Optical transparency induced by a largely Purcell-enhanced quantum dot in a polarization-degenerate cavity

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The optical and spin properties of quantum dots position them as promising candidates for photonic quantum information processing and as building blocks of quantum networks. To utilize quantum dots for such applications requires efficiently interfacing them with arbitrarily polarized light in photonic cavity structures. However, coupling quantum dots to cavities with sufficient cooperativity for quantum information processing while providing an efficient optical access to the dots from free-space optics remains challenging. Here, we efficiently couple InAs/GaAs quantum dots in a charge tunable device (a p-i-n-i-n diode) to a promising photonic structure, the nearly polarization-degenerate bullseye cavity, which improves the optical interface with the dots by over an order of magnitude. By leveraging the low charge noise associated with the diode, we observe spontaneous emission lifetimes of quantum dots as short as 80 ps (a Purcell enhancement of ≈15). These emission rates are four times faster than the rates previously observed on InAs quantum dots utilizing bullseye cavities with nearly degenerate polarization modes, and are close to the state-of-the-art emission rates observed on dots in microcavities. In addition to Purcell enhancement, the interaction between the bullseye cavity and the quantum dot with a cooperativity as high as 8 leads to a ≈80% dipole-induced transparency of light reflected from the cavity, which can be used for photon switching in quantum networks. Finally, due to the nearly degenerate polarization modes of the bullseye cavity, we can optically pump the spin of an electrically charged quantum dot coupled to it. Coherently controlling the quantum dot spin while leveraging the improved optical interface offered by the bullseye cavity could upgrade the potential of such dots for quantum information processing.

In recent years, optically-active quantum dots have emerged as useful resources for photonic quantum technologies. Quantum dots emit single photons with high brightness and indistinguishability, which makes them promising as sources of single and entangled photons for photonic quantum computing. In addition, these dots can be electrically charged with a single electron or a single hole, thereby offering a ground state spin qubit. Strongly coupling a quantum dot spin to a photonic cavity could provide an interface between a single photon and a single spin for quantum information processing, thereby contributing to the ongoing efforts of establishing quantum networks. Such strong coupling requires a sufficiently high cooperativity between the spin and the cavity, which typically involves the use of high-Q (> 10,000) cavities. However, high-Q cavities often feature poor optical access to external light from the free space due to their divergent far field emission patterns. This poor access limits the ability to optically excite and collect photons emitted from quantum dots, as well as to coherently control the quantum dot spin, which requires circularly polarized light.

To efficiently interface quantum dots with light often involves their coupling to low-Q (< 1000) cavities such as gratings and micropillars. Low-Q cavities can increase the optical density of states in the environment of a quantum dot, thereby Purcell-enhancing the rate of spontaneous emission of single photons from the dot. In addition, cavities that provide Gaussian far field emission patterns can improve the efficiency of exciting and collecting photons from the quantum dot via confocal optical setups. For example, circular gratings formed by the periodical etching of rings from a substrate material (“bullseye” cavities), have been used to optically interface single defects in diamond and quantum dots. Further improving the optical access to such low-Q cavities can be achieved by introducing ellipticity to the structure that breaks the degeneracy of the cavity polarization modes. However, this broken degeneracy reduces the potential of elliptical structures toward applications that require the coherent control of the quantum dot spin, which require the excitation of the spin circularly polarized light. Another downside of low-Q cavities is their high loss of photons, which may result in low spin-cavity cooperativities that significantly limit the performance of the cavities as spin-photon interfaces for quantum networking. To date, a low-Q cavity that provides a high cooperativity spin-photon interface
Here, we efficiently couple InAs/GaAs quantum dots embedded in a charge tunable device (a p-i-n-i-n diode) to bullseye cavities with nearly degenerate polarization modes. By leveraging the low charge noise associated with the device, we measure spontaneous emission lifetimes of quantum dots as short as \( \approx 80 \) ps (a Purcell enhancement of \( \approx 15 \)), which are four times shorter than previously observed optical lifetimes of InAs/GaAs quantum dots in nearly degenerate bullseye cavities, and are close to the state-of-the-art lifetimes of dots in microcavities [3, 4, 7, 8]. By measuring a dip in the reflected light from a bullseye cavity caused by its coupling to an uncharged quantum dot, we extract a cooperativity of \( \approx 8 \) between the cavity and the dot, which highlights the potential of the bullseye cavities as spin-photon interfaces. Finally, the nearly degenerate polarization modes of the bullseye cavities allow us to optically excite and measure the Raman signal emitted from electrically charged quantum dots. Combined with the enhanced efficiencies of optically exciting the quantum dot spin and collecting the emitted photons, the fabricated bullseye cavities offer a promising platform for quantum information processing utilizing electrically charged quantum dots.

