QUANTUM NETWORKS BASED ON CAVITY QED

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We review an ongoing program of interdisciplinary research aimed at developing hardware and protocols for quantum communication networks. Our primary experimental goals are to demonstrate *quantum state mapping* from storage/processing media (internal states of trapped atoms) to transmission media (optical photons), and to investigate a nanotechnology paradigm for cavity QED that would involve the integration of magnetic microtraps with photonic bandgap structures.

1 Introduction

No one can dispute that we live in an age of information; living in such an age, we experience an ever-increasing need for technology that allows us to share information in a secure, efficient, and reliable way. Quantum technologies show great potential for revolutionizing the methods by which we collect and distribute information, in diverse engineering contexts that range from computer architecture to the Internet. Seminal theoretical research in the field has identified a portfolio of tasks for which quantum methods are provably superior to their classical counterparts. For example, it has recently been shown that the communication complexity of a fundamental task such as appointment-scheduling can be drastically reduced through the use of quantum resources [1]. It is also known that the elementary protocol of quantum state teleportation [2] could provide a means for distributing cryptographic key with absolute and verifiable security [3], and that related methods could be used

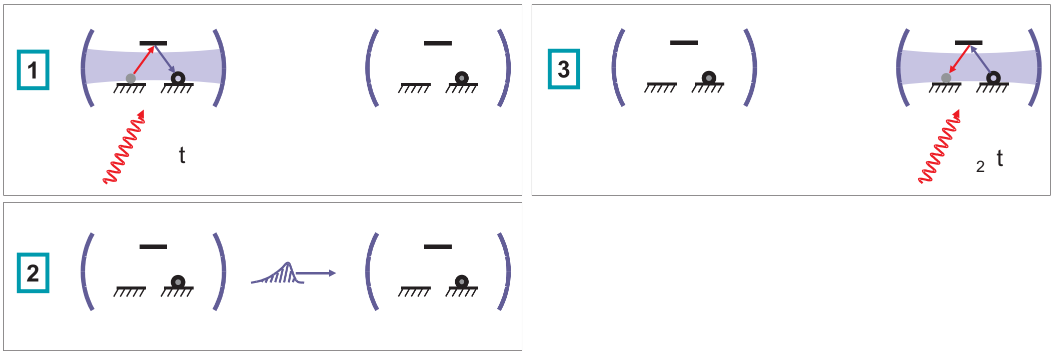

Figure 1. Transmission of quantum information between nodes in a quantum network. A qubit is initially stored in the internal state of an atom trapped within a high-finesse optical cavity, at the sending node (each node contains multiple atoms). 1: the atomic state is mapped to that of an optical photon via cavity QED, 2: the photon travels through a fiber to the receiving node, 3: the photonic state is mapped into that of a trapped atom at the receiving node. Multiple nodes connected in this fashion form a *quantum network*.

to enhance the capacity of noisy communication channels [4].

An ongoing program of research at Caltech focuses on development of the hardware and error correction protocols required to construct a *quantum network* (see Fig. 1). Here quantum nodes with memory and local processing capabilities will be connected by quantum communication channels that allow robust transmission of coherent quantum information among nodes of the network. Such a network would be capable of performing distributed quantum computations [5]. In our proposed implementation, trapped neutral atoms will provide quantum memory at each node of the network, and optical cavities will be utilized both to perform quantum gates and to transfer quantum information between nodes [6]. With a long-term view towards developing integrated and robust hardware for quantum nodes, much of our work is aimed at exploring a revolutionary new technical paradigm for cavity QED based on magnetic microtraps and optical photonic bandgap structures [7]. In the following sections, we first provide an overview of this new technical paradigm and then describe the quantum repeater protocol that will enable robust quantum communication in the presence of channel decoherence.

