

Center for Quantum Networks

NSF Engineering Research Center



Thrust 3 - Quantum Materials, Devices, and Fundamentals

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Thrust 3 - Materials, Devices -Overview

Goal: Materials, devices and chip-scale systems that enable more efficient and “friendly” quantum repeater nodes.

Challenges:

- **Quantum memory limitations:** operating temperature, inhomogeneous broadening, emission wavelength, speed...
- **Quantum frequency conversion** and photon **collection efficiency** limitations?
- Performance limits of **superconducting single photon detectors**?
- **Electronics**, both cryo and room temperature, needed to control thousands of memories?
- **Integrated photonics based ZALM source**?

Project A: Quantum Memories Beyond SiV (**Freedman, Englund, Eichenfield**)

Project B: Superconducting Electronics (**Berggren, Mundy**)

Project C: Qubit Conversion Technologies (**Loncar, Mundy, Eichenfield**)

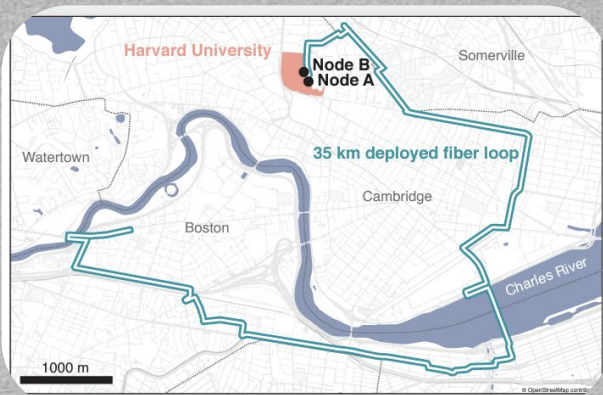
Project D: Quantum Logic on Spin Qubits (**Lukin**)

Project E: Qubit Control (**Eichenfield, Loncar, Englund**)

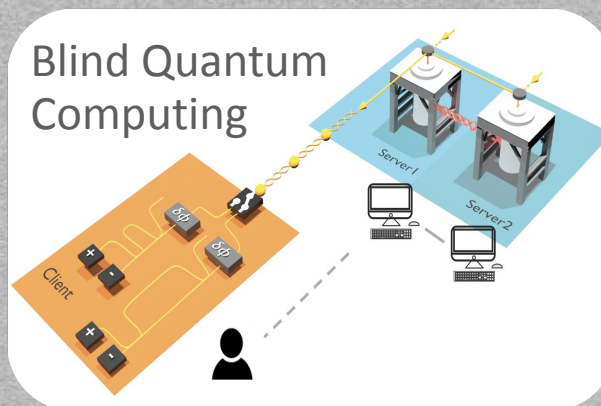
Project F: Integrated Multiplexed Swaps (**Eichenfield**)

Project G: Efficient Photon Coupling (**Camacho, Loncar, Englund, Eichenfeld**)

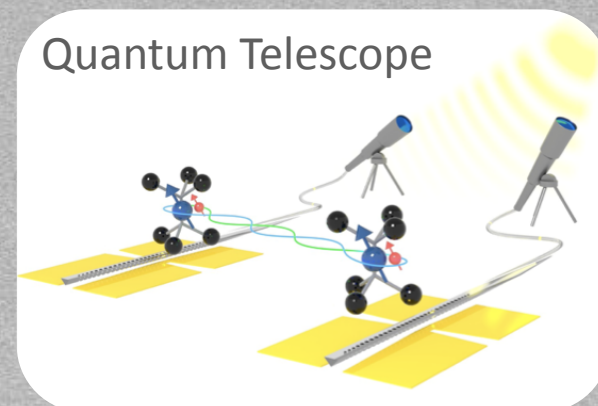
Y1-Y4: City-scale quantum-memory-based quantum-comms! Y5: Applications!



Can M Knaut et al, "Entanglement of Nanophotonic Quantum Memory Nodes in a Telecommunication Network". *Nature*, **629**, 573 (2024)



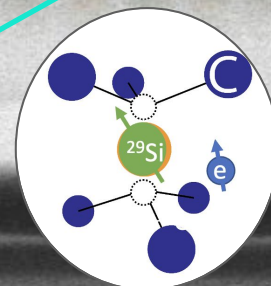
Wei, Stas, Suleymanzade, Baranes et al., *Universal distributed blind quantum computing with solid-state qubits*, *Science* **388**, 509-513 (2025)



Stas, Wei, Sirotin et al., *Entanglement Assisted Non-local Optical Interferometry in a Quantum Network*, arXiv:2509.09464 (2025)

Diamond nanocavity enables strong spin-photon interactions

Silicon Vacancy Centers deterministically incorporated into device



Efficient fiber coupling of photons

Project Goals:

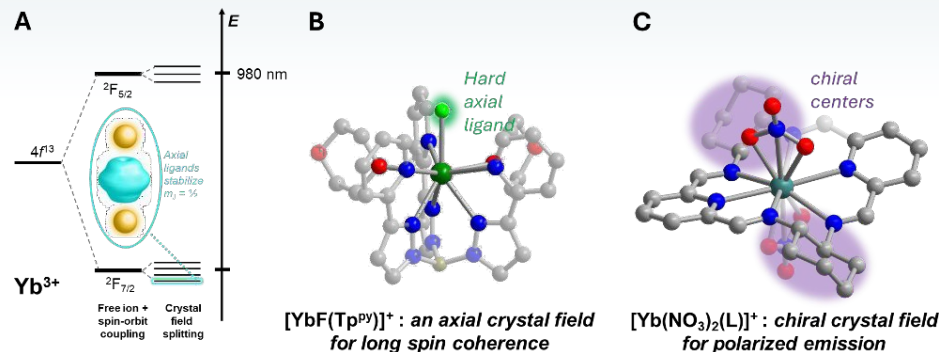
- Synthesize and design a series of Yb^{3+} molecules to correlate spin coherence times to crystal field symmetry
- Investigate chiral antenna ligands for spin polarized emission
- Perform resonant optical experiments including measurements of optical storage lifetimes and optical coherence times (Englund Lab)
- Attempt optical initialization of the Yb^{3+} electron spin and ODMR experiments

Barriers:

- Fast spin decoherence due to magnetic anisotropy
- Parity forbidden optical transitions lower quantum yield

Methodologies to Overcome Barriers:

- Synthetic manipulation of the Yb^{3+} electronic structure to minimize anisotropy
- Ligand induced mixing of optical transitions to relax optical selection rules and increase quantum yield

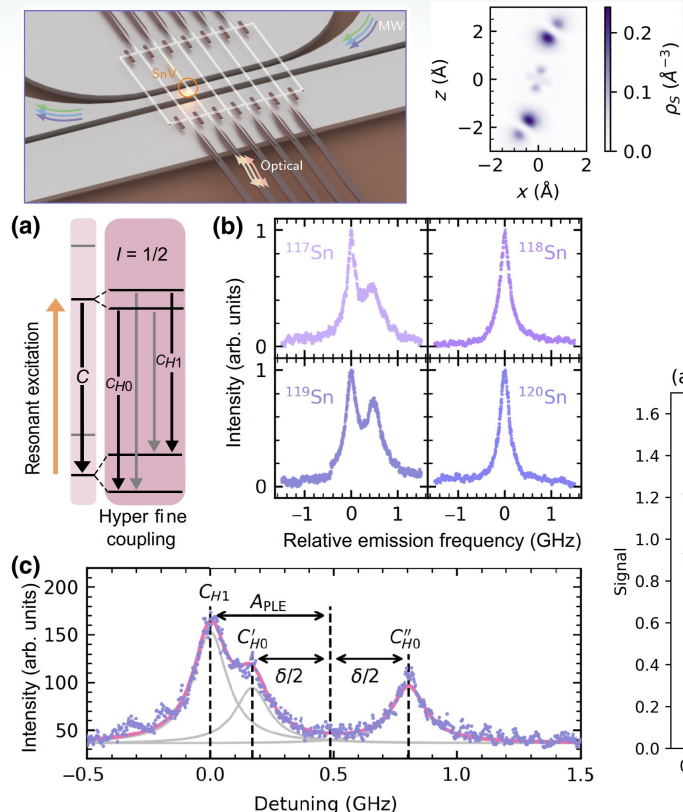


Recent achievements:

