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Single Photon Sources and Their Applications

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A classic experiment, done by Hanbury Brown and Twiss in 1950’s, revealed that the photoelectric pulses produced by illuminated photo detectors do not occur strictly at random [1]. In their experimental set-up, the joint photo detection probability \( P(r_1, t_1; r_2, t_2) \) at two photo detectors placed at two different points in space \( (r_1 \text{ and } r_2) \), at two different times, was found to be smaller than the joint detection probability at equal time \( P(r_1, t; r_2, t) \); i.e
\[
P(r_1, t_1; r_2, t_2) \leq P(r_1, t; r_2, t).
\]
(1)
This observation agrees with the prediction made by classical theory of light (see [2], Sec. 9.9). However quantum mechanical treatment of the Hanbury Brown-Twiss effect reveals that it should also be possible to have a case where the different time photoelectric detection becomes more probable than equal time photoelectric detection ([2], Sec. 14.6.1), i.e
\[
P(r_1, t; r_2, t) < P(r_1, t_1; r_2, t_2).
\]
(2)
This phenomenon is called \textit{antibunching}.

A simple interpretation of antibunching may be given in terms of the quantum theory of light. According to the quantum picture, light is a manifestation of discrete quantized packets of energy (photons). From this theory, it is evident that if only one photon is incident on the beam splitter, then it can not be simultaneously detected at both the detectors. In that case the joint probability of equal time photo detection at the two detectors will be zero. Hence, in a Hanbury Brown-Twiss set-up one will be able to observe antibunching, if a source of light can produce considerable amount of such “single photons”.

The definition of a single photon source may be given as following:

\textit{A single photon source may be defined as a source of light which produces antibunched photons.}

Since it has been realized that eavesdropping leaves signature on quantum mechanically encrypted information, much emphasis has been given to study quantum cryptography and quantum communications. It has turned out that single photon sources are unavoidable tools for quantum communications. For this reason, it is extremely important to develop efficient and reliable single photon sources. Because antibunching can not be achieved by attenuating normal laser sources, completely new ideas are required to develop single photon sources.
The key to develop a single photon source was hidden in the work of Kimble and Mandel on resonance fluorescence [3, 4]. This work was followed by an important experiment in 1977 [5], where antibunched photoelectric counts were observed from the light radiated by sodium atoms which were continuously excited by a dye-laser source. These results clearly showed that, electronic transitions in some atoms or molecules may emit single photons and this phenomenon is now widely used to produce single photons in laboratories. The most popular methods, to make single photon sources at room temperature, involve using single fluorescent molecules, colloidal semiconductor quantum dots (nanocrystals) and color centers of diamond [6–9]. Sometimes the quantum dots are placed in photonic bandgap material hosts to enhance spontaneous emission and to produce light of definite polarization. Some host can also diminish emitter bleaching.

To describe the theory of producing single photons by electronic transitions, we consider a sample atom with the energy level structure given by Fig. 1 (cf. [10], Sec. 6.7, Fig. 6.12). When this atom is excited by a trigger pulse, the electron moves from the ground state to the exited state. This electron might return to the ground state in two steps emitting photons of two different wavelengths. The unwanted wavelength is removed by using a proper filter. If the time separation between the input pulses is large compared to the radiative life time of the atom, then, only one photon of a particular wavelength comes out of the filter for each input pulse. The trigger pulse, used to excite the atom, may be optical or electric. In references [6–9] optical trigger pulses were used. The first electrically driven single photon source was reported in Ref. [11].

In particular, one might use a GaAs light emitting diode with a layer if InAs quantum dots inserted within the active region (for example, see [10], p-121). The quantum dots might be exited by a programmed sequence of current pulses from a pulsed voltage source.
A low concentration of the quantum dots is necessary for good antibunching. A confocal microscope may also be used to focus a laser beam on a single emitter and to select the light radiated from a very few quantum dots. Such a system may be used as a single photon source in the laboratories.

However there are many drawbacks in these methods of producing single photons. The major problems are low efficiency and pollution by multiple photons. One of the best single photon source has been produced by Yamamoto et al. at cryogenic temperature [12] using hetero-structured quantum dots inside micro-cavity. Anyways, it still remains a big challenge to make good and efficient single photon sources at room temperature.

References and Notes