2 Nanotechnology for optical cavity QED with neutral atoms

During the past decade, advances in semiconductor crystal growth technique have led to the rapid development of optical microcavity devices. With the ultrahigh precision that can now be obtained over layer thicknesses, high reflectivity mirrors can easily be grown by depositing alternating layers of high- and low-index materials to define high-Q cavities in the vertical dimension. Recently, it has also become possible to microfabricate high reflectivity mirrors with *horizontal* orientation by etching periodic arrays of holes into a semiconductor substrate. These “photonic crystals” can be designed to fully suppress horizontal light propagation within certain frequency bands, called photonic bandgaps (see Fig. 2) [8,9].

When combined with high index-contrast slabs, in which the propagation of light is already confined to a plane, photonic bandgap mirrors can be used to confine light within “nanocavities” of extremely small volume. Such cavities can be produced simply by introducing defects into the photonic bandgap structure, for example by omitting one hole from the periodic array. The resonance wavelength of such a cavity can be lithographically defined by adjusting the precise geometry of the holes immediately surrounding the defect. In previous work this strategy has been employed to construct microcavity semiconductor lasers [10] with mode volumes as small as $2.5\,(\lambda/2n_{\mathrm{slab}})^3$.

Using the same fabrication techniques, it is also possible to guide, bend, filter, and sort light in 2-D photonic crystals. Such photonic waveguides could clearly be used as optical channels between nanocavities, and could also be used to define simple interferometers to combine cavity inputs/outputs. Tapered photonic waveguides could be pigtailed to standard optical fibers, as a means of bringing light into or out of the semiconductor slab. Using the techniques described above, we can easily envision fabricating semiconductor wafers in which multiple interconnected optical cavities are embedded at an areal density $\sim 10^6$ cm^{-2}. Such arrays of PBG nanocavities could replace the Fabry-Perot cavities that have been used in previous experiments on optical cavity QED with neutral atoms.

The basic parameter that measures coupling strength between an atom and an optical cavity is the so-called “vacuum Rabi frequency” $g \equiv \frac{d \cdot E_1}{2\hbar}$, where d is the atomic dipole-transition matrix element and E_1 is the electric field per photon in the cavity. To achieve

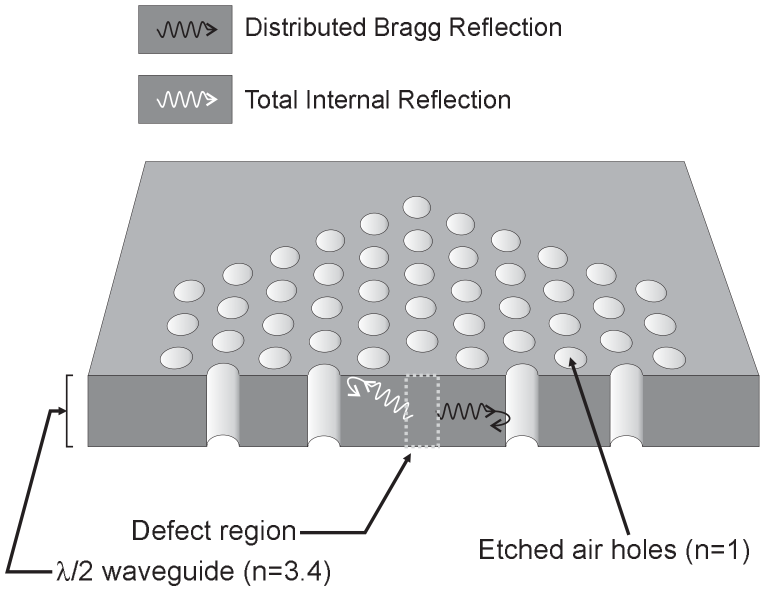

Figure 2. Schematic cross-section of the photonic crystal structure.

strong coupling we must have g sufficiently large compared to both the atomic dipole decay rate $\gamma_\perp$ and the cavity field decay rate κ. For the purpose of quantum information processing, we require that both the critical photon number m_0 and the critical atom number N_0 be less than one, where $m_0 = \frac{\gamma_\perp^2}{2g^2}$ and $N_0 = \frac{2\kappa\gamma_\perp}{g^2}$. As the dipole matrix element d is fixed by atomic structure, the only way to increase $g/\gamma_\perp$ is to construct cavities in which E_1 is as large as possible.

