Light matter interfaces for NV center in diamond

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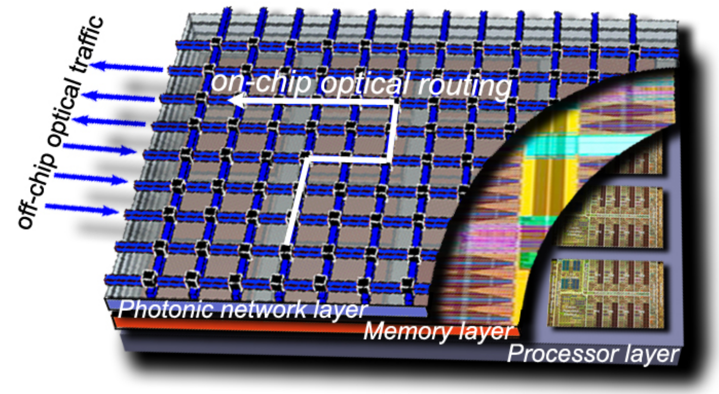
Integrated nanophotonics – next step in Information processing

Photons:

- Have no ohmical losses
- Have huge carries frequencies
- IBM already used photonics for processor interconnects

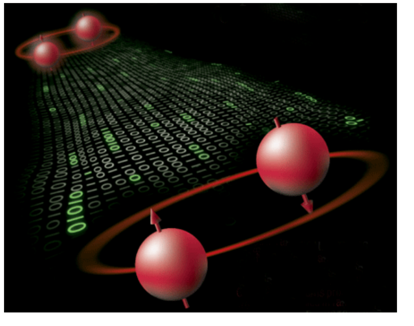


But…

Wide use require **new platforms** for photon switching and processing

Quantum communication:

- Offers new security level
- Exits on market as short range solution
- Need quantum repeaters for long distance

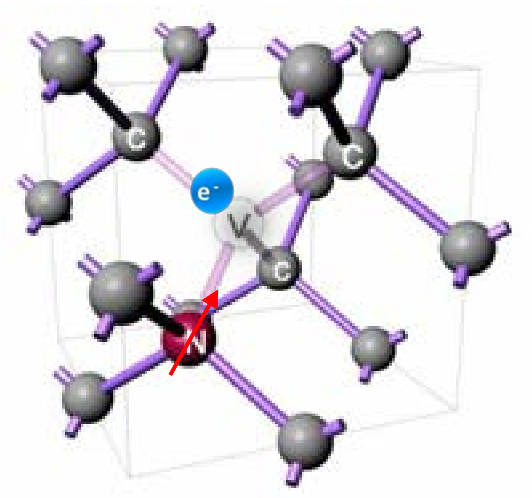


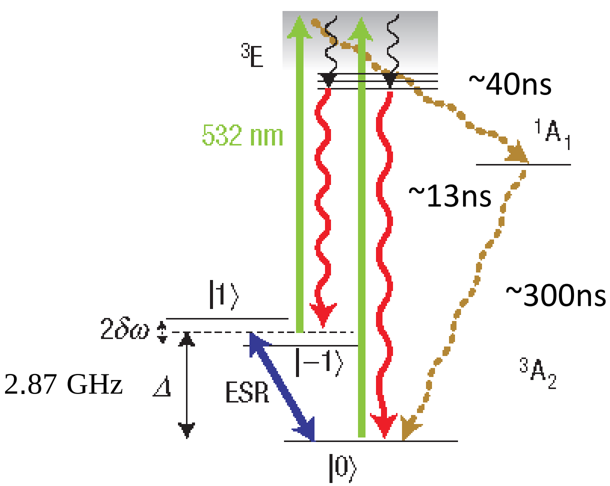
NEED TO INTEGRATE LIGHT AND MATTER ON QUANTUM LEVEL

Key element of active nanophotonics: interface of one atom and one photon

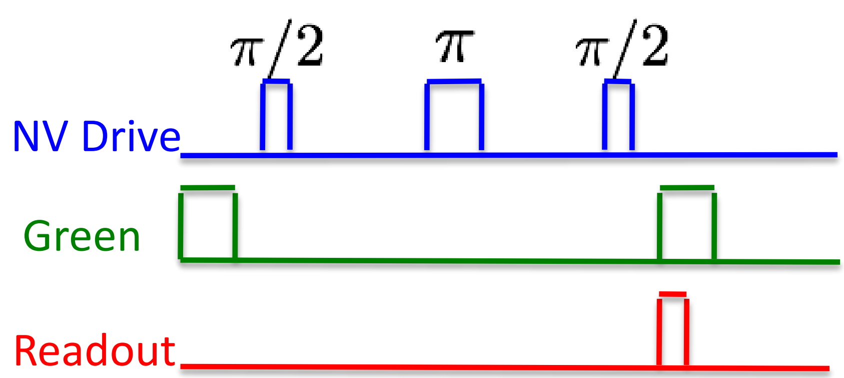
- ✓ Efficient photon reading and writing
- ✓ Single photon sources
- ✓ Nonlinear optics with single photons
- ✓ Many applications in quantum (and classical) information processing
- ✓ Sensors and metrology applications

NV- center in diamond

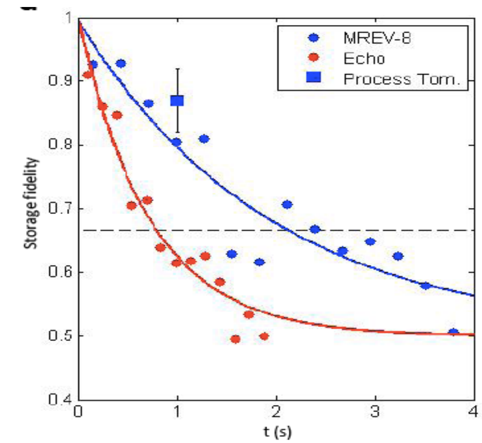




- Non-zero electronic spin (S=1, |ms|=0,1)
- Optical readout of the state
- Optical polarization of the state
- Microwave control over the spin
- Long coherence time up to ms
- Narrow emission line @ 637 nm
- Individual isolation with laser microscopy
- Can be created in nanoscale structures
- Accesses to the nuclear spin



Atom-like system: current efforts

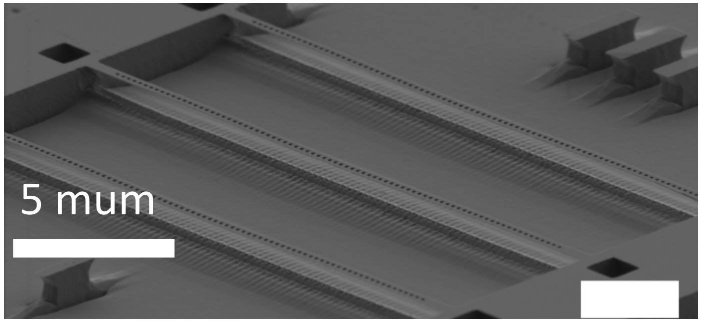


- Coupling to single nuclei: multi-second quantum memory in isotopically pure diamond

  P.Maurer et al (Science, 2012), Lukin group

- Coupling to single photons: diamond nanophotonics for quantum networks

  B. J. M. Hausmann et al (*Nano Lett.*, 2013) Loncar group

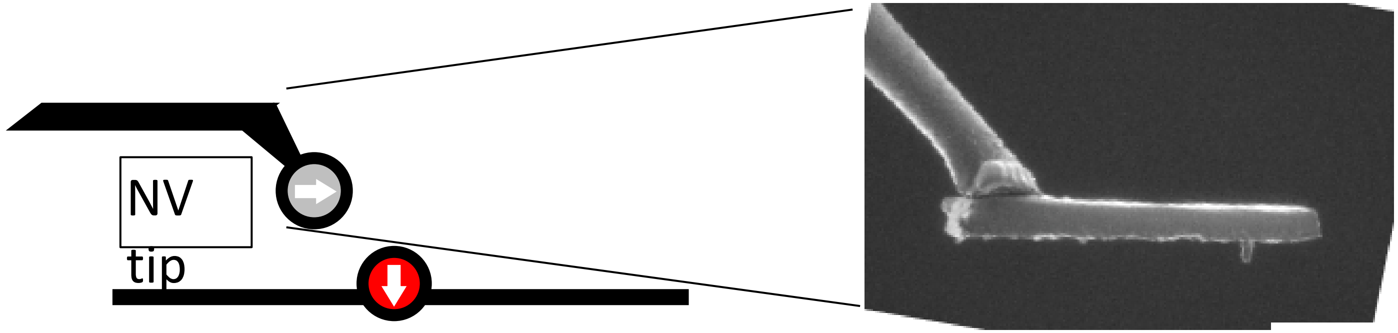


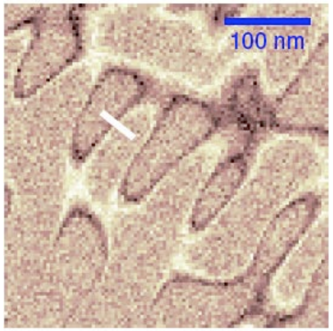
- Heralded entanglement between separated NV centers

  H. Bernien, et al *Nature*., (Nature , 2013) Hanson group

- Sensor and metrology: high resolution sensing of magnetic field

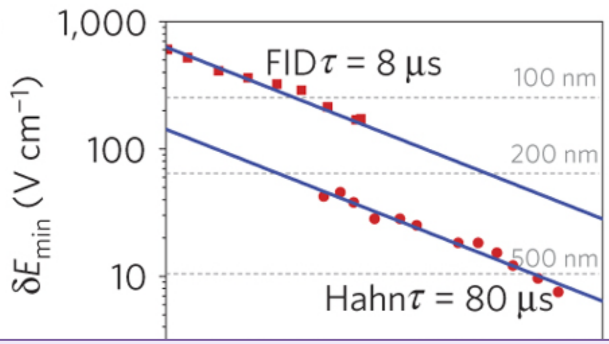
  P.Malinetsky et al (Nature Nanotechnology , 2012) Yacoby group





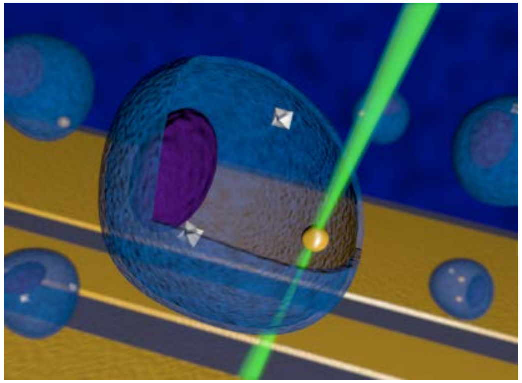
Applications to metrology

- Measurement of electric/magnetic field
- Temperature sensors
- Proposed: tension, force rotation sensors



Need spin readout with good signal to noise!

