Cavity QED with quantum dots in microcavities

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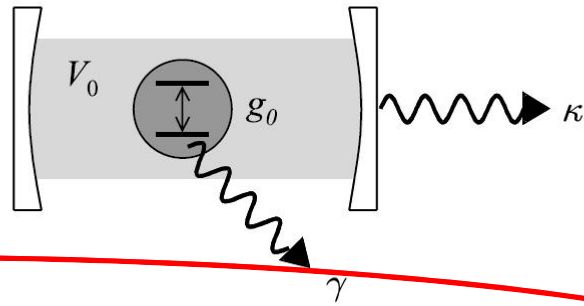
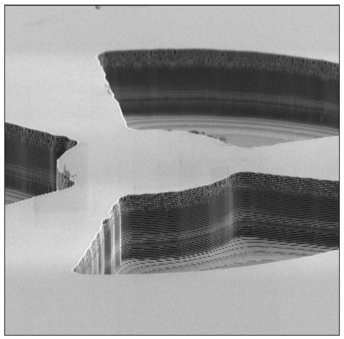
Universiteit Leiden

Cavity QED (= Quantum Electro Dynamics)



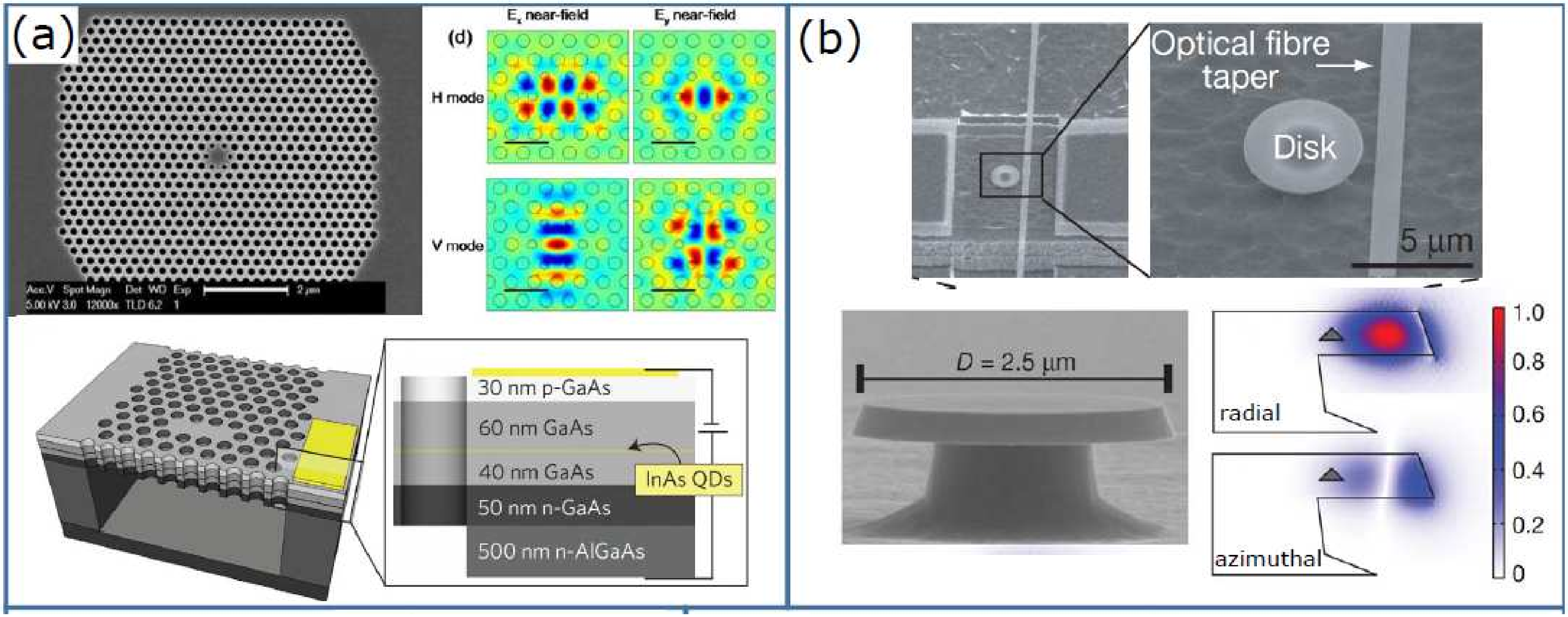
- Weak coupling: $g \ll \{\gamma, \kappa\}$
- Intermediate coupling: $\gamma < g < \kappa$ Cooperativity: $C = g^2/\kappa\gamma$
- Strong coupling: $g > \{\gamma, \kappa\}$
  (Dressed states)

Now: Quantum dots (artificial atoms)
& micropillar cavities



Semiconductor quantum dots in cavities

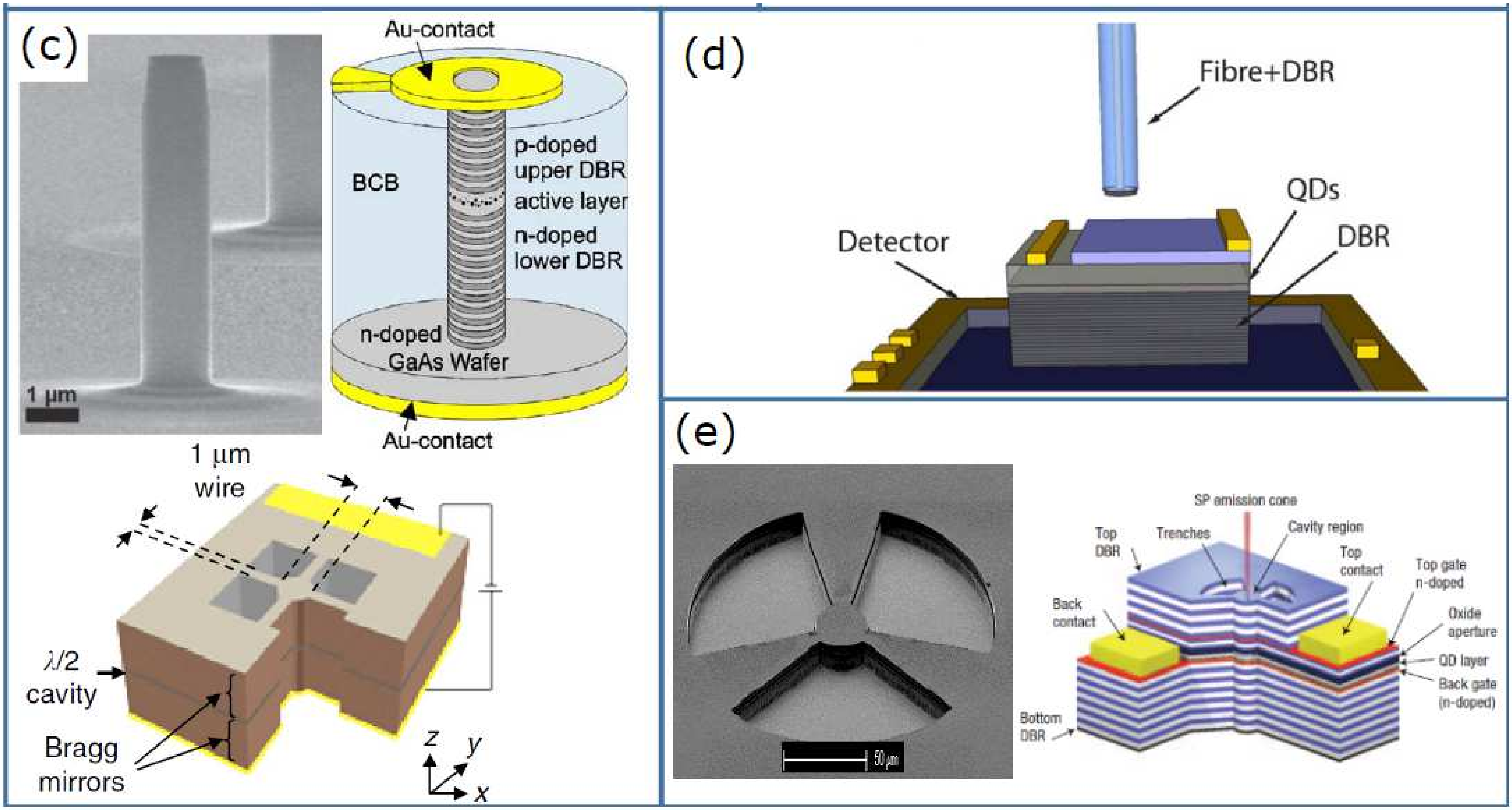
a) Photonic crystal cavity
b) Microdisk cavity



c)-e) Micropillar cavities

Semiconductor quantum dots in cavities

c)-e) Micropillar cavities

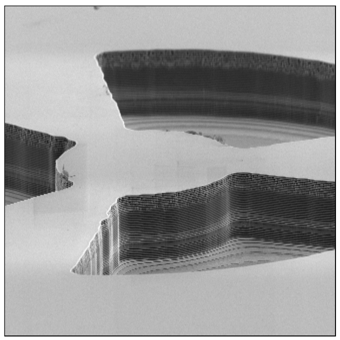


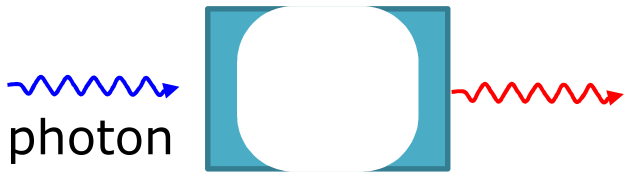
Outline

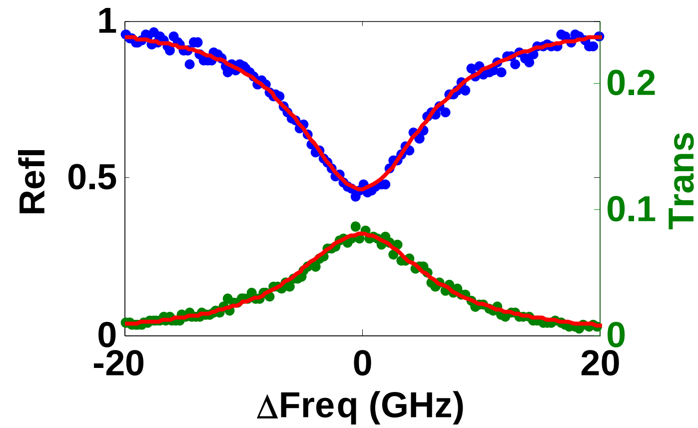
- Motivation
- Introduction of system: Qdots & microcavities
- Various experiments:
  1. Resonant spectroscopy
  2. Hysteresis effects & charge memory
  3. Coherence measurements

Motivation

Quantum dots (artificial atoms) and micropillar cavities

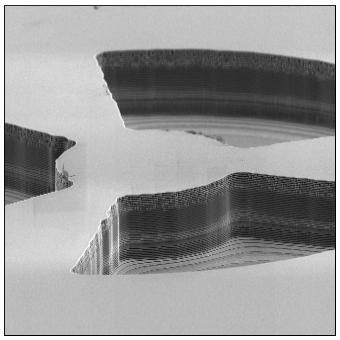




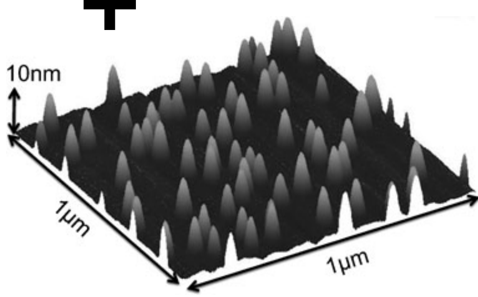


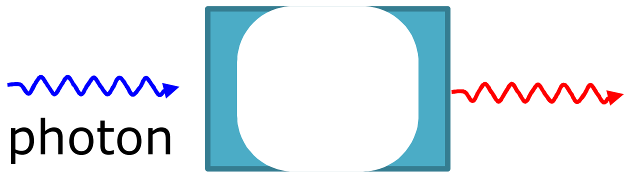
Motivation

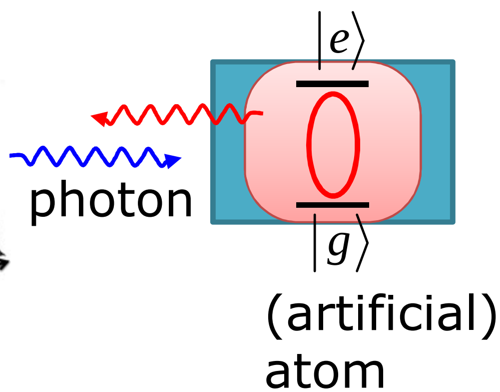
Quantum dots (artificial atoms) and micropillar cavities

