International Journal of Research in Engineering and Applied Sciences(IJREAS)
Available online at http://euroasiapub.org/journals.php
Vol. 12 Issue 06, June- 2022
ISSN(O): 2249-3905, ISSN(P) : 2349-6525 | Impact Factor: 8.202 |
Thomson Reuters ID: L-5236-2015

APPLICATIONS OF QUANTUM OPTICS IN QUANTUM INFORMATION SCIENCE

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ABSTRACT

An optical quantum memory is a type of quantum memory that is characterized by its interaction with light at optical frequencies. This interaction allows the memory to retain a quantum state that can be useful. Over the past decade, they have been the focus of much research, particularly to satisfy the requirements of their first two applications, which are quantum repeaters and linear-optical quantum computers. The primary focus of investigation in quantum optics is on the development of applications for quantum information, such as quantum computers, quantum communication, and quantum cryptography. Research in quantum optics and informatics frequently make use of phase representations, in particular representations of coherent states. Because of these representations, researchers have been able to investigate certain exponentially complex quantum many body systems from the ground up. As a result of the innovative applications it may serve, quantum cryptography has emerged as a significant topic of research within the discipline of quantum informatics. A variety of powerful quantum cryptography systems that are available for sale guarantee the distribution of keys across a distance of about 100 kilometers when used in fiber-optic communication links. The implementation of key distribution through the use of image transmission is an additional possible method that might be used to broaden the applications of quantum cryptography systems.

Keywords:*quantum optics, focusing quantum, cryptography,*

INTRODUCTION

Our exposition of quantum theory's core principles uses the traditional technique, which is based on textbook postulates. This presentation follows convention. This "pragmatic" approach recognizes quantum mechanics as an operational theory that predicts physical system testing under certain conditions. This "pragmatic" quantum mechanics approach recognizes it as an operational theory. We intentionally avoided semi-philosophical issues related to quantum physics and its paradoxical conceptions compared to macroscopic perception. We either didn't want to or couldn't discuss these things depending on how we felt. In light of this, topics such as the collapse of the wavefunction upon measurement, quantum correlations—also known as entanglement—between spatially separated systems, or their non-local nature, the shift from the quantum to the classical world, etc., are discussed in accordance with theory without delving into philosophical ramifications, which would be outside the scope of this book and defeat its purpose. The "Further Reading" section at the end of this book discusses the subjects covered in this section.

Quantum key distribution, computing, metrology, and other applications use optical quantum information processing (QIP). Realizing the full potential of these applications is vital for understanding quantum physics' strength and improving technology. These technologies require optical quantum memory that may be tailored to varied uses. Early on, it was recognized that to transmit data above the quantum channel loss limit, one needed to store quantum states of light and recover them when needed. This resource was also needed to create linear-optical quantum computing or any application that required the synchronization of many autonomous and probabilistic processes. One example is spontaneous parametric down conversion that creates photon pairs. This sparked strong experimental efforts, which led to several reviews on photon-echo quantum memories based on solid-state systems, quantum memories in the European integrated project "QAP"; quantum repeaters based on atomic ensembles and linear optics; quantum memories; quantum storage in atomic ensembles and trapped ions; and light-matter integration.

The development of optical quantum memory now focuses on producing a component that is helpful, and in some cases crucial, to most other optical QIP applications. This article discusses contemporary optical quantum memory experiments that use quantum technology to perform practical tasks. Reviewers focus on the application procedure. The topic is important because optical quantum memory research is moving quickly. This book focuses largely on experimental work published between 2010 and the present, together with a few theoretical concepts directly related to the applications we are discussing. We did this to shorten the book. Note that specific kinds of quantum memory promoted for a given usage are not necessarily exclusive to that application. Thus, this assessment is incomplete. However, we hope it will accurately portray optical quantum memory's current condition and stimulate future research in this exciting topic.

