Single photon from a quantum emitter? It's a matter of timing...

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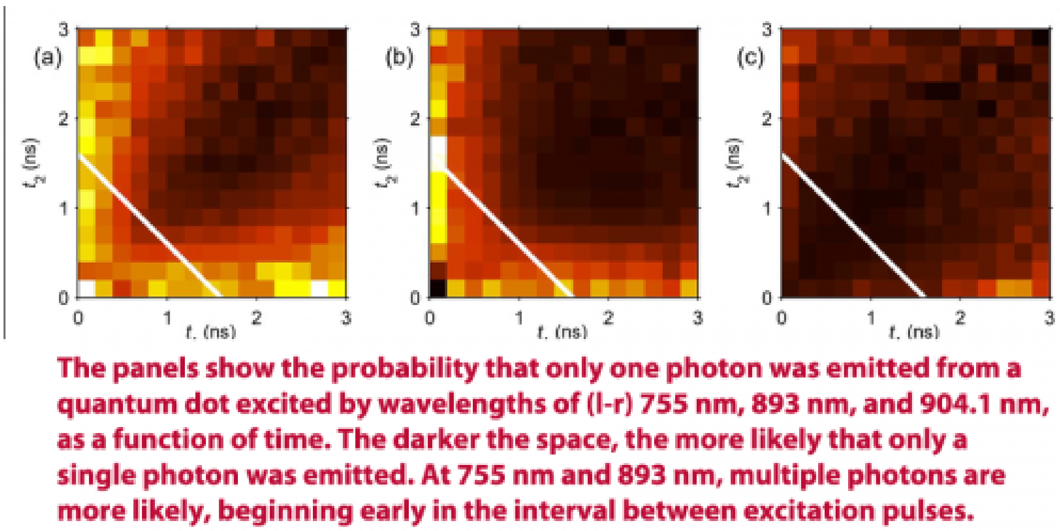

Plots of photon arrival times at each of two detectors show that the emission of only one photon following an excitation pulse is less likely than had been widely assumed.

(Phys.org) —Many systems envisioned for practical quantum information processing require the use of single, indistinguishable photons as carriers of information and logic operators. So researchers in the field need to be certain that their light sources can dependably produce individual photons in identical states.

The customary method of doing so involves analyzing temporal differences between photons generated by laser excitation pulses, and treats those differences as a static process. That is, only differences between photon detections are analyzed, and it does not matter when in the emission cycle the photons are detected.

But PML scientists recently devised a new method of examining the output of single quantum emitters, and discovered that in many situations the differences between photon events are not static, and thus both single-photon "purity" and consecutive-photon indistinguishability fluctuate dynamically over excitation-emission time scales. They also created a model to explain the physics of the phenomenon.

"We have found a good measure for modern photon sources," says Sergey Polyakov of the Quantum Measurement Division's Quantum Processes and Metrology Group, who co-authored a report on the findings in *Physical Review Letters* last October. "So now, if somebody gives me a source, I know exactly how to test it by performing experiments. I can see where it behaves as a good single photon source, or good indistinguishable photon source, and where it doesn't. Then, by knowing that, I can restrict its output and get only the 'good' part of the emission."

The team, led by co-author Glenn Solomon, studied light emissions from indium arsenide quantum dots (about 10 per square micrometer) embedded in a surrounding matrix of gallium arsenide. When the sample is excited by a pulsed laser, the laser energy excites electrons and holes, which propagate freely through the material and decay on different time scales. When a matched pair of opposite charge-carriers (called an exciton) recombines in the quantum dot, it emits light that travels through an optical fiber to the detection instruments. The time interval between laser pulses is 13 ns.

The researchers routed the quantum dot emission to a beam splitter and placed a detector with a time response of about 560 ps at the end of each beam path. The detectors were synchronized to the laser pulse, so that they could record the arrival time of each photon. That configuration enabled the team to observe the quantum dot output at different times during the 13 ns emission cycle.

For the first part of the experiment, designed to determine whether and when the quantum dot produced only a single photon in one excitation cycle, data were taken at three different excitation wavelengths: 755 nm, 893 nm, and 904.1 nm. The results showed a marked difference in the photon character for each of the cases that depends on when after the initial laser pulse the photon was detected, and these differences varied depending on the wavelength of the laser used.

