Quantum Memories in Photon-Atomic-Solid State Systems (QuMPASS)

July 25, 2013

David Awschalom, Ania Jayich
University of California – Santa Barbara

Spin physics
Coherent dynamics

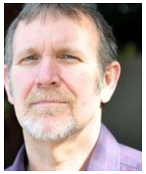
 

H. Jeff Kimble, Oskar Painter
California Institute of Technology

Atomic physics
Quantum optics

Evelyn Hu
Harvard University

Nanofabrication

Ray Beausoleil, Charles Santori
HP Laboratories

Optical networks

Slava Doborovitski
Ames Laboratory/Iowa State University

Quantum control

Michael E. Flatté
University of Iowa

Electronic structure

Nanophotonics, Cavity QED

MURI Concept & Approach

Integration of atomic and solid state systems

trapped atoms

...ic Goals for a Hybrid Quantum Memory S...

- Quantum memories that efficiently couple and store quantum states of light in material systems consisting of ensembles of cold atoms and/or diamond/SiC color centers
- ...ip" quantum connectivity for the quantum m... ...otons over integrated optical networks
- Single photon frequency conversion for interfacing atom and color center quantum elements.
- Fundamentally new toolkit for studying atomic physics with light.
- ...o control dynamics and interactions of ato... ...n eye towards functional quantum optical c...

Chip-scale atom trapping

Single photon frequency conversion

Mitigate decoherence

Tune spin-photon coupling

Integrate single spins 'on demand'

Fabricate high-Q diamond & SiC cavities

University of California Santa Barbara

IOWA STATE UNIVERSITY

THE UNIVERSITY OF IOWA

LABS hp

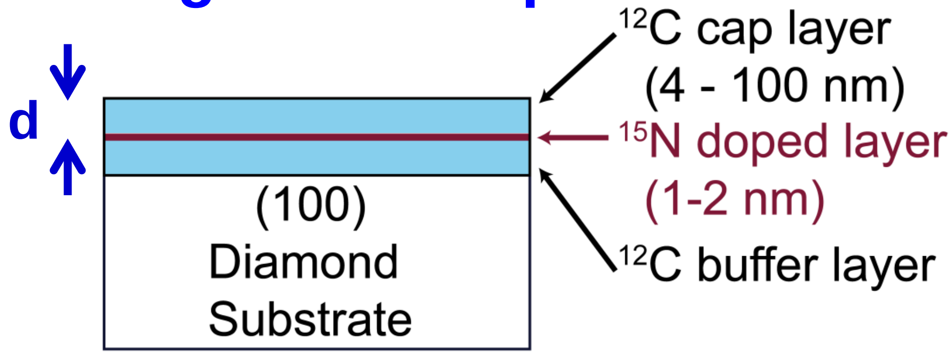
Cast of Characters

Institution	Qualifications	PD	GS
UC-Santa Barbara			
 David Awschalom	Professor of Physics. Expertise: spin dynamics and coherence in semiconductor quantum structures, nanophotonics and magnetics, solid state quantum information processing. Member NAS, NAE.	2	4
 Ania Jayich	Asst. professor of Physics. Expertise: nanoscale imaging of spin and charge, quantum computing, nanofabricating hybrid quantum systems of spins, phonons, photons. PECASE, AFOSR YIA	1	3
Caltech			
 H. Jeff Kimble	Professor of Physics. Expertise: quantum information, quantum dynamics of open systems, quantum measurement, cavity QED, realization of quantum networks. Member NAS.	3	5
 Oskar Painter	Professor of Applied Physics. Expertise: nanofabrication, semiconductor cavity QED, cavity optomechanics, integrated atomic and photonic systems at the nanoscale.	1	3

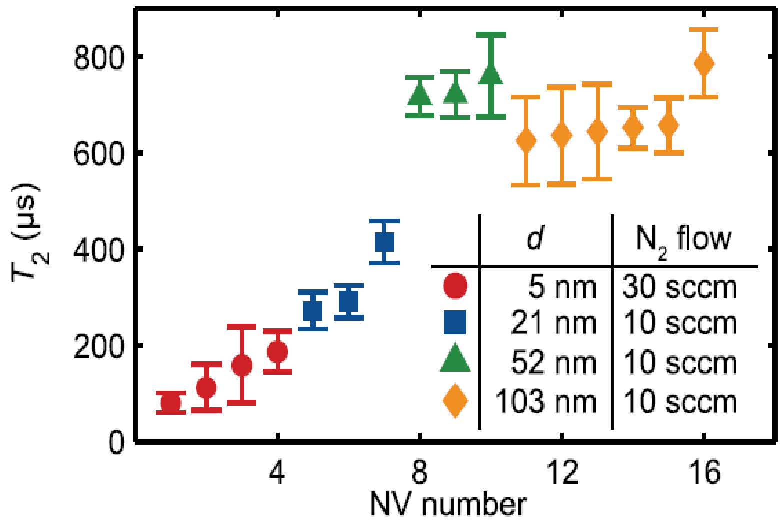
Cast of Characters

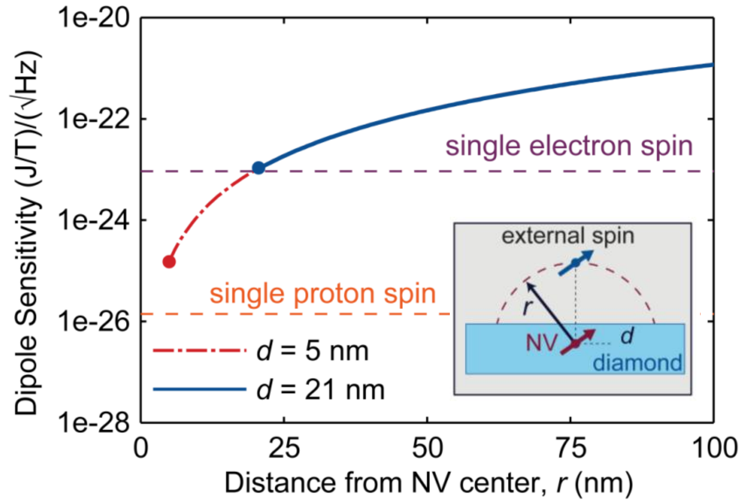
Institution	Qualifications	PD	GS
Harvard  Evelyn Hu	Professor of Applied Physics. Expertise: optical and electronic behavior in nanoengineered materials. Cavity QED in semiconductors, photonics in dielectric and metal cavities. Member NAS, NAE.	1	2
Ames Lab/Iowa State  Slava Dobrovitski	Scientist I. Expertise: Quantum non-equililbrium dynamics and decoherence in many-spin systems, quantum control of electronic and nuclear spins in solids, spins in semiconductors, spin impurities in diamond and silicon.	1	0
University of Iowa  Michael Flatte	Professor of Physics. Expertise: spin dynamics in semiconductors and metals, carrier dynamics in narrow-gap semiconductor superlattices, single-dopant properties in semiconductors, solid state quantum computation. Fellow AAAS, APS.	0	2
Student and faculty exchanges occurring across all institutions	**TOTAL**	**9**	**19**

Engineering shallow spins with N delta-doping



- ^{15}N delta-doped layer (1-2 nm thick) defines depth of NV
- Doped NV has nm-scale depth dispersion (σ < 4 nm), isotopic control





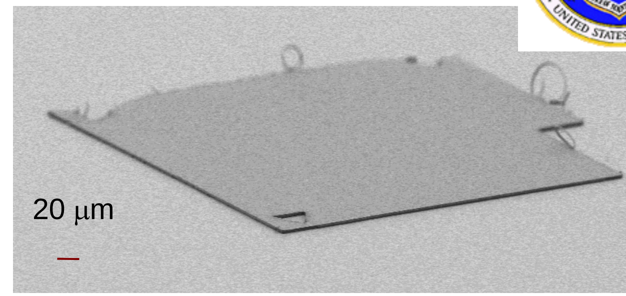
- Long and reproducible spin coherence
- T_2 > 100 μs d = 5 nm, > 800 μs 50 nm

- Single electron (proton) spin coupling possible by 1 sec (1 min) averaging

K. Ohno *et al*., *Appl. Phys. Lett*. **101**, 082413 (2012)

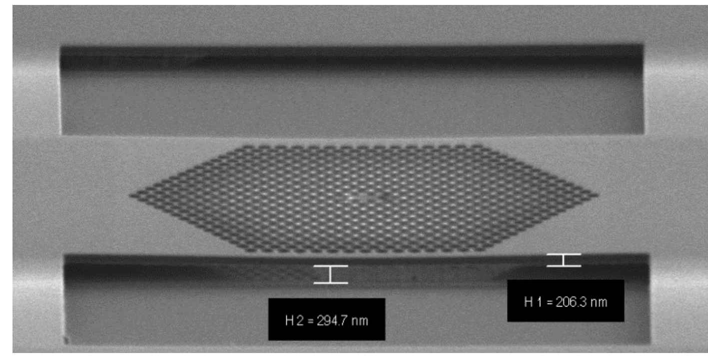
Diamond thin film photonics

Fabrication of high quality single crystal diamond films ~ 100 nm thick as building blocks for optical cavities with delta-doping

