Quantum information processing on photonic crystal chips

Dirk Englund, Andrei Faraon, Ilya Fushman, and Jelena Vuckovic

Semiconductor quantum dots integrated in nano-cavities exhibit atom-like properties that can make them useful for the design of functional quantum information networks.

A quantum computer could simulate extremely complex problems, such as protein folding or breaking data encryption codes, in a small fraction of the time used by its conventional counterpart. In addition, quantum channels could offer absolute security in communication because it is impossible to eavesdrop on a transmission without disturbing it. To date however, quantum computers have only solved trivial problems, and secure communication range is limited by the lack of amplifiers. Further progress in computing and signal amplification will require scalable systems that can perform basic quantum information processing (QIP) functions.

One of the most promising QIP approaches is the quantum network that combines the advantages of photons as information carriers and atomic systems as nonlinear gates and memory (see Figure 1). In the solid-state implementation, semiconductor quantum dots (QDs) form practical atomic systems that can be positioned in photonic nano-cavities to facilitate quantum information transfer to photons. The 2D photonic crystal (PC) offers a controllable electromagnetic environment, ideal for the compact integration and isolation of the fragile quantum system through suppression of spontaneous emission.

In this architecture, the nodes consist of PC cavities coupled to embedded QDs, and the photonic channels consist of PC waveguides.

Recently, we started building the architecture of a QIP network using the cavity-waveguide-cavity architecture illustrated in Figure 1(b). A QD in the source cavity can be controlled to emit preferentially into the cavity mode, which is then efficiently transferred to the target cavity. Other functions, such as the spectral filtering shown in the inset of Figure 1(b), can be directly integrated into the design.

Many QIP applications require the QDs to emit photons with identical wave packets. This indistinguishability can be improved by increasing the spontaneous emission rate of the coupled QDs beyond other decoherence mechanisms. Recently, we were able to measure a 67% wavefunction overlap for consecu...
Figure 2. (a) Photonic crystal (PC) structure with cavity and laser heating pad. (b) Spectrum of strongly coupled QD cavity system tuned through resonance by temperature tuning. (c) Cavity/QD anticrossing. The red lines show QD/cavity tuning when the two are uncoupled.

Figure 3. Resonant probing of a QD/cavity system. (a) The cavity and QD are scanned across the fixed probe by temperature tuning. The reflected intensity drops when the QD becomes resonant with the probe beam. (b) The QD is saturated at extremely low power, representing a large optical nonlinearity. $\langle n_{\text{cav}} \rangle$: the average number of photons in the cavity.

Improvements in indistinguishability exceeding 80−90%, however, will require a method such as coherent pumping to avoid spontaneous relaxation to the ground state of the QD exciton. Most proposals for mapping atomic to photonic qubits require that the QD-cavity coupling outpace other loss mechanisms, such as cavity and QD coupling to the environment. Several groups, including ours, have recently achieved this strong coupling regime in solid-state systems. Figure 2(a) shows the cavity and laser heating pad of one of our PC structures. Figure 2(b) shows the photoluminescence spectrum of the QD tuned through the cavity. As can be seen in Figure 2(c), the strong coupling regime results in QD/cavity anticrossing as the QD-like dispersion changes into a cavity-like dispersion (black trace).

The fabrication of a PC quantum network consisting of several QD/cavity nodes requires a set of tools to correct detunings between QDs and cavities. To this end, we have recently developed a technique to locally tune the temperature of the QD and cavity using laser heating, as shown in Figure 2(a). In addition, we can tune the resonance wavelength of cavities and waveguides by changing the refractive index of a photoactive chalcogenide glass layer deposited on top of the device.

Another requirement is to enable direct probing of the QD/cavity system by photons. This was recently achieved by scattering a weak laser beam off the PC cavity. When the probe beam is resonant with the QD, it destructively interferes with the reflected cavity field in a process analogous to dipole-induced transparency. The resulting reflectivity drop is shown in Figure 3(a). As the probe photon number is increased to roughly one photon per QD lifetime, the transmission dip vanishes. This saturation represents a giant optical nonlinearity which enables strong interaction only between two photons, a most promising development for elemental two-qubit quantum gates and for designing quantum repeaters for long distance quantum communication.

In conclusion, researchers are taking the first steps towards creating practical quantum networks. The use of PCs is especially attractive, as they provide tremendous control over embedded atoms and guided photons. Recently, our group achieved coherent probing and giant optical nonlinearity with QDs strongly coupled to PC cavities. Combined with a toolkit allowing the independent control of QDs and chip photonics, this work and significant advances by other researchers, such as coherent QD spin control, demonstrate that we are entering a new era for the coherent control of on-chip QIP systems that may significantly contribute to quantum computing and secure long-range communications.
Author Information

Jelena Vuckovic
Ginzton Laboratory
Stanford University
Stanford, CA

Jelena Vuckovic received her PhD from the California Institute of Technology in 2002 and joined the Stanford University faculty in 2003. Her research is focused on nano- and quantum photonic devices and circuits.

Dirk Englund, Andrei Faraon, and Ilya Fushman
Stanford University
Stanford, CA

Dirk Englund is a graduate student in applied physics at Stanford University. He received his BS in physics from the California Institute of Technology in 2002.

Andrei Faraon is a graduate student in applied physics at Stanford University. He received his BS degree in physics from the California Institute of Technology in 2004.

Ilya Fushman is a graduate student in applied physics at Stanford University. He received his BS degree in physics from the California Institute of Technology in 2003.

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