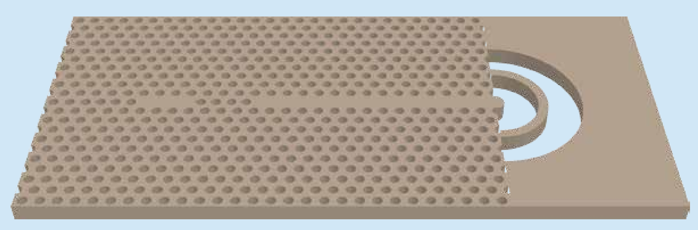
a. Guidelines for high coupling efficiency

- QDs placed near the end of the semi-waveguide.
- Low reflection of the outcoupler.
- **Density of states tailoring** through the use of slow light or cavities.

b. Two optimal designs:

- **Slow light** waveguide coupled to a fast light waveguide: high β and broadband.
- Cavity coupled to a waveguide: very high β but not broadband.





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[1] P. Lodahl, M. Sahand, and S. Søren. "Interfacing Single Photons and Single Quantum Dots with Photonic Nanostructures." Reviews of Modern Physics 87, no. 2 (2015)
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[3] P. Gallo, M. Felici, B. Dwir, K. A. Atlasov, K. F. Karlsson, A. Rudra, A. Mohan, G. Biasiol, L. Sorba, and E. Kapon. "Integration of Site-Controlled Pyramidal Quantum Dots and Photonic Crystal Membrane Cavities." Applied Physics Letters 92, no. 26 (2008)