Towards Realizing an "All-Photonic" Quantum Repeater based on a Spin-Photon Quantum Interface

Shuo Sun
JILA and Department of Physics, University of Colorado, Boulder, Colorado 80309, USA
shuosun@colorado.edu

Abstract: I will discuss our recent proposal on deterministic generation of photonic repeater graph states using only a single quantum emitter, our plans for its experimental implementation, and its applications in quantum repeaters and networks.

The building-block state is a specific type of cluster state with tree-type entanglement structure. Once one has multiple copies of a photonic building-block state, one can easily generate an arbitrary 3D photonic cluster states by applying Bell measurements between the corresponding pairs of building-block states. While the Bell measurements between two photons are probabilistic, the Bell measurements between two logic qubits realized by two building-block states can be made deterministic due to the specific error correction codes embedded in the entanglement structure of the building-block state. For this reason, the building-block state, also refereed to as the tree state, have a wide applications in photonic quantum computing, quantum repeaters, and quantum networks.

Despite its great applications, the generation of photonic building-block states is extremely difficult due to the challenge in creating optical nonlinearity at the single-photon level. Recently, several proposals discussed the possibilities of using quantum emitters to deterministically generate photonic cluster states. These proposals require many ancillary matter qubits (same as the depth of the tree), along with the capability to perform two-qubit entangling gates between the quantum emitter and all the ancillary qubits. This demanding requirement limits the scale of the building-block state that one can generate experimentally. In addition, since the entangling operation between the ancillary matter qubit and the quantum emitter is typically much slower than optical processes, the large number of entangling gates significantly reduces the generation rate. In fact, it has been recently shown that the slow entangling operation between the matter qubits is the dominant limiting factor for the performance of the cluster state based all-optical quantum repeaters.

Here, we propose a protocol to deterministically generate photonic building-block states of arbitrary size by using only a single quantum emitter [1]. We consider a system where the emitter is strongly coupled to a chiral waveguide that has a mirror at one end implementing a delayed feedback. Figure 1(a) shows the schematic setup. We assume the emitter has an energy-level structure as shown in the inset of Fig. 1(a). The two ground states $|g_0\rangle \equiv |0\rangle_s$ and $|g_1\rangle \equiv |1\rangle_s$ form a stable qubit, while the state $|g_2\rangle$ serves as an ancillary memory state. The quantum emitter also consists of two optically excited states $|e_L\rangle$ and $|e_R\rangle$, both of which can decay into the ground state $|g_1\rangle$ while emitting a photon into the waveguide. The chiral coupling between the emitter and the waveguide guarantees that the transitions $|g_1\rangle \leftrightarrow |e_L\rangle$ and $|g_1\rangle \leftrightarrow |e_R\rangle$ couple only to the left- and right-propagating modes of the waveguide, respectively. Each photonic qubit is encoded in the time-bin basis, where the presence of a photon in the earlier and later temporal modes are denoted as $|0\rangle_p$ and $|1\rangle_p$, respectively.

Figure 1(b) and (c) show the two elementary gates, the E gate and the CZ gate, in our protocol, along with the pulse sequences required to implement them. An E gate generates a new photon that inherits the state of the quantum emitter, while resetting the state of the emitter to $|1\rangle_s$. The CZ gate is applied between the emitter and a photon reflected from the mirror, such that the state $|1\rangle_p$ photon will pick up a π phase shift if the emitter is initially in state $|g_1\rangle$, while no phase shift otherwise.

As an example, we describe our protocol using a tree with a depth of 3 and branching parameters of $b_0 = b_1 = b_2 = 2$, as shown in Fig. 1(d). We start with the emitter prepared in state $|+\rangle_s = (1/\sqrt{2})(|0\rangle_s + |1\rangle_s)$. By continuously applying the E gate and a $(-\pi/2)$ spin rotation along the y axis of the Bloch sphere for 8 times, we generate 8 photons that are all in the state $|+\rangle_p = (1/\sqrt{2})(|0\rangle_p + |1\rangle_p)$. These photons will constitute the bottom layer of the tree. The 8 photons will travel sequentially in the left-propagating mode of the waveguide until they are reflected by the mirror. For each reflected photon, we apply a CZ gate when the photon arrives at the emitter. Since both the emitter and the photon are in the superposition state, the CZ gate entangles the emitter and the photon. Therefore, after the first two photons pass through the emitter, the emitter will be entangled with both photons. Before the third photon arrives at the emitter, we apply an E gate to generate a new photon (the ninth

