Coherent optical control of single quantum dot hole spin

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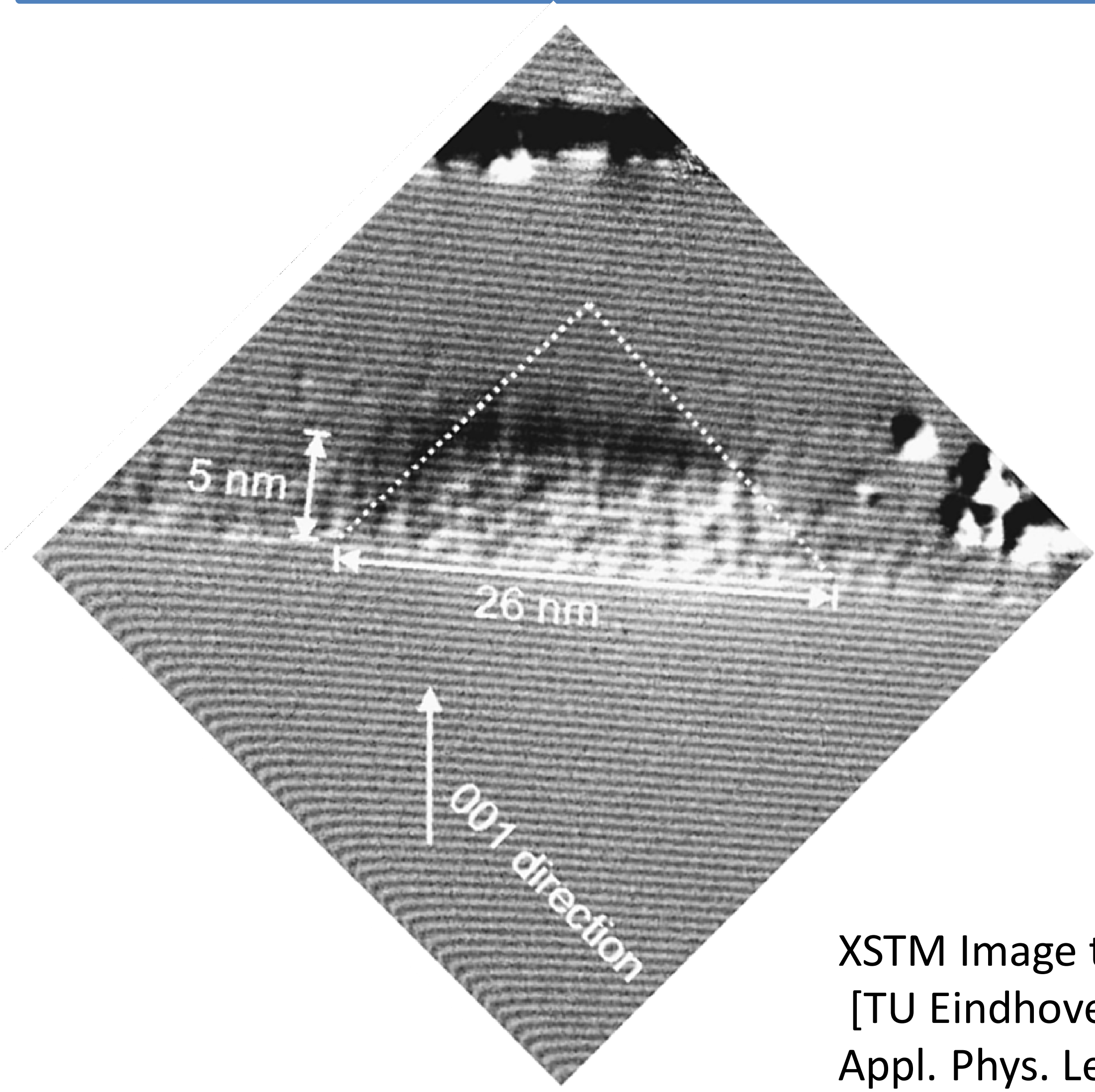
From September, Hitachi Cambridge Laboratory
Recent review see:
A. J. Ramsay, Semi. Sci. Tech. 25 103001 (2010).

Outline

- Photocurrent detection technique
- Coherent optical control of single hole spin
- Interfacing a quantum dot spin with a photonic circuit

Overview of photocurrent detection technique

Image of InAs/GaAs quantum dot



Dots vs Atoms

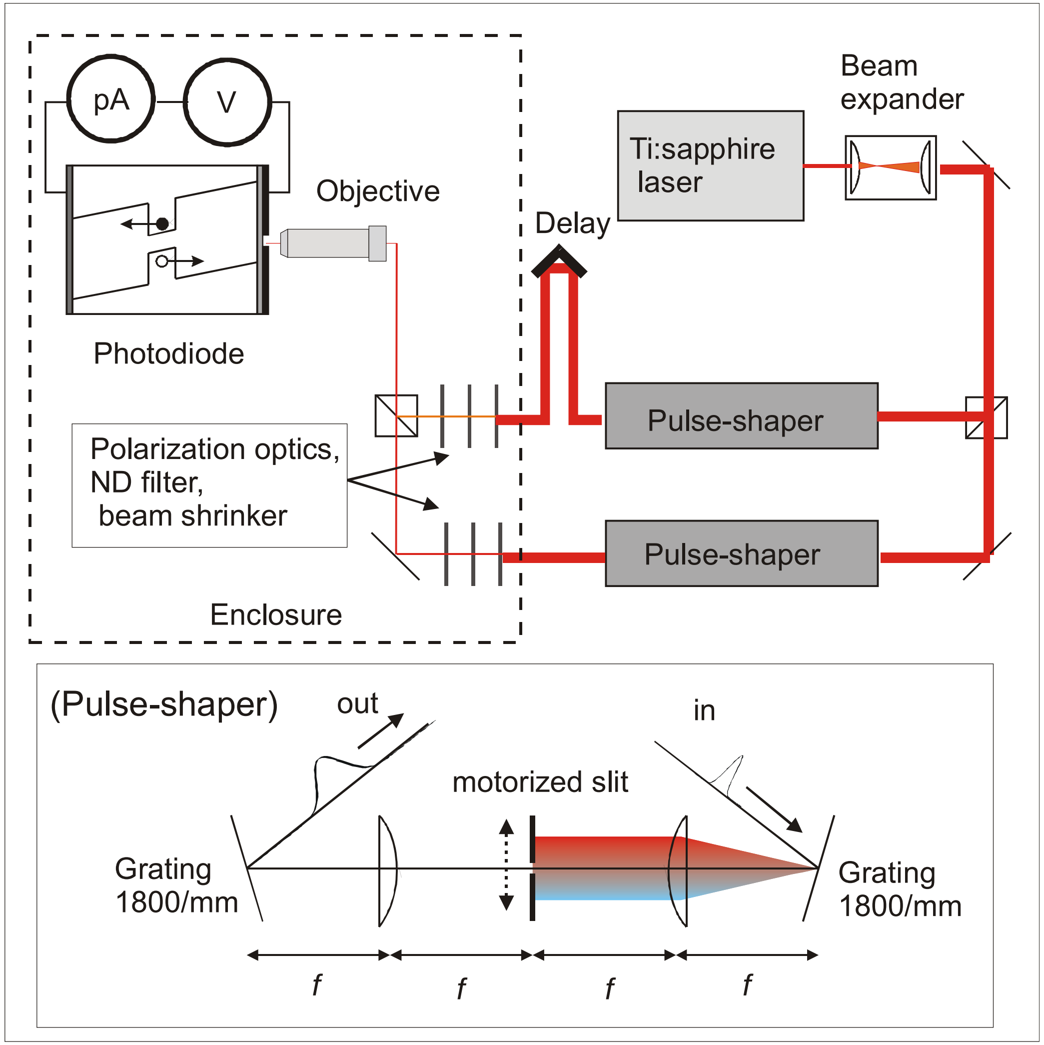
Con:
Inhomogeneous broadening
Dephasing

Pro:
Integrated circuits
Highly flexible and tunable
Strong optical dipole

XSTM Image taken from: D. M. Bruls et al,
[TU Eindhoven]
Appl. Phys. Lett. 81 1708 (2002).

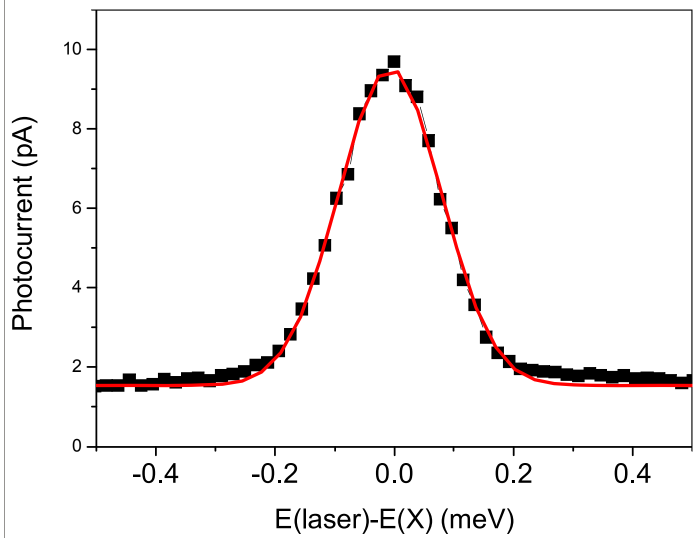
Two-color photocurrent setup

See also: Paderborn, TU-Munich, Tokyo, Cambridge

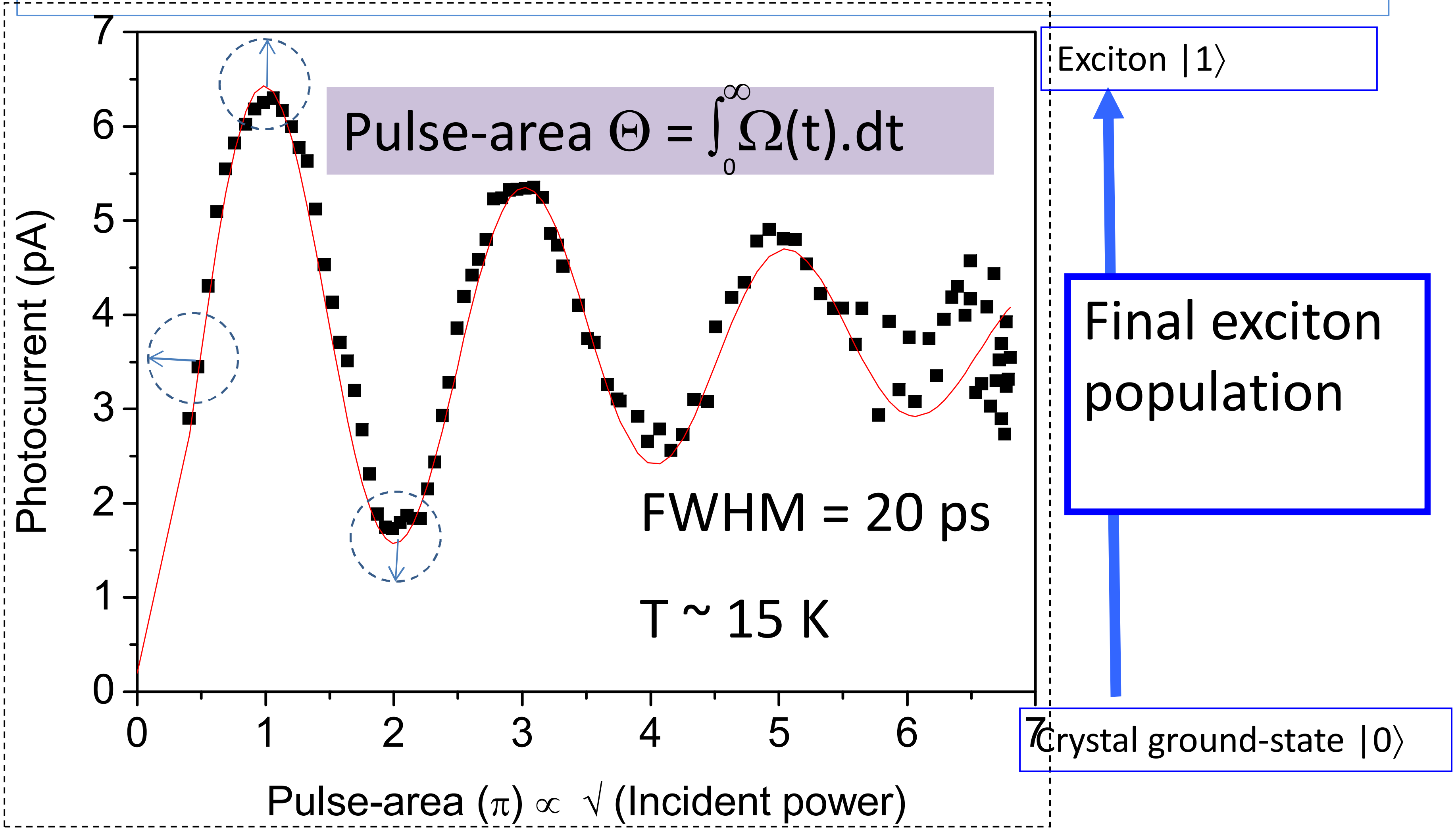


Can generate two synchronized pulses with independent:

- wavelength
- polarization
- time-delay
- intensity



2-level atom under resonant excitation: excitonic Rabi rotation



Engineering and Physical Sciences Research Council

Chapter 1: Coherent optical control of a single hole spin

T. M. Godden, J. H. Quilter, A. J. Ramsay,
S. J. Boyle, I. J. Luxmoore, J. Puebla-Nunez,
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Yanwen Wu, P. Brereton

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See T. M. Godden et al, Phys. Rev. Lett **108** 017402 (2012)

Rival papers: A. Greilich et al, Nature Photon. **5** 702 (2011); and K. DeGreve et al Nature Phys. **7** 872 (2011).