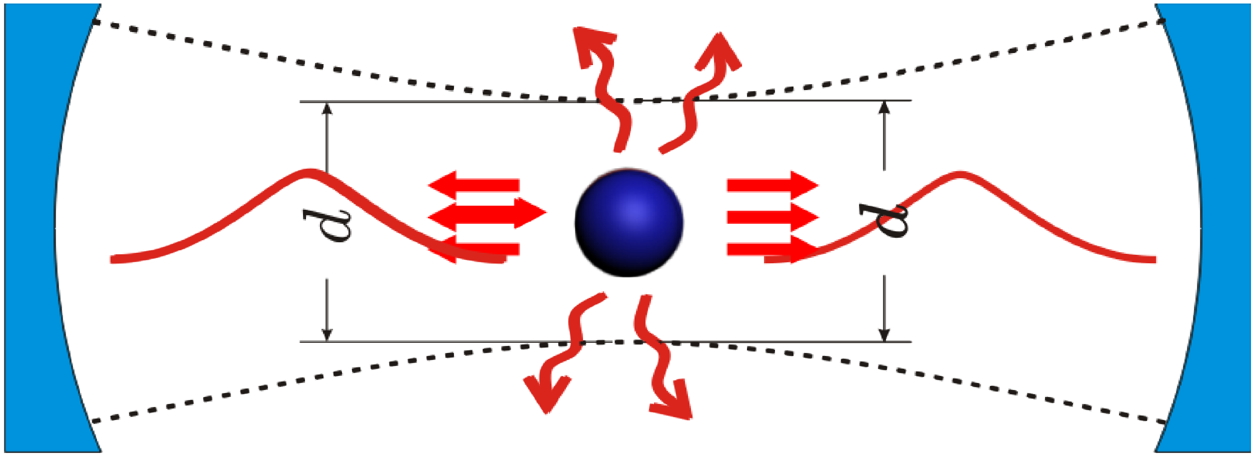
F. Dolde *et al.* Nature Physics **7**, 459–463 (2011)



- In Vivo sensors
- High resolution sensors
- High sensitivity solid state sensors

G Kucsko *et al.* *Nature* **500**, 54-58 (2013)

How to absorb one photon with atom? ?



cross-section

✓ Single photon - single atom interaction probability: $\sim \frac{\lambda^2}{d^2} F$

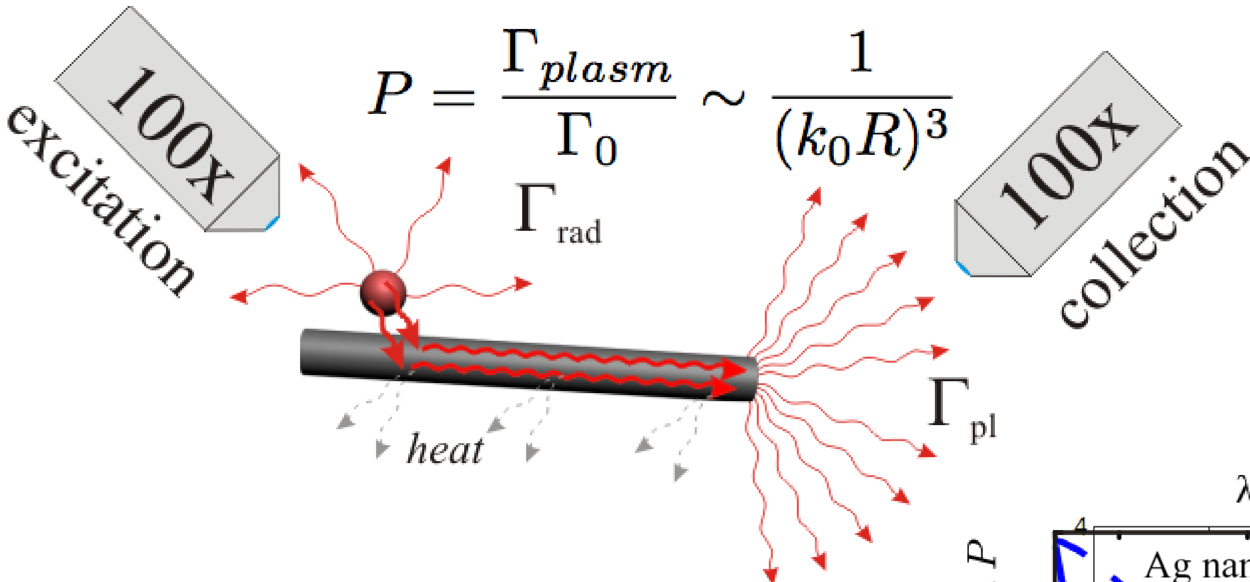
transverse localization

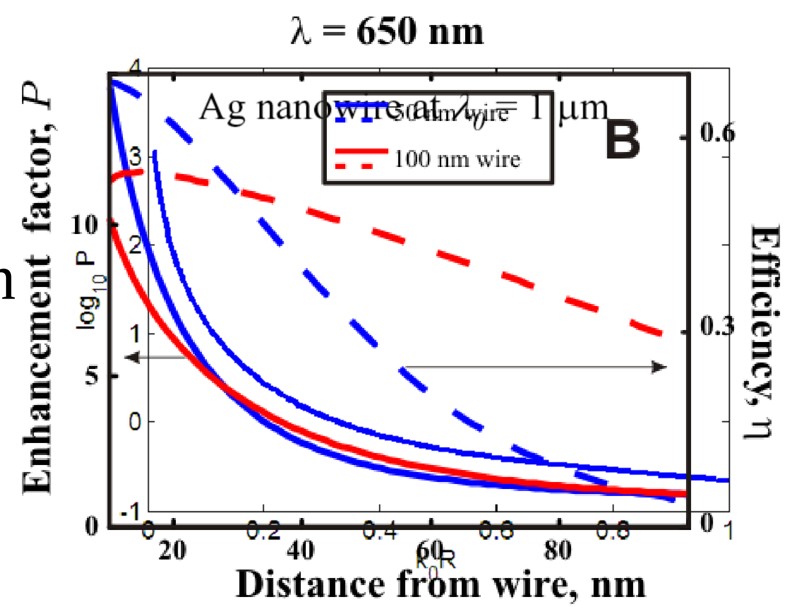
✓ *This talk :*

use unusual materials to improve interaction probability: efficient broadband photon collection using sub wavelength localization

Strong coupling with nanowire surface plasmons nanowire as a “super lens”

$$P = \frac{\Gamma_{plasm}}{\Gamma_0} \sim \frac{1}{(k_0 R)^3}$$



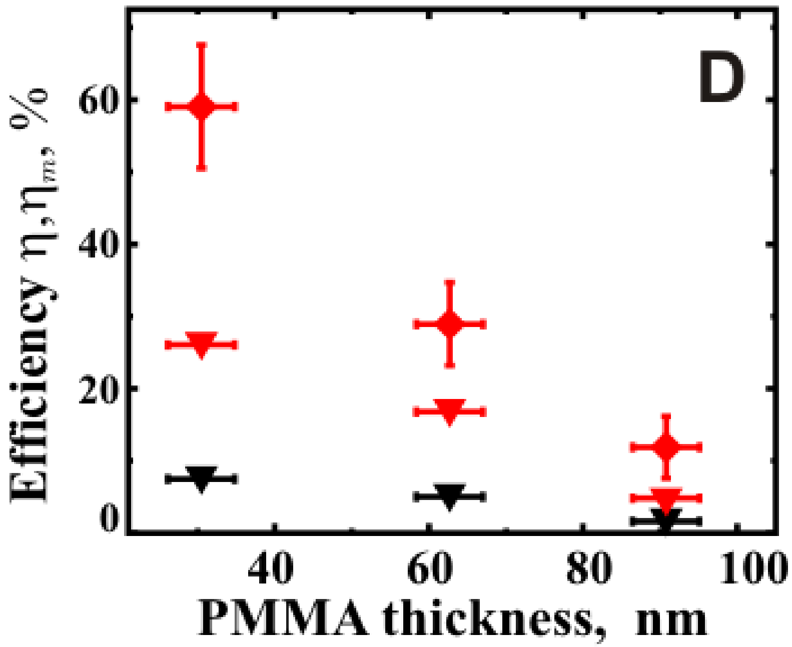


- ✓ Atom emission guided almost completely into the wire, this emission should be completely reversible
- ✓ Calculation for realistic system (perturbation theory, includes losses)

