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Comparative Advantages of Photonic Computers

Although there are many implementations of quantum computers, superconducting and trapped ion quantum computers have far and away the most advanced technologies as measured by the DiVincenzo Criteria. Industry and academic researchers of these technologies have developed: scalable systems with reliable initialization and long coherence times. Notably, trapped ion researchers have yet to practically implement ion chain linking, a significant obstacle to long term scalability. While they continue to advance these technologies, the main concern of superconducting and ion trap researchers is the addressability and frequency collisions of qubits. You may be asking yourself, if these technologies are so advanced, why am I interested in photonic computation?

Photonic computers have yet to satisfy any of the DiVincenzo Criteria, but they have potential to avert many of the challenges inherent to superconducting and trapped ion quantum computers. The main advantage of photonic computers is a photon's extremely weak interaction with the environment and other photons [17]. This means that photonic computers can be operated without vacuum, cooling and with a solely hardware limited clock speeds [17]. Additionally, since photons are already used in fiber optic cabling and wireless communication, photonic computers offer the most straightforward evolution from quantum computer to quantum communication system [17]. Even if trapped ion or superconducting qubit computers remain superior quantum computation platforms, as compared to photonic computers, photonics research may still be implemented as quantum repeaters in a future quantum communication network.

The main limitation for photonic computers is the difficulty in applying two-qubit gates, this is because photons can't interact with each other [17]. As a result, this non-interaction is both an asset and nuisance. Two-qubit gates are a key requirement, laid out in the DiVincenzo Criteria, because without multi-qubit gates, a universal set of gates and thus a quantum advantage is unachievable. Multi-qubit gates are integral to the generation of entangled superpositions utilized in quantum algorithms. Additional challenges arise from constant motion of photons, difficulty in miniaturizing and reprogramming photonic circuits. In this paper I will address methods to overcoming these hurdles and unleashing the thus far untapped potential of photonic computers.

The fundamental components of photonic computers are initialization hardware, modulation hardware, detection hardware and quantum optical memory. Researchers at leading photonics research companies, such as Xanadu, are highly interested in: simplifying, miniaturizing, reprogramming and increasing fidelity of each of these components [2].

There are several ways to initialize a photonic computer. The most common method is the production of what are called squeezed states [17]. A squeezed state is produced by modulating the uncertainty of a photon's phase space unevenly, as demonstrated in **Figure 1** [4]. In practice this happens when the phase uncertainty of a photon is modulated causing an opposing reaction in the photon's amplitude uncertainty [4,17]. This is because of the Heisenberg uncertainty principle's limitation that the uncertainty of position times the uncertainty of momentum is equal to or greater than hbar/2, a constant value. In this case phase is a measure of the photon's position and amplitude is a measure of its momentum. Because phase and amplitude are bound by their uncertainty relation, a decrease in phase or amplitude uncertainty will require an increase in the amplitude or phase uncertainty respectively. Squeeze states were first developed for use in communications, specifically in the advancement of signal to noise ratios, high fidelity amplification, gravitational wave detection and to lower optical loss in waveguides [6,17]. The first major implementation of squeezed state photons is from parametric down conversion [18]. This, like all implementations of squeezed state photons, is reliant on nonlinear optics. In this case second-order nonlinearity is required and squeezing has been measured up to 3.5 dB however, this process is dependent on a cavity in a crystal to generate the squeezed state, which can be unpredictable [6]. The now more dominant optical parametric oscillation (OPO) has been proven to be the most efficient source of the quadrature squeezed light, necessary for photonic computation [6]. Some implementations of OPO have generated 12.7 dB and reached efficiencies greater than 97% [6]. The inability to reach 100% is almost entirely reliant on intra-cavity losses, for which there has been extensive materials research [6]. The ideal system would generate single photons 100% reliably on demand however, no system approaching this currently exists [6]. Currently OPO is the best available technology, more specifically ring cavity OPO systems strike the best balance between intensity and efficiency [6]. One area of future development in the initialization of photonic computers is that of the single photon sources [6,17].