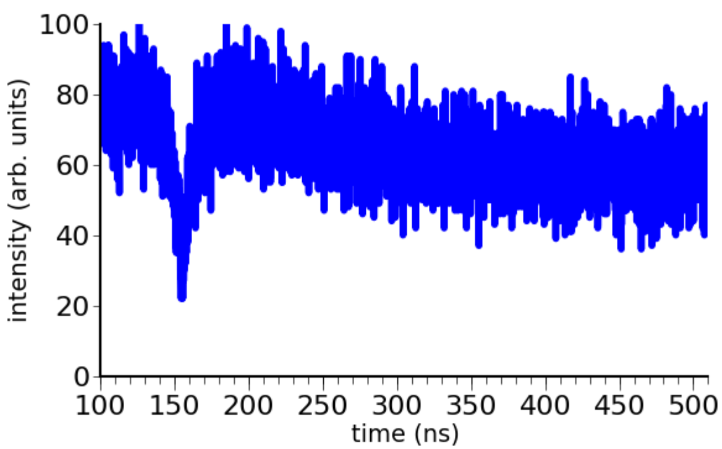


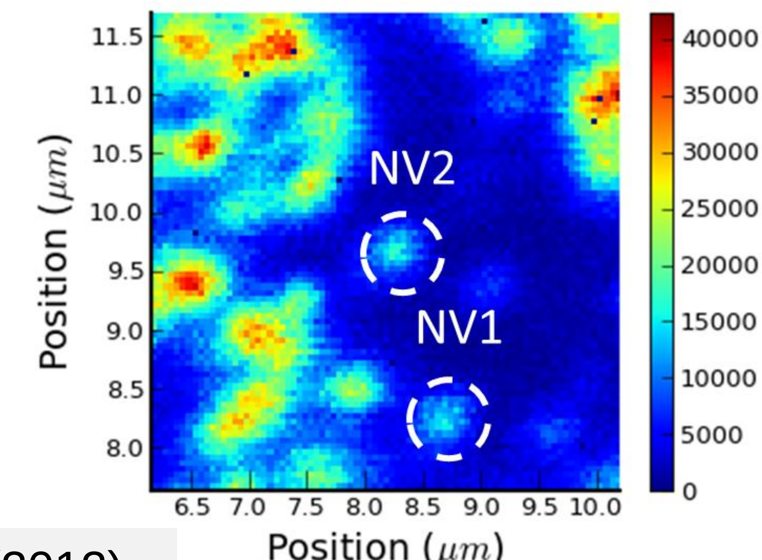
Formation of optically-isolated photonic cavities

- Stamp onto PMMA and subsequent removal of PMMA to form undercut cavities.



Doped diamond membranes: mapping and single spin design



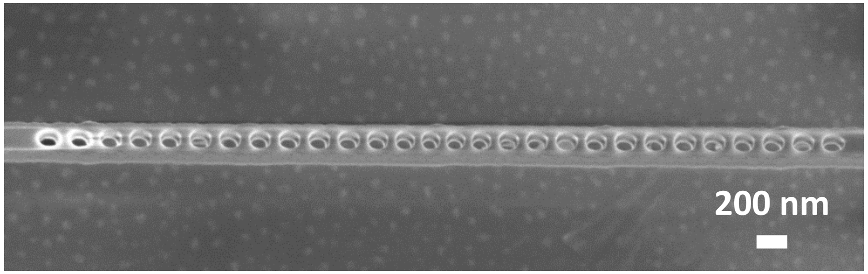


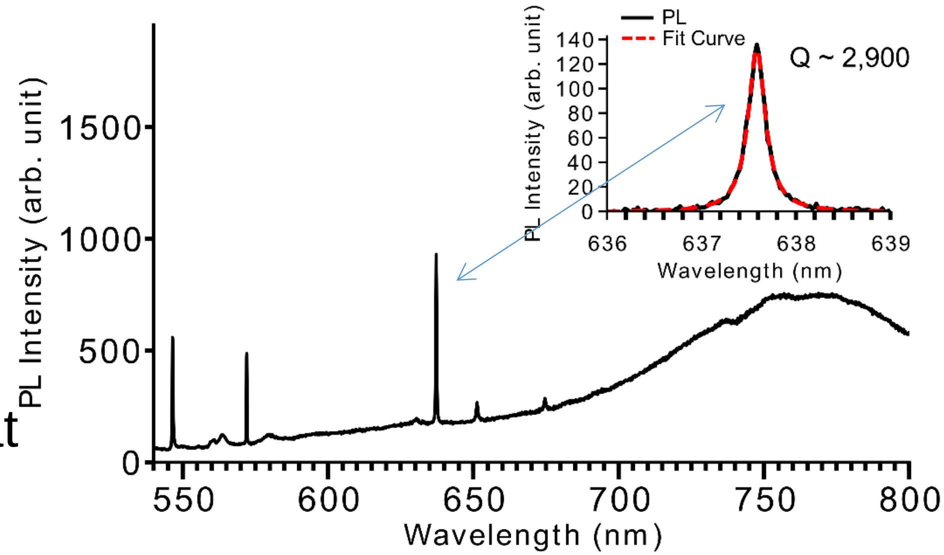
I. Aharonovich *et al*., *Adv. Mater*. **24**, OP54–OP59 (2012)

Diamond thin film photonics

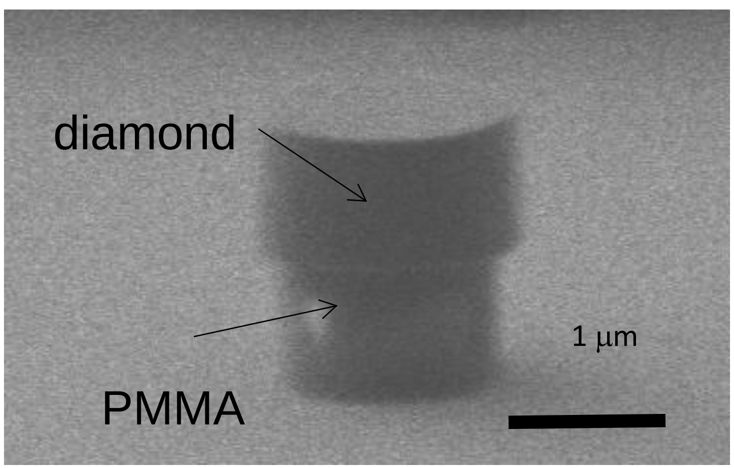
High Q's with the possibility of deterministic coupling

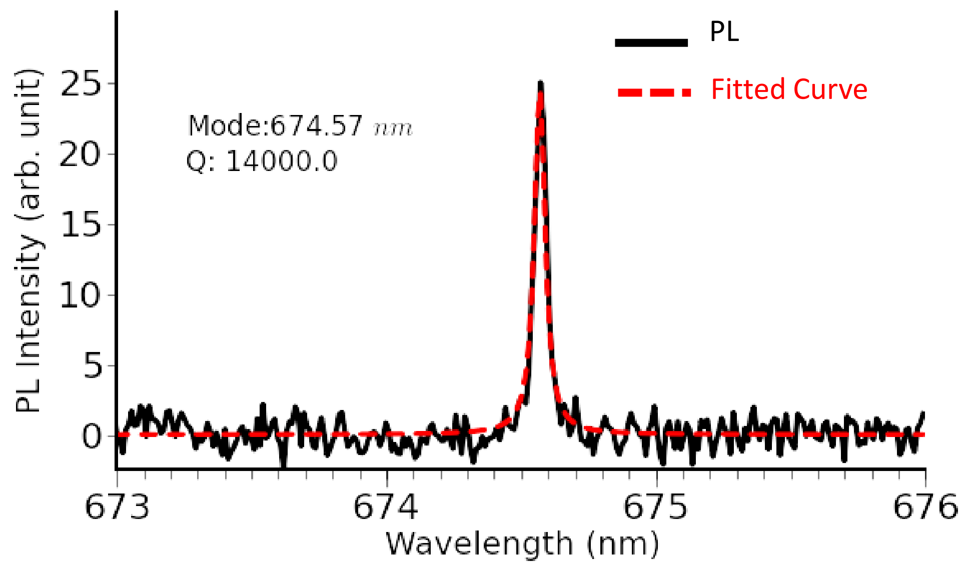
Photonic Crystal Nanobridge





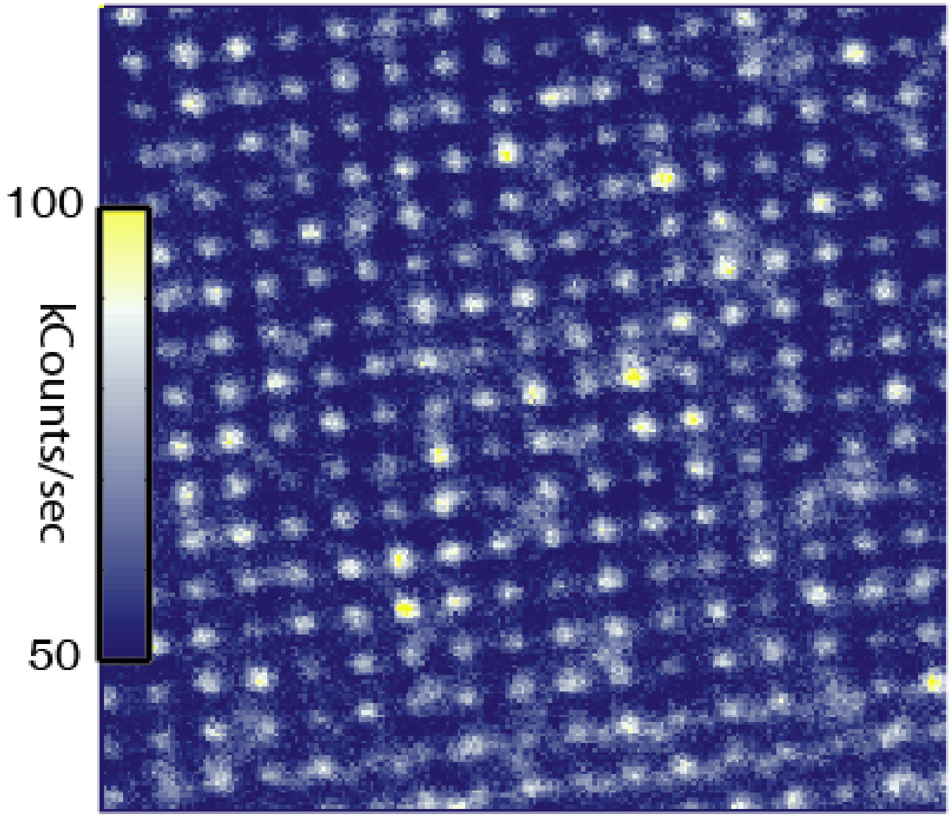
Cavity Q ~ 3,000 and V ~ 0.46 $(\lambda/n)^3$ at 637.6 nm was observed



