A multi-node room-temperature quantum network

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We present the first multi-node room-temperature memory-assisted quantum communication network using polarization qubits. Our quantum network combines several independent quantum nodes in an elementary configuration: (i) two independent polarization memory-generators working at rubidium transitions, (ii) two ultra-low noise room-temperature quantum memories, and (iii) a Bell-state qubit decoder and reading station. After storage and retrieval in the two table-top quantum memories, we measure a high-visibility Hong-Ou-Mandel interference of $V = 46.8\% \pm 3.4\%$ between the outputs. We envision this realization to become the backbone of future memory-assisted cryptographic and entanglement distribution networks.

I. INTRODUCTION: ROOM-TEMPERATURE QUANTUM NETWORKS

A quantum network, through the implementation of protocols such as Measurement-Device-Independent Quantum Key Distribution (MDI-QKD)1 and entanglement distribution using quantum repeaters 2, yields significantly promising technological and societal impacts 3. Over the last few decades, the experimental development of such a network has been delayed due to the limited capabilities of the individual components composing the network. In particular, the requirement of high-fidelity quantum storage is a stringent condition for scalability 4, 5. Indeed, each individual node must perform with high-efficiency, high-fidelity, and with minimal losses 6. In addition, engineering the inter-connectivity between these nodes must be as efficient as possible to scale up the network 7. Given recent advances, we have arrived at a critical point where we can interconnect several quantum devices to bring about the first generation of quantum networks. These first prototypes have been proven to show elementary quantum functionality, such as entanglement distribution over several kilometers 8–10 and quantum-state transfer and entanglement generation between light-matter quantum nodes using cold atoms, single atoms trapped in cavities 11, NV diamond centers 12, 13 and superconducting Josephson junctions 14. Despite these remarkable successes, the technological overhead of these realizations in terms of resources, cryogenic cooling, vacuum equipment, and laser cooling systems prevents the realization of larger quantum networks.

Room-temperature quantum technology offers a solution to this scaling problem. Further progress in the design and characterization of these devices to the level of practical implementations would have a tremendous impact on the field 15. Owing to innovative techniques, recent studies have demonstrated the potential of room-temperature quantum operation. Noiseless room-temperature quantum memories for single-photons and polarization qubits have been demonstrated 16–18, with coherence times of several seconds in ambient conditions 19. Furthermore, preliminary quantum cryptography networks using room-temperature memories are already available 20. The next step would be to design a quantum network that leverages room-temperature atomic systems to establish secure communication over extended distances. Such a network must be compatible with QKD protocols and quantum repeater architecture using entanglement.

Here we show the implementation of such a room-temperature quantum network of multiple light-matter interfaces and conducted preliminary studies on the interconnectivity between its components. The paper is structured in the following way: in section II we describe the overall structure of the room-temperature quantum network, including two polarization qubit sources (referred as Alice and Bob), two room-temperature quantum memories, and a Bell measurement station (Charlie). In section III, we show Hong-Ou-Mandel (HOM) interference experiments using the polarization qubit sources. In section IV we demonstrate the “the degree of indistinguishability” of the polarization qubits extracted from two independent quantum memories. We conclude with an outlook and discussion in Section V.

II. EXPERIMENTAL SETUP

The core of our implementation consists of interconnecting several quantum devices in a configuration akin to the one needed for memory-assisted MDI-QKD 21, 22 or polarization-entanglement-based quantum repeater nodes 2. This configuration requires two sources of polarization qubits, two quantum memories, and one Bell-state four-detector-measurement station.
FIG. 1: Experimental layout of the room-temperature quantum memory: the experiments consists of three setups located in two spatially separated laboratories. Left: we create 400ns long pulses using acoustic-optical modulators (AOMs). The pulses enter an optoelectrical section capable of randomly and sequentially, polarizing each pulse using electro-optical modulators (EOMs). Two independent setups are used (Alice and Bob). Right: Alice and Bob generate qubit pulses with approximately $< n = 10$ photons/pulse. After fiber propagation, the pulses are stored in two independent dual-rail atomic vapor quantum memories. The memories outputs are sent to a detection setup, in which they interfere in a non-polarizing beamsplitter (right inset). Coincidence detection is measured for varying parameters of the inputs (time delay, polarization).

