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Telecom Quantum Network Node via Atom-Nanophotonic Coupling

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Abstract: We propose neutral atoms coupled to telecom nanophotonic cavities as quantum network nodes. Our novel protocol for generating atom-telecom photon entanglement enables a scalable network architecture featuring identical qubits and direct telecom operation.

Impressive progress has been made in qubit control and entanglement generation in the last decade with demonstrations of up to three node quantum networks [1]. However, a practical quantum network architecture combining scalability, integration with processors, identical qubits, and integrated telecom operation remains an elusive goal. Here we propose neutral atoms coupled to telecom nanophotonic cavities as a platform that combines these capabilities into a single system schematically depicted in Fig. 1(a) [2]. Neutral atoms are excellent candidates for quantum network and processor applications due to their well-developed qubit control toolbox and inherently identical properties [3,4]. The ability to couple multiple atoms to the same nanophotonic cavity with high cooperativity as well as the ability to couple atomic qubits in a processor array to a nanophotonic cavity for information transfer have recently been demonstrated [5,6]. We demonstrate a scheme that can be used to efficiently and directly entangle an atom with a telecom photon mediated by a nanophotonic cavity. We show that the scheme can be implemented under experimentally realistic parameters including cavity coupling strength, finite atomic temperature, and laser noise. Further, we present our experimental progress towards realizing such a node architecture, including fabricating and characterizing high quality nanophotonic crystal cavities, coupling to these cavities via free space, and our compact vacuum chamber design compatible with atom arrays and photonic chip integration.

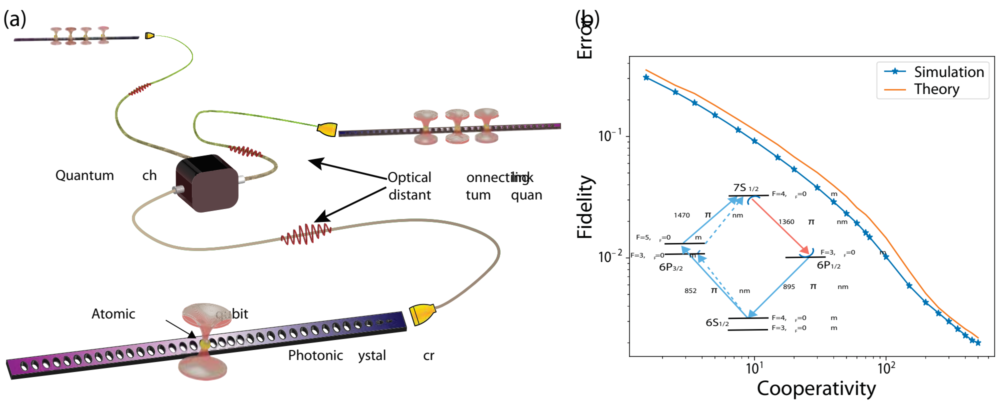

Fig. 1. (a) A quantum network based on neutral atoms coupled to photonic crystal cavity. (b) Fidelity error scaling for cesium atoms in the proposed scheme with cavity cooperativity. The inset shows the relevant level structure for an implementation of the scheme using cesium atoms. Here the $m_F = 0$ states of the $6S_{1/2}$ hyperfine manifold act as the qubit states $|0\rangle$ and $|1\rangle$. π polarized light fields transfer the population from $|0\rangle$ ($6S_{1/2}$, $F = 4$, $m_F = 0$) to the $m_F = 0$ states of $6P_{3/2}$ and then to $7S_{1/2}$. From $7S_{1/2}$ the atom preferentially decays to $6P_{1/2}$ by emitting a telecom photon into the cavity. Another light field transfers the population back to the initial $|0\rangle$ state.

Central to our scheme is the excited state telecom transition present in alkali atoms such as rubidium and cesium. We use a pulsed diamond excitation scheme through which the atom undergoes two successive excitations followed by stimulated emission into the cavity and coherent transfer back into the initial state. We utilize the hyperfine ground states as our qubit states, initialize the system in an equal superposition, and apply the diamond pulse sequence twice separated by a qubit π rotation in order to achieve time-bin entanglement of the hyperfine qubit states with a telecom photon.