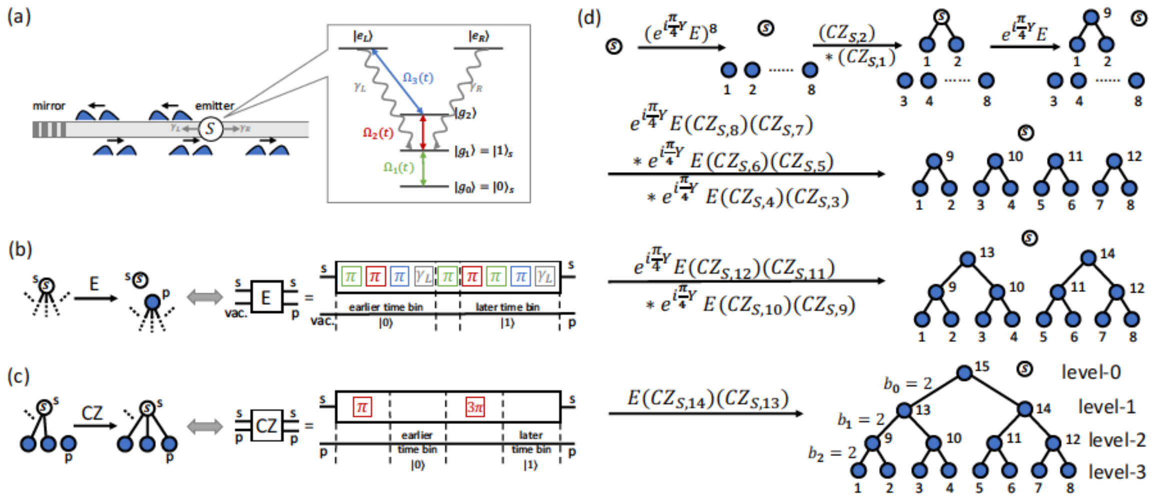

Fig. 1. (a) The schematic setup to generate a photonic tree cluster state with an arbitrary size. The inset shows the energy-level structure of the quantum emitter. (b),(c) The left-hand panels illustrate the effects of the E gate (b) and the CZ gate (c) applied on the joint emitter-photon quantum state. The right-hand panels show the corresponding required pulse sequences for implementation. The color of each block in the pulse sequence is used to indicate the optical transition [also color labeled in (a)] to which the rotation pulse is applied. (d) Graph representation of the procedure for generating a tree with branching parameters $b_0 = b_1 = b_2 = 2$.

photon) into the left-propagating mode of the waveguide. This E gate will transfer the state of the emitter into the ninth photon and reset the emitter to state $|1\rangle_s$. Thus the ninth photon becomes the parent node of the photons 1 and 2, and the emitter is detached from this subtree. A follow-up $(-\pi/2)$ rotation along the y axis on the emitter will prepare the emitter back to the $|+\rangle_s$ state again. Repeating the same procedure layer-by-layer in a bottom-up fashion, we are able to generate the whole tree.

One of the most important features of our protocol is that it can be widely applicable to a large range of tree-type photonic cluster states, such as repeater graph states and tree-encoded repeater graph states. Using these states, we can realize one-way quantum repeaters. We have done a quantitative analysis of the repeater performance using the states generated by our scheme, and compare it with existing schemes [2]. The results suggest that our generation scheme is more advantageous when we can achieve a large emitter-waveguide coupling.

While we described our protocol using a specific system consisting of a multilevel atom coupled to a chiral waveguide, it is worth noting that neither the specific atomic level structure nor the chiral coupling is essential to the realization of our protocol. In this talk, I will also talk about our visions in experimental realization of this scheme, in particular the use of a quantum-dot-based cavity QED system [3,4].

We acknowledge funding from National Science Foundation (Grant No. 1734006, 2016244, and 2137953). This work utilized resources from the University of Colorado Boulder Research Computing Group, which is supported by the National Science Foundation (awards ACI-1532235 and ACI-1532236), the University of Colorado Boulder, and Colorado State University.

References

1. Y. Zhan and S. Sun, "Deterministic generation of loss-tolerant photonic cluster states with a single quantum emitter," Phys. Rev. Lett. **125**, 223601 (2020).
2. Y. Zhan *et al.*, "Performance analysis of one-way quantum repeaters enabled by deterministic generation of photonic graph states," Manuscript under preparation.
3. S. Sun *et al.*, "A quantum phase switch between a single solid-state spin and a photon," Nature Nano. **11**, 539–544 (2016).
4. S. Sun *et al.*, "A single-photon switch and transistor enabled by a solid-state quantum memory," Science **361**, 57-60 (2018).