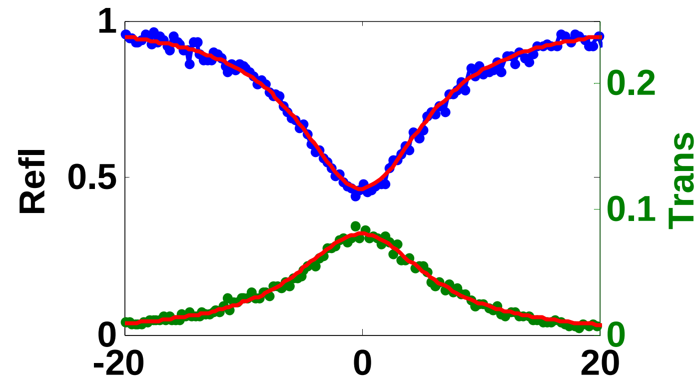


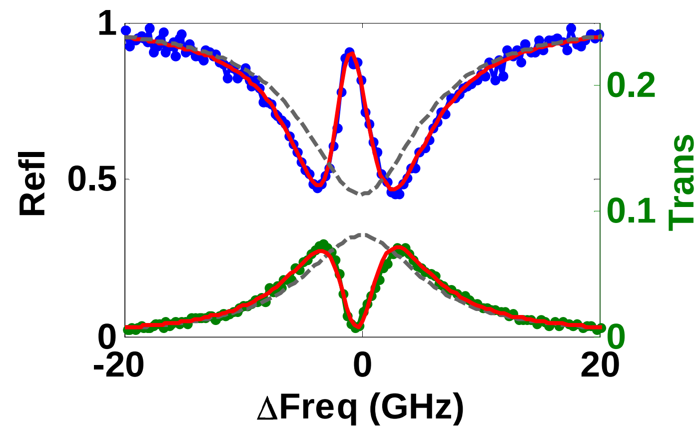
+







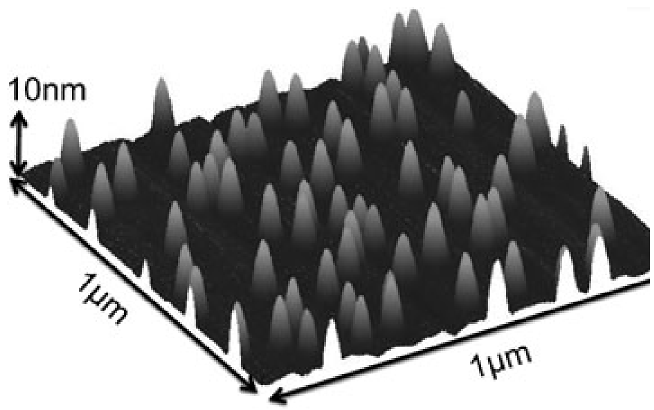


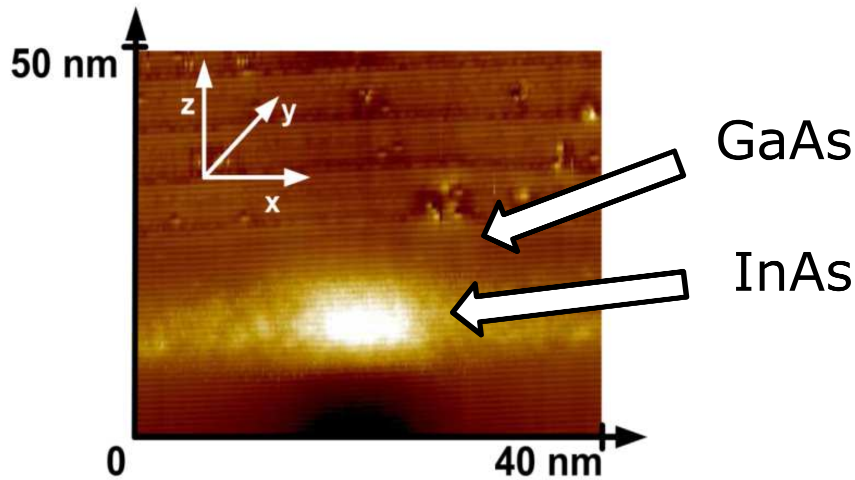


Towards QD–photon entanglement

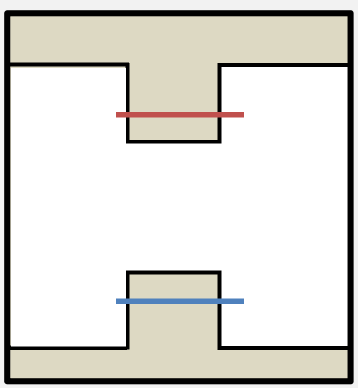
InAs Quantum dots

Artificial atoms

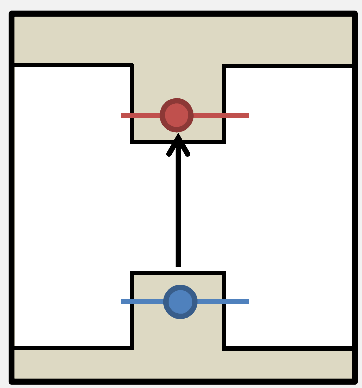




Ground state: $|0\rangle$

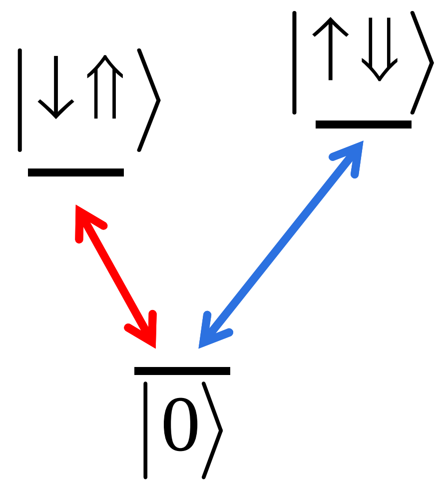


Excited state: $|\uparrow\Downarrow\rangle$

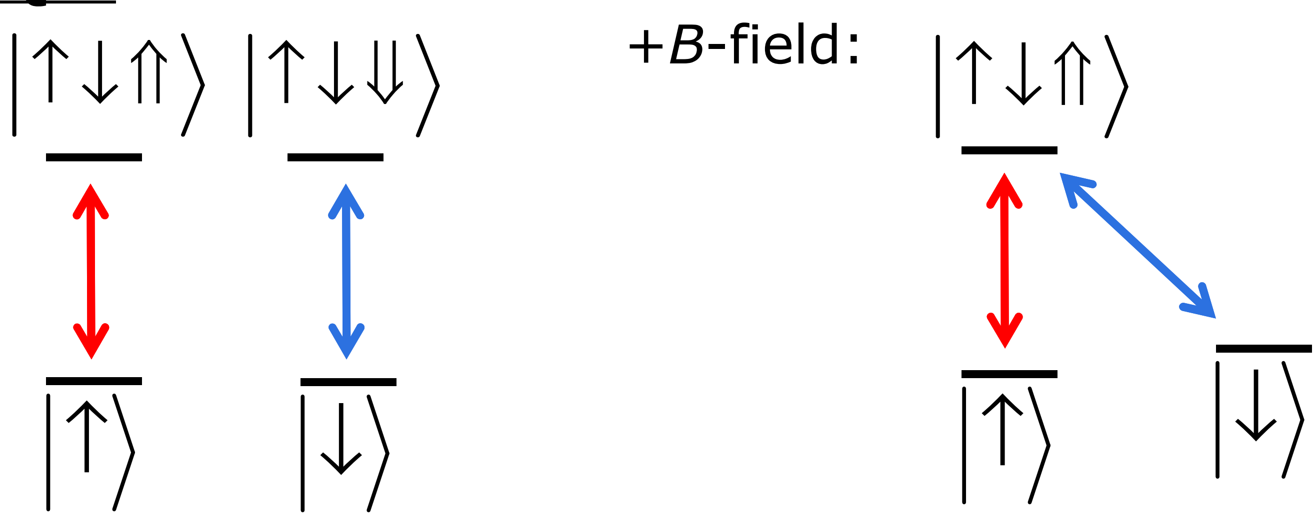


Artificial atoms

Neutral QD:



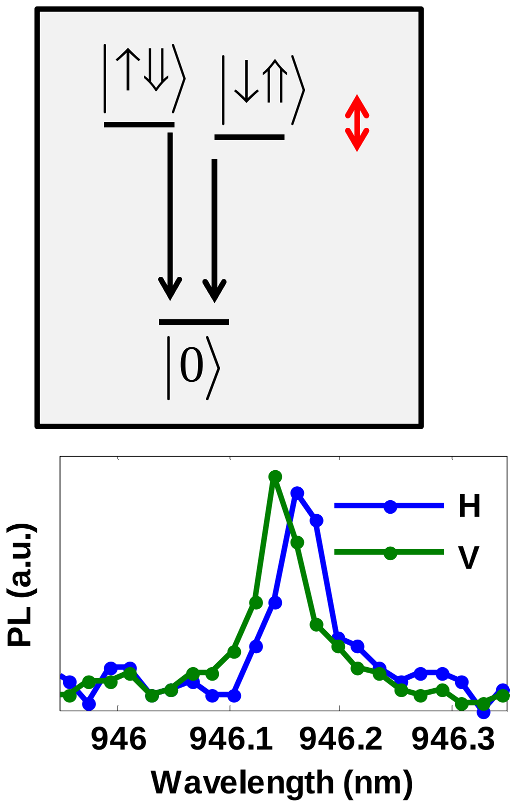
Charged QD:

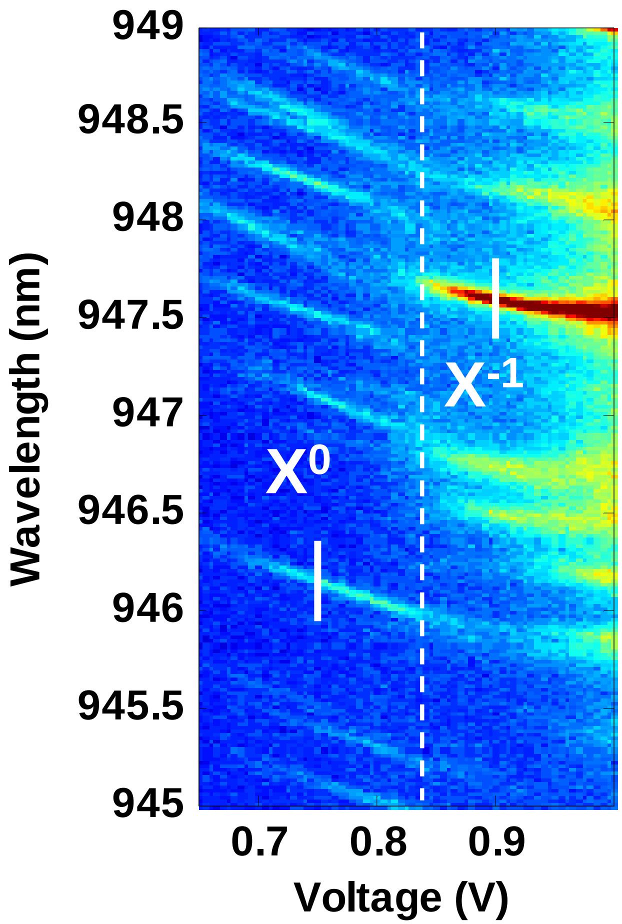


Voltage control

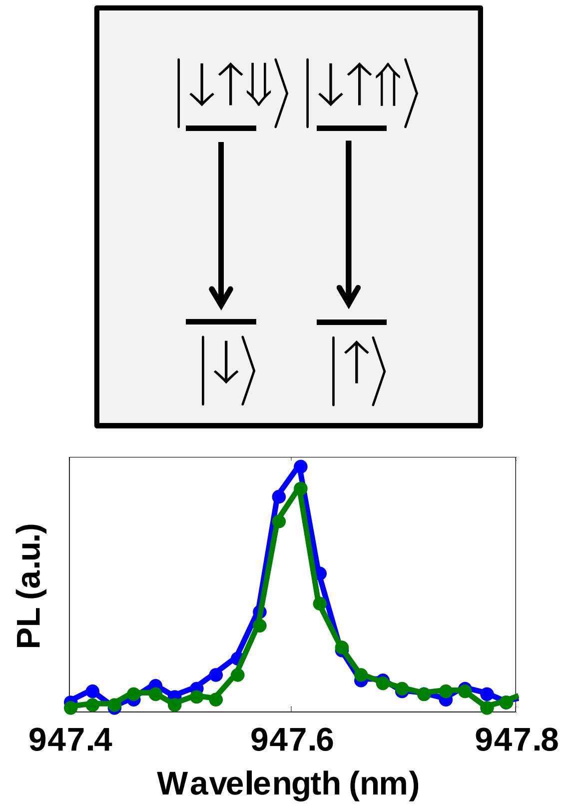
Voltage control of charge and energy (through Stark effect)

Neutral



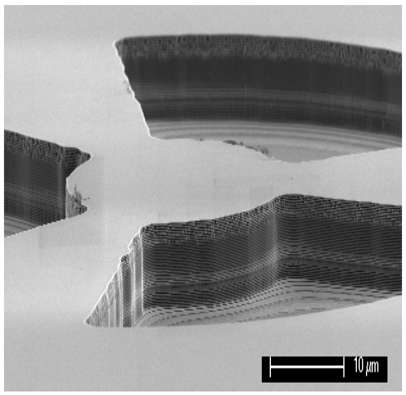


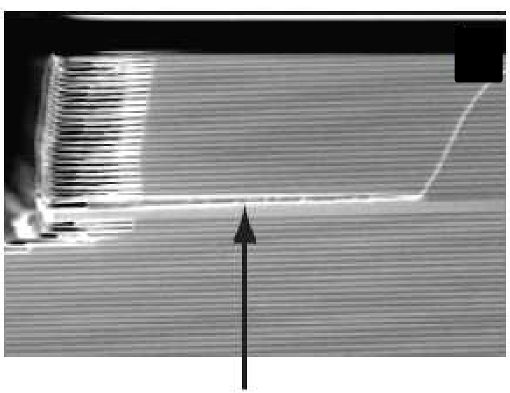
Charged



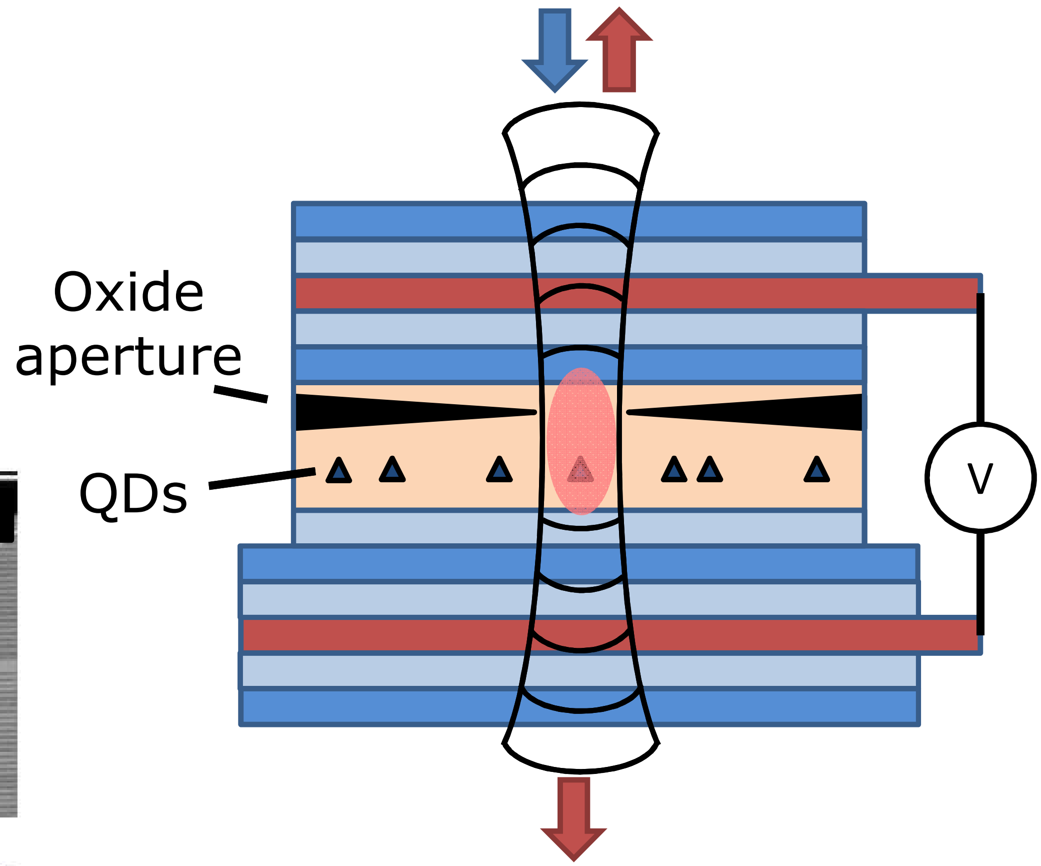
Micropillar cavities

Small volume (~2μm³) and high Q ~30k,
(Maximum Purcell factor ≈ 20)

