Single Photon Sources

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As the ability to use strange and puzzling quantum effects continues to grow, applications such as quantum cryptography and quantum computation are beginning to become possible for use in every day life. At the heart of this trend is the ability to create reliable single photon sources.\[1\][2]

Single photon sources are typically atomic emitters of a single kind. The emitters are triggered by either an optical or electrical pulse in order to excite the atom. As the atom relaxes to the ground energy state, energy is released in the form of photons. Typically, the emitters only emit light of a specific wavelength. In order to select only single photons, filters can be used to reject the excitation wavelength.\[1\]

The source emits photons on demand at a particular rate as defined by the temporal pulse separation of the laser, as long as this separation is longer than the fluorescence lifetime. The fluorescence lifetime is the time it takes for an emitter to relax to the ground state after being excited. The fluorescence lifetime is crucial in the creation of single photons. The emitter is not able to produce multiple photons within the fluorescence lifetime.\[3\]

Various types of emitters have been utilized as sources for single photons.\[4\][5] One such emitter is an object on the nano-scale inside an optical cavity on the order of the wavelength of the emitted photon. The optical cavity causes the nano-scale object to emit a photon in one particular direction as well as increase the efficiency of emission. Additionally, spontaneous emission of the desired wavelength and in the preferential direction is increased in the cavity as a result of cavity quantum electrodynamics effects, namely the “Purcell Effect.” Organic molecules are an example of such emitters that have been used to create single photon pulses. However, the organic molecules have a limited lifetime before they no longer emit photons and become bleached.\[1\]

Both hetero-structured and colloidal semiconductor quantum dots have also been utilized as emitters of single photons. Typical heterostructured quantum dots used are indium-arsenide quantum dots in gallium arsenide. When an electron-hole pair recombines in the quantum dot, the quantum dot emits a photon of a particular wavelength. Quantum dots have a high directionality of emission when placed inside a micro-cavity. The quantum dots are able to increase the emission efficiency in a micro-cavity. Hetero-structured quantum dots tend to be more stable than other possible single photon sources, such as organic molecules. Hetero-structured quantum dots also relax from the excited state to the ground state more quickly. However, InAs quantum dots require temperatures on the order of one Kelvin, which is not favorable for long range quantum information applications.\[1\][6]

Colloidal quantum dots, on the other hand, can operate in room temperatures. Colloidal quantum dots are very bright and emit over a broad range of wavelengths. However, colloidal quantum dots blink when excited by a laser, causing instability for fluorescence.\[7\]

An additional resource used as a single photon source comes from the single color center of diamonds. The nitrogen-vacancy
and other color centers of diamonds are able to produce photons in a singular fashion. The color center is excited by a laser and emits photons, mainly a single photon at a time. This system can also be run at room temperature, which is useful for many applications.[1]

Single photons have also been created through the technique of parametric down-conversion, where one photon enters a non-linear crystal and creates two photons that have a lower energy. The two photons that are created are coupled and have a particular polarization. By only allowing one polarization state to pass, a single photon is able to pass through the optical system. However, the crystal can create multiple photons that are in a state of entanglement.[4]

Single photon sources are a crucial part of quantum cryptography, the secure transfer of information using photons to transfer information. In quantum cryptography, a sender sends photons to a receiver with a particular polarization or other characteristic to be measured by the receiver. The photons are assigned values of information based on the basis in which they are read. The sender will encode the photon using a particular basis and the receiver changes between two orthogonal bases randomly. One of these bases is the same basis used by the sender. Since the information can only be properly correlated when the basis used to encode the data is also used to read it, the results will be in error half the time. If a third party attempts to intercept the information and relay it to the receiver using an incorrect basis, the amount of error that the receiver measures will increase. This will be noticed immediately by the receiver by analyzing the average error. However, there are inherent transmission errors associated with the sending of information.[8]

Transmission errors are increased with the use of certain sources, such as attenuated laser pulses. The technique of inserting optical filters in front of the laser beam to attenuate the pulse down to a single photon level is not entirely reliable. As a result of the probability of the photons, no photons may pass the optical filters on average. Additionally, there is a probability that more than one photon would pass the optical filters and cause a breach in security during the transfer of information.[1][8]

In order to create absolutely secure communications over long distances, single photon sources are utilized. Both single and entangled photons can be transmitted along fibers or in free space. In the case of entangled photons there are errors that arise with the transmission of multiple photons over the distance. Instead, single photons can be used in order to eradicate the errors from the transmission of entangled photons.[8]

Single photon sources are also important for the use in quantum computation.[1][4][8] Quantum computation is analogous to classical computation in that there are bits that are used to store information. In classical computing, bits are either 0 or 1 as a result of the existence or absence of charge on the plates of a capacitor, for example. However, in quantum computation, the concept of superposition of states is utilized so that a quantum bit, or qubit, is the superposition of both 0 and 1. As a result, the qubit can hold a far greater number of bits of informa-
tion, $2^N$ bits of information, where N is the number of qubits being examined in a registry. Photons are one possible example of a qubit and in order to create quantum computation, a steady flow of single photons is necessary. The single photons act as qubits and are then used to store information in the superposition of bits.[1][4][8]

In order to determine if single photons are being produced, the photons are measured for antibunching. Antibunching is when photons are produced with specific gaps between photons, opposed to random spacings. When a source shows antibunching, it is clear that single photons are being created because there is a gap between photons. Thus, no two photons are being created simultaneously. Antibunching is tested with a Hanbury Brown-Twiss setup that utilizes a beam splitter and two detectors. The source sends photons through the beam splitter that has two detectors at the outputs. The detectors are connected to a timer that measures triggers from the detectors. When one detector receives a photon, it sends a signal to the timer. This is the start signal and the timer begins to count until it receives a stop signal from the second detector. The second detector sends the stop signal once a photon is incident upon it. Thus the correlation between the two detectors shows the time difference in arrival of the two photons. If the time interval is zero, then the two photons hit the detectors simultaneously, meaning that the source emitted two photons at once. If no time intervals of zero are measured, then the source is creating antibunched photons, or single photons.[3]

Single photon sources are becoming an extremely important and crucial step to making novel applications of quantum-mechanical phenomena an everyday experience. Single photon sources are necessary for the ability to securely send information over long distances, store extremely large amounts of data in the form of qubits. As the efficiency of these single photon sources increases and the availability of room-temperature sources, these possibilities will become a true reality for the everyday consumer.
Bibliography