A. Polarization qubit sources.

Two independent acoustic-optical modulator units (AOM) temporally shape the probe fields. The AOMs are driven by two phase-locked signal generators operating at $80MHz$. Two arbitrary signal wave generators modulate the amplitude of the AOMs. These wave generators are triggered by the master trigger FPGA generating the 400ns FWHM Gaussian envelope of the probe pulses. Independent Electro-Optical Modulation units (EOM) are in place to encode the desired polarization states on the probe pulses. We modulate the output polarization based on the input applied voltage to the EOMs (usually in the range of $\approx 0 - 500V$). After calibration, we can generate $|H\rangle$, $|V\rangle$, $|D\rangle$ and $|A\rangle$ states. An FPGA-based circuit controls the high-voltage amplifiers for fast operation and trigger-synchronized control. The FPGA can be programmed to generate any sequence of polarizations including a fully random sequence. In these experiments, we employ the FPGA to generate a pre-assigned sequence of polarizations. The qubits are delivered to another location via 30m long single-mode optical fibers.

B. Quantum memories

The two identical room-temperature quantum memories are based on a lambda-type Electromagnetically-Induced Transparency (EIT) configuration, with a probe field frequency at the $5S_{1/2}F = 1 \rightarrow 5P_{1/2}F' = 1$ rubidium transition at a wavelength of 795 nm and a control field coupling the $5S_{1/2}F = 2 \rightarrow 5P_{1/2}F' = 1$ transition. We first lock the probe field to the $F=1$ to $F'=1$ transition using saturation spectroscopy, next we phase-lock the control-field exactly 6.8348GHz away from the probe laser. The experiments here described were achieved with one-photon detunings of $250MHz$.

Upon receiving the qubits at the probe input, a series of wave-plates compensate for the unitary polarization rotation of the optical fibers. Then, the probes pass through a Beam Displacer (BD) element to allow for storage of the polarization-encoded on each pulse. Any polarization state consists of a superposition of $|H\rangle$ and $|V\rangle$; the BD maps these polarization superpositions onto spatial-mode superpositions of the left and right rails, creating a total of four spatial-modes (rails) in total. Half-wave plates (HWP) rotate the polarization of the $|V\rangle$ rail to $|H\rangle$. Both rails are sent through a Glan-Laser polarizer (GL), where they are combined with control fields, before entering the Rb cells.

Four independent control beams coherently prepare two volumes in each of the two $^{87}$Rb vapor cells, containing Kr-Ne buffer gas, at $\approx 60^{\circ}$ in which each mode of polarization qubits are stored. Each vapor cell is placed at the center of three concentric mu-metal cylindrical shields creating a magnetic-field-free environment. Inside the vapor and under EIT conditions, we create four single-photon-level dark-state polaritons. Switching the control fields off stores the pair of qubits. Switching the control field back on, 1$\mu$s later, retrieves the photon pair with their encoded qubit information intact.
After successfully retrieving the stored qubits, polarizing beam splitters (PBS) separate the vertically polarized control fields with an extinction ratio of 42\text{dB}. Then, after recombining the rails, we use frequency filter setups which consist of two consecutive etalon Fabry-Perot cavities separated by a polarization-insensitive Faraday Isolator (FI). The etalons are 7.5mm and 4.0mm thick (for each setup), corresponding to a Free Spectral Range (FSR) of 13GHz and 21GHz respectively. Finally, the outputs of these filtering systems are fiber-coupled to the measuring station, Charlie.

C. Measurement station.

A four-SPCM-based multi-purpose measurement station, referred to as Charlie, can perform measurements necessary for HOM interference, Bell-state detection, and MDI-QKD protocols. The Alice and Bob input pulses are compensated for any polarization rotation at the input of Charlie before entering a 50 : 50 non-polarizing beamsplitter (NPBS). After the NPBS, a PBS at each port further splits the photon pulses into $H$ and $V$ and sends them to four separate SPCMs.

III. HOM INTERFERENCE BETWEEN POLARIZATION QUBITS

One of the significant challenges in creating MDI-QKD networks and quantum repeaters based on entanglement swapping consists in demonstrating successful HOM interference between qubits. For two indistinguishable single photons interfering at a non-polarizing beamsplitter, the probability that they are detected in opposite arms is zero[23]. In the case of weak coherent pulses, containing on average less than one photon, the coincidence rate drops at most to 50% due to the multi-photon components of the coherent state[24].

In our first set of experiments we probe the indistinguishability of the independent qubit sources. To do so, we bypass the quantum memories and remove the PBSs in the four-detector measurement setup. We then measure the coincidence rate of photons arriving at only two detectors simultaneously (see Figure 1).

There are two conventional approaches to measure HOM interference: the photons may be made distinguishable by scanning either the input polarization or the temporal overlap. We scan the delay parameter of the wave generator that creates the temporal envelope of Alice’s (or Bob’s) AOM. We observe a 48% decrease in the coincidence rate (dots in Fig. 2a) of horizontally-polarized inputs with an average of $\langle 0.4 \rangle$ photons per pulse. As expected, the width of the HOM curve matches the temporal width of the input pulses (200ns for this measurement) precisely (solid line in Fig. 2a).