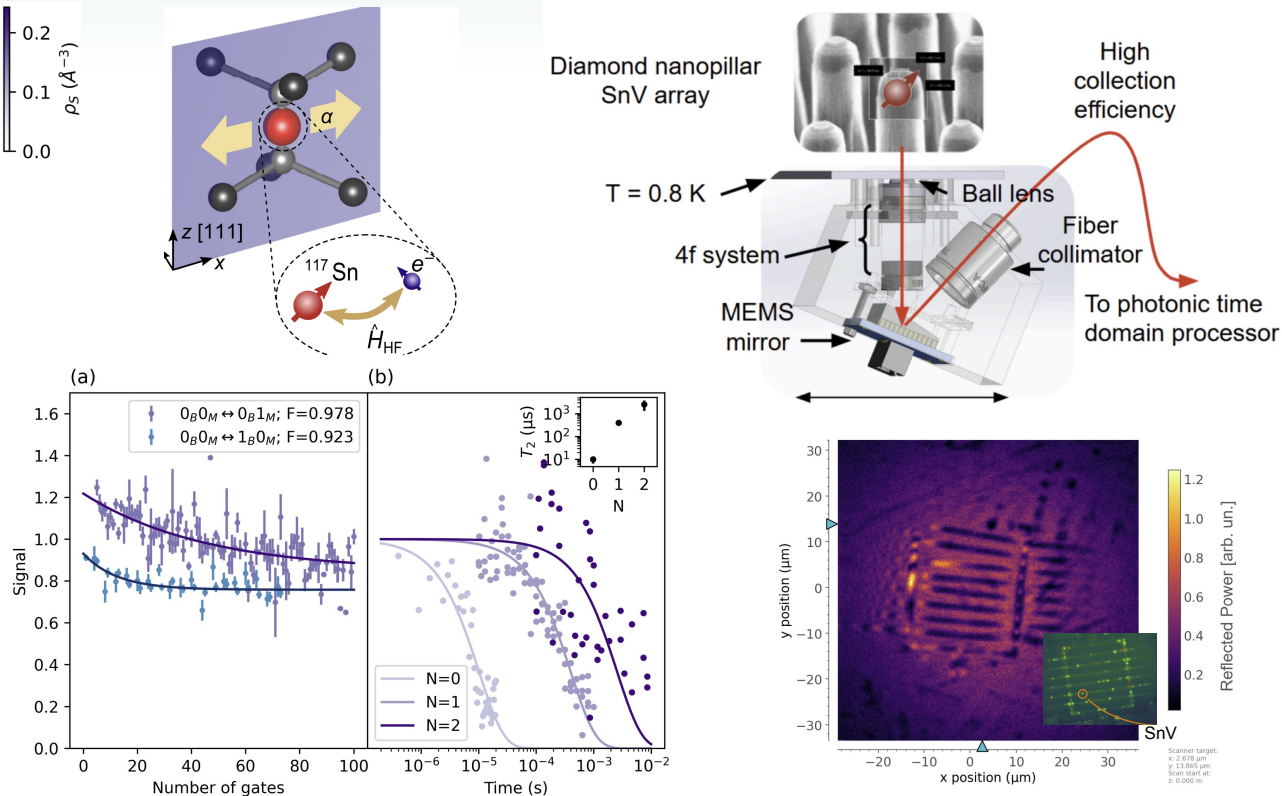
- Designed and synthesized several Yb^{3+} molecules as well as diamagnetic Y^{3+} analogues
- Grew magnetically dilute single crystals for characterization of the spin and optical properties
- Began optical measurements at 4K in the Englund lab cryostat

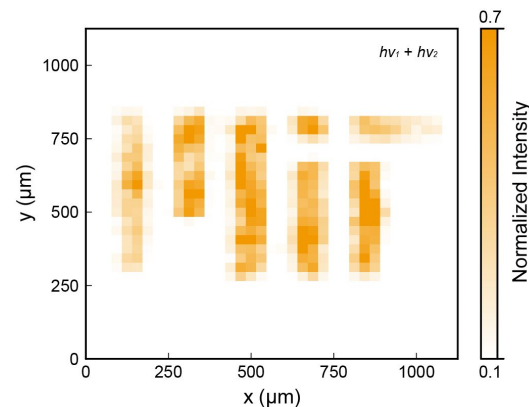
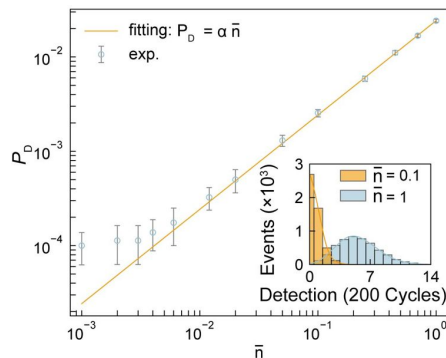
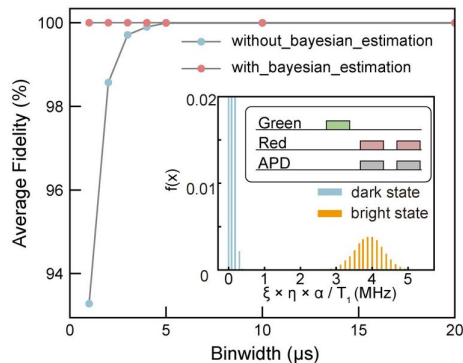
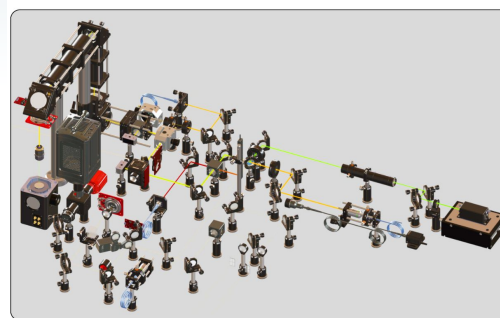
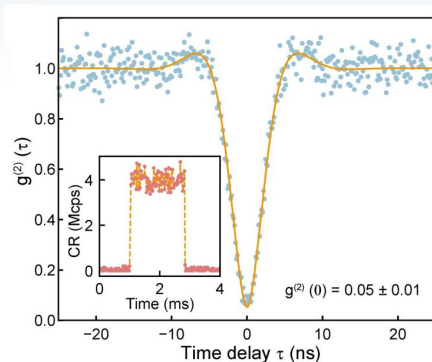
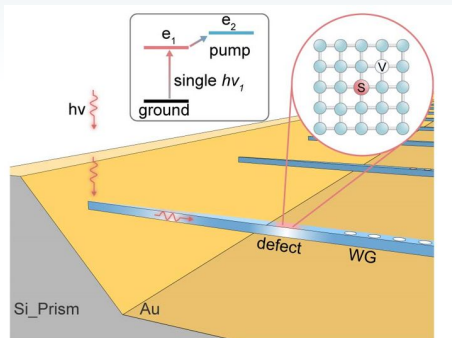
Freedman & Englund

Hyperfine Electro-Nuclear Spin-Photon Interface



Cryo-vacuo MEMS Scanner QuMemory Module







Project 3B: Superconducting Electronics



Project Goals:

- Detecting photons for quantum communication in a scalable, cost-effective manner
- Develop integrated nanowire detectors and electronics for photonic feedforward control
- Study high temperature materials for electronics applications

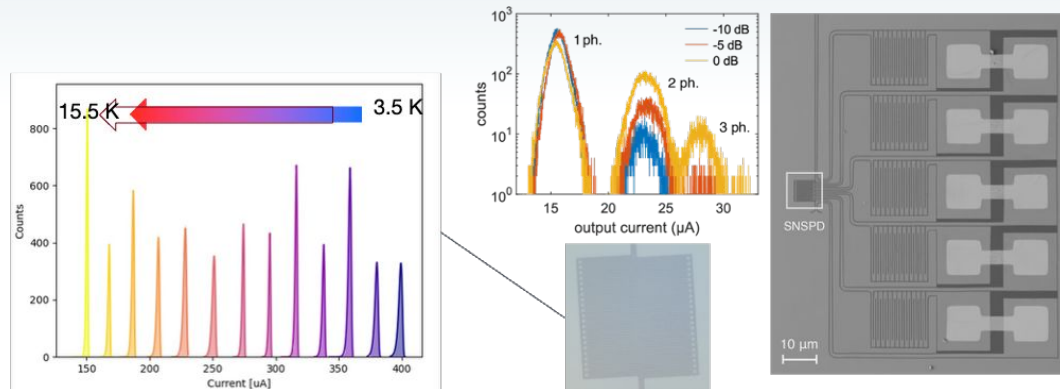
Barriers:

- High bit error rate in photon number resolving circuit
- Difficult to etch and protect sensitive high temperature materials

Methodologies to Overcome Barriers:

- Explore different circuit architectures
- Develop new fabrication techniques

Berggren & Englund



Recent achievements:

- SNSPD coupled to an integrated nanowire circuit to distinguish between photon-number states
- Nanowire logic gates for SNSPDs in Bell measurements
- Fabrication process for narrow-wire magnesium diboride electronics down to 200 nm and studied fluctuations in epitaxial film
- Hysteretic switching in YBCO nanowires at 72 K, which shows the possibility of YBCO-based nanocryotron electronics operating as high as 72 K



Project Goals:

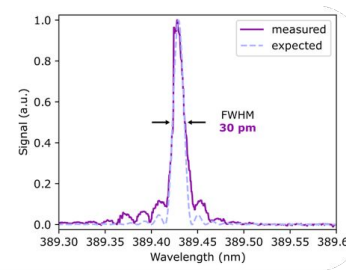
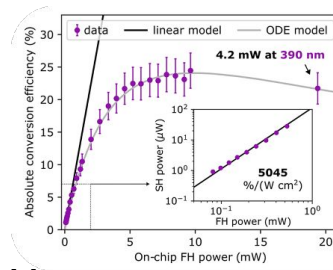
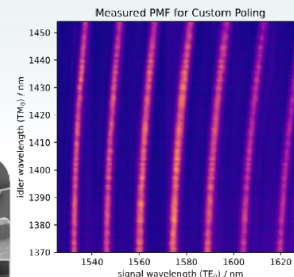
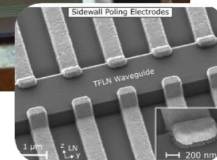
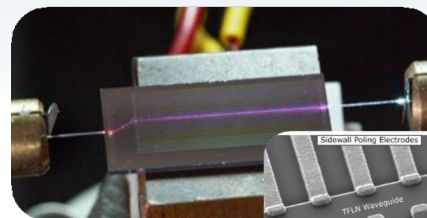
- Efficient frequency conversion for photons emitted by quantum memories (e.g. 737 nm wavelength) to telecom wavelength range (1,300 nm or 1,500 nm) using thin film lithium niobate (TFLN) photonics.
- Overcome inhomogeneous broadening of quantum emitters using electro-optic frequency shifting
- Multiplexed entangled photon pair sources for ZALM protocols

Barriers:

- Variations in strain environment result in different memories operating at different wavelengths
- Thickness variations in TFLN wafers as well as material etching nonuniformities make nonlinear frequency conversion less efficient and difficult/ impossible to target wavelengths of interest;

Methodologies to Overcome Barriers:

- Pole-after etch process developed and can take all imperfections into account
- TFLT pursued in addition to TFLN

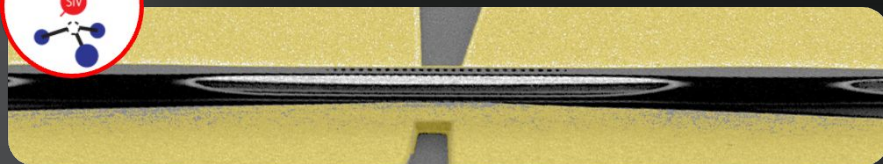
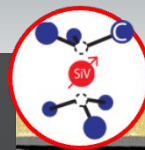


Recent achievements:

- Pole-after etch process for efficient and wavelength specific frequency conversion [[Comm. Physics, 8, 136 \(2025\)](#)]
- Side-wall poling for efficient and short wavelength frequency conversion [[arXiv:2503.16785 \(2025\)](#)]
- Multiplexed photon pair source [[in preparation](#)]
- Frequency shifting and shearing using TFLN phase modulators and photonic molecules [[Nat. Comm, 15, 1 \(2024\)](#)]
- Cascaded frequency shifters and shearing [[in review in Nature](#)]



Project 3C: Qubit Conversion Technologies



Cryo-compatible High-efficiency on-off chip coupling?

✓ Switch network for multiplexing + temporal based circulator

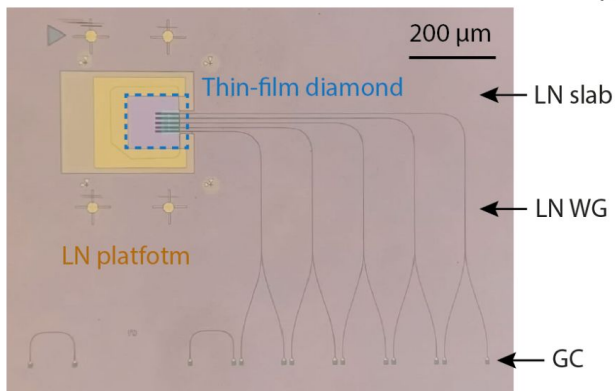
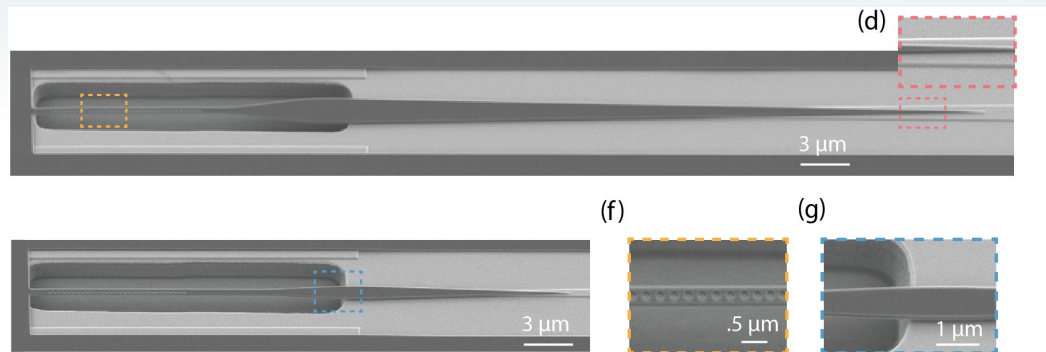
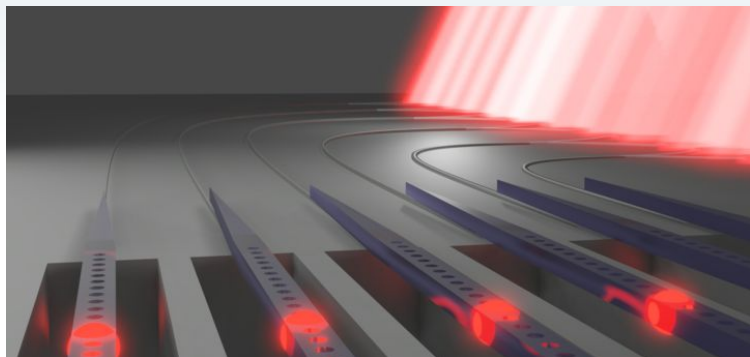
✓ Phase modulator for bridging inhomogenous distribution

✓ Intensity modulator for switching channel on/off

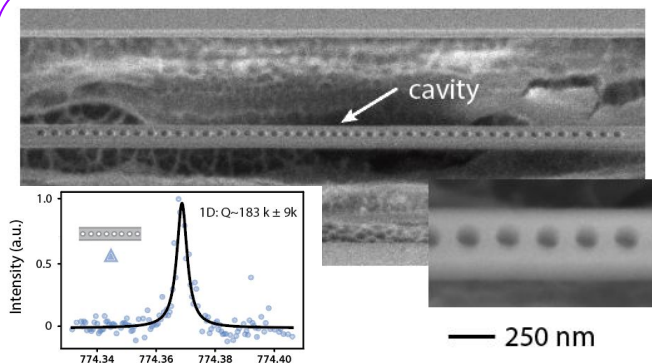
High-efficiency, low noise conversion from telecom to visible?

- Frequency shifting and pulse shaping to address inhomogeneous broadening
- Quantum frequency conversion for low loss long-distance propagation
- Fast switches to allow for multiplexing and increase the entanglement rates are low

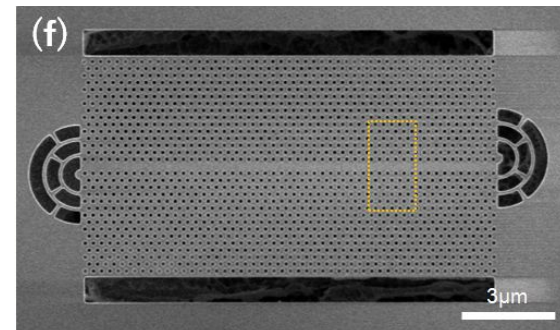
Project 3C: Diamond on LN Photonics



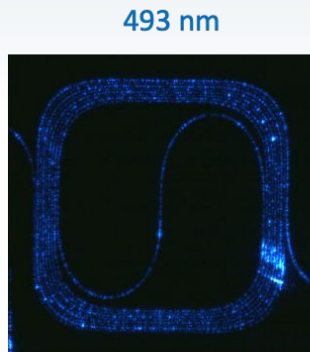
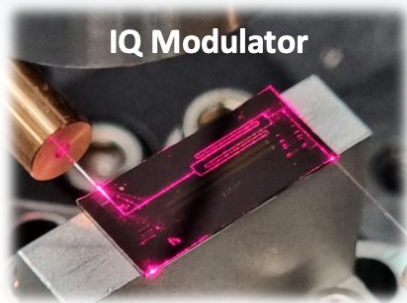
Sophie Ding, *in preparation*



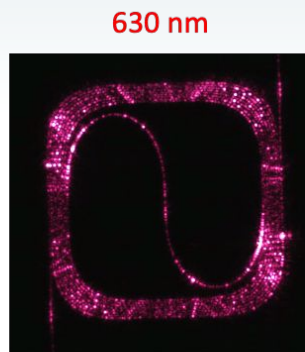
Thin film diamond cavities:
Thin film diamond PhC waveguides:



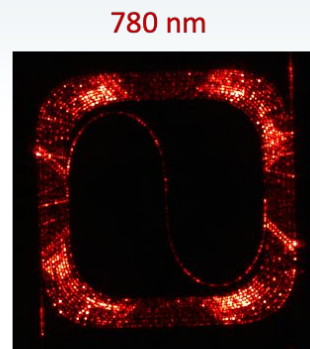
Ding et al, *Nature. Comm.*, **15**, 6358 (2024)
Ding et al, *Nano Letters*, **25**, 32 (2025)



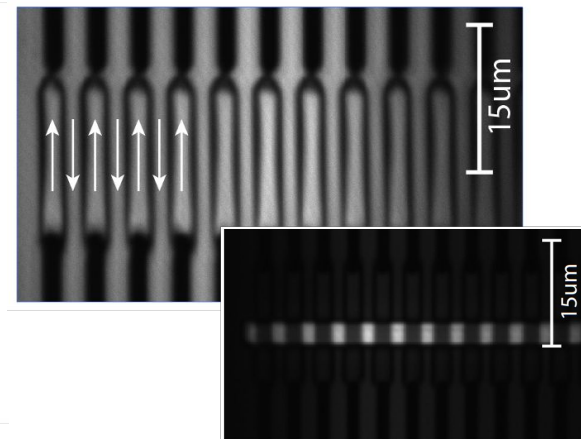
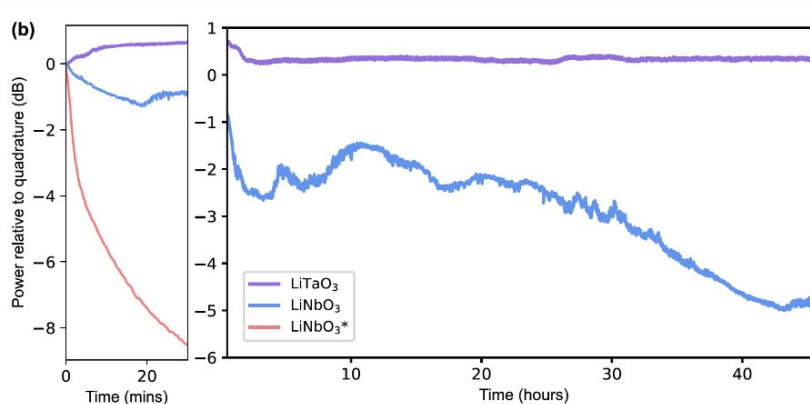
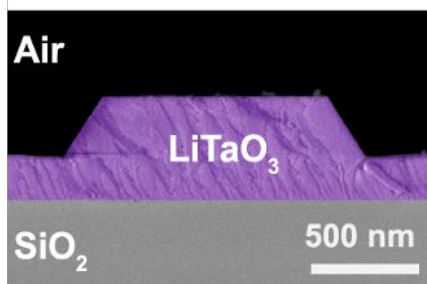
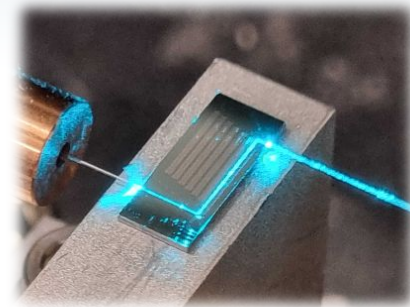
1.1 dB/cm



0.5 dB/cm



0.4 dB/cm



K. Powell, et al *Optics Express*, **32**, 44117 (2024)

K. Powell, et al *APL Photonics*, **10**, 9 (2025)

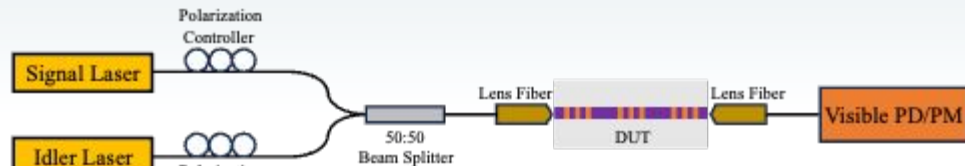
Loncar

A. Shelton et al, *APL Photonics*, **10**, 091302 (2025)

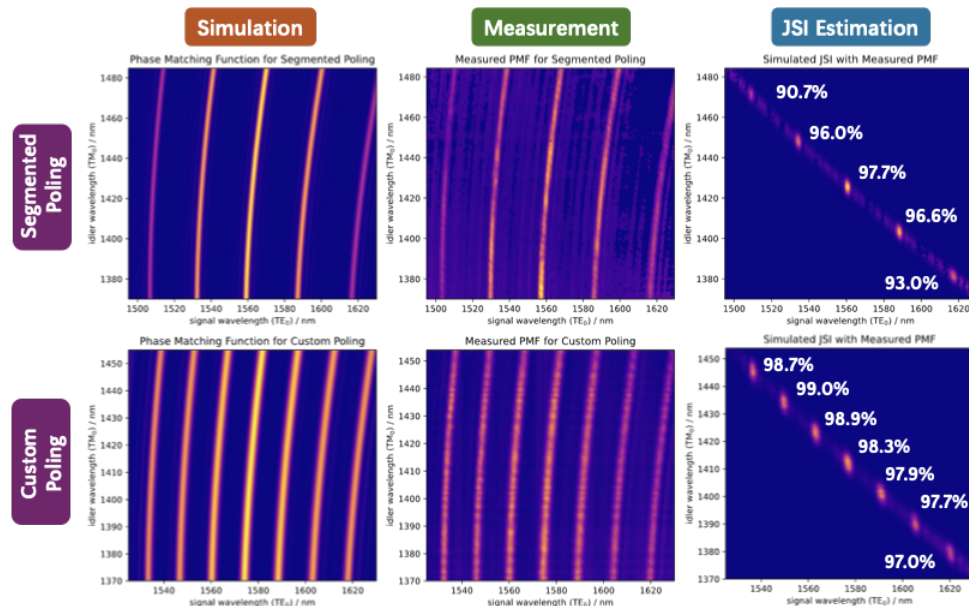
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Project 3C: ZALM source & Frequency Shifting