Wire – Qdot distance dependence

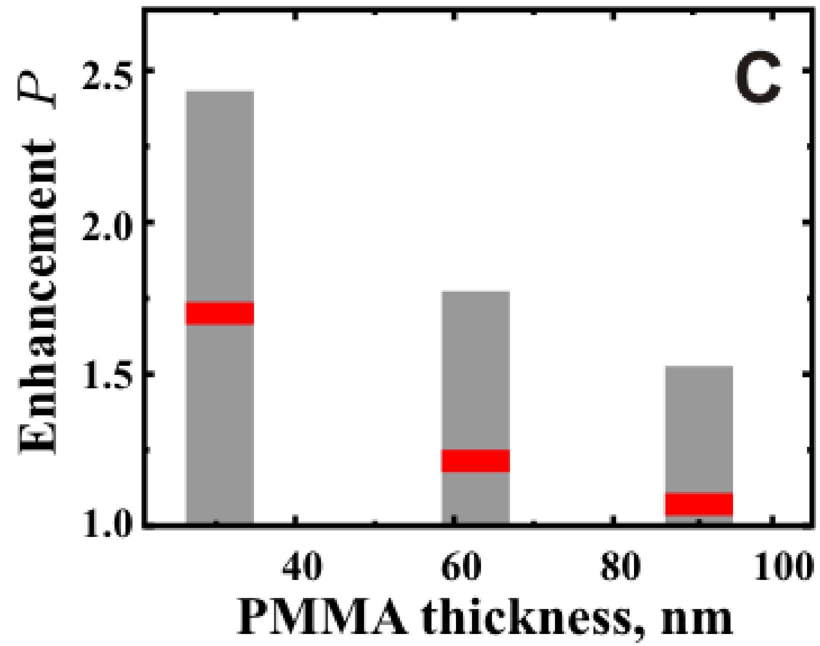
- Efficiency:

$$\eta = \frac{\Gamma_{pl}}{\Gamma_{tot}}$$



- Enhancement:

$$P = \frac{\Gamma_{tot}}{\Gamma_{rad}^{0}}$$



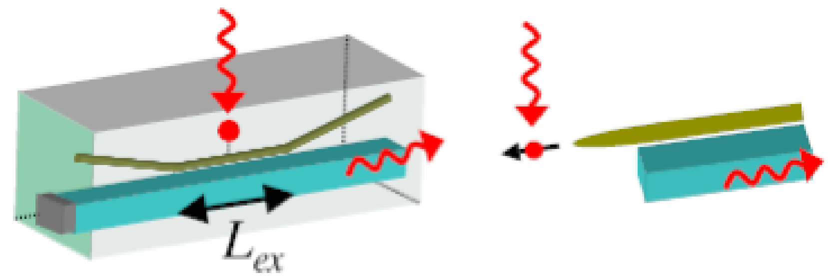
Nature **450**, 402-406

Ways to reduce losses in plasmonic based materials

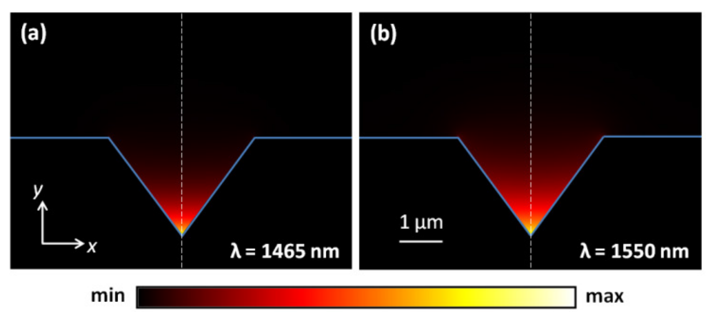
General idea: to combine properties of metal and dielectric at one:

- Combine plasmon wire with waveguide
- Grow high quality films
- Double wires geometry
- Grooves

OR…



Nature Physics 3, 807 - 812 (2007)

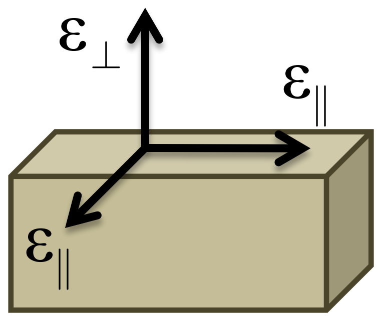


2012 / Vol. 20, No. 5 / OPTICS EXPRESS 5705

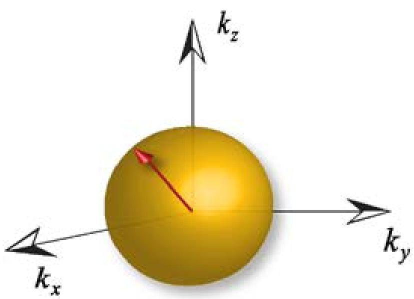
Hyperbolic Metamaterial: The idea

Spontaneous emission: $$\Gamma_{i\to f} = \frac{2\pi}{\hbar}\left|\langle f|H'|i\rangle\right|^2 \times \mathrm{PDOS}$$

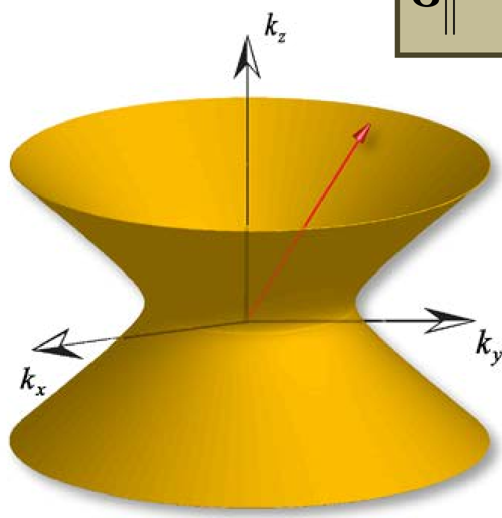
Uniaxial anisotropic medium:



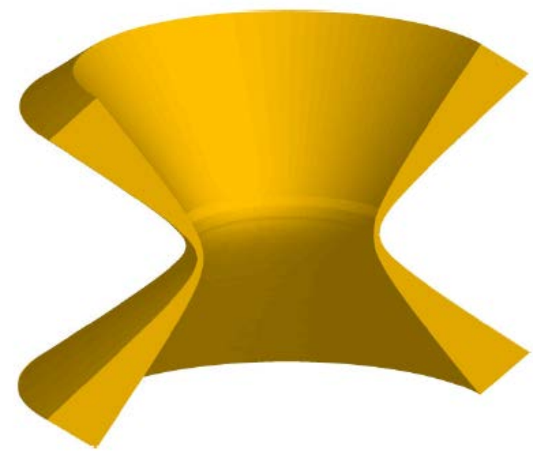
$$\frac{k_\perp^2}{\varepsilon_\parallel} + \frac{k_\parallel^2}{\varepsilon_\perp} = \frac{\omega^2}{c^2}$$



