Quantum Engineering

Academic and Research Staff
Professor Paola Cappellaro

Graduate Students
Ms. Clarice Aiello, Mr. Masashi Hirose

Technical and Support Staff
Ms. Laura M. von Bosau

Sponsors
NIST (award # 60NANB10D002), NEC Corporation, National Science Foundation (NSF)

Overview
The development of new technologies at scales approaching the quantum regime is driving new theoretical and experimental research on control in quantum systems. Quantum control finds an ideal application in quantum information processing (QIP), which promises to radically improve the acquisition, transmission, and processing of information. The Quantum Engineering Group explores methods to control physical systems that can deliver QIP devices (not only quantum computers but also simulators, measuring and communication devices, etc.), which exceed the capacities of the corresponding classical devices. These ideas are explored experimentally with a hybrid approach that combines ideas from quantum optics, mesoscopic physics, and magnetic resonance. Theoretical efforts focus on investigation of the coherent control of open quantum systems and decoherence avoidance.

1. Quantum Control of Spins in Diamonds

In a recently renovated laboratory we have begun the construction of a new apparatus that can simultaneously initialize and detect the state of single electronic spins, and manipulate their state as well as the state of nearby nuclear spins. The setup consists of a home-built scanning confocal microscope, able to excite electronic spins associated with the Nitrogen-Vacancy center in diamond [1] via green laser excitation at 532nm and to detect the fluorescence emitted by the color center in the range of 650-800nm.
The optical excitation provides a way to initialize the electronic spin into the ms=0 state of the ground state triplet (separated from the ms=±1 states by a zero-field splitting of 2.87GHz) via spin-non conserving optical transitions. At the same time, differences in fluorescence intensity enable state readout, distinguishing between the ms=0 and ms=± 1 states.

Microwave and RF control over a wide range of magnetic fields and frequencies is achieved via an arbitrary waveform generator (AWG) and broadband electronic components. This flexibility will allow us to explore control in different scenarios that impact the coherence properties of the system. Phase and amplitude control of the fields enable precise pulse shaping and high fidelity operations.
The experimental setup will be used to develop precise control for quantum information processing, both as a test-bed to study control strategies and decoherence mitigations, and as a promising system candidate for scalable quantum computation [2].

References
[1] L. Childress, M. V. Gurudev Dutt, J. M. Taylor, A. S. Zibrov, F. Jelezko, J. Wrachtrup, P. R. Hemmer, and M. D. Lukin, “Coherent Dynamics of Coupled Electron and Nuclear Spin Qubits in Diamond,” *Science* **314(5797):** 281-285 (2006).
[2] P. Cappellaro, L. Jiang, J. S. Hodges, and M. D. Lukin, “Coherence and Control of Quantum Registers Based on Electronic Spin in a Nuclear Spin Bath,” *Physical Review Letters* **102(21):** 210502 1-4 (2009).

Figure 1. (a) Our newly-created research lab space. **(b)** The confocal microscopy setup.

2. Magnetometry

The Nitrogen Vacancy (NV) center in diamond can be used not only for quantum information processing, but as well as a sensitive magnetic field sensor [3]. The advantage of such a solid-state sensor is its ability to combine high sensitivity with high spatial resolution, since the sensor can be confined in a small region of space and brought close to the magnetic field source. Another benefit is that it can be operated at room temperature, thus enabling in vivo magnetic sensing.

We explored strategies to improve the magnetometer sensitivities by exploiting either collective properties of an ensemble of NV centers (via the creation of a spin-squeezed state) or the presence of a Nitrogen spin bath in diamond nano-crystal. In both cases, the creation of entangled states, robust against decoherence, could enable magnetic field detection at the Heisenberg limit.

We further analyzed protocols for the detection of magnetic fields arising from ensemble of nuclear spins, for example in biological samples. Specifically, we showed how to extract spectroscopic information about the nuclear spins by measuring the time-correlation thanks to the long coherence time of the NV electronic spin.

References

[3] J. M. Taylor, P. Cappellaro, L. Childress, L. Jiang, D. Budker, P. R. Hemmer, A. Yacoby, R. Walsworth, and M. D. Lukin, "High-Sensitivity Diamond Magnetometer With Nanoscale Resolution," *Nature Physics* **4(10):** 810-816 (2008).

3. Simulations and Decoherence in Many-Spin Systems

Another major area will be the study of many-body quantum physics via magnetic resonance. Due to their long coherence times, nuclear spins in the solid state are an excellent platform to study many-body effects, such as the growth of quantum coherences and their decay due to the environment. Thanks to the good control achieved by nuclear magnetic resonance (NMR) techniques, it is as well possible to use this system to simulate other quantum systems of relevance for quantum information and condensed matter physics [4].

References

[4] P. Cappellaro, C. Ramanathan, and D. G. Cory, "Simulations of Information Transport in Spin Chains," *Physical Review Letters* **99(25):** 250506 1-4 (2007).

