Advancements Towards a Deployable Compact Diamond Quantum Device

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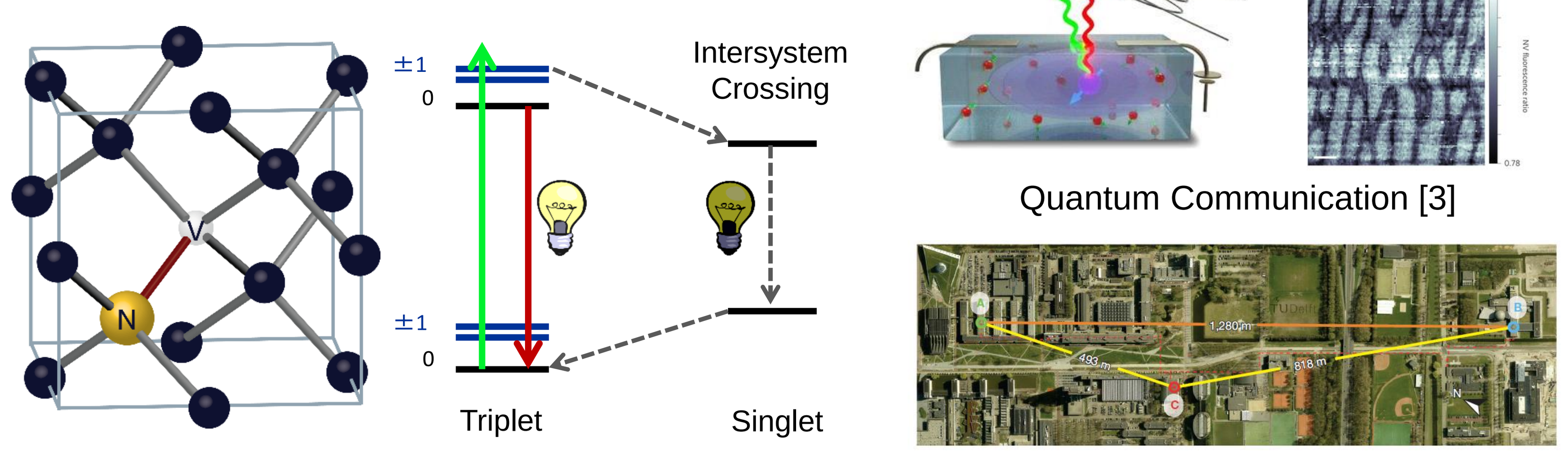
Abstract

The electron spin in nitrogen-vacancy (NV) center in diamond has been uniquely situated as a promising building block for quantum technologies as its long coherence time at room temperature and optical interface facilitate flexible readout protocols and enable versatility in applications. However, significant engineering challenges remain in realizing practical, deployable diamond-based devices in quantum communication, computing, and sensing. Among these roadblocks are poor photon collection due to diamond's high refractive index, experimental overhead in sub-optimal initialization fidelities for the NV center, as well as the bulkiness and high power-consumption of bench-top electronics used for generating quantum control sequences. To this end, I have explored nanophotonic structures that improve the performance and scalability of optical interfaces for NV centers in diamond, demonstrating a monolithic immersion metalens with NA > 1 across the NV emission spectrum. I have worked with fellow members of Quantum Engineering Laboratory to showcase a real-time initialization protocol with improved NV charge-state initialization. Through a collaboration with Prof. Aflatouni's group here at Penn, I have also implemented spin control experiments with the first iterations of CMOS microwave sequence generators that can be readily integrated with the NV device. With these advances, I continue to work towards the realization of efficient, compact diamond quantum devices.