Once light has been produced, it then needs to be modulated. The main components of photon modulation hardware are: electro-optic modulators, tunable waveplates and beamsplitters. Electro-optic modulators use the linear electro-optic effect, also called Pockels effect, to modify the refractive index of a nonlinear crystal, by applying an external electric field [7]. This can be used in a Mach Zehnder interferometer, to modulate amplitude [7,18]. Current generation electro-optic modulators can react with GHz frequency. This is why they are often used as fast optical switches [7]. Although there are many types of phase shifters, most researchers use thermo-optic phase shifters, which can be very sensitive to thermal loads imparted from neighboring components [8,9]. Thermo-optic shifters are responsible for ~.45 dB drop in signal per layer [1]. Thermo-optic phase shifters have a tunability time in the microseconds, making them well outperform any alternative regardless of their accuracy [8]. This is the main hardware limitation to the control clock speed. As mentioned in course notes, hyperfine trapped ion systems have a similar MHz clock speed and superconducting qubit systems have a much higher GHz clock speed. The last modulation component that we will cover is the beamsplitter. Although there are some tunable beamsplitters, known as a reconfigurable beamsplitter, they are very much in their infancy and most experimentalists use fixed reflectance, typically 50% reflectance multi-mode interference, beamsplitters for their small size and reliability [1,14]. Beamsplitters are responsible for ~.3 dB drop in signal per layer [1]. Finally, unintentional losses and modulation due to waveguide imperfections are not insignificant. Waveguide losses account for ~.2 dB/cm [1]. Current state of the art systems, such as Xanadu's, have a total system loss of ~8 dB and predict to drop this to ~3 dB by using higher quality components and more compact designs [1].

The next step in a photon's path is detection. Photon detector accuracy isn't just critical as the last stage in the computation process; detectors play an active role in the control system to determine how electro-optic modulators and thermo-optic phase shifters ought to be actuated [10,17]. The most common type of photon detector for photonic computers is the homodyne detector [13]. Homodyne detectors measure either position or momentum of a photon [18]. The great thing about homodyne detectors is their low sensitivity ceiling, meaning that they can detect very small electromagnetic fields [17]. This is done using a phase shifter, two mirrors, two 50% beamsplitter and a photodiode [12,17]. First, light is split using the primary beamsplitter, then mirrors reflect the light towards the second beamsplitter [12]. Before one side reaches the second beamsplitter, a phase shifter is applied to only one branch. The light is subsequently joined in the second beamsplitter and one resulting branch is detected [12]. This interference process allows the photodiode to analyze phase or relative amplitude [17]. Forward looking research into single photon detectors is a major field that is sure to impact photonic computation in the coming years however, right now this technology is not implementable.

