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MURI 11) MULTI-FUNCTIONAL LIGHT-MATTER INTERFACES BASED ON NEUTRAL ATOMS AND SOLIDS

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14. ABSTRACT

The objective of this MURI program is the development of light-matter interfaces with the quantum memory and local quantum processing capabilities using atomic and solid-state systems. Quantum repeater architectures, which use quantum memory elements as nodes and light for transmission, require storage lifetimes that are large compared to the classical communication time between nodes. Storage lifetime requirements are increased further by the actual communication process, where multiple successful entanglement distributions are necessary within the quantum memory lifetime for the formation of a single quantum bit. For communication over distances of 1,000 km, quantum memory lifetimes of many seconds are required. This team pursues a program aimed at development and implementation of such long-lived quantum memories that can be strongly coupled to light. A promising candidate for a platform to implement such nodes is a charged quantum dot embedded in a nanoresonator. The use of resonators can strongly enhance light-matter interactions and therefore efficiently transfer information between photons and stationary qubits, and realize photonic quantum gates. Team members also employ the hyperfine ground levels of ultra-cold atoms, and charged nitrogen-vacancy and silicon vacancy defect centers in diamond as memory qubits

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MULTI-FUNCTIONAL LIGHT-MATTER INTERFACES BASED ON NEUTRAL ATOMS AND SOLIDS

FINAL REPORT

PROGRAM OBJECTIVE and SCIENTIFIC APPROACH: The objective of this MURI program is the development of light-matter interfaces with the quantum memory and local quantum processing capabilities using atomic and solid-state systems. Quantum repeater architectures, which use quantum memory elements as nodes and light for transmission, require storage lifetimes that are large compared to the classical communication time between nodes. Storage lifetime requirements are increased further by the actual communication process, where multiple successful entanglement distributions are necessary within the quantum memory lifetime for the formation of a single quantum bit. For communication over distances of 1,000 km, quantum memory lifetimes of many seconds are required**.** This team pursues a program aimed at development and implementation of such long-lived quantum memories that can be strongly coupled to light. A promising candidate for a platform to implement such nodes is a charged quantum dot embedded in a nanoresonator. The use of resonators can strongly enhance light-matter interactions and therefore efficiently transfer information between photons and stationary qubits, and realize photonic quantum gates. Team members also employ the hyperfine ground levels of ultra-cold atoms, and charged nitrogen-vacancy and silicon vacancy defect centers in diamond as memory qubits. The activities during the first three years were devoted to the development of key capabilities required for the future realization of small-scale quantum processors and demonstration of basic scalable quantum communication protocols.

MURI CONSORTIUM RESEARCH TEAM MEMBERS:

PIs	Prof. Alex Kuzmich (University of Michigan, until 12/2013), Prof. Brian Kennedy (Georgia Tech, since 1/2014)
Co-PIs	Prof. Mikhail Lukin, Prof. Marko Loncar (Harvard University)
Co-PIs	Prof. Vladan Vuletic, Prof. Dirk Englund (Massachusetts Institute of Technology)
Co-PI	Prof. Mark Saffman, Thad Walker (University of Wisconsin)
Co-PI	Prof. Jelena Vuckovic (Stanford University)
Co-PIs	Prof. Luming Duan (University of Michigan)

MAJOR ACCOMPLISHMENTS: This MURI team has been breaking new ground in the area of atom-light interfaces. It has performed the initial experimental demonstrations of light-Rydberg atoms quantum interfaces, which has opened up unique opportunities for novel research: the first many-body Rabi oscillations were observed, and photon-photon interactions were demonstrated at the single-photon level. Significant advances in the area of NV and SiV centers and diamond nanophotonics exploit subwavelength localization of emitters from integrated structures. The first single-photon transistor is another notable breakthrough achieved in this program. Some of the most significant accomplishments are summarized below.

- **Rydberg single-photon source** (Kuzmich): In a seminal experiment, Rydberg excitations in an ultra-cold atomic gas were created and subsequently converted into light pulses. As the principal quantum number *n* was increased beyond 70, only a single excitation was retrieved from the ensemble of about 500 atoms.
  In this experiment, the dephasing of multiply-excited spin-waves acted as ``quantum scissors" which truncated the states with more than one excitation. The single photon source had a lower $g^{(2)}(0)$, higher probability of photoelectric detection, and was more than three orders of magnitude faster than a deterministic single photon source based on the classic Duan-Lukin-Cirac-Zoller protocol. Subsequently, deterministic entanglement of an optical atomic excitation and a light field was demonstrated.

- **Coherent many-body Rabi oscillations** (Kuzmich,Saffman,Walker): In the limit where only a single excitation is present in an ensemble of N atoms, a collective, many-body Rabi oscillation at a frequency $\sqrt{N}\Omega$ arises that involves all N atoms, even in inhomogeneous systems. When one of the two levels is a strongly interacting Rydberg level, many-body Rabi oscillations emerge as a consequence of Rydberg blockade. Such oscillations between the ground and Rydberg levels were observed in Kuzmich's laboratory using several hundred cold rubidium atoms and using, several atoms, in Saffman and Walker group. The strongly pronounced oscillations indicated high-quality blockade of the mesoscopic ensemble by just one excited atom.

- **Nonlinear quantum optical medium** (Lukin, Vuletic): The fundamental properties of light derive from its constituent particles—massless quanta (photons) that do not interact with one another. However, it has long been known that the realization of coherent interactions between individual photons, akin to those associated with conventional massive particles, could enable a wide variety of novel scientific and engineering applications.· Lukin and Vuletic groups demonstrated a quantum nonlinear medium inside which individual photons traveled as massive particles with strong mutual attraction, such that the propagation of photon pairs was dominated by a two-photon bound state. They achieved this through dispersive coupling of light to strongly interacting atoms in highly excited Rydberg states. The dynamical evolution of the two-photon wavefunction was measured through use of time-resolved quantum state tomography, and a conditional phase shift that exceeded one radian was observed, resulting in polarization-entangled photon pairs. This approach paves the way for quantum-by-quantum control of light fields, which included single-photon switching, all-optical deterministic quantum logic and the realization of strongly correlated many-body states of light.

- **Single-photon transistor** (Lukin, Vuletic): Using an atomic ensemble inside an optical cavity, they have also realized a single-photon transistor, where a single photon stored in an atomic medium can switch many photons incident in another direction. The realization of an all-optical transistor, in which one "gate" photon controls a "source" light beam, is a long-standing goal in optics. By stopping a light pulse in an atomic ensemble contained inside an optical resonator, we realized a device in which one stored gate photon controls the resonator transmission of subsequently applied source photons. A weak gate pulse induced bimodal transmission distribution, corresponding to zero and one gate photons. One stored gate photon produced fivefold source attenuation and could be retrieved from the atomic ensemble after switching more than one source photon. Without retrieval, one stored gate photon could switch several hundred source photons. With improved storage and retrieval efficiency, our work may enable various new applications, including photonic quantum gates and deterministic multiphoton entanglement.

- **Single-atom quantum switch** (Vuletic, Lukin): By analogy to transistors in classical electronic circuits, quantum optical switches are important elements of quantum circuits and quantum networks. Operated at the fundamental limit where a single quantum of light or matter controls another field or material system, such a switch may enable applications such as long-distance quantum communication, distributed quantum information processing, and metrology, and the exploration of novel quantum states of matter. By strongly coupling a photon to a single atom trapped in the near field of a nanoscale photonic crystal cavity, we realized a system in which a single atom switched the phases of a photon and a single photon modified them atom's phase. We experimentally demonstrated an atom-induced optical phase shift that was nonlinear at the two-photon level, a photon number router that separated individual photons and photon pairs into different output modes, and a single-photon switch in which a single "gate" photon controlled the propagation of a subsequent probe field. Those techniques paved the way to integrated quantum nanophotonic networks that involved multiple atomic nodes connected by guided light.

- **Minute-scale light storage** (Kuzmich): The memory lifetime in prior lattice memory was limited by the inhomogeneous differential Stark-shifts induced by the optical lattice. Kuzmich group subsequently observed quantum memory lifetimes in excess of 0.1 s by two-photon laser compensation of the differential optical lattice light shifts. More recently they achieved coherent light storage with a 0.32 s lifetime and 0.1 s qubit storage times by a ``magic''-valued magnetic field superposed onto the optical lattice to eliminate lattice-induced dephasing. While the clock coherence becomes first-order sensitive to magnetic field, it is weakly so, allowing greatly increased coherence times. In 2013 they reported an important advance of a minute-scale atomic memory, achieved by combining the magic-magnetic field technique with a dynamic decoupling microwave pulse sequence that is resonant on the clock transition.

- **Development of novel approaches to interfacing light with NV-centers and quantum dots** (Lukin, Loncar, Englund, Vuckovic): The realization of efficient optical interfaces for solid-state atom-like systems is an important problem in quantum science with potential applications in quantum communications and quantum information processing. Lukin and Loncar groups reported the observation of stable optical transitions in nitrogen-vacancy centers created by ion implantation. Through use of a combination of high temperature annealing and subsequent surface treatments, they reproducibly created nitrogen-vacancy centers with zero-phonon lines which exhibited spectral diffusion that was close to the lifetime-limited optical linewidth - a crucial step in the development of diamond-based devices for quantum optics, nanophotonics, and quantum information science. Lukin and Loncar groups also demonstrated a technique for coupling single nitrogen vacancy centers to suspend diamond photonic crystal cavities with quality factors up to 6000, and developed novel angled-etching approach to diamond fabrication. They have developed novel material processing techniques (ion implantation, and annealing) that result in stable centers in diamond nanostructures with linewidths <100MHz. Vuckovic group fabricated nanobeam photonic crystal cavities with modes of frequency separations greater than 700 nm. They fabricated nanobeam photonic crystal cavities with resonances at 1570 nm and 920 nm with *Q* factors of 10,000 and 3,000 respectively and used sum frequency generation with light input modes at 1955 nm and 1300 nm to upconvert light from 1300 nm to 780 nm. Englund group developed an all-diamond NV-cavity system in the strong Purcell regime. Quality factors of diamond planar photonic crystal nanocavities reach up to 10,000 -the highest Qs reported to date. They have achieved spectrally resolved Purcell factors well in excess of F=100 and cavity-coupled nitrogen-vacancy systems with spin coherence time approaching 1 ms. More than 80% of excited-state fluorescence is emitted into the zero phonon line, which represents by far the greatest spectral efficiency reported to date. Microwave strip lines are integrated on the chip for efficient spin control of cavity-coupled nitrogen-vacancy systems.