dielectric
$\varepsilon_\parallel, \varepsilon_\perp > 0$

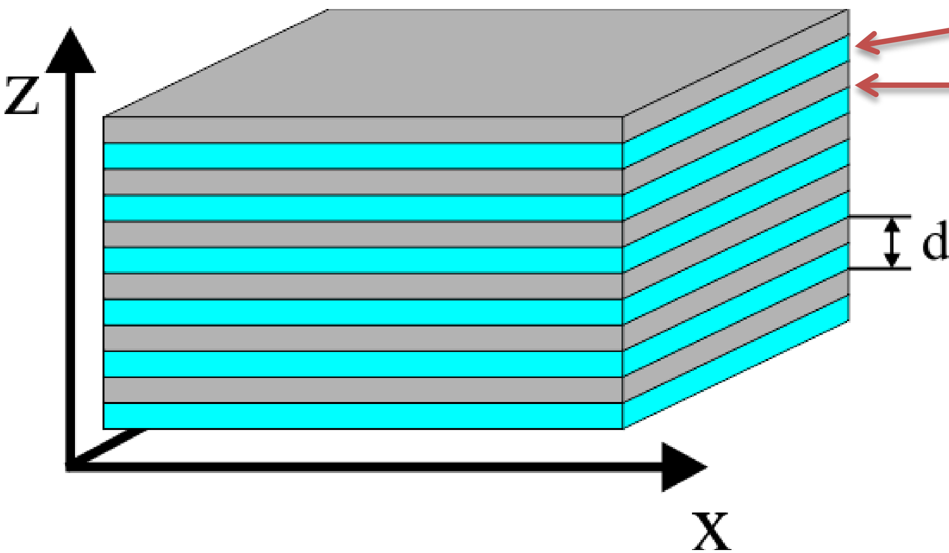


HMM
$\varepsilon_\parallel > 0,\ \varepsilon_\perp < 0$



unbounded |k|
singularity in PDOS
Appl. Phys. B, 100(1) 215, 2010

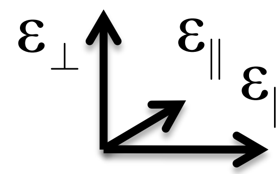
Hyperbolic Material: the structure

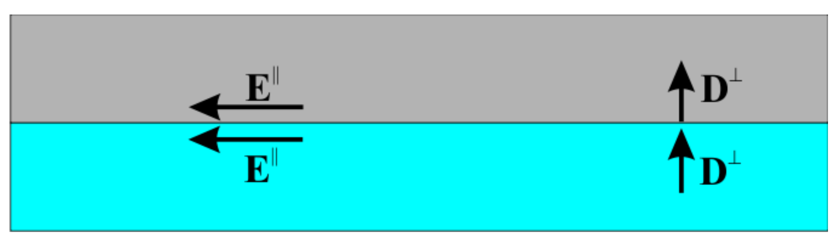


Metal $\varepsilon_m < 0$

Dielectric $\varepsilon_d > 0$

$d \ll \lambda$





$$\rho = \frac{d_m}{d}$$

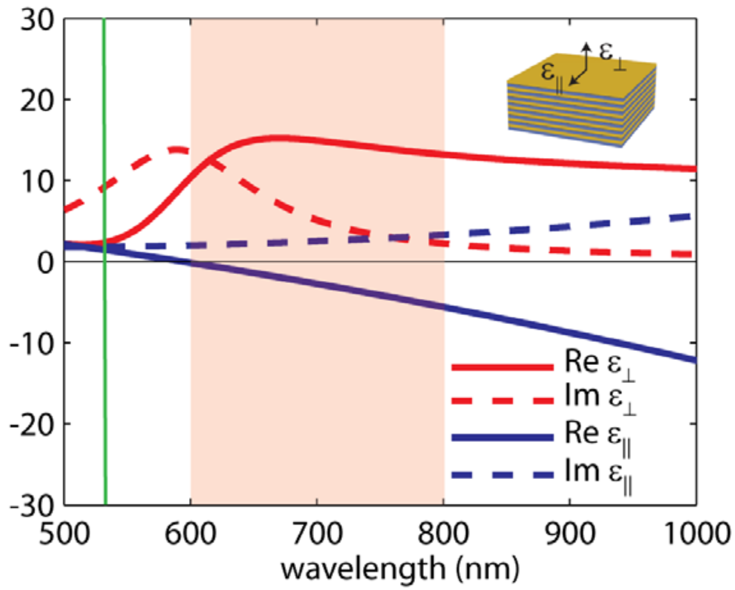
$$D^{\parallel} = D_m^{\parallel}\rho + (1-\rho)D_d^{\parallel}$$

$$E^{\perp} = E_m^{\perp}\rho + (1-\rho)E_d^{\perp}$$

$$\varepsilon_{\parallel} = \rho\varepsilon_m + (1-\rho)\varepsilon_d$$

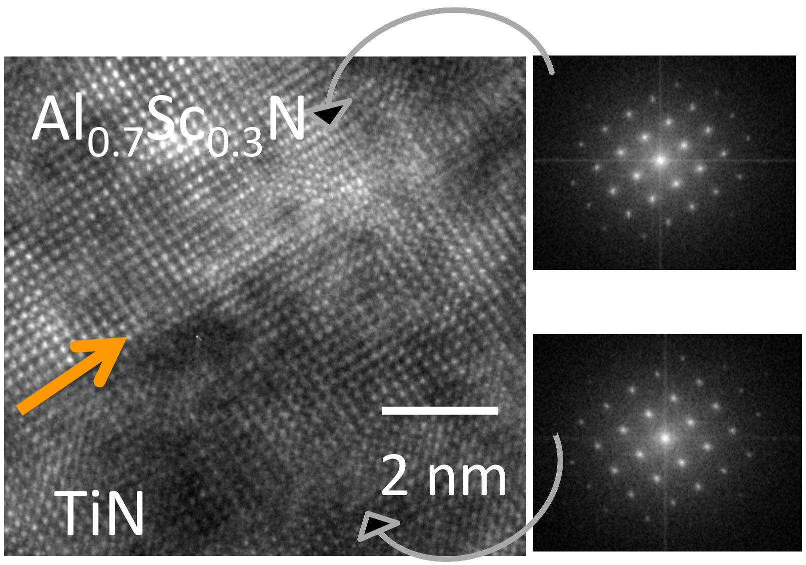
$$\varepsilon_{\perp} = \frac{\varepsilon_m\varepsilon_d}{\rho\varepsilon_d + (1-\rho)\varepsilon_m}$$

Hyperbolic CMOS-compatible metamaterial



M. Y. Shalaginov, et al CLEO Proceedings (2014)

- 10/10 nm, 20 layers,
- [001]-oriented MgO substrate
- epitaxially grown using reactive DC magnetron sputtering



G. Naik, et al PNAS (2014)

- 1st epitaxial single crystalline metal/semiconductor superlattice
- CMOS-compatible constituent materials

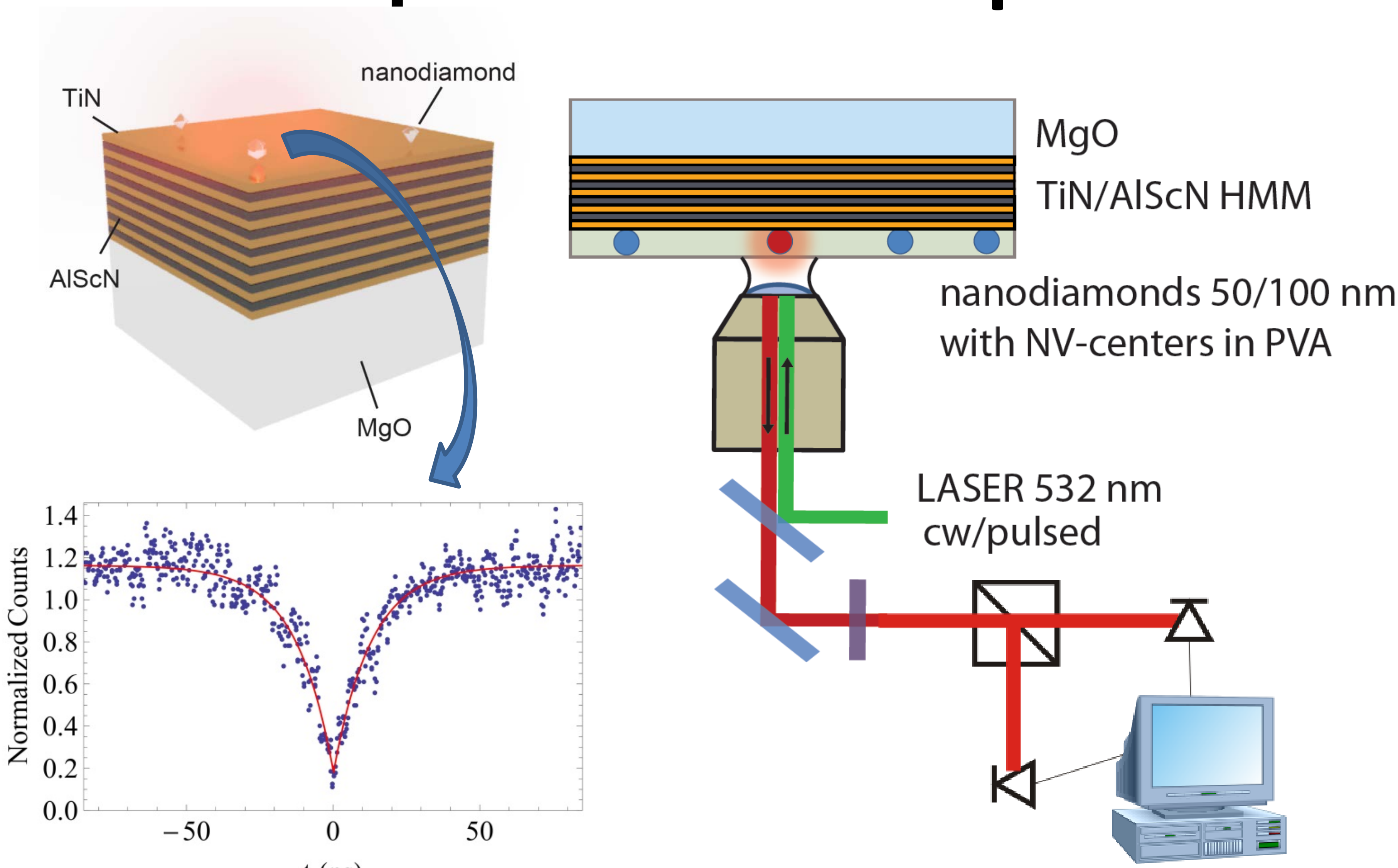
Key people in real experiment

+

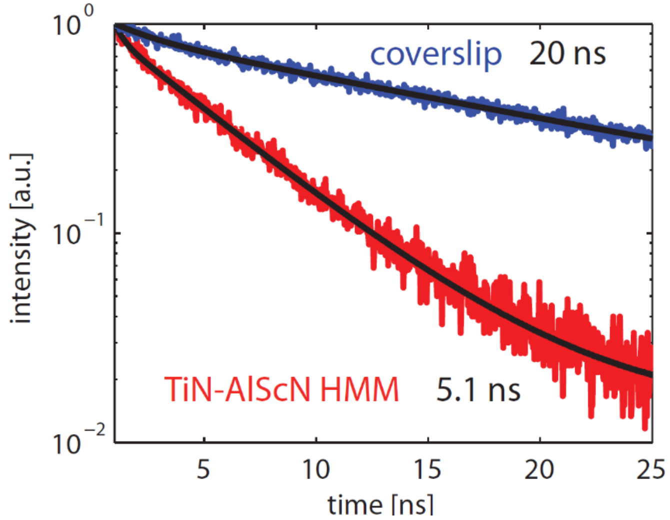
- Mikhail Shalaginov
- Sample fabrication/characterization & calculation