The final piece of hardware that we will discuss is quantum optical memory. Optical memory is important for its applications to quantum computation, quantum communication and as a single photon source. For the instance of quantum computation, precise timing is essential to attaining proper interference entanglement [5]. Additionally, quantum optical memory can generate and store states, which can then be injected into subsequent operations, meaning that more complex wave functions can be generated than typical hardware limitations would allow for [5]. One major downside of photonic computation is that unlike with trapped ion and superconducting qubits, a photon's constant motion [17]. Constant motion means that traditionally, each hardware element can only be used once per computation. Using quantum optical memory, stored wave functions can even be sent back up the optical path, so the same hardware can be reused. Storage of quantum states for any quantum computation platform would revolutionize computational potential, because of the ability to generate and inject increasingly information dense quantum states [5]. Quantum optical memory is also extremely useful for photonic implementations of quantum repeaters, which would be used in a future quantum communication network. Similar to quantum computation, quantum repeaters need precise timing of adjacent entangled states within a single optic fiber [5]. Using this storage and injection of quantum states, states can be transmitted over an arbitrary length with only a polynomial cost function [5]. Photonics is the leading technology for quantum communication applications [18]. Quantum communication could be an essential component for future security applications [5,18]. Quantum optical memory typically stores optic signals in atomic properties of a stored particle [5]. Finally, precise injection of single and especially single squeezed photons using current technology has a fundamentally imperfect probability [17]. Being able to store and quickly retrieve optical states means that the generation of these photons can be repeated until successful [5,17]. The states are then stored awaiting all other photons proper preparation, subsequently, all photons are released simultaneously. This means that even with current generation imperfect single photon sources we can achieve perfect single photon sources with perfect optical quantum memory. If quantum optical memory is mastered, then many of the shortcomings of photonic computer hardware technologies can be worked around. To recap, quantum optical memory can reuse photonic circuitry to generate more complicated computations than previously available [5]. It can increase quantum computation networks to arbitrary length with only a polynomial cost function [5]. It can improve precision measurements and solve the difficulties associated with single photon and squeezed single photon sources [5]. If quantum optical memory can be successfully implemented, this will have a profound reshaping of photonic computation and communication.

Quantum optical memory comes in three main forms: electromagnetically induced transparency (EIT), DLCZ protocol, photon echo and off-resonant faraday interactions (ORFI) [5]. A key element to understanding the ability of these techniques to store data reliably is the delay bandwidth product, which measures the ratio between reliable storage times and the needed duration of stored pulse [5]. If this ratio is greater than 1 successful quantum optical memory has been achieved. EIT uses nonlinear optic phenomenon within atoms to store photons [5]. Using a wavelength specific compound and electric tuning, the incoming light will observe an extremely high index of refraction [5]. This slows down and compresses the photon, until the photon reaches the end of the medium or is electrically detuned creating a very low index of refraction material [5]. This controlled switching from high index of refraction to low can be incredibly useful in implementation. Storage of pulses have been demonstrated up to 2.3 seconds [5]. This was achieved using a praseodymium doped Y2SiO5 crystal however, this process resulted in inhomogeneous broadening destroying any stored quantum state [5]. Other compounds have found slightly lower storage times, but have been able to decrease inhomogeneous broadening by a factor of 15 [5]. Squeezed single photon storage has also been demonstrated using this technique with storage times ~.5 microseconds however, only a modest squeeze was retained [5]. EIT is a very promising field for quantum optical memory, especially if inhomogeneity can continue to be decreased [5]. DLCZ was developed by Duan, Lukin, Cirac and Zoller [5]. DLCZ is very similar to EIT however, it is tailored to only be practical as a quantum repeater and as a single photon source [5]. Unlike other storage methods, after a photon is stored in the atom, a series of weak off-resonant pulses known as write pulses are applied to the atom [5]. A number of scattered photons, known as idler light is then filtered out. Any other photons can pass through this filter and be detected by a single photon detector [5]. The process of filtering erases spatial information about the atom, somehow storing the single photon's information with the same phenomenon as EIT [5]. Although this methodology does not directly store the photon it can store its information for ~400 ns [5]. Using this technique a single photon source with ~10% efficiency is attainable [5]. Photon retrieval has been measured as high as 84% [5]. Using Hong-Ou-Mandel effect researchers were able to identify that photons generated using DLCZ are "largely indistinguishable" [3,5]. DLCZ will most likely be used as a single photon source in future implementations of photonic computers. Photon echo also uses a similar phenomenon as EIT however, it takes advantage of the parasitic inhomogeneous broadening previously mentioned [5]. There are two main types of photon echo: controlled reversible inhomogeneous broadening (CRIB) and atomic frequency combs (AFC) [5,12]. CRIB operates very similarly to spin-echo error correction; by flipping the phase at regular intervals, one can use the inhomogeneous broadening generated during the first interval to cancel out the inhomogeneity created during the second interval. This allows researchers to preserve the quantum state [5]. This flipping is done by reversing the applied electric field applied to the crystal in EIT [5]. The unfortunate downside is that in order to obtain the required optical properties, the crystal used for EIT needs to be cooled to ~4 K [5]. This is a simple but very effective method to extend storage fidelity however, efficiencies are still only 41% [5]. AFC works by offering the photon a series of regularly spaced detuned atoms for the photon to interact with [5,12]. This allows a photon with many entangled states to more sensitively be stored and critically limits unintentional re-emission [12]. Assuming only transverse broadening, this is the most effective method of storing photons currently [5]. AFC has been demonstrated in crystals for up to 20 microseconds with an efficiency of ~9.1% [5]. This is not great especially compared to CRIB however, theoretical models indicate a potential 90% efficiency with better materials and manufacturing [5]. Finally, ORFI utilizes the Faraday interaction between photons and atoms to store information in atoms [5]. This works by passing the incoming photon pulse through the off-resonant atomic gas enclosed in the cell as shown in **Figure 2** [5]. The pulse is then phase shifted, and its polarization is measured. Using this measurement, a magnetic field is applied to the atomic gas to displace their angular momentum [5]. Now the information is stored in the atomic angular momentum [5]. One issue with this is the unknown starting state of the atomic gas can greatly affect the stored information [5]. In 2004 researchers were able to demonstrate a preparation state, which starts the atoms in a known state, averting the need for squeezed states [5]. Although fast progress is being made on a number of quantum optical memory systems, researchers still have a long way to go before they can unlock the radical potential promised.