We have performed numerical calculations (via finite-difference time-domain modeling [12]) of the mode properties for several possible PBG defect cavities. In one case we have obtained $V_{\rm eff} = 0.09\,(\lambda/2)^2$ together with $Q \approx 1.6 \times 10^4$. This particular geometry incorporates a central "defect" hole of reduced diameter $\sim$ 108 nm. To couple most strongly with the cavity field, an atom should be trapped at the center of this hole. While further optimization of the geometry may still be possible, these parameters already lead to $g \approx 5.6$ GHz with $\kappa = 11$ GHz, or $m_0 \approx 5.4 \times 10^{-8}$ photons and $N_0 \approx 1.8 \times 10^{-3}$ atoms.

In addition to the creation of semiconductor nanostructures, modern microfabrication techniques also allow the patterning of conducting wires and ferromagnetic materials at the $1 - 10$ μm scale. As a result, it should be possible to construct magnetic microtraps with field gradients on the order of 10^8 G/cm and field curvatures $\sim 10^8$ G/cm^2 [14,15]. With this magnitude of field curvature, *e.g.*, an Ioffe configuration trap would hold a Cs atom with $\eta \sim 0.35$ in the axial coordinate and $\eta \sim 0.035$ in the radial coordinates [14], and provide a well-defined bias field $\sim$ 1 G at the trap center.

Our initial integration scheme will be to deposit micron-scale wires on the surface of a photonic crystal membrane, such that each PBG cavity is surrounded by a concentric microtrap. Fig. 3 shows one possible configuration. Current-carrying wires arranged in a

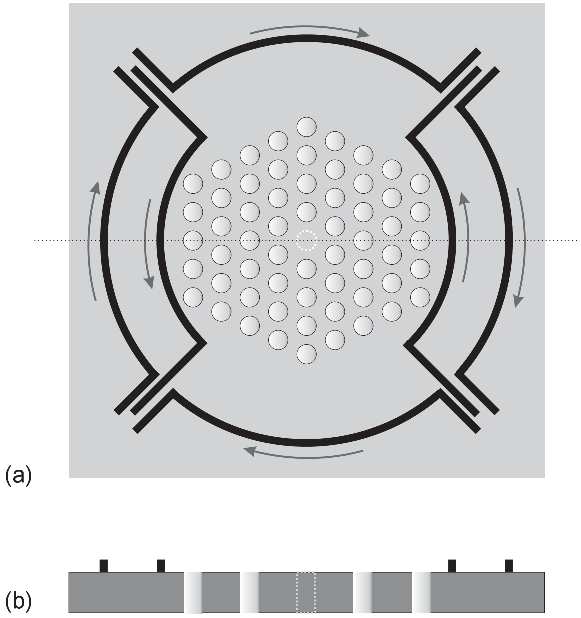

Figure 3. Schematic of an integrated PBG cavity and planar magnetic microtrap. (a) Top view showing arrangement of the current-carrying wires. Arrows indicate the direction of current flow. (b) Cross-section through the defect cavity (as indicated by the dashed line in (a)), showing wire deposition on the surface of the semiconductor slab.

suitable modification of Weinstein and Libbrecht's 'Ioffe *c*' configuration [14] can project a magnetic field with a stable minimum at the geometric center of the PBG cavity, such that one or more atoms could be confined within the defect hole and (as discussed above) would therefore experience strong coupling. A similar geometry can be envisioned for a microtrap based on permanent magnets, rather than current-carrying wires. This would involve the use of techniques for electroplating ferromagnetic material (such as nickel [16]) into selected holes around the perimeter of each PBG cavity.