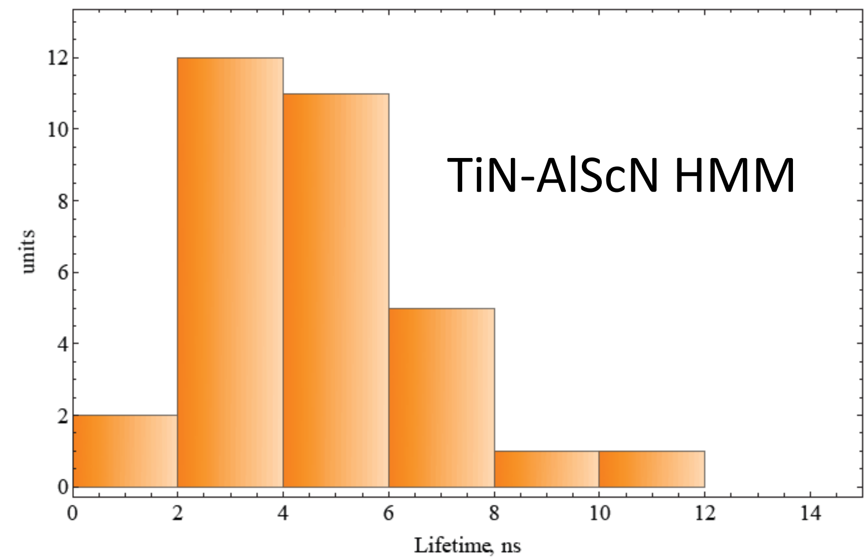
- Vadim Vorobiev
- Optical characterization

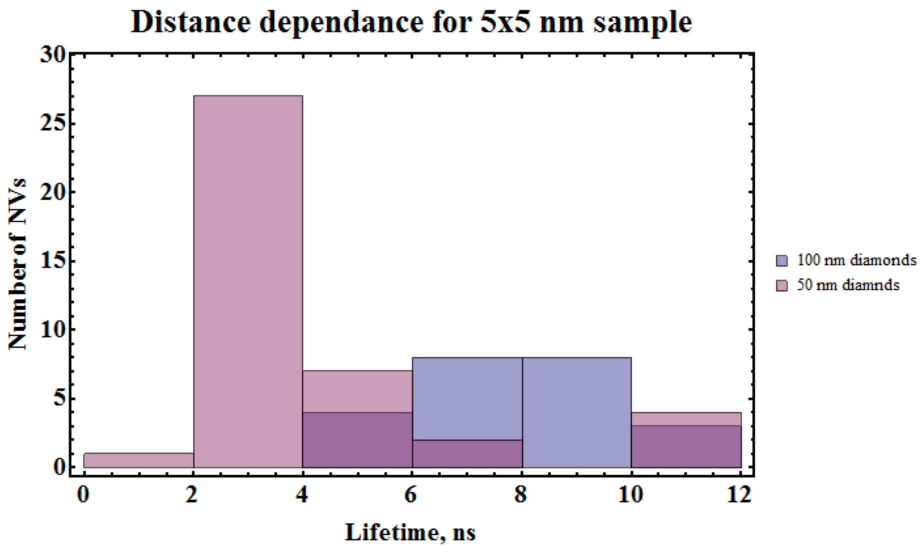
Experimental Setup



Experiment: modification of the lifetime





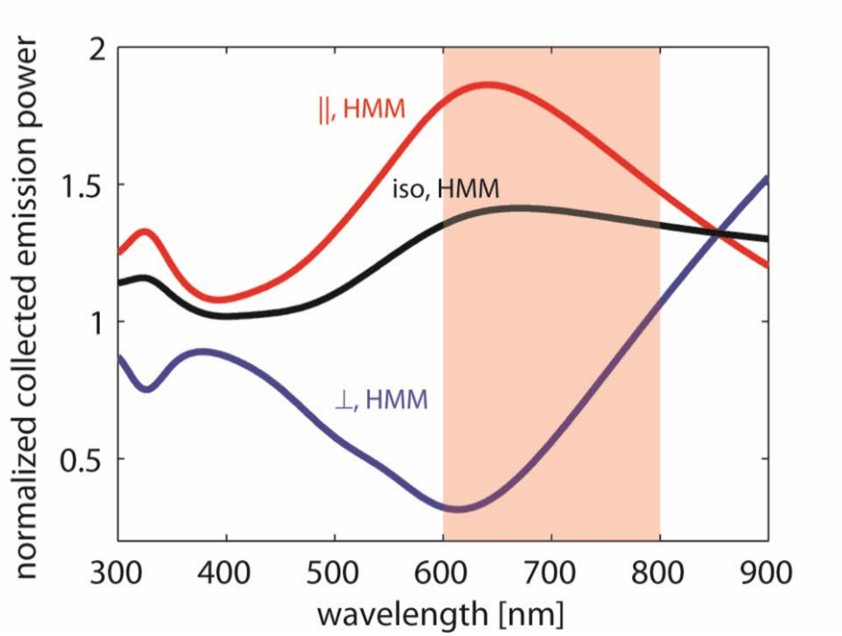


$\tau_{HMM} = (4.8 \pm 2)$ ns

$\tau_{coverslip} \approx 20$ ns

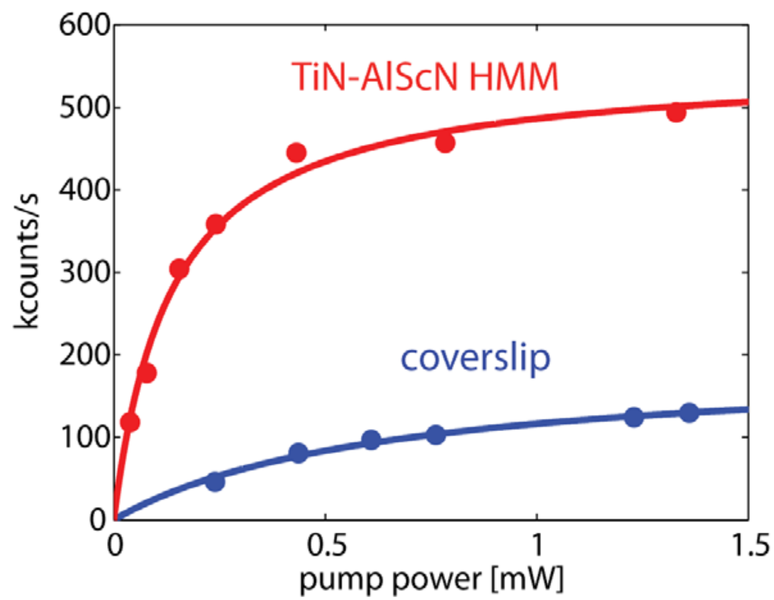
Measured Purcell factor ≈ 4.2

Collected emission enhancement



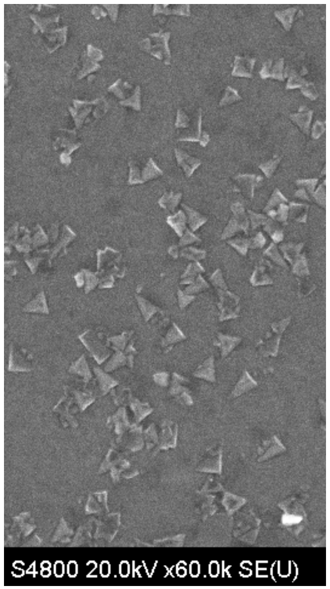
- Emission rate in free space is modified due Fresnel reflection
- Theoretical value of collected counts enhancement is 1.5

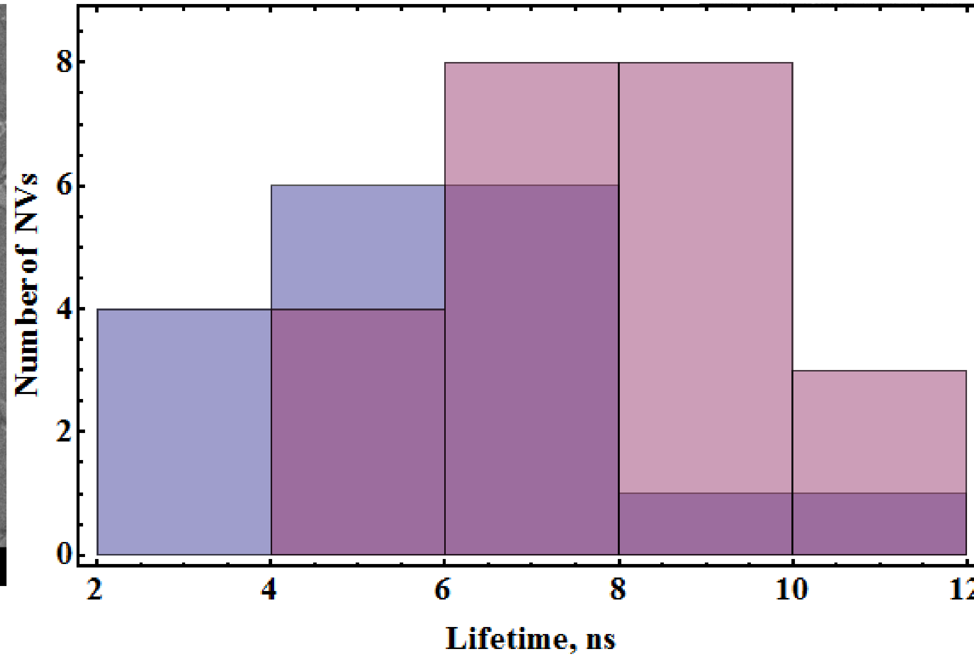
$$I = I_0 \frac{p}{p + p_0}$$

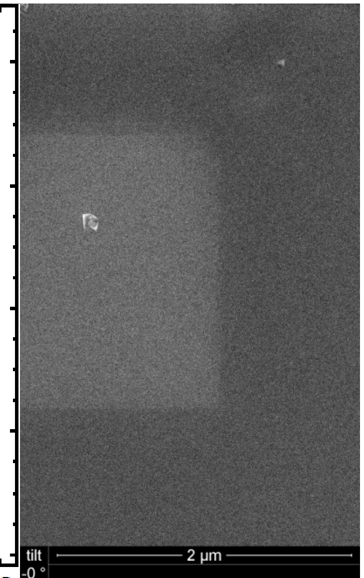


- Some of NV show 4-5 times more emission…

Quality of HMM







Sample with standard procedure

- Measured emission enhancement is around 5

Sample with new procedure:

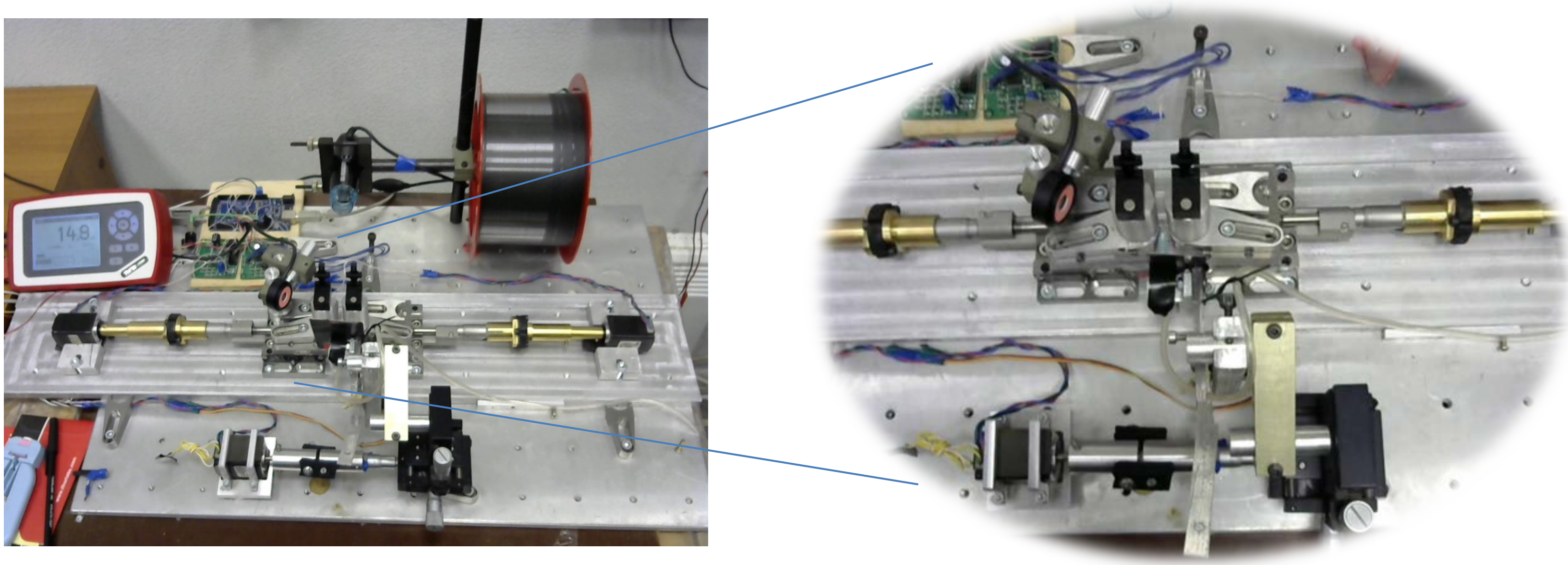
- Measured emission enhancement is around 2

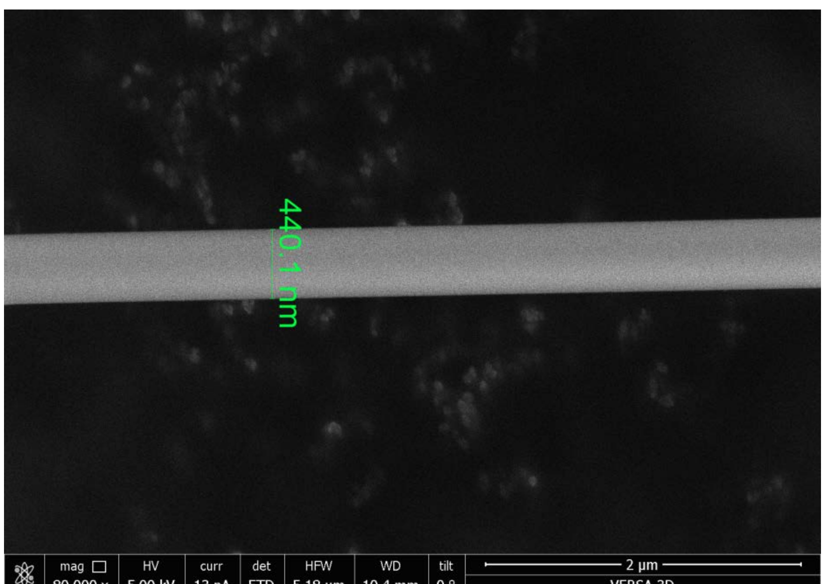
Defects act as a random antenna!

What next?

- Antenna can help convert HMM modes into light
- Integration with the fiber
  - Goal is to integrate with fiber NV, antenna, HMM
  - First step – place NV on the fiber

Fiber poling

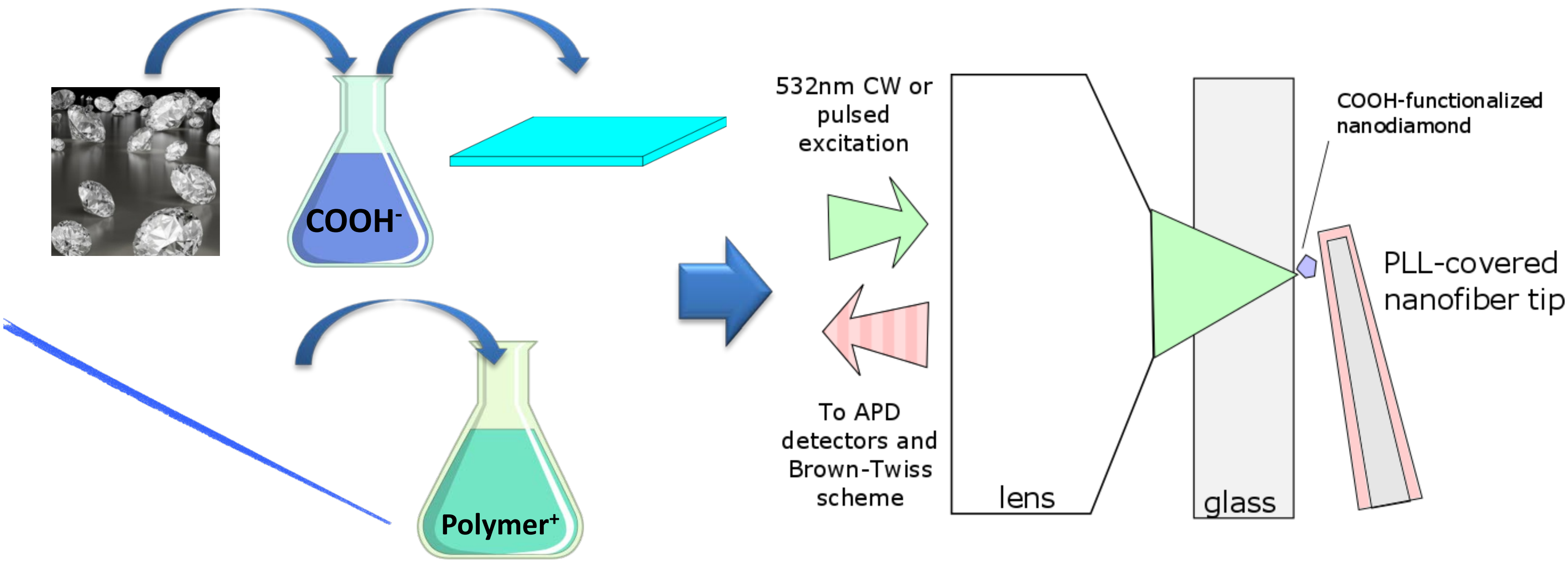




We can now reproducibly get:

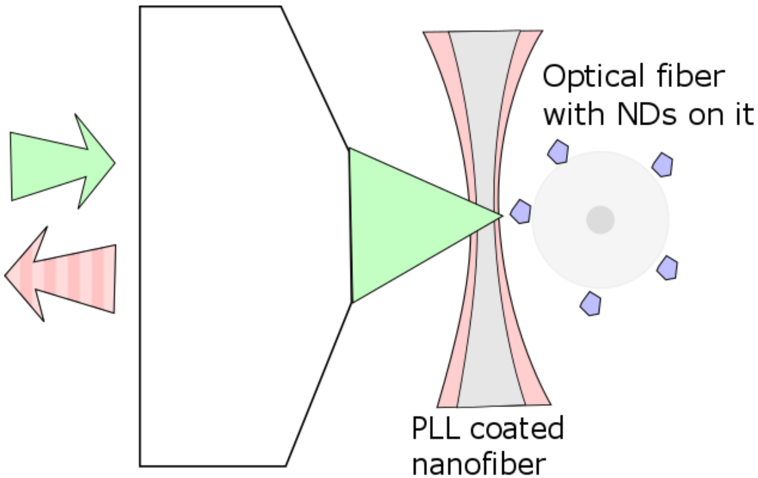
- ~440nm diameter
- ~90% transmission (dust dependent)