Optics on a quantum scale

Quantum optics is a subfield of optical physics that investigates the interactions between individual photons, also known as particles of light, and atoms and molecules. Other subfields of quantum optics include atomic and molecular physics. The examination of the particle-like features of photons is included in this topic. Photons have been used to validate many of the paradoxical predictions of quantum physics, including entanglement and teleportation. Photons are an important instrument for quantum information processing and have been used to verify many of these predictions.

Quantification of the energy and velocity of light as it moves across a restricted space is accomplished by counting the number of particles known as photons in an integer form. Quantum optics is the branch of physics that studies both the fundamental properties of light and the ways in which it behaves as quantized photons. The first important step that led to that knowledge was taken by Max Planck in 1899 when he created an accurate model of the blackbody radiation spectrum using the hypothesis that light is emitted in discrete units of energy. This was the first significant step that led to that understanding. The photoelectric effect, which Albert Einstein explained in a paper published in 1905 and for which he would go on to receive the Nobel Prize in 1921, offered more evidence that this quantization held true. Niels Bohr presented evidence that proved how his theory of the quantized energy levels of atoms, and more especially the spectrum of discharge emission from hydrogen, coincided with the premise that quantization may be applied to optical radiation. After these findings, gaining a deeper comprehension of the dynamic relationship that exists between matter and light was absolutely necessary for the progression of quantum mechanics as a whole. In 1960, however, the terms atom physics and quantum electronics were more commonly used since the subfields of quantum mechanics that dealt with the interaction of matter and light were largely believed to be studies of matter rather than studies of light at the time. The study of the fundamentals, design, and applications of laser technology became an important field of study. At the same time, the quantum mechanics that is the basis for lasers was researched with a greater focus on the properties of light [dubious - discuss], which led to the common usage of the term quantum optics.

Quantum information

The information on the state of a quantum system is referred to as quantum information. It is the fundamental entity that is studied in quantum information theory, and it is able to be modified through the use of techniques that are used in quantum information processing. Both the technical concept of quantum information in terms of Von Neumann entropy and the generic computational phrase are referred to as "quantum information." It is an area of study that draws from a number of different disciplines, including quantum physics, computer science, information theory, philosophy, and cryptography, amongst others. The study of it has implications for other fields as well, including cognitive science, psychology, and neuroscience. The extraction of information from tiny levels of matter is the primary emphasis of this approach. In science, observation is one of the most significant means of gaining knowledge, and measurement is necessary in order to quantify the observation. This makes measurement an essential part of the scientific process since it allows scientists to quantify their observations. Due to the uncertainty principle, exact measurements of non-commuting observables cannot be performed simultaneously in the field of quantum mechanics. This is because an eigenstate in one basis is not the same as an eigenstate in the other basis. An observable is said to be well-defined (definite) in accordance with the eigenstate–eigenvalue relationship if the state of the system is an eigenstate of the observable. A quantum state can never include conclusive information about both non-commuting observables at the same time because any two non-commuting observables cannot be concurrently well-defined.

The state of a quantum system contains an encoding of some kind of information, which is a physical entity. Quantum mechanics is concerned with the examination of the properties of matter at the microscopic level, whereas quantum information science is focused on extracting information from those properties, and quantum computation is the manipulation and processing of information, as well as the performance of logical operations, using techniques that are associated with quantum information processing. Quantum information, much like classical information, is capable of being processed by digital computers, transported from one point to another, modified with algorithms, and evaluated using computer science and mathematics. In the same way that the bit is the fundamental building block of classical information, qubits are the fundamental building blocks of quantum information. The Von Neumann entropy is one method that may be used to measure quantum information. Because of the likelihood that it would interfere with existing processing, communication, and cryptography, the discipline of quantum computing has recently emerged as a topic of intense study interest.

