

## Cavity-enhanced charge-driven feedback loop in single quantum dot photocurrent spectroscopy

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This study investigates a charge-driven feedback loop on single quantum dots (QDs) embedded in micropillar cavities under electrical readout. The coupled quantum-dot-microcavity system demonstrates a significant reduction in hysteresis under temperature sweep when the QD is in resonance with the cavity mode. To describe the experimental results, we develop a feedback model for the photocurrent response which incorporates a quadratic Stark shift to accurately fit the observed asymmetries and hysteresis in the spectra. Supported by this model, we attribute the observed reduction in hysteresis to an interplay between cavity-enhanced effective excitation power and the competition between radiative and nonradiative recombination by cavity quantum electrodynamics effects in the Purcell regime. This work provides important insights that can guide future optimization of QD-based devices for applications in quantum technologies.

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## I. INTRODUCTION

Quantum dots (QDs) have emerged as promising candidates for a wide range of applications in photonics and quantum information technologies due to their discrete energy levels and tuneable optical properties [1]. The integration of QDs into microcavity structures further enhances their potential by enabling light-matter interactions as demonstrated in the regime of cavity quantum electrodynamics (cQED). For instance, cQED describes the coupling of quantum emitters like QDs with optical cavities, leading to significant enhancements in photon emission rates through the Purcell effect in the weak coupling regime or the formation of hybrid light-matter states in the strong coupling regime [2–5]. This light-matter interaction is crucial for the development of efficient single-photon sources and quantum logic gates, as it ensures high fidelity and on-demand photon generation, which are essential for quantum communication and information processing technologies [6,7].

A significant challenge in utilizing QDs for practical applications is the presence of frequency noise and spectral jitter, which can degrade the performance of QD-based devices. These fluctuations are induced by charge and spin noise in the QD environment, leading to an inhomogeneous broadening of the emission linewidth and reducing the coherence and indistinguishability of the emitted photons [8–12]. For example, the tunneling of holes from resonantly excited excitons

out of the QD has been observed to cause an asymmetric line shape and hysteresis in the resonance fluorescence signal in electrically controlled QD devices [13]. Interestingly, this study has also highlighted the potential of using a built-in feedback loop to dynamically stabilize the emission frequency and reduce spectral jitter, thereby improving the coherence and stability of the emitted photons. Moreover, Al-Ashouri *et al.* demonstrated a significantly suppressed photon noise by nearly 50% in a micropillar structure [14].

In this context, photocurrent (PC) spectroscopy of single QDs embedded in microcavity structures offers a powerful tool for probing these interactions. Unlike conventional photoluminescence measurements, PC spectroscopy allows for direct electrical readout of the QD states, providing unique insights into the underlying charge dynamics and their interplay with optical properties. This technique enables the study of complex phenomena such as the cQED-controlled anticorrelation between radiative recombination and nonradiative tunnel escape in the Purcell regime [15,16] or the accurate characterization of the  $g$  tensor in neutral and charged excitons [17]. However, frequency jitter in the electrical readout (PC signal) of QDs can degrade the performance of quantum information technologies [18]. Implementing dynamic stabilization techniques, such as built-in feedback loops, can help to overcome such issues as it enhances the electrical readout of single-QD states, improving the accuracy and reliability of charge-state detection and qubit readout.

In this study, we perform single-QD photocurrent studies in electrically contacted QD micropillar cavities operating in the weak coupling regime of cQED. We focus on nonlinearities in the photocurrent response under resonant excitation of the target QD and explore the bistable behavior observed in bias-dependent measurements. Our studies reveal a charge-driven feedback loop in the PC signal of single QDs as described by Merkel *et al.* [13] in the photoluminescence signal. Building upon work by Merkel *et al.* [13], we extend the previously

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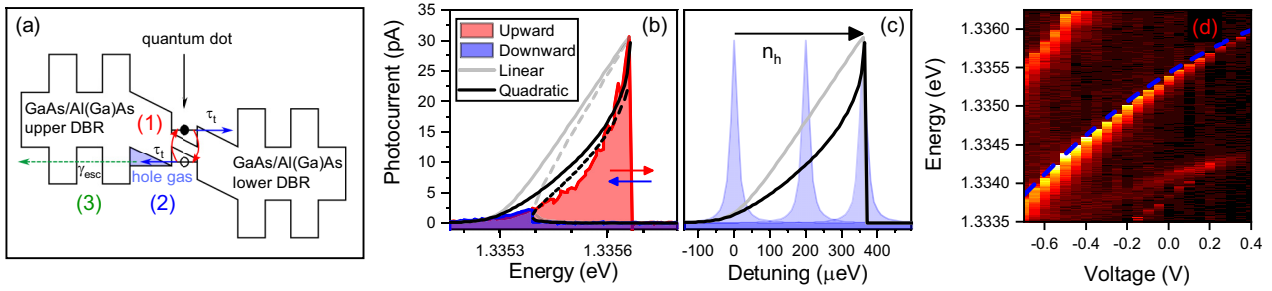