We perform measurements on InAs quantum dots embedded in GaAs, deterministically charged by applying a DC bias voltage on a low charge noise p-i-n-i-n diode [Fig. 1(a)] [24, 34]. Under the application of an external magnetic field of \( B = 9 \) T perpendicular to the sample growth axis (Voigt geometry), we observe Zeeman splitting of a single optical transition of the dots into two and four transitions for uncharged and electrically charged quantum dots, respectively [13, 35]. Our measurements of the emission lifetimes of quantum dots via these optical transitions exhibit decays on timescales of 1.1-1.3 ns, consistent with previous observations on such dots [32].

To improve the optical interface of the quantum dots, we fabricate bullseye cavities by etching rings from the semiconductor membrane consisting of the p-i-n-i-n diode and a sacrificial AlGaAs-Si layer [white areas in Fig. 1(a)]. Figure 1 (b) shows the SEM image of a typical fabricated structure, where the dark areas represent the etched material and the vertical and horizontal tapered lines represent "bridges" that prevent the structure from collapsing [31]. A finite-difference-time-domain simulation of the far field emission pattern of the cavity results in a Gaussian pattern with waist smaller than the numerical aperture (0.68) of collecting photons via the objective lens of our confocal optical setup. Such matching between the far field emission pattern and the numerical aperture highlights the potential of the cavity in efficiently exciting and collecting photons from quantum dots coupled to it. In addition, the simulated far field emission pattern is polarization independent. This polarization independence positions bullseye cavities promising for the coherent control of the spin of electrically charged quantum dots coupled to the cavity, which typically requires pulses of circularly polarized light [14, 18, 19].

To study the impact of the bullseye cavities on the optical properties of quantum dots, we locate a cavity coupled to two separate uncharged dots [Fig. 2 (a)]. By applying above-band laser light (an \( \approx 860 \) nm non-resonant excitation), we generate charge carriers in the wetting layer of the sample that induce spontaneous photon emission from the cavity [solid blue line in Fig. 2 (a)]. The measured quality factor of \( \approx 1070 \) of the cavity agrees with our theoretical predictions from finite-difference-time-domain simulations. After the observation of photon emission from the cavity, we tune the voltage of the p-i-n-i-n diode to the bias plateau where two quantum dots are neutral and the environmental charge noise is minimal. We identify the spontaneous emission of photons from the dots [dashed red lines in Fig. 2 (a)] by reducing the power of the above-band laser to eliminate the photoluminescence from the cavity. Sweeping the external magnetic field from \( B = 0 \) to \( B = 9 \) T [35] verifies that these dots are two separate
and uncharged dots, with one dot (labeled ”BE, Dot 1”) on spectral resonance with the central frequency of the cavity, and the other (labeled ”BE, Dot 2”) slightly detuned from this frequency.

FIG. 2. (Color online) (a) Photoluminescence spectra of a bullseye cavity (solid blue line) and two uncharged quantum dots coupled to the cavity (dashed red line). (b) Time-resolved measurements of the optical lifetimes of quantum dots in bulk (dotted green line), as well as of two quantum dots coupled to a bullseye cavity labeled in (a) as ”Dot 1” (solid blue line) and ”Dot 2” (dashed red line).