Control of pseudo-spin of heavy-hole $m_J = \pm 3/2$: motivation

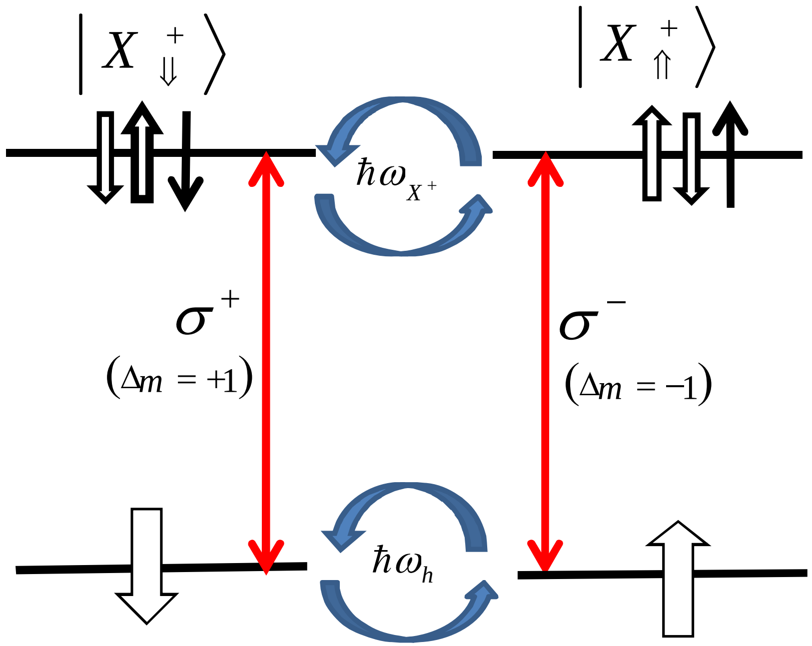
- A spin trapped in a quantum dot is a potential qubit [1-4].
- The main source of dephasing for electron spin is the nuclear-hyperfine interaction.
- Because of p-type wavefunction, the hyperfine interaction is about 10 times weaker for the hole due to suppression of contact term [5,6].
- A key prerequisite for using a hole spin as a qubit is the ability to perform arbitrary rotations of the spin-vector.

For papers on electron spin control: [1] D. Press et al, . *Nature* **456**, 07530 (2009); [2]A. Greilich er al, Nature Physics, 1126, 262-266, (2009); [3] J. Berezovsky, *et al. Science* **320**, 349 (2008); [4] Danny Kim et al Nature Physics, **1863**, 223-229 (2011)

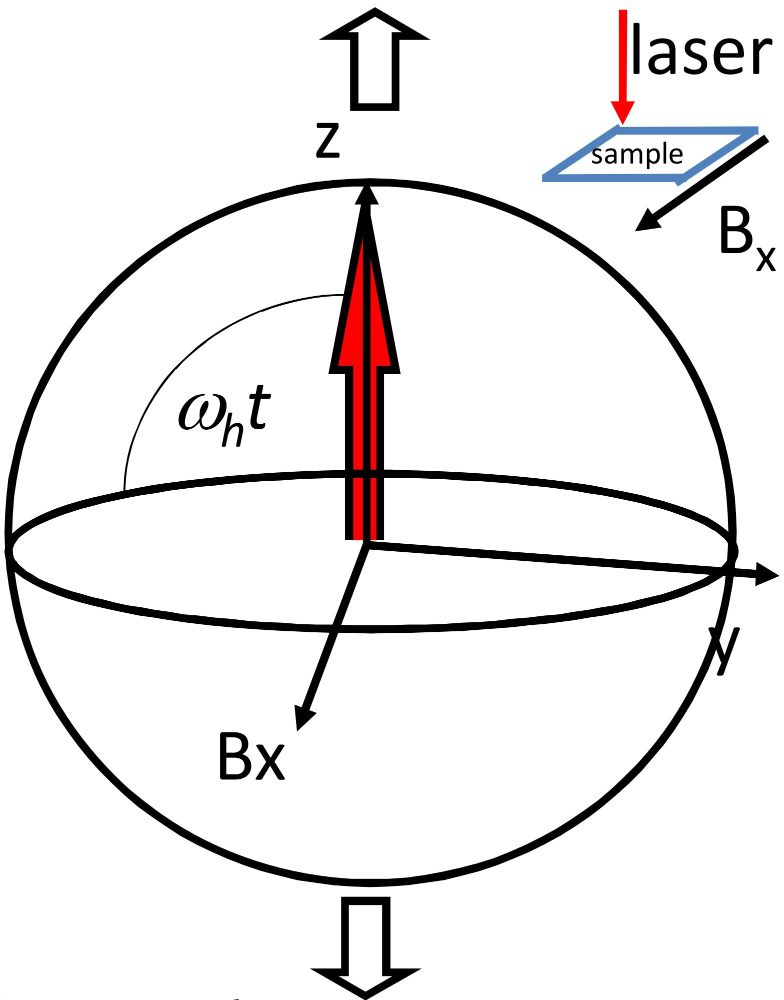
[5] Jan Fischer et al PHYSICAL REVIEW B **78**, 155329 (2008)

[6] E. A. Chekhovich et al. PRL 106, 027402 (2011)

Energy level diagram and spin precession



Bloch sphere



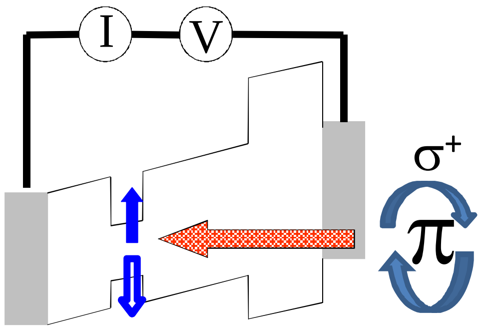
Here ⇓ And ⇑ Are $\frac{1}{\sqrt{2}}\left(h \pm i\bar{h}\right)$

Are NOT energy eigenstates of the system, they are the superpositions of the hole spin eigenstates (which lie along B-field)

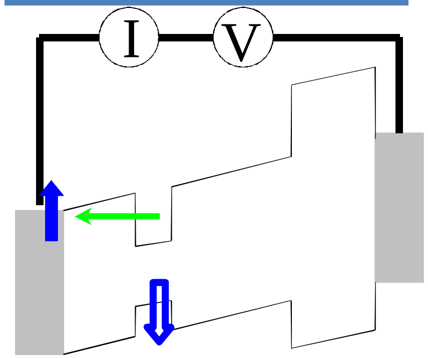
$$\Delta E_h = \hbar\omega_h = g_h \mu_B B_x$$

Initialization control and readout of a single hole spin.

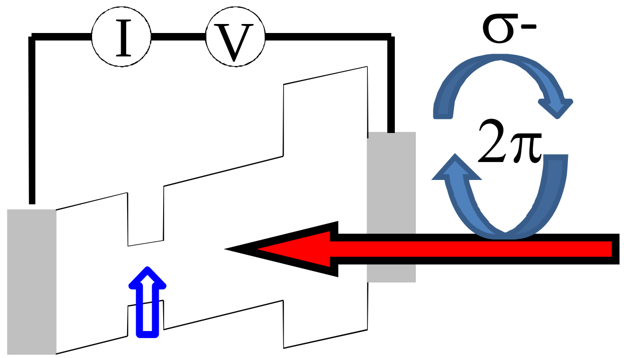
1: Prepare spin polarized electron hole pair



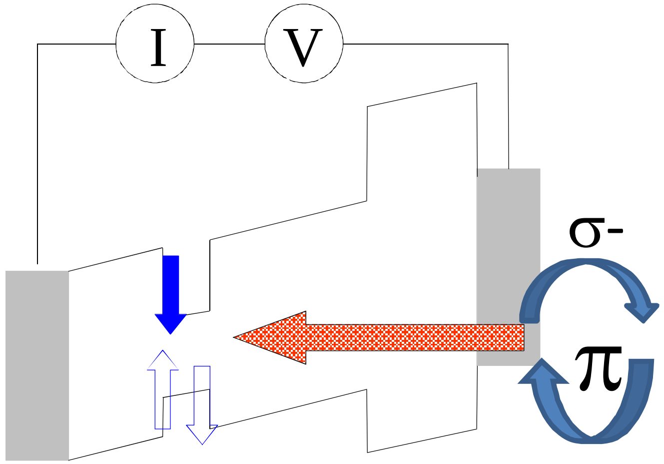
2: Electron tunnels,→ spin polarized hole



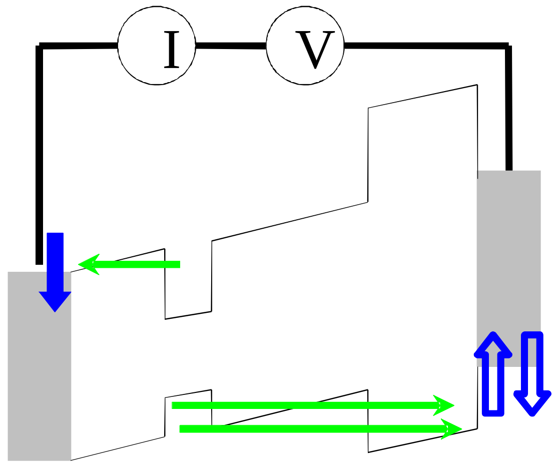
3: Rotate spin using a 2π pulse.



