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Light, meet matter: Single-photon quantum memory in diamond optical phonons at room temperature

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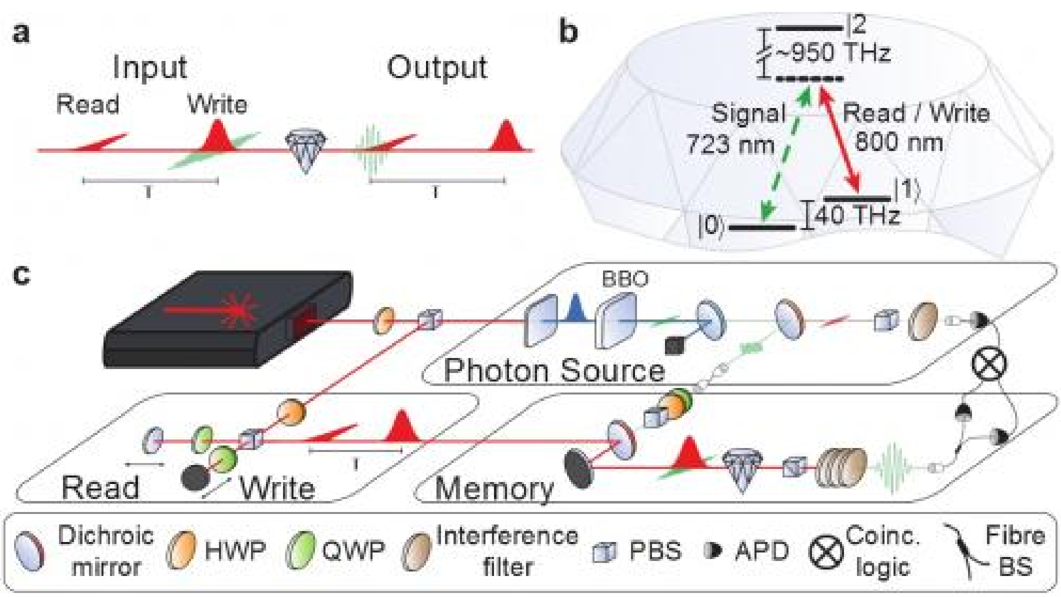


Experimental concept, energy level diagram, and setup. (a) The memory protocol. A horizontally (H) polarized single photon (green, 723 nm) is written into the quantum memory with a vertically (V) polarized write pulse (red, 800 nm). After a delay τ, an H-polarized read pulse recalls a V-polarized photon. (b) Energy levels in the memory. The ground state j0i and the storage state |1>correspond to the crystal ground state and an optical phonon, respectively. The signal photon and the read-write pulses are in two-photon resonance with the optical phonon (40 THz) and are far detuned from the conduction band j2i. (c) The experimental setup. The laser output is split to pump the photon source and to produce the orthogonally polarized read and write beams. The photons are produced in pairs with one (signal) at 723 nm and the other (herald) at 895 nm. The signal photon is stored in, and recalled from, the quantum memory. The herald and signal photons are detected using APDs and correlations between them are measured using a coincidence logic unit. Credit: D. G. England, K. A. G. Fisher, J-P. W. MacLean, P. J. Bustard, R. Lausten, K. J. Resch, and B. J. Sussman, Storage and Retrieval of THz-Bandwidth Single Photons Using a Room-Temperature Diamond Quantum Memory, *Phys. Rev. Lett.* 114, 053602 (2015).

(Phys.org)—Photonic quantum technologies – including cryptography, enhanced measurement and information processing – face a conundrum: They require single photons, but these are difficult to create, manipulate and measure. At the same time, quantum memories enable these technologies by acting as a photonic buffer. Therefore, an ideal part of the solution would be a single-photon on-demand read/write quantum memory. To date, however, development of a practical single-photon quantum memory has been stymied by (1) the need for high efficiency, (2) the read/write lasers used introducing noise that contaminates the quantum state, and (3) decoherence of the information stored in the memory.