We also observe HOM interference using polarization by varying the polarization of one of the qubit inputs. This was achieved by rotating the input polarization of one of the pulses using automatized wave-plates to enhance the precision. Eventually, perpendicular qubit polarizations will result in two distinguishable photons with a maximum coincidence rate at the outputs of the NPBS. To ensure that the setup is balanced for all the input states, we measure the HOM oscillation versus the relative polarization angle for all four-qubit states (see Fig. 2 b and c) achieving a 48\%\pm0.2% decrease in the coincidence rate.

IV. SECOND-ORDER INTERFERENCE OF STORED AND RETRIEVED PHOTONS

A practical high-repetition quantum repeater node requires four quantum memories to store two pairs of
entangled photons. For the entanglement swapping process to be successfully performed, a major requirement is to successfully interfere with the output of two quantum memories \[25, 26\]. One of the significant challenges to create a workable quantum repeater is to demonstrate successful Hong-Ou-Mandel (HOM) interference between two stored photons \[27, 28\]. This fundamental step is described in this section.

To show that our memories are capable of preserving the qubit information encoded in initial states upon retrieval, we must guarantee that the temporal envelope, frequency and the polarization of the retrieved photons remain the same after storage. To preserve the indistinguishability of the input qubits, it is necessary that all four memory rails have identical EIT bandwidths (to preserve the frequency) and storage efficiencies (to maintain the polarization). We have done this by carefully adjusting all the laser detunings (adjusting the AOM frequencies) and control field powers (adjusting the AOM amplitude modulation) of each individual rail in the quantum memories. In the classical calibration data of the four EIT ensembles, we have measured equal characteristics of the retrieved photons.

Furthermore, we must assure that the two independent filtering systems have similar bandwidths and identical transmissions for \(|H\rangle\) and \(|V\rangle\) polarizations. Fig. 3 shows the four etalons, without birefringence, temperature tuned to have maximum simultaneous transmission at the qubits frequency. The Lorentzian bandwidths of the filtering etalons are \((22.100 \pm 0.007)\)MHz and \((17.490 \pm 0.007)\)MHz for the memory 1 system and, \((15.26 \pm 0.01)\)MHz and \((13.99 \pm 0.01)\)MHz for the memory 2 system. The relative difference between the etalons bandwidths does not impact the indistinguishability of the photons negatively as these lines are more than one order of magnitude wider than the EIT line width. After matching the parameters of all the rails, we proceed to store polarization qubits at the few-photon level in the two memories.

Figure 4 shows the 1\(\mu\)s long storage of two \(|D\rangle\) polarized pulses from Alice and Bob in the two dual-rail memories on a quantum level. We use input photon numbers of \((14)\) and \((10)\) for Alice and Bob, respectively, in order to solely study the timing and fidelity characteristics of the retrieved photons.

We stored the qubits with an average efficiency of 8% in both of the memories. We choose to lower the efficiency by decreasing the control fields’ strength in order to avoid significant background effects on the fidelity after storage. The transmission for both filtering systems is \(\approx 3\%\). This results in output mean photon numbers of \(\approx 0.02\) and \(\approx 0.014\) for Alice and Bob, respectively.

We generate temporally identical outputs by carefully matching all the relevant parameters in the quantum memories such as two-photon detunings, storage time, filtering transmission, and the EIT linewidths. The coincidence rate is measured versus the relative polarization of the output pulses (see Figure 4). First, both memories retrieve identical photons with the same temporal shape, frequency, and polarization, resulting in a minimum coincidence rate. Then, we rotate the polarization of one of the output pulses before it reaches the beamsplitter to make them distinguishable. Doing
so results in a peak in the coincidence rate after 45°
degrees rotation, resulting in an interference visibility of
\( V = 46.8\% \pm 3.4\% \) (red dots and line in Figure 4).

\[ \begin{align*}
V_{HOM} &= 2\mu_1\mu_2 \cos^2[\phi] \\
&= \frac{\mu_1\mu_2}{(\mu_1 + \mu_2)^2} + \frac{\mu_1 - \mu_2}{(\mu_1 + \mu_2)^2} \\
&= \frac{2\mu_1\mu_2}{(\mu_1 + \mu_2)^2} \cos^2[\phi] \\
&= \frac{2\mu_1\mu_2}{(\mu_1 + \mu_2)^2} \left( \frac{\mu_1^2 + \mu_2^2}{\mu_1 + \mu_2} \right)
\end{align*} \]

\[ \left( \frac{\mu_1^2 - \mu_2^2}{\mu_1 + \mu_2} \right) \]

The relevance of the careful matching of the memories’
storage properties in the HOM visibility can be stressed
further by measuring the visibility for unmatched pulses
interacting with the memory. We repeat our analysis
using the two leftover “leakage” peaks (parts of the original
inputs that memories do not store (see Figure 4)
that have different temporal bandwidths. We measured
a HOM visibility of \( V = 19.4\% \pm 1.5\% \) (blue dots and line
in Figure 4), testifying to the mismatch of their temporal
shapes.