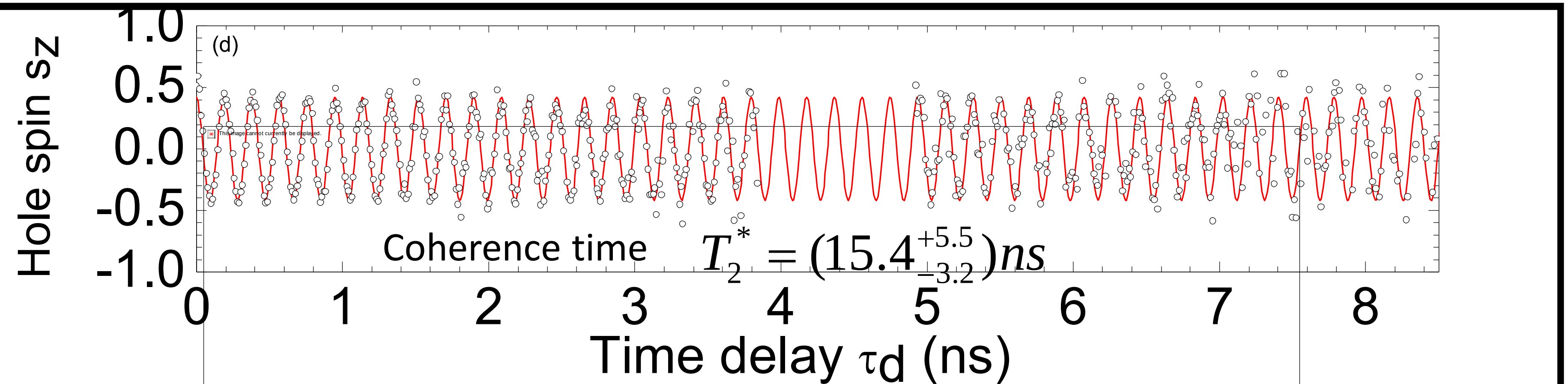
4: Create charged exciton conditional on hole spin. Using co/cross polarised π pulse

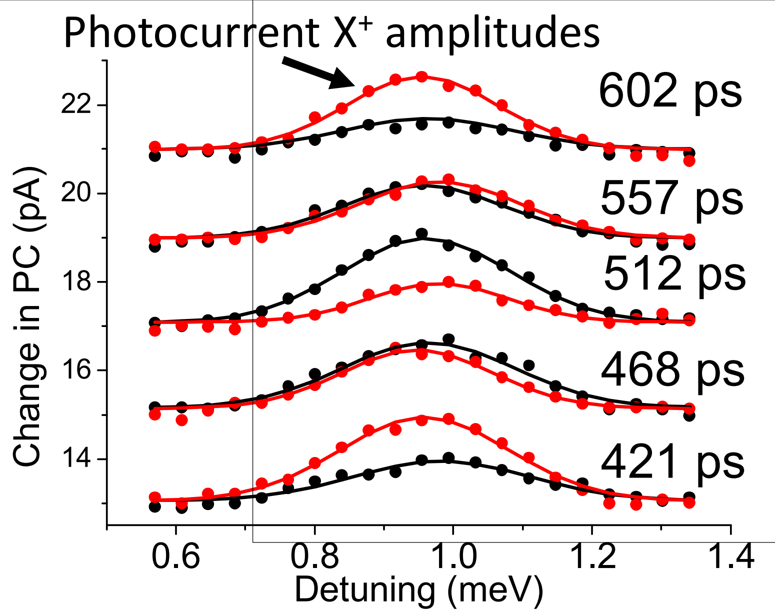


5: Carriers tunnel from dot and are read out



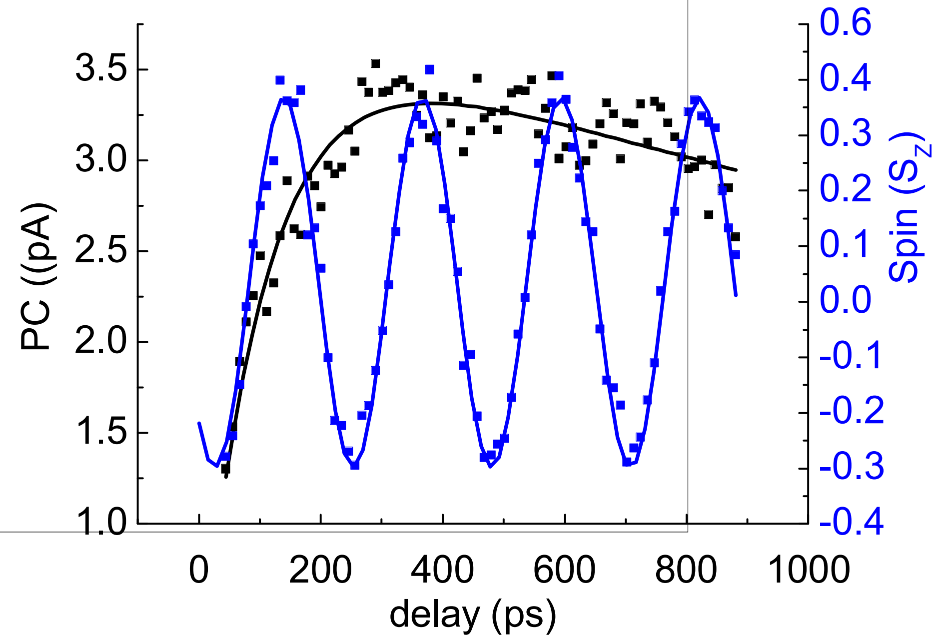
Larmor precession: rotation about x





$PC_{++} \sim \boldsymbol{sin^2(\omega_h t/2)}$

$PC_{+-} \sim \boldsymbol{cos^2(\omega_h t/2)}$



$$\frac{PC_{+-} - PC_{++}}{PC_{+-} + PC_{++}} \propto S_Z$$

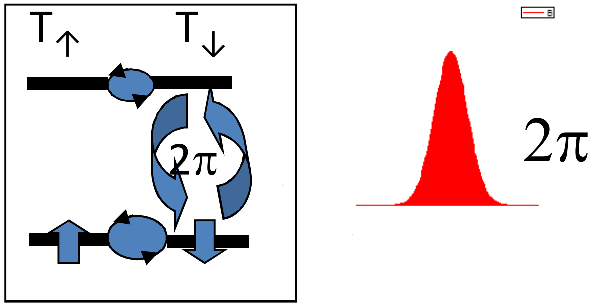
Three-pulse experiment: hole spin control

1) T<Tcontrol Hole spin precesses about B-field

$$\psi(t<t_C)=\frac{1}{\sqrt{2}}\left(\cos(\omega_h t)\left|\Uparrow\right\rangle\ +i\sin(\omega_h t)\left|\Downarrow\right\rangle\right)$$

$Eq.1$

2) T=Tcontrol: **2π pulse resonant with h-X^+ when S_z=0 with σ−**



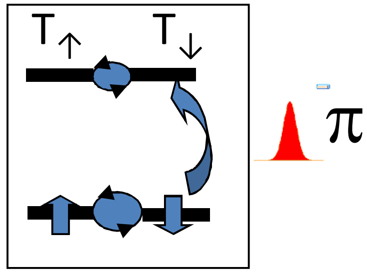
$$\psi(t>t_C)=$$

$$\frac{1}{\sqrt{2}}\left(\cos(\omega_h t)\left|\Uparrow\right\rangle+i\sin(\omega_h t)\left[\cos\left(\frac{\Theta}{2}\right)\left|\Downarrow\right\rangle+i\sin\left(\frac{\Theta}{2}\right)\left|\overline{T}\right\rangle\right]\right)$$

$$\Theta=2\pi\Rightarrow$$

$$\psi(t>t_C)=\frac{1}{\sqrt{2}}\left(\cos(\omega_h t)\left|\Uparrow\right\rangle-i\sin(\omega_h t)\left|\Downarrow\right\rangle\right)\_\_\_\_\_\ Eq.2$$

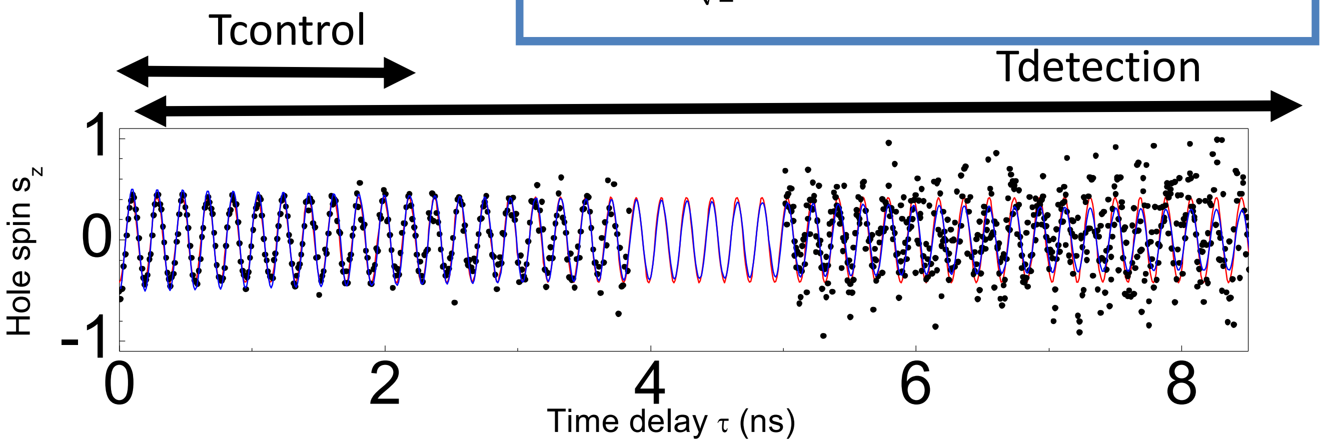
3) T=Tdetection: measure PC h-X^+ with σ±