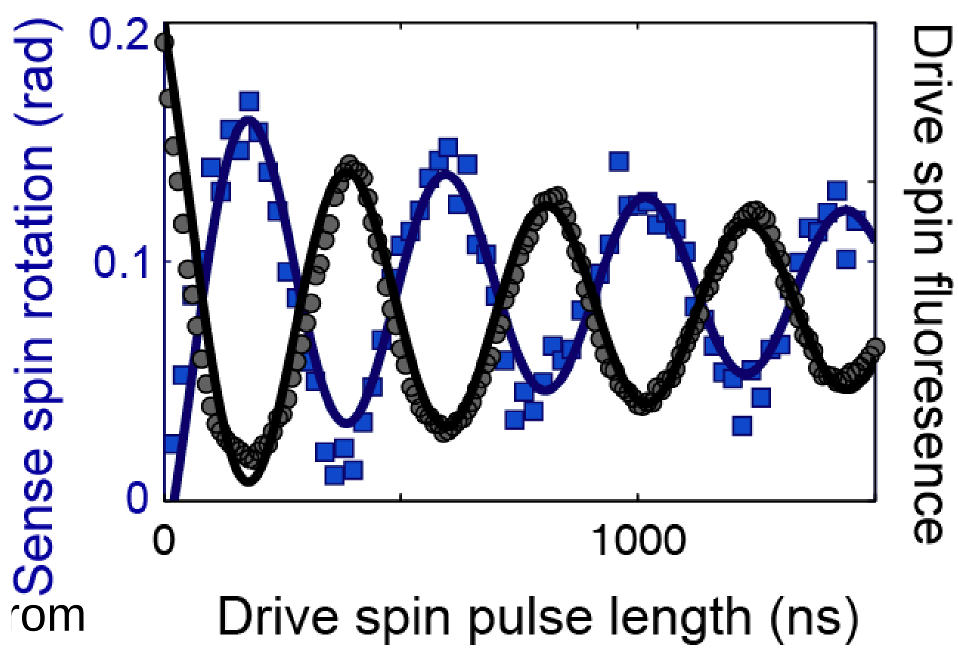


Cavity Q ~ 14,000!

Designing quantum states & spin interactions



Double electron-electron resonance: 6H data

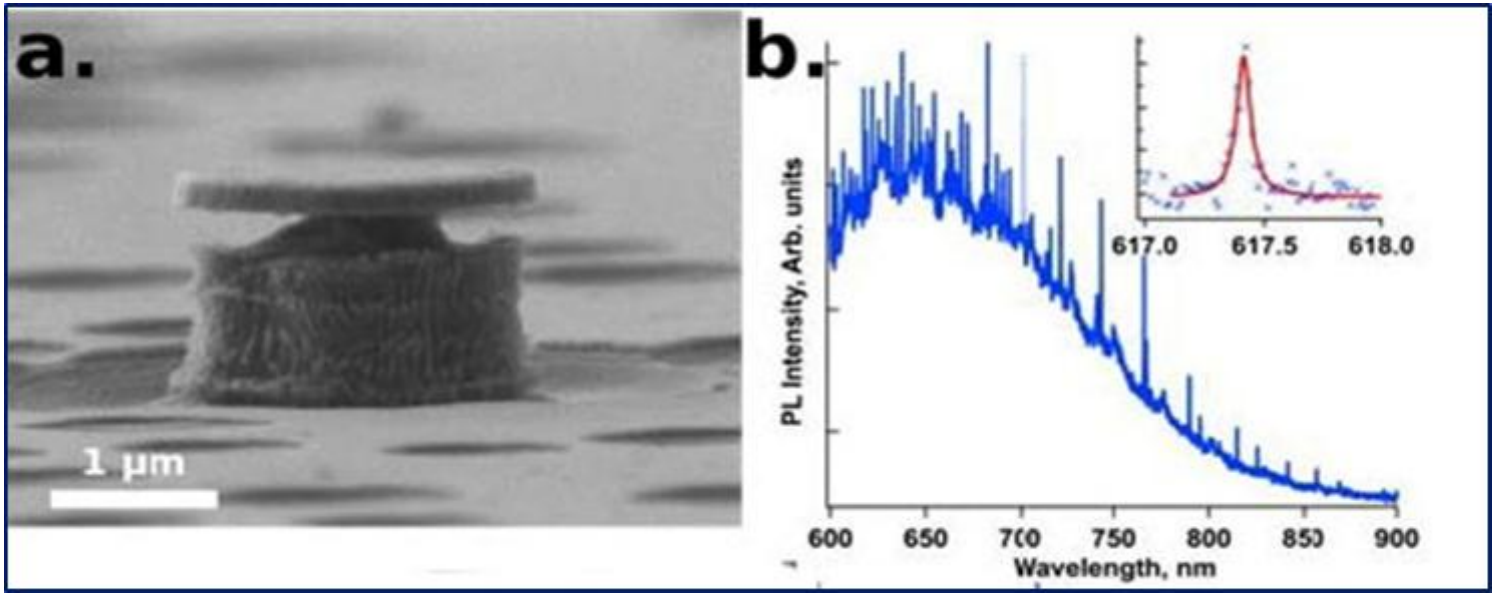


- Magnetic dipole coupling between inequivalent spins are observed
- Interacting yet separately addressable quantum states
- Coherent and incoherent interaction components are distinguished.

A.L. Falk *et al.*, *Nature Comm.* **4**, 1819 (2013)

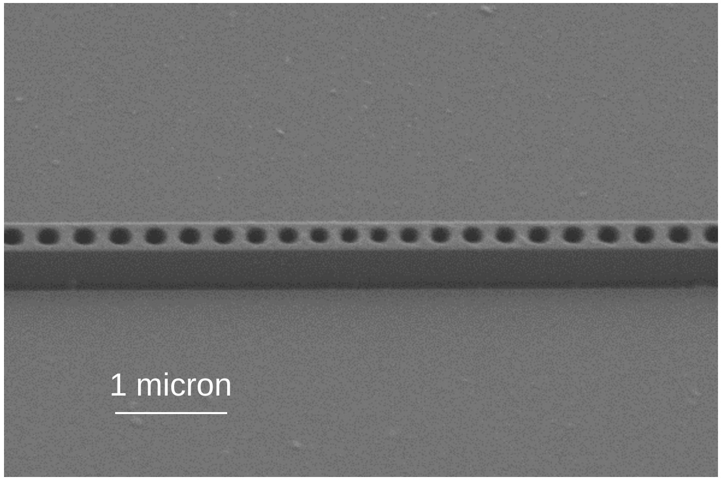
SiC thin film photonics

SiC microdisk Q>9200 (our instrumental resolution)



High Q derived from selective wet chemical etch on an all-SiC substrate

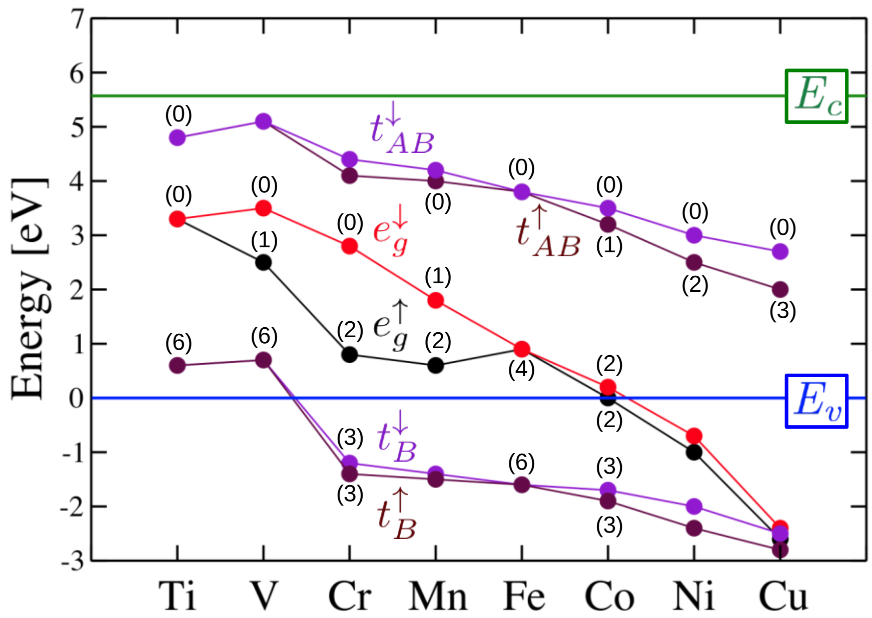
Dry etch procedures for high resolution SiC structures established



Novel spin centers in diamond

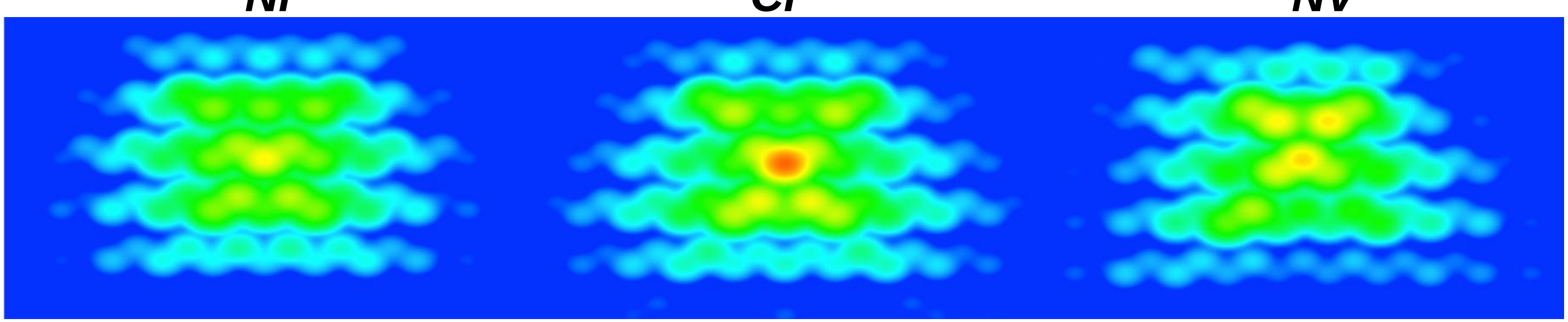
Are there other centers for improved spin manipulation or memory?

