Free space quantum communication with quantum memory

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The realization of an elementary quantum network that is intrinsically secure and operates over long distances requires the interconnection of several quantum modules performing different tasks. In this work we report the interconnection of four different quantum modules: (i) a random polarization qubit generator, (ii) a free-space quantum communication channel, (iii) a quantum memory and (iv) a qubit decoder, in a functional elementary quantum network capable of storing a sequence of random polarization qubits in a manner needed for quantum information distribution protocols. We create weak coherent pulses at the single photon level encoding polarization states \(|H\rangle, |V\rangle, |D\rangle, |A\rangle\) in a randomized sequence. The random qubits are sent over a 20m free space link and coupled into a dual rail room temperature quantum memory and after storage and retrieval are analyzed in a four detector polarization analysis akin to the requirements of the BB84 protocol. We have obtained quantum bit error rates of 11.0% and 12.9% for the Z and X bases for single-photon level operation. Our results pave the way towards memory assisted free space quantum cryptographic networks.

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I. INTRODUCTION

The field of quantum information has recently seen remarkable progress regarding the implementation of elementary quantum devices and quantum communication protocols. On one hand, the advent of photonic quantum communication using long distance free space links [1-6] has opened the possibilities to securely exchange quantum states and entanglement [6-8]. These developments together with quantum key distribution protocols have enormous potential for the creation of a global, secure quantum information exchange network [9-14]. On the other hand, an entirely different community of quantum scientists has developed sophisticated quantum light matter interfaces capable of receiving, storing and retrieving photonic qubits [15-19]. Such devices, collectively known as quantum memories already operate with high fidelities [20-22], long storage times [23,24] and high storage efficiencies [25,26]. Furthermore, quantum memories already operate at room temperature while being portable [27,28], thus facilitating their interconnection with other quantum devices.

The construction of an interconnected set of many quantum devices that performs secure communication protocols in outside settings and with moving targets remains a big challenge [30-32]. However, putting together a network of a few quantum nodes and quantum channels is within experimental reach [33,34]. The emergent behaviour of such small quantum networks should allow us to realize more sophisticated quantum procedures [35]. An important example of such an elementary network will be the modular connection of quantum cryptography systems operating over free-space quantum channels [35], assisted by room temperature quantum memories increasing the distance, security and connectivity of quantum key distribution protocols [14,15].

Paramount to the creation of such a free-space memory assisted quantum communication network is the use of shot-by-shot unconditional quantum memories capable of supporting the specific technical demands of outside-of-the-laboratory quantum communication channels. Among them, accepting random qubit states necessary to perform quantum key distribution protocols, having a minimized quantum bit error rate (QBER) and receiving spatially multi-mode signals, while simultaneously being cost effective. These capabilities will allow the construction of elementary quantum networks without the need for frequency conversion among their components, that are intrinsically secure, quantum coherent and compatible with long distance operation.

Here we report the creation of such an elementary quantum network in which we mimic these desired properties into a scaled down experiment. To our knowledge, our results represent the first time that the ideas of quantum communication, as used in the well known BB84 protocol, are combined with quantum storage. Our results are obtained by cascading four different quantum modules: a random polarization qubit generator, a free space quantum communication channel, a quantum memory and a qubit decoder. Such a setup creates the quantum connectivity needed to perform long distance communication of random polarization qubits.

II. EXPERIMENTAL PROCEDURE.

A. Preparation of a random stream of qubits: Alice Module.

Our elementary quantum network starts with the creation of a sequence of four polarization states \(|H\rangle, |V\rangle, |D\rangle, |A\rangle = 1/\sqrt{2}(|H\rangle + |V\rangle), |A\rangle = 1/\sqrt{2}(|H\rangle - |V\rangle)\) in a distant laboratory (Alice’s station, Laboratory II in Fig. 1). We create the qubits using 400ns-long
FIG. 1: Experimental setup for long distance quantum communication. In Laboratory II Alice creates a random sequence of four orthogonal qubits ($|H\rangle$, $|V\rangle$, $|D\rangle$, $|A\rangle$). The 400ns-long qubits are produced every 40 $\mu$s. The qubits propagate in a free-space quantum communication channel over a distance of $\sim$ 20m and are then directed into a dual rail room temperature rubidium vapor quantum memory in Laboratory I. The control storage pulses are time-optimized to the arrival of the qubits in front of the memory. In Bob’s site a four detector setup measures all possible basis at the exit of the memory to determine the quantum bit error rate (QBER). PBS: polarizing beam splitter, WP: wave plates, AOM: acousto-optical modulator, BD: beam displacer, GL: Glan-laser polarizer.

pulses produced every 40 $\mu$s by 4 individual acousto-optical modulators (AOMs). In order to compensate for small deviations in the length of each AOM track, the AOMs are each driven by independent sources regarding their amplitude and frequency modulation. The setup is designed to generate either an ordered sequence of four qubits in cycles of 160 $\mu$s (see Fig. 2) or a train of qubit pulses where the modulation sources are controlled by a FPGA chip programmed to randomly trigger one of the four AOM’s. The resulting random sequence of pulses is attenuated to the single-photon-level and then sent into free space quantum channel module.

