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A qubit-photon controlled-NOT gate using a quantum dot strongly coupled to a cavity

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Abstract: By using a quantum dot (QD) strongly coupled to a photonic crystal nanocavity, we demonstrate a picosecond timescale controlled-NOT logic gate between a QD and a photon, which is a fundamental building block for complex quantum logic. Coherent control of the QD qubit state by optical pulses results in a modification of cavity reflectivity, enabling a conditional bit-flip on the polarization state of a photon incident on the cavity.

1. Introduction

The ability to interface light with solid-state qubits is essential for future development of scalable and compact quantum information systems that operate on ultra-fast timescales. Photons act as ideal carriers of quantum information and can serve as an efficient quantum link between matter qubits to create large scale quantum networks (*1*). These networks can enable long distance quantum communications (*2*) as well as universal quantum computers (*3*).

2. Experiment

Our system implements a controlled NOT (CNOT) logic gate between a solid-state and photonic qubit on picosecond timescales by exploiting strong light-matter interactions with an optical cavity. The solid-state qubit is composed of a single InAs QD coupled to a photonic crystal cavity. We utilize the two bright exciton states, denoted $|+\rangle$ and $|-\rangle$ (Fig. 1A), representing the two anti-aligned spin configurations of the electron and hole, to both store quantum information in the QD and create a strong optical interface. Proper selection of the magnetic field (Faraday configuration) tunes the σ_+ transition on resonance with the cavity while the σ_- transition is highly detuned (*4*, *5*). In this configuration states $|g\rangle$ and $|-\rangle$ are the qubit states of the QD, while the σ_+ transition is used to couple the qubit to a photon.

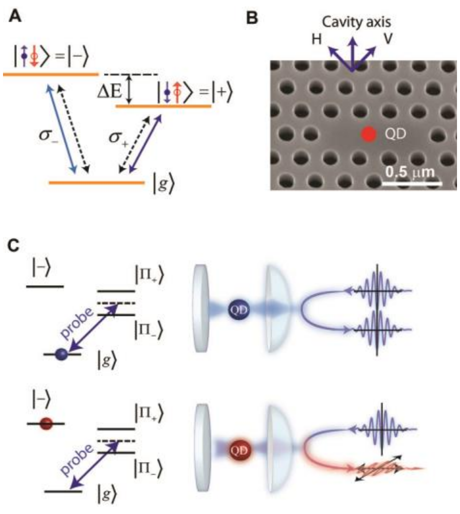

Figure 1. Implementation of a QD-photon CNOT operation. (A) Energy level structure of a neutral QD coupled to an optical cavity under a magnetic field. (B) SEM image of the fabricated device and the cavity axis relative to the photon polarization. (C) Illustration of CNOT operation.

The photonic qubit is encoded using the polarization states $|H\rangle$ and $|V\rangle$, which are rotated 45 degrees relative to the polarization axis of the cavity (Fig. 1B). If the QD is in state $|g\rangle$ it can strongly interact with the cavity by absorbing a cavity photon. In this case, the photon polarization is unchanged after reflection from the cavity (Fig. 1C top panel). If the QD is in the $|-\rangle$ state then it is decoupled from the cavity, and the photon polarization is flipped (Fig. 1C bottom panel). Thus, the state of the QD determines whether the photonic qubit will experience a bit flip, which implements a complete CNOT operation.

To demonstrate the CNOT operation, we utilized pump-probe excitation with a 10 ps pump pulse resonant with the σ_- transition and a 75 ps probe pulse resonant with the σ_+ transition. Fig. 2A plots the measured probe intensity in the *H* direction when the incident probe photon is polarized in the *V* direction as a function of the square root of the average pump power *P*. The blue circles indicate measured data when the probe is set to arrive after the pump by an 80 ps delay. The red curve indicates measured data when the pump-probe

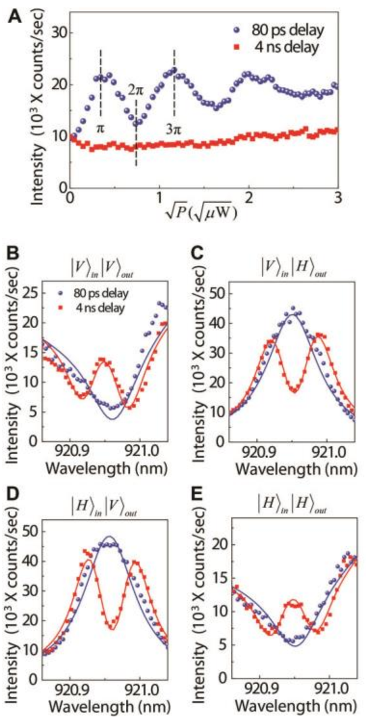

Figure 2. Demonstration of controlled bit flip by pulsed pump-probe excitation. (A) Blue circles (red curve) plot the change in the probe signal at 80 ps (4 ns) pump-probe delay time. (B)-(E) CNOT operation for all four combinations of input-output polarizations. Cavity spectra are measured with a π pump pulse.

delay is increased to 4 ns, which is much longer than lifetime of the $|-\rangle$ state. As the pump power is increased, a clear oscillatory behavior is observed for 80 ps pump-probe delay. This sinusoidal behavior is caused by Rabi oscillation of the QD between the ground state and the $|-\rangle$ state. The π pulse condition is achieved at an average pump power of 0.12 µW. In contrast, no oscillation is observed when the pump-probe delay is set to 4 ns because the QD has had sufficient time to decay to the ground state after it has been excited.

The CNOT operation was tested for the four possible combinations of input and output photon polarization either $|V\rangle$ or $|H\rangle$. Figures 2B-E show the cavity spectrum measured by tuning the probe beam frequency over the cavity resonance while pumping the σ_- transition of the QD with a π pump pulse. Comparison of panels B and C with panels D and E shows that when the probe is resonant with the σ_+ transition frequency and the QD is in state $|-\rangle$ (80 ps delay), a bare cavity spectrum is observed and the polarization of the probe is rotated. In contrast, when the QD is in state $|g\rangle$ (4 ns delay) a coupled cavity-QD spectrum is observed where the photon polarization is largely preserved after reflection.

3. Conclusion

In conclusion, we have shown that strong coupling between a cavity and a single QD can enable a CNOT operation on the polarization state of an incident photonic qubit. The method demonstrated in this work can be extended to solid-state qubits that utilize electron and hole spin of a charged QD (*6*-*8*). Such qubits exhibit significantly longer coherence time, opening up the possibility for engineering long-lived qubit-photon entanglement and future implementation of QD based quantum networks.

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