Optical locking for quantum memory and communication

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Ultra-long photon storage can be used to improve long-distance quantum memory for quantum communications.

Optical fiber technologies have ushered in the global network era, where one can access the Internet anywhere at anytime. In classical optical communications, signal recovery is based on intensity amplification. However, quantum signal recovery is achieved with quantum purification, which offers unconditionally secure data transmission. For this, a quantum repeater plays the important role of extending the transmission distance. Thus, the purification process is an essential step in long-distance communications and information processing in distributed quantum networks.

Quantum memory is an essential part of the quantum repeater, because repeaters are allocated to the same optical transmission line and share entangled photons. As a unique property of quantum nature, entangled photons can be easily obtained from spontaneous parametric down-conversion processes. Here, the required minimum quantum memory photon storage time depends on the maximum transmission distance. At least 1s of storage time is required for transatlantic or transpacific quantum transmission. Unfortunately, this length of storage time has not yet been demonstrated. Higher photon absorption efficiencies achieved over the last decade have prompted researchers to focus on ensemble-based quantum memory. Photon echoes in particular have been revived for quantum memory applications because of their coherent rephasing properties. However, conventional photon echoes bring two major drawbacks—poor storage time on the order of 100μs and retrieval efficiency of less than 1%. Rephasing optical pulses induces population inversion, and spontaneous emission noise is inevitable in these photon echoes. However, our work shows that these hurdles can be overcome.

Recently, we proposed an ultralong quantum memory protocol using on-resonance Raman echoes. With an optical locking technique, we were able to extend the storage time up to the spin population decay of approximately 100s. The optical locking mechanism transfers excited atoms into an auxiliary spin state to provide a conditional halt to the population decay. We used a pair of deshelving optical pulses to achieve optical locking and

Continued on next page
transfer populations between the optical and spin states. Since a spin state is more robust against decay than its optical counterpart, optical locking extends photon storage time. Any extension of this capability is limited by spin dephasing (~10μs) because the optical phase is unlocked.\textsuperscript{4} We demonstrated a spin dephasing-independent quantum memory protocol\textsuperscript{5} by modifying conventional, stimulated (three-pulse) photon echoes\textsuperscript{6} using optical locking.

In stimulated photon echoes, individual optical phase information excited by a data pulse was coherently transferred into optical population information. This resulted in a spectral grating, which is a redistribution of the atom population in optical inhomogeneous broadening, by the ensuing optical pulse—see Figure 1(a). This spectral grating is independent of optical dephasing and can last up to the spin lifetime under the optical locking process by lock pulses (B1 and B2) without loss of coherence—see Figure 1(b).\textsuperscript{5} The third pulse triggered rephasing by converting the spectral grating back into the optical coherence grating, which results in a photon echo (or rephrased coherence burst)—see red line, Figure 1(c). Thus, the photon echo storage time, on behalf of B1 and B2, can be extended up to the spin population decay time. We solved intrinsically low retrieval efficiency in photon echoes—caused by reabsorption and governed by Beer’s law—by adapting a phase conjugate scheme. Here, the phase conjugate is a direct result of the well-known backward four-wave mixing processes. We observed an enhanced (50×) echo signal with a storage time of 1s.\textsuperscript{5}

It has been reported that a single photon of noise can demolish quantum fidelity.\textsuperscript{2} However, this analysis neglects some practical parameters. For example, in an optical medium of yttrium silicate doped with rare-earth praseodymium ions (Pr\textsuperscript{3+}, 0.05 atom%),\textsuperscript{5,4} the total number of atoms is 4.7×10\textsuperscript{18} per unit volume (cm\textsuperscript{3}).\textsuperscript{5} If rephasing is applied to the stimulated photon echoes, population inversion, and ensuing quantum noise from spontaneous emission, occur. Our detailed calculations—using a pencil-like propagation geometry for the interaction volume (10\textsuperscript{-6}cm\textsuperscript{3}), temporal ratio of echo duration to spontaneous emission decay (10\textsuperscript{-9} at 10GHz), and area ratio of signal light to omnidirectional noise photons (10\textsuperscript{-5} on a 20cm diameter virtual sphere)—showed the effective fraction of atoms causing noise is ~0.01. This is negligibly small and could not alter the photon echo fidelity—see Figure 1(d).\textsuperscript{5} However, a critical problem in photon echoes is echo-triggered stimulated emission. We recently reported that double rephasing with control deshelving pulses produced complete, noise-free photon echoes.\textsuperscript{8}

In summary, we presented a new quantum memory protocol with ultralong photon storage for long distance quantum communications, surpassing current limitations. We achieved near perfect retrieval efficiency by applying optical locking to conventional stimulated photon echoes. We controlled spontaneous and stimulated emission problems by using a double rephasing technique. Since quantum memory is an essential element in quantum computing, communications, and cryptography, our efforts to develop the technique for even longer quantum storage is ongoing.

This work was supported by the Creative Research Initiative program (grant 2010-0000690) of the Korean Ministry of Education, Science, and Technology via the National Research Foundation.

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References

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