OBJECTIVES

1. To research optical quantum memory applications.
2. Studying Quantum Optics Applications in Quantum Information Science

SPONTANEOUS PARAMETRIC DOWN-CONVERSION

The most important source of photons for us comes from a process known as spontaneous parametric down-conversion. During this procedure, a laser pump photon would split into two daughter photons with longer wavelengths. In the past, these daughter photons were referred to as the "signal" and the "idler." Within a small number of optical materials with nonlinear optical susceptibilities, such as BBO, LiIO3, and KDP, the process can take occur with a low probability (at most 1012), although this is not always the case. The "phase-matching conditions" of energy and momentum conservation generate entanglements in these degrees of freedom; in addition to enabling precise control over the emission modes of daughter photons, these circumstances make it possible to entangle these degrees of freedom. Entanglement may also be readily produced by polarization, which is another point to consider.

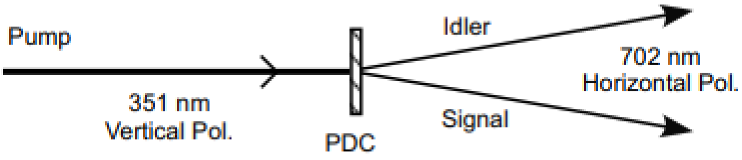

Figure 1. Spontaneous parametric down-conversion (type-I phase matching).

Single-photon source

Parametric down-conversion (PDC) is beneficial for building a single-photon source at visible or telecommunications spectrum wavelengths because it creates photon pairs without resonating. One might potentially use individual atoms, quantum dots, or contaminants as emitters. Using one photon as a spark ignites the other photon into a single-photon Fock state.Number thirteen Thus, if we detect only one photon in the idler channel, "heralding" the presence of exactly one signal photon, we let the signal pulse continue into a storage system to be released. If two or more photons are detected in the idler beam, the signal pulse stops. The mode of the produced photon can be crucial for coupling to other systems (fibers for quantum key distribution, interferometers for all-linear optic quantum computation, atoms for "stored light" or high-efficiency detectors, etc.). One innovative way to manage this occurrence is down-conversion, which limits the observed mode of the heralding idler photon. Because the photons generated during down-conversion have energy and momentum correlations, limiting one photon's mode restricts the other's mode even further.

In fact, production efficiency, photon delivery on demand, and single-photon emission statistics all lower single-photon production quality. A PDC-based single-photon source typically has a pulsed pump laser, a nonlinear crystal that forms photon pairs, a herald detector, and an optical shutter to suppress photons between heralds. An extra low-loss switchable optical storage cell is needed to release photons "on demand." Each of these areas needs improvement, opening up new opportunities. First, an ideal source must efficiently convert pump beams into photon pairs. Ideal sources require this. Recent advances in crystal structure engineering allow us to do more with single-piece crystals. Periodically poled lithium niobate (PPLN) in bulk and waveguide structures allows greater nonlinear susceptibilities than typical down-conversion crystals, which may boost conversion efficiency. One way to boost conversion efficiency is this.

As mentioned, the procedure's success depends on excluding situations where a single pulse generates numerous photon pairs. One possibility is to utilize photon counters with high quantum efficiency to discriminate photon quantities. Multiplexing can be used to provide "photon-counting" detectors some of the characteristics of photon-number detectors. The detectors will count photons. Figure 2 shows this principle most simply with the upper beamsplitter. It shows how this component can reduce the risk of an undetected double pair by two (based on single-photon detection efficiency). By using more spatial (or temporal) modes, the technique can discriminate better.

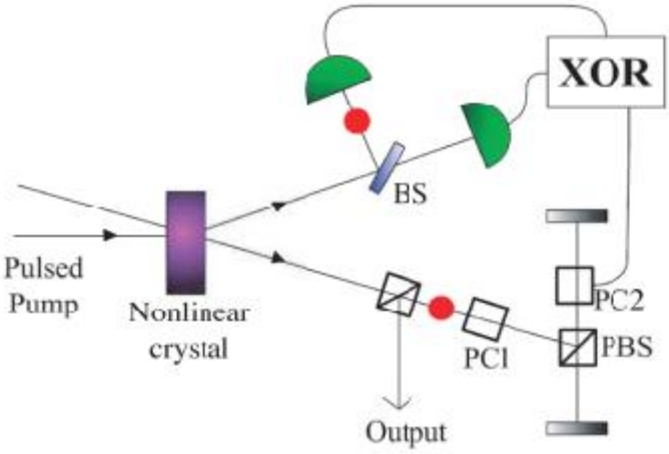

Figure 2. Setup to generate single photons on demand.