- Use spin-orbit interaction for spin manipulation with electric fields
- Internal degrees of freedom more isolated from the lattice (d levels)
- Strong possibilities for photon-spin entanglement through Faraday rotation



Calculation of the wave function of the spin centers – more spread out than DFT suggests…

Ni ***Cr*** ***NV***



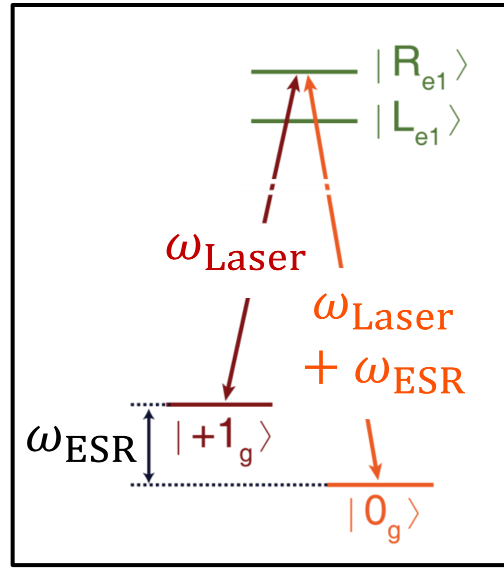
More spread than NV ***More localized than NV***

T. Chanier et al., *Phys. Rev*. B **86**, 085203 (2012)

Full photonic control of a single spin

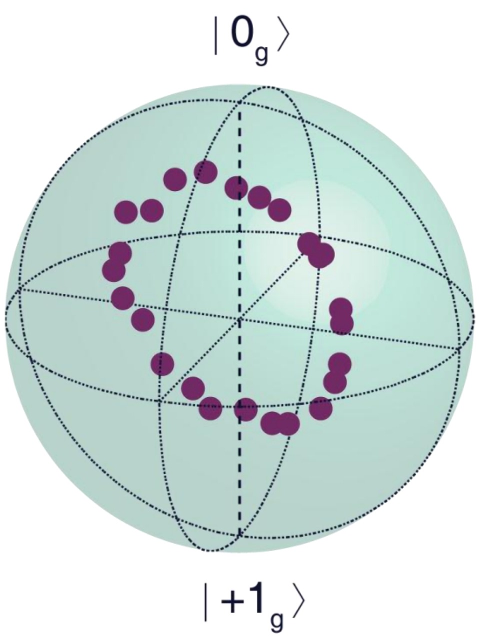
- coherent all-optical control of individual electron spins
- borrow atomic physics technique: use lambda system dynamics
- coherent population trapping with spins
- applicable to many defects in semiconductors

Λ system in NV c

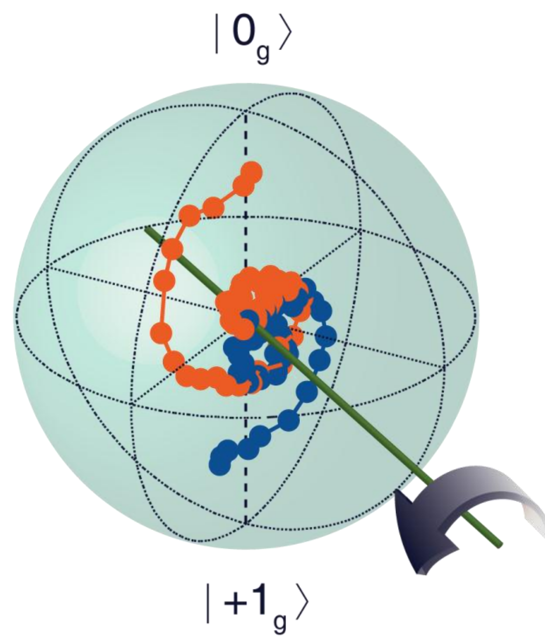


Demonstrate set of control schemes along arbitrary bases:

Initialization and Readout: Coherent Population Trapping



Unitary Rotation: Stimulated Raman Transitions



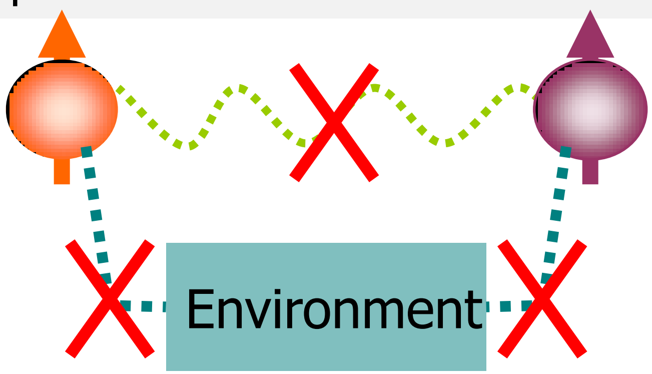
- ➢ Time-domain control of single spins via light
- ➢ Techniques enable investigation of new solid-state qubits

C.G. Yale, B.B. Buckley, *et al.*, *Proc. Natl. Acad. Sci.* **110**, 7595 (2013)

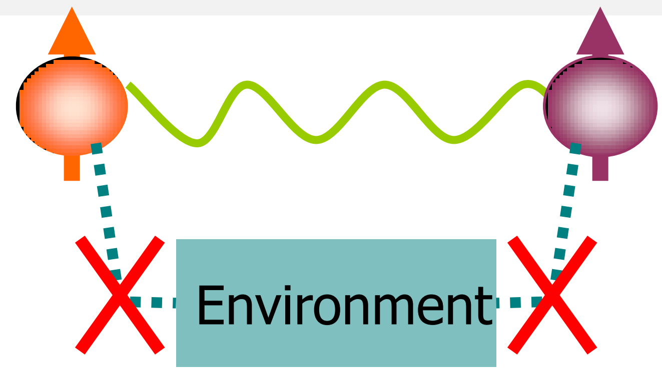
Quantum dynamics and coherence protection

- Model and optimize dynamics of spins and coupling to photons
- Exact simulations: time-dependent Schrodinger eqn (<30 spins, $10^9 \times 10^9$ Hilbert space)
- Approximate simulations – modeling < 10^4 spins

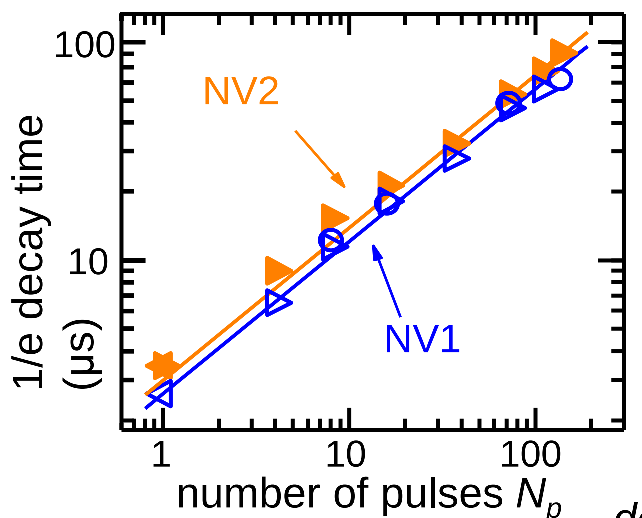
Suppress decoherence from environment



Protected memory:
isolate qubits



Protected quantum interface:
isolate environment,
preserve coupling between qubits



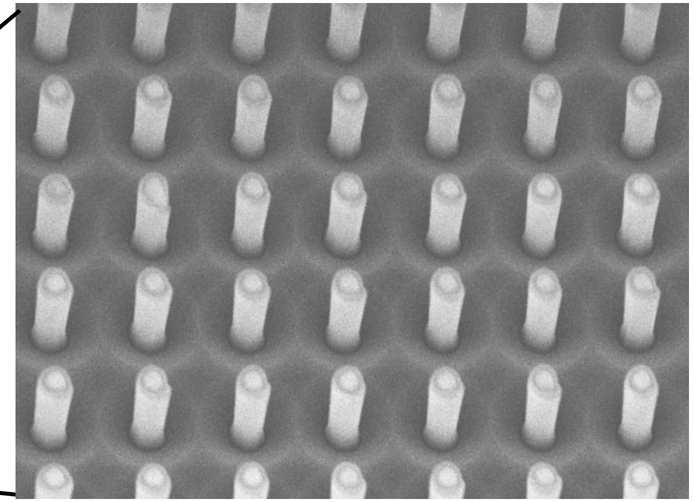
Quantum control
Using time-dependent magnetic field
and/or optical pulses
to ensure desired evolution of the system