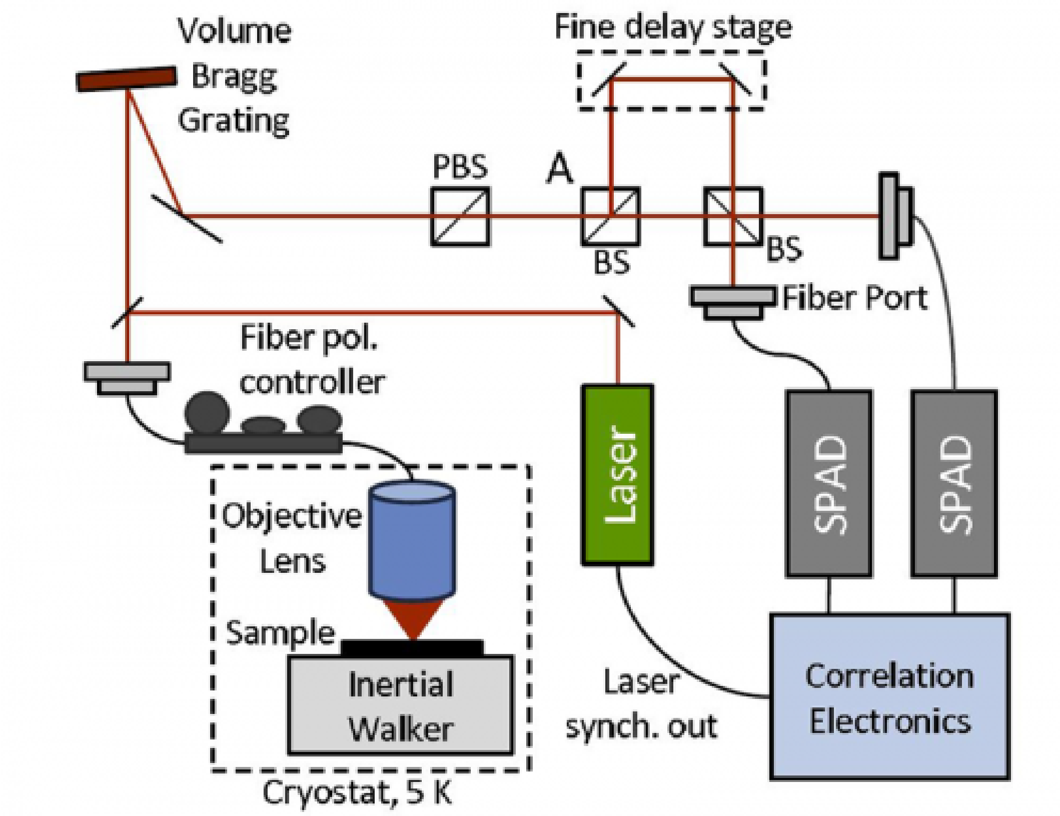

Diagram of laboratory set-up. BS stands for "beam splitter," and PBS is "partial beam splitter." SPAD stands for "single photon avalanche diode," a sensitive photodetector.

"What we think is happening," Polyakov says, "is that in some cases each laser pulse excites a whole lot of charge carriers. Some of them disappear; some of them have their own exit paths. And of course there is one path that excites the quantum dot and produces a photon.

"So if you shine your laser light for one pulse, you may think you're exciting the quantum dot only once. But there are multiple excitations in the material, with different lifetimes depending on the wavelength of the excitation, and another long-lived carrier can sometimes find its way into the quantum dot and make it emit again – within the same pulse cycle. So instead of getting one photon, you actually get two."

For example, the data show that the 893 nm pulse has a much lower probability of producing a single photon early in the pulse cycle because it generates a greater range of free carrier states that can potentially populate the exciton state. Whereas the 904.1 nm excitation has a more limited effect, and thus a higher probability of producing single photons throughout the entire emission cycle.

A computer simulation of that mechanism produced excellent agreement with the observed results.

"In the second part of the experiment," Solomon says, "we looked at how indistinguishable successive photons are."

The diagnostic test for indistinguishability is based on a quantum phenomenon called coalescence: When two identical photons enter a beam splitter, both will always exit in the same direction. So when a detector is placed on either possible beam path from the splitter, indistinguishable photons will register as a click on only one detector. If both detectors register a hit, it indicates that the photons were not indistinguishable. The researchers examined the results from excitations at 755 nm.

"What the data say is that if the photons come early in the cycle, they're more distinguishable," Solomon says, "And if they arrive later in the cycle, they are more likely to be indistinguishable." The likely reason is that, after a longer time interval, more of the carrier pairs have decayed, leaving the quantum dot in isolation.

The results follow more than a decade of work by Solomon and colleagues on indistinguishable photons – an essential component of quantum optics and quantum computation schemes that depend on sources of identical consecutive photons. In 2002, he and colleagues at Stanford showed that quantum dots could serve as a source of photons sufficiently indistinguishable to enable important quantum-optical experiments.

A few years later, Solomon, Polyakov and co-workers including Alan Migdall, leader of PML's Quantum Optics Group, demonstrated that it was possible to generate indistinguishable photons from two separate quantum dot about 47% of the time. In 2011 the same researchers, with colleagues elsewhere, reported a means of generating indistinguishable photons from two very different sources: a quantum dot and parametric down-conversion in a nonlinear crystal.

The latest experiments, which have never been performed before in any context, may provide a means of evaluating other single quantum emitters besides quantum dots. "It should apply generally to optically excited emitters," Solomon says. "And in cases where people are using electrical excitation instead of optical excitation for single emitters, we think the outcomes should be similar."

The team expects to expand the research, investigating which excitation wavelengths can produce the cleanest signals. They also want to see what happens when the temperature of the sample is raised. "The temperature in these experiments is around 4 K," Solomon says. "We'd like to raise it toward room temperature, where these effects would presumably be much more important. Relaxation out of these reservoir states would be much slower, and those thermal effects should make the system worse."

More information: prl.aps.org/pdf/PRL/v109/i16/e163601

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