The key innovation that our plan brings to the table is the utilization of a succession of power pulses of a more moderate intensity to pump the down-conversion crystal. This makes it more likely that at least one pair will be created during the course of the series, but it makes it less likely that two pairs will be created within any particular pulse. By keeping a hold on the signal photon until the predetermined release time, it is possible to generate a source of single photons that produces intermittent output. As a result of this trade-off, the single photon rate that can ultimately be achieved will be slightly lower than the pump rate. To begin, we are developing a source that is capable of emitting single photons at a predetermined rateof ~ 50 kHz. For this purpose, we are using a frequency-tripled (1064 nm → 355 nm) short-pulsed (~ 1/2 ns) Nd: YAG laser [JDS Uniphase #DNV- 005010-000]. By recycling each ~ 1.2-µJ pump pulse ~ 20 times, we expect a net single-pair probability of 70%, but a net double-pair probability of only 3%. Utilizing the aforementioned methodologies to search for instances of double-photon emission in the idler arm allows for an additional reduction of the aforementioned.19 in total. Last but not least, a constraint on the single photon probability is the loss that occurs in the optical storage cavity, more specifically in the polarizing beam splitter and the Pockels cell. However, the effects can be mitigated to some degree by adopting a strategy that involves multiple attempts: Even after we have stored a single photon in the cavity, we will proceed to keep an eye on the idler arm in the hopes of spotting another likely candidate for a single signal photon pulse. If one is located, we get rid of the one that was previously stored, even though it was greatly weakened, and put this one into the cavity instead. By only sending the photon that has been kept for the shortest amount of time, the effects of loss can be mitigated. With these techniques, we anticipate a chance of greater than 90% for a single photon and a probability of less than 2% for many photons.

If this prototype power source works, we will examine using a Ti-Sapphire laser to raise speed to above 1 MHz. This source has superior control over the output spatio-temporal mode, which may be important for quantum lithography, but producing lower rates than solid state devices like single quantum dots.10.3. The construction of single-photon sources is a natural step towards entanglement on demand. We may easily modify down-conversion sources to produce maximally entangled photon pairs in polarisation or other degrees of freedom. This is the bonus. Finally, the nondegenerate down-conversion process converts telecom photons to visual photons.

Arbitrary single-qubit state creation

Gate operations must be precise and repeatable for quantum computing to survive. Error-per-gate operation should be fewer than 104 to 106.1 for fault tolerance. Thus, fine-grained gate operations and critical input states are major milestones in quantum information processing. This work requires strict tolerances, which we achieve by using photon polarisation states, which are optical qubits. Thus, while large-scale quantum computers made of optical qubits are unlikely, these systems offer a unique and useful platform for experimental research on state creation, manipulation, and characterization, as well as decoherence strategies.

A single-photon signal beam condition occurs when the idler photon from a PDC source is detected. Previous sentence demonstrated this. After that, we can utilise a birefringent half-waveplate (HWP) and quarter-waveplate (QWP) to perform local unitary transformations to these photons' polarisations (Fig. 3a). Signal photons can be passed through a birefringent delay device to introduce decoherence. We can introduce decoherence. If the element's eigenaxes are aligned along H and V, the H and V wave packets are separated by a distance greater than their coherence lengths, interweaving polarisation and frequency. If this additional degree of freedom is traced (a frequency-independent measurement), the reduced density matrix for the polarisation alone will be partially mixed.21 In the single photon example, these methods can exactly change the initial pure horizontal state |Hi into any pure or mixed state. Thus, we constructed many single-qubit states. We estimate that we can reliably identify over 3 × 106 single-qubit states with a fidelity of over 99.8%.