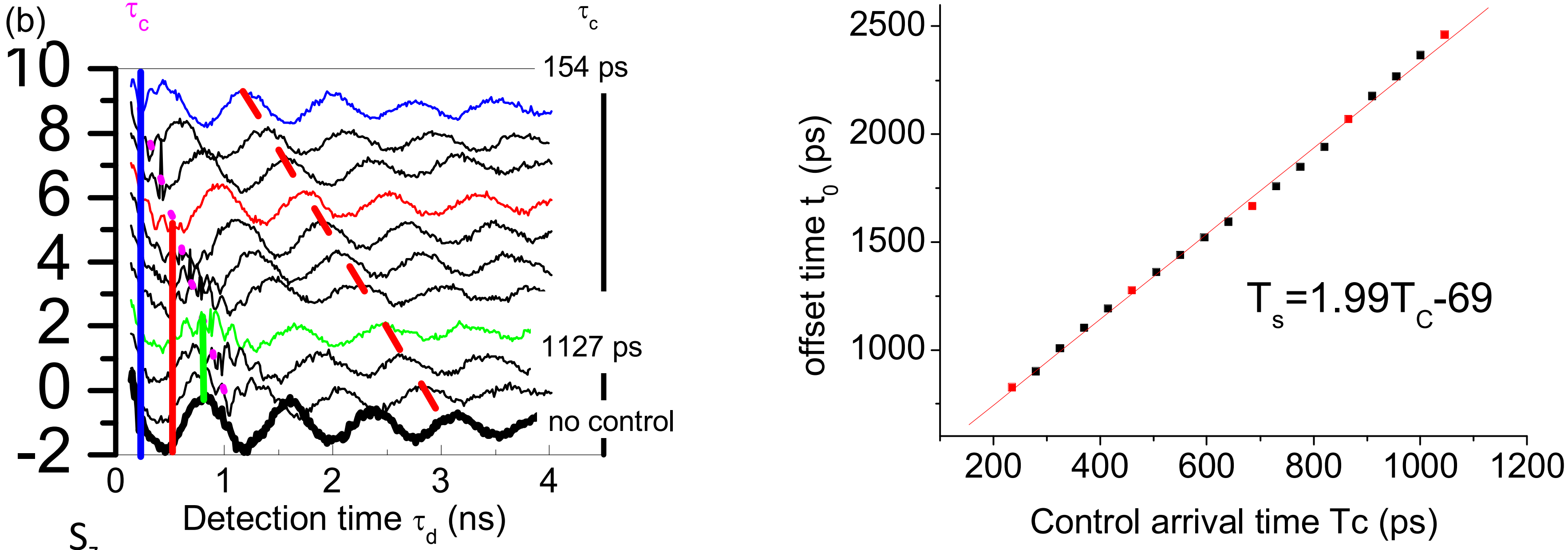
$PC_{++}=\sin^2(\omega_h t/2)$

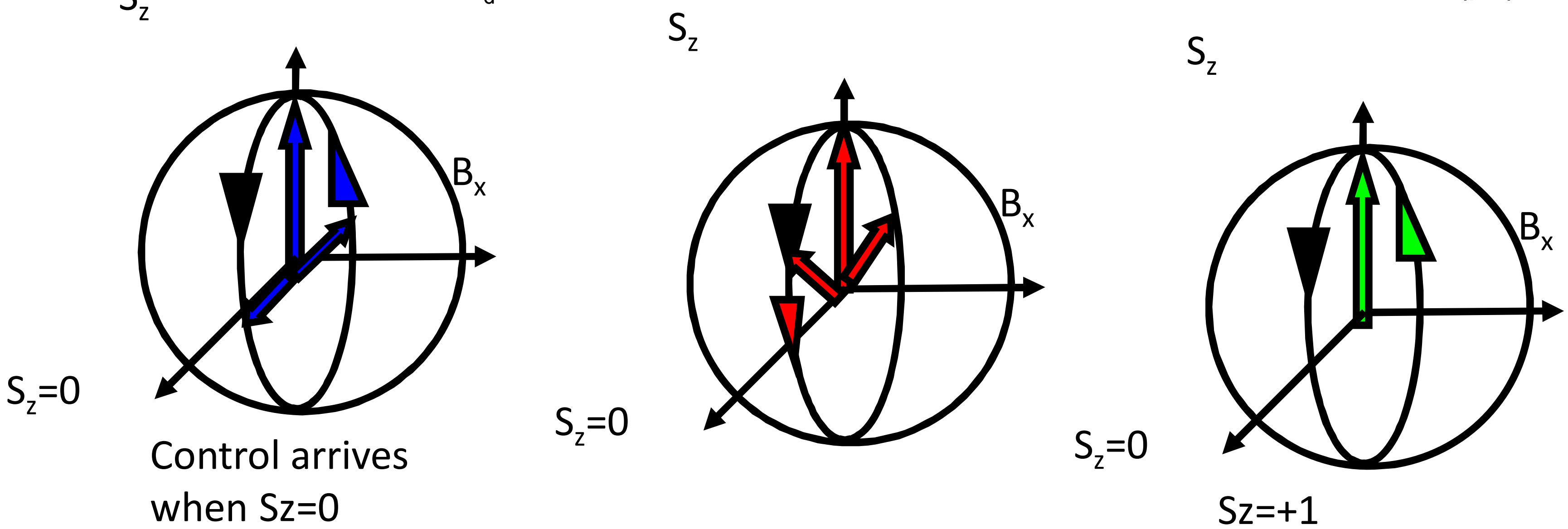
$PC_{+-}=\cos^2(\omega_h t/2)$

$\Delta PC=\cos(\omega_h t)$

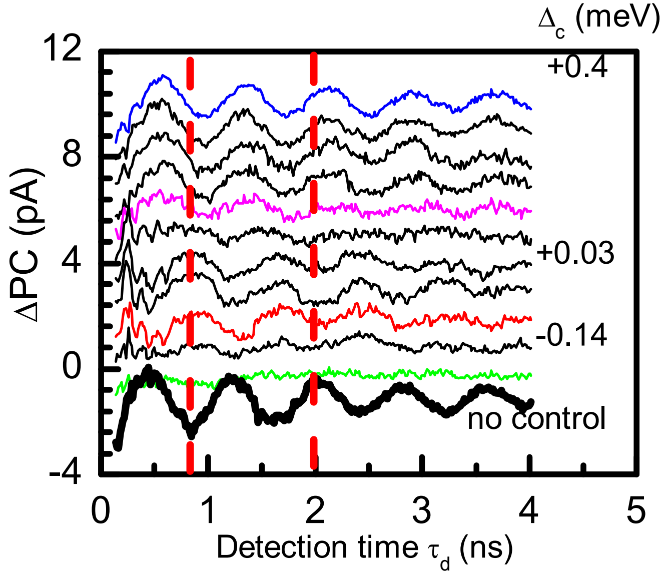


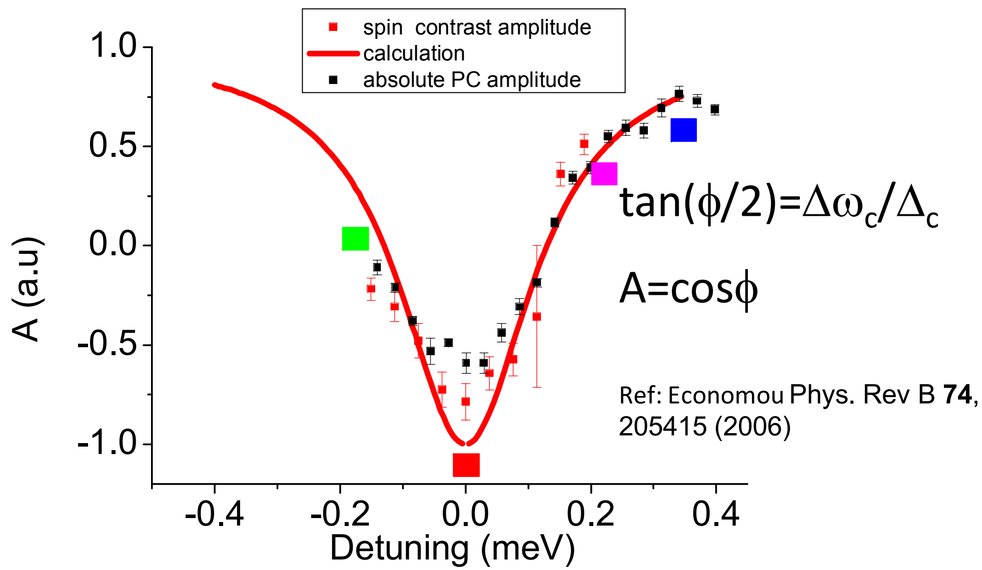
Control of phase of Larmor precession

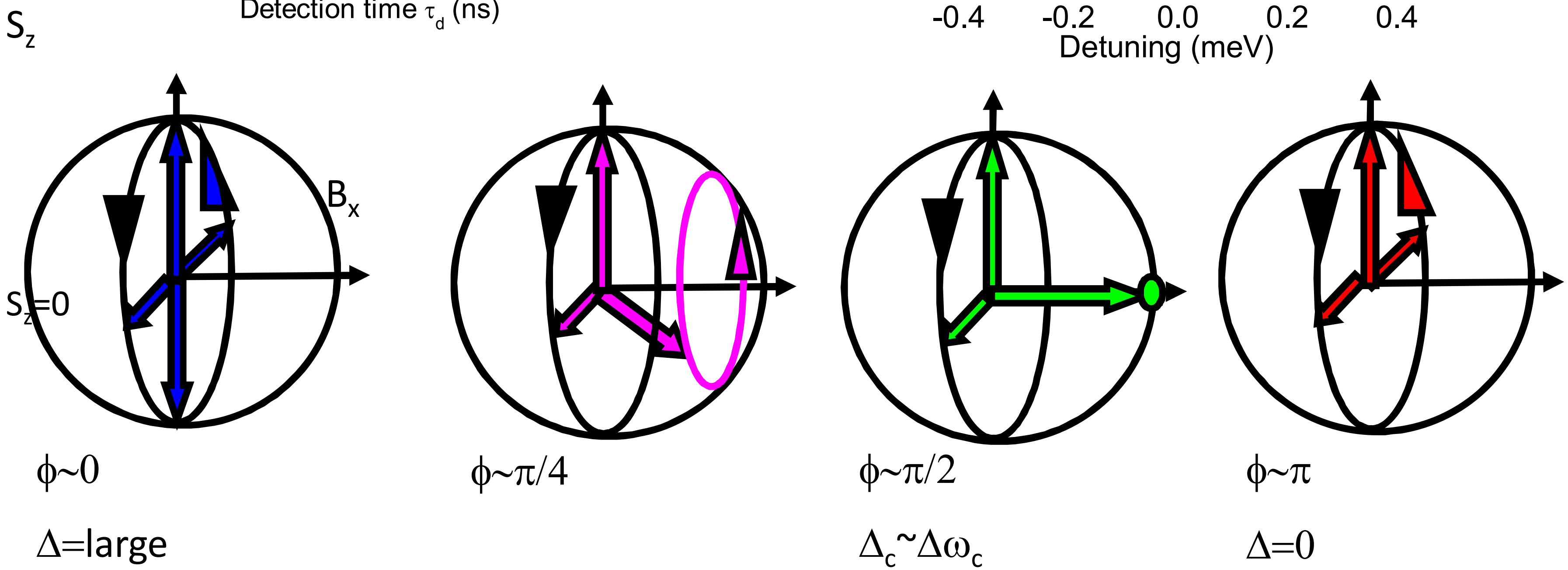




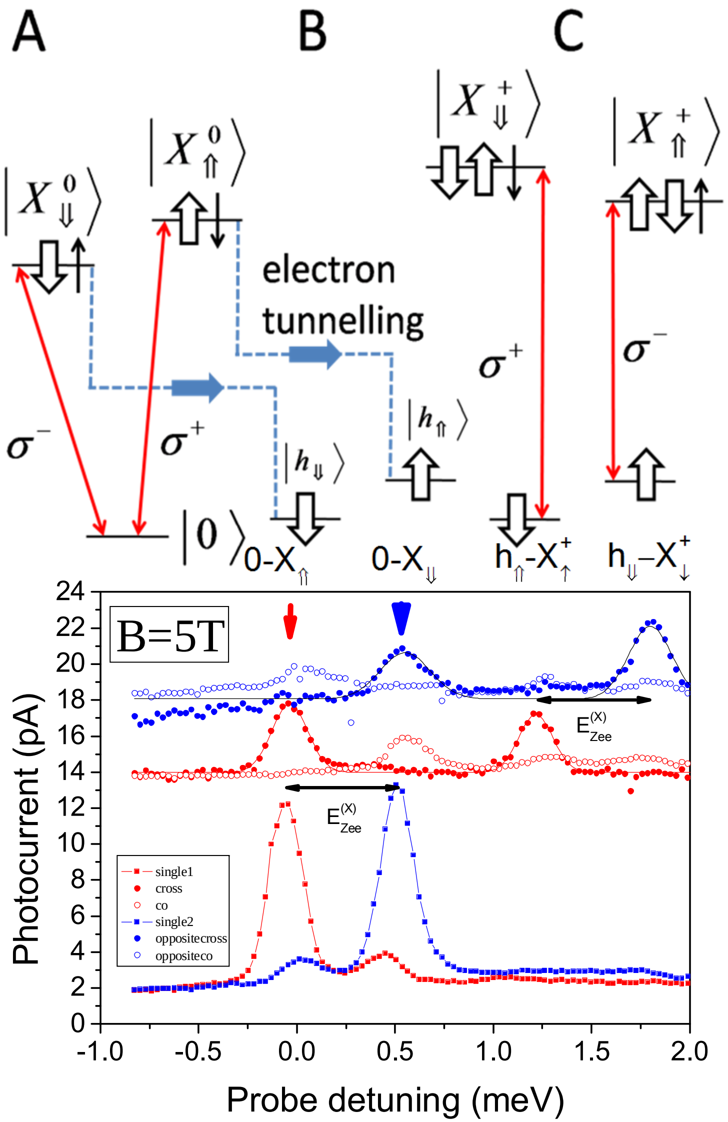
Control of amplitude of Larmor precession: detuning dependence of rotation angle

