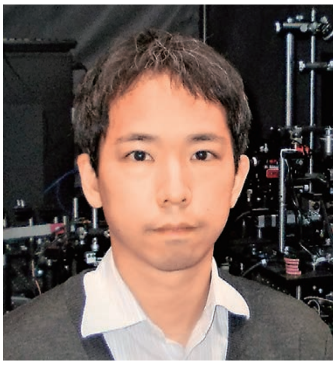
Investigation of Nano- and Quantum-Structures Based on the Single-photon Counting Method

Toward the realization of higher performance colloidal-dot quantum emitter



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Research and development into quantum technology is accelerating throughout the world in preparation for a revolution in info-communications and information processing. Using microscopic, nano-sized materials allows easy manufacturing of "quantum emitters" that emit special light with non-classical properties. Quantum emitters can be used for a variety of purposes, including use in info-communications. This has led to research being carried out all over the world with the aim of making them brighter, more stable, capable of room temperature operation, etc. In this article, we introduce the characteristics of colloidal-dot quantum emitters made from a semiconductor nanoparticle material known as colloidal quantum dots, and an original measurement system we developed for accurately evaluating the emitter performance.

Nano-Sized Quantum Emitter, the Key to Quantum ICT

In recent years, researches are being carried out all over the world on a variety of emitters capable of generating non-classical light, which cannot be explained by concepts of classical waves. Examples include emitters that generate a series of single photons, which cannot be split any further, and emitters that generate quantum-correlated entangled photon pairs and indistinguishable photons. These emitters have the potential to realize tap-proof communication through quantum cryptography, or be used in, high-speed information processing technology that is overwhelmingly superior to existing computers. Among emitters capable of generating non-classical light, the nano-sized quantum emitter is one of the most expecting candidates to achieve outstanding performance. Nano-sized quantum emitters are emitters made of microscopic, nano-sized materials, and are characterized under the laws of quantum mechanics. As competition heats up around the world to develop cutting-edge "quantum ICT technology," the development of nano-sized quantum emitters, which are efficient at generating non-classical light, is also accelerating dramatically.

The Characteristics of Colloidal Quantum Emitters

Our research focused on a material known as the colloidal quantum dot (CQD), and we are carrying out experiments to investigate its performance as easily quantum emitters.

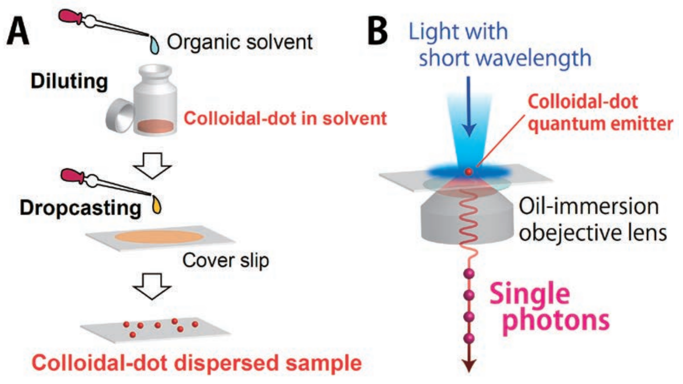

Figure 1 A: How a colloidal quantum dot (CQD) dispersed sample is made. It is diluted to a low concentration using organic solvent, then dropcast onto a cover slip. B: How single photons are generated using the CQD dispersed sample. Irradiating it with a short wavelength light results in the emission of single photons with long wavelengths. This system is characterized by its ability to be operated at room temperature.

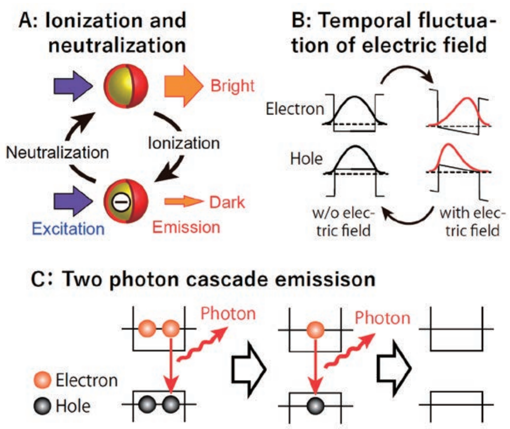

Figure 2 Examples of physical phenomena that affect the performance of the colloidal-dot quantum emitter.

The CQD is a semiconductor nanoparticle that exhibits high luminescence efficiency at room temperature, and it is a material that allows the low cost manufacturing of quantum emitters. The particles are around 2 – 10 nanometers in diameter, and they are characterized by dramatic changes in their properties, such as the color of the emitted light (wavelength), depending on their size, shape, material quality, etc. In this research, we set up our colloidal-dot quantum emitter (a quantum emitter made from CQD) according to the procedures shown in Figure 1.

Irradiating dispersed, low-concentration CQD with a short wavelength light causes the CQD to emit single photons with long wavelengths. The single photons emitted from the CQD have low directivity, but a microscope component known as an "oil-immersion objective lens" can be used to reduce loss, realizing greater brightness.