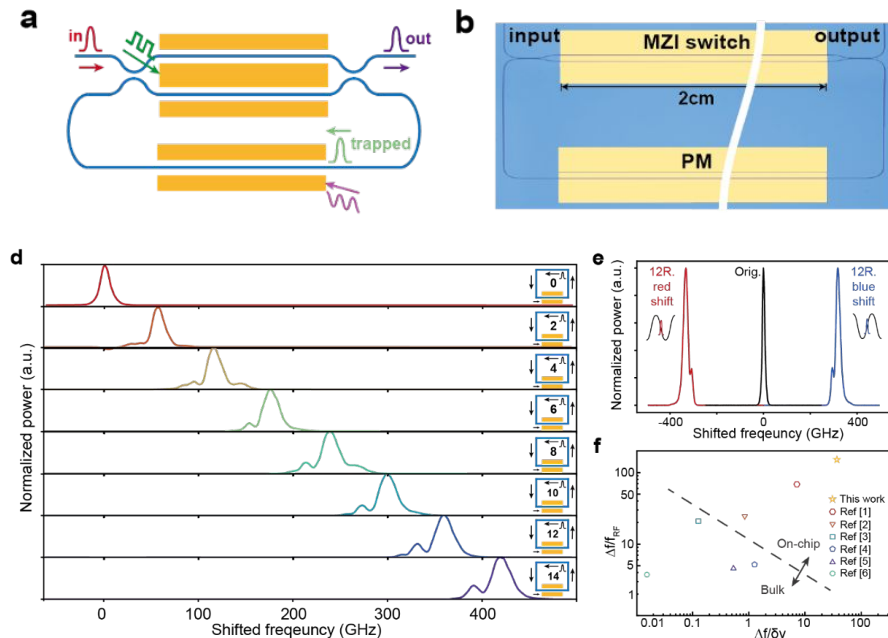


Cascaded frequency shifting developed for spectral control of generated photons



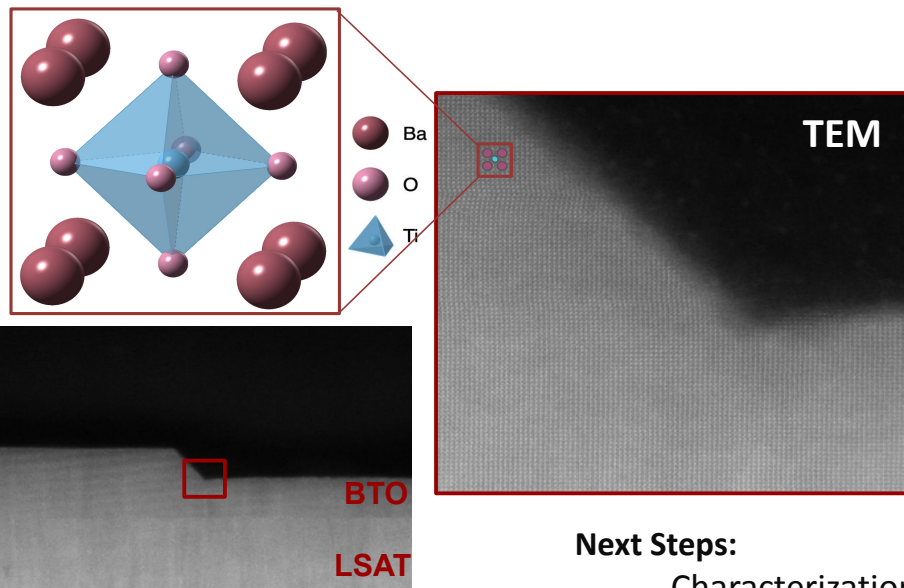
J. Yang et al, *in preparation*

Loncar

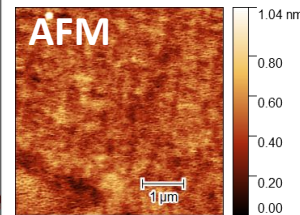
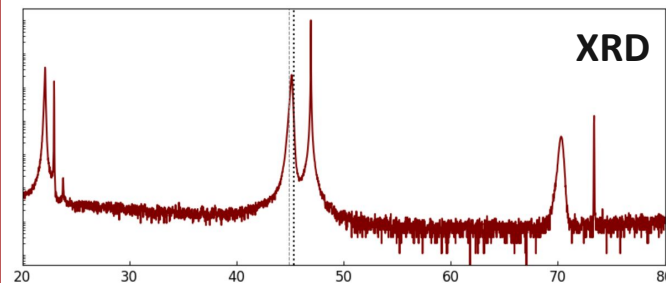


X. Li et al, arXiv:2509.25102 *in review in Nature*

- **Idea:** Barium Titanate (BTO) integrated photonics to leverage large ($>1000\text{pm/V}$) pockels coefficient
- **Requires:** development of high-quality crystalline thin-films with device-compatible thickness
- **Our approach:**
 1. Hybrid molecular beam epitaxy (hMBE) for stoichiometric self-regulated growth of $>200\text{nm}$ films

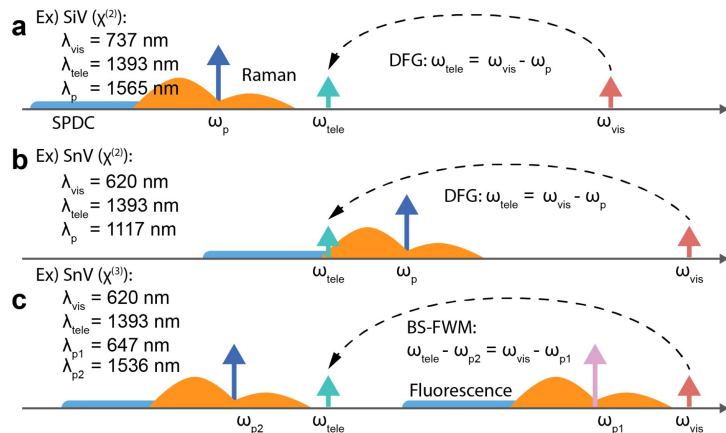
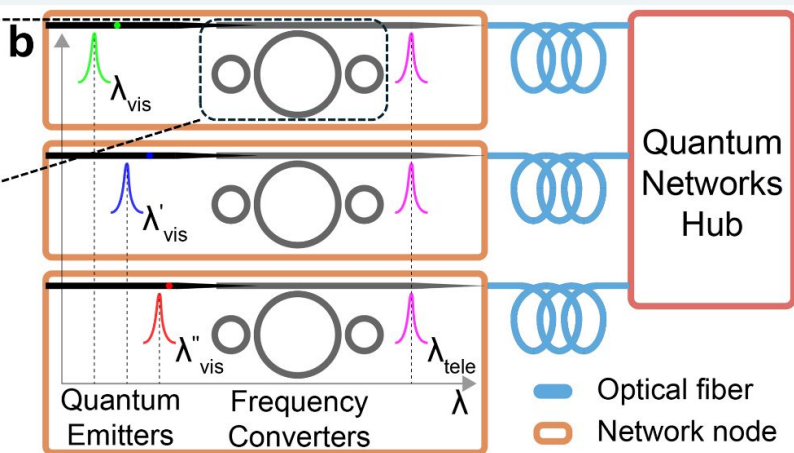
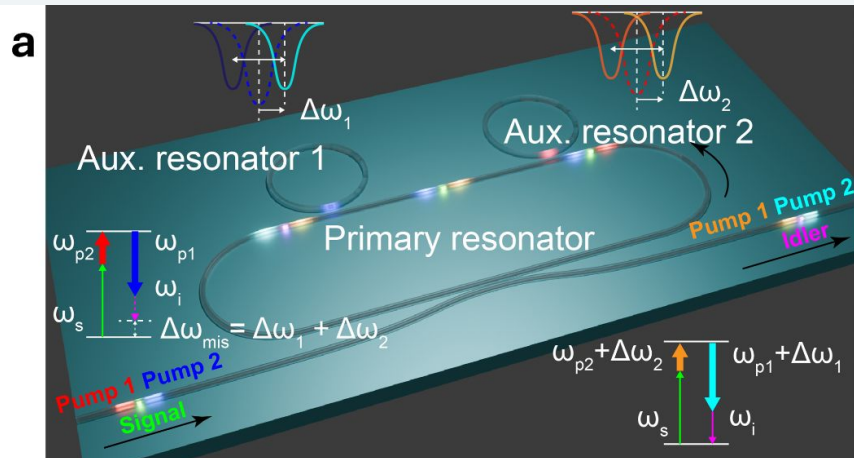


TEM, XRD, and AFM reveal high-quality BTO films grown via hMBE robust to nanofabrication



Next Steps:

Characterization of material optical losses and modulator performance



Challenge:

- In $\chi^{(2)}$ -based quantum frequency conversion between SnV photon and telecom photon, Raman-Stokes processes scattering from the pump into the idler mode become a significant noise process degrading entanglement fidelity

Approach:

- Low-noise $\chi^{(3)}$ -based quantum frequency conversion allows for pump frequency arrangement that puts Raman-Stokes processes far from idler mode, vastly improving entanglement fidelity. Ultra-low loss silicon nitride also allows for low pump powers and we have devised methods for active phase matching.



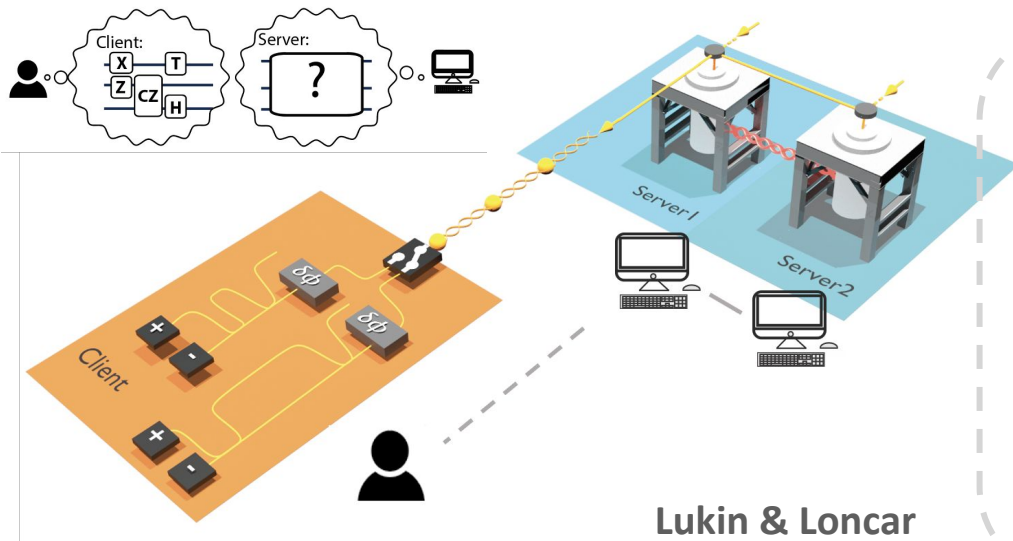
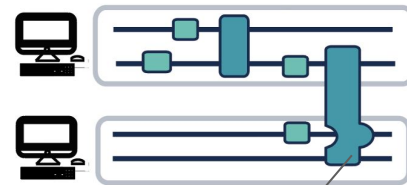
Project 3D: Blind Quantum Computing



- **Idea:** quantum computation + quantum-enabled privacy
- **Requires:** exchange quantum info between clients and servers, naturally using photons
- **Our approach:**
 1. Efficient light-matter interface using the cavity-QED system
 2. Integrated multi-qubit control for quantum logics