Researchers use the previously discussed hardware elements to implement three main types of photonic computers: qubit, continuously variable (CV) and hybrid qubit-CV. Qubit type photonic computers use descritized degrees of freedom of light [17]. Typically using polarization, propagation direction or arrival time to encode the quantum information [17]. The most basic example is polarization. For example, if a is the coefficient of the |0> state, b is the coefficient of the |1> state, q denotes qubit state, h denotes the state of horizontal polarization and v denotes the state of vertical polarization, then $a|0>_q + b|1>_q = a|0>_h|1>_v + b|1>_h|0>_v$ [17]. In this instance, it is very easy to implement single qubit gates by simply applying waveplates [17]. Two qubit gates, such as CNOT, can theoretically be implemented using the Kerr effect [7]. The Kerr effect requires nonlinear variance of the refractive index based on the input light; however, no known materials have the third-order nonlinearity, which is needed to implement a pi phase shift on single photons [7,17]. A pi phase shift is needed to implement CNOT gates. Another implementation of qubit type photonic computers is the Knill, Laflamme and Milburn (KLM) type photonic computer [15,16,17]. KLM was notably designed to only use linear optics however, KLM designs also need single photon sources and detectors, which can only unreliably be generated using active linear optics [16,17]. The implementation of quantum optical memory would solve this issue of unreliable single photon sources, as previously discussed [17]. Even with these yet undeveloped technologies: single photon sources, detectors and quantum optical memories, KLM can generate only probabilistic CNOT gates [15,16]. This is not great however, using quantum teleportation we can increase the probability of successful CNOT gate application [16,17]. With the addition of many ancillary qubits this measurement probability approaches a deterministic result [17]. Although this approach has had successful experimental implementation, it is not practical to implement as a scalable technology [17]. This is because of the small ratio of logical to ancillary qubits needed to bring fidelities within comparison to superconducting and trapped ion qubits. There are deterministic approaches to apply two-qubit gates to photonic qubits; however, they rely on interacting a photon with a single atom in an optical cavity [17]. This approach introduces many of the challenges associated with superconducting and trapped ion systems, which negates the photonic benefit [17]. In general, qubit only photonic systems suffer from a low probability of successfully applying two-qubit gates [18]. This is a major issue while scaling, because probabilistic success will decrease exponentially with a linear increase of multi-qubit gate layers, as a result of compounding probabilities [17].

