Single and Entangled Photon Sources

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***Introduction** – Graham Jensen*

The possibility of totally secure communication through the application of quantum mechanical properties was introduced in 1984 by Bennett and Brassard in their paper, "Quantum Cryptography: Public Key Distribution and Coin Tossing". As Bennett and Brassard outlined, quantum communication makes it impossible for an eavesdropper to intercept a message without detection by the desired parties. This phenomenon paves the way for a future of indecipherably secure communication, even with the advent of more powerful and even quantum computers[1]. To utilize the powerful advantages of quantum communication systems, single or entangled photon sources are necessary. An outline of the theory of these sources and a subset their applications are described below.

***Single Photon Sources** – Samantha To*

A single photon source uses the excitation of the electromagnetic field to emit a single photon of a single mode k localized in both time and space. Photon sources can be characterized by the following second order correlation function.

$$g^{(2)}(\vec{r}_1, \vec{r}_2, t_2 - t_1) = \frac{\langle : \hat{n}(\vec{r}_1, t_1)\, \hat{n}(\vec{r}_2, t_2) : \rangle}{\langle \hat{n}(\vec{r}_1, t_1) \rangle \, \langle \hat{n}(\vec{r}_2, t_2) \rangle}$$

where n denotes the photon-number operators a†, a, and :: represents the operator normal ordering, or in other words, the annihilation operator a on the right of the creation operator a†. According to this correlation function, in order for a photon source to emit one photon at a time, g(2)(0) = 0 with g(2)(τ) > g(2)(0). This shows that after the material went through emission, it must be excited again before a second photon can be emitted[2].

One way to achieve this is to attenuate a laser beam to single-photon level through the use of optical filters. This attenuated laser beam is a good approximation for single photon emission, but there is always a possibility that bunches of photons will be emitted at one time. To truly obtain a single photon source, one must rely on fluorescence lifetime. A laser beam is focused on a sample of low concentration on the order of 10^-10 molecular concentration of emitters. Due to the low concentration of emitters and the fluorescence lifetime, ideally, one emitter is excited and only one photon is emitted[2].

There are two categories of single photon sources: deterministic and probabilistic[2]. Deterministic single photon sources emit one photon at any arbitrary time determined by the experimenter. These quantum systems include color centers, quantum dots, single atoms, and atomic ensembles. Color centers are formed with a nitrogen atom in an adjacent lattice position in diamond. Quantum dots are created with molecular beam epitaxy where tiny islands of smaller bandgap semiconductors are embedded in a larger bandgap semiconductor. Single atoms are designed for cavity quantum electrodynamics where the emitted single photon enhances the dynamics of the atom-cavity system and the cavity aids the emission of single photons[2].

Probabilistic photon sources emit a pair of photons where the first photon is used to herald the creation of the second single photon. In practice, these sources involve a laser excitation of a nonlinear optical material such as parametric down conversion in bulk crystals and four-wave mixing in optical fibers. In parametric down conversion, a pump laser is aimed at a material with optical nonlinearity, creating two photons where the conservation of momentum and energy determine the wave vector relation between the two photons. Four-wave mixing is the process where two uncorrelated photons are converted into two correlated photons in centrosymmetric materials such as glass. This type of single photon emission is not reliable due to dark current and stray light that interfere with the resolution of the photon sources[2].

Single photon sources are important for current research in quantum information and cryptography. Single photon sources are used in quantum information and cryptography for encoding of information and communication. A single photon can be detected at long distances away from the source and still contain its information. With the use of single photons, communication can be completely secured as any intercept would not be able to decrypt the message and the communicators would be able to see that the single photon had been intercepted[2].

***Entangled Photon Sources** – Graham Jensen*

The notion of quantum entanglement was first proposed by Einstein, Podolsky, and Rosen in 1935. The group proposed a paradox (known as the EPR paradox) which was designed to show a flaw in the current theory of quantum mechanics. David Bohm proposed a simplified version of this situation where a pi meson decays down to an electron and positron. Quantum theory predicts that if the spin of one of the particles is measured the other must be the opposite, no matter the distance between them. Einstein believed this “spooky action at a distance” is in violation of the theory of relativity, citing the impossibility of faster than light information travel. His conclusion was that quantum mechanics is an incomplete theory and there lies a hidden variable that was yet to be discovered. However, John Bell mathematically proved that any hidden variable theory is incompatible with quantum mechanics. His theorems were later demonstrated experimentally, confirming Bell’s findings[3]. The concept of entanglement can also be applied to photons, leading to applications in quantum communication.

The use of entangled photons for quantum cryptography was proposed by Arthur Ekert in 1991[4,5]. Ekert’s protocol, known as E91, includes a photon pair entangled in polarization with paths split so one photon is received by Alice and the other by Bob. To ensure a secure connection is present, a Bell's theorem is performed to check for eavesdroppers[5]. This protocol was first implemented in by Kwiat et al. in 2000[4,6]. This experiment showed the viability of Ekert's protocol as well as an exploration of potential eavesdropping strategies[6]. Since Kwiat's paper, further study of this field has been performed including a recreation of Kwiat's experiment using equipment found in an undergraduate laboratory[7]. This course's lab 1 is one such experiment.

In lab 1 of this course, entangled photons are used to verify the violation of Bell's inequality[7]. Currently, the most popular method (and the one used in lab 1) of producing entangled photons is through spontaneous parametric down conversion (SPDC). A 100mW ion-argon pump or diode-laser beam is incident on a pair of orthogonally polarized type I Beta Barium Borate crystals. As the pump beam interacts with these nonlinear crystals, single photons split into entangled "signal" and "idler" photons with wavelengths longer than the pump. Because a type I crystal is used, the polarization of the signal and idler photons will be identical but opposite of the pump polarization[4]. SPDC photon pairs are also produced simultaneously. This property may be utilized as a trigger for the detection of this event. By adding a pair of avalanche photodiodes (APDs) in the paths of the entangled photons, an incidence of SPDC may be measured. With the inclusion of rotating linear polarizers set in the beam paths of the entangled photons, a verification of the violation of Bell's inequality can be reached[4].

References

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