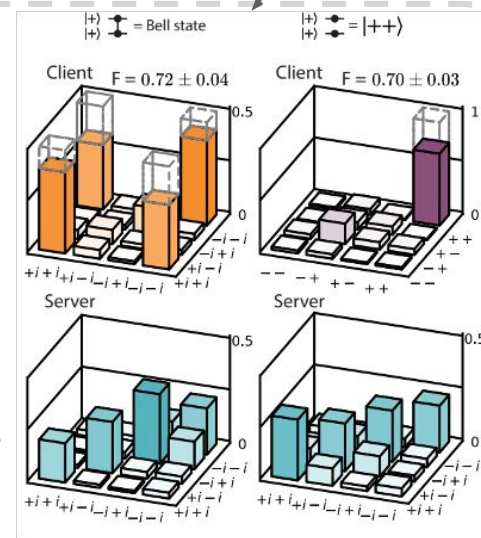
Universal blind logics

1. Controlled by clients
2. Hidden from servers



e.g. 2Q blind gate between servers:

Info. leakage to servers < 0.12 bits (full info: 1 bit)

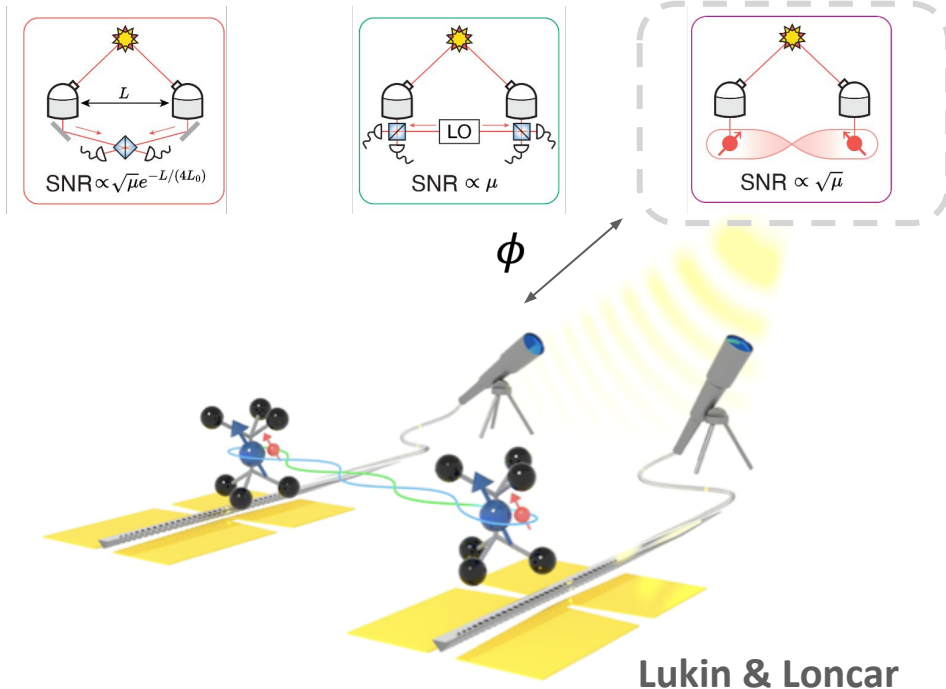




Project 3D: Quantum Telescopes

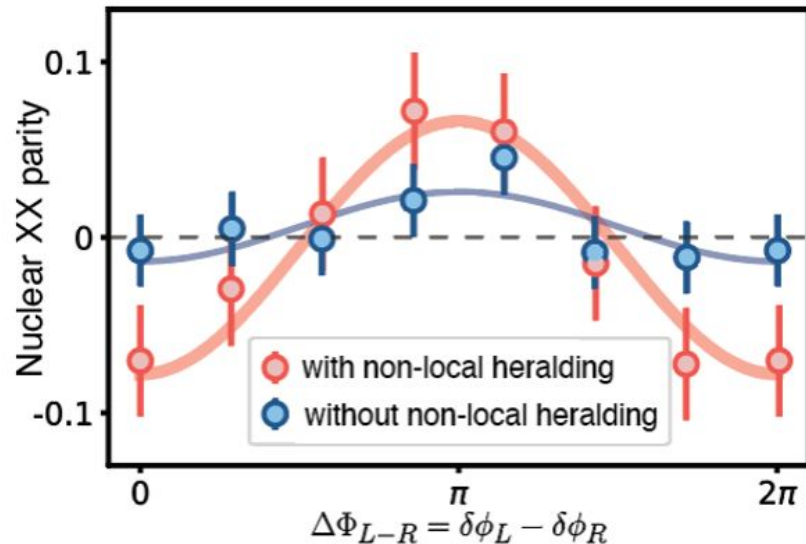


- Idea:** remote entanglement to enable non-local phase sensing, with the sensitivity better than classical approaches



Key: Using entanglement to perform non-local heralding

- Knowing arrival of a photon without destroying nonlocal phase info ϕ
- Effectively enhance signal-noise ratio (SNR)

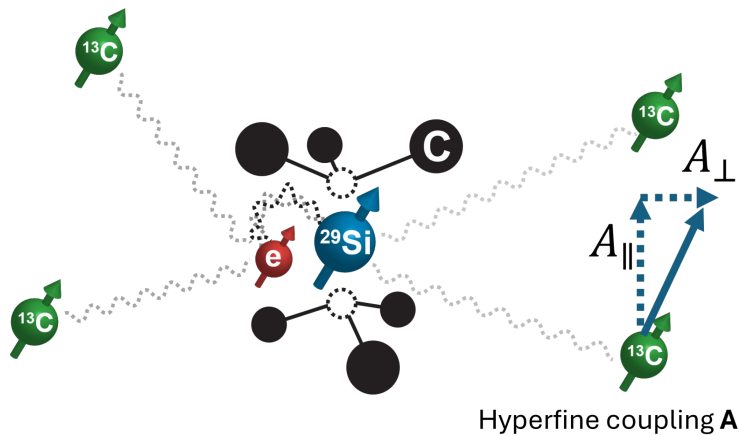
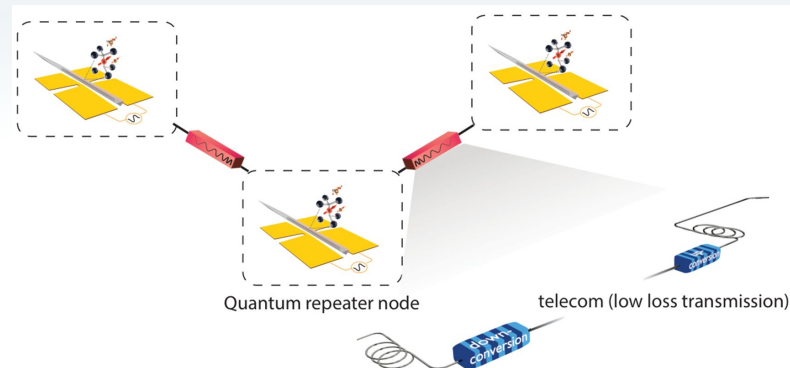




Challenge: Photon loss over long distances for large scale quantum networks

Solutions:

1. Conversion from SiV 737 nm to low-loss 1350 nm telecom wavelength¹
2. Integration of a quantum repeater node using an additional memory robust against repeated entanglement attempts