B. Propagation of qubit streams: Free space quantum channel module.

The qubits created in the Alice station propagate in a free-space quantum communication channel over a distance of $\sim$ 20m without shielding or vacuum propagation and are then directed to a quantum memory setup in a different laboratory. We have chosen the characteristics of this setup as a test bed of the interconnectivity of this station and the quantum memory setup under more challenging out-of-the-laboratory operation. Of particular interest are the shot-by-shot changes in the mean input photon number due to the air turbulence between the laboratories and the capability of the memory to receive random polarization inputs, pulse-by-pulse. By careful alignment the loss in the free space propagation is set to be less than 4%. Together with 63% fiber coupling efficiency at the receiving end of the quantum memory setup this yields a total transmission of 59% for the quantum communication channel. The shot-by-shot fluctuations in the mean photon number were measured to be $\sim$ 5%.

C. Storage of incoming pulses: Quantum Memory Module

Located in Laboratory I is the room temperature quantum memory in which we store the incoming qubits. The quantum memory is based upon a warm $^{87}$Rb vapor and controlled using electromagnetically induced transparency (EIT). Two independent control beams coherently prepare two volumes within a single $^{87}$Rb vapor cell at 60$^\circ$ C, containing Kr buffer gas to serve as the storage medium for each mode of the polarization qubit. We employed two external-cavity diode lasers phase-locked at 6.835 GHz. The probe field frequency is stabilized to the $5S_{1/2}F = 1 \rightarrow 5P_{1/2}F' = 1$ transition at a wavelength of 795 nm while the control field interacts with the $5S_{1/2}F = 2 \rightarrow 5P_{1/2}F' = 1$ transition. Polarization elements supply 42 dB of control field attenuation (80% probe transmission) while two temperature-controlled etalon resonators (linewidths of 40 and 24 MHz) provide additional 102 dB of control field extinction. The total probe field transmission is 4.5% for all polarization inputs, exhibiting an effective, control/probe suppression ratio of 130 dB [27]. The control field pulses are time-optimized to the arrival of the qubits in front of the memory (see Fig. 2a).
FIG. 2: Storage of a sequence of qubits. (a) A stream of polarization qubits with on average 3.5 photons propagates through a free space quantum communication channel of 20m. In the quantum memory site, the single-photon level qubits are received and stored sequentially using timed control field pulses. (b) Histograms for each of the polarization inputs after storage (dark blue) and background floor (light blue). Each histogram is presented in a 2µs time interval (see dashed black divisions). The fidelities are estimated from the signal-to-background ratio.

D. Measuring the random stream of qubits: Bob module.

After passing through the polarization independent frequency filtering system, the stored pulses enter the Bob module, which is equipped with a non-polarizing beam splitter (separating the $Z = \{|H\>, |V\>\}$ and $X = \{|D\>, |A\>\}$ bases) and two polarizing beam splitters whose outputs are detected by four single-photon counting modules (SPCM). Each SPCM corresponds to a different polarization state. This allow us to compare the detected sequence with the originally sent qubits and estimate the influence of the photonic background of the memory in the evaluation of the QBERs.

III. EXPERIMENT 1: STORAGE OF A SEQUENCE OF FOUR POLARIZATION QUBITS AFTER FREE SPACE PROPAGATION.

In our first experiment, a string of four ordered polarization qubits ($|H\>$, $|V\>$, $|D\>$ and $|A\>$) is sent from Alice module to the memory and Bob terminal through the free space channel in order to test the compatibility of all the modules and the performance of the quantum memory at the single photon level (see Fig. 2). The characterizations of the qubits after storage is done with a single detector placed after the memory bypassing the polarization analysis setup. We create histograms using the time of arrival and estimate a best-case-scenario fidelity of the stored polarization qubits containing on average 1.6 photons per pulse right before the memory. Our analysis shows that even with the additional constraint of shot-by-shot fluctuations in intensity due to free space propagation and the addition of randomly polarized background photons in the memory, maximum fidelities (estimated using the signal-to-background ratio) of 92% for $|H\>$, 92% for $|V\>$, 90% for $|D\>$ and 93% for $|A\>$ can still be achieved. These results are clearly above the classical threshold limit of 85% for the corresponding efficiencies thus providing the necessary condition of unconditional quantum memory operation [27]. They also show that our room temperature quantum memory implementation operates with the same parameters regardless of the polarization input, a fundamental attribute if the memory were to work as either a synchronization device for quantum cryptography protocols in which a stream of random qubits is used to distribute a quantum key or as memory for polarization entanglement in a quantum repeater architecture.