- **Novel protocols for light-matter interfaces** (Duan, Kennedy, Lukin, Saffman, Walker): Theory work by the Duan group has investigated several experimental systems for the light-matter interface, including quantum dots, nitrogen vacancy centers in diamonds, atomic ensembles, and photons. They proposed schemes to use these systems to generate a class of many-particle entangled states, the so-called Dicke squeezed states, which can be used for quantum metrology and network applications. They also proposed an experimental method to detect many-body entanglement in the vicinity of the Dicke states. For diamond defects, in collaboration with Lukin's group, they proposed and analyzed a scheme to realize remote state transfer between spin quantum memories. Kennedy and Kuzmich groups proposed that rather than trying to avoid excitation of more than a single atom via the Rydberg blockade mechanism, multiple Rydberg excitations are allowed to mutually interact and dephase. The interaction-induced phase shifts suppress the contribution of multiply-excited states in phase-matched optical retrieval. The dephasing mechanism therefore permits isolation and manipulation of individual spin-wave excitations for the generation of atom-atom and atom-light entanglement. Kennedy group investigated motional dephasing of atoms in an atomic ensemble quantum memory suspended in a 1-d optical lattice. The theory enables identification of orientation and alignment of the density matrix of the quantum memory, through photon correlation measurements with photons retrieved from the quantum memory. They also developed an analytical theory to explains the microsecond dynamics for both Rydberg dipolar and van der Waals interactions. Saffman group have developed new adiabatic pulse protocols that allow high fidelity quantum gates to be performed on ensembles with unknown atom number. Using double pulse STIRAP or ARP sequences they implement a universal set of gates on collectively encoded qubits with high fidelity despite unknown atom number. They have also analyzed the possibility of using circular Rydberg states for higher fidelity entangling gates. By combining precision metrology and quantum networks, Lukin group proposed a quantum, cooperative protocol for the operation of a network, which consisted of geographically remote optical atomic clocks, and showed that such a network could be operated near the fundamental limit set by quantum theory, which yielded an ultra-precise clock signal. Realization of such a global quantum network of clocks may allow construction of a real-time single international time scale (world clock) with unprecedented stability and accuracy. Several of the theoretical proposals are being implemented experimentally.

(a) NV Centers work at Columbia/MIT (Englund)

1. Development of Solid State Spin-Photon Interfaces

MIT demonstrated efficient coupling of an NV center to an optical nanocavity, achieving the highest reported Purcell factor and also performing coherent spin manipulation of the cavity-coupled NV, for the first time(Li, Schröder, et al. 2015). However, this early NV-cavity demonstration had very low fabrication yield, so in much of the later part of the program, we focused on developing methods to improve yield and scale up the NV-cavity fabrication, while also improving low-temperature NV properties. The results include new methods for direct implantation of NV and SiV centers into diamond nanocavities(Schröder, Trusheim, et al. 2016; Schukraft et al. 2016; Schröder, Mouradian, et al. 2016; Al 2017). We also developed hybrid cavity designs that can be spectrally tuned and integrated on large-scale photonic integrated circuits(S. Mouradian and Englund 2016). We also developed circular diamond gratings that achieve the highest photon count rate from NV centers(Li, Chen, et al. 2015).

2. Efficient Coupling of Spin Qubits to Waveguides and Fiber

MIT developed an efficient interface to couple from NV centers within diamond waveguides into optical silica fiber. This allowed the highest (at the time) collection rate of NV fluorescence into single-mode fiber(Patel et al. 2016). We also developed an approach for the scalable incorporation of high-quality spin qubits into photonic integrated circuits(S. L. Mouradian et al. 2015). This approach overcomes low fabrication yield.

3. NV Implantation for Multi-Spin Qubit Registers

Solid-state quantum memories will likely require at least about ten spins to enable full error correction. To this end, we developed methods of implanting multi-NV spin registers into diamond in a way that is compatible with their incorporation into nanocavity photon interfaces. Recent results have pushed spatial resolution to record low levels(Scarabelli et al. 2016; Bayn et al. 2015) below 20 nm.

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51. Patel, R., Schroder, T., Wan, N., et al., "Efficient Single Photon Generation using a Fiber-integrated Diamond Micro-Waveguide," Conference on Lasers & Electro-optics (2015)

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60. Mihir Pant and Dirk Englund, "High-Dimensional Unitary Transformations on Temporal Modes," SIPQNP 2015 (2015)
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62. Dirk Englund, "Computing, Communicating, and Sensing with Spins and Photons," Engineering Now: Insights from the Labs at MIT: 2016 National Academy of Engineering Symposium at MIT (2016)
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64. Dirk Englund, "Semiconductor Quantum Technologies for Information Processing and Sensing," US Naval Undersea Warfare Center Research Seminar Series (2016)
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71. Dirk Englund, "Semiconductor Quantum Technologies for Communications and Computing," Niels Bohr Institute Colloquium (2017)
72. "Dirk Englund, "Networking Quantum Memories on Photonic Integrated Circuits," Physikalisches Kolloquium, Department für Physik FAU Erlangen-Nürnberg (2017)"
73. Dirk Englund, "Semiconductor Quantum Technologies for Communications and Computing," Center for Ultracold Atoms, MIT (2017)
74. Dirk Englund, "Quantum Information Processing with Spins and Photons in Semiconductor Circuits," Vienna Physics Colloquium (2017)

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B. NV, SiV centres, quantum gates and nanophotonics work at Harvard

B(i) Lukin

Efficient interfaces between photons and quantum emitters form the basis for quantum networks and enable nonlinear optical devices operating at the single-photon level. By coupling silicon-vacancy (SiV) color centers to a diamond nanophotonic device, we realized a quantum optical switch controlled by a single atom-like crystal defect. In our approach, SiV centers are deterministically positioned in diamond photonic-crystal cavities using targeted silicon implantation. We observed that the cavity transmission is substantially attenuated by a single SiV center, is nonlinear at less than one photon per system's bandwidth, and can be switched by optically controlling SiV metastable orbital states. Photon correlation measurements are used to verify optical switching at the single-photon level. Our approach enables the realization of fully integrated, scalable nanophotonic quantum devices.

We proposed and analyzed heralded quantum gates between qubits in optical cavities. They employ an auxiliary qubit to report if a successful gate occurred. In this manner, the errors, which would have corrupted a deterministic gate, are converted into a non-unity probability of success: once successful the gate has a much higher fidelity than a similar deterministic gate. Specifically, we described that a heralded, near-deterministic controlled phase gate (CZ-gate) with the conditional error arbitrarily close to zero and the success probability that approaches unity as the cooperativity of the system, C, becomes large. Furthermore, we described an extension to near-deterministic N- qubit Toffoli gate with a favorable error scaling. These gates can be directly employed in quantum repeater networks to facilitate near-ideal entanglement swapping, thus greatly speeding up the entanglement distribution.

We reported direct measurement of population dynamics in the excited state manifold of a nitrogen-vacancy (NV) center in diamond. We quantified the phonon-induced mixing rate and demonstrated that it can be completely suppressed at low temperatures. Further, we measured the intersystem crossing (ISC) rate for different excited states and develop a theoretical model that unifies the phonon-induced mixing and ISC mechanisms. We found that our model was in excellent agreement with experiment and that it can be used to predict unknown elements of the NV center's electronic structure. We discussed the model's implications for enhancing the NV center's performance as a room-temperature sensor.

We demonstrated a method for efficient coupling of guided light from a single-mode optical fiber to nanophotonic devices. Our approach makes use of single-sided conical tapered optical fibers that are evanescently coupled over the last ~10 μm to a nanophotonic waveguide. By means of adiabatic mode transfer using a properly chosen taper, single-mode fiber-waveguide coupling efficiencies as high as 97 (1)% are achieved. Efficient coupling is obtained for a wide range of device geometries, which are either singly clamped on a chip or attached to the fiber, demonstrating a promising approach for integrated nanophotonic circuits, and quantum optical and nanoscale sensing applications.

Publications

1.A. Sipahigil, R. E. Evans, D. D. Sukachev, M. J. Burek, C. T. Nguyen, J. Borregaard, M. K. Bhaskar, J. L. Pacheco, H. Atikian, R. M. Camacho, F. Jelezko, E. Bielejec, H. Park, M. Loncar, M. D. Lukin, "Quantum optical switch controlled by a color center in a diamond nanocavity," *Science*, submitted (2016).

2. R. E. Evans, A. Sipahigil, D.D. Sukachev, A. S. Zibrov, M. D. Lukin, "Coherent optical emitters in diamond nanostructures via ion implantation," arXiv:1512.03820, (2015).

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8. M. L. Goldman, A. Sipahigil, N. Y. Yao, S. D. Bennett, M. Markham, D. J. Twitchen, A. Kubanek, M. D. Lukin, “Phonon-Induced Population Dynamics and Intersystem Crossing in Nitrogen-Vacancy Centers,” *Physical Review Letters* 114 (14), 145502 (2015).

9. K.D. Jahnke, A. Sipahigil, J.M. Binder, M.W. Doherty, M. Metsch, L.J. Rogers, N.B. Manson, M.D. Lukin, F. Jelezko, “Electron-Phonon Processes of the Silicon-Vacancy Centre in Diamond,” *New Journal of Physics 17* (4), 043011 (2015).

10. T.G. Tiecke, K.P. Nayak, J.D. Thompson, T. Peyronel, N.P. de Leon, V. Vuletic, M.D. Lukin, “Efficient Fiber-Optical Interface for Nanophotonic Devices,” *Optica* 2 (2), 70-75, (2014)

Awards: Julius Springer Prize, 2015

Students and Postdocs Supported by Award

Graduate Students (5)

Alp Sipahigil, Ruffin Evans, Polnop Samutpraphoot, Alexander Keesling-Contreras, Michael Goldman

Postdocs (5)

Denis Sukachev, Kristiaan DeGreve, Crystal Senko, Hannes Bernien, Manuel Endres

B(ii) NV Center work at Harvard (Loncar)

In the first two years of the project the project concentrated on a thin film platform and an angle-etched approach. During year 2015 our activities were focused on two main fronts:

Development of cQED platform based on SiV color centers embedded inside diamond photonics crystal cavities:

Together with Misha Lukin we have demonstrated a photon switch based on SiV center implanted inside diamond photonics crystal nano beam cavity (Q~10,000 @ ~740nm wavelength). Our system features cooperativity of C~1 which allowed us to explore its performance as a single-photon switch. For example, we demonstrated that SiV-cavity system scatters single-photon fields in the vertical direction (outside the cavity) while two-photon fields are transmitted through the cavity. Furthermore, the state of the switch could be controlled by controlling the spin-degrees of freedom of SiV.

Development of efficient fiber-diamond cavity coupling:

Using tapered optical fiber – fabricated by HF erosion of standard silica fibers – in contact with tapered diamond waveguide, we were able to demonstrate fiber-diamond waveguide – diamond cavity coupling efficiency exceeding 90% (experimental). This is of great interest for future development of cQED with diamond as it allows for efficient in- and out-coupling of photons.

Publications and Awards

1) B.J.M. Hausmann, B. Shields, Q. Quan, P. Maletinsky, M. McCutcheon, J.T. Choy, T.M. Babinec, A. Kubanek, A. Yacoby, M.D. Lukin, and M. Lončar, *"Integrated diamond networks for quantum nanophotonics"*, *Nano Letters*, **12**, 1578 (2012). *http://pubs.acs.org/doi/abs/10.1021/nl204449n*

2) B. J. M. Hausmann, B. J. Shields, Q. Quan, Y. Chu, N. P. de Leon, R. Evans, et al, *"Coupling of NV centers to photonic crystal nanobeams in diamond"*, *Nano letters*, **13** (12), 5791-5796 (2013). http://pubs.acs.org/doi/abs/10.1021/nl402174g

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6) M. J. Burek, D. Ramos, P Patel, IW Frank, M Loncar, *"Nanomechanical resonant structures in single-crystal diamond", Applied Physics Letters*, **103** (13), 131904 (2013) http://scitation.aip.org/content/aip/journal/apl/103/13/10.1063/1.4821917

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15) Z. Lin, T. Alcorn, M. Loncar, S. G. Johnson, A. W. Rodriguez, *"High-efficiency degenerate four wave-mixing in triply resonant nanobeam cavities"*, arXiv:1311.4100

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17) M. J. Burek, J. D. Cohen, S. M. Meenehan, T. Ruelle, S. Meesala, J. Rochman, H. A. Atikian, M. Markham, D. J. Twitchen, M. Lukin, O. J. Painter, and M. Lončar, "Diamond optomechanical crystals." *arXiv:1512.04166* (2015)

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19) Z. Lin, S.G. Johnson, A.W. Rodriguez, M. Loncar, "Design of diamond microcavities for single photon frequency down-conversion", *Optics express*, **19**, pp. 25279-25294 (2015).