Entangled state creation

The processes for a single qubit from the previous section can be applied to each down-conversion crystal output to create arbitrary product states for two photons. We can generate arbitrary product states with these states because the signal and idler polarizations have no quantum connections. These make up only a tiny fraction of the two-qubit Hilbert space. The figure shows how to construct entangled states with a second down-converter with an orthogonal optic axis 9 to access the remaining information. A certain pair of signal and idler photons may have been created in the first crystal, which has vertical polarizations, or the second crystal, which has horizontal polarisations. Because only polarisation measurement can distinguish between these two possibilities, these photons' quantum state is a superposition of |V i|V i and |Hi|.Hi. Because each crystal responds to only one pump polarity, the input pump polarisation can be changed to vary the respective weights of the two down-conversion processes. Additionally, a birefringent phase plate is linked to one output to regulate the relative phase of the two contributions. This makes producing nonmaximally entangled states of the kind easy.

$$|\psi\rangle \propto |H\rangle|H\rangle + \epsilon e^{i\phi}|V\rangle|V\rangle$$

When paired with arbitrary single-photon local unitary transformations, which are carried out with the help of a HWP-QWP-HWP combination, any pure 2-qubit state can be created. In order to obtain states that are not pure but do contain some degree of mixedness, it is necessary to introduce decoherence. Once again, this is accomplished by inserting lengthy rods made of birefringent quartz into either one of the arms or both of them. If the resulting relative timing of the photon detections is, in principle, adequate to identify the polarization, then the lowered density matrix for the polarization alone will be (partially) mixed. Using these strategies, we were able to prepare a variety of states containing two qubits. Recent developments have led to the discovery of the components required to construct two qubits in any state requested, which can be parameterized by fifteen real integers operating independently.

The density matrices can be topographically determined by first measuring the polarization correlations in 16 different bases and then performing a maximum-likelihood analysis on the data. It has been determined which valid density matrix is the one that is the most congruent with the outcomes of the experiment.thirty adverbs After the installation of a fully automated system, we are now able to carry out our tomographic measurements in a manner that is both more efficient and precise. This automated method will make it possible to deploy an adaptive tomography procedure, in addition to shortening the total amount of time needed to complete measurements and dramatically lowering the level of uncertainty associated with those measurements. The system will first generate a rough estimate of the current state before devoting the majority of the available time to performing an optimal set of measurements as part of the data gathering process. Using this form of optimal quantum tomography, our goal is to push the boundaries of what is possible in terms of characterizing quantum states.

Because of the automated process we used, we were able to produce a substantial number of states with a wide range of entanglement and purity levels. The "tangle-entropy" plane, which is shown in Fig. 4b, is an effective tool for quickly gaining an understanding of these states. The tangle is a measurement of entanglement, and states that are maximally entangled have a value of 1, whereas states that can be separated have a value of 0 for the tangle. In a similar manner, the entropy of pure states is equal to zero, whereas the entropy of fully mixed states is equal to one (linear). Because it is impossible to have a state that is both entirely mixed and completely entangled at the same time, there is an implicit boundary between states that are physically conceivable and those that are not because it is impossible to have a state that is both completely mixed and completely entangled at the same time. This border is formed by "maximally entangled mixed states" (MEMS), which have the highest degree of entanglement conceivable for their entropies and are referred to as "Mixed States with Maximum Entanglement.