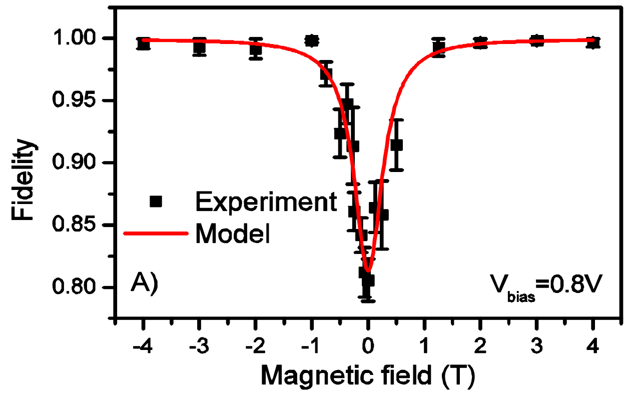


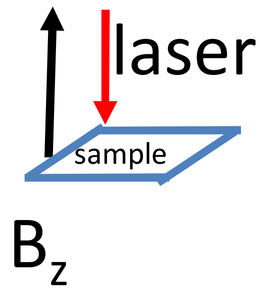


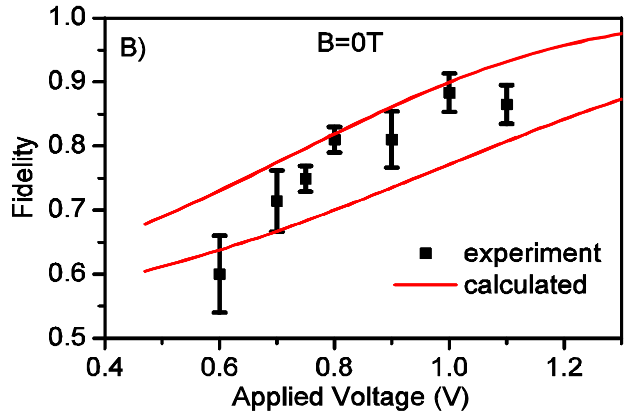


Fast high fidelity spin preparation in Faraday geometry magnetic field





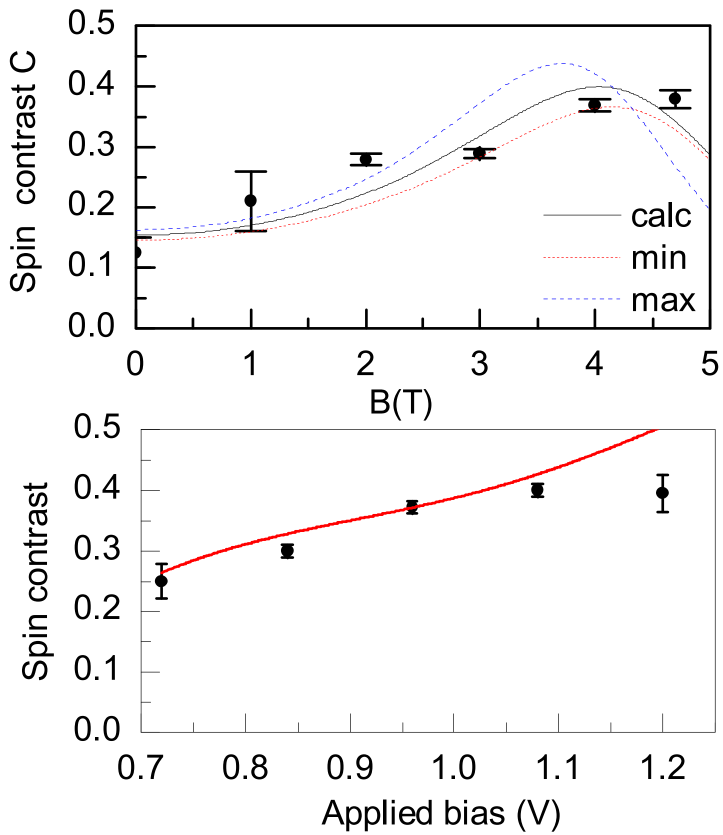




B-field suppresses electron-hole spin entanglement => near perfect spin preparation

See T. M. Godden, APL **97** 061113 (2010).

Fast preparation in Voigt geometry

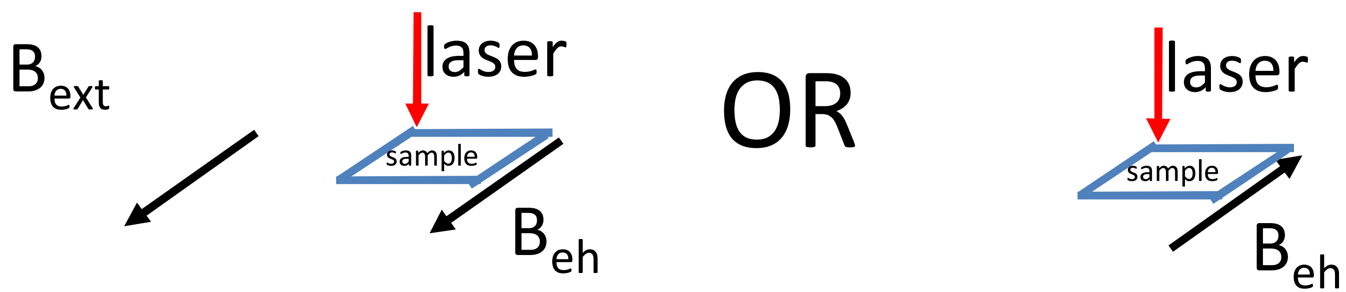


For moderate exchange energy,
contrast limited to 50%

See, T. M. Godden et al, PRB 85 155310 (2012).

Variant of the Hanle effect

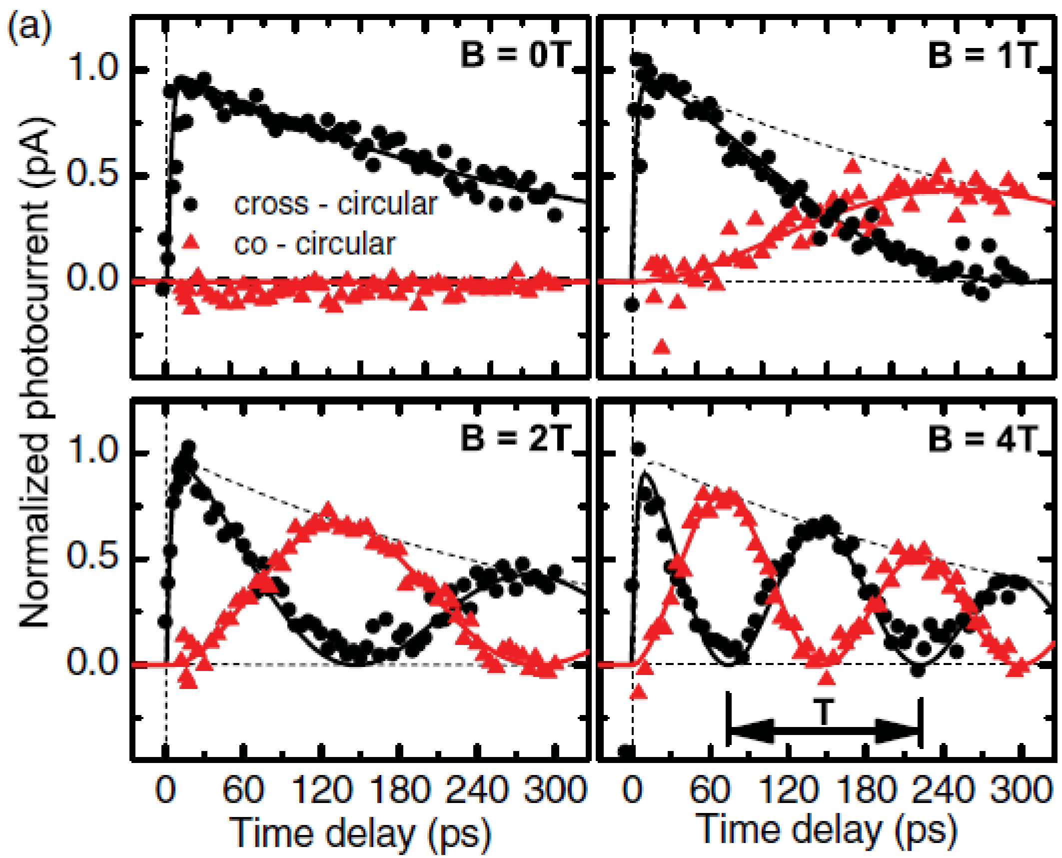
Exchange interaction $\Rightarrow$ Hole experiences effective magnetic field due to electron, but direction is unknown, when electron tunnels "measure" an effective field of



Synchronized   Not synchronized

For moderate electron-hole exchange field, contrast limited to 50% for

High-fidelity hole spin preparation due to picosecond electron-tunneling time:
K. Muller et al, PRB 85 241306R (2012).



Conclusions

- Coherent optical control of a single hole spin, done
- Gate time of 14 ps, compares to 15ns extrinsic coherence time using no tricks to enhance coherence
- Spin preparation is not ideal in this B-field geometry, and coherence time limited by hole tunnelling – (see T. M. Godden PRB **85** 155310 (2012).)

Please see: T. M. Godden, PRL **108** 017402 (2012).

Spin preparation see A. J. Ramsay PRL **100** 197401 (2008). and T. M. Godden APL **97** 061116 (2010).

Interfacing a quantum dot spin with a photonic circuit

I. J. Luxmoore et al ArXiv:1206.3051 (2012).

I.J. Luxmoore[1], N.A. Wasley[1], A.J. Ramsay[1], A.C.T. Thijssen[2], R. Oulton[2], M. Hugues[3], S. Kasture[4], Achanta V. G.[4], A.M. Fox[1] and M.S. Skolnick[1]

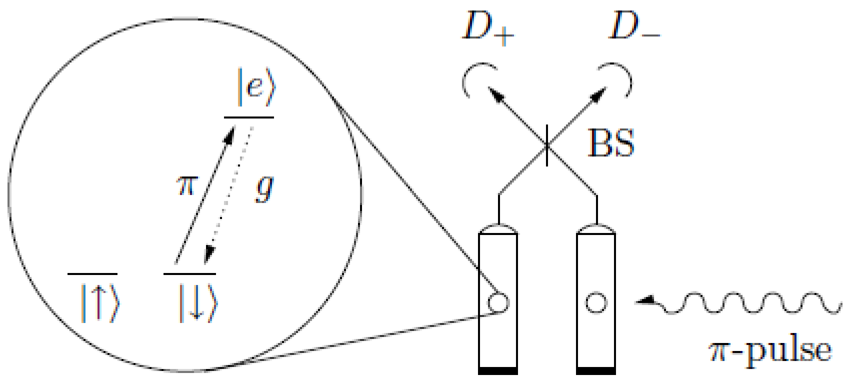
[1]Department of Physics and Astronomy, University of Sheffield, UK

[2]H.H. Wills Physics Laboratory, University of Bristol, UK

[3]Department of Electronic and Electrical Engineering, University of Sheffield, UK

[4]Tata Institute of Fundamental Research, Mumbai, India

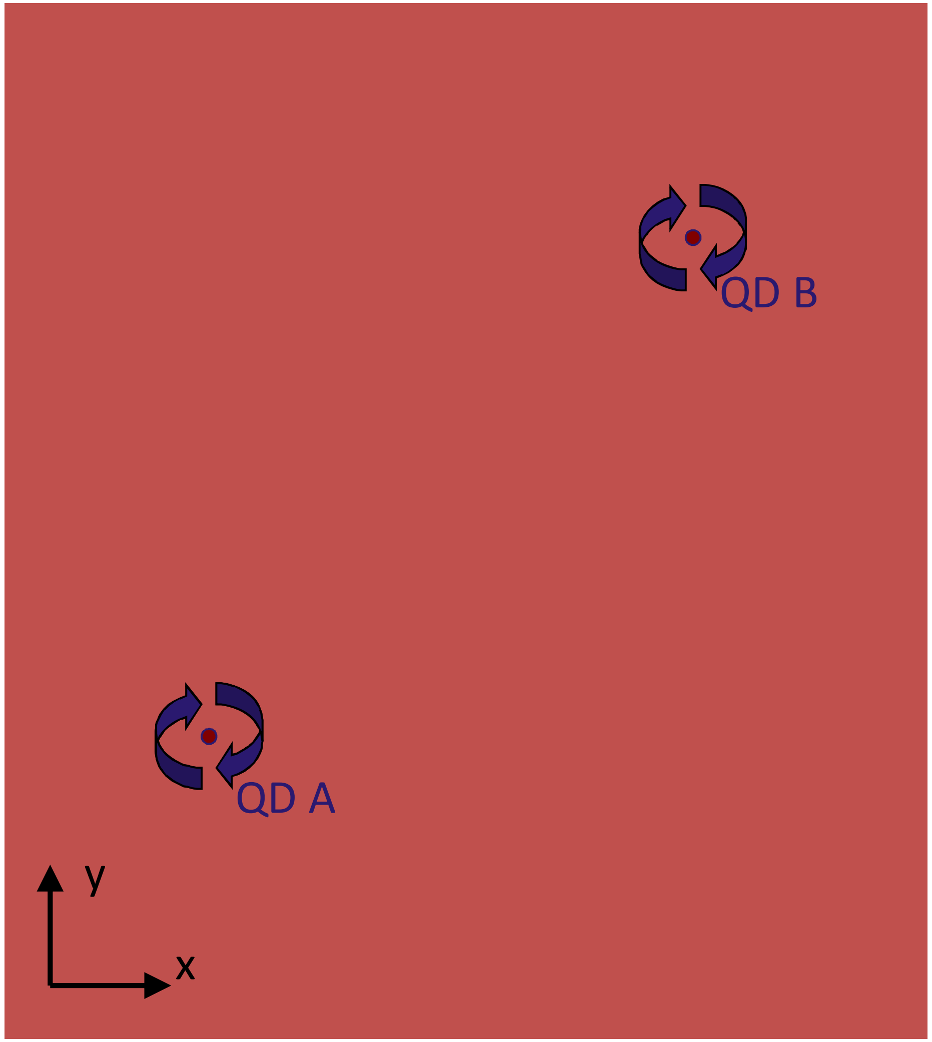
Remote entanglement of two spins via measurement



See S. D. Barrett and P. Kok, PRA 71 060310 (2005).