Students and postdocs supported by the award: three students, 1/3 effort each (1 total).

Awards:

M. Loncar: promoted to named tenured faculty position - official title Tiantsai Lin Professor of Electrical Engineering; grad student Birgit Hausmann won graduate student fellowship from Harvard Quantum Optics Center.

Patents/ technology transfer:

Prof. Lukin anf Prof. Loncar filed total of three patents related to the work done within the scope of the MURI program and have established strong collaboration with industrial partner Element 6. Specifically, they have a grant from Element 6 that is aimed at reduction in reflectivity from diamond surfaces using diamond nanostructuring techniques that we have developed within the scope of this MURI. Using these techniques, they are able to reduce reflectivity of diamond wafers by more than an order of magnitude (~1% vs 30% in the case of structured and non-structured diamond surfaces, respectively). They have also formed Quantum Diamond Technology, Inc (QDTI), a startup that is seeking to commercialize developments in the field of quantum diamond photonics and sensitive magnetometry. QDTI funded the DARPA SBIR Phase II grant (for magnetic field imaging). They are also actively exploring opportunities for realization of stable single photon emitters based on color centers in diamond (silicon vacancy in particular) for QKD applications. To this end, they recently started collaboration with Sandia National Lab.

C. Neutral atoms research at MIT and Harvard (Vuletic, Lukin)

Accomplishments

We have demonstrated a quantum optical medium that is nonlinear at the single-photon level and transmits one photon but absorbs two. If the medium is irradiated with a coherent state of light (attenuated laser beam) then the output light consists of a train of single photon pulses as evidenced by a photon-photon correlation function at zero time separation of the photons of $g_2(0)=0.04$. The medium is implemented by means of electromagnetically induced transparency (EIT) that involves the ground state of Rb atoms and a highly excited Rydberg state up to principal quantum number n=100. As two such Rydberg atoms interact strongly via a steep $1/R^6$ potential, two photons are excluded from a “blockade region” of ~10 μm in size. This blockade region then spreads through the medium due to the bandwidth limitation of EIT that leads to a broadening of any spatial structure that is smaller than the Fourier transform of the EIT bandwidth. Ultimately we observe that while one photon is in the Rydberg medium, a second photon cannot propagate. This leads to a photon output rate set by the size of the medium and the photon group velocity that is highly constant over two orders of magnitude in input photon rate.

By detuning the coupling laser that induces EIT from the intermediate state, we have realized for the first time a bound state of two photons. The Rydberg blockade now gives rise to an index of refraction of the medium that depends on the distance between two photons. The situation can be approximately described by a Schroedinger equation with an attractive potential well that supports one bound state. We have also observed a two-photon phase shift exceeding □/4, and deterministic polarization entanglement between two photons.

Using an atomic ensemble inside an optical cavity, we have also realized a single-photon transistor, where a single photon stored in an atomic medium can switch many photons incident in another direction. In the same system, we have also realized the cross-modulation of two laser beams at the single-photon level.

Publications

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(2) *Coherence and Raman Sideband Cooling of a Single Atom in an Optical Tweezer*. J.D. Thompson, T.G. Tiecke, A.S. Zibrov, V. Vuletic, and M.D. Lukin, Phys. Rev. Lett. **110**, 133001 (2013); http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.110.133001

(3) *Coupling of a Single Trapped Atom to a Nanoscale Optical Cavity*. J.D. Thompson, T.G. Tiecke, N.P. de Leon, J. Feist, A.V. Akimov, M. Gullans, A.S. Zibrov, V. Vuletic, and M.D. Lukin, Science **340**, 1202 (2013); http://www.sciencemag.org/content/340/6137/1202.abstract?sid=f3684da2-4383-4829-96a4-f9a18ad521b4

(4) *All-Optical Switch and Transistor Gated by One Stored Photon*. W. Chen, K.M. Beck, R. Bücker, M. Gullans, M.D. Lukin, H. Tanji-Suzuki, and V. Vuletic, Science **341**, 768 (2013); http://www.sciencemag.org/content/341/6147/768.abstract?sid=7d31591e-9028-48c6-8d51-72932968f5d0

(5) *Attractive Photons in a Quantum Nonlinear Medium*. O. Firstenberg, T. Peyronel, Q.-Y. Liang, A.V. Gorshkov, M.D. Lukin, and V. Vuletic, Nature **502**, 71 (2013); http://www.nature.com/nature/journal/v502/n7469/full/nature12512.html

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(8) *Quantum Nonlinear Optics – Photon by Photon*. D. Chang, V. Vuletić, and M.D. Lukin, Nature Photonics **8**, 685–694 (2014).

(9) *Efficient fiber-optical interface for nanophotonic devices*. T.G. Tiecke, K.P. Nayak, J.D. Thompson, T. Peyronel, N. de Leon, V. Vuletić, and M.D. Lukin, Optica **2**, 70-75 (2014).

(10) *Cross Modulation of Two Laser Beams at the Individual-Photon Level*. K.M. Beck, W. Chen, Q. Lin, M. Gullans, M.D. Lukin, and V. Vuletić, Phys. Rev. Lett. **113**, 113603 (2014).

Awards

Vladan Vuletic, Fellow of the APS 2012; http://www.aps.org/units/damop/fellowship/index.cfm?year=2012

Thibault Peyronel, DAMOP thesis prize finalist 2014; http://www.aps.org/programs/honors/dissertation/amo.cfm

Vladan Vuletic, Marko Jaric Prize 2014; http://www.fondjaric.rs/

Students and postdocs supported

Three postdocs (Tobias Tiecke, Mahdi Hosseini, and Robert McConnell) and 6 students (Hao Zhang, Alexei Bylinskii, Akio Kawasaki, Dorian Gangloff, Qiyu Liang, and Boris Braverman) have been supported in part by this project.

D. Neutral atoms research at Wisconsin (Saffman, Walker)

Research Accomplishments:

Activities at Wisconsin have included experimental and theoretical research. Experiments primarily involved ensemble qubits using small atomic ensembles of order 10 Rb atoms in an optical dipole trap. Two significant experimental advances were demonstrated with ensembles. In [4] we demonstrated that atomic Fock states of 1 or 2 atoms could be prepared using Rydberg blockade. We also directly verified the predicted dependence of the ensemble Rabi frequency on number of atoms N, with no adjustable parameters.

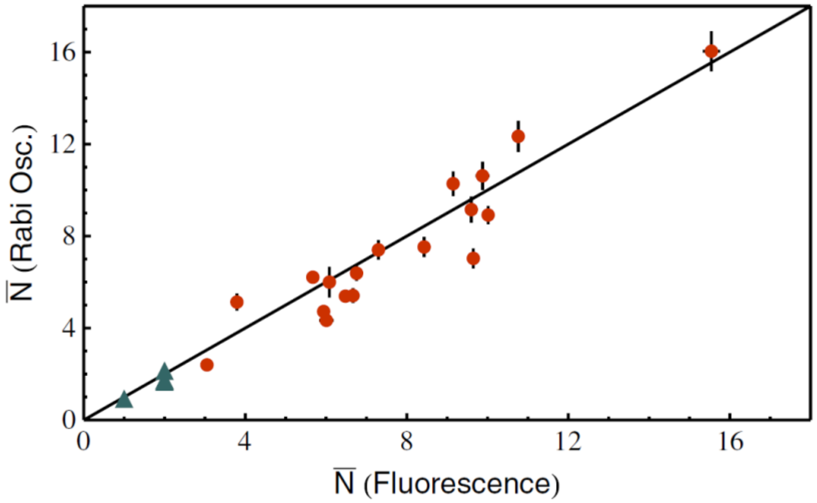

Figure showing measurement of ensemble Rabi frequency as a function of atom number. From [4].

In [6] we extended our ability to control ensemble qubits by demonstrating preparation of entangled |W> states. The states |0>$_N$, all N atoms in hyperfine state |0> , and |W>, the symmetric superposition of one of N atoms in hyperfine state |1> form a computational basis for the ensemble qubit. In [6] we measured the coherence of ensemble qubits as a function of the atom number N and demonstrated by using an entanglement witness that the ensemble atoms were in an entangled state. We also demonstrated strong Rydberg blockade between two ensembles separated by 10 microns.

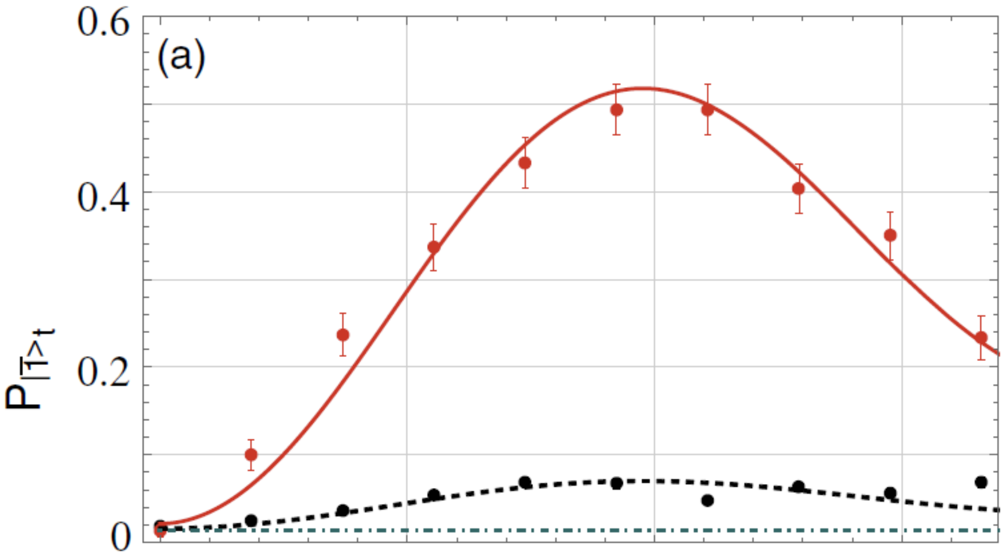

Figure showing ensemble to ensemble blockade (difference between red and black curves). From [6].

These experiments form the basis for ongoing efforts at deterministic entanglement of two ensembles and ensemble-photon entanglement. That goal has proved challenging due to an observed limit of about 60% for the fidelity with which a |W> state can be prepared. The reasons for this limit are not completely clear, but may be due to short range atomic collisions in the disordered ensemble. Near the end of this MURI project we began preparation of a repulsive 1D optical lattice to limit short range interactions. Experiments with the 1D lattice are ongoing under support from the NSF.

We also used an improved experimental apparatus developed during the MURI project to demonstrate low-loss, high fidelity measurement of the quantum state of single atom qubits[12]. The improved apparatus provided better optical access with a two-chamber design and an all-glass science cell. Low-loss readout was achieved by optimizing the intensity and polarization state of the measurement light to minimize heating and off-resonant Raman transitions during the state measurement.