IV. EXPERIMENT 2: STORAGE OF A RANDOM SEQUENCE OF POLARIZATION STATES WITH HIGH PHOTON NUMBER.

After showing unconditional memory operation over the free space network, we now show that the network also operates with high fidelity on a pulse-by-pulse basis, demonstrated by full polarization analysis at Bob location. This is done by randomizing the polarization input of the experiment. Further insight into our current capabilities is obtained by analyzing the quantum bit error rates (QBER) $Q_X$ and $Q_Z$ for $X$ and $Z$ bases after propagation and storage. Starting with pulses containing high number of photons ($\sim$ 100 photons, see Fig. 3), we evaluated the QBER after storage of the random polarization states. An average QBER of 0.57% for the two orthogonal bases have been measured within a region of interest equal to the input pulse width. This QBER is compatible with the typical error rate obtained in a standard quantum key distribution experiment. The importance of this result is two-folded: 1) the storage process at room temperature does not intrinsically add non-unitary
rotation to the states, and in the limit of high signal-to-background has negligible effect on the total QBER: 2) the memory is capable of storing and retrieving a generic polarization qubits on a shot-by-shot level.

V. EXPERIMENT 3: STORAGE OF A RANDOM SEQUENCE OF POLARIZATION QUBITS.

Finally the complete state measurement in the two bases was used again for an input of 1.6 photons before the memory, corresponding to 3.5 photons at Alice station. The evaluated QBERs after storage for polarization qubits are $Q_Z = 11.0\%$ and $Q_X = 12.9\%$ over a 100 ns region (see Fig. 4). The increase of the QBERs is only due to the background noise which is much more significant at the single-photon level. Nonetheless, the fidelities (corresponding to 1–QBER) still remain higher than the classical limit for the corresponding storage efficiency. The latter result is rather counter-intuitive when dealing with superpositions $|D\rangle$ and $|A\rangle$ as it implies that the two rails forming the quantum memory store or miss the pulse coherently (in order to preserve the storage fidelity for that particular polarization), as opposed to retrieving rather $|H\rangle$ or $|V\rangle$ at any given time in a shot-by-shot experiment. This ability is crucial in networks performing quantum key distribution protocols and it also shows that the memory is currently capable of receiving entangled polarization states without distorting them. We do mention that this last experiment constitutes the quantum communication part of the well known BB84 protocol [39], with the addition of a synchronizing quantum memory between Alice and Bob.

VI. DISCUSSION.

Further insight into our current capabilities is obtained by analyzing the quantum key distribution rate ($R$) per channel efficiency for sharing random secret key, encoded in random polarization states, between Alice and Bob. $R$ depends on the quantum bit error rate (QBER) and the mean photon number $\mu$. In the infinite key length limit, it is given by: $R = \mu(e^{-\mu}(1 - H(Q_X)) - H(Q_Z)f(Q_Z))$, where $Q_X$ and $Q_Z$ are the QBERs, $H(x)$ is the binary Shannon entropy function and $f(Q_Z)$ is the efficiency of the classical error correction protocol. We have evaluated the absolute key rate vs. the input photon number and our average QBER with $f(Q_Z)=1.05$ [40]. Our results, including quantum memory operation (QBER = 11.9\% for $\mu = 1.6$) lie just outside of the region for positive key rate generation, indicating that our quantum communication is still not fully-secure.

This drawback can be overcome by applying new avenues of research to our current memory technology, specifically: (i) a substantial decrease in the background obtained by applying re-pumping schemes, (ii) an increase in the speed (bandwidth) of the memory together
with shorter pulse duration and (iii) an increase in the success rate of the storage procedure by means of heralding.

We envision that in the short term these advancements will provide the capabilities to use room temperature quantum memories outside of the laboratory, receiving qubits from ultra-long free-space quantum channels. Because free-space propagation does not require the challenge of frequency conversion to the infrared, our setup can also be used for short-distance proof-of-concept memory-assisted QKD experiments. For example, performing Hong-Ou-Mandel (HOM) photon interference using photons retrieved from two memories, together with memory-assisted temporal shaping of the outgoing qubits \cite{41,42,43}, will make possible to store two random streams of qubits independently in each memory and to perform Bell measurements after simultaneous retrieval events.

In conclusion, we have achieved the first proof of principle combination of free-space propagation of random single-photon level polarization qubits and their storage and retrieval in a room temperature quantum memory. Our results effectively constitute the quantum part of the BB84 protocol with the addition of a quantum memory and pave the way for more sophisticated memory assisted device independent QKD protocols.

VII. ACKNOWLEDGMENTS

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