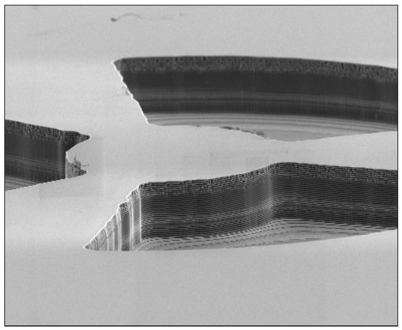


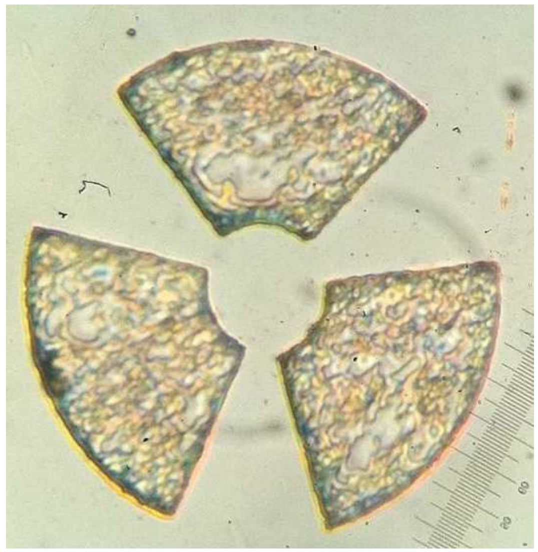


tapered oxidation aperture

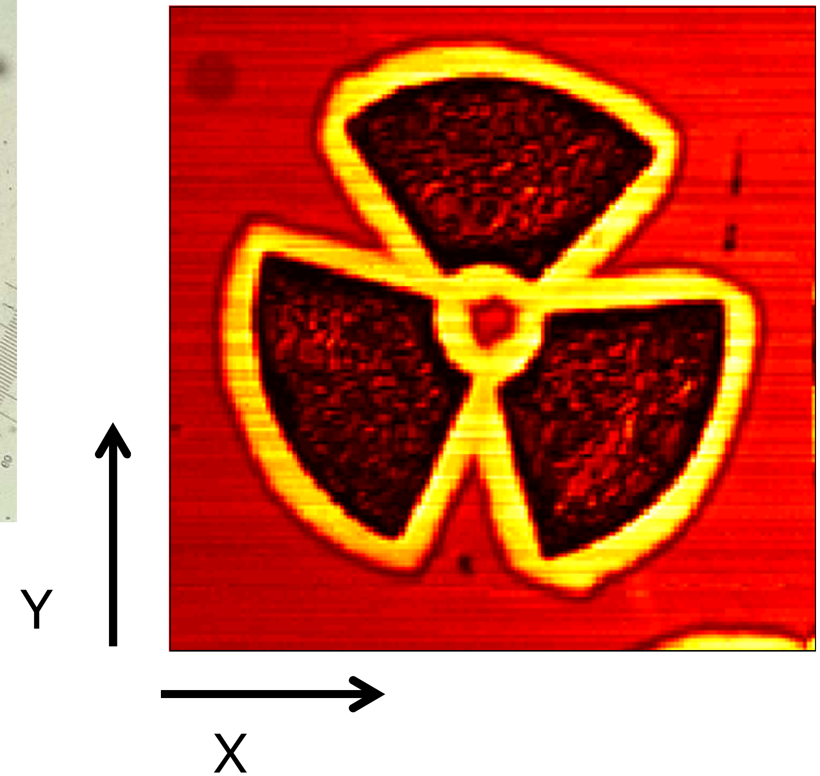


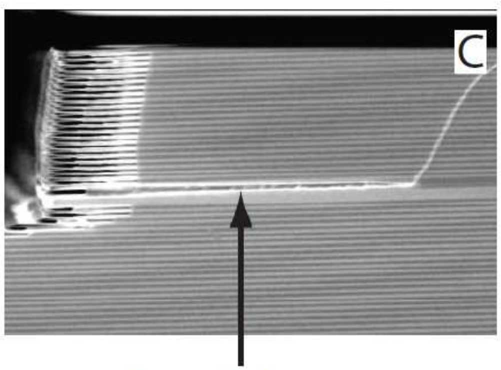
Viewing the aperture





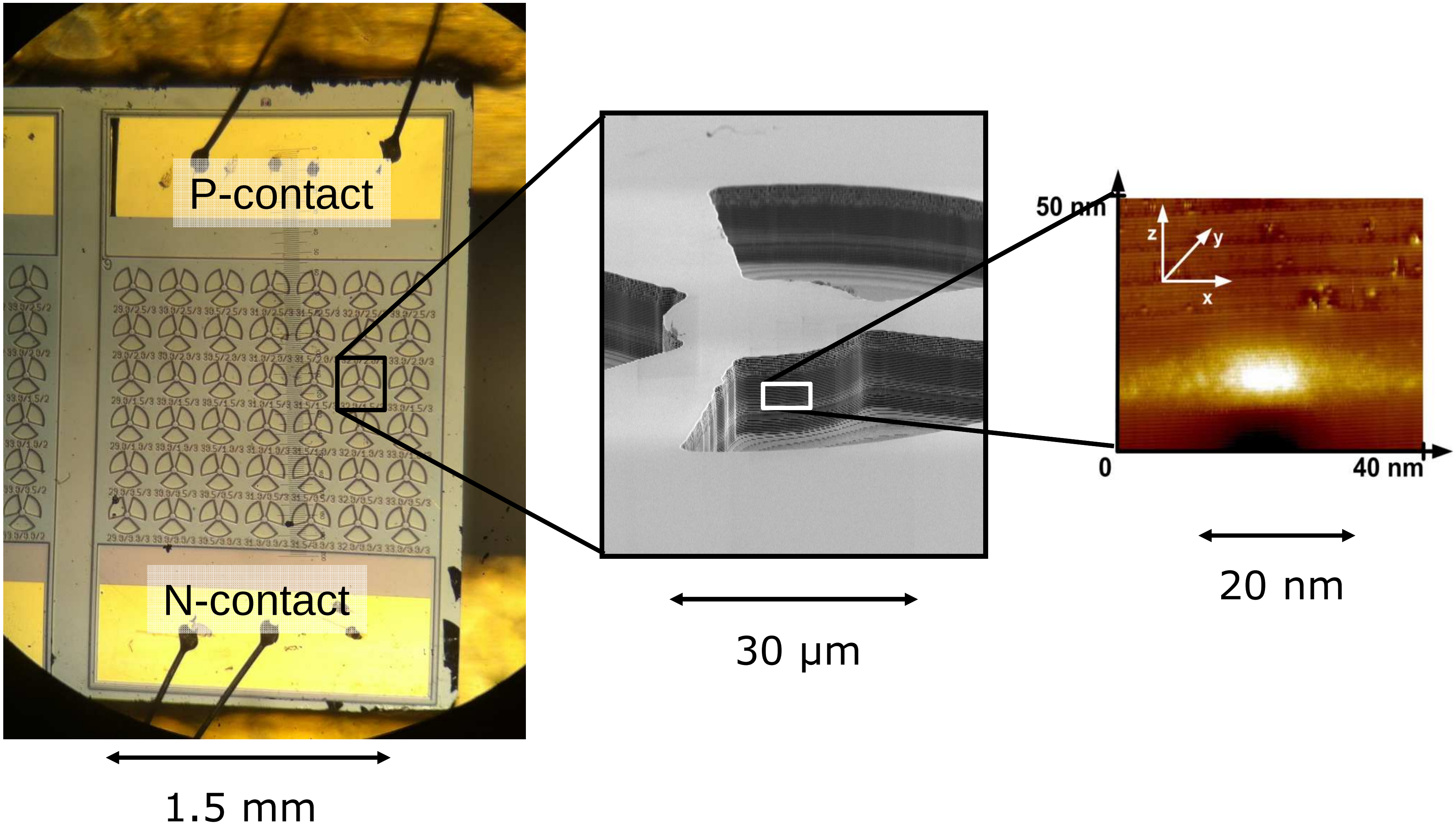
Reflectance at 1064 nm



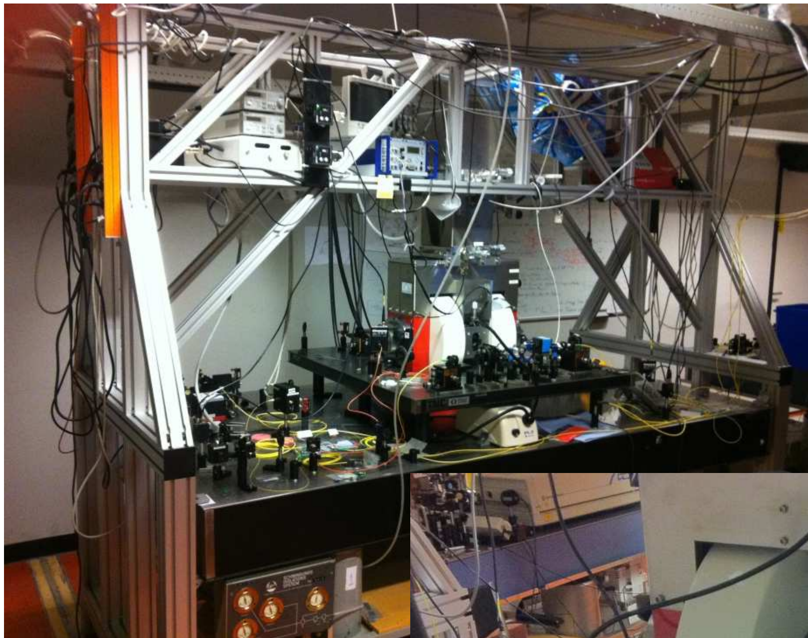


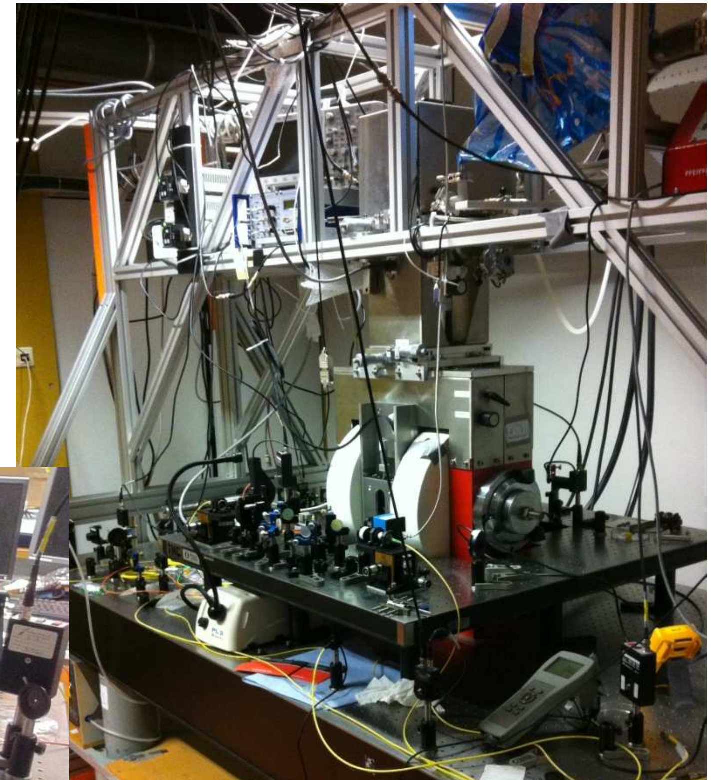
tapered oxidation aperture

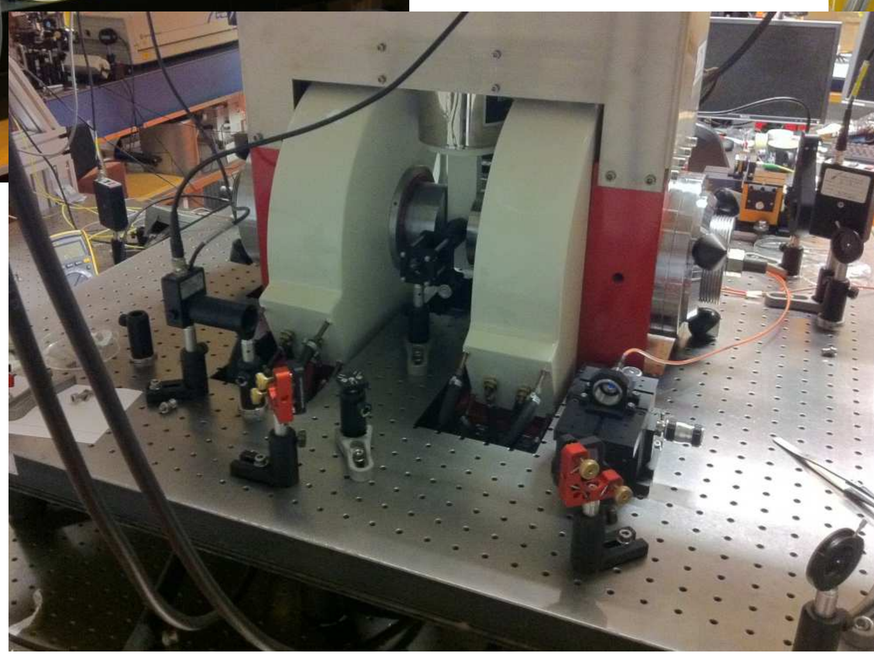
Sample



Setup

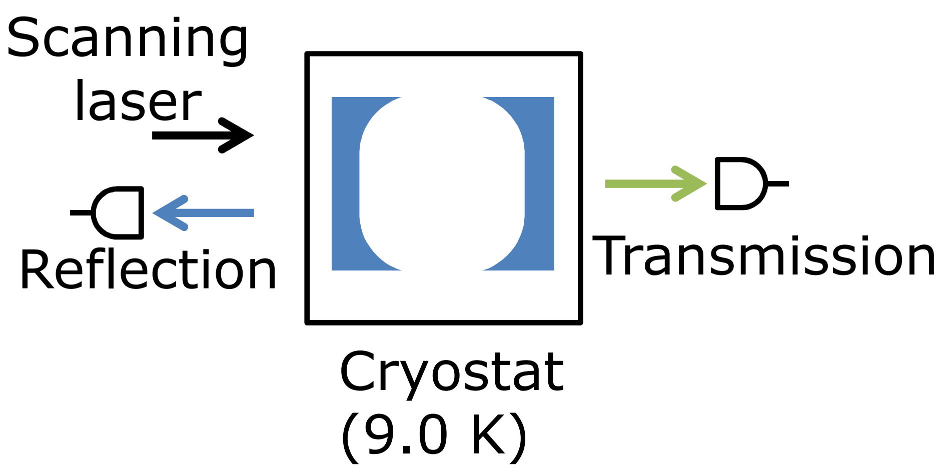


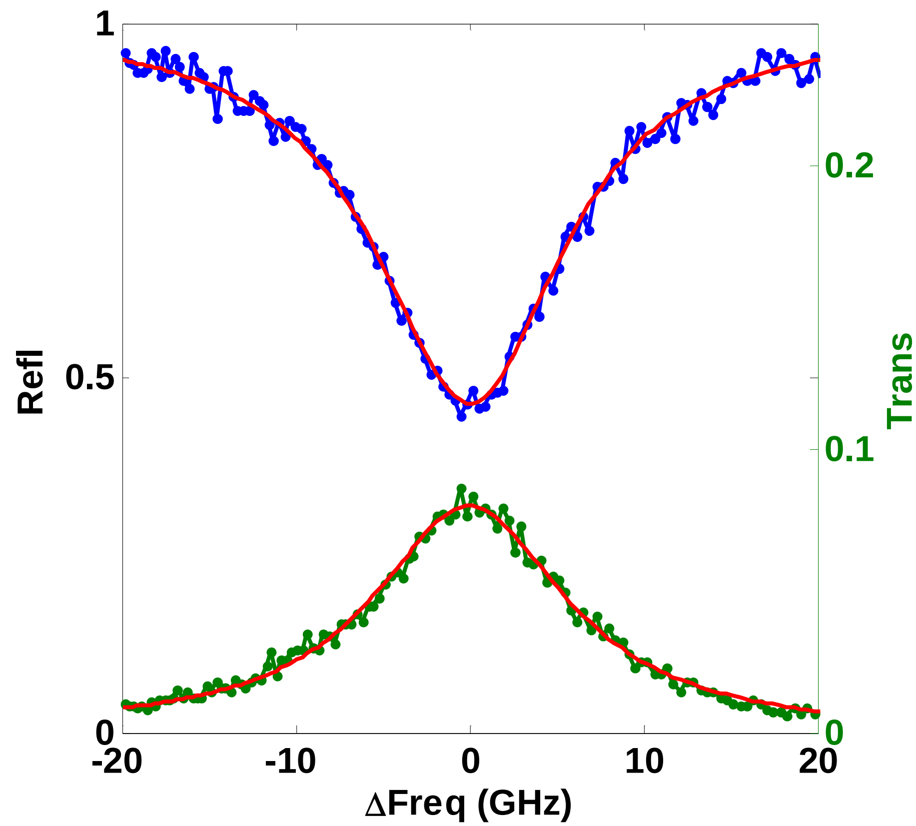




1. Resonant spectroscopy

'Empty' cavity:

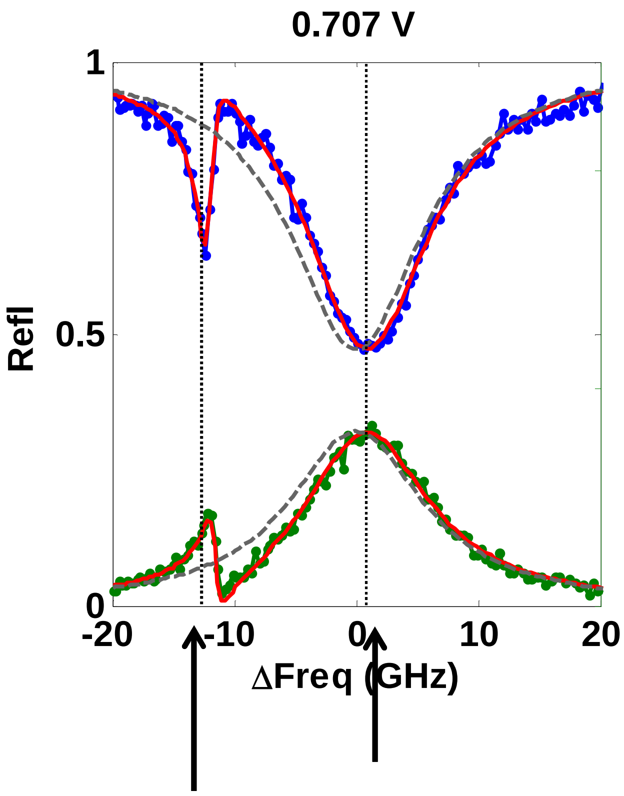


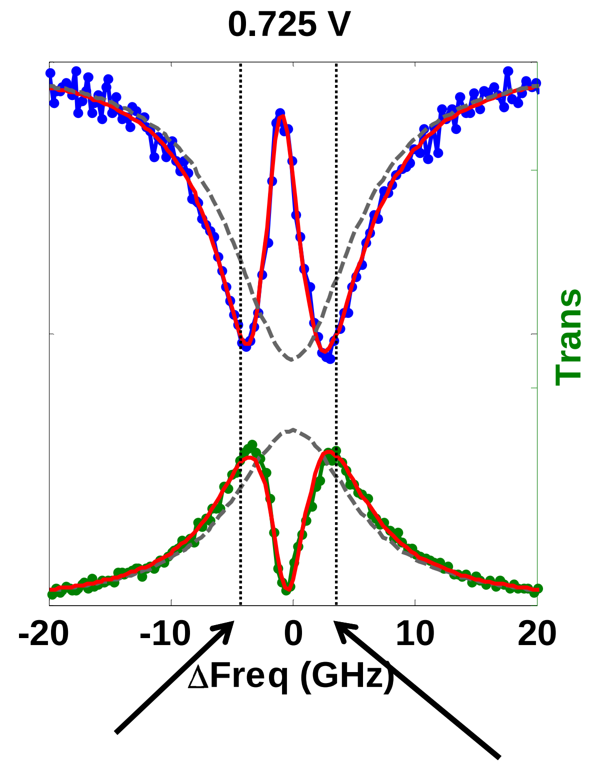


$Q = 2.7 \times 10^4$

1.Resonant spectroscopy

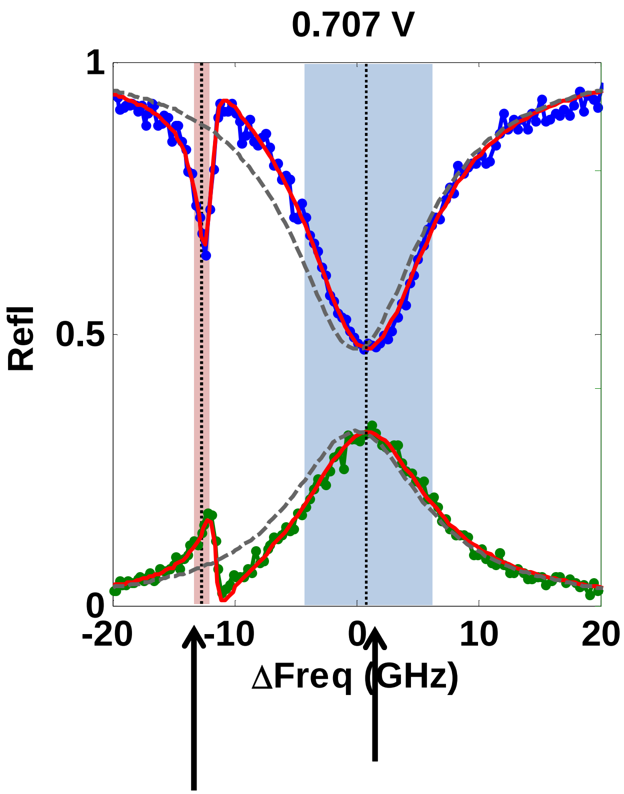
<u>QD-cavity coupling</u>



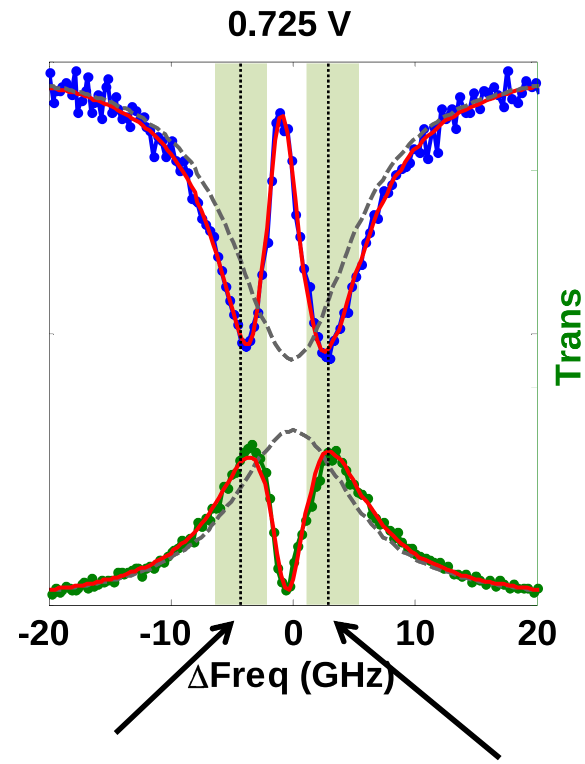


1. Resonant spectroscopy

QD-cavity coupling

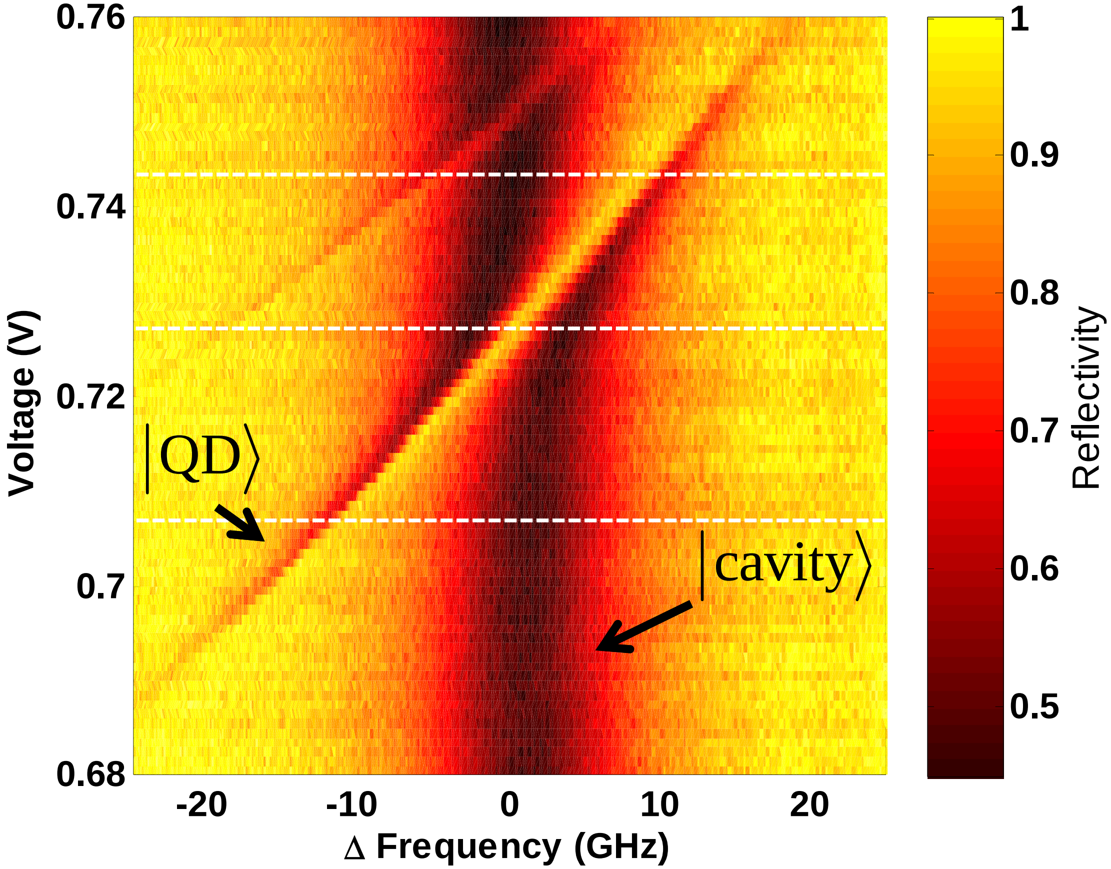


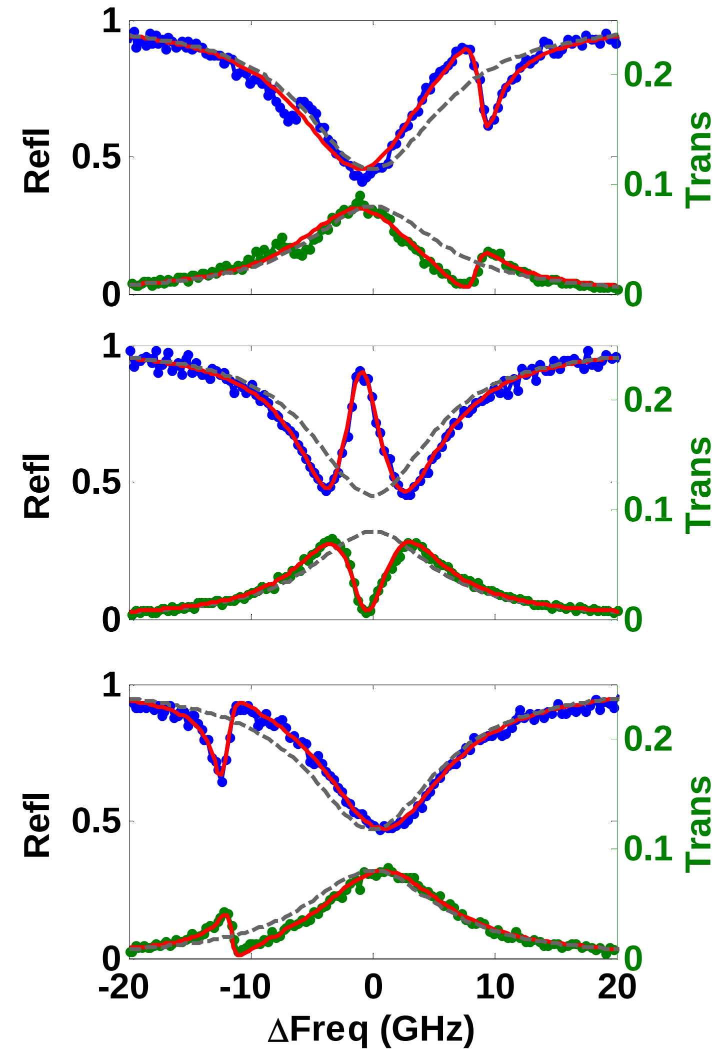
$|QD\rangle$ $|cavity\rangle$



$\frac{1}{\sqrt{2}}\left(|QD\rangle - |cavity\rangle\right)$ $\frac{1}{\sqrt{2}}\left(|QD\rangle + |cavity\rangle\right)$

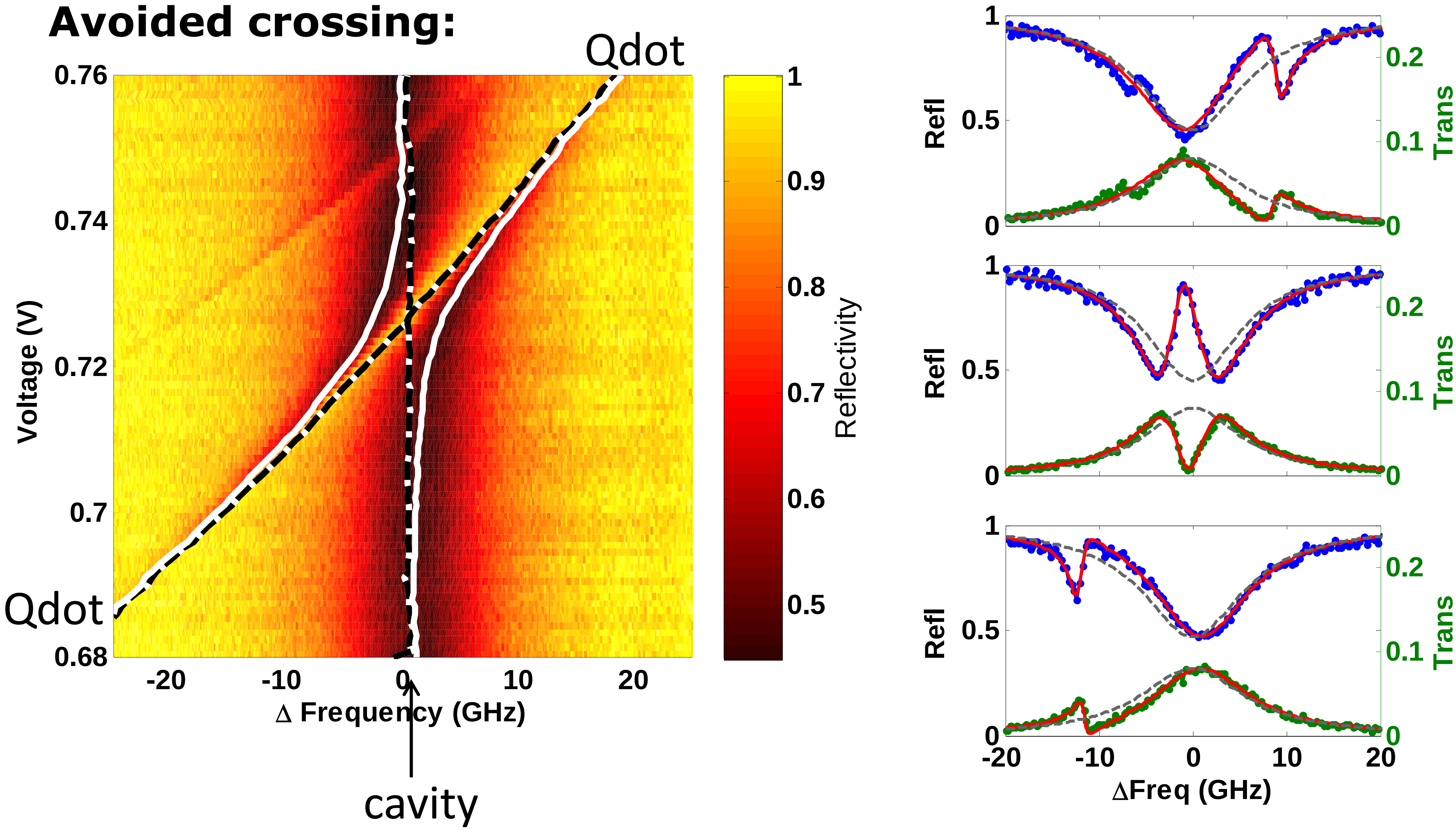
QD-cavity coupling





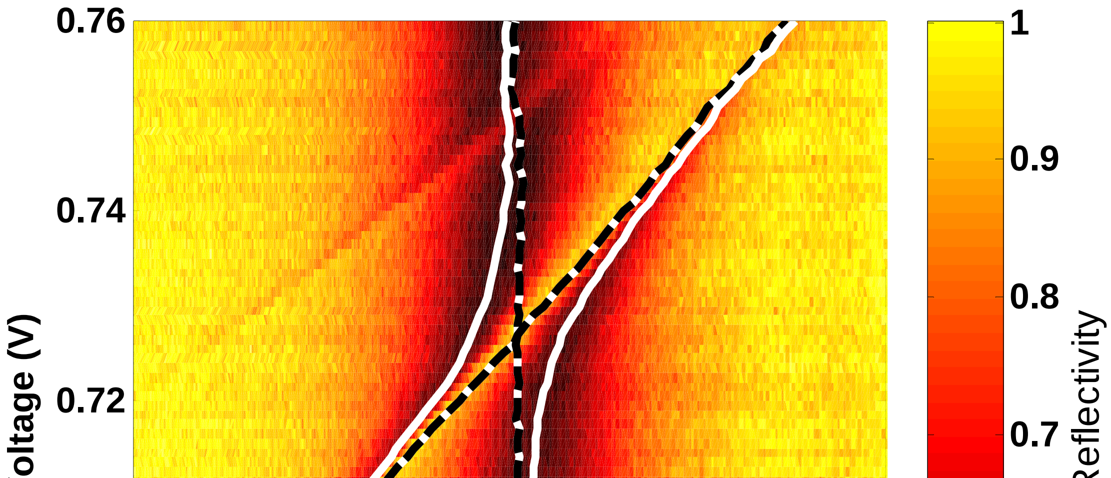
QD-cavity coupling

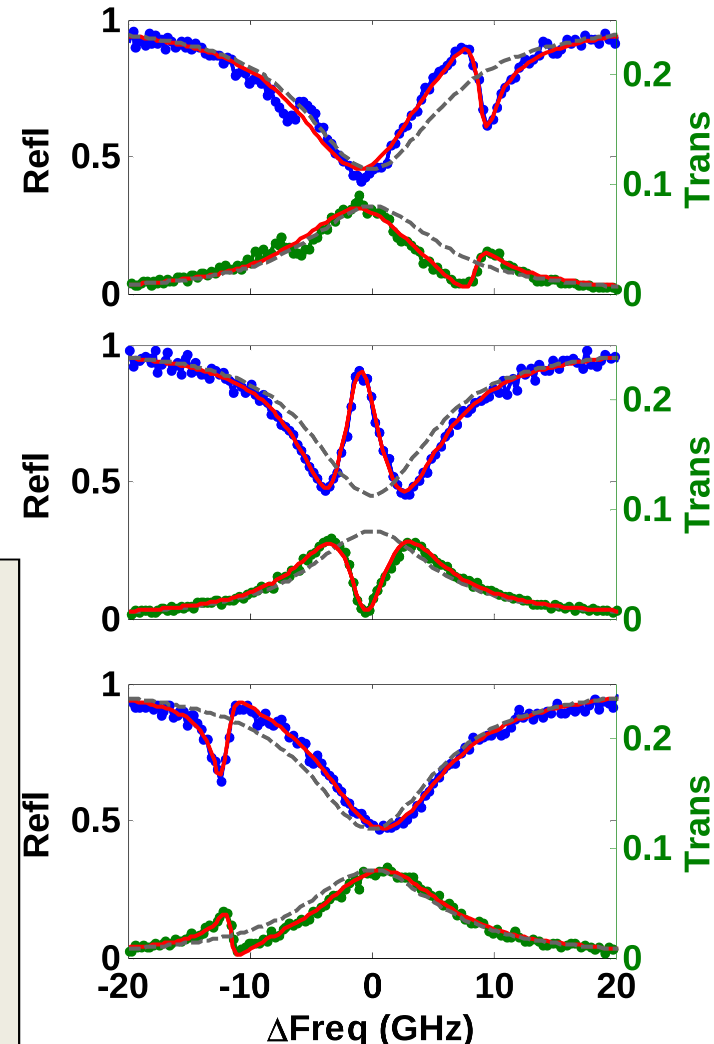
Avoided crossing:



Conclusion 1: QD-cavity coupling

Avoided crossing:

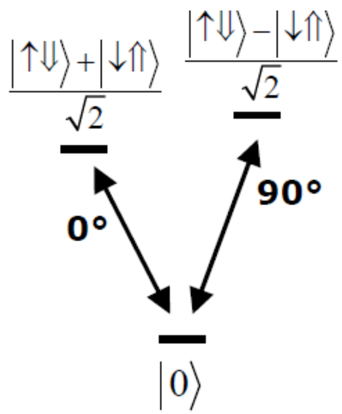


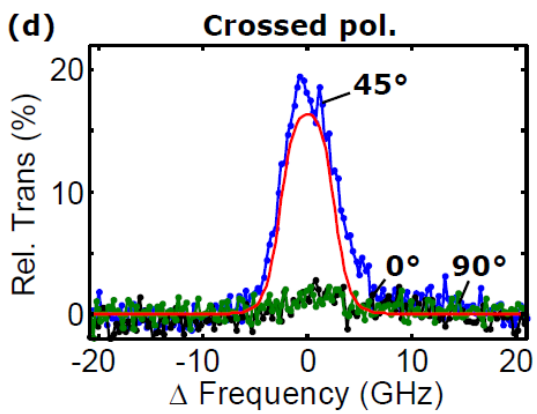


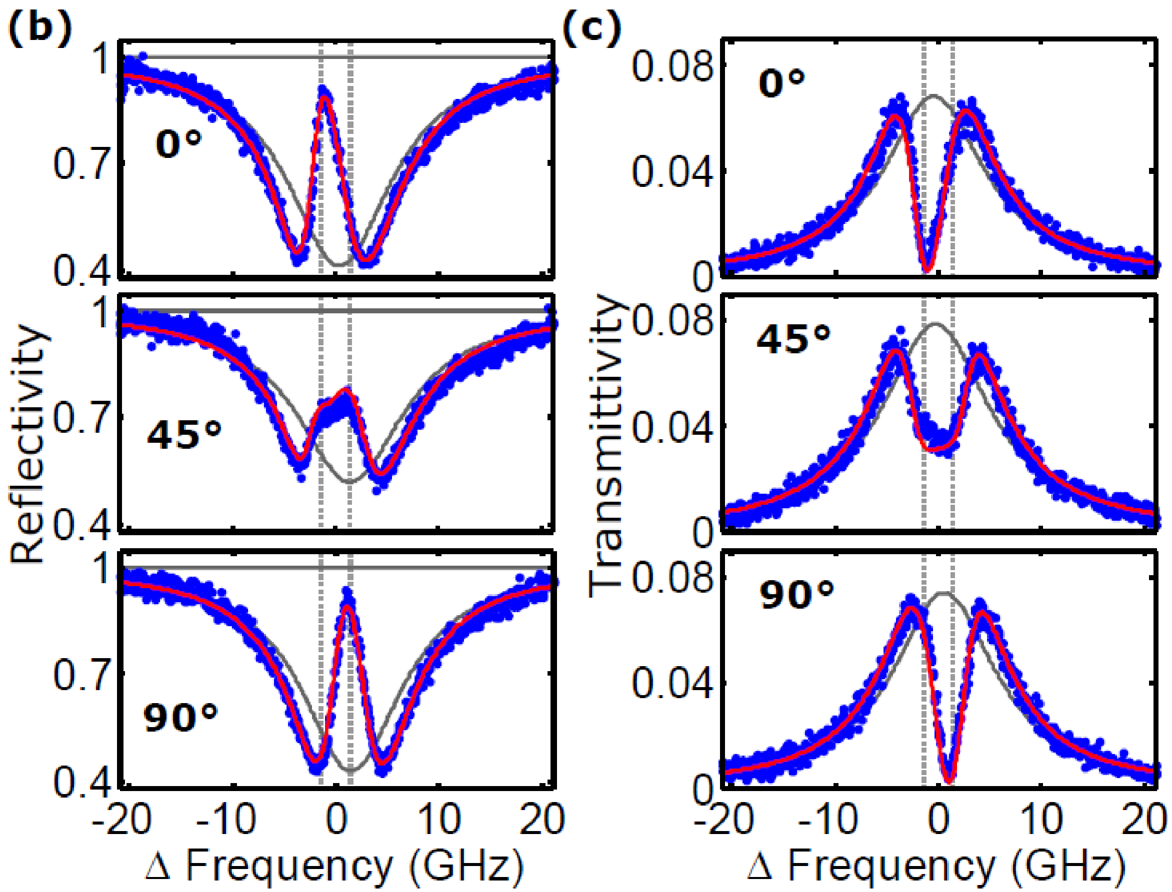
- First Polarization degenerate CQED system!
- Voltage control
- Single-photon transistor!
- Polarization properties can be observed more easily