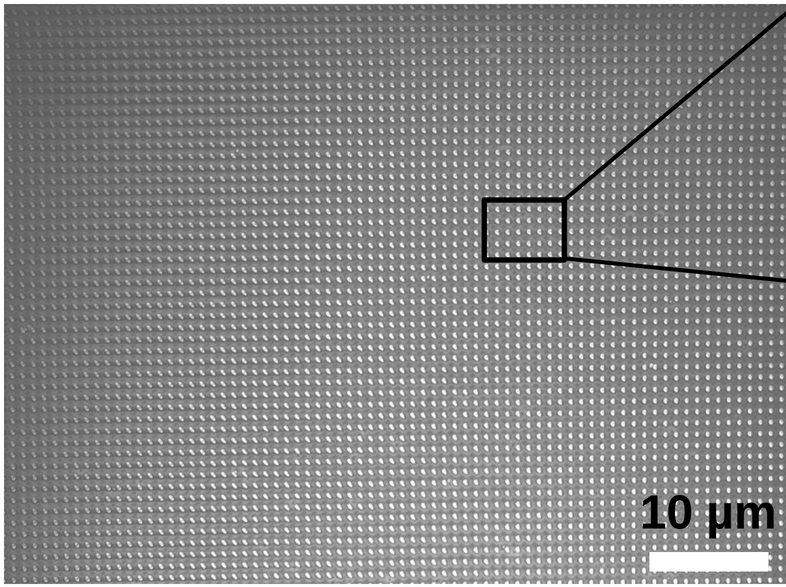
de Lange et al., Science **330**, 60 (2010)

Large area arrays of single crystal posts

Large-area arrays, high uniformity
Up to 3 microns long, 100 nm diameter

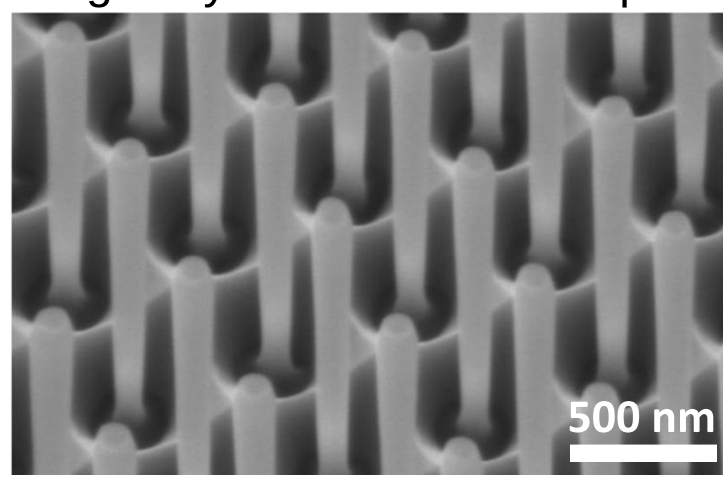
300 nm diameter, 1 µm long singl crystal diamond nanoposts



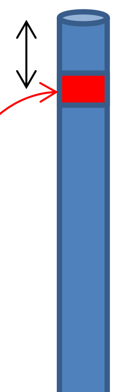


Part of a 3 mm X 3 mm patterned diamond

100 nm diameter, 1 µm long single crystal diamond nanoposts

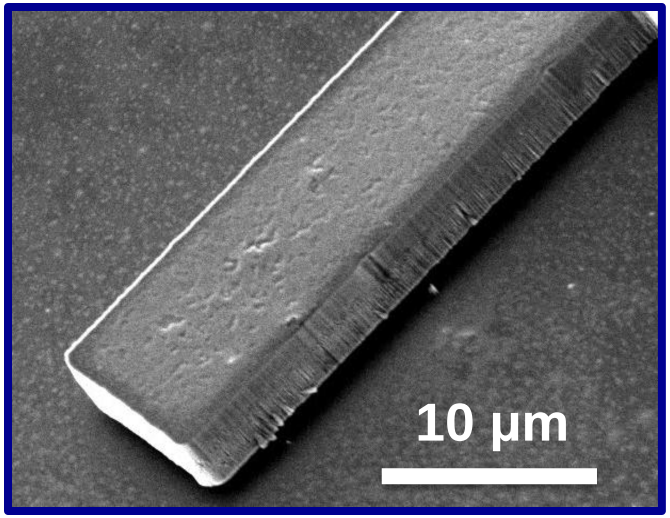


Probes with integrated spins for imaging hybrid structures

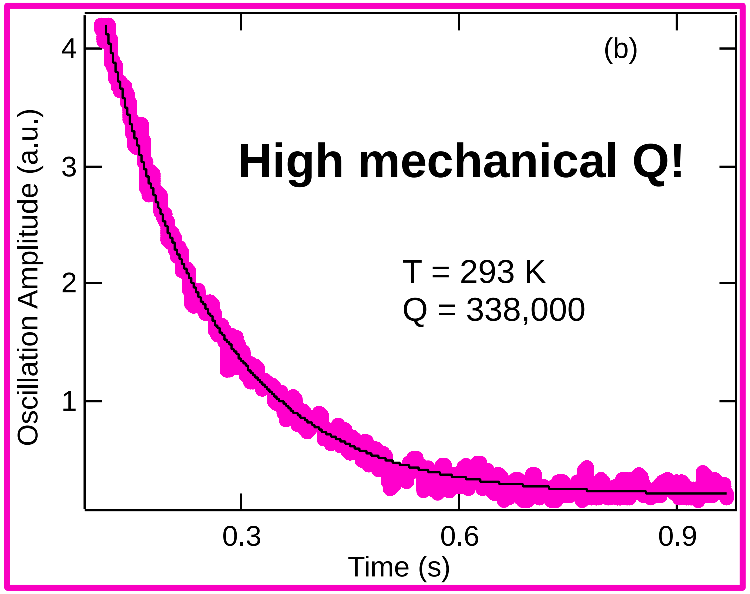


Single-crystal diamond cantilevers

Suspended cantilever

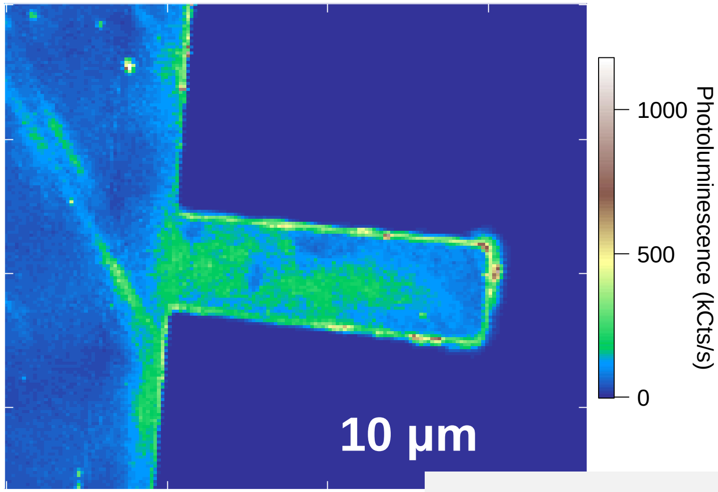


Cantilever ringdown measurement

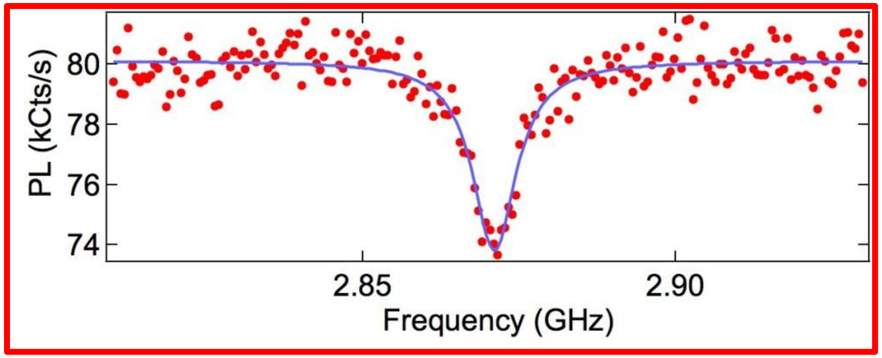


Ovartchaiyapong *et al*, *APL* 101, 163505 (2012)