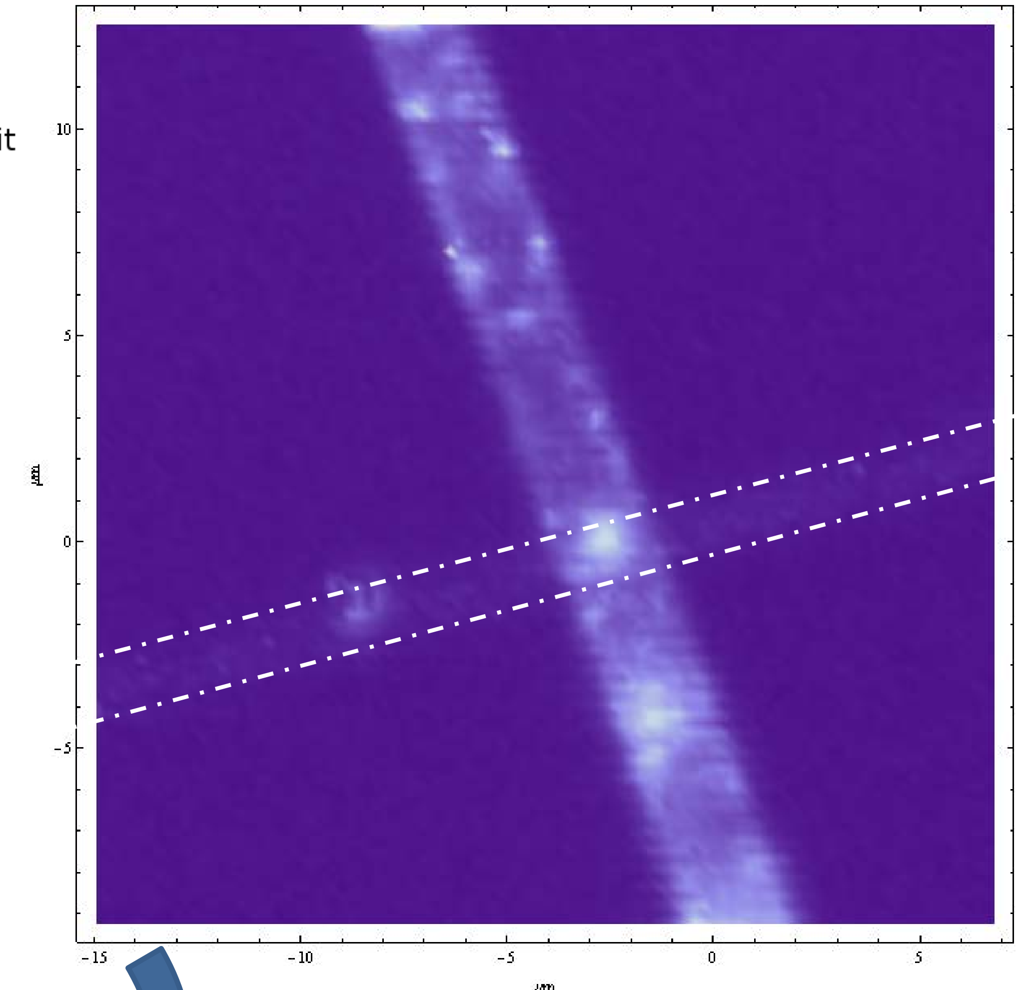
Placing nanodiamond on the fiber

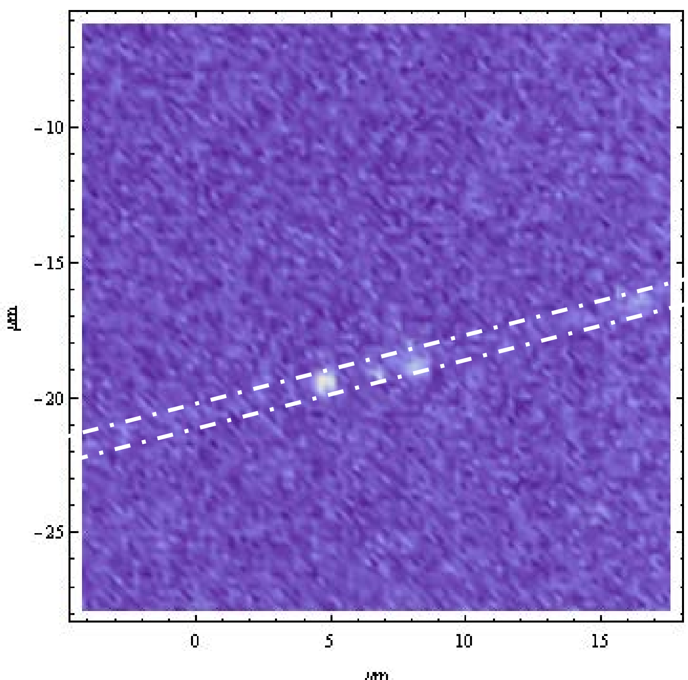


- Functionalize nanodiamond with – COOH group.
- Cover the target (nanofiber) with catione polymer(poly-l-lysyne).
- Pick-up under confocal microscope

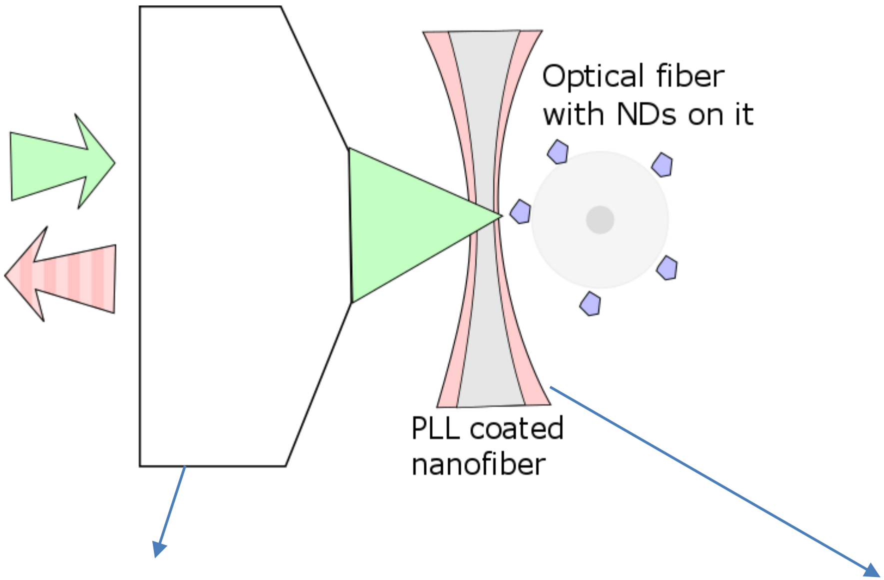
ND on the nanofiber waist



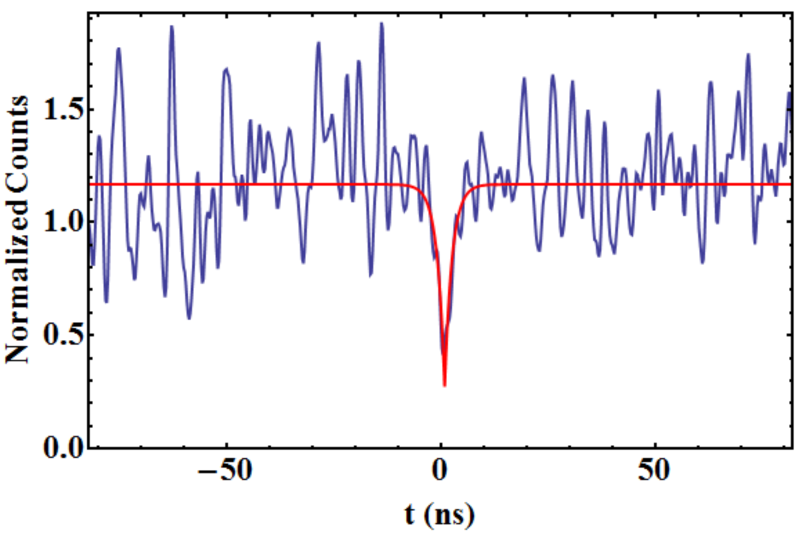


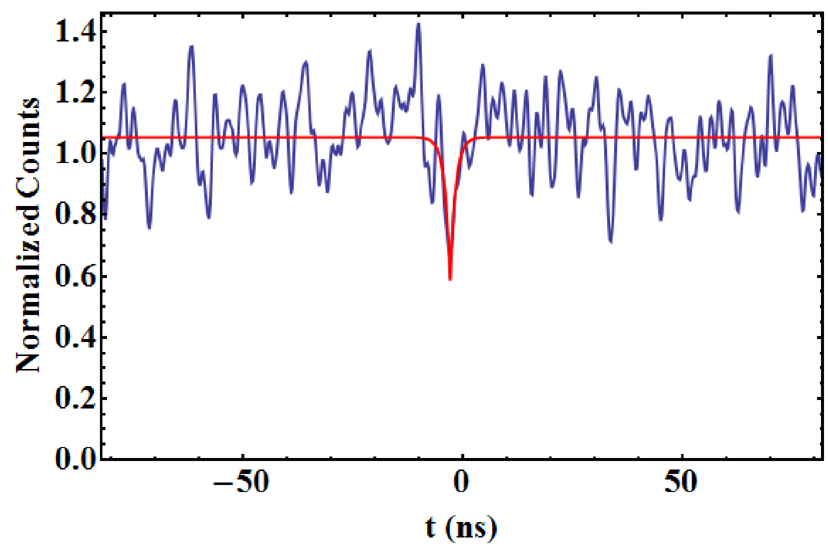


ND on the nanofiber waist

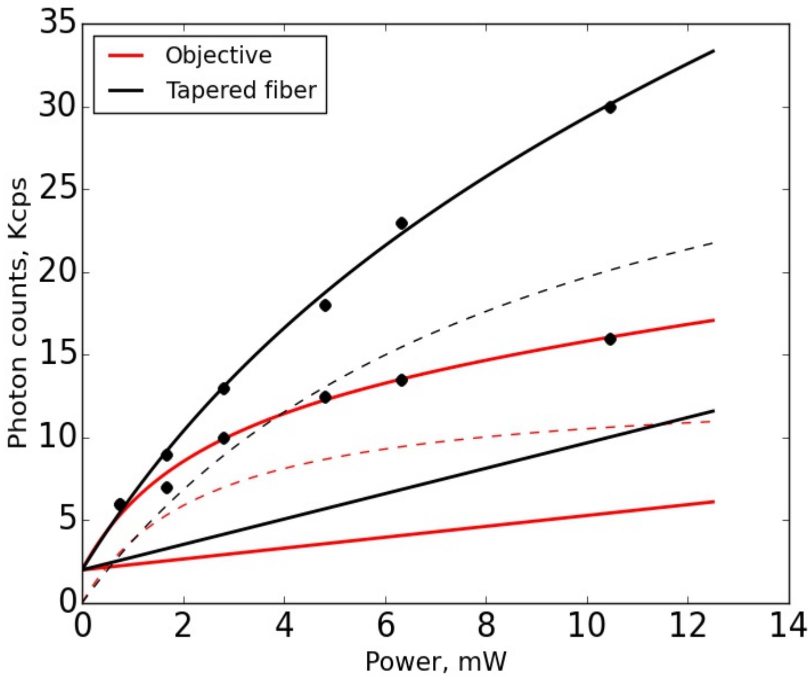


- Fiber could be used as substrate to pickup single NV center
- G2 registered via fiber end