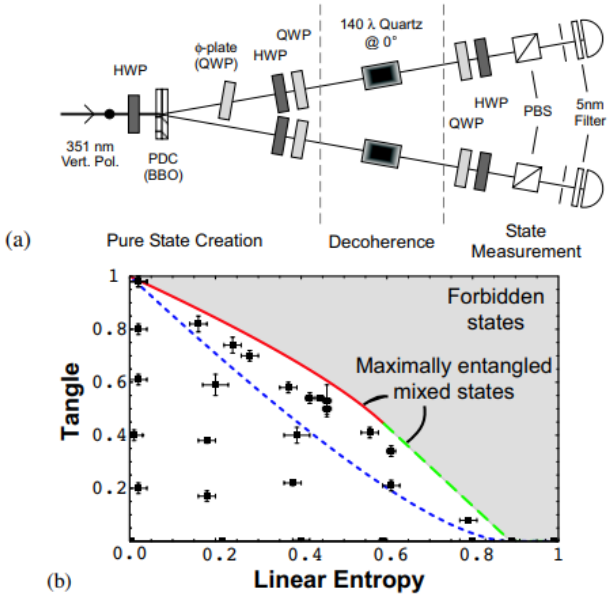

Figure 3. Experimental arrangement for two-photon state creation and verification

DETECTORS

Extremely challenging technological challenges, such as high-efficiency photon detection and counting the quantity of photons in a certain time interval, have enormous potential applications in quantum information processing and transmission, fundamental physics, and other fields of study. For instance, it is only unquestionably conceivable to violate Bell's inequalities — which reveal the non-local aspect of quantum mechanics — when detection efficiencies are extremely high. This is a feat that has not yet been done in any optical experiment, therefore it cannot be said that it has been accomplished. In addition to the undeniable significance it holds for metrology, the most recent proposals to realize scalable quantum computing via linear optics alone call for photon-counting detectors with exceptionally high efficiencies (more than 99%).32, 6, In addition, it is essential that the detectors have the capacity to differentiate between 1 and 2 photons, or, to put it another way, between n and n + 1, in addition to the quantity of photons that have been incident upon them. The development of many-photon entangled states, which may be highly beneficial in other quantum information technologies such as quantum lithography, may also be made achievable by such detectors33. These entangled states can be produced by combining a large number of photons. Last but not least, there are additional applications, such as telecom fiber-based quantum cryptography, whose performance is now hampered by substandard infrared detector performance.

Current photon detectors

Much worse is the situation with single-photon detection in the infrared. Up until now, infrared-optimized APDs—typically made of Ingas or Ge—have been the most effective way to detect these photons. Nevertheless, these detectors have a high dark count (50,000 – 100,000 s−1), a comparatively low quantum efficiency (10%), and require cryogenic cooling.37 Although efficiencies of up to 20% are possible, the resulting additional dark count noise makes these detectors less useful, for example in quantum cryptography, where the efficiency sets a limit on the bit rate and distance that the key distribution protocol can achieve. For these and other applications, then, any enhancements above baseline IR APDs would be advantageous.

Infrared up-conversion detector

The infrared singlephoton detection method can be significantly improved by the nonlinear process of frequency up-conversion, which is the opposite of down-conversion. With silicon APDs, we can detect an infrared photon (at 1550 nm) after upconverting it to a visible one (at 631 nm), which is better than the infrared APDs that are currently in use. We use a relatively weak input laser, a bulk crystal of PPLN, and a powerful escort laser pulse at 1064 nm (from a pulsed Nd: YAG laser) to achieve high-efficiency frequency up-conversion. One photon from the input beam and one from the escort beam are up-converted into a single output photon via the quasi-phase matching of the PPLN. Because to energy efficiency, the output frequency ωo = ω631 is the sum of the input frequency ωi = ω1550 and the escort frequency ωe = ω1064.