Figure 2 (b) compares the spontaneous emission lifetimes of the two dots in the bullseye cavity to a similar representative measurement on a quantum dot in the bulk. In the presence of the cavity, the emission lifetime shortens from ≈ 1.2 ns [dotted green line in Fig. 2 (b)] for bulk dots down to ≈ 160 ps (a Purcell enhancement of ≈ 7.5) for the dot spectrally detuned from the cavity, and down to ≈ 80 ps (a Purcell enhancement of ≈ 15) for the dot resonant with the cavity. The latter lifetime is close to the state-of-the-art lifetimes measured on InAs/GaAs quantum dots embedded in microcavities [3, 4, 7, 8], and is shorter by a factor of ≈ four than those previously measured on InAs quantum dots in bullseye cavities with nearly degenerate polarization modes [25, 32]. We attribute this improvement over previous work to two main factors. First, our fabrication of bullseye structures involves the etching of a sacrificial layer below the cavity [round cornered white rectangle in Fig. 1 (a)], whereas the rings of the bullseye structures in previous fabrications [25, 32] were not etched all the way down to this layer. While such partial etching improves the collection efficiency of photons scattered from the sample, it reduces the quality factor of the bullseye cavity [25], thereby providing a smaller Purcell enhancement compared to the ones observed by us after etching the sacrificial layer. The second factor that contributes to the enhanced optical emission rate is the deterministic charging capabilities provided by the p-i-n-i-n diode, which result in a reduction of the charge noise in the cavity’s environment [24, 34]. This low charge noise reduces the effects of spectral wandering of the cavity that may degrade the Purcell enhancement of the emission of the quantum dots coupled to it.

To study the potential of bullseye cavities as spin-photon interfaces, we measure the reflectivity of light from a cavity coupled to an uncharged quantum dot in the absence of external magnetic field. We sweep the frequency of a weak (≈ 0.5 nW) continuous-wave laser and measure the intensity of the signal reflected from the cavity [blue dots in Fig. 3 (a)]. A dip in the cavity reflectivity with a contrast of ≈ 80% emerges at the wavelength of the optical transition of the quantum dot, representing the interference of the incident light induced by the quantum dot dipole [36]. We also observe an asymmetric reflectivity pattern, namely a Fano resonance [37–39], possibly related to a small splitting between the cavity polarization modes or to an additional interference effect resulting from the Fabry-Perot cavity that constitutes the membrane of our sample [35]. The measured reflectivity agrees with simulation results based on a theoretical Jaynes-Cummings model [24, 35, 40] [red line in Fig. 3 (a)] considering coupling strength of g = 35 GHz between the quantum dot and the cavity and photon losses from the cavity and the dot of κ = 310 GHz and γ = 1 GHz, respectively [35]. The relatively high cooperativity between the dot and the cavity extracted from the model, C = \( \frac{2g^2}{\kappa \gamma} \approx 8 \), suggests that bullseye cavity can be used for photon switching and for interfacing single photons with single spins [20, 23].

We can estimate the efficiency of coupling photons to quantum dots in such interfaces by plotting the intensity of light reflected at the cavity dip as a function of the incident laser power [Fig. 3 (b)]. Fitting the experimentally measured trend of the dip reflectivity versus power to the theoretically simulated one reveals that light from the free space accesses the quantum dot in the cavity with a modest efficiency of ≈ 8% [35, 40]. The main factor limiting this efficiency is the mismatch between the numerical aperture of the objective lens in our confocal setup (0.68) and the angle of the cavity.
FIG. 3. (Color online) (a) The intensity of laser light reflected from a bullseye cavity coupled to an uncharged quantum dot ($B = 0$) as a function of the spectral detuning of the laser from the optical transition of the dot. The blue dots represent experimental results and the dashed red line represents simulation results considering a Jaynes-Cummings model. The quantum dot optical transition induces transparency of the cavity reflectivity, which can be used for photon switching. (b) The intensity of reflected at the cavity dip coupled to a quantum dot (normalized by the reflectivity of a bare cavity) as a function of the incident laser power. The blue dots represent experimental results and the dashed red line represents simulation results considering an efficiency of 8% of optically accessing the cavity from free space optics.