On the theoretical side we engaged in several projects. We have collaborated with Mikkel Andersen's group at Otago, NZ, on understanding their protocol for high fidelity single-atom loading. The protocol involves controlled energy transfer to atom pairs using light assisted collisions, followed by slow cooling of the heated atoms. If the energy transfer to the atom pair is less than twice the trap depth, a single atom can leave the trap without the other one leaving simultaneously. If both atoms remain, they can undergo a second light assisted collision and leave the trap. This work resulted in an unprecedented 91% success rate for loading single atoms into an optical trap[3].

We have collaborated with Ilya Beterov in Novosibirsk on design and analysis of protocols for high fidelity quantum gates acting on ensemble qubits. We developed new adiabatic pulse protocols that allow high fidelity quantum gates to be performed on ensembles with unknown atom number N[1,5,8,11]. Using double pulse STIRAP or ARP sequences we implement a universal set of gates on collectively encoded qubits with high fidelity despite unknown N. We have also analyzed the possibility of using circular Rydberg states for higher fidelity entangling gates[2] as well as the resonant Rydberg interaction strength between different atomic elements[7].

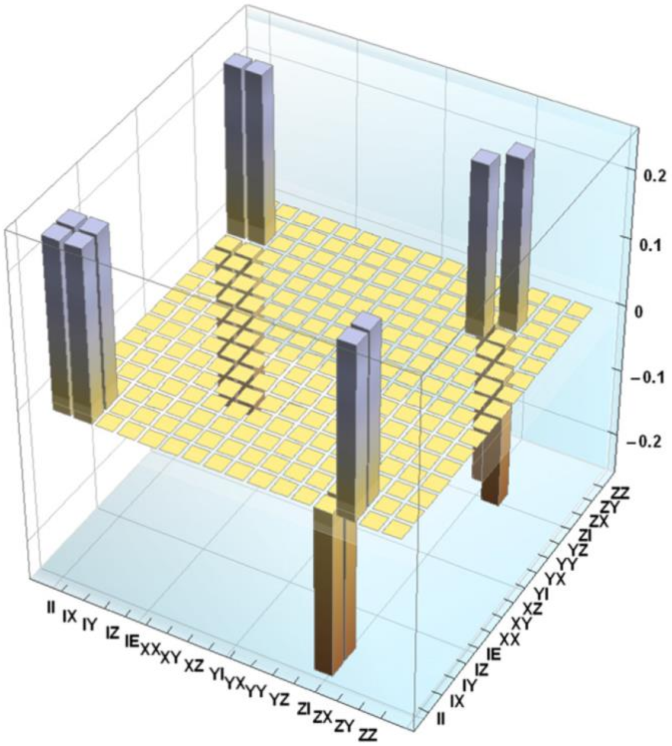

Figure showing the simulated process matrix for a CNOT gate between two ensemble qubits. From [8].

In [10] we analyzed in detail the conditions for doubly magic optical traps for atomic qubits that are simultaneously insensitive to both optical intensity noise and magnetic field noise. We showed that by adding frequency sidebands to the trap light doubly magic traps could be implemented at a wide range of wavelengths and for different hyperfine states, including the standard M=0 clock states.

In [9] we reviewed the progress and challenges of recent research in quantum computing with neutral atom qubits.

Publications in refereed journals:

1) I.. I. Beterov, M. Saffman, E. A. Yakshina, V. P. Zhukov, D. B. Tretyakov, V. M. Entin, I. I. Ryabtsev, C. W. Mansell, C. MacCormick, S. Bergamini, and M. P. Fedoruk, Quantum gates in mesoscopic atomic ensembles based on adiabatic passage and Rydberg blockade, Phys. Rev. A **88**, 010303(R) (2013). http://journals.aps.org/pra/abstract/10.1103/PhysRevA.88.010303

2) T. Xia, X. L. Zhang, and M. Saffman, “Analysis of a controlled phase gate using circular Rydberg states”, Phys. Rev. A **88**, 062337 (2013). http://journals.aps.org/pra/abstract/10.1103/PhysRevA.88.062337

3) A. V. Carpentier, Y. H. Fung, P. Sompet, A. J. Hilliard, T. G. Walker, and M. F. Andersen, "Preparation of a single atom in an optical microtrap", Laser Phys. Lett. **10** (2013) 125501 (2013).
http://iopscience.iop.org.ezproxy.library.wisc.edu/1612-202X/10/12/125501/

4) M. Ebert, A. Gill, M. Gibbons, X. Zhang, M. Saffman, and T. G. Walker, Atomic Fock State Preparation Using Rydberg Blockade, Phys. Rev. Lett. **112**, 043602 (2014).
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http://iopscience.iop.org/article/10.1088/1054-660X/24/7/074013/meta

6) M. Ebert, M. Kwon, T. G. Walker, and M. Saffman, **Coherence and Rydberg blockade of atomic ensemble qubits** Phys. Rev. Lett. **115**, 093601 (2015).
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.115.093601

7) I. I. Beterov and M. Saffman, **Rydberg blockade, Förster resonances, and quantum state measurements with different atomic species** Phys. Rev. A **92**, 042710 (2015)
https://journals.aps.org/pra/abstract/10.1103/PhysRevA.92.042710

8) I. I. Beterov, M. Saffman, E. A. Yakshina, D. B. Tretyakov, V. M. Entin, G. N. Hamzina, and I I Ryabtsev, **Simulated quantum process tomography of quantum gates with Rydberg superatoms** J. Phys. B **49**, 114007 (2016).
http://iopscience.iop.org/article/10.1088/0953-4075/49/11/114007/meta

9) M. Saffman, **Quantum computing with atomic qubits and Rydberg interactions: Progress and challenges** J. Phys. B **49**, 202001 (2016)
http://iopscience.iop.org/article/10.1088/0953-4075/49/20/202001/meta

10) A. W. Carr and M. Saffman, **Doubly magic trapping for Cs atom hyperfine clock transitions** Phys. Rev. Lett. **117**, 150801 (2016)
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.117.150801

11) I.I. Beterov, M. Saffman, E.A. Yakshina, D.B. Tretyakov, V.M. Entin, S. Bergamini, E.A. Kuznetsova, and I.I. Ryabtsev, **Two-qubit gates using adiabatic passage of the Stark-tuned Förster resonances in Rydberg atoms** Phys. Rev. A **94**, 062307 (2016)
https://journals.aps.org/pra/abstract/10.1103/PhysRevA.94.062307

12) M. Kwon, M. F. Ebert, T. G. Walker, and M. Saffman, **Parallel low-loss measurement of multiple atomic qubits** Phys. Rev. Lett. **119**, 180504 (2017).
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.119.180504

Awards:

2013 – M. Saffman named Fellow of the Optical Society of America, *For groundbreaking contributions to neutral atom quantum computing with Rydberg state interactions.*

Students and postdocs supported:

Xianli L. Zhang (postdoc, now staff physicist at Microsemi Corporation)
Michael Gibbons (postdoc)
Alex T. Gill (PhD awarded March 2014, now scientist at Draper Lab)
Matt Ebert (PhD awarded August 2017, now postdoc at UW Madison)
Minho Kwon (PhD student, PhD expected in 2018)
Joshua Cherek (undergraduate research assistant)
Laura Fleming (undergraduate research assistant)
Erik Meyers (undergraduate research assistant)
Andrew Micklich (undergraduate research assistant)
Kevin Sampson (undergraduate research assistant)
Sunil Upadhyay (undergraduate research assistant)

Outreach:

The UW Madison Physics department holds an annual physics fair open house for the public (http://wonders.physics.wisc.edu/physics-fair.htm). This includes poster and demonstration presentations as well as lab tours. Professors Saffman and Walker often participate in the fair with presentations about atomic physics and quantum computing. In fall 2013 and 2014 Professor Saffman gave presentations to 6th and 7th graders at Eagle School near Madison about quantum computing. Professor Saffman also mentored two high school students during the course of the MURI project. The high school students worked in the lab alongside PhD students and postdocs and gained valuable exposure to a variety of technical skills used in modern atomic and quantum physics experiments.

E. Neutral atoms and theoretical work at Georgia Tech and Michigan (Kuzmich, Kennedy, Duan)

E(i) Kuzmich, Kennedy

The main aim of our work has been the development of methods for entanglement generation and distribution based on a combination of long-term quantum state storage in the ground hyperfine atomic levels and fast, on-demand entanglement generation using Rydberg-level atomic interactions. Theoretical studies of Rydberg atom interactions involved analysis of spin-wave dephasing and its dynamics and role in the generation of non-classical and entangled states and quantum gates. The main accomplishments include:

1. Proposal and initial demonstration of an in-situ method for determination of Zeeman content of atomic memories.

2. Minute-scale light storage. Quantum repeater architectures, which use quantum memory elements as nodes and light for transmission, require quantum memory storage lifetimes that are large compared to the classical communication time between nodes. We reported an important advance of a minute-scale atomic memory, achieved by combining the magic-magnetic field technique with a dynamic decoupling microwave pulse sequence that is resonant on the clock transition.

3. Proposal of spin-wave Rydberg dephasing, a dissipative mechanism for the generation of quantum states of light and atom-light entanglement. Alkali atoms excited to Rydberg levels have been known to be good candidates for quantum computation on the MHz scale. We proposed an alternative approach that circumvents some of the challenges of Rydberg-blockade mechanism and makes it possible to realize fast entanglement generation and distribution in larger atomic ensembles.

4. The first realization of a Rydberg single-photon source. We generated Rydberg excitations in an ultra-cold atomic gas and subsequently converted them into light. As the principal quantum number n was increased beyond about 70, only a single excitation was retrieved from the ensemble of about 500 atoms.

5. Observation of the emergence of localized collective atomic excitations in a strongly interacting atomic gas.

6. First observation of many-body Rabi oscillations. In the limit where only a single excitation is present in an ensemble of N atoms, a collective, many-body Rabi oscillation arises that involves all N atoms, even in inhomogeneous systems. When one of the two levels is a strongly interacting Rydberg level, many-body Rabi oscillations emerge as a consequence of Rydberg blockade. We observed such oscillations between the ground and Rydberg levels using several hundred cold rubidium atoms. The strongly pronounced oscillations indicated high-quality blockade of the mesoscopic ensemble by just one excited atom.

7. State-insensitive trapping of ground and Rydberg atoms and on-demand atom-light entanglement: We developed of a state-insensitive optical lattice, where the differential energy shift between the ground and Rydberg levels is eliminated by tuning the lattice to one of the ``magic" wavelengths at 1004 nm or 1012 nm. The matched trapping potentials preserve the

ground-Rydberg quantum optical coherence, enabling generation of the on-demand entanglement between an optical ground-Rydberg coherence and a light field.

8. Quantum memory with strong controllable Rydberg-level interactions: Realization of distributed quantum systems requires fast generation and long-term storage of quantum states. Ground atomic states enable memories with storage times in the range of a minute, however their relatively weak interactions do not allow fast creation of non-classical collective states. Rydberg atomic systems feature fast preparation of singly excited collective states and their efficient mapping into light, but storage times in these approaches have not yet exceeded a few microseconds. Here we demonstrate a system that combines fast quantum state generation and long-term storage. An initially prepared coherent state of an atomic memory is transformed into a non-classical collective atomic state by Rydberg-level interactions in less than a microsecond. By sheltering the quantum state in the ground atomic levels, the storage time is increased by almost two orders of magnitude. This advance opens a door to a number of quantum protocols for scalable generation and distribution of entanglement.