The problem: a single waveguide cannot transmit circular polarization

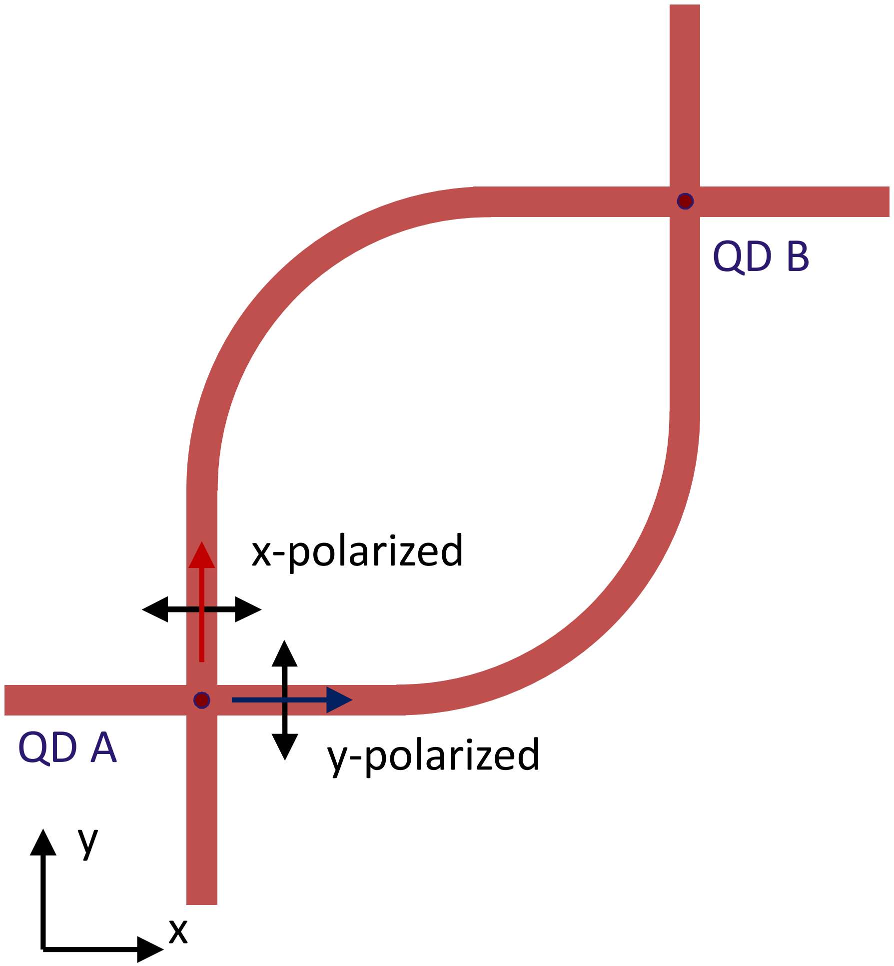
- Need to transfer circularly polarized photon (x+iy) from A to B.
- Two possible routes:
  - Out of plane
  - In-plane
- Planar waveguide cannot support longitudinal polarization component.



A solution: use two waveguides and map spin to which-path state

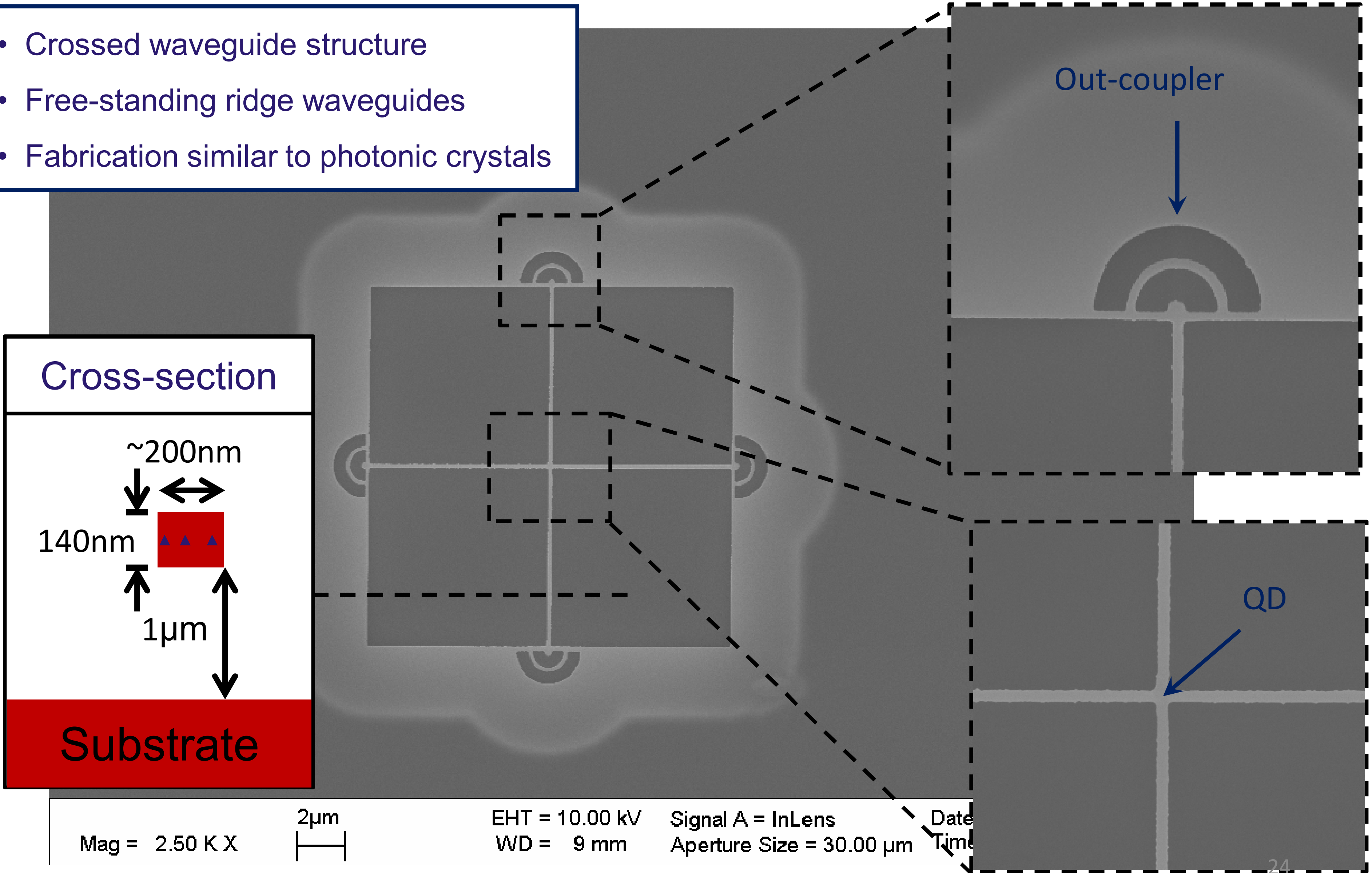
Our solution:

- Use crossed waveguide structure
  – polarization of emitted photon converted to "which-path" state.
- Recombine light in two waveguides to recover polarization state of emitted photon.



Spin to guided-photon interface

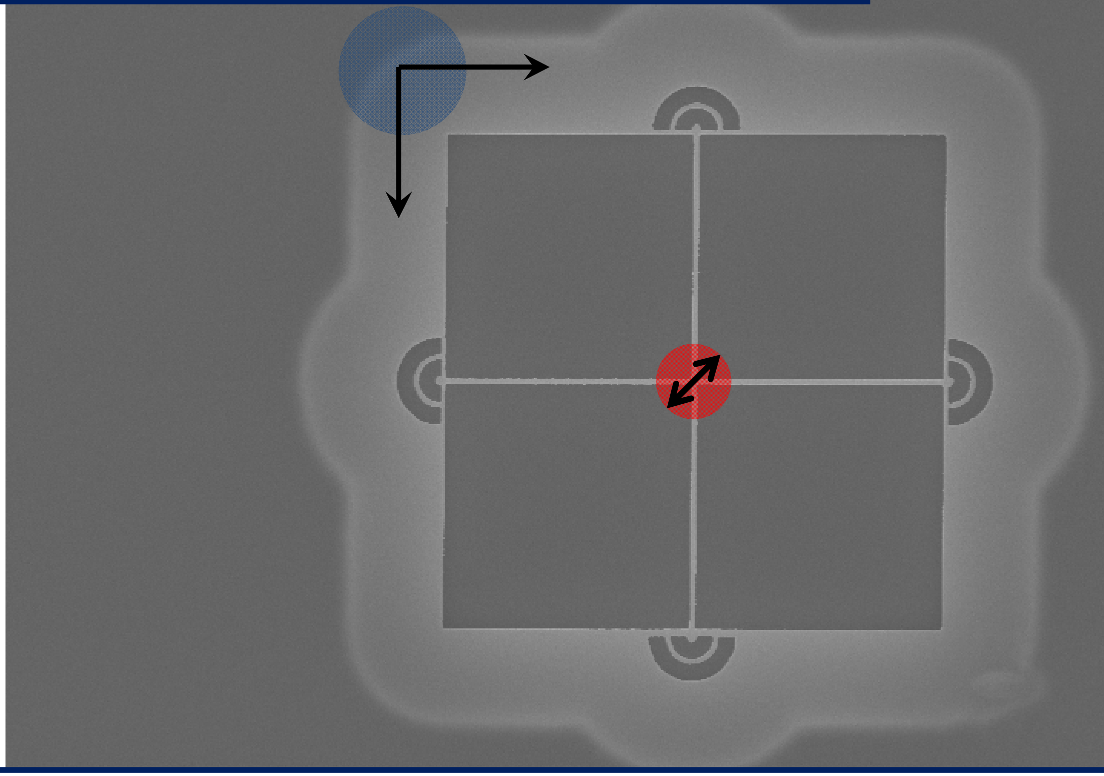
- Crossed waveguide structure
- Free-standing ridge waveguides
- Fabrication similar to photonic crystals

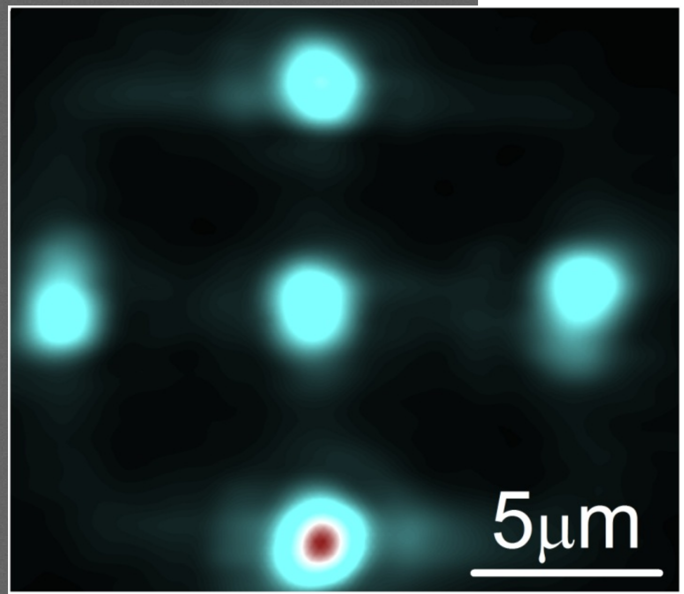


Out-coupler design - Faraon et al. OpEx 16, 12154 (2008)