The next major type of photonic computers are CV systems. CV systems utilize continuous degrees of freedom of light, such as amplitude and phase. Typical implementations of CV systems modulate amplitude and phase. This is done through the use of three components: electro-optic modulators, modifiable waveplates and beamsplitters [17]. CV systems can apply any gaussian gate [17]. To do this they need squeezing gates, which are based on second-order nonlinear effects, so any gaussian gate can be produced with only second-order nonlinear effects [17]. This is supported by current optic materials [17]. CV systems can also apply non-gaussian gates, such as cubic phase gates which operate based on third-order nonlinear effects [17]. As aforementioned, third order nonlinearity is not achievable for low power systems with current optical materials [17]. Importantly, using quantum teleportation, can allow CV systems to apply multi-qubit gates deterministically [17]. This quantum teleportation is the transfer of an unknown quantum state from an input state to a different output state using ancillary squeezed states, as shown in **Figure 3 a)** [17]. As shown, homodyne detectors can simultaneously measure position and phase of different ancillary states, then modify the electro-optical modulator accordingly. Additional basic operations such as squeezing gates and cubic phase gates are shown in **Figure 3 b)** and **c)** respectively [17]. This is a demonstration of how unitary operations can be deterministically applied to CV photonic circuits. Although this theoretically works, this requires infinite squeezing or reliable quantum optical memory, which are both currently impractical [5,17]. One last technique is the use of so-called "one-way computation" [11,18]. One-way computation utilizes cluster states, which first entangle photons into one large superposition then measure, with homodyne detectors, and electro-optically modulate the photon to apply a unitary [11,18]. Important to one-way computing is photon counting in the homodyne detectors which is impossible to do with current technology [11].

The hybrid qubit-CV system takes the best of both worlds from CV and qubit photonics. This hybrid system utilizes the deterministic gates from CV systems and combines it with the noise resistant and error correctable features of qubit systems [17]. It is very easy to see why this is the most popular photonics platform of late [18]. Unfortunately, the higher complexity of hybrid optical circuits yields a more dramatic optical loss; optical loss is currently the largest inhibitor to development of more functional photonic computers [1]. Typical qubit photonics are delivered in short pulses meaning a high uncertainty of frequencies [17]. This is incompatible with CV systems, so one must generate pulses short enough to operate in the qubit portion of the photonic circuitry, while also leaving uncertainty of frequency low enough that the phase can store meaningful information for the CV portion of the circuitry. A side effect of using a hybrid methodology is the ability to implement multi-photon systems. This means that one can store redundant information which is useful for error correction in an ancillary photon to help with error correction [17]. Compared to traditional photonic systems, wherein one must encode whole qubits for additional error correction efficiency, this is a great advantage [17]. GKP has been shown to best address photon loss errors using this multi-photon approach [17]. Using this technique, there is a threshold of finite squeezing of ~20 dB of optical squeezing, above which the squeezing imperfections can be filtered out by error correction [17]. Currently, optical squeezing has reached ~15 dB [17].

Finally, time domain multiplexing of one-way computation and other more complicated utilizations beyond the scope of this paper should prove to have a profound impact on computational potential of future photonic computers [17]. In summary, there are a number of main photonic technologies, which if implemented would produce an effective photonic NISQ computer or quantum repeater. Although this technology is currently far inferior to superconducting and trapped ion systems, continued materials research will hopefully unleash the vast potential promised by photonic quantum computer advocates.