9. A pair of neutral atoms separated by several microns and prepared in identical s states of large principal quantum number experience a van der Waals interaction. If microwave fields are used to generate a superposition of s states with different principal quantum numbers, a null point may be found at which a specific superposition state experiences no van der Waals interaction. An application of this Rydberg state in a quantum controlled-z gate is proposed, which takes advantage of GHz rate transitions to nearby Rydberg states. A gate operation time in the tens of nanoseconds is predicted.

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F. Bariani, P.M. Goldbart and T.A.B. Kennedy, “Dephasing dynamics of Rydberg atom spin waves,” Phys. Rev. A 86, 041802R (2012).

Y. O. Dudin, L. Li, F. Bariani, and A. Kuzmich, “Observation of coherent many-body Rabi oscillations,” Nature Physics **8**, 790 (2012).

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S. D. Jenkins, Y. O. Dudin, R. Zhao, D. N. Matsukevich, A. Kuzmich, and T. A. B. Kennedy, ‘‘In situ determination of Zeeman content of collective atomic memories,” J. Phys. B **45**, 124006 (2012).

Y. O. Dudin and A. Kuzmich, “Strongly interacting Rydberg excitations of a cold atomic gas,” Science **336**, 887 (2012).

F. Bariani, Y. O. Dudin, T. A. B. Kennedy, and A. Kuzmich, “Dephasing of multiparticle Rydberg excitations for fast entanglement generation,” Phys. Rev. Lett. **108**, 030501 (2012).

Awards

Elected Fellow American Physical Society 2009, A. Kuzmich
Elected Fellow American Physical Society 2010, T.A.B. Kennedy
APS Outstanding Doctoral Thesis Research in Atomic, Molecular or Optical Physics 2013, Y. O. Dudin.

Students and postdocs supported

X-F. Shi (postdoc), F. Bariani (postdoc)
Y.O. Dudin, L. Lin, P. Svetlichnyy, G. Singh (deceased)

Outreach

Kennedy has presented wave physics demonstrations and experiments at Sweet Apple Elementary School.

E.(ii) Duan

Accomplishments:

The major progress associated with this project includes:

- We had studied several experimental systems for multi-functional light-matter interface, including atomic ensembles, quantum dots, nitrogen vacancy centers in diamonds and photons. We proposed schemes to use these systems to generate a class of many-particle entangled states, the so-called Dicke squeezed states, which can be used for quantum metrology and network applications. We proposed an experimental method to detect many-body entanglement in the vicinity of the Dicke states. For diamond defects, in collaboration with Lukin's group at Harvard, we proposed and analyzed a scheme to realize remote state transfer between spin quantum memories. We also collaborated with experimentalists to realize several network related experiments, including demonstration of the dot-photon entanglement and the nonlocality distillation.

- We investigated the Rydberg atomic ensembles and the diamond defects. For the Rydberg atomic ensembles, we optimized schemes to efficiently generate many-body entanglement, proposed method to detect these entangled states, and considered applications of these states for quantum metrology and implementation of quantum network protocols by transferring the states to photons through the light-matter interface. For the diamond defects, we investigated their applications for realization of local quantum registers which enhanced information processing capability and optimize their interface coupling with the photons.

- We searched for efficient detection methods to verify various kinds of many-body states and entanglement that have favorable polynomial scaling with the number of qubits. The sub-exponential scaling of state verification is critical for its implementation in many-qubit systems. To make this possible, we require having some priori information about the state or entanglement to be verified. This is typically the case for real experiments as experiments are usually targeted to prepare certain definite states. Due to influence of noise, the real state prepared of course is different from the target state; however, it is not arbitrary and often lies in a small corner of the enormous Hilbert space of n-qubits. We can make use of this priori information to design much more efficient state/entanglement verification method. The detailed technique depends on the class of states/entanglement to be prepared, and the latter is motivated by their applications in realization of scalable quantum information processing. We considered in particular the graph states, the symmetric states, the entangled ground states of frustrated many-body Hamiltonians, etc., with applications in mind as a resource for universal quantum computation, networking, or precision measurements.

- we have proposed a scheme to realize quantum routers and a hybrid quantum network connecting remote superconducting qubits. The router is a key element for a network. We describe a scheme to realize genuine quantum routing of single-photon pulses based on cascading of conditional quantum gates in a Mach-Zehnder interferometer and report a proof-of-principle experiment for its demonstration using linear optics quantum gates. The polarization of the control photon routes in a coherent way the path of the signal photon while preserving the qubit state of the signal photon represented by its polarization. We demonstrate quantum nature of this router by showing entanglement generated between the initially unentangled control and signal photons, and confirm that the qubit state of the signal photon is well preserved by the router through quantum process tomography.

- We have proposed a scheme to realize quantum networking of superconducting qubits based on the opto-mechanical interface. Superconducting qubits is a promising system for realization of quantum computation; however, it is difficult to connect distant superconducting qubits in different cryostats. The superconducting qubits interact with the microwave photons, which then couple to the optical photons through the opto-mechanical interface. The interface generates a quantum link between superconducting qubits and optical flying qubits with tunable pulse shapes and carrier frequencies, enabling transmission of quantum information to other superconducting or atomic qubits. We show that the scheme works under realistic experimental conditions and it also provides a way for fast initialization of the superconducting qubits under 1 K instead of 20 mK operation temperature.

Graduate Students supported by the project:

Dongling Deng (1 year)
Zhen Zhang (1 year)
Shengtao Wang (0.5 year)
Tanvi Gujarati (1 years)
Zhenyu Zhang (0.5 year)

Awards

Elected Fellow of the American Physical Society 2009

Publications:

[1]. Z Yin, WL Yang, L Sun, LM Duan, Quantum network of superconducting qubits through opto-mechanical interface, arXiv preprint arXiv:1407.4938, Physical Review A 91 (1), 012333 (2015).

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demonstration of a quantum router, Scientific Reports 5, 12452 (2015).

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(F) Quantum dots work at Stanford (Vuckovic)

Proposed Coupling of an Electron Spin in a Semiconductor Quantum Dot to a Nanosize Optical Cavity

The spin states of a singly charged QD have been shown to possess coherence times in the microsecond range. The use of ultrafast optical techniques with charged QDs provides the possibility of performing a very high number of spin manipulations within the spin coherence time and opens avenues for their use as qubits for quantum information applications. However, the efficiency of spin initialization and manipulation achieved so far is not high. To attain the efficiency necessary for practical applications, one needs to enhance the light-matter interaction. This can be achieved by embedding the charged QD in a cavity. We have proposed a scheme to efficiently couple a single quantum dot electron spin to an optical nano-cavity, which enables us to simultaneously benefit from a cavity as an efficient photonic interface, as well as to perform high fidelity spin initialization and manipulation achievable in bulk semiconductors. Our numerical analysis (with full field quantization and with realistic system parameters) confirmed that nearly 100% spin initialization fidelity is achievable with a speed beyond the GHz range, as well as spin manipulation, benefiting from a cavity not only as a photonic interface but also to speed up the spin control.

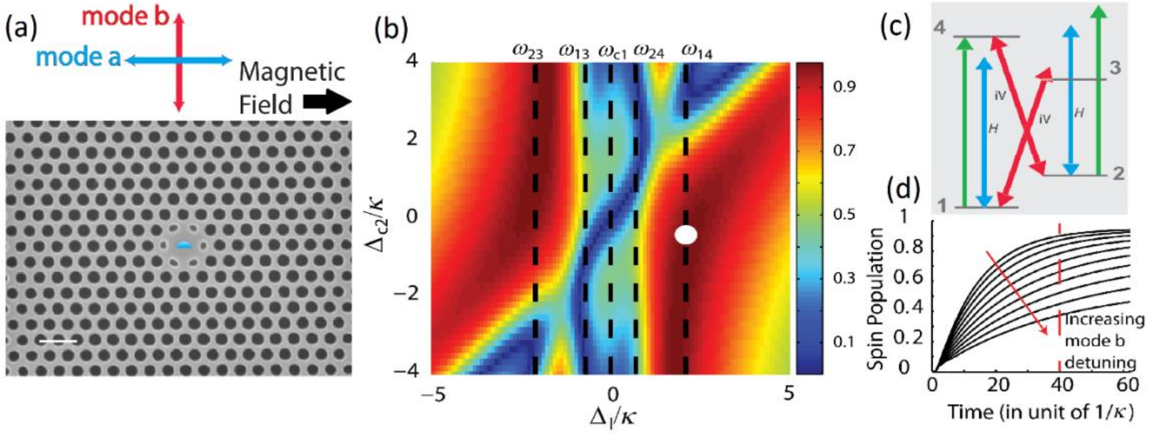

Figure JV1: (a) Scanning electron microscope image of a bimodal photonic-crystal nanocavity fabricated in a GaAs membrane with embedded quantum dots. The blue dome at the center of the cavity depicts an optimally placed QD. The scale bar is 500 nm. Due to the C6 symmetry of the cavity, it can support two orthogonally polarized near-degenerate modes. (b) Initialization fidelity $|\rho_{11}-\rho_{22}|$ as a function of the cavity mode b frequency $\Delta_{c2}=\omega_{c2}-\omega_o$ and the pump laser wavelength $\Delta_l=\omega_l-\omega_o$. The white point marks the situation where we get optimal spin initialization fidelity the pump laser is tuned to the highest energy QD transition (1-4) (shown in (c)), and the cavity mode b is tuned to the diagonal transition that shares the same excited state (2-4). (d) The spin initialization as a function of time for different cavity detunings Δ_{c2}, with the laser being fixed at the highest QD transition frequency. Δ_{c2} is changed from 0 to 2. We note that the spin-initialization time is only around 40/κ~300 ps.

A. Majumdar *et al.* “Proposed Coupling of an Electron Spin in a Semiconductor Quantum Dot to a Nanosize Optical Cavity”, *Physical Review Letters* **111**, 027402 (2013).

Deterministic Charging of Quantum dots in Photonic Crystal Nanoresonators

One of the fundamental components of a quantum network is the node that interfaces photons with stationary qubits capable of storing, manipulating and delivering quantum information. Charged quantum dots coupled to photonic crystal cavities provide a promising method to implement such nodes. The ground states of quantum dots containing a single carrier are characterized by long coherence times and are optically addressable, which makes charged quantum dots excellent candidates for stationary qubits. Photonic crystal nanoresonators on the other hand, can confine light to extremely small volumes (of the order $(\lambda/n)^3$) and therefore can enhance light-matter interactions to efficiently transfer information between flying and stationary qubits. Quantum dot charging can be either passive using delta doping or active (controllable) using Schottky or p-i-n junctions.

Here we have demonstrated deterministic charging of a quantum dot in a novel p-n-i-n junction architecture that not only allows for on-demand quantum dot charging but also for precise control of the quantum dot resonance wavelength. Application of an external bias allows for wavelength tuning by more than a nanometer. Figure 1(a) shows the characteristic I(V) curve for the junction. Figure 1(b) shows the spectra of several quantum dots (thin grey lines) along with the cavity resonance (thick black line) as a function of the bias.

