Fast optical control of a coherent hole spin in a microcavity

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Spin-photon interfaces are a key ingredient for quantum technologies, enabling quantum information to be mapped between stationary spins and photons travelling at the speed of light. Spin-photon interfaces are also promising as a deterministic source of entangled photonic graph-states [1], which serve as resource states for measurement-based quantum computation and one-way quantum repeaters. The ideal spin-photon interface combines both a highly coherent spin and coherent, efficient photon emission. Self-assembled semiconductor quantum dots (QDs) are demonstrated excellent on-demand sources of indistinguishable single-photons. Gated devices allow deterministic charging of the QDs, and impressive progress has been achieved in mitigating the impact of magnetic noise from the host nuclear spins on electron-spin decoherence [2]. Although the ingredients for a leading spin-photon interface (high-fidelity spin control, long coherence times, high-efficiency photon extraction) have been demonstrated in individual quantum dot experiments, combining all these components at a state-of-the-art level is an important outstanding challenge.

Here, we demonstrate a system that combines the best of all worlds: we achieve fast and high-fidelity coherent control of an InGaAs QD hole-spin with coherence metrics significantly exceeding the state-of-the-art for this system ($T_2^* = 530$ ns, $T_2 = 40\ \mu$s), all on a QD embedded in a tunable open microcavity with an exceptionally high end-to-end single photon source efficiency. Many spin rotations can be carried out and many photons can be created before the spin loses its coherence; the photons are extracted with high efficiency. We use a microwave-modulated control scheme [3], making coherent rotations around an arbitrary Bloch sphere axis trivial and allowing all-optical cooling of the host nuclei to extend the hole spin coherence. We achieve a maximum π-pulse fidelity of 98.7%, and ultra-high Rabi frequencies above 1 GHz. Upon cooling the nuclear spin ensemble, we observe the injection of collective nuclear spin excitations (nuclear magnons [4]) activated by the hole spin. Our work demonstrates the potential for semiconductor QDs as fast, efficient, and coherent spin-photon interfaces.

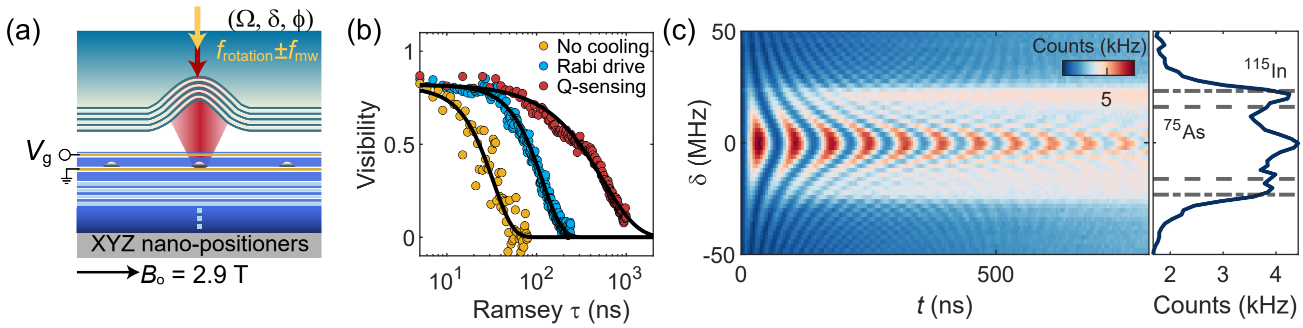

Figure 1: **(a)** Tunable open microcavity, consisting of a gated InGaAs quantum dot sample integrated with a highly reflective bottom mirror and a free-standing top mirror allowing flexible tunability of the cavity length and position. **(b)** Ramsey interferometry to measure the hole spin coherence for no nuclear bath cooling (yellow circles, $T_2^* = 30 \pm 3$ ns), Rabi drive-based nuclear cooling (blue circles, $T_2^* = 110 \pm 10$ ns) and quantum sensing-based cooling (red circles, $T_2^* = 530 \pm 20$ ns). **(c)** High-quality Rabi chevron after nuclear bath cooling; the sidebands are due to the injection of collective excitations into the nuclear ensemble (nuclear magnons).

References

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