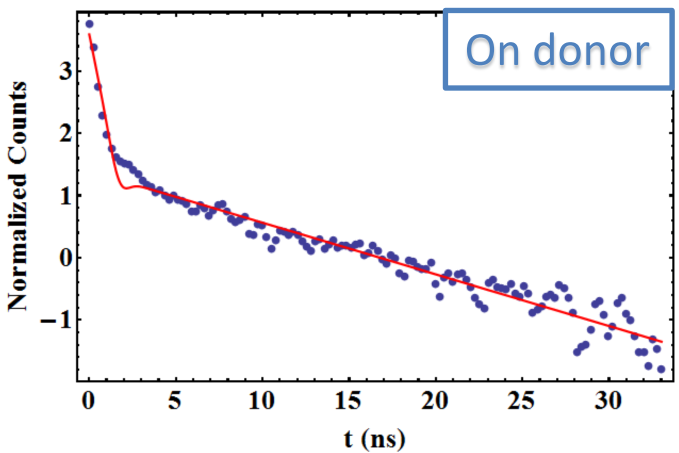


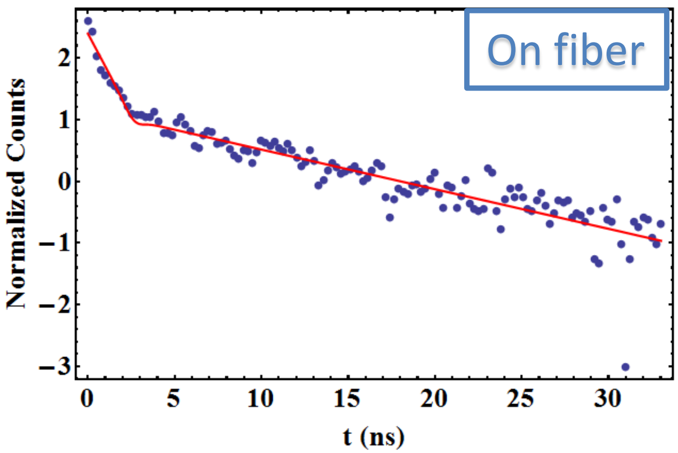


Number of counts



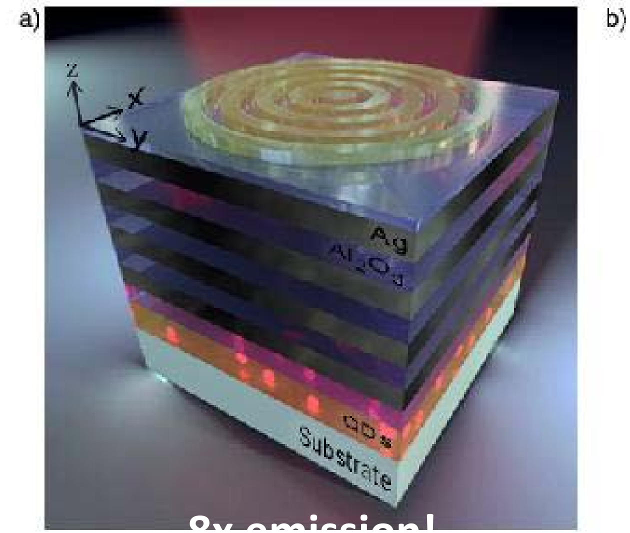
- **2X** more counts
- No modification of NV lifetime
- Losses on fiber connections are about 90% - may be improved
- Only one fiber end was used.



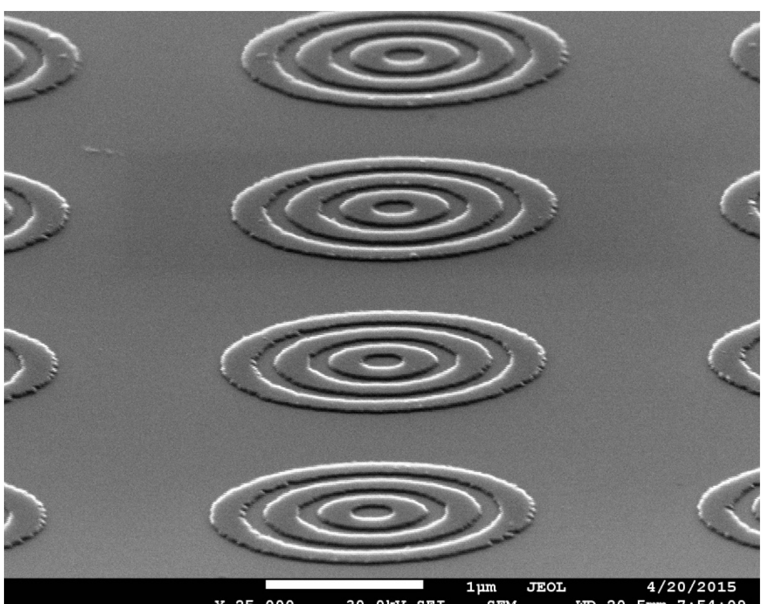


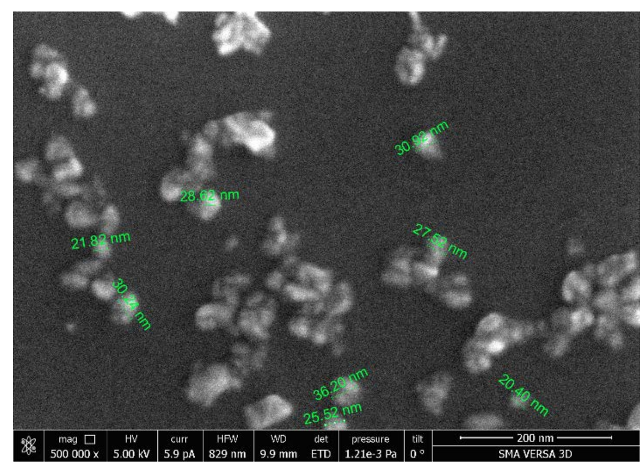
Outlook:

- Antenna can help convert HMM modes into light
- Smaller nano diamonds with nice NV concentration
- Integration with the fiber



Tal Galfsky, *et al.*, arXiv: 1404.1535





Team and collaborators

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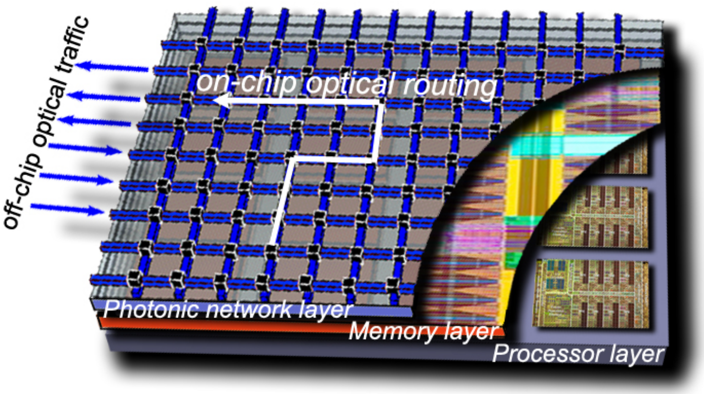
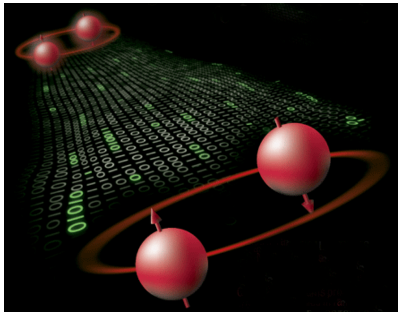
Misha Lukin
Hogkung Park
Marco Loncar

Integrated nanophotonics – next step in Information processing

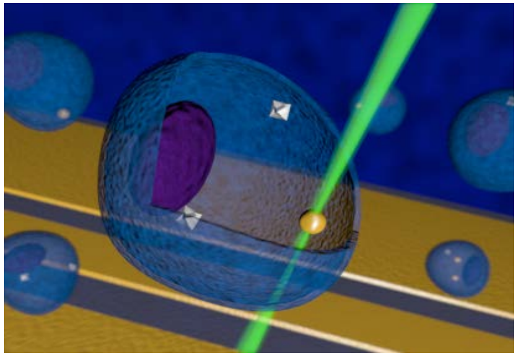
All optical computation



Quantum communication



Quantum sensing



NEW PLATFORMS ARE COMING!

Thank you for you attention!