Spin Qubits in Diamond

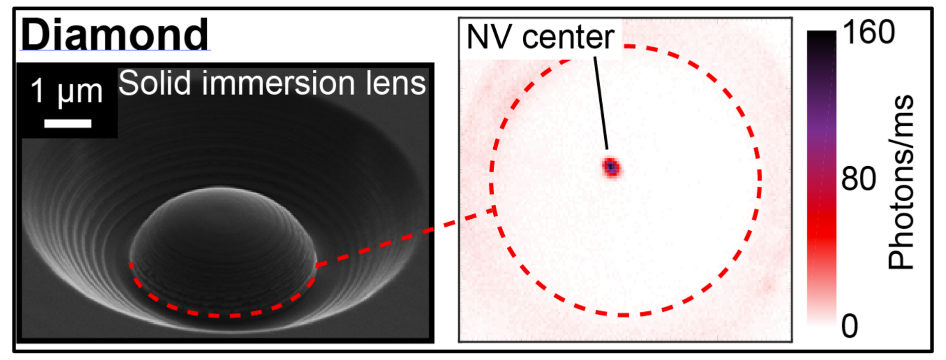
Nitrogen-Vacancy (NV) centers

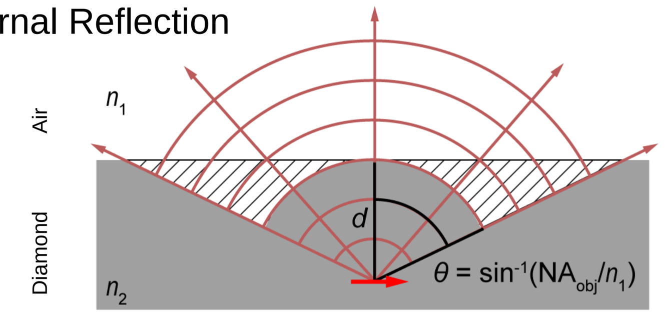
NV Atomic Structure | NV⁻ Electronic Structure | Efficient Readout [1] | Magnetometry [2] | Quantum Communication [3]



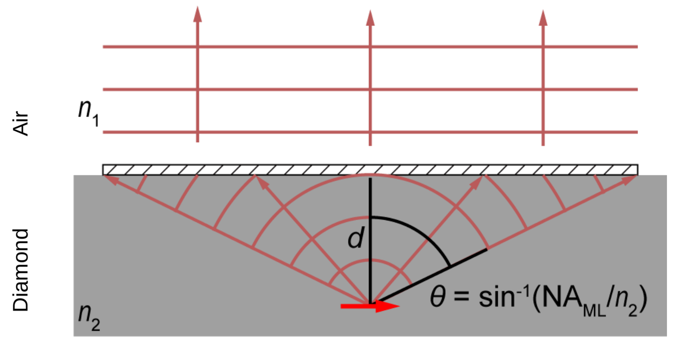
Enabling direct fiber-coupling of NV centers

High Refractive Index and Total Internal Reflection





Uniform OPL with a SIL, diverging emission from NV

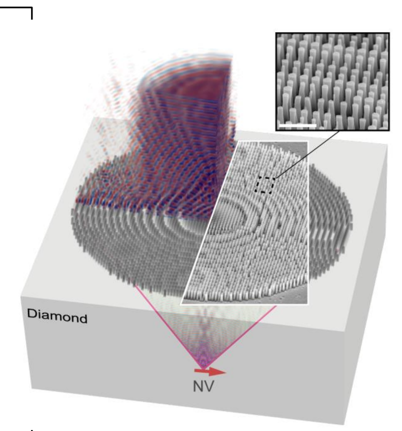


Flat immersion optic at the air-diamond interface

Existing approach
- Solid immersion lens (SIL) using focused ion beam (FIB)

Challenges
- Material loss, slow fabrication, still requires high NA objective

New solution
- Monolithic metalens at the air-diamond interface [4]