FIG. 1. (a) Schematic band structure of the QD-micropillar device under study depicting the creation of the hole gas at the interface of the upper DBR. (b) PC spectrum of a single QD for a laser scan in upward (red) and downward (blue) directions. Gray (black) lines represent the stationary solutions of the rate equation with a linear (quadratic) Stark shift. The dashed lines are the unstable solutions. (c) Schematic illustration of the Lorentzian absorption lines at three different hole-gas concentrations  $n_h$ . The gray (black) line represents the PC signal for a scan in upward direction with a linear (quadratic) Stark shift, as the resonance is dragged by the electric field of the hole gas. (d) Bias-PC spectra of the QD for laser scans in upward direction. The blue dashed line represents a quadratic fit of the peak positions.

used feedback model to include a quadratic Stark shift, resulting in a more accurate representation of the observed line shapes in the PC spectra. We further investigate the excitation-power dependence of the bias-induced hysteresis in these PC spectra and explore how the presence of a cavity mode (CM) influences this behavior. By tuning the QD into spectral resonance with the CM, we observe a significant reduction in hysteresis, which we attribute to the Purcell effect and the cavity's spectral selectivity enhancing the effective excitation power. Our findings provide deep insights into the complex interactions between QDs and microcavities, offering valuable information for the design and optimization of QD-based photonic and quantum devices. The results underscore the potential of utilizing such feedback loops for frequency stabilization in electrical readout, paving the way for enhanced coherence and stability in quantum communication and information processing applications.

## II. EXPERIMENTAL METHODS

The QDs under study were grown in Stranski-Krastanov growth mode and localized in an electrically contacted micropillar structure, allowing electrical readout and improving optical confinement [19,15]. They feature a lower distributed Bragg reflector (DBR) comprising 27  $\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}/\text{GaAs}$  mirror pairs and an upper DBR with 23 mirror pairs. The active region consists of a QD layer made of  $\text{In}_{0.6}\text{Ga}_{0.4}\text{As}$ , centrally located within a  $1\text{-}\lambda$  GaAs cavity at the antinode of the electric field to maximize light-matter interaction. The doping profiles in the DBRs are optimized for minimizing free-carrier absorption while maintaining good electrical conductance, with  $p$ - and  $n$  doping gradually decreasing towards the active region, forming a pin-diode structure. Figure 1(a) gives a schematic illustration of the band structure near the active region. The devices are patterned into micropillar cavities with ring-shaped gold contacts around the upper facets using electron-beam lithography, allowing efficient current injection while preserving optical access along the cavity. A detailed description of the sample is given in the Supplemental Material (SM) [20].

For PC spectroscopy the samples are mounted and bonded onto a chip carrier designed for electrical feedthrough. A

programmable voltage source is utilized to apply constant voltages, and current measurements are carried out using an ultralow-noise current amplifier [22]. This transimpedance amplifier converts the measured current into a measurable voltage, which is adjusted to match the input range of the data acquisition card. For optical excitation, a confocal dark-field microscope setup is used to precisely focus the beam of a tunable diode laser with a typical linewidth below 100 kHz onto a single micropillar cavity. To enter the PC regime and enable efficient tunneling of the photoexcited carriers, the diode is reversely biased. A PC spectrum is obtained by scanning the wavelength monitored laser line through the resonance of the QD. Hereby photons whose wavelengths match the QD resonance are partly absorbed in the active layer, leading to the generation of photocarriers. The sample is maintained in a helium flow cryostat, allowing precise temperature control in the range from 4.5 to 300 K. A low-temperature environment below 40 K is necessary for minimizing thermal noise and enhancing the sensitivity of the measurements. Thanks to the narrow-linewidth diode laser, in combination with the ultralow-noise current amplifier, this setup enabled precise PC spectroscopy in the subpicoampere regime.

The excitation-power values reported in this work represent the total laser power measured in the setup at a beamsplitter before entering the microscope objective. The actual power experienced by the quantum dot is significantly lower due to optical losses in the setup, the large mismatch between the laser focal spot size and the QD absorption area, and additional photon losses from cavity-detuning effects. As these factors make an exact determination of the absorbed power challenging, the reported values should be interpreted as indicative of trends in the power series rather than absolute values.