A quantum dot charging event is usually accompanied by a jump-like spectral shift of the dot resonance over several nanometers, but only observation of a Zeeman splitting under magnetic field in the Voigt configuration provides conclusive evidence of charging. A field in the Voigt configuration is tangential to the plane of the sample. Application of such a field splits the exciton transitions into a quadruplet with two of the transitions polarized parallel and two polarized perpendicular to the magnetic field. The spectral structure of charged excitons along with their polarization properties can be fully captured by the Zeeman interaction. Application of forward bias in our p-n-i-n junction often results in spectral jumps of the quantum dot resonances, indicating possible charging events. A detailed study of the spectral structure of these quantum dots as a function of the magnetic field shows a clear Zeeman splitting, which is direct and conclusive evidence of on-demand charging. Figure 1(c) shows a quantum dot transition after the spectral jump as a function of the applied magnetic field in the Voigt configuration. A complete quadruplet spectral structure indicates charging. Although in these experiments the nearby cavity modes are used only for efficient light collection, future work will aim at interfacing the charged quantum dots with the degenerate photonic crystal nanoresonators for efficient spin initialization and manipulation as we have previously proposed.

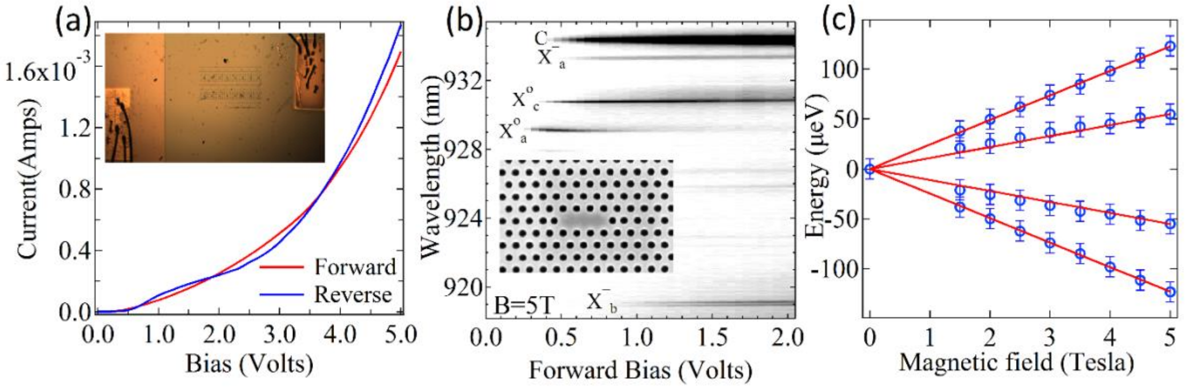

Figure JV2: (a) I(V) curve for both reverse and forward bias on a structure that shows signs of deterministic charging. The junction is a p-n-i-n structure. The inset is a microscope image of the sample. The wire bonded contact pads are seen at the two sides while an array of nanocavities can be seen between the pads (b) Spectroscopic study as a function of the bias voltage: the thick line (C) corresponds to an L3 cavity resonance and the thin lines are QDs. Note that the cavity hardly shifts its energy when tuning the forward bias whereas the QD can be tuned for more than 1nm. The inset is an SEM image of the L3 cavity. (c) Spectroscopic study of the photoluminescence of a charged QD in a photonic crystal nanoresonator for increasing magnetic field featuring the peak locations. The fourfold splitting shows deterministic charging of this particular QD in the p-n-i-n structure.

K. G. Lagoudakis *et al.* "Deterministically Charged Quantum Dots in Photonic Crystal Nanoresonators for Efficient Spin-Photon Interfaces", *New Journal of Physics* **15**, 113056 (2013).

Spin Pumping and Repumping of a Hole Spin in a p-type δ-doped InAs Quantum Dot

Quantum information processing relies on robust quantum bits that feature long coherence times and immunity to the surrounding environment. The electron spin in charged quantum dots (QDs) has been successfully used for quantum information applications, but is limited by its short coherence time due to strong hyperfine interactions with the surrounding nuclear spin bath. The p symmetry of the heavy-hole Bloch wave function significantly reduces the contact hyperfine interaction with the surrounding nuclei, making the hole spin in positively charged quantum dots a very attractive and robust candidate for the implementation of qubits with long coherence times. Previous studies of hole-spin initialization and coherent control predominately relied on tunable p-i-n or Schottky diode structures for quantum dot charge control. In these structures charging occurs either by voltage-controlled tunneling of charge carriers into the QD from a close-by reservoir or by tunnel ionization of photogenerated excitons. Although these methods reliably charge the QDs, they suffer from noise that is induced by the electric field fluctuations, can be subject to spin decoherence from the nearby reservoir, and they require a multistep process for charging of the QDs. δ-doped samples, on the other hand, do not require the same level of complex nanofabrication or suffer from the aforementioned drawbacks. However, δ-doped samples have additional challenges in their growth, most notably the introduction of impurities, which is detrimental to the optical properties of the dots. Thus, successful growth of high quality δ-doped samples is highly favorable for use in quantum information processing. We have grown high quality p-type δ-doped InAs quantum dots in bulk and have demonstrated a novel scheme for coherent spin pumping and repumping of a hole spin in a positively charged quantum dot by means of a single-laser driving scheme under a high magnetic field in the Voigt configuration. Modeling of our system showed excellent qualitative agreement with the experimental findings and further explored the performance of the single-laser scheme for spin pumping and repumping.

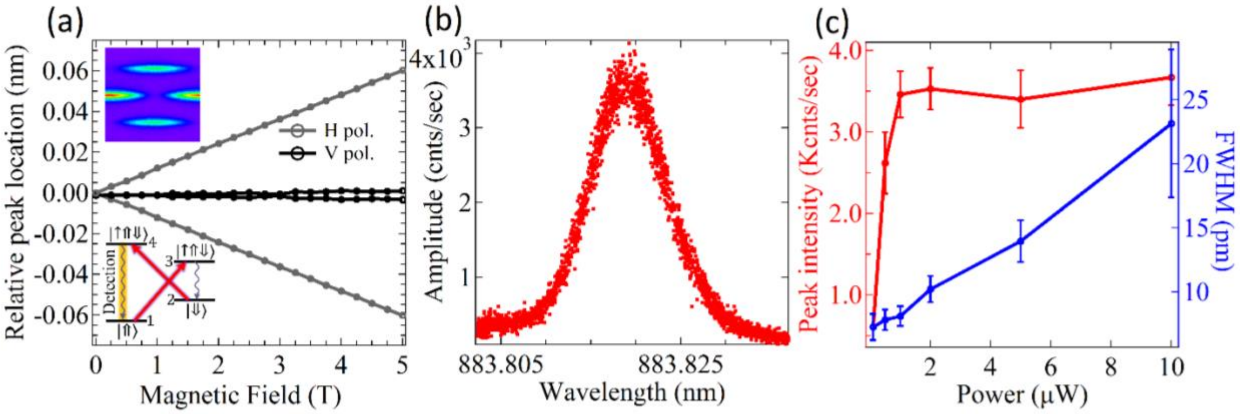

Figure JV3: (a) Zeeman splitting of the positively quantum dot spectra and their evolution into a quadruplet as a function of the magnetic field. Note how the two inner transitions are almost degenarate. Top inset: Polarization scan of the QD photoluminescence showing the two outer transitions to be orthogonally polarized to the two degenerate inner ones. Bottom inset: Four level system with the detection and excitation scheme. (b) Rate of detection events as a function of the wavelength of the pump-repump resonant laser for 2 μW excitation power. (c) Peak intensity (red) and spectral width (blue) of the resonance as a function of the driving laser power.

K. G. Lagoudakis *et al.* “Hole-Spin Pumping and Repumping in a p-type δ-doped InAs Quantum Dot”, *Physical Review B* **90**, 121402(R) (2014).

Initialization of a spin qubit in deterministically positioned nanowire quantum dots

A fault-tolerant quantum repeater or quantum computer using solid-state spin-based quantum bits will likely require a physical implementation with many spins arranged in a grid. Self-assembled quantum dots (QDs) have been established as attractive candidates for building spin-based quantum information processing devices, but such QDs are randomly positioned, which makes them unsuitable for constructing large-scale processors. Recent efforts have shown that quantum dots embedded in nanowires can be deterministically positioned in regular arrays, can store single charges, and have excellent optical properties, but so far there have been no demonstrations of spin qubit operations using nanowire quantum dots. Here we demonstrated optical pumping of individual spins trapped in site-controlled nanowire quantum dots, resulting in high-fidelity spin-qubit initialization.

The sample consisted of InAsP QDs embedded in deterministically positioned InP nanowires, grown in collaboration with the group of Val Zwiller in TU Delft and the National Research Council of Canada (Dr. Dan Dalacu and Dr. Philip Poole).

The spin qubit consists of the spin states of a trapped charge in the nanowire quantum dot that we probe by the application of a magnetic field in the Voigt configuration (magnetic field perpendicular to QD growth axis). The magnetic field lifts the degeneracy of the ground and excited states and gives rise to a four level system. This lifting of the degeneracy is observed as a gradual evolution of the initial QD spectral line into a quadruplet. A laser resonant to transition

2→3 initializes the spin to state $|\Uparrow\rangle$ (or state 1) while a very weak above-band laser randomizes the ground states and allows for the cycling of the population as seen by the observation of photons from the transition 3→1. Tuning the frequency of the resonant laser while recording the observed photons gives rise to a Lorentzian peak. High fidelity initialization is clearly evidenced by the suppression of the signal when the randomization laser is turned off. The resonant laser initializes the spin to the $|\Uparrow\rangle$ (or state 1) and although it is left on, the detector only shows dark counts demonstrating high fidelity initialization. We have also investigated the behavior of the observed spin-pumping resonance as a function of the pumping power and we see that it quickly saturates at about 200nW, while for much higher powers some broadening is eventually introduced by the pumping laser.

Using a rate-equation model of the spin pumping experiment to analyze our experimental results, we showed that our data is consistent with optical spin pumping causing spin qubit initialization with a fidelity of 99% in less than 10 ns and we have extracted a lower bound value for the T_1 of 3 μsec.

With this experiment we have therefore shown that in the InAsP-QD/InP-nanowire system a charged quantum dot in a Voigt magnetic field does yield two optical Λ-systems that can be manipulated, and we have demonstrated optical spin pumping and high fidelity spin initialization. These experiments were performed on site-controlled nanowires, making this the first demonstration of optical pumping of a site-controlled quantum dot spin.

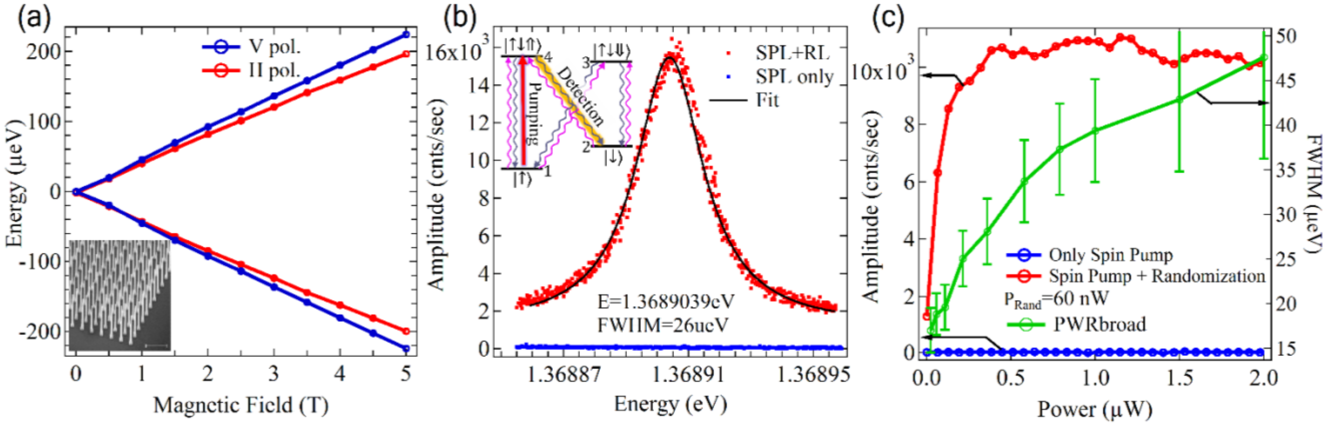

Figure JV4: (a) Zeeman splitting of the quantum dot spectra and their evolution into a quadruplet as a function of the magnetic field. Inset: An array of deterministically positioned nanowires. (b) Detected photons from the diagonal transition marked as "detection" as a function of the spin pumping laser (SPL) frequency (red points) indicating spin pumping. When the randomization laser (RL) is turned off, the signal drops to the dark counts of the detector showing high fidelity spin initialization. Inset: four level structure with the detection and driving scheme. (c) Spin pumping peak counts as a function of the resonant laser power for excitation with the randomization laser on (red) and off (blue). The linewidth of the peak is shown in green against the right axis.