Recent researches have revealed that various physical phenomena affect the performance of the colloidal-dot quantum emitter as shown in Figure 2. Figure 2A shows the neutralization and ionization of a single CQD, which is one of the causes of temporal fluctuation (photoluminescence blinking) in the strength of emissions. Figure 2B shows how the presence or absence of an electric field inside the CQD results in a phenomenon in which the wave function of electrons changes, leading to temporal fluctuation in the color of emissions. Figure 2C shows the process in which two photons are emitted sequentially from a single CQD in a phenomenon known as "two-photon cascade emission." It is not just the case of CQD, but the performance of many nano-sized quantum emitters is affected strongly by these physical phenomena. The development of a high-performance nano-sized quantum emitter will require a deeper understanding of the mechanisms behind how these phenomena occur, and advanced technologies to control them.

Analyzing Emitters Using the Single-Photon Counting Method

To observe and analyze the variety of physical phenomena as shown in Figure 2, this resaerch utilizes the "single-photon counting method." The use of this counting method enables us to record the times of single-photon detection, at a high temporal resolution of around 10 picoseconds, in a text file. Figure 3 shows a schematic diagram of the measurement system developed for this research. A low-noise, high-sensitivity super-conducting nanowire single-photon detector is used, to analyze the characteristics of temporal fluctuation in the strength of emissions and two-photon cascade emissions with extreme precision.

In this system, the generated photons are passed through an optical element (beam splitter) to split the beam into half before they are passed through two optical fibers to measure what is known as their intensity correlation. If the single photons are being generated in an orderly manner at regular intervals, the probability of the two split photon beams entering the optical fibers at the same time will be 0%. So, the signal indicating the delay time between two photons being zero will be eliminated when using a two-channel single-photon detector to measure the coincidence count. Figure 4 shows an example of actual data of the intensity correlation obtained through experiments. The data shows that the ratio between the maximum coincidence count value and the value when the delay time between two photons is zero is around 0.01. The lower the value, the higher the performance, and tha value of 0.01 indicates its top-class performance as a single-photon emitter among all emitters around the world operable at room temperature.

Data obtained through recent experiments suggests that performance can be improved even further by making use of the characteristics of super-conducting nanowire single-photon detectors. We expect that the further experiments will prove the limitation of performance improvement of nano-sized quantum emitters at room temperature.

Future Prospects

This research proved how easy it is to make a high-performance single-photon emitter (colloidal-dot quantum emitter) by making use of CQD. If technology could be developed in the future to efficiently generate not only single photons, but also entangled photon pairs and indistinguishable photons, we can expect a dramatic spread in the practical application of ICT technology using non-classical light throughout society. Meanwhile, experiments using the advanced single-photon counting method have also made it clear that it is possible to quantitatively evaluate the non-classical properties and optical characteristics of a variety of nano materials, including CQD. In the next stage of research we will involve R&D into further improving the performance of nano-sized quantum emitters, while also aiming to ensure the advanced use of the single-photon counting method, and the extensive application of non-classical properties seen in nano and quantum structures.

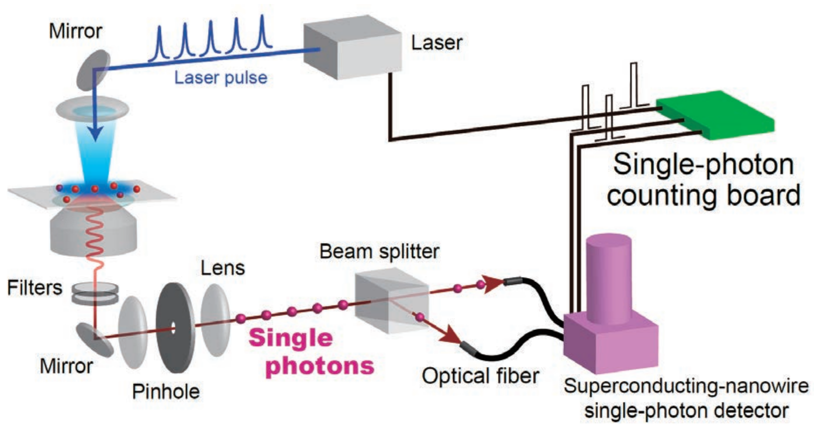

Figure 3 Schematic diagram of the counting system developed for this research. The generated single photons are detected by a super-conducting nanowire single-photon detector, and the signals are recorded by a single-photon counting board.

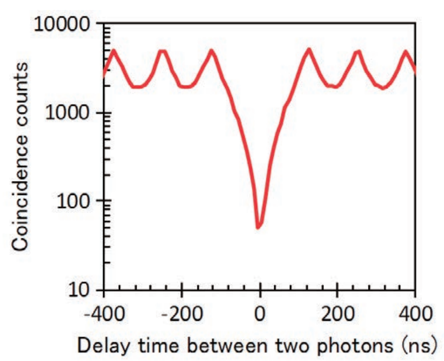

Figure 4 Example data on the coincidence count of single colloidal quantum dot emissions. It shows that the ratio between the maximum coincidence count value and the value when the delay time between two photons is zero is around 0.01, which is indicative of its ability to achieve top-class performance in the world.