Figure 1

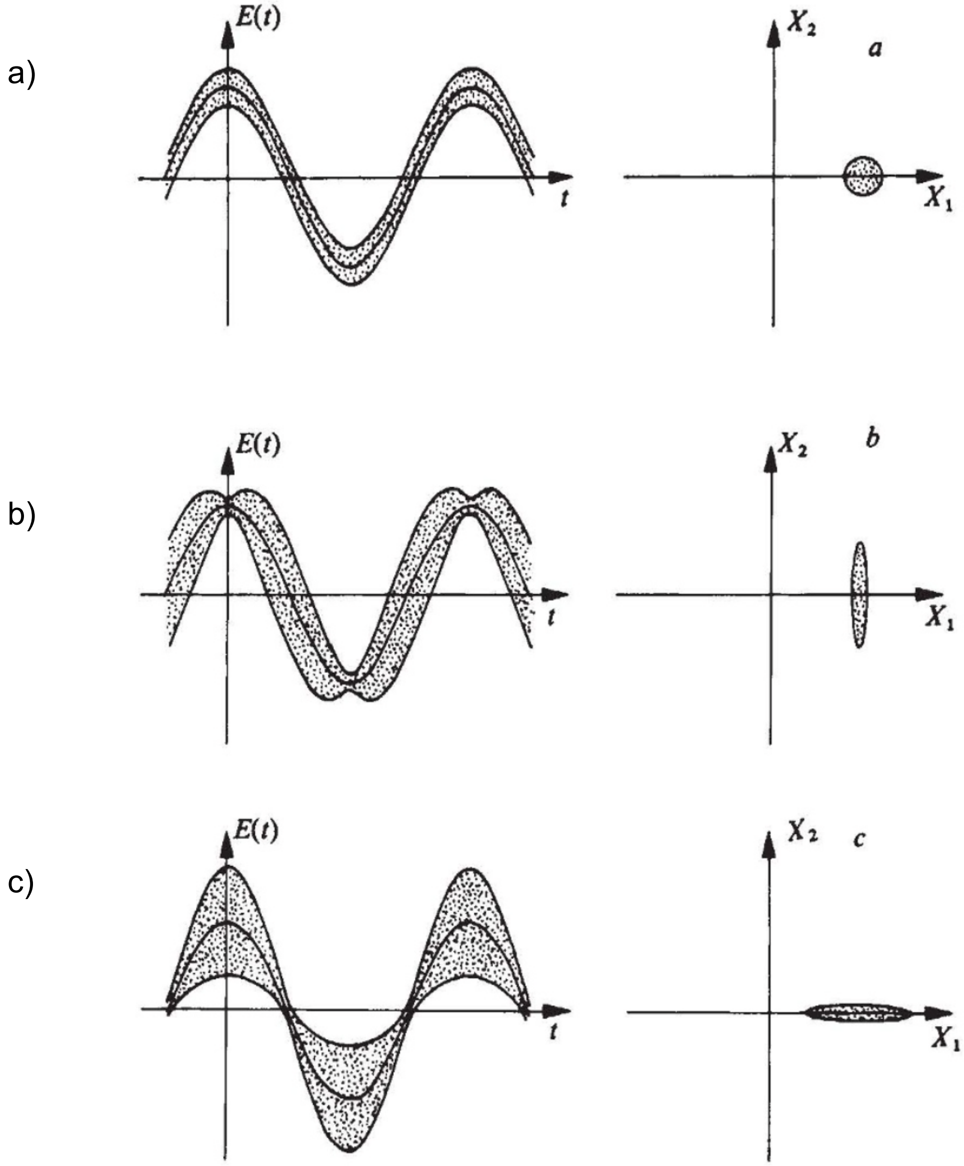

Figure 1 Squeezed states of light. **a)** Uncertainty of phase and amplitude are matching causing a circular phase space [4]. **b)** Uncertainty of phase is greater than uncertainty of amplitude. Since the uncertainty magnitudes are not matching, there is an elliptical phase space [4]. **c)** Uncertainty of amplitude is greater than uncertainty of phase. Since the uncertainty magnitudes are not matching, there is an elliptical phase space [4].