Polarization resolved scans

Neutral QD:



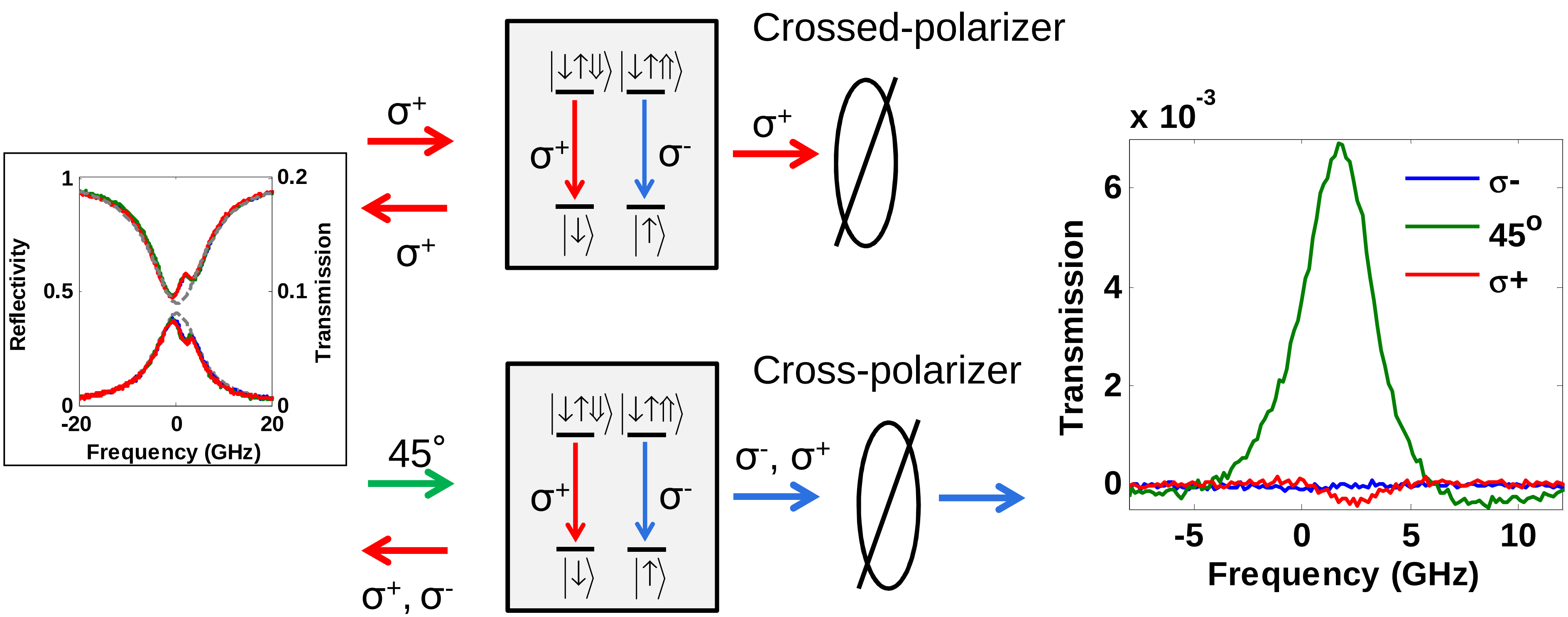




Transitions are linearly polarized

Polarization resolved scans

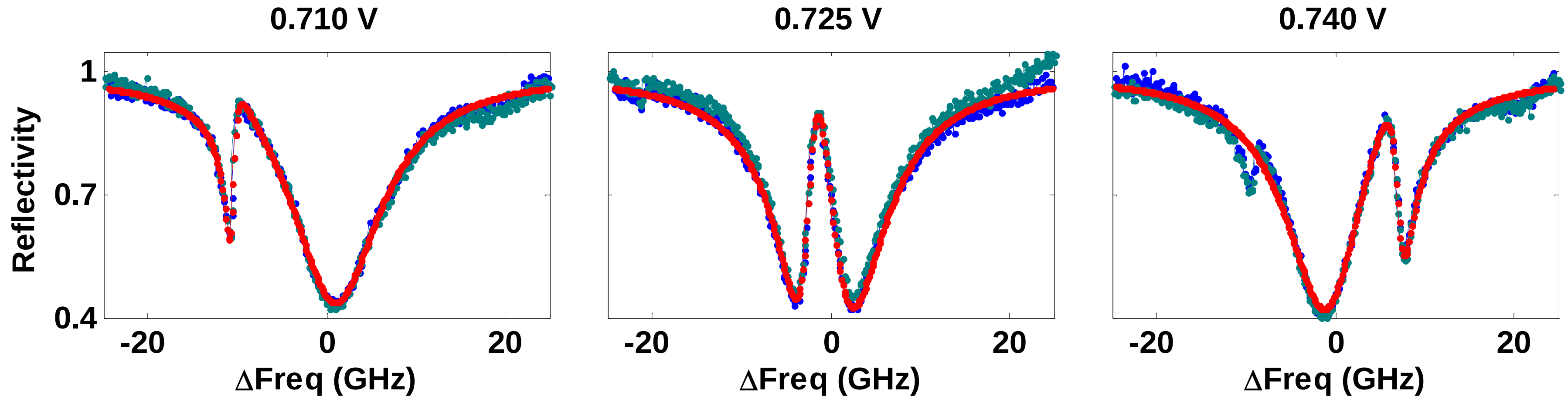
Negative QD:



Transitions really circular polarized!

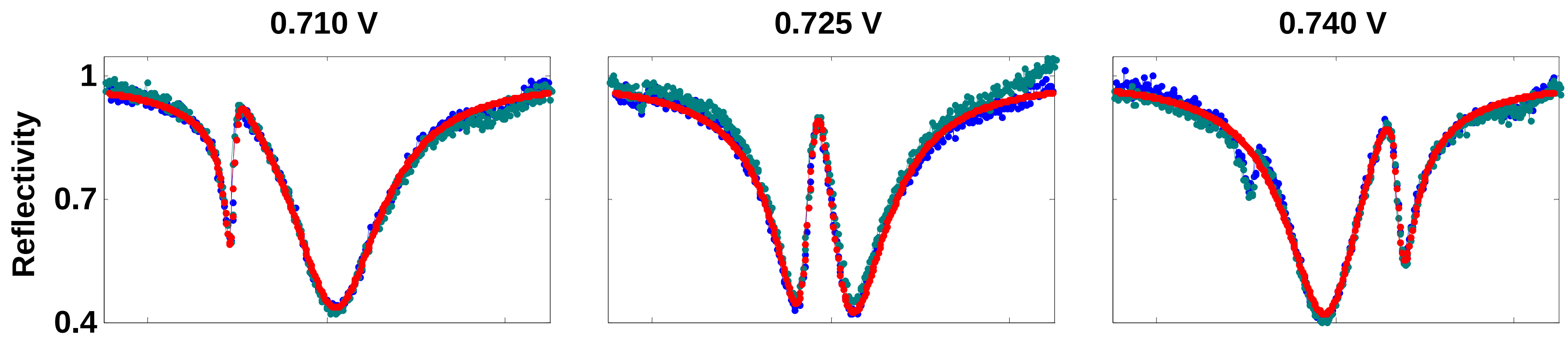
2. Modified lineshapes & hysteris at higher intensities

1pW laser intensity:

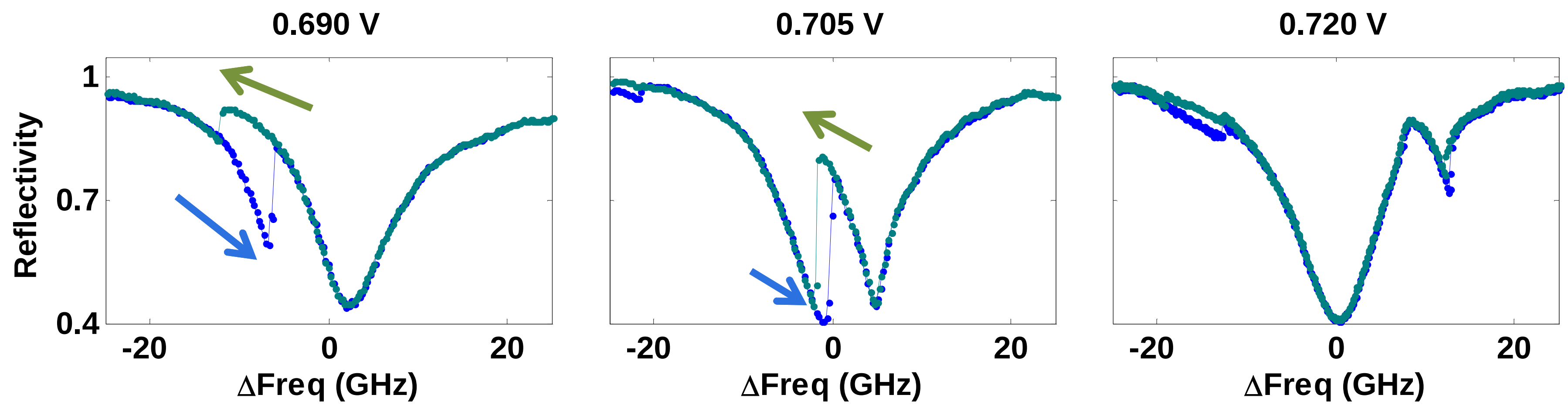


2. Modified lineshapes & hysteris at higher intensities

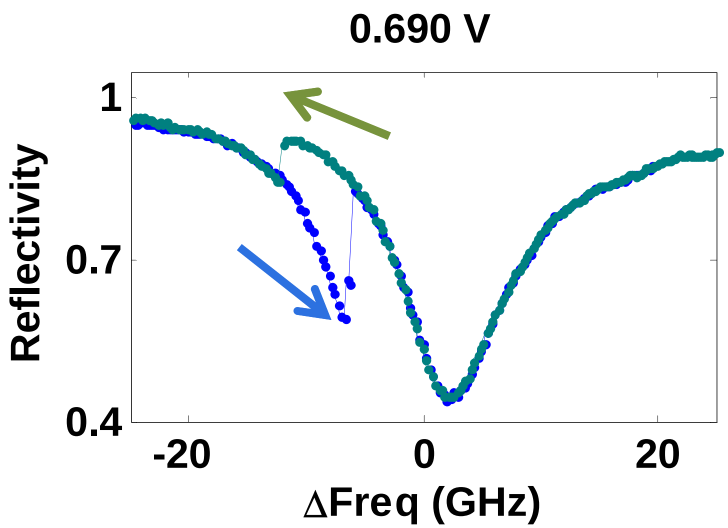
1pW laser intensity:



1nW:



Hysteresis effects



ARTICLES
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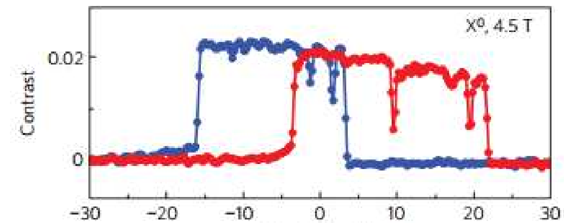
nature physics

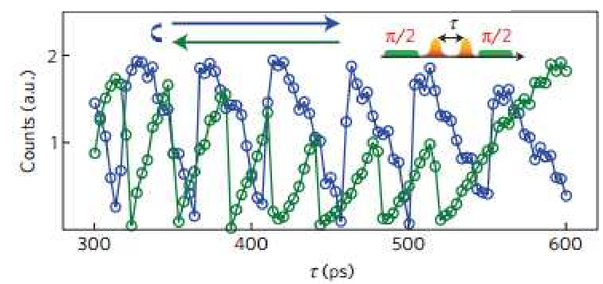
Confluence of resonant laser excitation and bidirectional quantum-dot nuclear-spin polarization

C. Latta[1*], A. Högele[1*†], Y. Zhao[2†], A. N. Vamivakas[2], P. Maletinsky[1], M. Kroner[1], J. Dreiser[1], I. Carusotto[3], A. Badolato[4], D. Schuh[5], W. Wegscheider[5†], M. Atature[2] and A. Imamoglu[1‡]



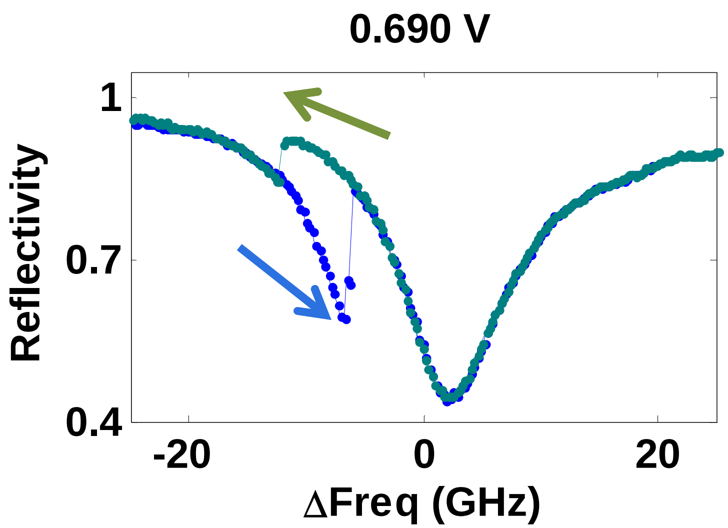
Ultrafast coherent control and suppressed nuclear feedback of a single quantum dot hole qubit

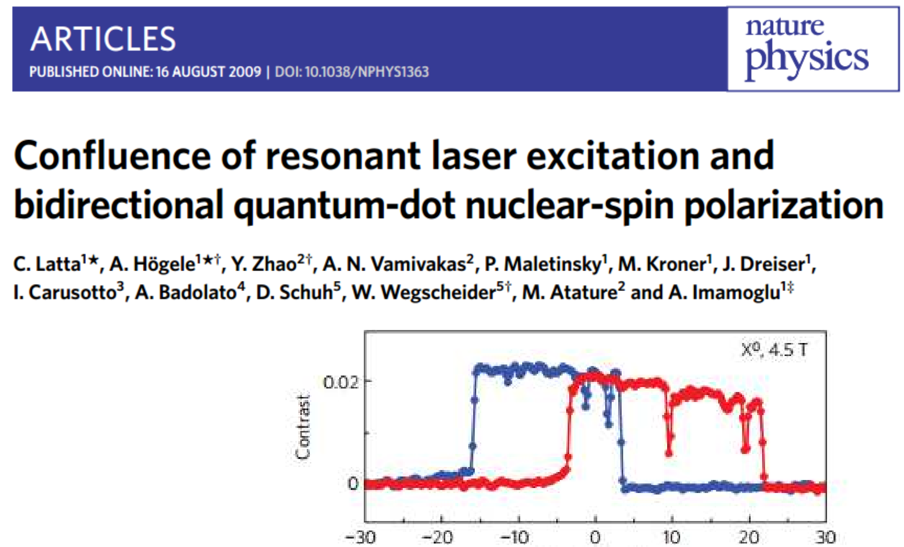
Kristiaan De Greve[1*], Peter L. McMahon[1], David Press[1], Thaddeus D. Ladd[1,2†], Dirk Bisping[3], Christian Schneider[3], Martin Kamp[3], Lukas Worschech[3], Sven Höfling[1,3], Alfred Forchel[3] and Yoshihisa Yamamoto[1,2]