K. G. Lagoudakis *et al.* "Initialization of a Spin Qubit in a Site-Controlled Nanowire Quantum Dot", *New Journal of Physics* **18**, 053024 (2016).

Nonclassical higher-order photon correlations with a quantum dot strongly coupled to a photonic-crystal nanocavity

A strongly coupled quantum-dot–cavity system can produce nonclassical light by filtering the input stream of photons coming from a classical coherent light source through mechanisms described as “photon blockade” and “photon induced tunneling”. The concept of photon blockade can be extended from single photons to two photon Fock-state generation by coupling the probe laser to the second manifold of the Jaynes-Cummings ladder via a two-photon transition. This approach can potentially be further generalized to create third- and higher-order photon states inside the cavity through multiphoton transitions to the corresponding manifold. Int this work, we reported the probing of these multiphoton transitions into the higher manifolds of the Jaynes-Cummings ladder of a strongly coupled quantum-dot–photonic-crystal nanocavity system by measuring the third- and fourth-order autocorrelation functions $g^{(3)}(\tau1,\tau2)$ and $g^{(4)}(\tau1,\tau2,\tau3)$ to detect the nonclassical character of the probe laser light, transmitted through a photonic-crystal nanocavity containing a strongly coupled quantum dot probed with a train of coherent light pulses. We contrasted the value of $g^{(3)}(0,0)$ with the conventionally used $g^{(2)}(0)$ and demonstrated that, in addition to being necessary for detecting two-photon states emitted by a low-intensity source, $g^{(3)}$ provides a more clear indication of the nonclassical character of a light source. We also presented preliminary data that demonstrated bunching in the fourth-order autocorrelation function $g^{(4)}(\tau1,\tau2,\tau3)$ as the first step toward detecting three-photon states. A source of such higher-order photon states might enable efficient generation of the highly entangled NOON states, which are particularly interesting for quantum metrology and high-resolution quantum lithography and sensing. Last, these higher-order autocorrelations have the potential to be used for monitoring phase transitions in condensed-matter simulations based on photon gases.

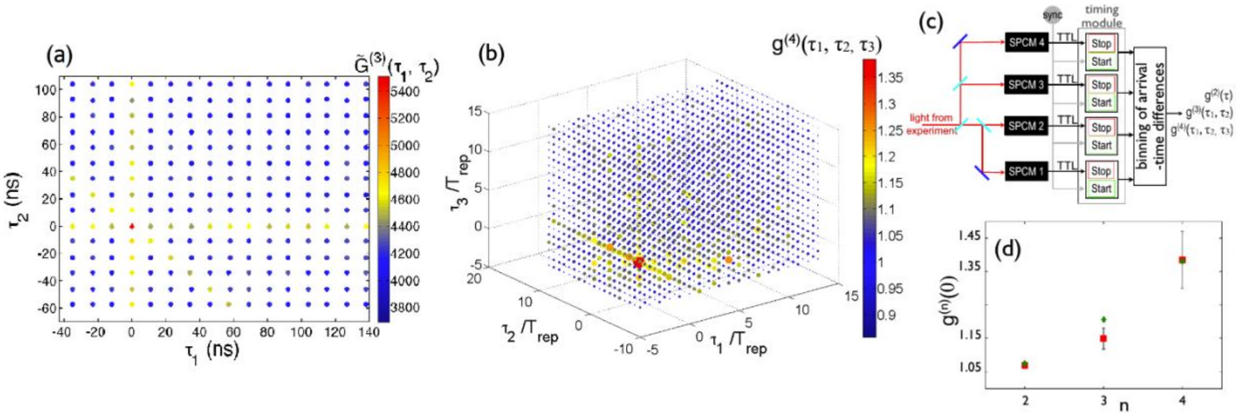

Figure JV5: (a) Three-photon coincidence counts $G^{(3)}(\tau1,\tau2)$ observed in the photons transmitted through the resonantly probed system. (b) A visualization of the time-binned and normalized fourth-order autocorrelation function $g^{(4)}(\tau1,\tau2,\tau3)$. To guide the eye, the value of each peak is represented both by color and size of the plotted data point. (c) Schematics of the expanded HBT setup used to detect arrival times of up to four-photon events used to obtain autocorrelation functions up to the fourth order, $g^{(4)}(\tau1,\tau2,\tau3)$ shown in (b). (d) Increasing values of the autocorrelation functions $g^{(n)}$ at zero time delay(s), plotted as a function of their order n (the red squares with error bars represent experimental data, while the green diamonds plot the results of a numerical simulation). To obtain a sufficient number of four-photon coincidences over a reasonable data collection time, the system was probed with $P_{\text{probe}} \approx 1.0$ nW, which partially saturated the dot and resulted in lower observed values of $g^{(3)}(0,0)$ and $g^{(2)}(0)$ in this particular measurement.

A. Rundquist *et al.* "Non-Classical Higher-Order Photon Correlations with a Quantum Dot Strongly Coupled to a Photonic-Crystal Nanocavity", *Physical Review A* **90**, 023846 (2014).

Self-homodyne Interference for Nonclassical Light Generation

It is very tempting to model the physics of an L3 photonic crystal cavity as a single mode of a harmonic oscillator (a discrete scattering channel). Under certain cross-polarized reflectivity conditions, this accurately models the system. The detuned transmission profile resembles the bare cavity's Lorentzian profile at high excitation powers. However, the L3 photonic crystal has a rich mode structure -shown in the following figure- that is not well-approximated by a single mode. We discovered that it is necessary to consider an additional scattering channel that is due to a roughly constant background density of photonic states (a continuum channel). The discrete and continuum channels can interfere to generate a lineshape that is similar to a Fano resonance. The lineshape can be changed between Lorentzian-like or Fano-like in cross-polarized reflectivity by altering the detection and excitation conditions. We observed that the effects on nonclassical light generation are dramatic and manifest in the grey boxed regions that represent the frequency of the emitter-like polariton. The mixing action of combining the reflected laser light with light scattered by the strongly-coupled system is a type of homodyne measurement, which has the power to emphasize the incoherent or nonclassical portion of the scattered light over the coherent or classical portion. When the transmission profiles are decomposed into their incoherent and coherent portions of emission, the coherent portions (blue) are primarily due to the classically scattered light from a subset of almost harmonically spaced dressed states or the continuum modes and hence look predominantly like the Lorentzian or Fano lineshapes. This light is due to the mean of the electric field. Meanwhile, the incoherent portions of the emissions (green) are the result of the nonlinearity in the Jaynes-Cummings system and hence from the nonclassically scattered light. This light is due to the fluctuations of the electric field.

Under the Lorentzian-like conditions, the coherent portion of the transmitted light (blue) dominates the incoherent portion (green). However, under the Fano-like conditions, the incoherent portion of the transmitted light dominates and over 90 % of the coherently scattered portion is suppressed at the frequency of the emitter-like polariton. In this way, the effect of the quantum nonlinearity in the Jaynes-Cummings ladder is emphasized, with great potential to allow highly dissipative systems to still exhibit robust signatures of nonclassical light generation.

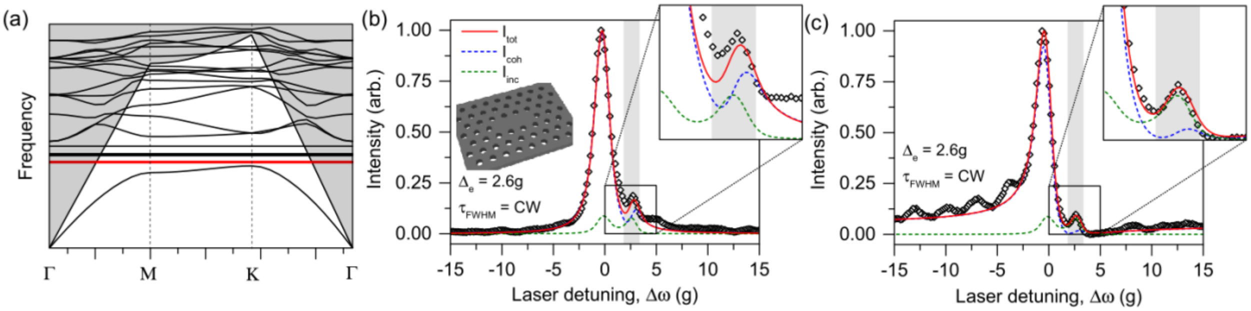

Figure JV6: Origin of self-homodyne interference. **a** Complicated mode structure of a planar L3 Photonic crystal cavity. Red and black horizontal lines depict the cavity's fundamental and higher order modes, respectively. Curved lines represent photonic crystal guided modes. Grey region indicates leaky modes that are above the light line. **b** Transmission spectra under excitation conditions that produce a Lorentzian-like profile, fit to a quantum optical model. In the inset, we provide a schematic of a planar L3 photonic crystal cavity. **c** Transmission spectra under excitation conditions that produce a Fano-like profile, fit to a quantum optical model.

K. A. Fischer *et al.* "Self-Homodyne Measurement of a Dynamic Mollow Triplet in the Solid State", *Nature Photonics* **10**, 163–166 (2016).

Self-homodyne enabled generation of indistinguishable photons

The rapid generation of non-classical light serves as the foundation for exploring quantum optics and developing applications such as secure communication or generation of NOON-states. While strongly coupled quantum dot-photonic crystal resonator systems have great potential as non-classical light sources due to their promise of tailored output statistics, the generation of indistinguishable photons has been obscured due to the strongly dissipative nature of such systems. Here, we demonstrate that the recently discovered self-homodyne suppression technique can be used to overcome this limitation and tune the quantum statistics of transmitted light, achieving indistinguishable photon emission competitive with state-of-the-art metrics.

