Photonic Crystals: From Cavity Reflectivity to a Quantum Network

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We have just published a paper titled:
Controlling cavity reflectivity with a single quantum dot

The paper can be found here: http://www.nature.com/nature/journal/v450/n7171/full/nature06234.html

See also the Q&A article by Dirk Englund here.
This article is meant to give an introduction to the technology of Photonic Crystals (PC's) and how they can be applied to quantum information processing on the chip. Photonic crystals offer a highly versatile platform for manipulation of light and an unprecedented degree of control over light matter interaction on a chip. [2] The development of this technology has come along in two main avenues. The first is the development of tools for controlling light on a chip with a focus on systems level integration for optical communication and optical signal processing. The second is the development of tools for strong interactions between light and matter, where the focus has been on single elements of an optical network that can be used to enhance quantum effects, such as getting more light out of emitters. We review work along both of these avenues and show that they can come together to realize a quantum information processing device in solid state. There are many challenges which need to be overcome in order to realize useful devices. Luckily, developments in PC's for optics and communication can be directly transferred to quantum information processing devices at a system level, which is where this research will head in the next years. On the quantum side, a breakthrough in material science and manipulation of "atoms" inside these chips will be needed in order to realize a quantum memory and stable quantum bits.

Overview of Photonic Crystals:
A top-view image of a photonic crystal is shown on the right. Light (indicated by the yellow lines) can travel in a waveguide and couple to a cavity where it circulates for a time that is given by the quality factor (Q). These are the two basic elements of a PC circuit: waveguides channel information, and cavities facilitate information processing.

The higher the quality factor, the longer the light stays in the cavity and interacts with matter. Light can leak vertically off the chip or laterally back into the waveguide. The challenge is to make the losses out-of plane low compared to those to the waveguide and keep the total losses small. The Q is determined by cavity design and extremely high Q values have been achieved [3]. The dimensions of each optical element, such as a cavity are quite small (1 micrometer or so), and so many such cavities can be integrated into a small chip area.
The benefit of photonic crystals is that the performance is primarily determined by design. Given a high index semiconductor, such as Si or GaAs one can make splitters, waveguides, filters, multiplexers and de-multiplexers that operate at any wavelength by choosing the hole radii, hole spacing and membrane thickness. The in-plane mirrors, which are created by the holes, have an extremely high bandwidth of reflectivity: for example ~ 500 nm at a center wavelength of 1500 nm.

Thus, photonic crystals are a sort of optical breadboard on a chip. By removing and shifting holes in a clever manner all elements for controlling the flow of light can be made (long-lived optical buffers have not been demonstrated, but remain an active area of research).

How do Photonic Crystals Apply to Quantum Information Processing on a Chip?:

There are many material systems that have potential for realizing a quantum computer [for a comprehensive review see Ref 4 Ch 7]. A computer, whether quantum or classical, must have a means of taking information inputs, doing something to them, and giving information outputs. The information must be encoded in some way and transformed in time. Light happens to be great ways to transport information, because it weakly interacts with the environment, which is why it is used for long distance communication today. Unfortunately photons (particles of light) do not interact well with each other and cannot be easily stored. Atoms, on the other hand, can be easily stored but interact strongly with their environment. A promising approach to QC is to combine the information carrying property of photons with the storage property of atoms [5] into a "quantum network". This quantum network approach relies on atoms in optical cavities that isolate them from their environment, and allow only the interaction with photons sent along particular channels.

A schematic loosely based on the proposal in [5] is shown below. Photons (red line) carry quantum information between atom-cavity nodes. These nodes (circles) are connected in a large network. The basic element are two cavities connected by a photonic channel each with an atom inside. The quantum bits (qubits) are the two states of the atom labeled as logical zero or one. An external clock photon (blue lines) mediates the interaction. When a photon comes into the cavity, it can change the state of the atom and so write information into it. The information can be released by applying another photon. Atoms at neighboring nodes interact via this light channel. With the ability to manipulate each atom individually and two atoms at a time, we can do arbitrary computation.

There have been many developments in the field of atomic physics toward the realization of such a platform [Kimble]. However, atomic physics experiments are not easily scalable, and recent development of atom chips, while promising, still require large setups. A solid state analogue to this architecture would be preferable.

Luckily, we know how to make artificial atoms and we know how to make excellent cavities in solid state. Semiconductor structures, known as quantum dots, can be grown on a variety of semiconductors and can be tailored to behave like single atoms. Quantum dots , unlike atoms, are easily localized in space, bright, and controllable with temperature and strain. Since they behave very similarly to atoms, we can borrow all the tricks from atomic physics and use electric and magnetic fields to control the individual quantum dots. Quantum dots can even operate at room temperature, although low temperatures (4-50K) are still required for the current state of the art experiments.