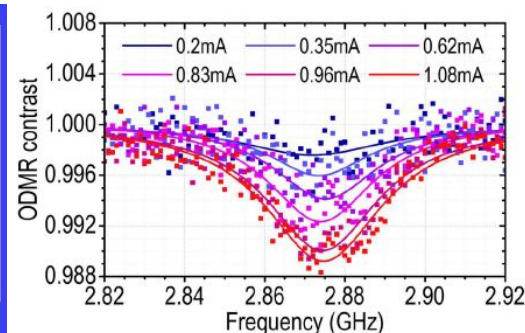
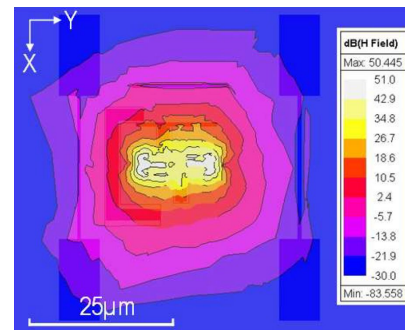
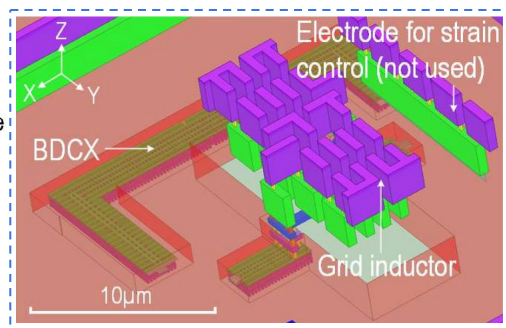
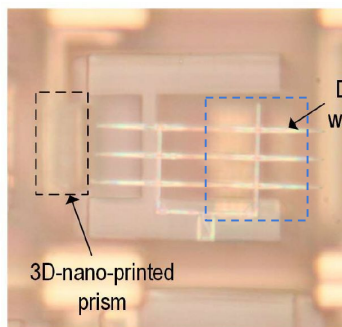
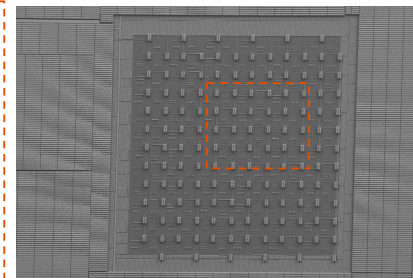
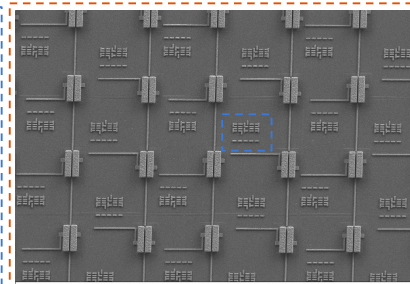
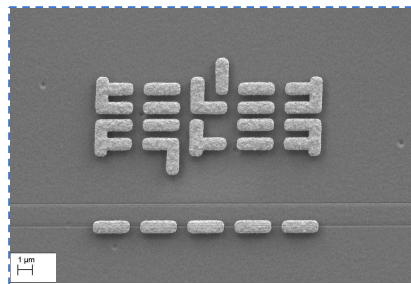
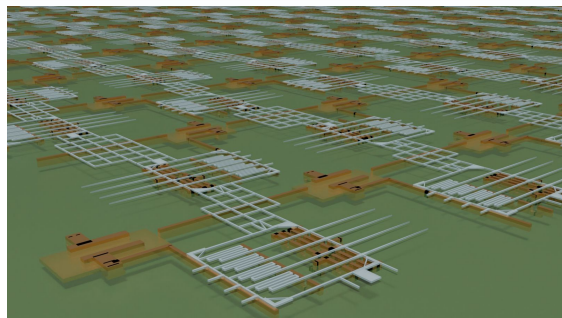


Future directions:

1. Develop ^{13}C nuclear spins as memories that remain coherent over hundreds to thousands of entanglement attempts
2. Demonstrate memory-enhanced generation of two concurrent spin-photon entangled pairs, followed by quantum repeater functionality with entanglement swapping in a three-node SiV quantum network

¹Knaut et al., *Entanglement of Nanophotonic Quantum Memory Nodes in a Telecom Network*, Nature **629**, 573–578 (2024).

CMOS Platform for Scalable Heterogeneous Integration



Team: Yuyang (Asher) Han, Jinchun Wang, Ruonan Han, Dirk Englund, et al.

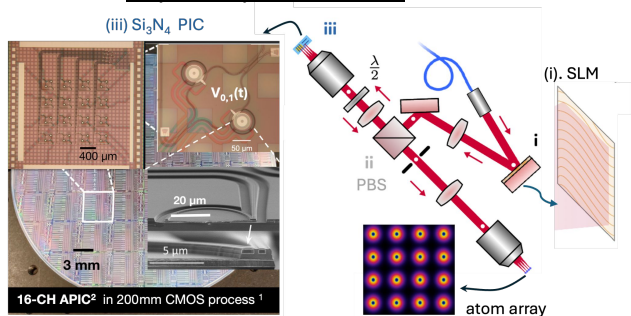
Publication: ISSCC (2026) under review

Englund

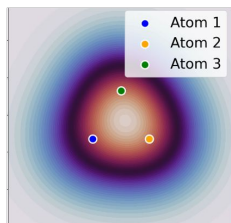
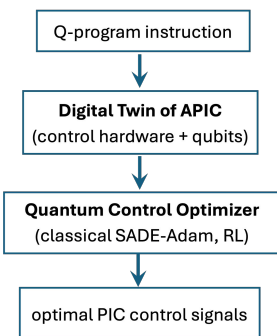
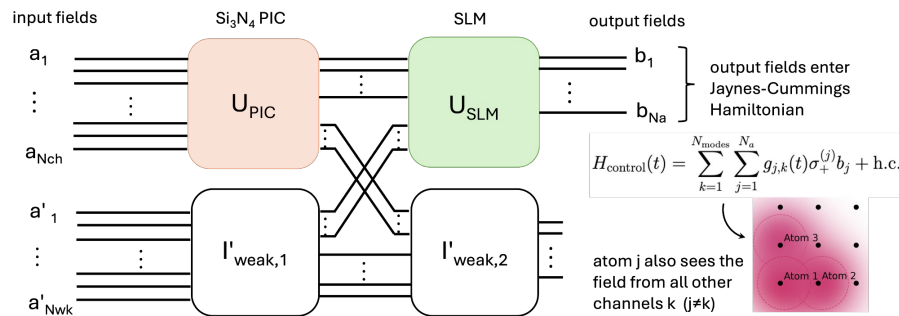


Hardware Co-Designed Optimal Control via Reinforcement Learning

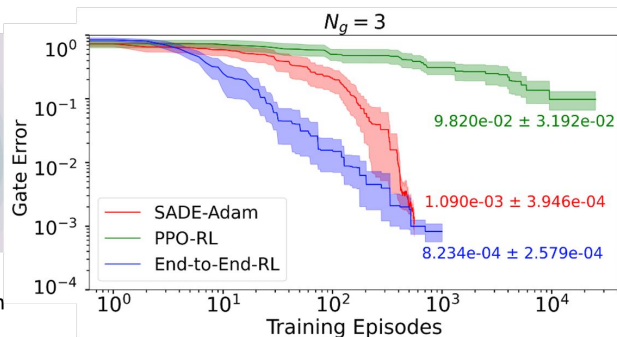
Physical System of APIC



Digital Twin of APIC



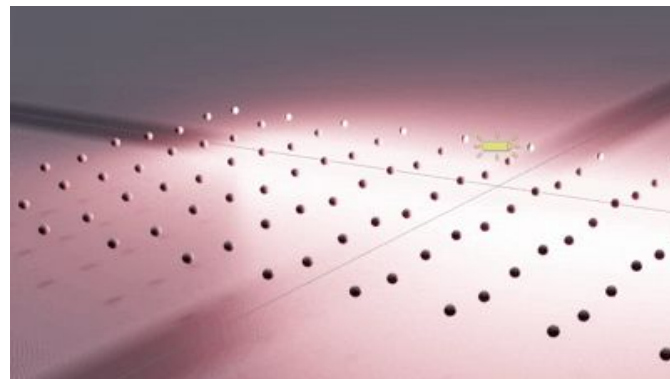
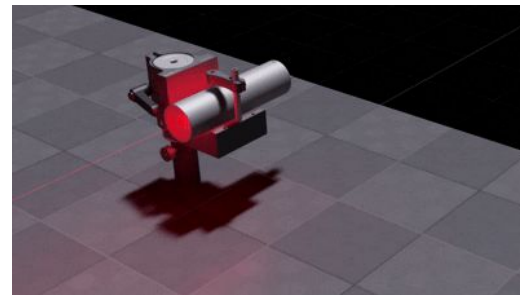
- beam waist 2.0 μm
- atom spacing 3.0 μm
- $T_{1q\text{-gate}}$ set to 100 ns



- DT model serves as env. for RL
- $U_{\text{target}} = R_1 \otimes R_2 \otimes R_3$
- R_i : single-qubit gate, random Clifford
- each curve shows the average over 5 random sets (shaded region shows std. deviation)