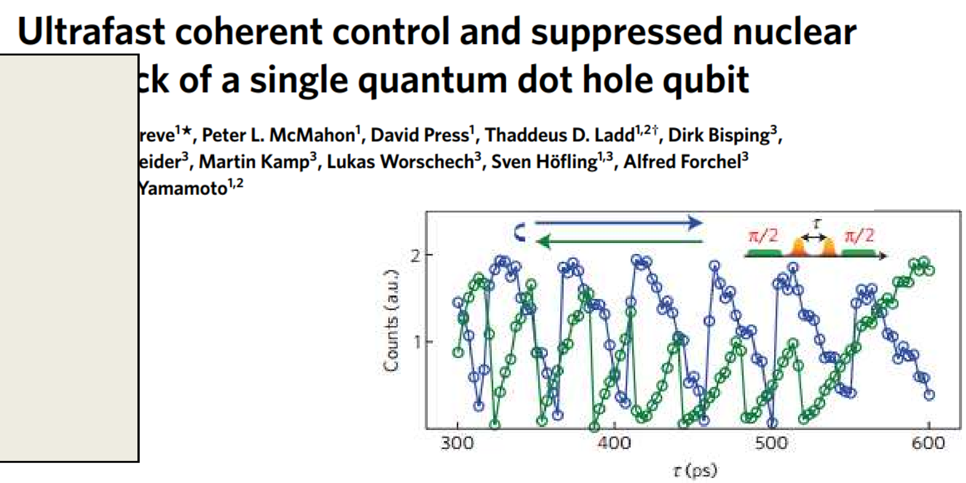


Review: [Urbaszek *et al*. Rev. Mod. Phys. 2013]

Hysteresis effects







But:

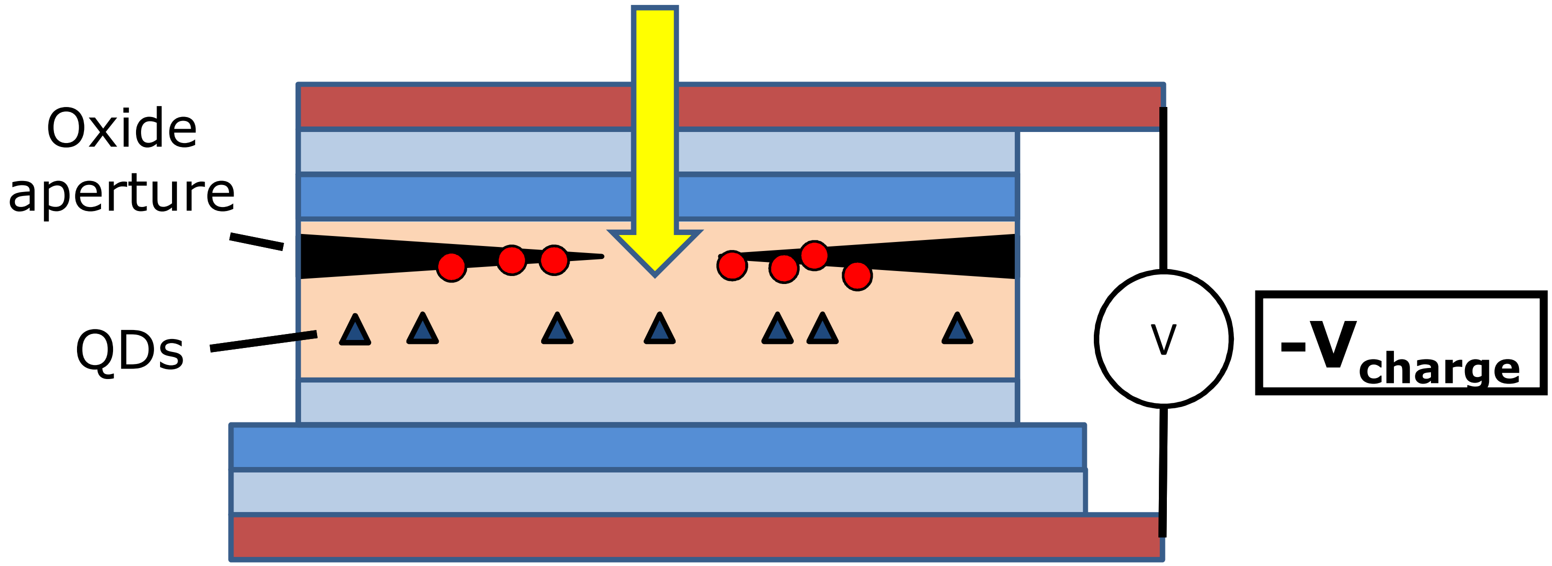
- Only on red side
- Independent of *B*-field, polarization,..
- Only blue shift!

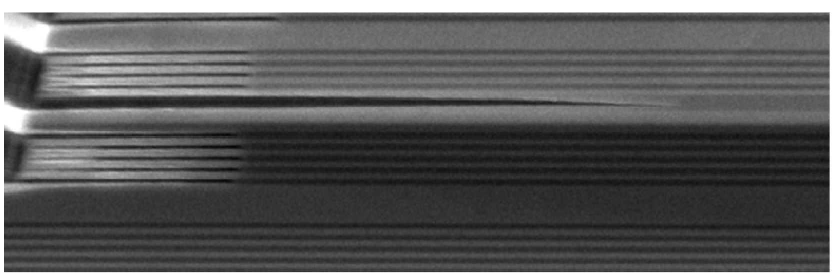
Review: [Urbaszek *et al*. Rev. Mod. Phys. 2013]

Charges trapped behind oxide aperture

Resonant laser excites charges, trapped by aperture

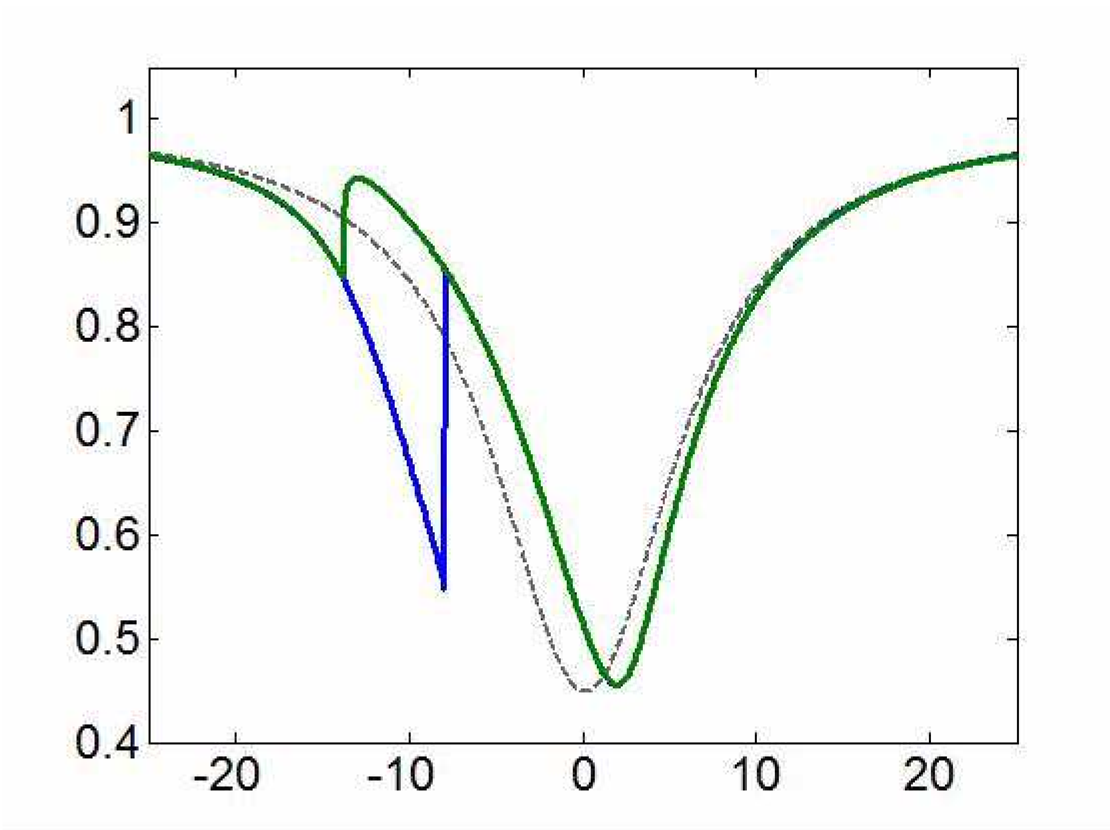
Electric field over QDs decreases





Hysteresis: red side

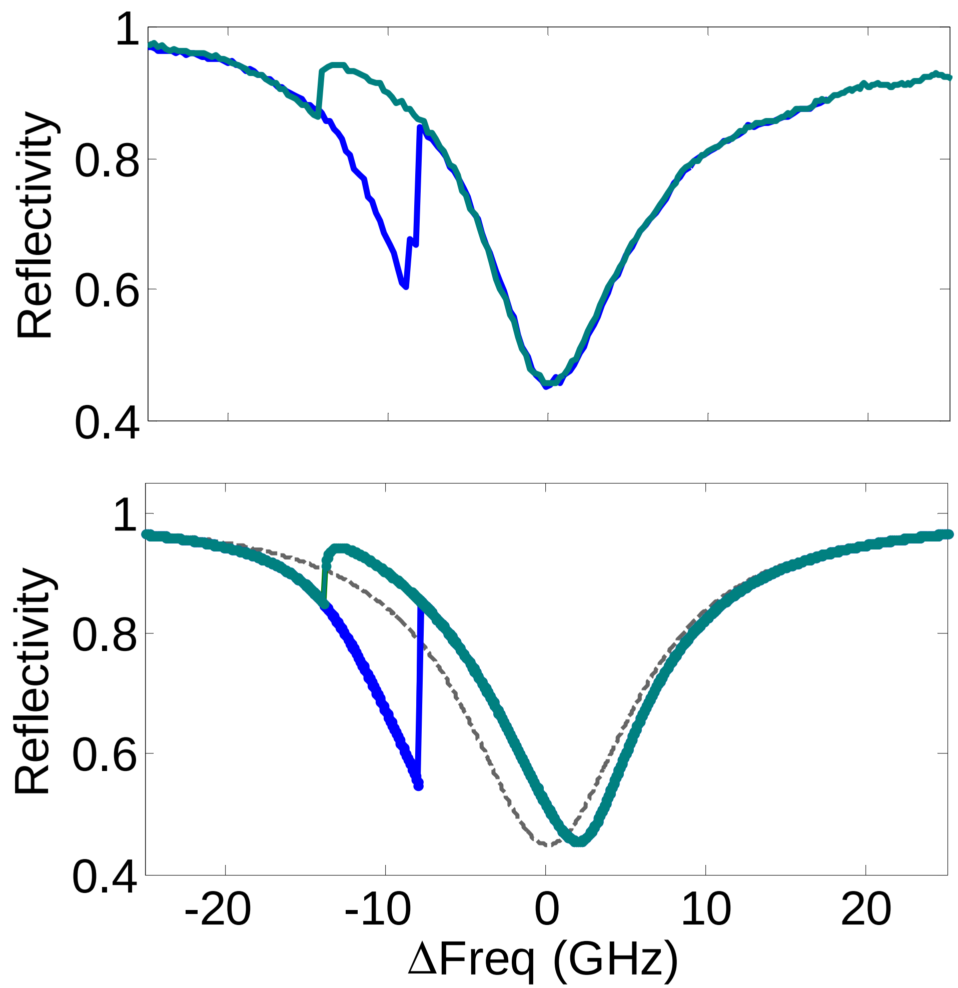
Input: QD blueshift when larger field in cavity



Hysteresis: red side

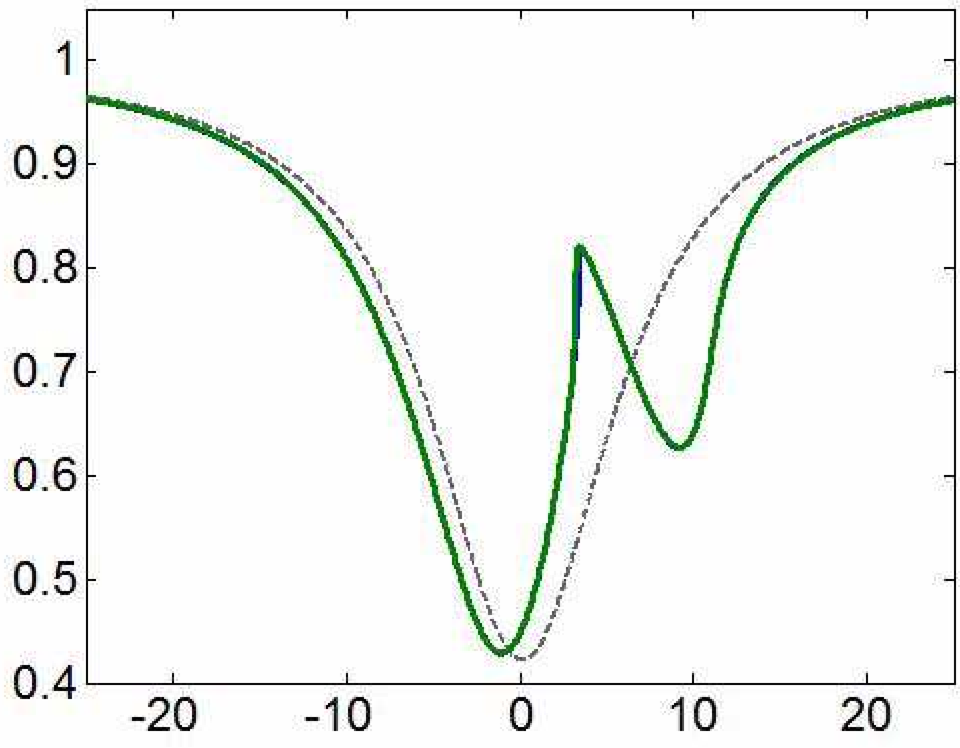
Input: QD blueshift when larger field in cavity

Model:



Hysteresis: blue side

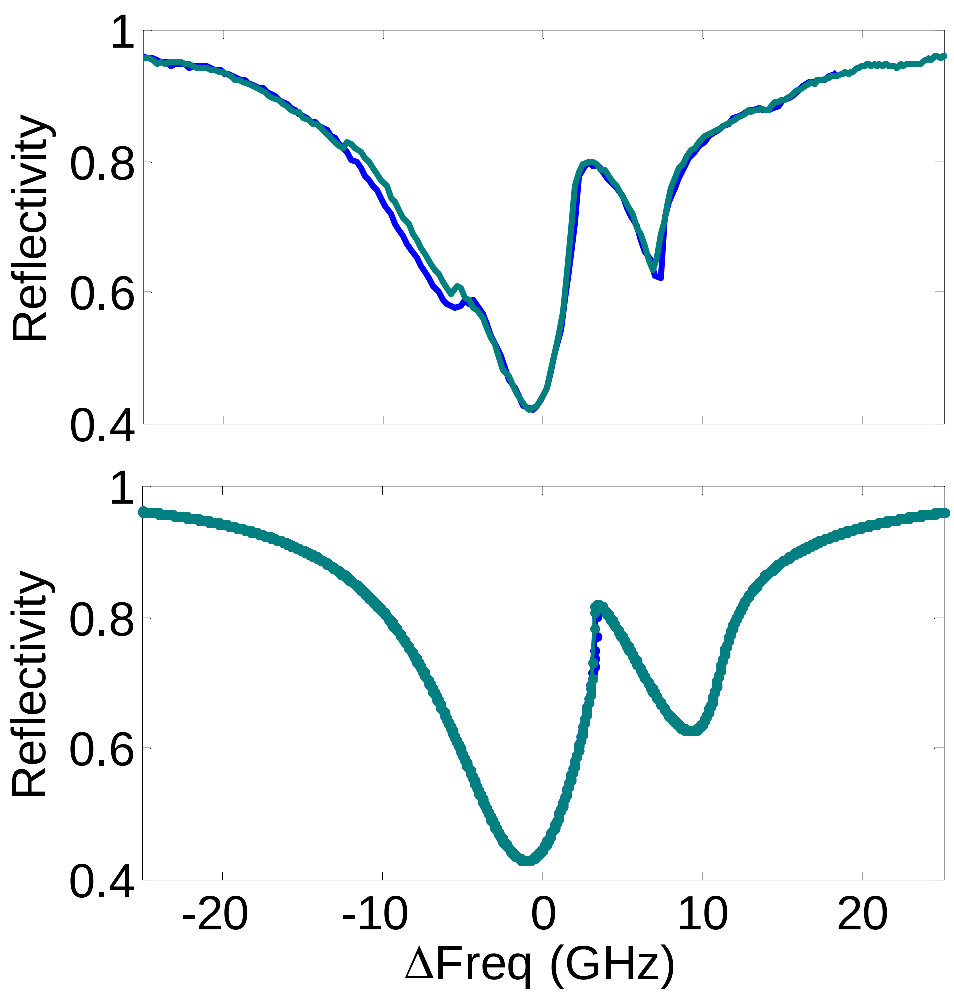
Input: QD blueshift when larger field in cavity



Hysteresis: red side

Input: QD blueshift when larger field in cavity

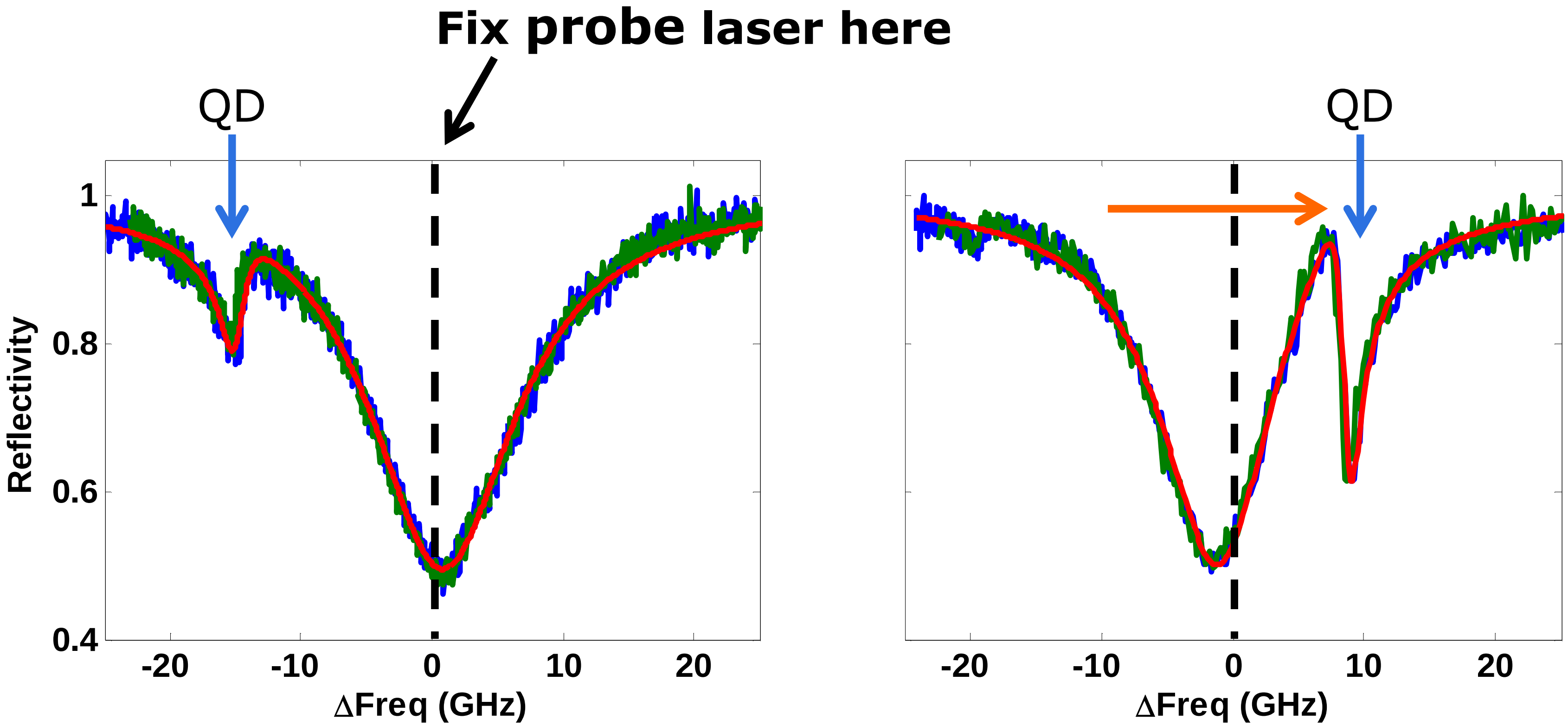
Model:



QD dragging: on which time scale?