Confocal image of cantilever

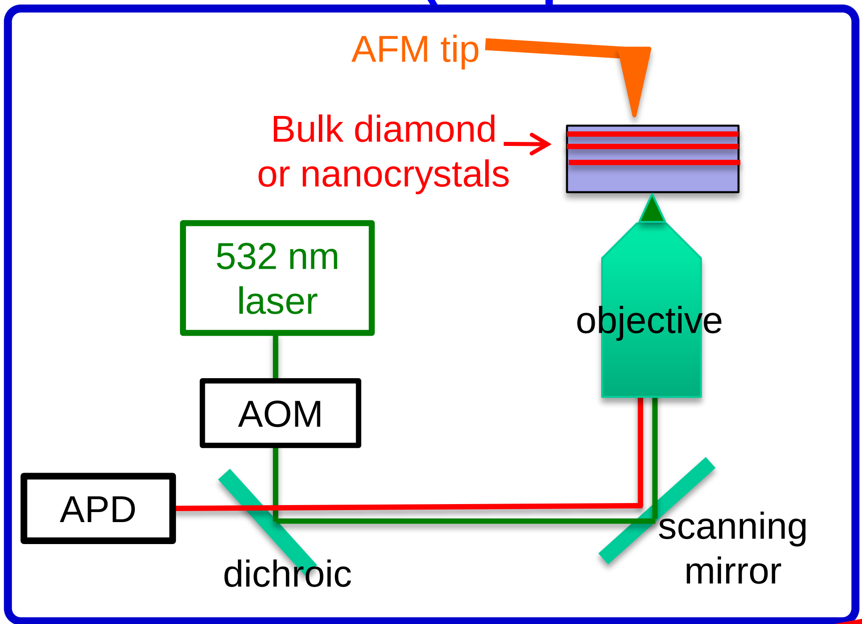


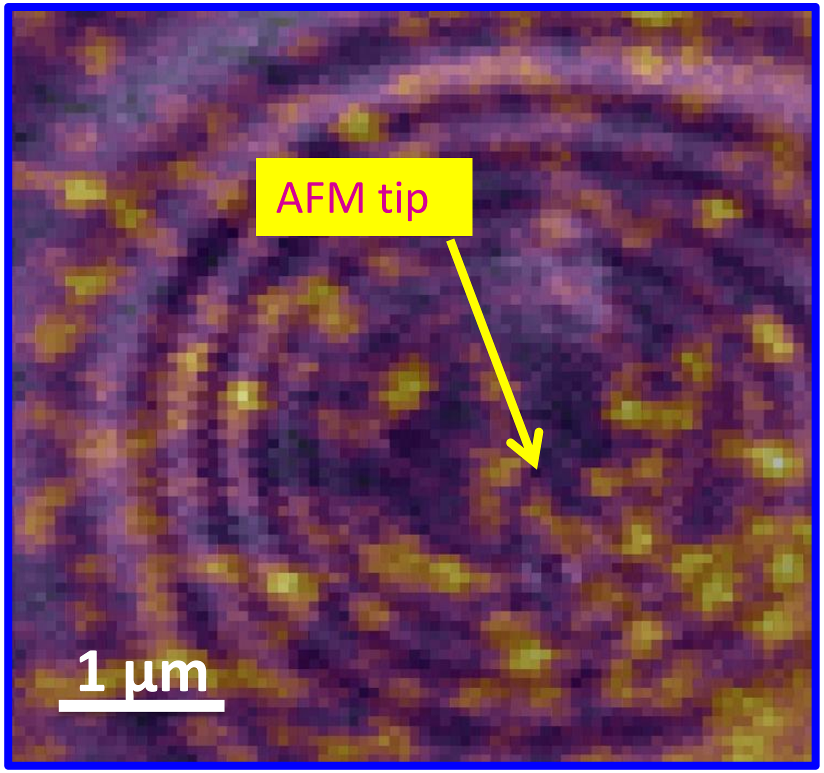
ESR spectrum of NV in cantilever



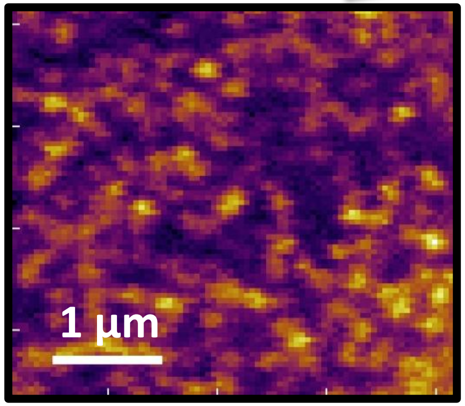
P. Ovartchaiyapong *et al*., *Appl. Phys. Lett*. **101**,163505 (2012)

Combined AFM/confocal setup
(Couple & scan NV centers on tip to PCs)

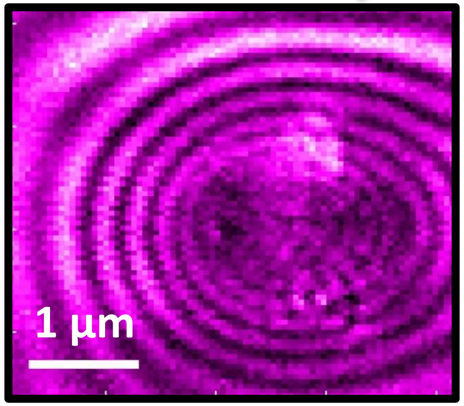




Overlaid image: confocal image of AFM tip over diamond NV's

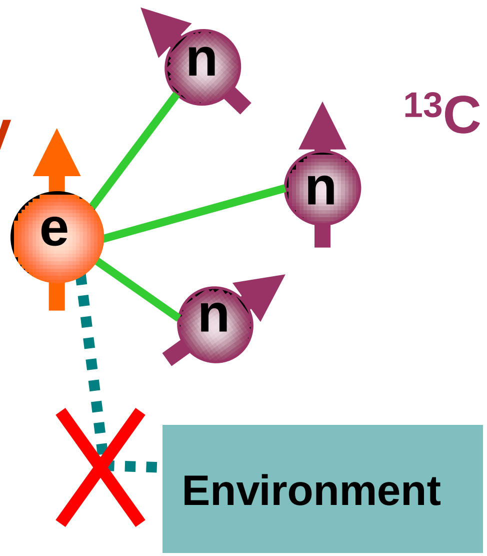


Fluorescence image of NV centers



Reflectance image of AFM tip

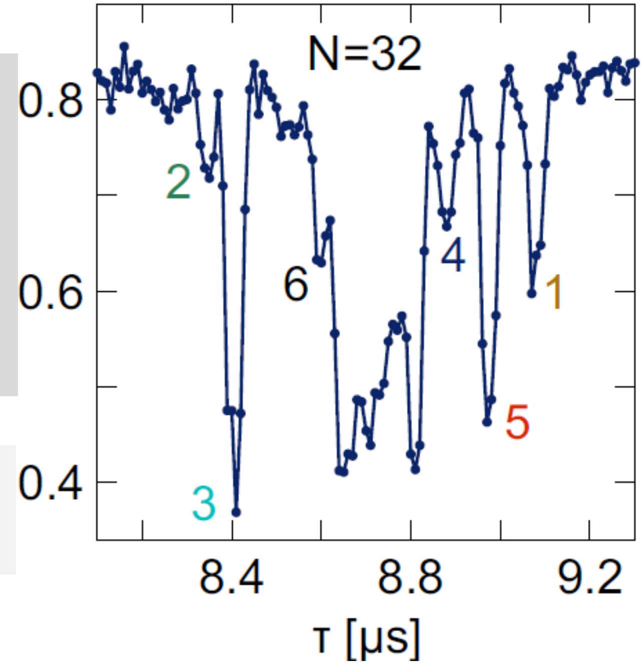
Medium-scale decoherence-protected quantum registers



Apply resonant decoupling idea to:

- identify ^{13}C nuclei, weakly coupled, suitable for quantum register
- perform individual electron-nuclear quantum gate on each pair,
- combine them to achieve fully operational register

Use nuclear spins as a local memory
- Identified six ^{13}C nuclear spins, 0.5-1 nm from NV center, couplings 20-80 kHz
- Demonstrated robust e-n operations on independent addressed spin pairs

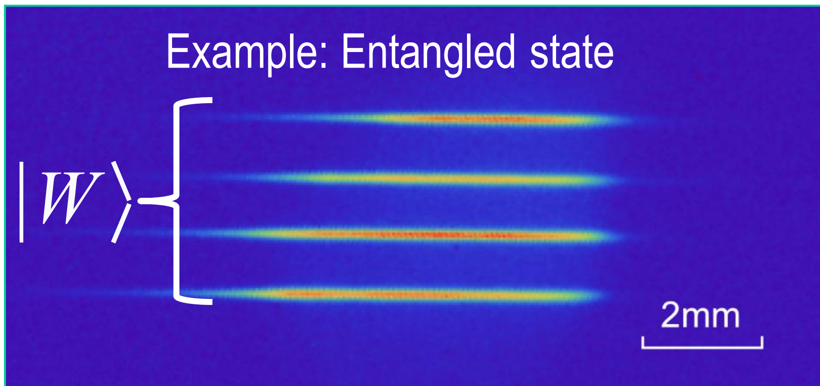


T. H. Taminiau et al, *Phys. Rev. Lett*. **109**, 137602 (2012) [Editor's suggestion], also highlight in Science 338, 173 (2012)

Atomic quantum memories in nanoscale optical circuits

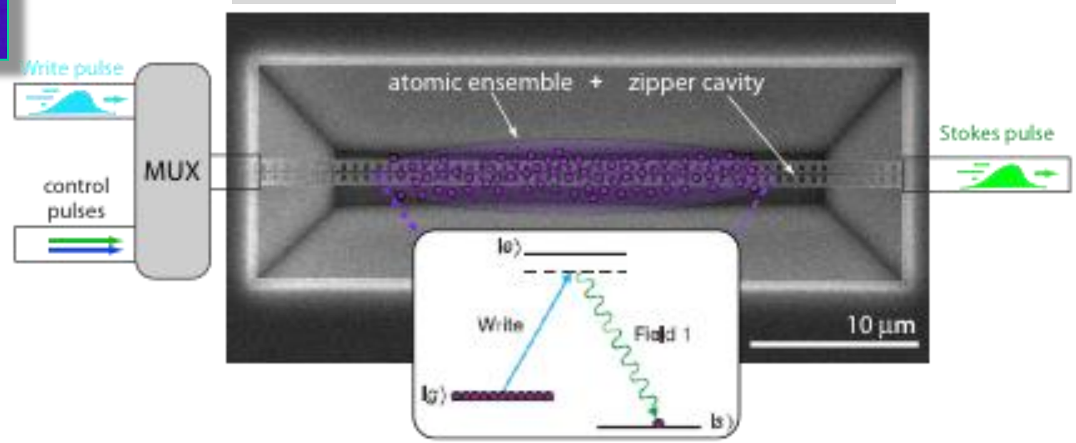
- Develop the scientific and technical capabilities to achieve functional quantum memories that efficiently couple and store quantum states of light in ensembles of cold atoms, including reading and writing entanglement states of matter and light.
- We will accomplish these goals by way of efficient "on chip" quantum connectivity provided by photons over integrated optical networks.