3 Quantum repeater architecture

Any quantum communication scheme will have to deal with losses and other noise (such as phase shifts) in the quantum channel connecting the sending and receiving nodes. Unfortunately, standard quantum error correction schemes as developed for quantum computing will not be practical for two reasons. First, such schemes typically work only if the error probability is sufficiently small, and second, they would require a large overhead in qubits to protect a single qubit against one error. Here we review an error correction protocol that solves for photon absorption errors to all orders (i.e., it works irrespective of the error rate) and that nevertheless requires only a moderate overhead in resources. Subsequently we describe a quantum repeater scheme that allows one to reinforce the quantum signal at intermediate nodes, thus allowing communication over long distances.

Quantum error correction schemes require entangled states of at least 5 qubits to protect one qubit against a single general error. In the specific physical setup described in the present proposal, however, not all possible errors are equally likely to occur. In particular, whereas photon absorption is a common error, the inverse process, the spontaneous creation of a photon with a particular polarization and optical frequency is extremely unlikely. This fact allows one to encode the quantum information in such a way that the photon absorption error can be corrected to all orders with just two entangled atoms per node. Without going into the technical details (see [17,18]), we present here just the basic ideas.

1. The logical $|0\rangle$ and $|1\rangle$ are encoded in the absence and presence of a photon in a particular mode, respectively, so that the error $|0\rangle \mapsto |1\rangle$ has been eliminated.

2. We use an *auxiliary* qubit in the sending node that contains no information about the actual qubit we wish to communicate, to send a photon. This way, if that photon is absorbed, no information will be lost. This part of the protocol is repeated until we know that the photon arrived. Only then do we involve the qubit that contains the actual information.

3. In order to detect photon absorption, we do not have to monitor the environment. The auxiliary atom in the sending node is used twice: its state is communicated in two transmissions to two atoms in the receiving node. Between the two transmissions a NOT operation is applied (i.e., we interchange $|0\rangle \leftrightarrow |1\rangle$) to the sending atom. The two atoms receiving the information should, therefore, be in different states. Photon absorption can thus be unambiguously detected by measuring whether the two atoms are in the state $|0\rangle|0\rangle$.

4. As a bonus, the application of the NOT operation symmetrizes and thereby corrects for all systematic phase errors.

Two atoms per node are sufficient to achieve a high communication fidelity F (defined as the overlap between the actual and desired final state). If there is need for further correction of the remaining phase errors, one extra atom per node is needed [18].

The probability of photon absorption increases exponentially with the length of the communication channel. Thus, while the above error correction scheme in principle works just as well for large-distance communication, it would require an exponentially large number of transmissions. In order to reduce the number of transmissions, we need, just as for classical communication, intermediate nodes—quantum repeaters—where the signal is "amplified." Of course, since true amplification of quantum signals is not possible, the procedure used is more subtle than in the classical case, and is in fact a variant of standard entanglement purification schemes [19], modified to encompass the restrictions on the amount of physical resources.

Several quantum repeater schemes have been discussed in Ref. [20]. The most efficient scheme takes the form of a concatenated error correction code. It makes use of two simple sub-procedures.

1. Two pairs of imperfect EPR pairs of entangled qubits can be used to distill a single pair of *higher* fidelity between nodes A and B.

2. Two pairs of imperfect entangled states connecting nodes A with B, and B with C, resp., can be used to create a single EPR pair of *lower* fidelity between nodes A and C.

When one has more than one intermediate mode, repeating procedure 2 would lead to a fidelity that decreases exponentially with the total number of nodes. In order to achieve a certain minimum final fidelity, one has to periodically purify the entangled states obtained thus far with procedure 1. The whole protocol is then a concatenated procedure in that the purification has to be repeated at different levels: starting at the lowest level one purifies all EPR pairs between adjacent modes, at the next level one purifies the lower-fidelity EPR pairs between more distant nodes as gotten by procedure 2, and so on.

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