We can easily calculate for E631(z), the electric field strength of the 631-nm light, as a function of the propagation distance z in the crystal using the formulas that characterize the field evolution in a nonlinear medium40. We discover

$$E_{631} \propto \sin\left(\sqrt{\frac{\omega_{1550}\,\omega_{631}}{n_{1550}\,n_{631}}}\frac{d_Q E_{1064}}{c} z\right),$$

$$E_{631} \propto \sin\left(\frac{\pi z}{L_c}\right),$$

where this process's spatial period Lc is

$$L_c \equiv \sqrt{\frac{\pi^2\, n_{1550}\, n_{631}\, c^2}{\omega_{1550}\,\omega_{631}\, d_Q^2 |E_{1064}|^2}}.$$

Here, dQ is the effective nonlinear coefficient and n1550 and n631 are the LiNbO3 indices of refraction at 1550 and 631 nm, respectively. We are able to employ the greatest nonlinear tensor element (d33 = 40 pm/V), more than an order of magnitude bigger than the useable element without quasiphase matching, because the process is quasi-phase matched. We see that the system's development, driven by the external electric field, is substantially equivalent to a Rabi oscillation between the input (1550-nm) and output (631-nm) states.

We measured this up-conversion process in the non-depletion domain, where output intensity is linear with input intensity. A silicon photodiode measures output intensity at varied input intensities. In our experiment, the 1550 nm input beam is continuous and the 1064 nm escort beam pulses to produce a 631 nm pulsed output beam.38 The absolute conversion efficiency from input to output is low since most input light goes through the crystal between escort pulses. We estimate a peak conversion efficiency of about 80% using the pulse repetition rate (≈ 7.2 kHz) and beam intensity profile. A brief pulsed 1550 nm source can focus photons into the crystal while the escort field intensity is almost maximum, increasing this. With an escort pulse width of 500 ps, a 100-ps signal pulse has a conversion effectiveness of above 99%. We are implementing this improvement.

We measured high-efficiency up-conversion down to the single-photon level and intensity up-conversion to construct a "classical" input beam. A series of neutral density filters attenuates our 1550-nm source so that only one photon overlaps with the escort pulse. The efficiency at the single photon level matches the 80% result reported at greater input intensities by counting 631-nm photons with a Si APD during the escort pulse. In single photon experiments, the background chance of a dark count inside a 1-ns window around photon arrival was measured to be 3 × 10−4. This was mostly due to escort pulse fluorescence. This background should decrease by an order of magnitude with design improvements.

In addition to "classical" input beam intensity up-conversion, we found high efficiency single-photon up-conversion. A series of neutral density filters attenuates our 1550-nm source so that only one photon overlaps with the escort pulse. The efficiency at the single photon level matches the 80% result reported at greater input intensities by counting 631-nm photons with a Si APD during the escort pulse. In single photon experiments, the background chance of a dark count inside a 1-ns window around photon arrival was measured to be 3 × 10−4. This was mostly due to escort pulse fluorescence. This background should decrease by an order of magnitude with design improvements.

Finally, we will describe a unique high-efficiency photon counting method.43, 42 We propose a compound mechanism that converts one photon into many photons instead of one photo-electron. We use the high-efficiency approach for projective quantum state measurements in ion traps and controlled light absorption to solve the problem.43 We want to use a cell to store alkali vapor like rubidium or cesium. This vapor will coherently absorb incident beam radiation in a controlled manner. Many auxiliary lasers prepare vapor atoms for their initial quantum state and govern radiation field interaction. The radiation to be detected is guided into the cell with a "escort" pulse, giving each photon a modest chance to excite an atom via a Raman transition to a metastable state. The huge number of atoms makes it practically certain that an atom will absorb a photon. Any metastable atom is repeatedly stimulated by a strong read-out laser to detect spontaneous decay photons. Due to the typical cycling transition rate of 100 MHz, many photons are produced, making the probability of not detecting any extremely low for reasonable detector efficiency. If an image photon detection device is used, counting excited atoms can accurately distinguish input states with different photon numbers. In a realistic system with 50,000 cooled Cesium atoms in a cigar-shaped region (2 mm × 100 μm × 100 μm), we estimate a photon detection efficiency of 99.8%, assuming a 10% net efficiency for each photon from the cycle transition. However, some crucial "dark counts" issues remain.