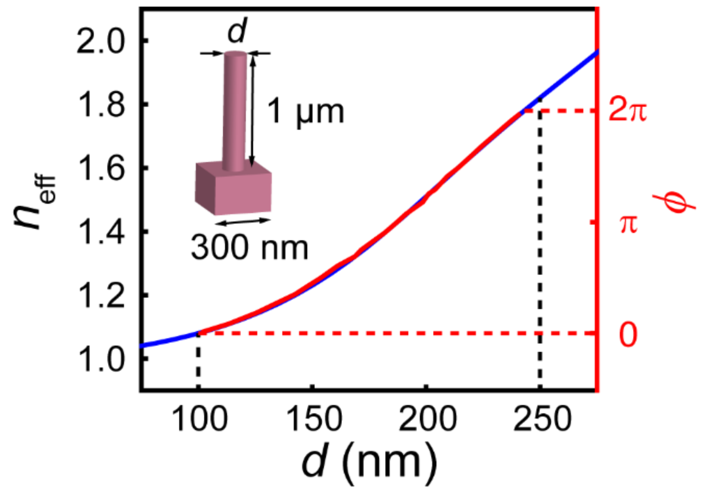


A Monolithic Diamond Metalens

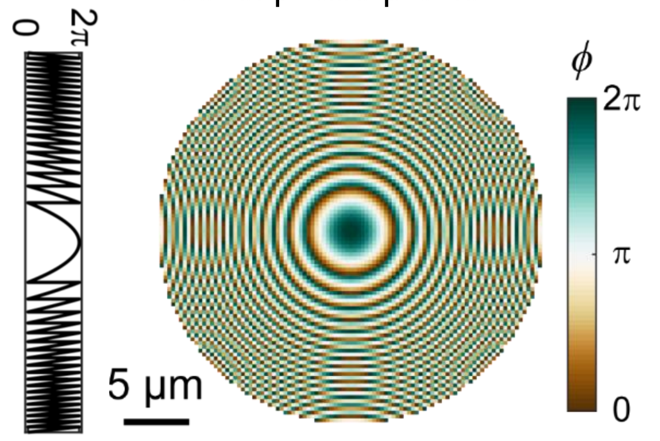
Metalens design

Subwavelength elements approximate a Fresnel lens

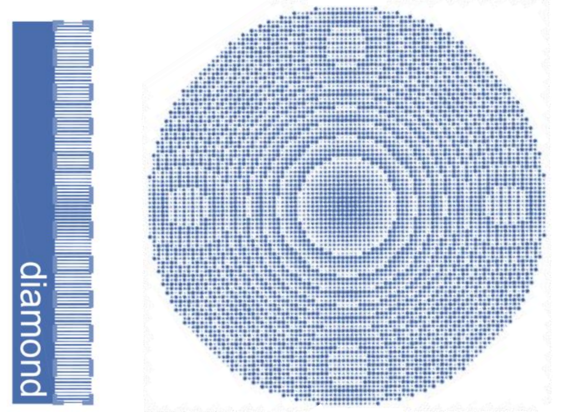
Effective refractive index



Fresnel phase profile

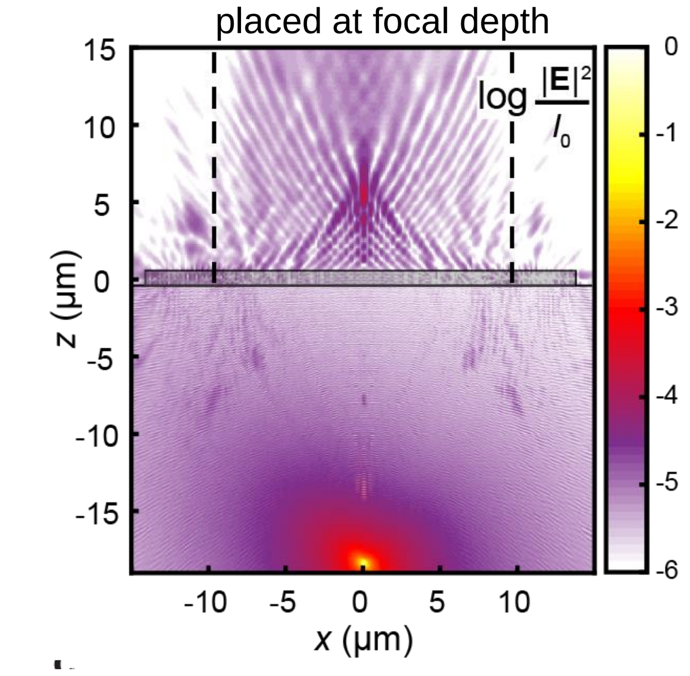


Discretized into pillars