Over the past few years, there has been much progress in combining these artificial atoms with PC cavities, and this research has resulted in generation of single photons, which have applications to secure communication and observation of quantum effects [6]. Furthermore, we know how to make the two stable logic states inside the quantum dot and transfer information between them. This field of research is now at a technologically exciting point, where the goal is to take all the separate pieces: cavities, quantum dot state manipulation and optical signal processing, and put these together to realize first the two-node network above, and then a large quantum information processing circuit.

Where are we now?

In our group we have focused on photonic crystal cavities and optical manipulation of quantum dots. In order to implement the network approach, we need to realize the interactions shown by the red and blue arrows in the above schematic. This means that external light needs to be coupled into the cavity. Furthermore, we need to verify that the presence of the quantum dot does something to the light, because otherwise there will be no way to make the two remote cavities interact with each other. This is exactly what has been done in our recent work [Nature]. In this experiment we have verified that we can couple light into the cavity and that the presence of the quantum dot affects this light.

A little more detail:

The actual photonic crystal device is shown on the right. It is a suspended membrane of GaAs. There are two essential elements: a heating pad and a cavity. The heating pad allows us to optically control the wavelength of our quantum dot and the cavity and modulate these. The modulation is paramount to getting a nice coupling, because it allows us to see what we're doing.

In the experiment we scatter laser light from the high Q photonic crystal cavity with an embedded quantum dot. In order to observe only the light that is coupled to the cavity, we use a cross-polarization measurement scheme, which is detailed in the image below.

The experiment itself takes place on an optical table. The chip is inside a Helium flow cryostat at temperatures of ~ 20 K, which is shown in the inset of the following figure. The schematic of the optics in front of this cryostat is also shown below. There are two lasers: a heating laser with power that is modulated by a triangle wave, and a probe laser that is vertically polarized. The output is sent to a spectrometer, where we can image the cavity resonance, quantum dot resonance and probe laser in time as shown on the inset. With the triangular modulation of the heating laser, the resonances of the cavity and quantum dot change and pass through the probe laser as shown on the top right inset.

The polarizing beam splitter (PBS) is quite good at filtering out noise, and we can see the cavity very clearly as shown in the video below. In the video there are two bright spots. The top spot corresponds to a laser beam that is focused on the cavity, while the bottom spot corresponds to a heating laser, that locally heats the pad and modulates the resonance. When the cavity crosses the laser in frequency, it scatters the light, and we see the bright signal from the cavity. Relative to the above diagram, the cavity is now at the top left and the heating pad is at the bottom right. In the actual experiment we use a small aperture to only let the bright cavity spot through.

Now if we look at the signal on a detector that resolves the power in time, what we see is the following power modulation. In the case of a cavity without the quantum dot, we expect to see just the cavity shape given by the dashed line. However, because the quantum dot is inside the cavity, it modifies the phase of light that interacts with it, and this results in destructive interference, which does not allow light to pass through. This is a single quantum dot modulating the amplitude of a laser beam by more than 50%.

So what we see is that we can tell that a quantum dot is inside the cavity by scattering light off of it. We can now

think of using this property to control the flow of light on the chip and attempt to do some logic.

Conclusion and outlook:

This is only a first step in realizing the two node structure shown before. The quantum dots used in our experiment only have one logic state. The excited state of the quantum dot is extremely short lived (10 picoseconds here), and this cannot be used for logic. Thus, the next step is to combine research on making multiple stable levels with our cavities and verifying that we can transfer the quantum dot from the logical one state to the logical zero state. Finally, we can move away from one cavity and scale to two and more. However, this is not all. The demands for making a quantum computer are quite stringent. The probability for losses from light scattering and imperfect timing and interactions must be below at least about 10-4 per operation. This means that much more work has to be done on the technology side in developing lossless structures and low loss couplers between cavities, as well as efficient coupling of light on and off the chip.

Further Reading:

A really nice animation of a photonic crystal information processing device can be found on the CUDOS site:

http://cudos.org.au/cudos/education/Animation.php

The book by Nielsen and Chuang [4] is an excellent reference on quantum information processing. There are two more articles on cvitae.org, which have a more detailed description of approaches to quantum computing that were not described in this article:

A "linear optics quantum computer" with only conventional optical elements can be found here. Another promising approach, a "cluster state quantum computer", relies on large entangled states that could be generated with multiple connected cavities proposed by Briegel is discussed here

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