Quantum state transducer

For distributed quantum computing, it is desirable to faithfully up-convert a single photon in any polarization state to a higher frequency while preserving the original polarization. Photons at 1550 nm, which have the best fiber optic transmission, would be best for long-distance qubit transfer between quantum computers. Because qubit storage or processing may require visible spectrum photons, such as those from atomic transitions, a single photon-level wavelength conversion method must be developed while coherently maintaining the polarization state.

The single-crystal up conversion approach in Sect. 3.2 uses only one 1550 nm photon polarization. To accurately convert any polarization state, a second PPLN crystal can be added in series with the first, with its optic axis rotated by 90◦ about the propagation direction. An escort laser polarized at 45° with equal horizontal and vertical components can up-convert the input photon's horizontal and vertical components in the first and second crystals. Remember that this method is the opposite of using two down-conversion crystals to create entangled states.

After removing all escort photons, we will have one output photon. A phase difference between the horizontal and vertical components of the final photon will result from PPLN crystal dispersion and birefringence. The transformation methods can change the final polarization state to fit the input.

Quantum memory

There are several quantum information processing applications that use photon quantum memories. Cryptography protocols that use special relativity, linear optics scalable quantum computing, quantum repeaters2, 48 for long-distance teleportation and quantum key distribution, and, as discussed in a companion essay in these proceedings,49 quantum mechanics-based cryptography protocols. To store a photon's state, quantum information can be transferred to an atom. Specifically, photon state must be stored. Systems for "stopped light" at the photon level or longer than one millisecond are not yet technologically feasible. We chose a simpler approach and used an ultralow-loss optical delay line. Our delay line resembles Herriott cells used in long path-length spectroscopy, unlike Pittman and Franson's approach. Two high-reflectivity mirrors are separated by about one meter. One has a small aperture through which light enters and departs the delay line a predetermined number of times. Astigmatic mirrors have long been used in delay lines. This ensures that the mirrors' spot pattern occupies most of the space, unlike spherical mirrors. This reduces coupling hole light loss before the departure cycle. Unfortunately, these mirrors are hard to build to our strict criteria. Instead, we used a pair of cylindrical mirrors at almost right angles but twisted slightly to create effective astigmatism (see companion article 49). We have shown that an early prototype of the technology can store light for almost a second.

Our transmission rate is less than 20% since our mirrors are not coated for the 670 nm optical wavelength. After 80 passes (159 reflections), the bounce reflection probability is 98.9%.

Since mirrors with reflectivities of 99.99% are available, transmissions of over 98% are expected. Keeping the photon's polarization in the delay line is also preferred. All incidence angles in our system are close to normal, therefore horizontal and vertical polarization are indistinguishable. Thus, polarization is expected to have little effect on the system. Initial measurements on our storage cavity prototype support this claim.

The fact that the criteria for a "reentrant ray" (a ray that will depart via the entrance hole after a specific number of passes) apply to all incident rays as long as they do not miss one of the mirrors is one of the storage system's benefits, if designed properly. A realistic system needs such a capability because it is not always possible to determine the direction of photons collected. This suggests that our delay line might store several photons simultaneously or a single photon for multiples of the basic cavity storage length. This allows an extension of the system described here to store quantum states for up to 10 microseconds with a loss of less than two percent (assuming mirror reflectivity of at least 99.999%, which is still an order of magnitude less than the current state of the art).

CONCLUSION

In this article, we have discussed a number of different uses for quantum memory, as well as some of the recent advances in experimental technology that have been made in the direction of realizing these applications. The many applications each have their own distinct set of requirements for quantum memory, and the majority of the experimental work is focused on establishing the potential of satisfying one or a subset of these requirements. The way has been paved for the creation of quantum memories that are capable of performing all of their functions. On the one hand, it is imperative that all of the needed characteristics be incorporated into a single system. On the other hand, the incorporation of nonlinear processing capabilities with quantum memory would unquestionably prove beneficial for optical QIP in general. First and foremost, it is important to note that optical quantum memories are no longer considered a theoretical marvel. Their notoriety is growing, and they have become an indispensable component in an ever-increasing variety of optical quantum information processing applications in recent years.

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