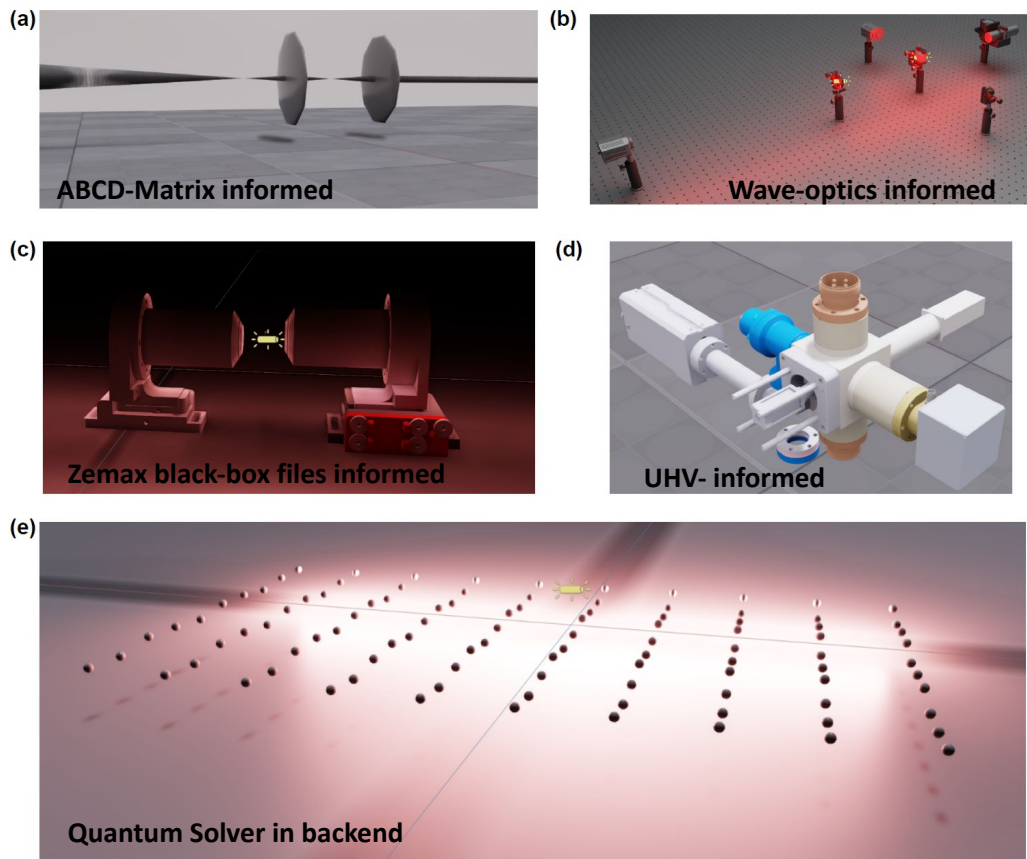
Project 3E: Qubit Control

Physics informed digital twin with NVIDIA
Omniverse & Zemax Ansys team



Englund

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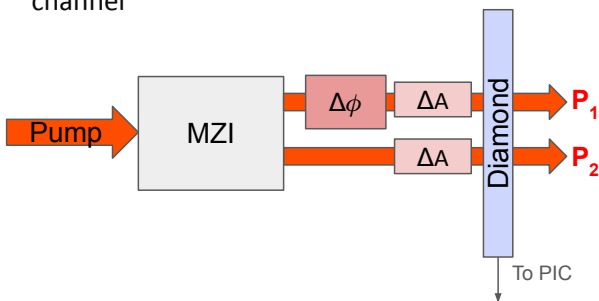


Motivation:

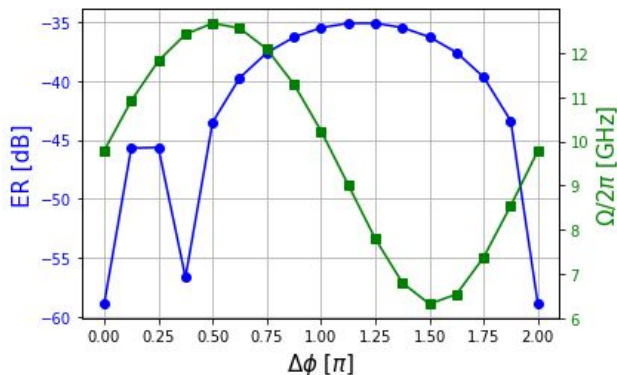
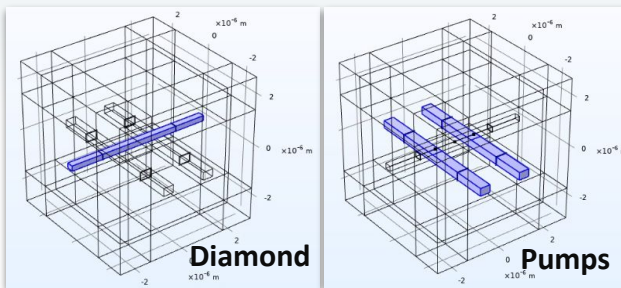
- Pump scattering into mode collecting SnV-emitted photons prevents high-fidelity heralded entanglement from false-detection events.
- Resonant excitation overlaps spectrally with emitted photons, pump scattering dominates collected signal, reducing entanglement fidelity from false-heralds

Goal: Efficient suppression of resonant pump photons → isolate **single-photon** from emitter

Concept: Evanesccently excite emitter with one pump waveguide, control relative phase and amplitude of second pump waveguide to cancel scattering into diamond collection channel



Simulation:

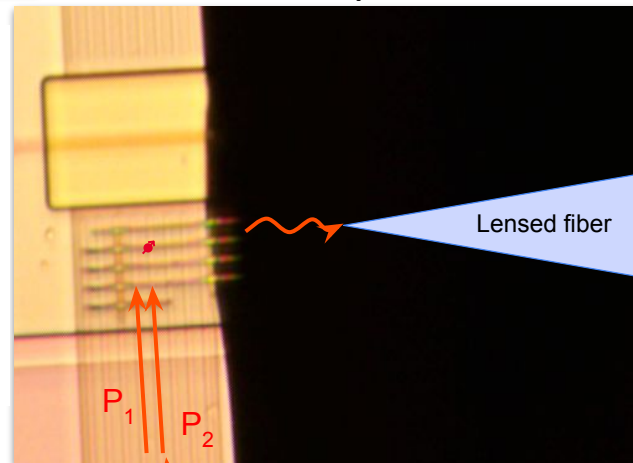


Simulations yield nearly 60dB pump extinction with high Rabi rate, but difficult to accurately model due to non-identical mesh points in scattering regions.



Experiments currently underway!

Proof-of-concept device:



Off-chip phase and amplitude control

Project Goals:

- Designing efficient, scalable interfaces for spin-photon entanglement of color centers
- Efficiency Enhancement: Improve the efficiency, scalability, and reliability of quantum networks by enhancing spin-photon interfaces and quantum memory systems.
- Scalability: Develop multi-emitter spin-light interfaces within a single system to scale quantum networks effectively.
- Digital Twin Creation: Develop a digital twin for quantum networks to simulate and optimize spin-photon interfaces and quantum memory systems.

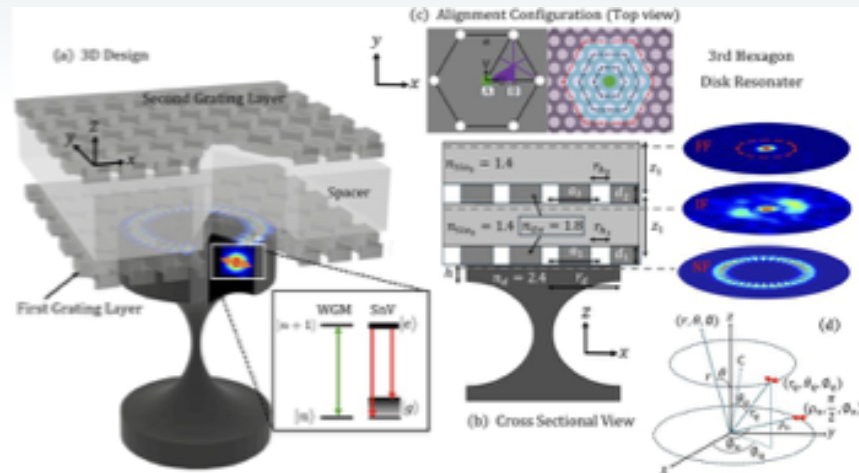
Barriers:

- Purcell enhancement and coupling efficiency are often inversely correlated
- Manufacturing variations reduce efficiency

Methodologies to Overcome Barriers:

- Further Enhanced Quantum Efficiency
- Optimization of Spin-Photon Interfaces
- Alignment-Free Coupling

Camacho & Englund



Future work

- Improving Entanglement generation
- Combine frequency conversion + spatial conversion
- Digital Twin Creation

S. Mirzaei-Ghormish, et al, "High-efficiency vertical emission spin-photon interface for scalable quantum memories," arXiv:2503.20111 (2025)

Thrust 3 Summary

3A: Lanthanide-based molecular color centers with engineered Yb^{3+} fields for tunable spin–optical coherence.

3A: Antenna and chiral ligands enhance yield and enable spin-selective processes.

3B: SNSPD-based logic circuits for scalable quantum communication.

3B: High-Tc MgB_2/YBCO devices operate up to 72 K with CMOS compatibility.

3C: Wafer-scale thin-film ferroelectrics (TFLN, TFLT) for nonlinear frequency conversion and wavelength trimming; UV generation demonstrated; Strategies for on-chip ZALM developed;

3C: Thin film diamond cavities and waveguides demonstrated and integrated with TFLN.

3D: SiV-based repeater nodes with asynchronous Bell-state measurements and ^{13}C memories.

3D: Metro-area network developed and used for blind quantum computing and astronomy;

3E: Piezo-actuated and strain-engineered photonics for tunable emitters.

3E: Diamond spin–phonon systems (LiNDa, phononic crystals) with long coherence and high-Q coupling.

3F: Architectures for multiplexed entanglement swaps.

3F: Reduced loss and improved throughput for scalable quantum networks.

3G: Cavity-QED and dual-layer photonic interfaces with >95% fiber mode overlap.

3G: >90% modeled coupling for SiV/SnV centers for scalable repeater nodes.

