Controlling quantum bits

Can excitons be used to achieve scalable control of quantum light? Steffen Michaelis de Vasconcellos explained to *Nature Photonics* that the optoelectrical control of exciton qubits in quantum dots offers great promise.

■ Why use excitons for quantum information processing?

One of the great challenges in the field of quantum information technology is the interface between photons ('flying quantum bits', referred to as qubits), which are used for quantum telecommunications, and a stationary qubit system, which is used for quantum information processing. Excitons — weakly bound electron–hole pairs that form when a photon enters a semiconductor — are a promising candidate as a building block for such an interface. Excitons not only exhibit the required excellent coupling to a light field, but are also a solid-state system, thus providing on-chip integration with classical electronics or other quantum computation hardware through semiconductor technology. Until now, the scalability of such an exciton qubit system was highly questionable, but our new approach of optoelectronic control can solve this issue.

■ What is your qubit?

Our qubit is based on the exciton ground-state transition in a single InGaAs quantum dot; the 'zero' corresponds to the ground state of the empty quantum dot, whereas the 'one' corresponds to the occupancy of a single exciton in the quantum dot. One of the most interesting features of the exciton qubit is its excellent coupling to photons. The exciton can be generated by, and also converted back into, a photon. The photon's properties are conserved in this process, thus allowing the exciton to be considered as stored or stationary light. By manipulating the exciton qubit we can modify the quantum state of the incoming photon and re-emit it afterwards. This coherent optoelectronic functionality may be very interesting for interfaces between quantum communication channels and quantum computation hardware.

■ How are exciton qubits controlled?

Until now, exciton qubits have been manipulated using all-optical approaches with tailored optical pulses from ultrafast lasers. The laser must be carefully tuned to control its energy, intensity, timing and phase. Unfortunately, each qubit requires its own control laser beam, thus rendering

Steffen Michaelis de Vasconcellos and his colleagues have realized optoelectronic control of the quantum phase of light using excitons in quantum dots.

this approach impractical for the individual manipulation of many qubits.

Our hope was to develop a scalable technique by selectively controlling more than one qubit with a single laser. Our approach does not rely on full control of the laser; instead we use it as a clock signal with fixed intensity, delay and phase. In our experiment we temporally detuned the qubit by applying an radiofrequency electric field across the quantum dot, which caused an energy shift due to the Stark effect. On the optics side, we used a Michelson interferometer to create two picosecond pulses with a fixed delay time and optical phase between them. The first pulse created a coherent superposition between the 'zero' and 'one' of the qubit with a defined quantum phase, which was subsequently manipulated by the electric signal during the delay time. The second pulse probed the quantum phase of the qubit by converting the quantum phase into a measurable occupancy, which we then read-out quantitatively using photocurrent spectroscopy. By varying the electric signal we were able to clearly see the expected quantum phase gate operation.

■ What are the main challenges of your technique?

The really challenging part of the experiment is applying the electric signal

synchronously with the laser pulses. We used the thirtieth harmonic of the laser repetition frequency and controlled radiofrequency phase shifting to achieve strictly synchronous electric and optical signals. A future challenge is temperature; our experiment was performed at liquid helium temperature (4.2 K) because higher temperatures cause the exciton coherence time to decrease rapidly. There are currently only a few ways of lifting this restriction for the material system used in our experiments.

One important point is that our experimental method is not limited to quantum dot excitons, and can in principle be applied to any two-level optically accessible system that exhibits the Stark effect. For example, rare-earth ions in crystals or nitrogen–vacancy centres in diamond are promising candidates that might offer similar quantum control at higher temperatures.

■ What are your future directions of research?

We hope to apply this concept to other promising qubit systems, and would also like to improve and extend the experiment itself. By using shorter electric pulses, possibly below 50 ps, we can obtain greater control and smaller delays between the laser pulses — we have so far been working 'on the edge' of the coherence time (lifetime) of the exciton. We would also like to demonstrate one of the most promising advantages of this approach — the scalability — by achieving simultaneous, independent electrical control of multiple qubits. Future challenges might then be the electrical control of the coupling between qubits and the creation of entangled states between them. Once this is achieved, the application of such systems to quantum repeaters for long-distance quantum telecommunications may not be too far away.

INTERVIEW BY DAVID PILE

Steffen Michaelis de Vasconcellos and his colleagues have a Letter on the coherent control of a single exciton qubit by optoelectronic manipulation on page 545 of this issue.