far field emission mode corresponding to a $1/e$ relative intensity ($\approx 0.36$) [Fig. 1 (c)]. This mismatch leads to a factor $\approx 3.6$ degradation in the efficiency that can be avoided by changing the lenses in our experimental setup. By adding a distributed Bragg reflector to the sample and fabricating bullseye cavities far spectrally detuned from the wetting layer, we expect to optically access quantum dots in next generation bullseye cavities with efficiencies of over 60%. Beyond improving the rates of optical excitation and photon collection, an efficient access of light to the cavity may enable multi-pulse coherent control of quantum dot spins in the cavities [19].

We examine a bullseye cavity coupled such a quantum dot spin, namely a single electron spin qubit confined in a ("charged") quantum dot. Under an external magnetic field of $B = 9$ T, the application of a series of ultrashort above-band laser pulses (i.e., they are much shorter than the optical emission rates of the dot) reveals a $\sim 1$ nm spectral detuning of the optical transitions of the dot from the main resonance of the cavity [as illustrated in Fig. 4 (a)]. Compared to dots in the bulk, the laser power required for the saturation of the photoluminescence signal from the quantum dot in the cavity is an order of magnitude weaker, and the intensity of this signal is $\approx 25$ stronger. As photons emitted via different optical transitions of charged quantum dots have polarizations orthogonal to each other, our observation of photoluminescence from all four transitions indicates the ability to optically access the dot with arbitrarily polarized light. We note, however, that the photoluminescence signals collected from the horizontally polarized transitions are weaker than the ones collected from the vertically polarized transitions. These differences in the intensity arise due to a small spectral splitting of polarization modes of this particular cavity due to fabrication imperfections [35]. Despite such quantitative differences, the ability to access quantum dots with light beams orthogonal to each other is crucial for the realization of pulse sequences for coherently controlling the quantum dots spin for quantum information processing, which typically require circularly polarized light [14, 18, 19].

To further emphasize the potential of controlling the quantum dot spin in the bullseye cavity, we use laser pulses resonant with one of the optical transitions of the dot to optically pump the spin. Varying the free evolution time between these pulses and measuring the emission of Raman signal from the dot results in the saturation behavior depicted in Fig. 4 (b). The sharp peak of the Raman signal emitted under the application of the first pulse indicates the optical initialization of the spin to one of its ground states. After such an initialization of the spin, the application of additional pulses that pump the same optical transition should not induce any Raman signal. Experimentally, however, the pulses induce undesired Raman signals that saturate for the free evolution time of $\approx 30$ ns between the pulses. This saturated Raman signal represents the relaxation of the quantum dot spin, which reduces the spin initialization fidelity. The observed spin relaxation is dominated by two physical mechanism. First, the natural spin relaxation time of quantum dots in our sample is limited to several tens of ns due to the tunneling of the electron confined in the dot. These natural relaxation times can be further extended by orders of magnitude by modifying the tunnel barriers (GaAs layers) of the diode [41, 42]. The second cause for the short spin relaxation time observed here is the spectral proximity
FIG. 4. (Color online) (a) The photoluminescence spectrum of an electrically charged quantum dot coupled to a bullseye cavity, under an ultrafast pulsed above-band excitations with an average optical power of 10 µW. The number of photons collected from the quantum dot is ∼25 times larger than the number of photons collected from dots in the bulk under 100 µW above-band excitations. (b) Raman signals collected from the quantum dot under resonant excitation pulses at varying times. The sharp peaks indicate the optical pumping of the spin, and the increasing heights of these peaks with time indicate the relaxation of the quantum dot spin on a timescale of of ∼30 ns.

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