Transition advances in quantum optics with atomic ensembles into the world of lithographically fabricated quantum optical circuits.



Fluorescent image
from 4 atomic ensembles
(quantum memories)
Globally store entangled state
Kimble group (2010)

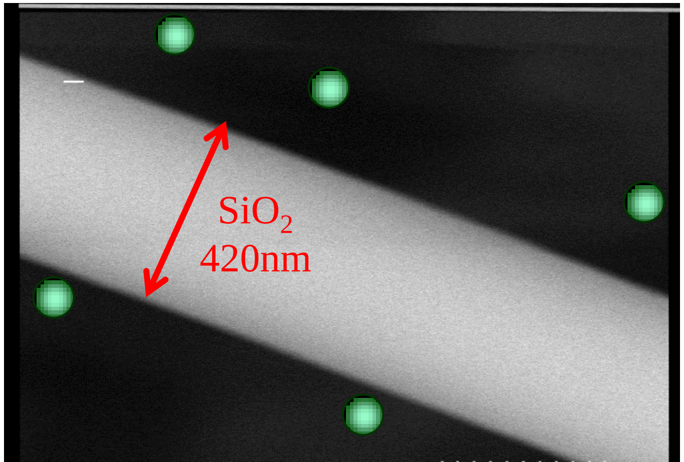
Zipper cavity [Painter group (2009)]
coupled to an atomic ensemble



1-D Nano-traps for quantum optical memories

Development and characterization of atomic quantum memories

Implementation of a nano-fiber optical trap



"Demonstration of a State-Insensitive Nano-fiber Trap"
A. Goban *et al.*, *Phys. Rev. Lett*. **109**, 033603 (2012)
[Accompanied Physics Synopsis section]

Optical depth = 66 ± 17
OD/atom ≈ 8%

Linewidth = 5.7 ± 0.1 MHz
Frequency shift < 0.5 MHz

Trap lifetime $\tau \approx$ 15 ms
extended to $\tau \approx$ 150 ms with PG cooling

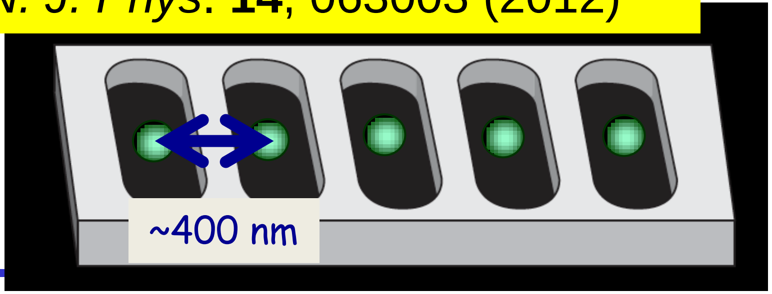
Nano-fiber optical trap for ≈ 800 Cs atoms 200 nm from surface

Advancement of optical interfaces to/from quantum memories

Theoretical protocols for functional **QM** (i.e., quantum logic)

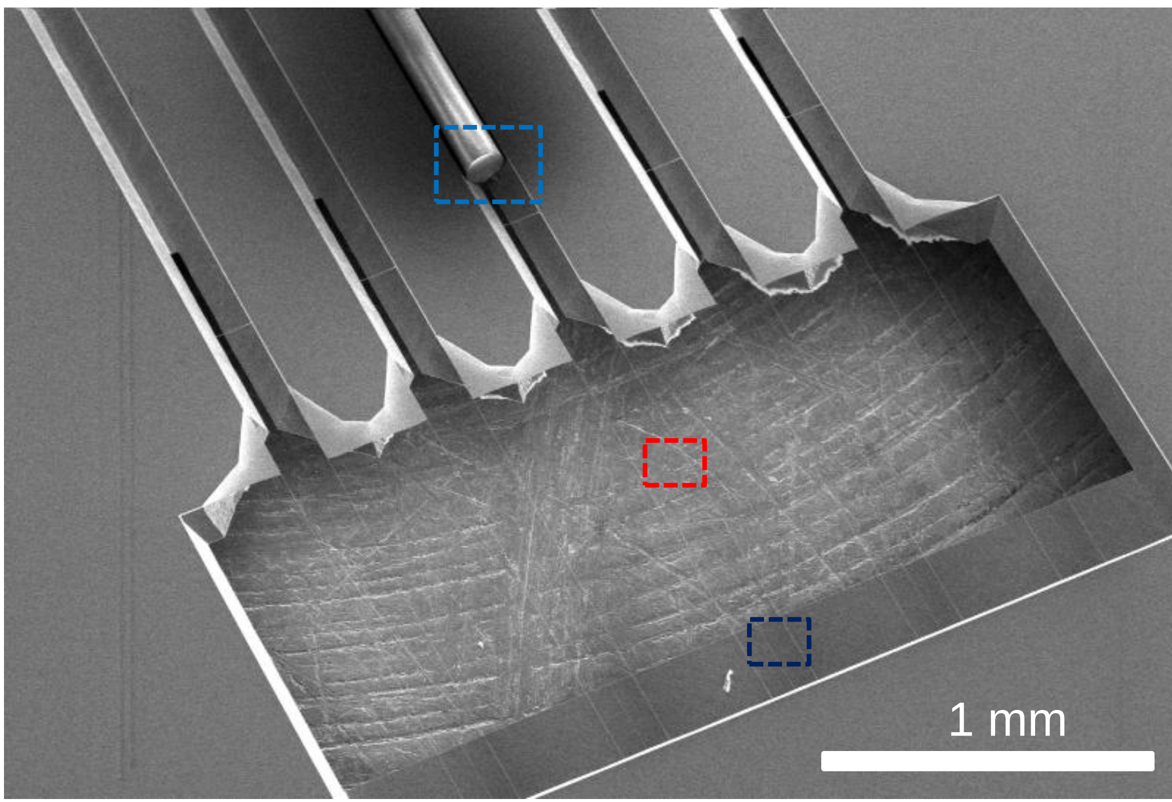
"Cavity QED with Atomic Mirrors", D. Chang *et al.*, *N. J. Phys*. **14**, 063003 (2012)

Design of atomic traps in 1-d photonic crystals
with strong single atom-photon interactions
Kimble – Painter groups

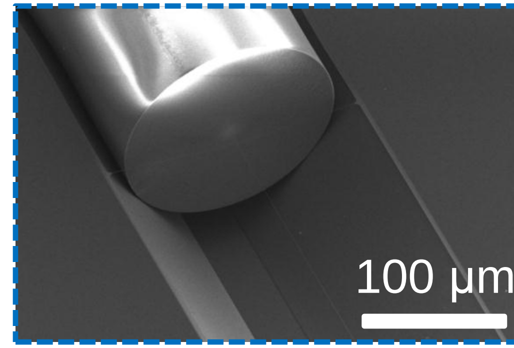


Atomic quantum memories in nanoscale optical circuits

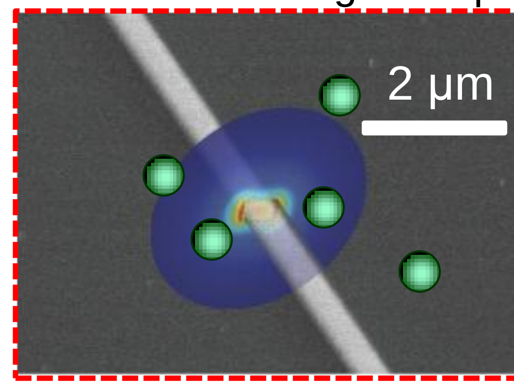
- Develop the scientific and technical capabilities to achieve functional quantum memories that efficiently couple and store quantum states of light in ensembles of cold atoms, including reading and writing entanglement states of matter and light.
- Engineer efficient “on chip” quantum connectivity by photons over integrated optical networks.