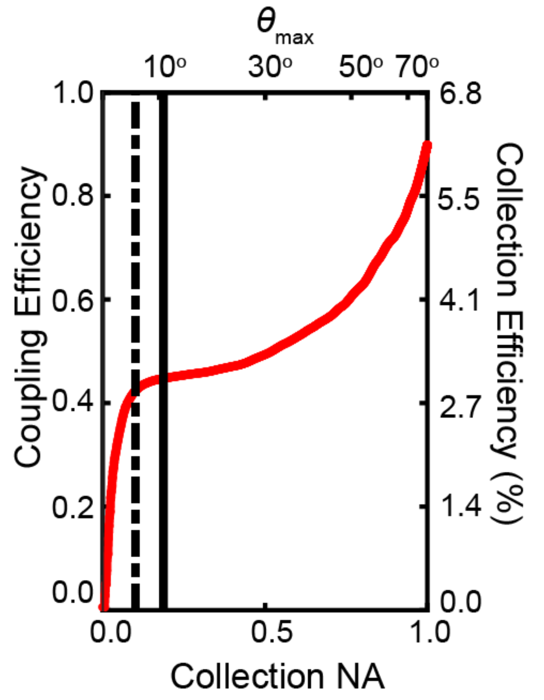


NA and collection efficiency

Full field 3D simulation with NV placed at focal depth

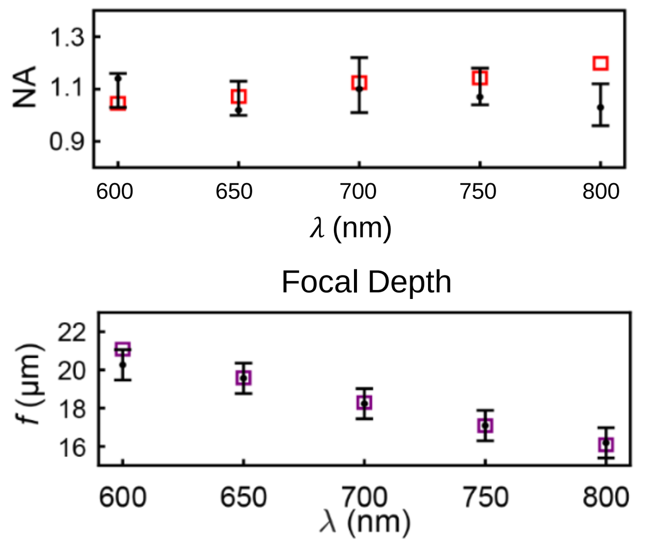


Limited transmission outside of 20μm diameter



Within that 20μm, only 40% can be collected into a fiber

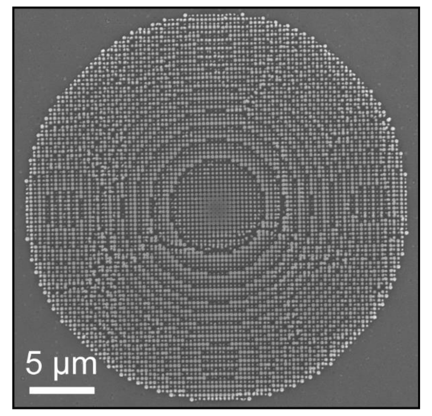