Recently, scientists at National Research Council of Canada, Ottawa and Institute for Quantum Computing, University of Waterloo demonstrated storage and retrieval of terahertz-bandwidth single photons via a quantum memory in the optical phonons modes of a room-temperature bulk diamond. The researchers report that the quantum memory is low noise, high speed and broadly tunable, and therefore promises to be a versatile light-matter interface for local quantum processing applications. Moreover, unlike existing approaches, the novel device does not require cooling or optical preparation before storage, and is a few millimeters in size. The scientists conclude that diamond is a robust, convenient, and high-speed system extremely well-suited to evaluating operational memory parameters, studying the effects of noise, and developing quantum protocols.

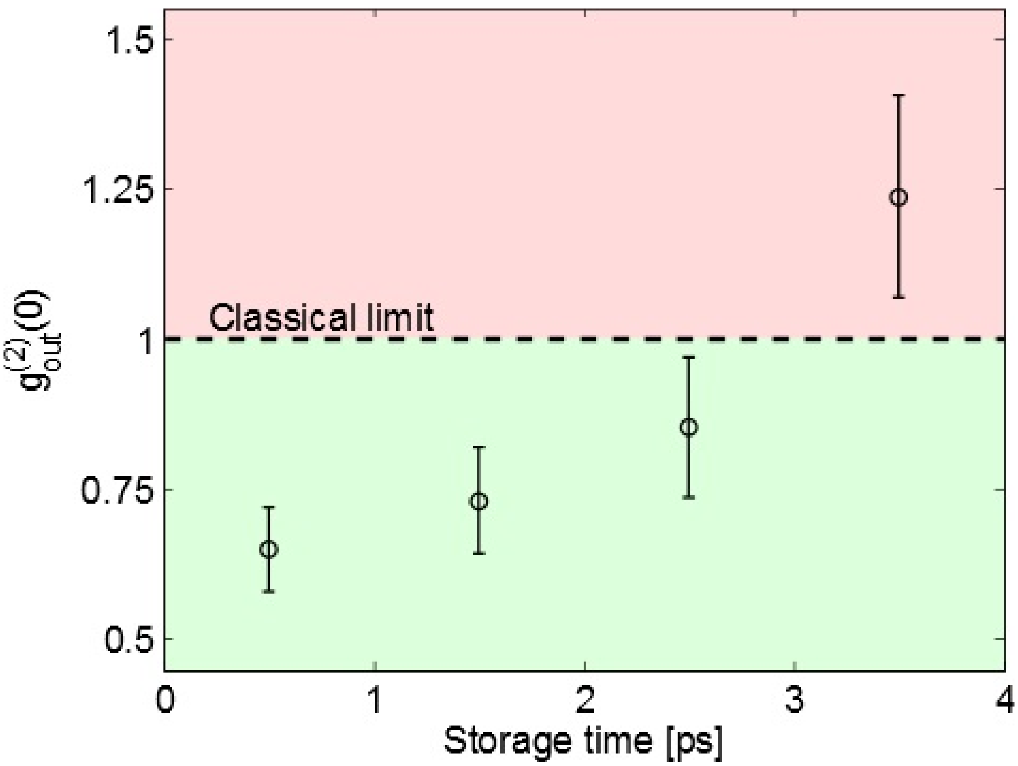
Prof. Benjamin J. Sussman discussed the paper that he, Prof. Kevin Resch, Dr. Duncan G. England, and their colleagues published in *Physical Review Letters*. "The possibility of using single photons in quantum technologies offers a host of new opportunities in measurement and communications," Sussman tells *Phys.org*. "However, it's challenging to do so because the light we typically use – that is, from the sun, light bulbs, or lasers – contains tremendous numbers of photons." Therefore, much of the technology for manipulating and measuring light (including naturally-evolved light-detecting biological organs, such as our eye) have been designed to deal with larger numbers of photons – and in addition, background noise from the faintest light source can mask these single photons.

