# Coherent probing of a strongly coupled quantum dot

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Towards on-chip quantum computers..

The idea of a quantum computer was first proposed by Richard Feynman in 1981 as a way to solve intractable quantum mechanical problems[1]. Since then, quantum computers were proven to be inherently superior at solving certain problem than their classical counterparts[2,3]. In addition, communication across quantum channels offers absolute security because it is impossible to eavesdrop on a transmission without disturbing it [4,5] To date, quantum computers have solved only trivial problems, and secure communication is limited to about 200 km [6]. Continued progress in computing and signal amplification in communication will require scalable systems that can perform basic quantum information processing functions. We have recently developed a technique to coherently probe an atomic system -- a semiconductor quantum dot -- that is strongly coupled to a photonic crystal nanocavity. The article is published in Nature[7].

On the web:

Nature: Controlling Cavity Reflectivity With a Single Quantum Dot, Dirk Englund, Andrei Faraon, Ilya Fushman, Nick Stoltz, Pierre Petroff, Jelena Vuckovic, Nature, vol. 450, number 7171, pp. 857-861 (2007)

- Stanford researchers develop a quantum "light switch" Stanford Report story (Dec. 7, 2007)

- Optics.org: Two teams unveil quantum-dot light switch (Dec. 7, 2007)

- Nanotechnology Now (Dec. 11, 2007)

- Pro-Physik (in German) (Dec. 12)

- Office of Naval Research - news

-On Cvitae: Dirk Englund, Andrei Faraon, Ilya Fushman, Jelena Vuckovic

Pro-Physik (Dec. 12)

Questions & Answers on
Controlling Cavity Reflectivity With a Single Quantum Dot

Q: What's the goal of your research?

Whether classical or quantum mechanical, information is ultimately stored in some physical system -- for example, on your hard drive it's stored in local magnetization. The magnetization is stored across a large number of atoms, and the ensemble behaves classically, rather like larger magnets that we know from our macroscopic world. However, if the information is stored and manipulated in things that behave quantum mechanically (like the magnetization of a single atom), then a much more powerful computer could be constructed. Such a quantum computer could simulate intractable problems in nature (like protein folding in biology or drug discovery), or it could be used to decrypt classical encoding (which makes it interesting for national security or policing). It is also possible to build long-range communication systems that are unconditionally secure (even against a quantum computer). This is called quantum cryptography.

Q: Why are QED systems an important area of research?

Several approaches exist for implementing quantum information systems. One would like to use photons, which are great for carrying quantum information. But they do not interact, so it's difficult to use them for logic gates. Atomic systems are much better at interacting, but are bad for communication. So one way that people hope to achieve quantum computers and long-distance quantum cryptography is to combine the best of both worlds through something called a quantum network. This network combines atomic nodes that are connected through photonic quantum bits (qubits). The interface between photons and emitters is governed by quantum electrodynamics. Our group pursues this approach.

One of the major difficulties in the network approach is transferring the quantum information from the atom-like particle (a quantum dot in our case) to the photon. We place the quantum dot inside cavities, which recirculates the photon so that it has a much longer interaction time with the quantum dot. Our photonic crystal system allows cavities with extremely low loss and small volume, so the photon is kept extremely close to the quantum dot for a long time, and can thus interact efficiently with it.

Q: What's the advance that you're reporting in this issue of Nature?

First, let's start with some background. The quantum network idea actually grew out of atomic physics and envisions single atoms or ions that are extremely carefully manipulated in space, using very elaborate elaborate setups. The solid-state approach, which we and the Painter group pursue, has the advantage that the setup is potentially much simpler -- most of the setup is just written on a microchip. Also, the atom is replaced by an ensemble of atoms that forms the quantum dot and is much easier to handle.

First introduced in the late 1990s, this solid-state approach with quantum dots has been playing a catch-up game with atomic physics. Three years ago, a major milestone was reached when the solid-state community achieved a thing regime called strong coupling between an emitter (e.g., QD) and photonic cavity. Strong coupling is important because it means that the emitter and cavity field interact so rapidly that they outpace interaction with the environment -- in effect, the fragile quantum system becomes isolated from the noisy outside world. This isolation is crucuial for a quantum computer.

This strong coupling regime had been explored only by an excitonic path, i.e., by elevating the QD into an excited state and watching how it decays. However, the excitonic path introduces randomness into the system that makes it useless for a quantum computer. What is different in ours and Painter's work is that we have achieved a way to probe the quantum system directly by photons. This is extremely important because it opens the possibility to exchange quantum information between the photon and quantum dot, which is fundamental to the quantum network idea. It's crucial to enabling gates for a quantum computer and elemental quantum information processing for long-range quantum cryptography.