Measured NA and focal depth



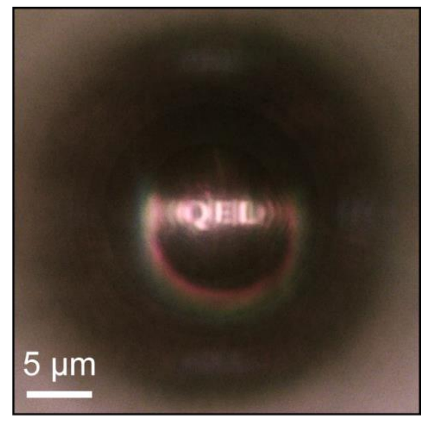
NA ≈ 1.1 across NV emission spectrum

Imaging a Single NV Center

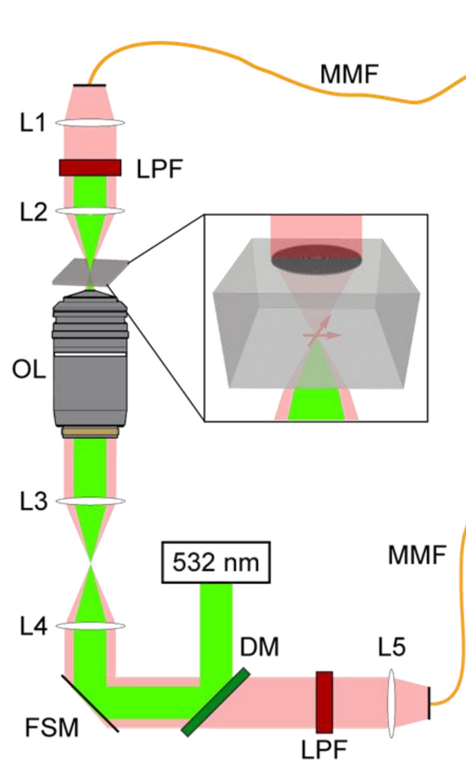
SEM Image



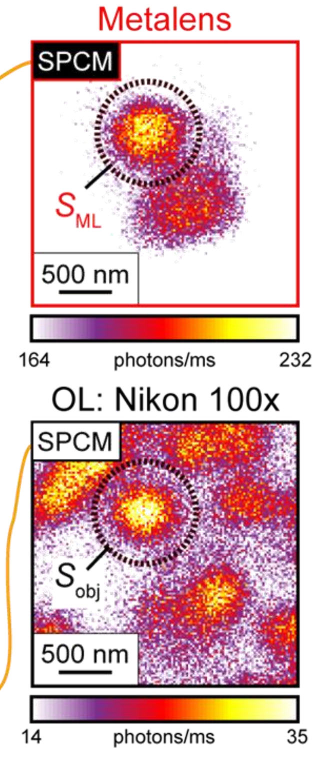
Forming an image



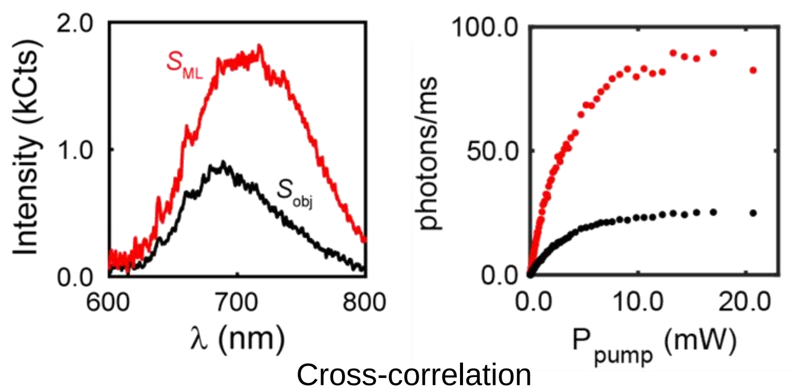
Experimental Setup



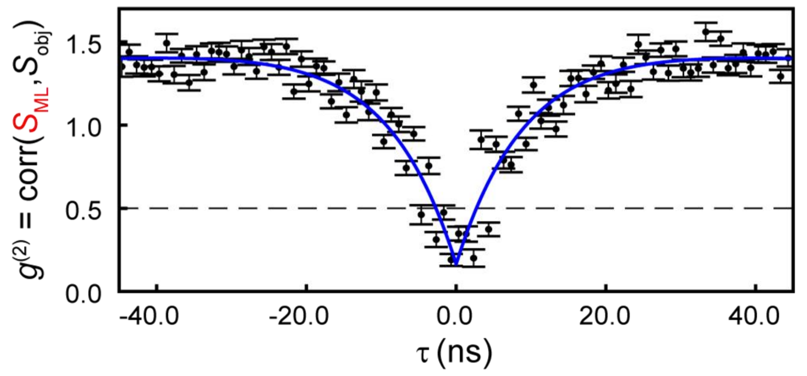