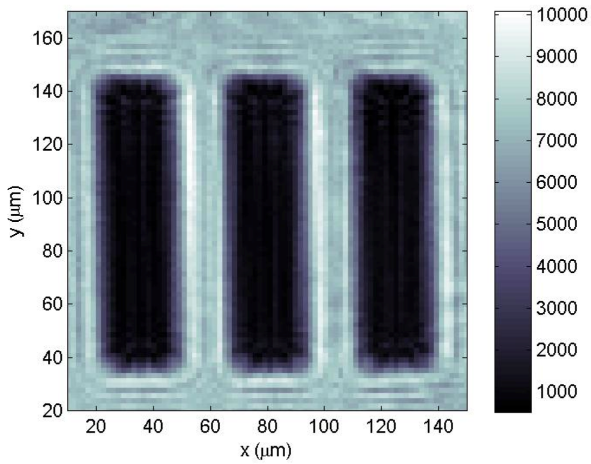

Figure 2. Confocal image of a target, showing the resolution achieved by the setup.

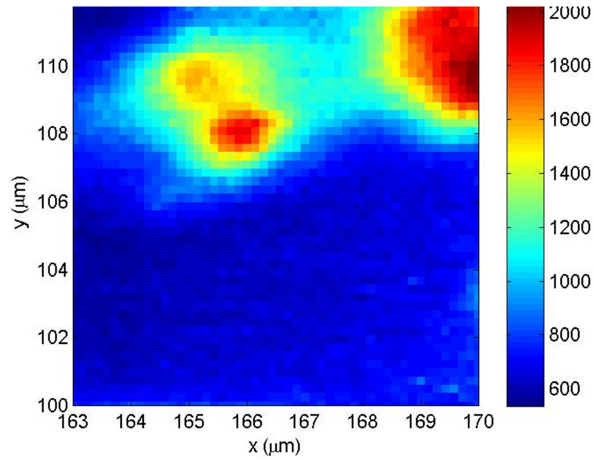

Figure 3. Confocal image of single NV centers.

Publications

Journal Articles, Published

[1] W. Zhang, P. Cappellaro, N. Antler, B. Pepper, D. G. Cory, V. V. Dobrovitski, C. Ramanathan, and L. Viola, "NMR Multiple Quantum Coherences in Quasi-One-Dimensional Spin Systems: Comparison With Ideal Spin-Chain Dynamics," *Physical Review A* **80(5):** 052323 1-13 (2009).

[2] P. Cappellaro and M. D. Lukin, "Quantum Correlation in Disordered Spin Systems: Applications to Magnetic Sensing," *Physical Review A* **80(3):** 032311 1-7 (2009).

Journal Articles, Accepted for Publication

[1] C. A. Meriles, L. Jiang, G. Goldstein, J. S. Hodges, J. Maze, M. D. Lukin and P. Cappellaro, "Imaging Mesoscopic Nuclear Spin Noise With a Diamond Magnetometer.," *Journal of Chemical Physics*, forthcoming, arXiv:1004.5426.

[2] C. Altafini, P. Cappellaro, and D. G. Cory, "Feedback Schemes for Radiation Damping Suppression in NMR: A Control-Theoretical Perspective," *Systems and Control Letters*, forthcoming.

Journal Articles, Submitted for Publication

[1] P. L. Stanwix, L. M. Pham, J. R. Maze, D. LeSage, T. K. Yeung, P. Cappellaro, P. R. Hemmer, A. Yacoby, M. D. Lukin, and R. L. Walsworth, "Coherence of Nitrogen-Vacancy Electronic Spin Ensembles in Diamond," submitted to *Physical Review Letters,* arXiv:1006.4219.

[2] G. Goldstein, P. Cappellaro, J. R. Maze, J. S. Hodges, L. Jiang, A. S. Sørensen, and M. D. Lukin, "Environment Assisted Precision Measurement," submitted to *Physical Review Letters,* arXiv:1001.0089.

[3] G. Goldstein, M. D. Lukin, and P. Cappellaro, "Quantum Limits on Parameter Estimation," arXiv:1001.4804.

Meeting Papers

[1] C. Altafini, P. Cappellaro, and D. G. Cory, “Feedback Schemes for Radiation Damping Suppression in NMR: A Control-Theoretical Perspective", in *Proceedings of the IEEE Conference on Decision and Control*, Shanghai, China, December 2009, pp. 1445-1450.

Invited Talks

[1] P. Cappellaro, “Nanoscale diamond magnetometer with quantum-limited sensitivity”, 3rd Nano-MRI Research Conference: Exploring the Frontiers of Magnetic Resonance Imaging, Paris, France, July 2010.

[2] P. Cappellaro, “High-sensitivity diamond magnetometer with nanoscale resolution”, California NanoSystem Institute (CNSI) Lunch Seminar, University of California, Santa Barbara, May 2010.

[3] P. Cappellaro, “Quantum metrology with spins in diamond” CIFAR Program in Quantum Information Processing, Innsbruck, Austria, May 2010.

[4] P. Cappellaro, “High-sensitivity diamond magnetometer with nanoscale resolution”, IBM Physical Sciences Colloquium, IBM TJ Watson Research Center, 2009.