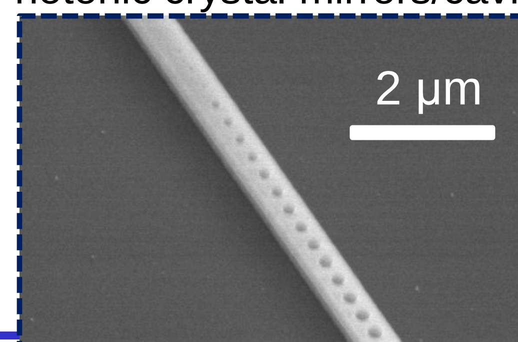
Efficient collection fiber



Evanescent atom-light coupling



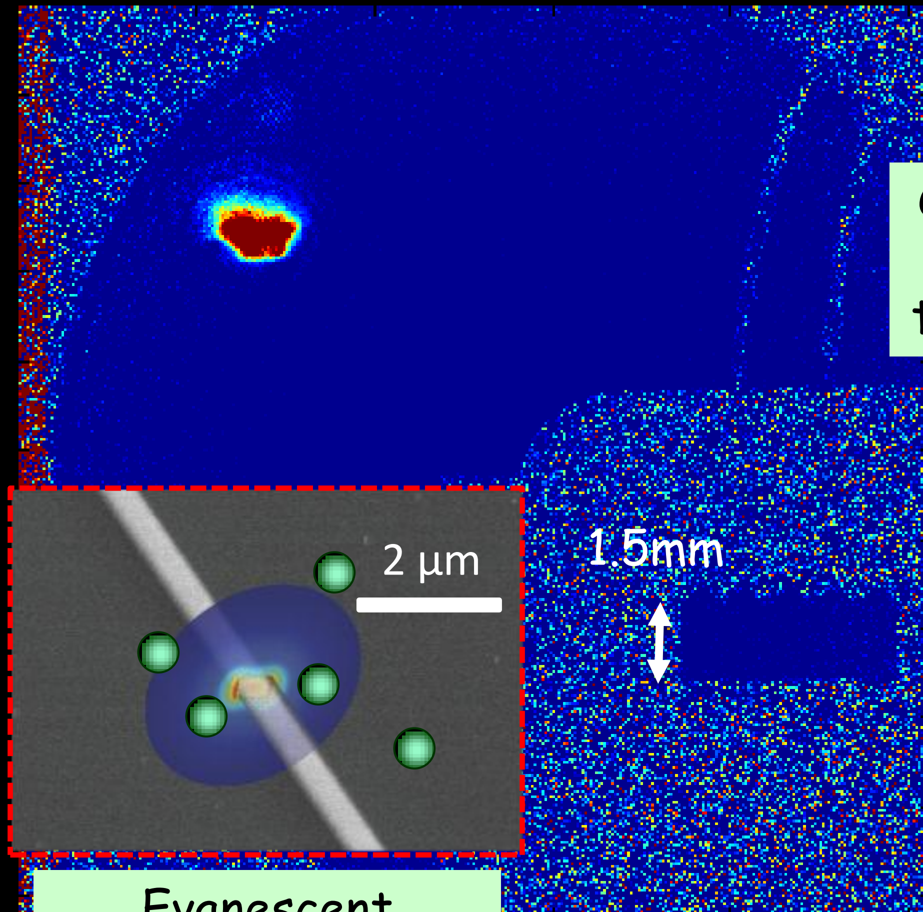
Photonic crystal mirrors/cavities



Cold atom device loading – Kimble & Painter Groups

$N_i \sim 10^7$ Cs atoms
at $\rho \sim 10^{12}/cm^3$
T ~ 10μK

SiN device –
~ 300nm x 200nm
waveguide
terminated by
1-d mirror



Optical fiber
butt-coupled
to SiN device

$N_f \sim 5 \times 10^6$ Cs atoms
at $\rho \sim 10^{11}/cm^3$
T ~ 20μK

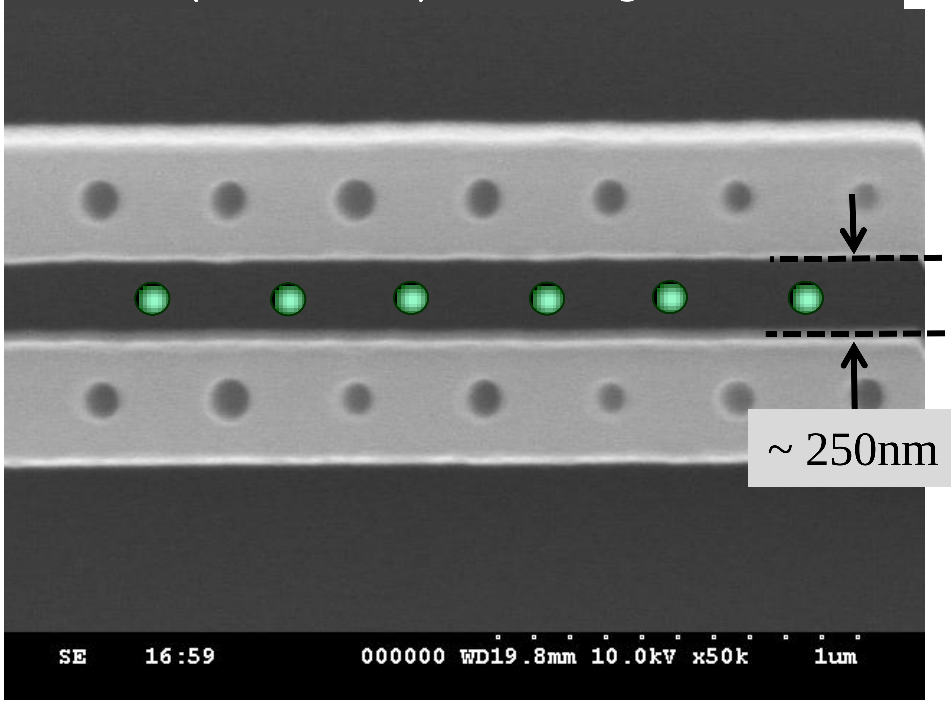
Evanescent
atom-light coupling

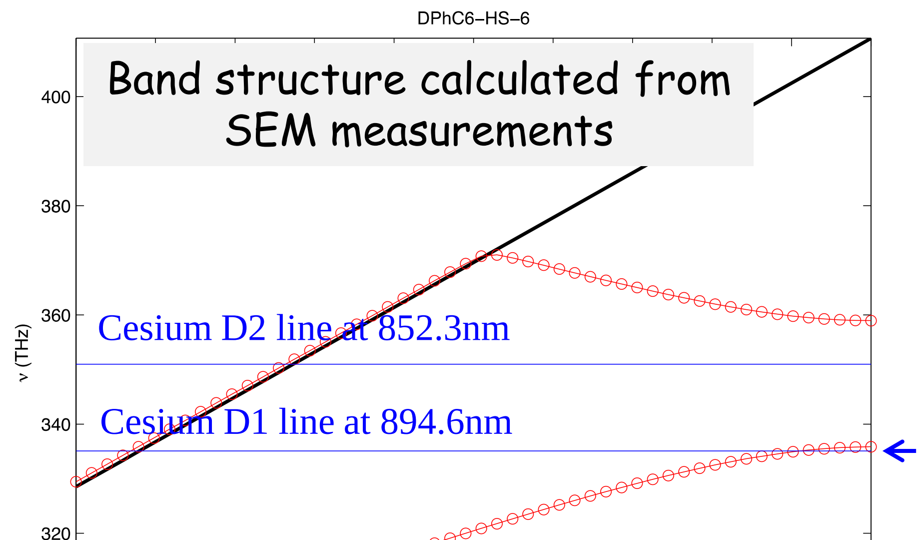
Nano-Scale Quantum Optical Circuits with 1-D Photonic Crystals

<u>Dual beams:</u> 1-d photonic waveguides with conventional through holes

- Fabrication difficulties due to small hole sizes

SEM of photonic crystal waveguide section





Band structure in good agreement with our reflection measurements using Mach-Zehnder interferometer (w/o atoms)

- This structure is currently in vacuum chamber
- Attempting to measure absorption of guided probe mode in dielectric band (near Cs D1 line) due to cold atoms near/within the photonic crystal waveguide

Budget plan

BASE PERIOD:

	06/01/11-09/30/11	10/01/11-09/30/12	10/01/12-09/30/13	10/01/13-05/31/14	3-Year Total
UCSB	$166,667	$500,000	$500,000	$333,333	$1,500,000
Caltech	$158,333	$475,000	$475,000	$316,667	$1,425,000
Harvard	$66,667	$200,000	$200,000	$133,333	$600,000
U. of Iowa	$58,333	$175,000	$175,000	$116,667	$525,000
Iowa State	$50,000	$150,000	$150,000	$100,000	$450,000
TOTAL	**$500,000**	**$1,500,000**	**$1,500,000**	**$1,000,000**	**$4,500,000**

OPTION PERIOD:

	06/01/14-09/30/14	10/01/14-09/30/15	10/01/15-05/31/16	2-Year Total
UCSB	$166,667	$500,000	$333,333	$1,000,000
Caltech	$158,333	$475,000	$316,667	$950,000
Harvard	$66,667	$200,000	$133,333	$400,000
U. of Iowa	$58,333	$175,000	$116,667	$350,000
Iowa State	$50,000	$150,000	$100,000	$300,000
TOTAL:	**$500,000**	**$1,500,000**	**$1,000,000**	**$3,000,000**

Significant accomplishments to date

- Developed digital doping of spins in nanometer-scale diamond plane
  K. Ohno *et al*., *Appl. Phys. Lett*. **101**, 082413 (2012)
- Demonstrated all-optical control of single spin quantum states along arbitrary bases
  C.G. Yale, *et al*., *Proc. Natl. Acad. Sci.* **110**, 7595 (2013)
- Measured and manipulated spin states in polytypes of SiC
  A.L. Falk *et al.*, *Nature Comm.* **4**, 1819 (2013)
- Fabricated photonic cavity structures and spin coupling with diamond and SiC
  I. Aharonovich *et al*., *Adv. Mater*. **24**, OP54–OP59 (2012)
  Jonathan C. Lee, *et al*., *Optics Express* **20**, 8891(2012)
- Designed and measured single crystal diamond cantilevers with spins
  P. Ovartchaiyapong *et al*., *Appl. Phys. Lett*. **101**,163505 (2012)
- Performed atom trapping along optical nanofibers in a state-insensitive optical trap
  A. Goban, *et al., Phys. Rev. Lett.* **109**, 033603 (2012)
- Theoretically investigated atoms trapped along a nanoscopic optical waveguide
  D. E. Chang, *et al., Phys. Rev. Lett.* **110**, 113606 (2013)
- Designed one-dimensional photonic crystals for strong 1D atom-photon interactions
  C.-L. Hung, *et al*., (2013); available as arXiv:1301.5252
- Substantial advances in solid state spin cavity fabrication
  photonic crystal cavities with Q ~ 3,000 and V ~ 0.46 $(\lambda/n)3$
  suspended diamond micro-disk cavities with Q > 10,000
  SiC microdisks with Q > 9000