PL Scans



PL spectra | Saturation Curves



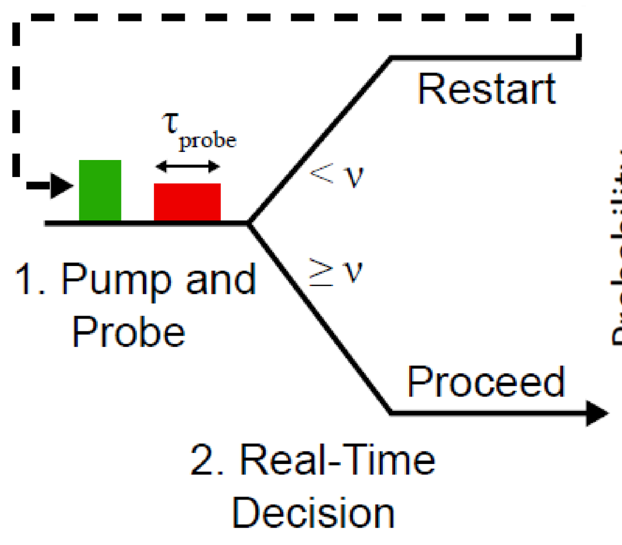
Cross-correlation



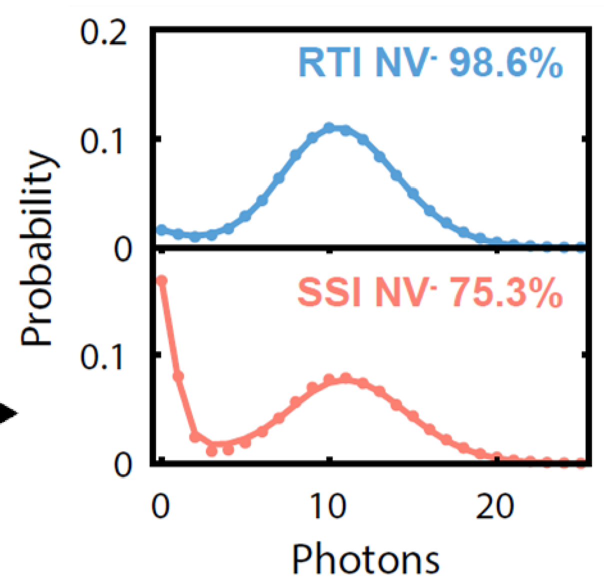
Real-time Charge State Initialization

Real-time logic through field-programmable gate array

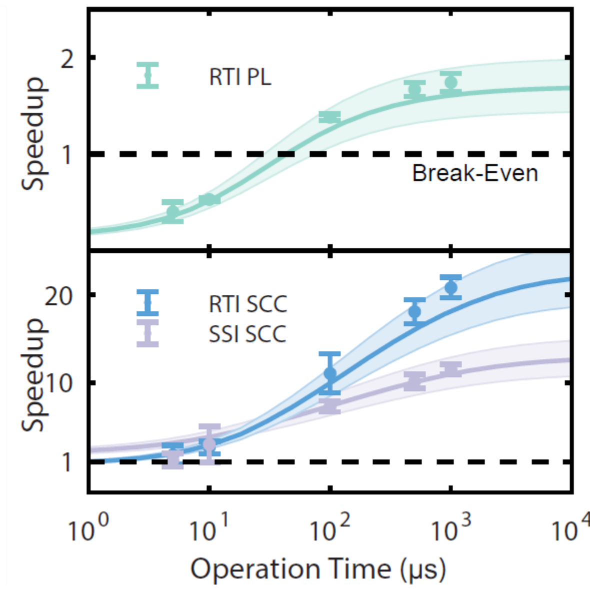
Experiment decision tree [5]