V. DISCUSSION AND OUTLOOK

We have presented individual experiments addressing
various challenges to create the quantum connectivity
needed to perform long-distance quantum communic-
ation with polarization qubits in a memory-assisted
quantum network. While other groups have shown
retieval from four-memory systems using the Duan-
Lukin-Cirac-Zoller (DLCZ) protocol [29], our system
incorporates a polarization qubit architecture that has
been proposed to achieve a higher entanglement distrib-
ution rate [2]. We have reached a number of different
benchmarks within this new architecture: input prepara-
tion of polarization qubits at rubidium wavelengths,
simultaneous storage using four light-matter interfaces,
scalability through room-temperature operation, and
verification of identical storage and retrieval from the
memories through Hong-Ou-Mandel interference.

We verified the purity of two independent qubit input
sources through HOM interference. It has been shown
that the theoretical visibility for coherent states at
the single-photon level should be \( \frac{1}{2} \). This difference can be
explained by investigating the theoretical value for the
visibility for attenuated coherent states [30]:

\[ V_{HOM} = 2\mu_1\mu_2 \cos^2[\phi] \]

\[ \frac{\mu_1\mu_2}{(\mu_1 + \mu_2)^2} \]

\[ \left( \frac{\mu_1^2 - \mu_2^2}{\mu_1 + \mu_2} \right) \]

\[ \left( \frac{\mu_1^2 + \mu_2^2}{\mu_1 + \mu_2} \right) \]

\[ \frac{2\mu_1\mu_2}{(\mu_1 + \mu_2)^2} \]

\[ \left( \frac{\mu_1^2 - \mu_2^2}{\mu_1 + \mu_2} \right) \]

\[ \left( \frac{\mu_1^2 + \mu_2^2}{\mu_1 + \mu_2} \right) \]

\[ \frac{2\mu_1\mu_2}{(\mu_1 + \mu_2)^2} \]

\[ \left( \frac{\mu_1^2 - \mu_2^2}{\mu_1 + \mu_2} \right) \]

\[ \left( \frac{\mu_1^2 + \mu_2^2}{\mu_1 + \mu_2} \right) \]

\[ \frac{2\mu_1\mu_2}{(\mu_1 + \mu_2)^2} \]

\[ \left( \frac{\mu_1^2 - \mu_2^2}{\mu_1 + \mu_2} \right) \]

\[ \left( \frac{\mu_1^2 + \mu_2^2}{\mu_1 + \mu_2} \right) \]

We have created a prototype network of four quantum
light-matter interfaces. Not only can this network
uniquely implement a dual-rail protocol to store
polarization qubits, but it can also function at the
single-photon level at room-temperature with low noise.
This implementation is ideally suited to be used in
cryptographic networks assisted by quantum memories,
as long as suitable visibilities are measured.

The central figure-of-merit to this system is the single-
photon-level HOM interference between the outputs of
the quantum memories, which has been seen to have
a visibility of \( V = 46.8\% \pm 3.4\% \). The decrease in
visibility from 50% can be sufficiently explained from
Equation (1) when incorporating the slight mismatch in
pulse strength before the two memories, in combination with the estimated elliptical drift in polarization. This visibility demonstrates the ability for this network to operate at single-photon level, which is sufficient criteria to implement MDI-QKD protocols.

Each of the individual photonic memories is sufficiently optimized such that their output degrees of freedom, including output temporal envelopes, frequency, and polarization, are matched well enough to get excellent HOM visibility. We observe a decrease in visibility with unmatched pulses, which signifies how mismatched states can affect the HOM interference.

Variable-delay MDI-QKD protocols using time-bin qubits have already been demonstrated[31]. Our network can implement similar memory-assisted protocols using polarization qubits. In separate experiments, we have shown that our memories are capable of operating on a shot-by-shot basis [20], which makes them an ideal test bed for the storage of polarization entanglement. Additionally, this gives our realization important perspectives to operate as a network for MDI-QKD protocols that are assisted by entanglement [22]. Together with the development of heralding mechanisms, we envision our quantum network configuration to become the backbone of future quantum repeater applications.

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