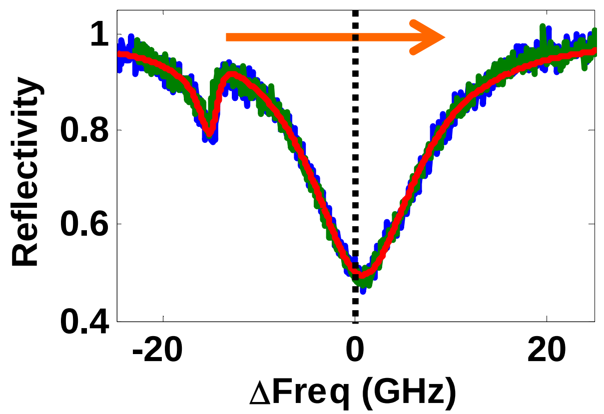
Weak probing:

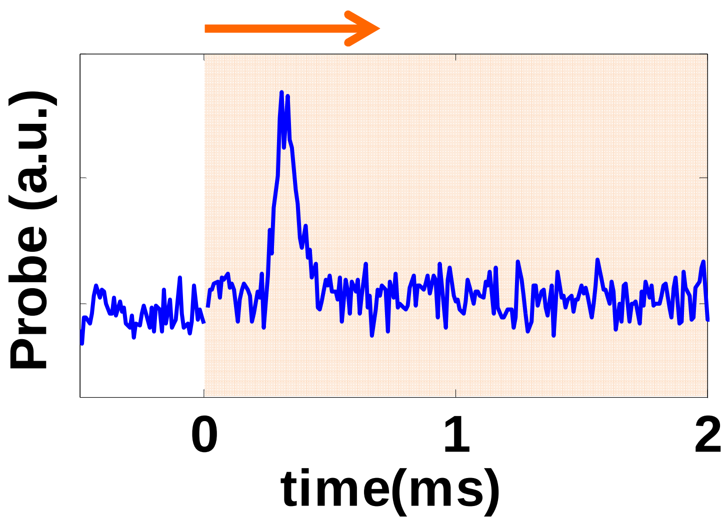
Weak probe + pump laser:



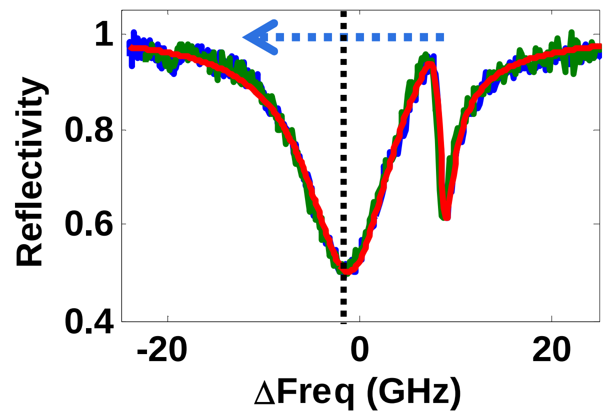
Measuring charge build up and decay

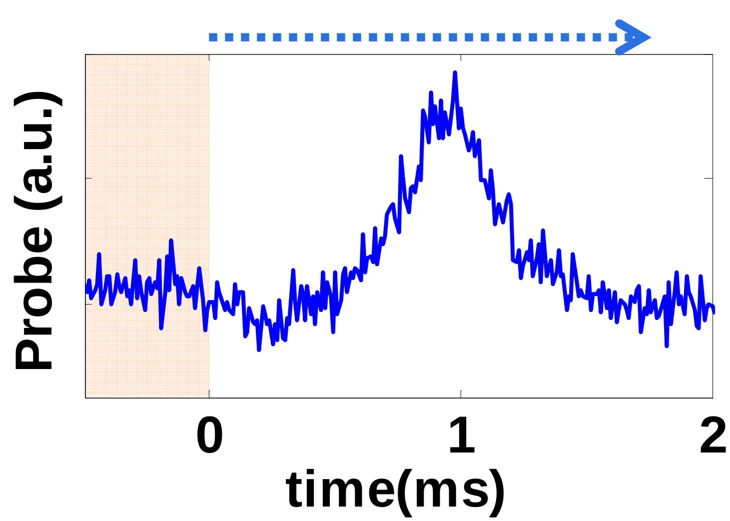
Switch pump ON:





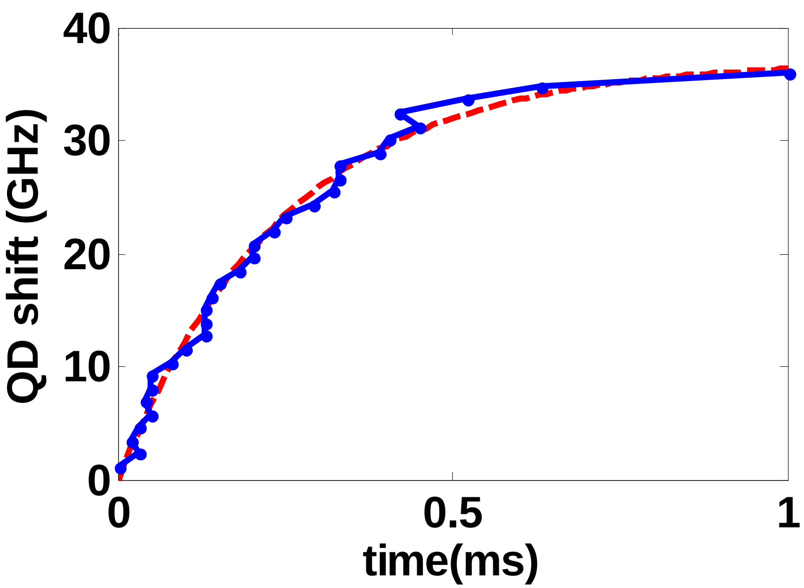
Switch pump OFF:





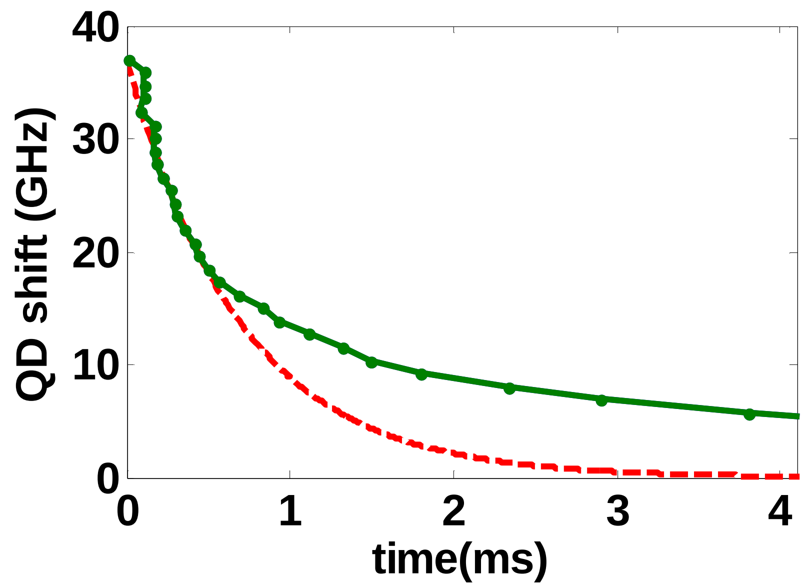
Probing charge build-up and decay

Charge buildup:



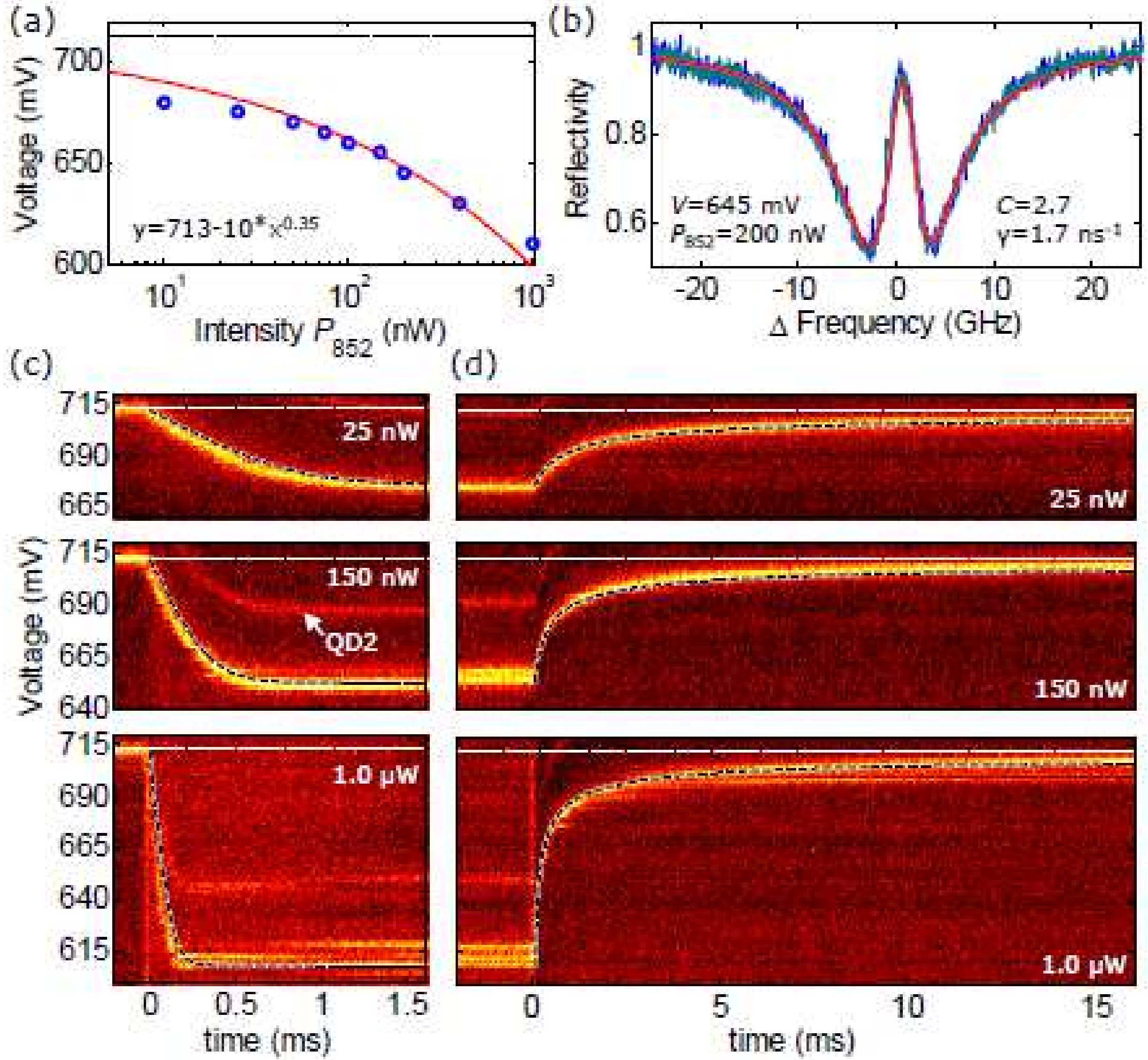
$\tau \approx 0.25$ ms

Charge decay:



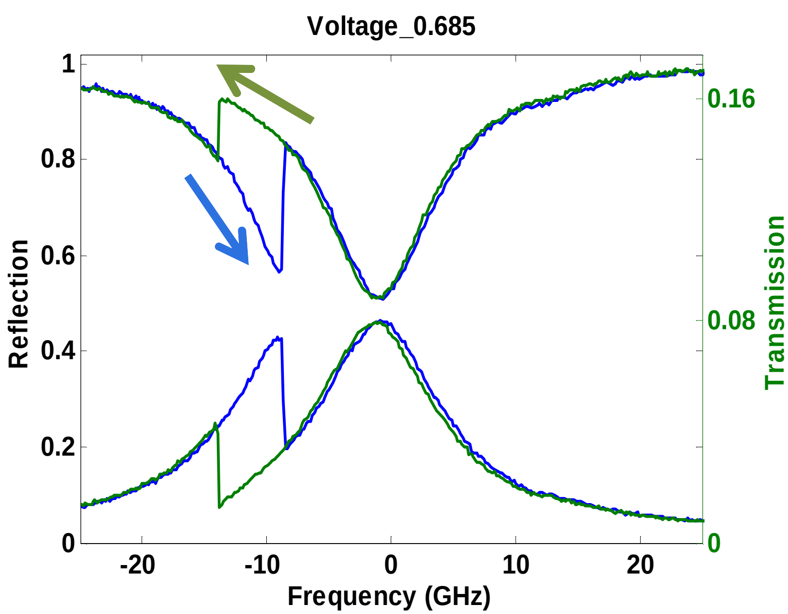
$\tau \approx 0.7$ ms
+ slow ~15 ms decay