Charge state initialization



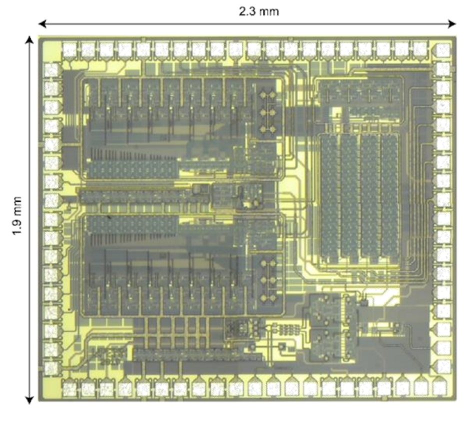
Measurement speedup



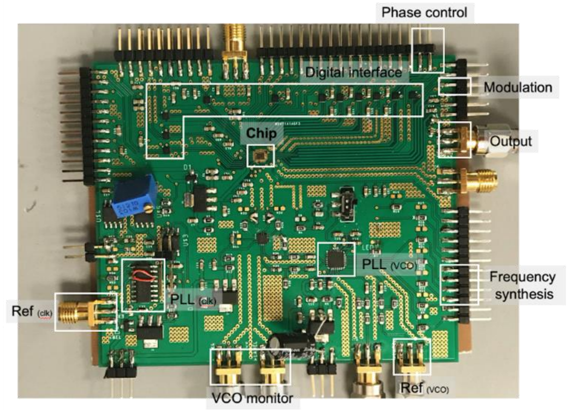
CMOS μ-wave pulse generators

CMOS co-design: classical components tailored for the NV center

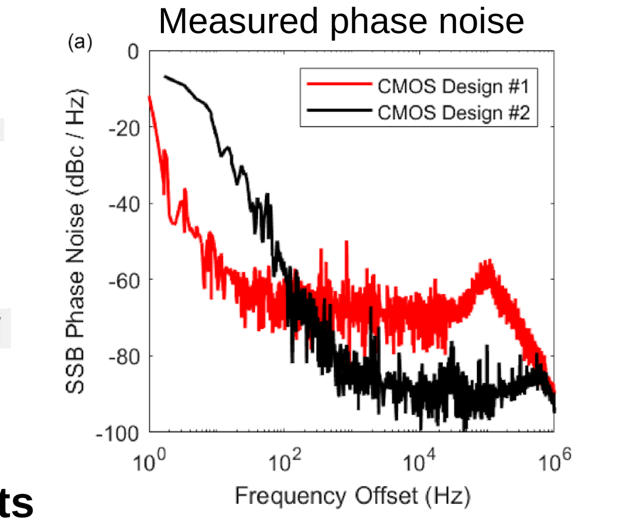
Custom CMOS chip



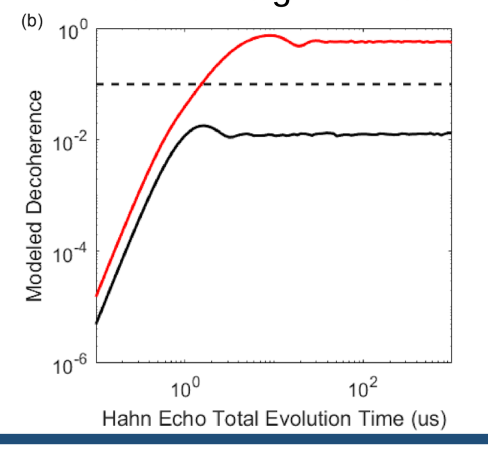
Mounted on custom PCB



Measured phase noise

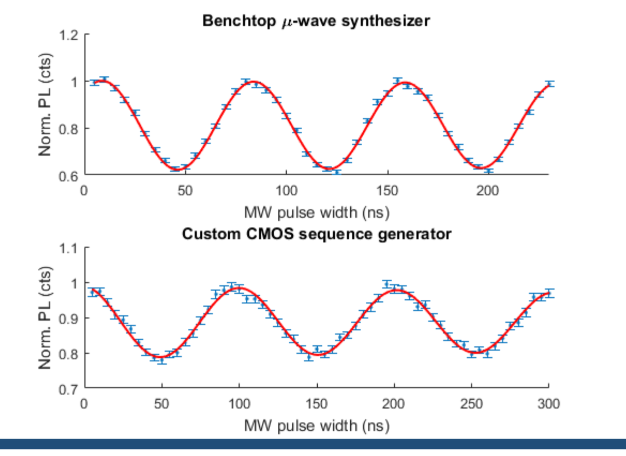


Simulated decoherence from control signal noise

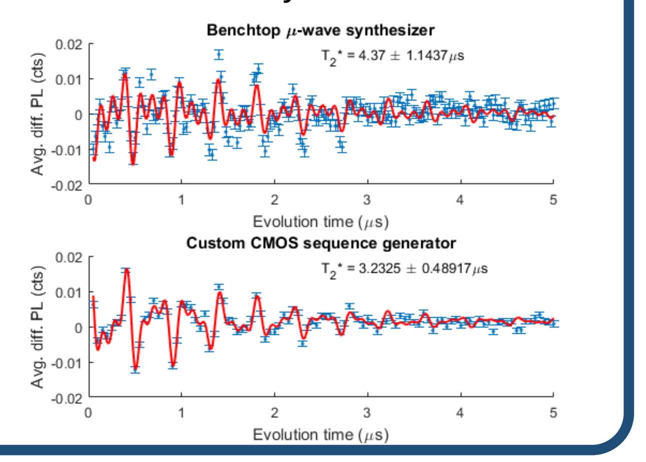


Spin control measurements

Rabi oscillations



Ramsey oscillations



Acknowledgements & References

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1. Hopper *et al.*, *Micromachines* **9**, 437 (2018).
2. Hensen *et al.*, *Nature* **526** (2015).
3. Pelliccione *et al.*, *Nat. Nanotech.* **11** (2016).
4. Huang, Grote *et al.*, *Nat. Commun.* **10**, 2392 (2019).
5. Hopper *et al.*, *Phys. Rev. Applied* **13** (2), 024016 (2020).