Figure 2

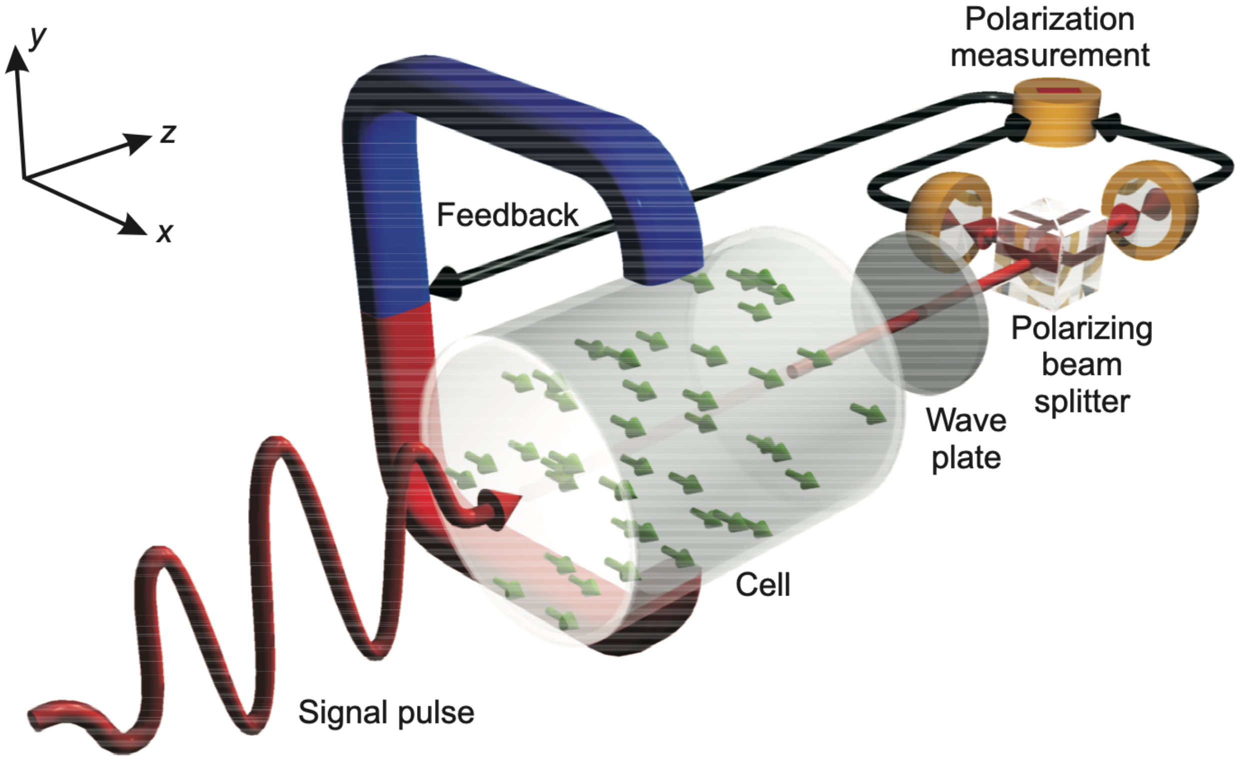

Figure 2 Off resonant Faraday quantum memory. Magnetic modulation of the angular momentum of off resonant atomic gasses stored in the cell can store polarization information of incoming signal, by measuring the signal's polarization after passing through atomic gas [5].