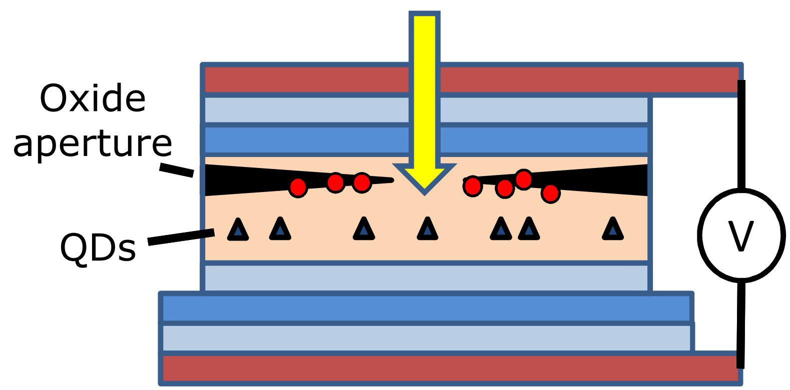
Probing charge build-up and decay



Conclusion 2: Hysteresis & charge memory

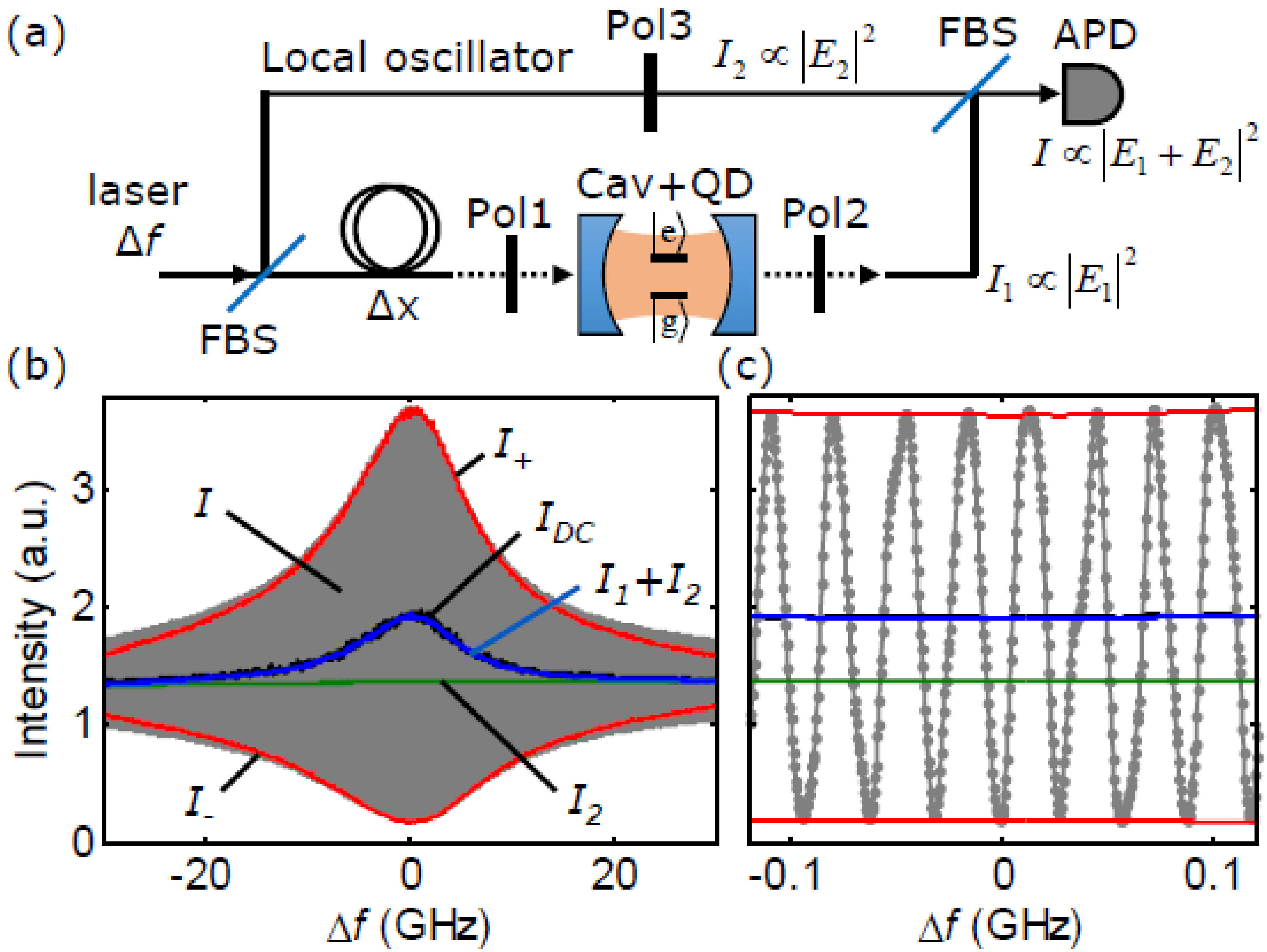
- Hysteresis effects observed at higher power (> 10 pW)
- Slow dynamics: time scale ~ ms
- Intriguing power dependence: ~ P^{β} with $\beta \approx 0.35$
- Most likely cause: carriers trapped at oxide aperture



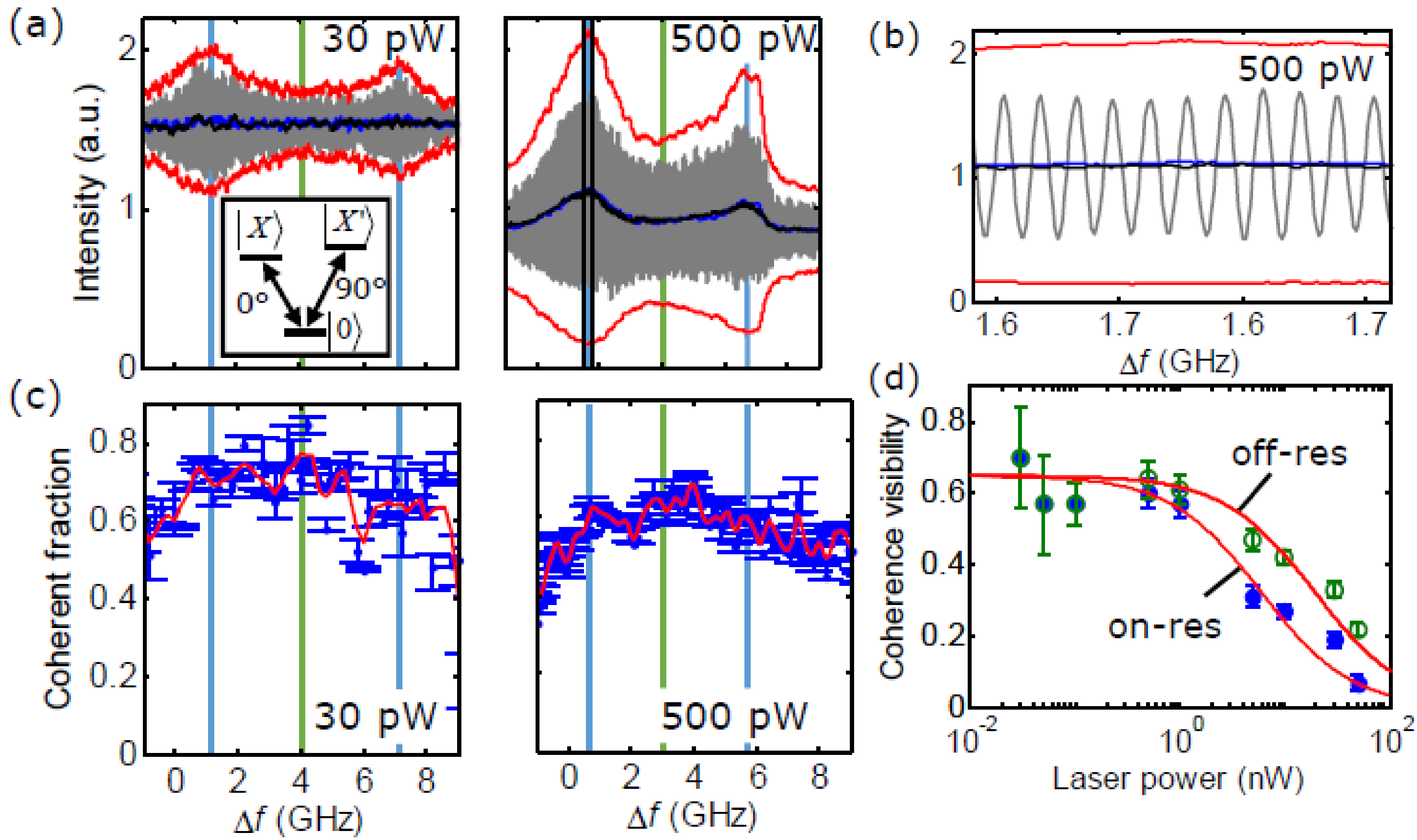


3. Coherence measurements

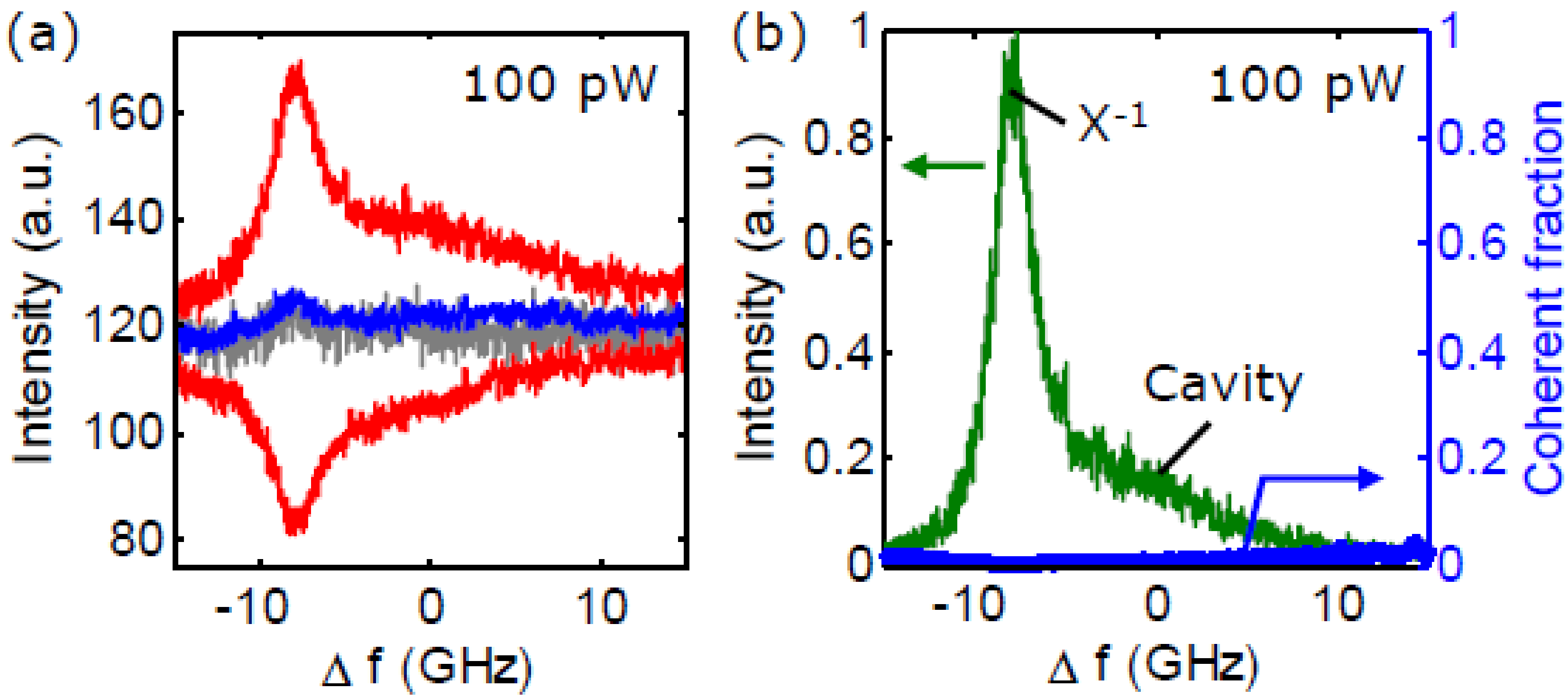
sanity check:
empty cavity



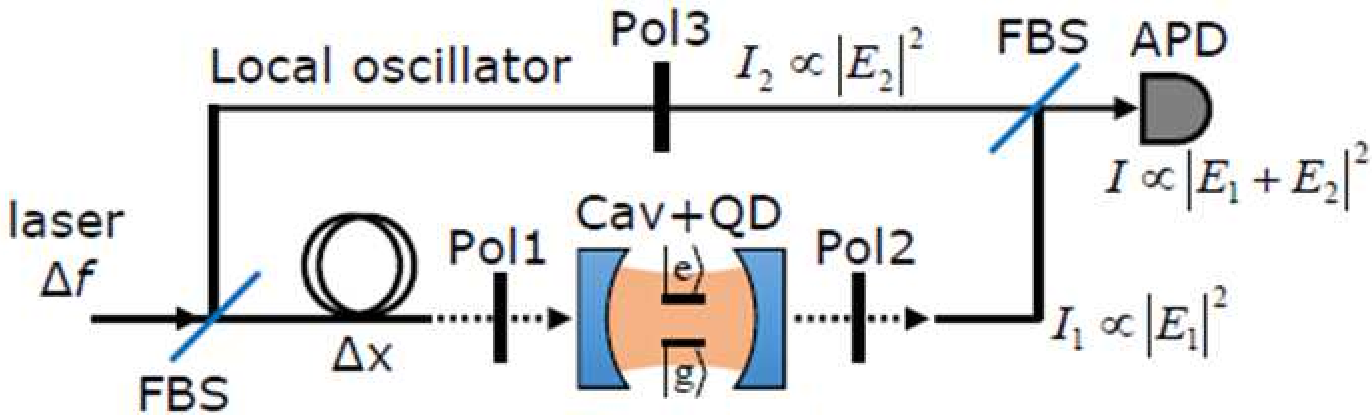
3. Coherence around neutral Qdot resonance < 1

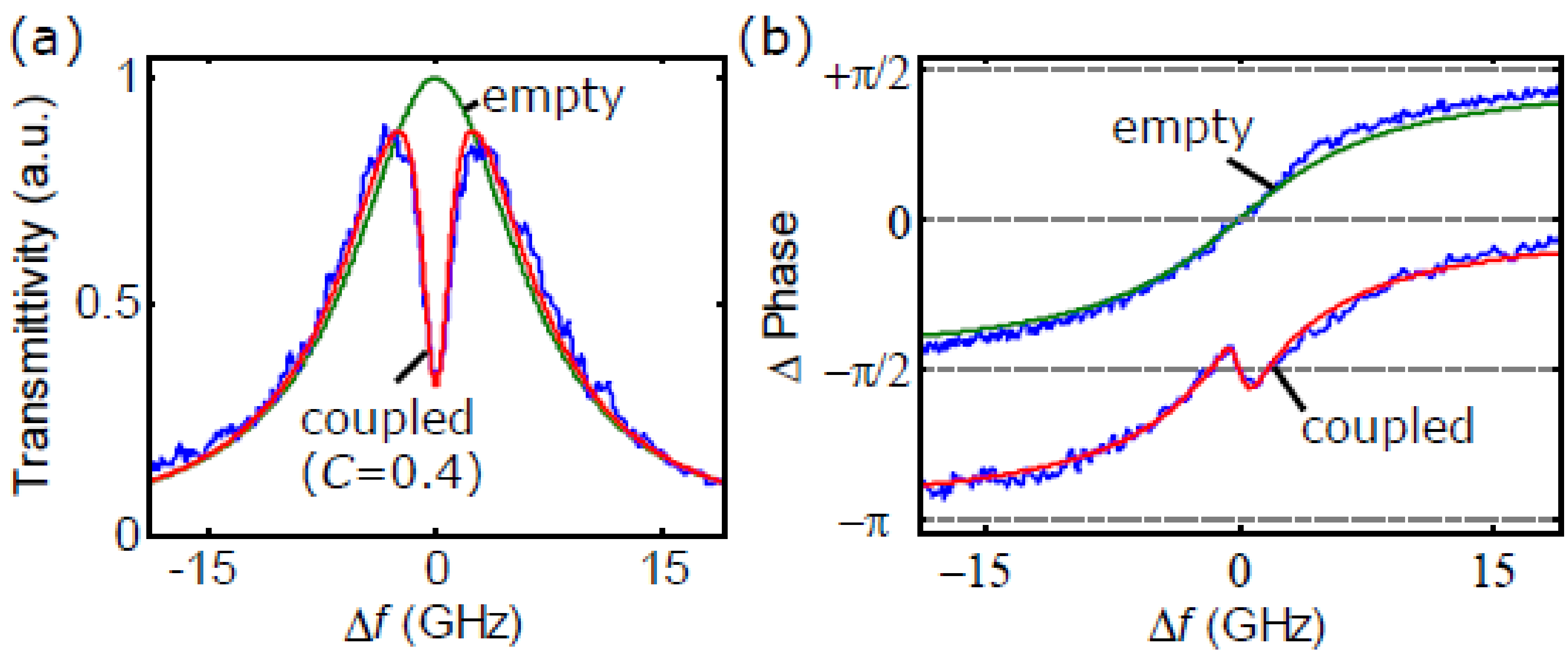


3. Coherence around charged Qdot resonance < 0.05

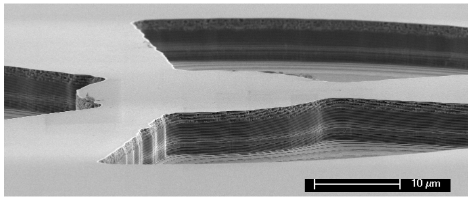


3. Phase variations around resonance



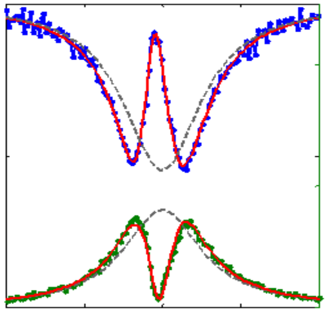


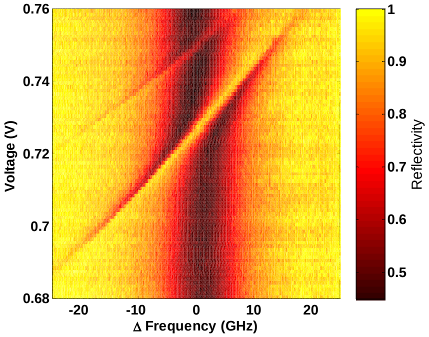
Conclusion



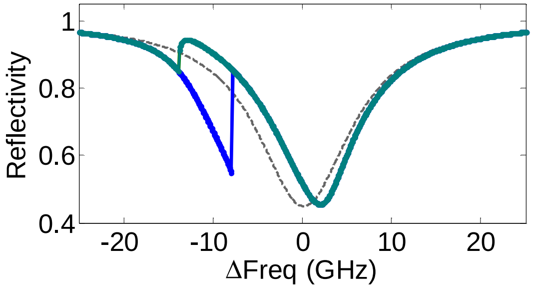
- Quantum dot in microcavity = versatile quantum system

1. Resonant spectroscopy

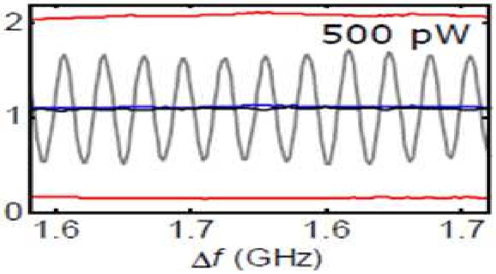




2. Hysteresis effects & charge memory



3. Decoherence directly observed



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