"Creating a single photon is also a formidable problem," Sussman continues, adding that to generate single photons the scientists employ a low probability stochastic quantum optics process called *spontaneous parametric down-conversion* (SPDC). The method of generation is very effective, but the challenge is that – being a probabilistic process – a photon is generated not on demand, but unpredictably. "We have to wait for success and then perform an experiment, which means most of the time the experiment fails," Sussman explains. "However, quantum memories are very interesting because they act as photon buffers, and can convert a probabilistic process into a deterministic one. This effectively turns a repeat-until-success single-photon source into an on-demand source."

Sussman notes that the most difficult technical obstacle was verifying the non-classical photon statistics of the memory output. To determine whether single photons were actually retrieved from quantum memory, the scientists performed a so-called $g^{(2)}$ measurement (the degree of coherence between two fields) in which the output photon was coupled into a 50:50 beam splitter, and detectors placed at both output ports. "Because single photons are indivisible, one would never expect to measure coincident detection in both arms – and this is what we were able to confirm. Nevertheless, experiments aren't perfect – and where the single photon is even slightly contaminated by background noise, we very occasionally make a coincidence measurement. As a result, measuring enough of these coincidences in order to collect significant statistics required over 150 hours of continuous data acquisition." He adds that graduate students Kent Fisher and JP MacLean worked tirelessly to perform the experiment.

"A quantum memory is a conversion between quantum states of light and matter," Sussman tells *Phys.org*. "However, decoherence is constantly destroying the crucial quantum nature of the matter system, and thus the advantages of quantum technologies. Typically the narrow linewidths of the quantum levels involved limit the bandwidth of such memories to the gigahertz range or below. Our challenge was therefore to work with very short pulses of light to beat decoherence – that is, to perform our operations before the system decays. Again, ultrafast Spontaneous Parametric Down-conversion is the most popular source of high purity single photons – but with femtosecond oscillators it produces THz-bandwidth photons that can't fully be utilized in lower bandwidth systems. We were able to bridge this three orders of magnitude gap between light and matter by building an ultrafast capable quantum memory."

Since all quantum systems suffer from decoherence effects when they interact with an external environment, isolating the quantum system from its environment is a universal problem in quantum technology. "The key insight behind our experiment was that ultrafast lasers can avoid decoherence. Rather than try to isolate our memory from the environment, we address it on timescales that are fast compared to decoherence by using ultrafast laser pulses of ~200 femtoseconds duration."



The heralded second-order correlation function of the memory output as a function of storage time. Values below the classical limit of g(2)out = 1 demonstrate the quantum characteristics of the output field. Nonclassical statistics are observed for storage times up to ~3 ps. Error bars are from Poissonian counting statistics. D. G. England, K. A. G. Fisher, J-P. W. MacLean, P. J. Bustard, R. Lausten, K. J. Resch, and B. J. Sussman, Storage and Retrieval of THz-Bandwidth Single Photons Using a Room-Temperature Diamond Quantum Memory, *Phys. Rev. Lett.* 114, 053602 (2015).

Sussman notes that ultrafast lasers were developed to study picosecond and femtosecond dynamics in molecular and bulk phonon vibrations. "It's therefore not surprising that we'd employ these vibration or similar systems as substrates to operate at ultrafast speeds for quantum processing – and Dr. England was able to leverage his expertise in these two areas to bridge the National Research Council and Institute for Quantum Computing teams and make the project a success."

The paper states that because the quantum memory is low noise, high speed and broadly tunable, it promises to be a versatile light-matter interface for local quantum processing applications. Sussman explains that the interface between light and matter is an important frontier for quantum information science, in that it combines the advantages of photonic qubits (which move fast and have long decoherence times) with those of matter qubits (stationary and with strong interactions). "The diamond memory is an important innovation because it provides a robust and convenient platform on which to investigate this interface," which he adds are due to its key advantages:

• the memory is broadly tunable, and so can be used for many different photon sources

• the high speed of the memory allows millions of experiments per second, which is important for synchronous detection of multiple spontaneous quantum events – that is, it is critical for experiments with a low probability of success and where many repeat efforts are required