In Fig. 1(b) we demonstrate this scheme using the clock states of cesium as our qubits and show that the infidelity present in the scheme decreases exponentially with increased cavity cooperativity. We also analyze the fidelity dependence in the presence of undesired state transitions due to atomic sub-levels and polarization impurity. We use FDTD simulations to investigate the effect of the nanophotonic cavity on the polarization of the addressing laser fields in the atomic trapping region and find that the polarization impurity is on the order of 5 percent. We show that for realistic quality factors, our scheme is robust against this level of polarization impurity and high fidelity entanglement can still be generated. Further, we show that these infidelities can be compensated with increased cavity cooperativity.

We design and fabricate cavities that are compatible with our scheme. An SEM image of example cavities is depicted in Fig. 2 (a). We use FDTD simulations to tune the thickness of the nanophotonic structures in order to optimize the atomic trapping location with respect to the evanescent field, increasing the cooperativity for a given quality factor. Since the evanescent field decays exponentially with increasing distance from the cavity,

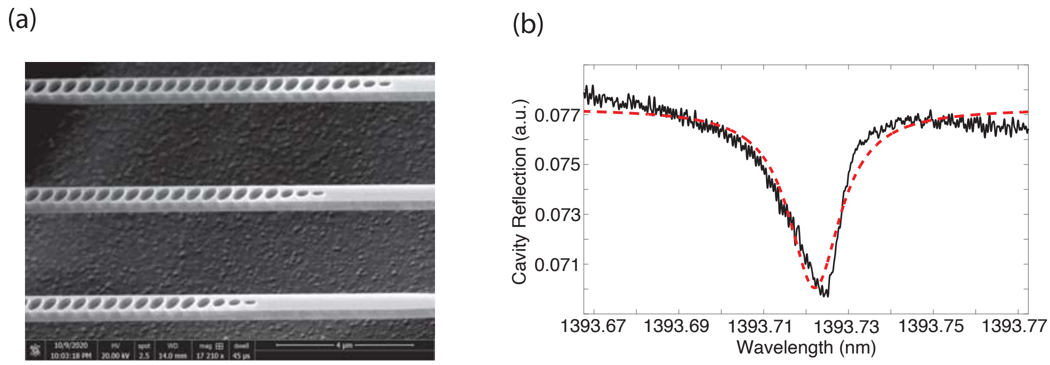

Fig. 2. (a) SEM image of fabricated nanophotonic devices. (b) Reflection spectrum of one of the devices with total Q factor $\sim$ 100,000.

we optimize for a trapping region close to the cavity surface with minimal polarization impurity. For our chosen thickness of 330 nm, we simulate a cavity with a quality factor of 200,000 and show that a fidelity of up to 93% is feasible accounting for the effect of polarization impurity. Given the feasibility of high fidelity entanglement with these parameters, we fabricate prototype cavities with total quality factors of $\sim$ 100,000 as shown in Fig. 2 (b). Optimization of the nanofabrication protocol allows for further improvements of the experimental quality factors. Finally, we will present these results along with our progress in experimental trapping of atoms near nanophotonic structures.

References

1. Pompili, M. *et al.* Realization of a multinode quantum network of remote solid-state qubits. *Science* **372**, 259–264 (2021).
2. Menon, S. G., Singh, K., Borregaard, J. & Bernien, H. Nanophotonic quantum network node with neutral atoms and an integrated telecom interface. *New Journal of Physics* **22**, 073033 (2020).
3. Endres, M. *et al.* Atom-by-atom assembly of defect-free one-dimensional cold atom arrays. *Science* **354**, 1024–1027 (2016).
4. Bernien, H. *et al.* Probing many-body dynamics on a 51-atom quantum simulator. *Nature 2017 551:7682* **551**, 579–584 (2017).
5. Samutpraphoot, P. *et al.* Strong coupling of two individually controlled atoms via a nanophotonic cavity. *Physical Review Letters* **124**, 063602 (2020).
6. Dordević, T. *et al.* Entanglement transport and a nanophotonic interface for atoms in optical tweezers. *Science* **373**, 1511–1514 (2021).