Figure 3

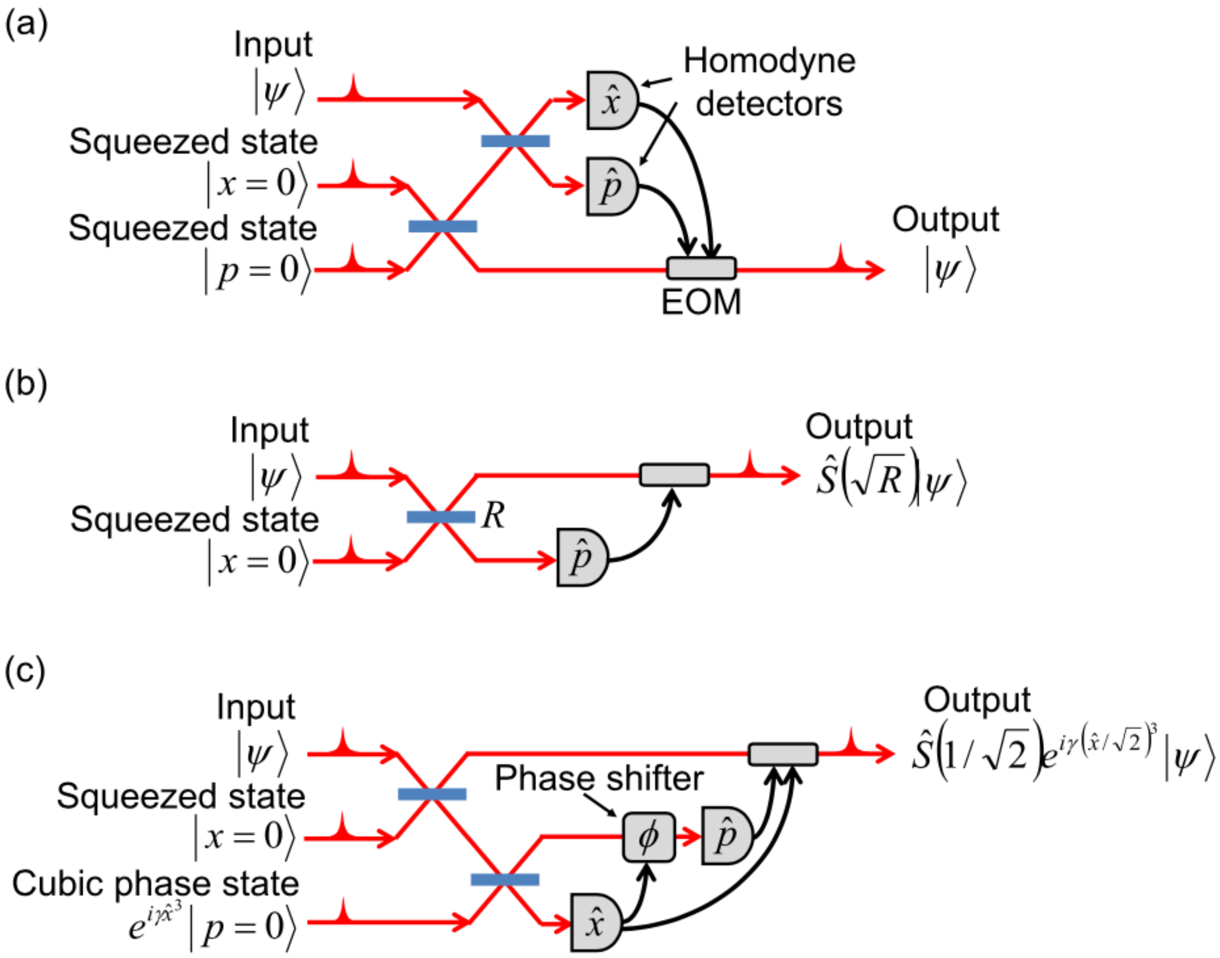

Figure 3 Photonic circuit models for CV systems implementing quantum teleportation. Here |x=0> and |p=0> represents the phase and amplitude squeezed state respectively. **a)** Using two ancillary squeezed states, one phase squeezed and the other amplitude squeezed to teleport the quantum state from one photon to another. This is done using homodyne detectors, electro-optic modulators and beamsplitters [17]. **b)** A similar teleportation technique can be used to implement squeeze gates [17]. **c)** With the addition of a waveplate or a modulated waveplate, a quantum teleportation based cubic phase gate [17].

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