• the memory is low noise – even at room temperature – making it a simple test bed system which does not require any bulky and expensive cryogenic or vacuum apparatus

The system described in the paper has some advantages over previous efforts to implement optical quantum memories, including single atoms in a cavity, ultracold atoms, atomic vapors, molecular gases, and rare-earth doped crystals, and other platforms. "Our system has two interesting features: low noise and high bandwidth. "The noise floor of the memory is principally a measurement of the background introduced by parasitic processes driven the strong read/write pulses," Sussman explains. "This noise degrades the integrity of the quantum state stored by the memory. Practically speaking, the noise floor is measured by blocking the input photon and measuring what comes out of the memory if nothing is put in. As the intention is to store and retrieve single photons, it's critical that the noise floor remains a fraction of the single-photon, or the quantum, level."

One important feature of diamond is that optical phase matching requirements suppress parasitic processes. Another factor is that in many systems, it is often necessary to employ cryogenic or laser cooling to isolate a quantum system from environmental noise – but due to the large energy of the diamond optical phonon, the Boltzmann inversion at room temperature is sufficient such that there is no need to cool the diamond. The memory therefore operates with quantum-level noise at room temperature. In addition, he continues, their previous work with Walmsley's group at Oxford looked at creating entanglement between two different diamonds[1]. "We continue to build on this diamond platform and have now shown that it is possible to store single photons. The entanglement experiments suggest that it should be possible to store entangled states of light in diamond, which is encouraging for some future research directions."

While, as mentioned, significant work has been put into developing ultrafast spontaneous parametric down-conversion sources compatible with a specific quantum memories, Sussman says that their system takes the opposite approach. "We have a memory with bandwidth larger than that of the photon source. The bandwidth of a stored pulse here is ultimately only limited by the large 40 THz energy of the phonon," although he acknowledges that in this investigation that it was experimentally limited by their longer duration 2 THz write pulse.

Interestingly, when *Phys.org* asked how advanced acoustic metamaterials such as synthetic phononic crystals might relate to their research, Sussman agreed that modifying the phonon band structure and density of states would be very useful for customizing the memory energy levels and controlling decoherence.

In terms of research plans, Sussman says that much research has gone into long coherence time quantum memories for use as a component in long-distance quantum communications. "In a complementary way, there are a number of interesting opportunities where coherence times are shorter but bandwidths are higher. Because the diamond quantum memory can utilize short pulses, a significant number of operational time bins can be performed before the system decoheres. Our next steps will involve storage and generation of more elaborate single-, multi-, and entangled photon states, as well as looking at very interesting opportunities for sensing and color conversion."

Sussman adds that, broadly speaking, the researchers work in three areas: developing optical methods of controlling quantum systems; developing novel quantum systems; and combining these to then develop quantum technology applications. "The state-of-art in laser technology now allows quantum systems to be manipulated with extreme precision, and the implications are that it will be increasingly easy to build quantum technologies that are capable of performing in ways not possible with traditional methods. I think some of the next big steps will be in extending the technologies built for quantum communications to sensing."

For Sussman and his colleagues, the future is ripe with possibility. "The current areas of research where quantum memories are of considerable interest are quantum information processing and communications – but in the future the individual components needed to build these systems will surely find applications beyond these areas. As examples, sensing and imaging will surely be affected by the development of robust quantum components including sources, memories, gates, frequency converters, and detectors that can be combined in new ways. It's not hard to envision that this will ultimately have impacts in range of important additional applications, including those as varied as astronomy, chemical sensing and medical imaging."

More information: Storage and Retrieval of THz-Bandwidth Single Photons Using a Room-Temperature Diamond Quantum Memory, *Physical Review Letters* (2015) **114:** 053602, doi:10.1103/PhysRevLett.114.053602

Related:

[1]Entangling Macroscopic Diamonds at Room Temperature, *Science* (2011) **334**(6060): 1253-1256, doi:10.1126/science.1211914