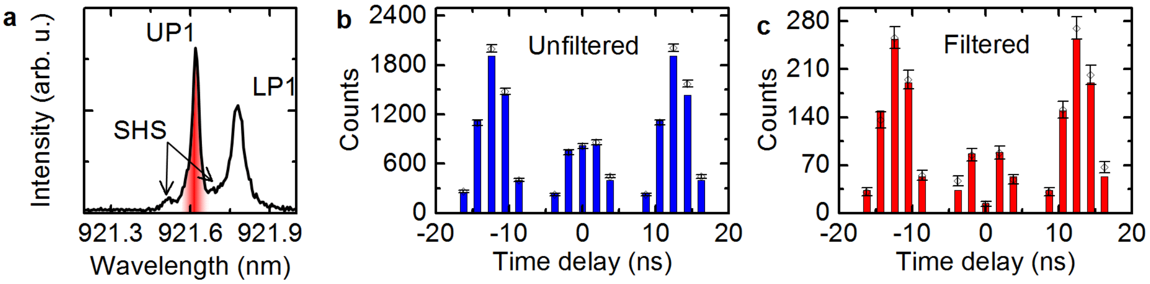

Figure JV7: (a) Spectrum of the strongly coupled QD-cavity system when excited with a 16ps short pulse in resonance with the upper polariton (UP1) subject to self-homodyne suppression. (b)-(c). Measured two-photon interference (auto-correlation) for exciting the system with double pulses separated by 1.9ns. In (b) the complete emission is analyzed while in (c) the emission in frequency filtered on UP1, removing phonon-assisted separation through LP1 and imperfect suppression of the coherently scattered laser. The attenuation of the three center peaks results from single-photon character of the emission and two-photon interference. In (c) state-of-the-art values of $g^{(2)}(0) = 0.05\pm0.04$ and $|g^{(1)}(0)|=0,96\pm0.05$ are obtained.

K. Müller *et al.* "Self-Homodyne-Enabled Generation of Indistinguishable Photons", *Optica* **3**, 931-936 (2016).

Coherent Generation of Nonclassical Light on Chip via Detuned Photon Blockade

The on-chip generation of nonclassical states of light is a key requirement for future optical quantum hardware. In solid-state cavity quantum electrodynamics, such nonclassical light can be generated from self-assembled quantum dots strongly coupled to photonic crystal cavities. Their anharmonic strong light-matter interaction results in large optical nonlinearities at the single photon level, where the admission of a single photon into the cavity may enhance (photon tunneling) or diminish (photon blockade) the probability for a second photon to enter the cavity. Here, we demonstrate that detuning the cavity and quantum-dot resonances enables the generation of high-purity nonclassical light from strongly coupled systems. For specific detunings we show that not only the purity but also the efficiency of single-photon generation increases significantly, making high-quality single-photon generation by photon blockade possible with current state-of-the-art samples.

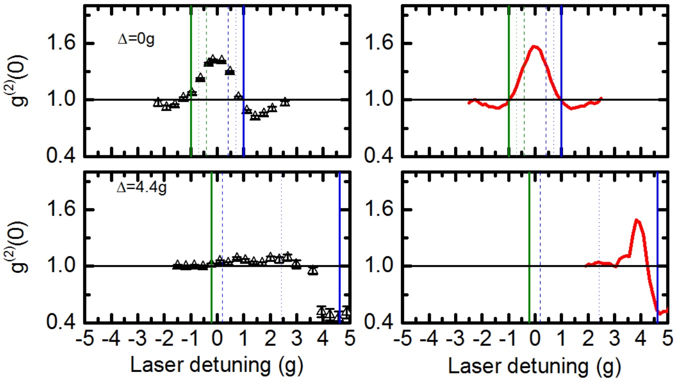

Figure JV8: $g^{(2)}(0)$ as function of the laser detuning for two different QD-cavity detunings: (left) experiment and (right) simulation. With detuning the depth of the anti-bunching is more pronounced. The positions of the first upper and lower polariton branch are indicated by blue and green lines, respectively. The energies for subsequent climbs from first to second rung are indicated by dashed lines and the energies of a two-photon excitation of the second rung by dashed lines

K. Müller et al. "Coherent Generation of Nonclassical Light on Chip via Detuned Photon Blockade", *Physical Review Letters* **114**, 233601 (2015).

Ultrafast Polariton-Phonon Dynamics of Strongly Coupled Quantum Dot-Nanocavity Systems

We investigate the influence of exciton-phonon coupling on the dynamics of a strongly coupled quantum dot-photonic crystal cavity system and explore the effects of this interaction on different schemes for nonclassical light generation [2]. By performing time-resolved measurements, we map out the detuning-dependent polariton lifetime and extract the spectrum of the polariton-to-phonon coupling with unprecedented precision. Photon-blockade experiments for different pulse-length and detuning conditions (supported by quantum optical simulations) reveal that achieving high-fidelity photon blockade requires an intricate understanding of the phonons' influence on the system dynamics. Finally, we achieve direct coherent control of the polariton states of a strongly coupled system and demonstrate that their efficient coupling to phonons can be exploited for novel concepts in high-fidelity single-photon generation.

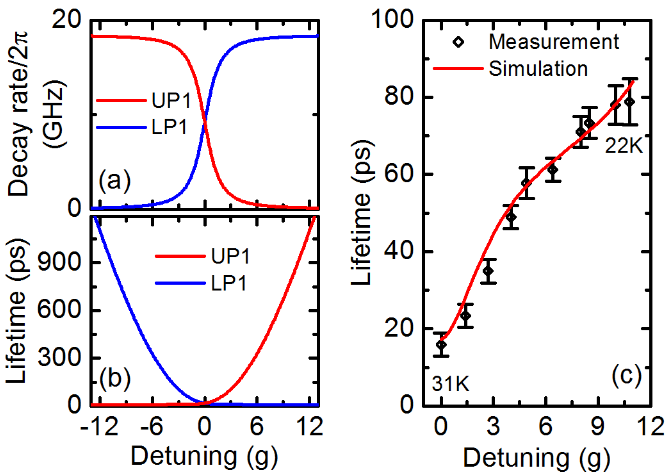

Figure JV9: Calculated decay rates (a) and lifetimes (b) of the polariton branches as a function of the QD-cavity detuning for an ideal JC-system. (c) Measured lifetimes fitted with a model taking into account the coupling to phonon allows to extract the coupling of the polariton-to-phonon coupling.

K. Müller et al. "Ultrafast Polariton-Phonon Dynamics of Strongly Coupled Quantum Dot-Nanocavity Systems", *Physical Review X* **5**, 031006 (2015).

Tuning the Photon Statistics of a Strongly Coupled Nanophotonic System

The nonlinear ladder of hybridized light-matter states of a strongly coupled quantum-dot-photonic-crystal cavity system is a promising platform for the generation of non-classical states of light. We have shown that we can tune the photon counting statistics of the emission by changing the excitation conditions. By detuning the quantum emitter from the cavity resonance and tuning the excitation laser, we strongly enhance either single- or two-photon emission processes. The strongly dissipative nature of nanophotonic systems typically obscures any quantum character of the emission. By applying a self-homodyne interference and frequency-filtering we overcome this obstacle. This allows us to tune the emission from the nanophotonic system from single photons in the photon-blockade regime to an emission with a strong two-photon component in the photon-tunneling regime. We measure second-order coherence values of $g^{(2)}(0) = 0.063 \pm 0.010$ and $g^{(2)}(0) = 1.490 \pm 0.034$. Furthermore, we have modelled the generation of two photons at a time by rate equation model that captures the dominant processes of emission both in the single- and multi-photon regimes. We also performed quantum-optical simulations that fully capture the frequency filtering of emission from our solid-state system and simulate a third-order coherence value of $g^{(3)}(0) = 0.872 \pm 0.021$.

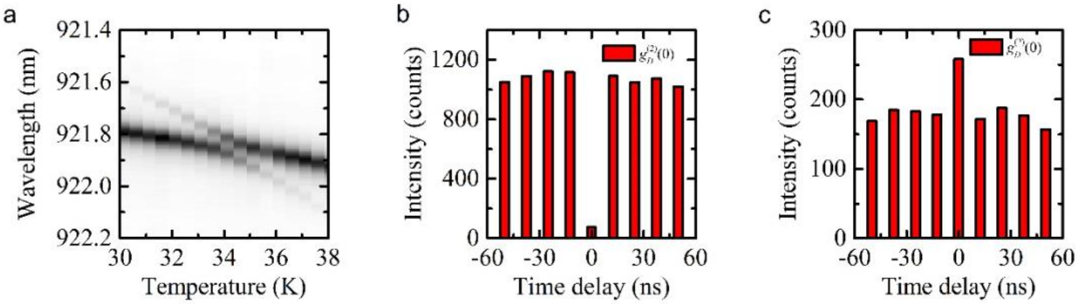

Figure JV10: **a** Anticrossing of a strongly coupled system in a cross-polarized reflectivity measurement. Hanbury Brown-Twiss measurement yielding a second-order coherence value of **b** $g^{(2)}(0) = 0.063 \pm 0.010$ in the photon-blockade regime and **c** $g^{(2)}(0) = 1.490 \pm 0.034$ in the photon-induced tunneling regime.

C Dory *et al.* “Tuning the Photon Statistics of a Strongly Coupled Nanophotonic System”, *Physical Review A* **95** (2), 023804 (2017).

Complete Coherent Control of a Strongly Coupled Quantum Dot-Cavity Polariton System

Strongly coupled quantum dot-photonic crystal cavity systems provide a promising optical on-chip integratable platform for quantum optical applications. However, their strongly dissipative nature has obscured the observation of full coherent control which is required for multiple applications. We have overcome this obstacle by exploiting a phonon-assisted population transfer, spectral filtering and self-homodyne suppression. We demonstrated coherent control of a QD-cavity system with one- and two-pulse experiments leading to Rabi (one pulse, increasing excitation power) and Ramsey oscillations (two pulses, fixed excitation power, increasing inter-pulse delay. The latter reveal dephasing times of approximately 70 ps. We also demonstrated complete coherent control of the polaritonic QD-cavity system (two pulses, increasing excitation power and inter-pulse delay) as shown in the following Figure. The demonstration of complete coherent control further highlighted the great potential of strongly coupled QD-photonic crystal cavity systems. Protocols that were so far only demonstrated for bulk QDs are now feasible within nanophotonic systems where we can take advantage of the benefits of the photonic crystal platform, like for example efficient coupling to waveguides or high emission rates.

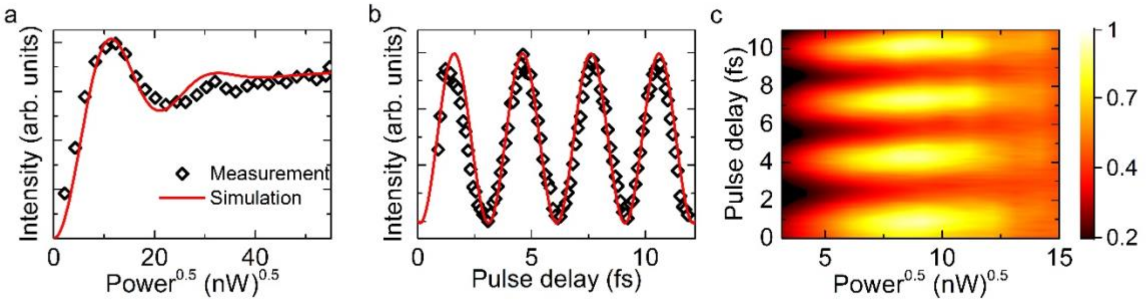

Figure JV11: **a** Rabi oscillations investigated under increasing excitation power. **b** Ramsey fringes measured in a two-pulse experiment with increasing inter-pulse delay. **c** Complete coherent control demonstrated in a two-pulse experiment increasing excitation power and inter-pulse delay.

C. Dory *et al.* *"Complete Coherent Control of a Strongly Coupled Quantum Dot-Cavity Polariton System"*, *Scientific Reports* **6**, 25172 (2016).