Q: What has enabled this advance?
The central part of this experiment -- the photonic crystal chip with embedded quantum dots -- is fabricated by semiconductor growth and nanofabrication techniques. The sample was grown by our collaborators Nick Stoltz and Pierre Petroff at UC Santa Barbara, and the structures were fabricated by us at the Stanford Nanofabrication Facility. This sample is mounted in a cryostat, a kind of vacuum chamber that's cooled to about 10 degrees above absolute zero by liquid helium. Then the sample is probed in an optical setup using a set of laser beams and low-noise detectors.
The cavity localizes light into a region which is only couple of hundred nanometeres in each dimension by employing a periodic arrangement of holes around it, which we call photonic crystal (see Fig. 1 in the paper). The cavity is made of a semiconductor called Gallium Arsenide. The quantum dot is embedded inside of the cavity; it is a nanoscale inclusion of another semiconductor - Indium Arsenide - inside of it, and has dimensions of about 10 nanometers. The quantum dot can be viewed as an artificial atom, as electrons inside of it can occupy only discrete energy levels, as a result of strong quantum confinement - same as in atom; as a result of that, quantum dot exhibits discrete spectral lines at its output (again, same as an atom).

Q: Why has this never been achieved before?
Our results require, first of all, high-quality quantum dots embedded in low-loss cavities with very small mode volume. Such quantum dots and cavities only became available in the last few years. The the combination of advances in these areas, the first demonstration of strong coupling (as mentioned above) was possible three years ago by groups from the United States, France, and Germany. Since then, research groups have been trying to create the direct probing approach through a photonic channel (as opposed to the previous excitonic pathway). This came with several hurdles, which required our group to develop a special optics setup to separate the reflected beam that had interacted with the cavity from a high background noise. Using a cross-polarized setup, we were able to improve signal - to - noise by more than a factor of 1000. The Painter group also had to overcome these technical challenges, and they solved them using their fiber-based approach.
Q: Could you explain the key differences between your research and that published by Kartik Srinivasan and Oskar Painter on the same subject?
Our results were independently achieved in a different physical system by Oskar Painter and Kartik Srinivasan at Caltech. Both experiments use quantum dots in cavities. What's different is the optical architecture. The Painter group uses circular resonators consisting of gallium arsenide which are manually brought near a tapered optical fiber. One of the remarkable things about their approach is very high coupling efficiency. In our case, the cavity consists of a photonic crystal, a periodic lattice of air holes in gallium arsenide. There has been tremendous interest in photonic crystals because they allow fully lithographic fabrication -- much like computer chips today. They are also ideal for combining several of such quantum dot-coupled cavities into the quantum network that I mentioned above. Integration between different QD/cavity systems is as easy as drawing waveguides between them, as we have already demonstrated in an earlier publication.

Q: What are the key applications?
Our research represents a crucial step towards exchanging quantum information stored in photons with quantum information stored in solid-state atomic systems. This may lead to quantum information processing such as an on-chip quantum computer or a quantum repeater (a kind of signal amplifier) for long-range quantum cryptography.

In addition, we have demonstrated an extremely large optical nonlinearity, which could find applications in all-optical signal processing (e.g., as an all-optical switch). Such an advance would speed up internet and interconnect links.

Q: What are the next steps for you and your colleagues?

Having achieved coherent probing and giant optical nonlinearity with QDs strongly coupled to PC cavities we are hopeful to be entering a new era of coherent control of on-chip quantum systems. This opens many exciting possibilities. For one, we want to demonstrate efficient quantum information transfer from photons to quantum dots. Generally, we will also work on scaling up the size of the quantum network to a larger number of nodes (QDs coupled to cavities) that are connected through waveguides. We hope that such systems would then allow useful quantum information processing for quantum computing and secure long-range communication.

Q: What do you see as the key problems that have to be solved?

Reaching the strong coupling regime with single QDs has been a major step forward. However, in creating a PC quantum network consisting of several QD/cavity nodes, we need a set of tools to correct detunings between QDs and cavities. To this end, we developed a technique to locally tune the emission wavelength of QDs and the resonance frequency of cavities using a laser heating technique. In addition, we are developing a technique to tune the resonance wavelength of cavities and waveguides by changing the refractive index of a photoactive film. With this toolkit in hand, we think that we can overcome fabrication imperfections and QD differences. Then a remaining challenge will be creating a QD system containing at least two states in which we can store quantum information.

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