PL mapping

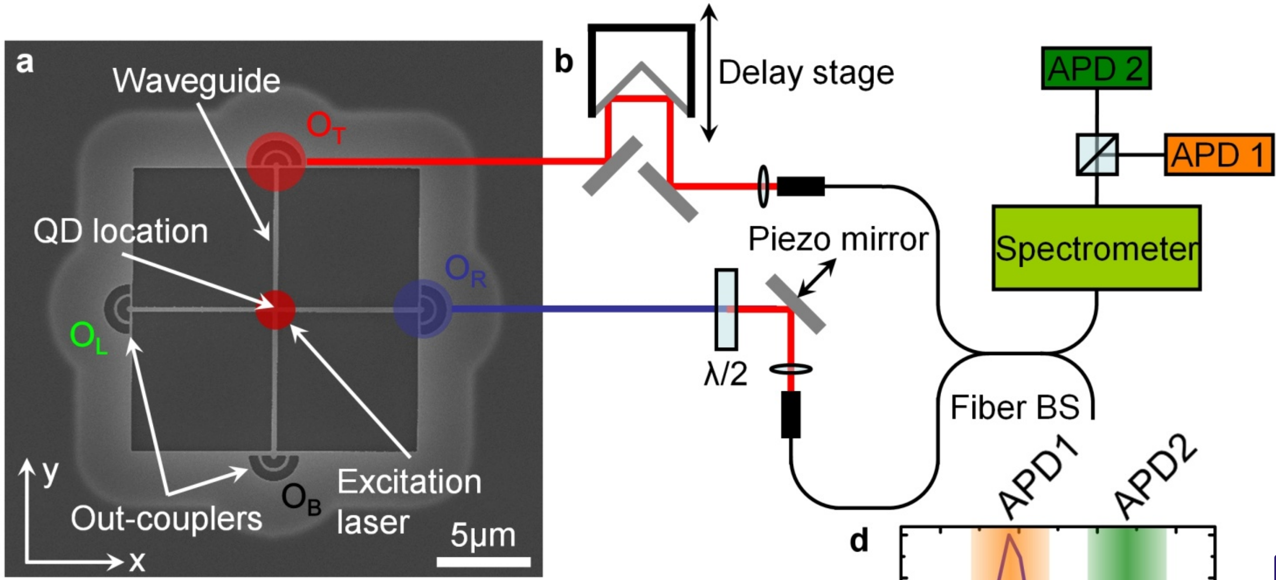
- Laser excite PL at intersection.
- Collection fiber scanned in image plane.
- PL integrated over QD distribution.

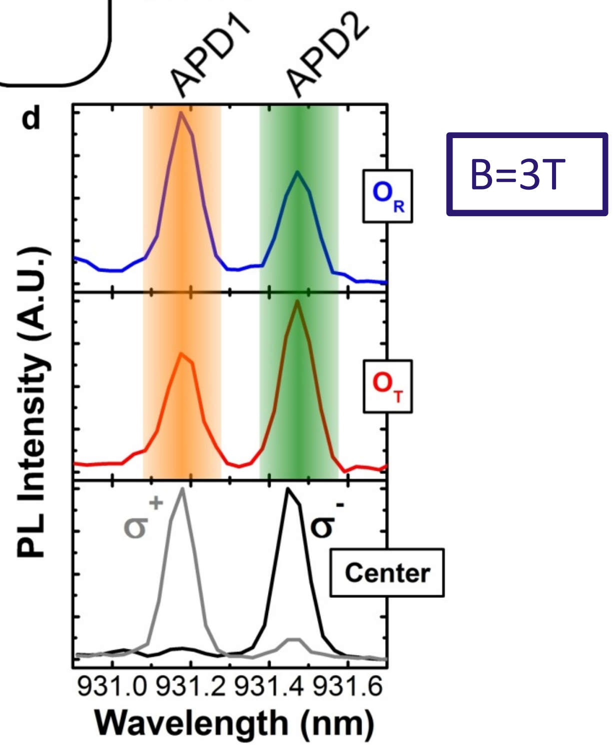




Emission from QDs excited at intersection transmitted along the waveguides and scattered vertically by out-couplers.

Characterization of device-A



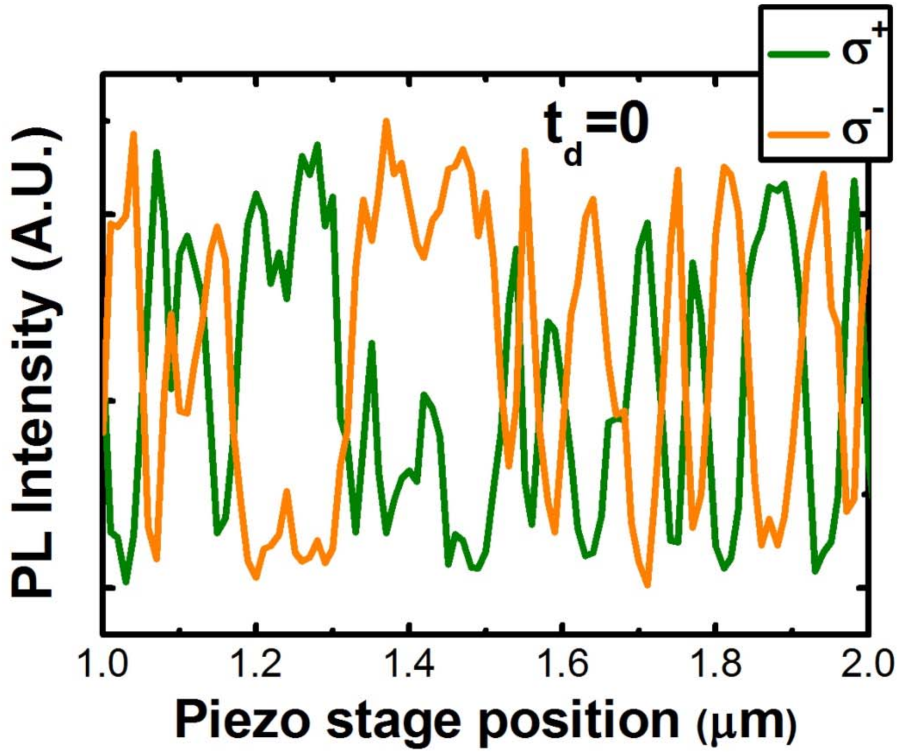


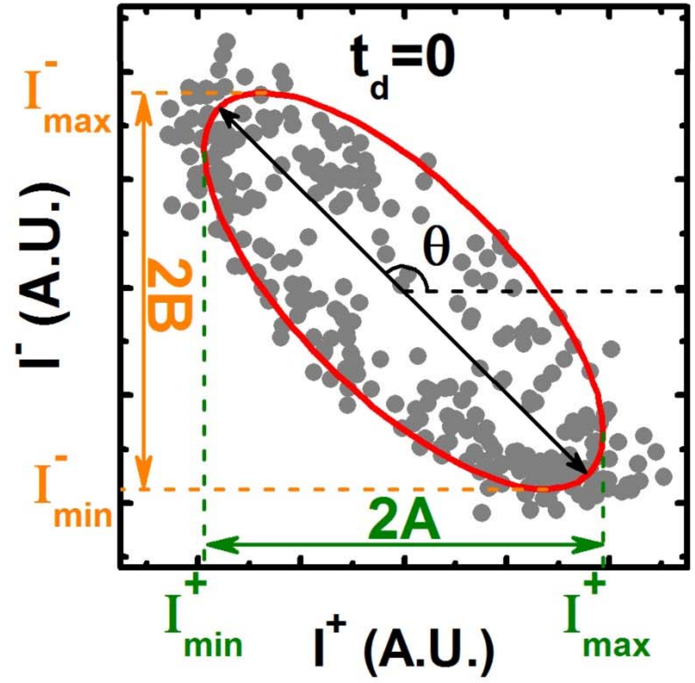
- Faraday geometry B-field – gives well defined circularly polarized states separated by Zeeman energy.
- Circularly polarized states observed from centre and out-couplers.
- Interference performed using fiber beam-splitter
- **<u>Aim</u>: Interfere two states simultaneously – look for phase difference, ΔΦ.**
    - **For cross circular polarization expect ΔΦ=π**

Interference measurements to demonstrate coherence between different paths of device-A

- Piezo varied over a few wavelengths
- Interference fringes recorded for σ^+ and σ^- on separate detectors
- Instabilities in interferometer – do not get uniform period in interference
- Plot intensity of σ^- against σ^+
- Elliptical fit used to extract ΔΦ.

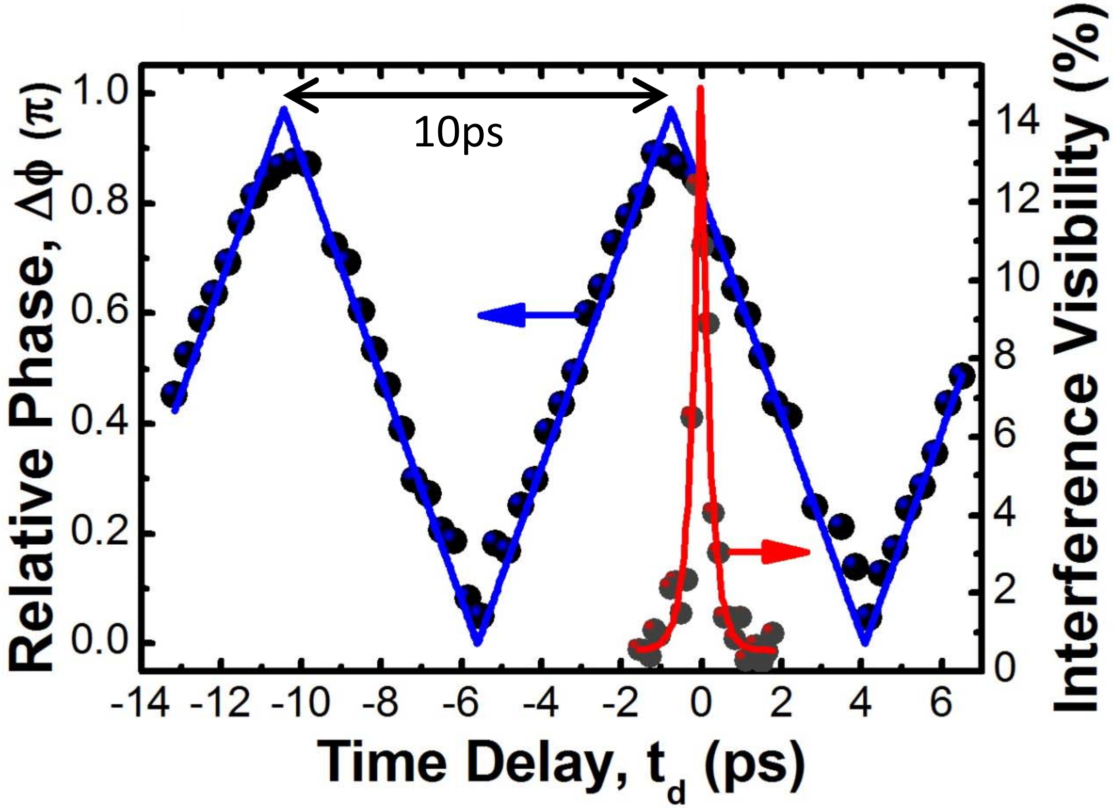
$$\Delta\phi = cos^{-1}\left[\frac{A}{B}\tan(\theta)\right]$$





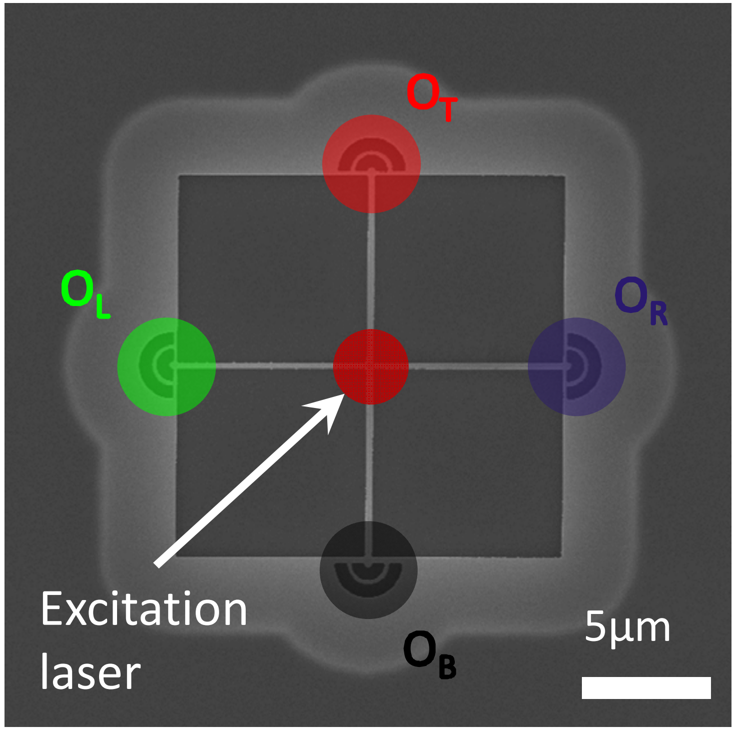
Device-A operates according to the plan

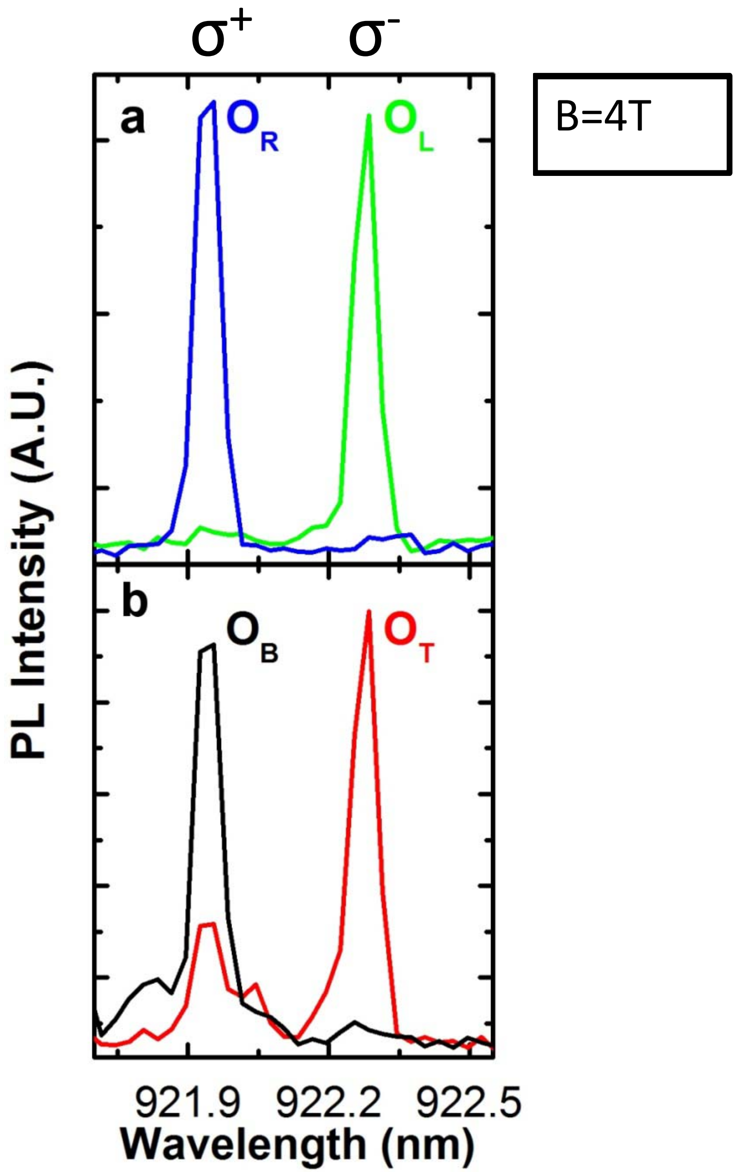
- Interested in ΔΦ at t_d=0
  - Determine zero delay using broadband interference of QD distribution.
- Oscillation period of 10ps corresponds to Zeeman splitting of 0.41meV



- t_d=0, **ΔΦ=0.91π -** phase information retained => in-plane spin transfer possible.

Device-B: direct read-out of spin up/down

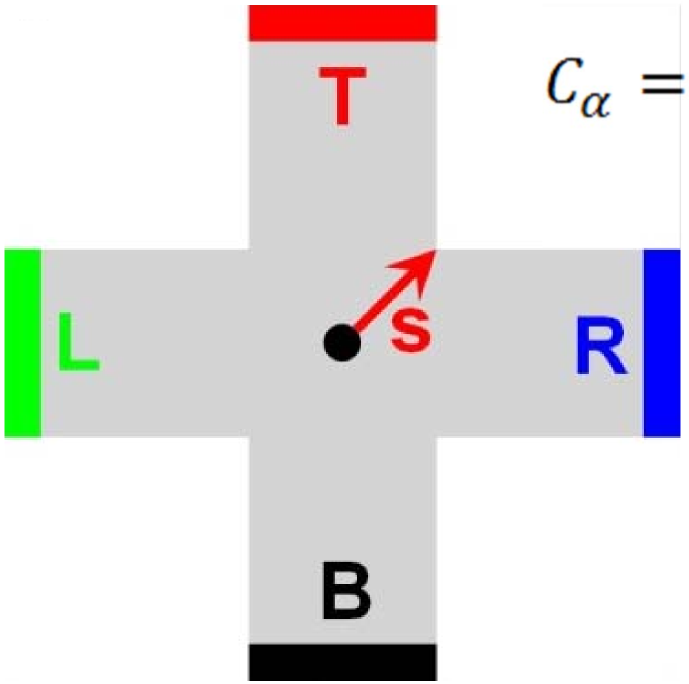




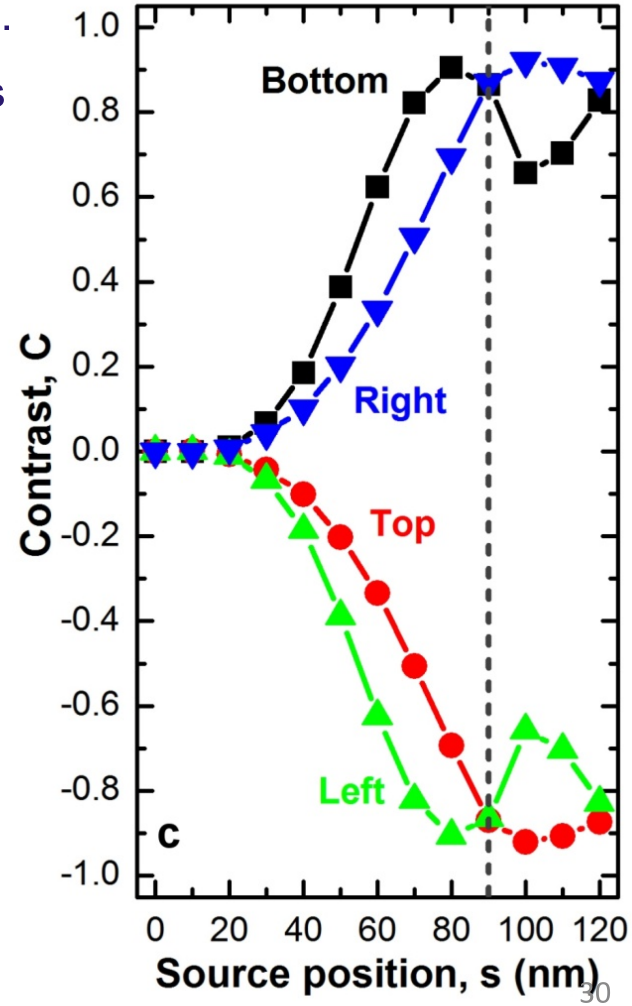
- Second device shows very different behaviour
- Identify σ^+ and σ^- by observing from centre
- When observed from out-couplers:
    - σ^+ line leaves by R and B out-couplers.
    - σ^- line leaves via L and T out-couplers.

FDTD Simulations: influence of dot position on polarization to which-path map

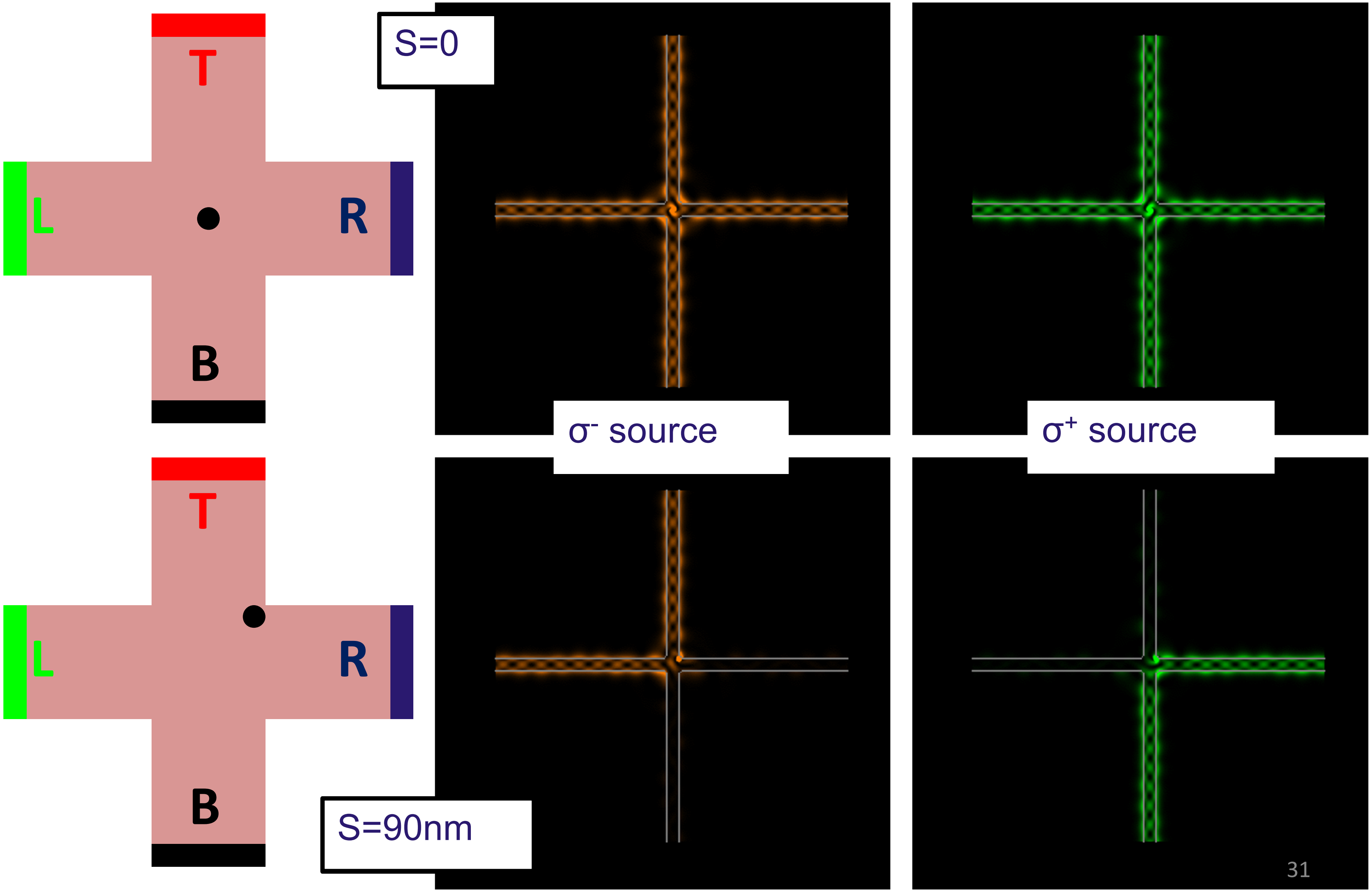
- **Why do we only observe one polarization from each output coupler?**
  - Experimentally observe C_R=0.92 and C_L=-0.93
- Use FDTD to investigate position of QD within intersection.
  - If QD located at s=90nm – experimental observations reproduced.
  - Similarly, for device-A, s<50nm.



$$C_\alpha = \frac{(I^+ - I^-)}{(I^+ + I^-)}$$



FDTD Simulations of device-B



Conclusion

- Proposed and demonstrated a scheme for interfacing a quantum dot spin qubit to a guided-photon.
- Demonstrated the operation of the device in two regimes dependent on QD location:
  - In-plane read-out of full spin state
  - Direct read-out of spin up/down
- Work provides a blue-print for the construction of a scalable on-chip network of solid-state spins.