## III. FEEDBACK LOOP IN PHOTOCURRENT

The presented experiments were performed on a single electrically contacted micropillar with a diameter of  $1.7\text{ }\mu\text{m}$ . The PC spectrum depicted in Fig. 1(b) presents a detailed analysis of the resonance behavior of a single QD under laser excitation. For this measurement, an applied bias of 0 V and an excitation power of 240 nW are utilized. The

spectrum reveals two distinct signals: an upward scan (red), where the laser energy is incrementally increased, and a downward scan (blue), where the energy is decremented. The QD signal notably deviates from the typical expected Lorentzian line shape of a QD transition, instead displaying a broader, strongly asymmetric profile characterized by a gradual increase at lower energies with an abrupt decrease at higher energies. This asymmetry in line shape is accompanied by a pronounced hysteresis effect: the upward scan (red) exhibits a significantly higher amplitude and broader linewidth compared to the downward scan (blue). Such characteristics have been previously reported, but in the resonance fluorescence signal of AlGaAs QD mesas without cQED effects, where the authors presented a charge-driven feedback loop mechanism which generates a hole gas near the QD, detuning the resonance via the Stark effect [13].

The band-structure diagram in Fig. 1(a) illustrates three important processes for this feedback loop mechanism. First, electron-hole pairs are generated in the QD as the excitation laser comes into resonance (1). These excitons can be field ionized by tunneling processes (2), where the electrons due to the smaller effective mass escape to the back contact while the holes become trapped at the GaAs–Al(Ga)As interface, forming a hole gas. This hole gas slowly dissipates by tunneling through the Al(Ga)As barrier (3). The accumulation of positive charge in the hole gas gradually detunes the QD resonance through the quantum confined Stark effect, as demonstrated in Fig. 1(c) for an upward scan. As the scanning laser comes in resonance with the exciton, the number of stored holes increases, which again blueshifts the QD resonance. This reduces the overlap with the laser, thereby decreasing the pumping efficiency and subsequently the number of holes in the gas. Such negative feedback results in dragging the PC resonance in the direction of the laser scan, thereby effectively broadening the resonance signal. As the leakage and pump rate of the hole-gas balance, the scanning laser coincides with the maximum of the exciton line. Now, a slight decrease in the number of holes will redshift the resonance, further reducing pumping efficiency until the resonance almost completely shifts out, resulting in positive feedback with a sharp drop in fluorescence. Interestingly, Al-Ashouri *et al.* utilized this built-in feedback loop in order to stabilize the QD resonance by taking advantage of the negative feedback on the low-energy side of the resonance, where the frequency shift induced by the hole gas is negatively proportional to a change of the excitonic resonance [14].

Initially, we tried to model the PC response of our microcavity system using a rate-equation approach with a simple linear Stark shift. However, the experimental data, especially the asymmetric line shape observed in Fig. 1(b), were not accurately captured by this. As the resulting line shape is connected to the internal resonance shift by the Stark effect, we incorporated a quadratic Stark shift into the model, to achieve a better fit. The gray and black lines represent the stationary solutions of the rate equation model for a linear and quadratic Stark shift. The quadratic response to an electric field is a common observation for the quantum confined Stark effect in *p-i-n* diode structures [23–25] and is also confirmed by our bias-dependent measurements, as shown in Fig. 1(d). The simulation with a quadratic Stark shift provides a

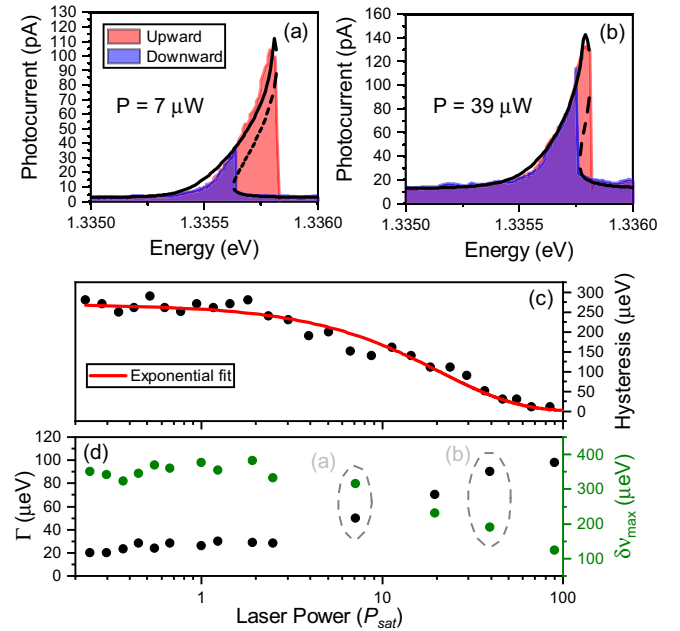


FIG. 2. (a), (b) PC spectrum of a single QD at an excitation power of 7 and 39  $\mu\text{W}$ . The red (blue) solid line depicts the signal for a scan in upward (downward) direction. The solution of the rate equation is presented by the black solid line, with the dashed lines representing unstable solutions. (c) Hysteresis as the difference between the energy of the peak PC signal in upward and downward directions as function of the excitation power. The red solid line corresponds to the fit with an exponential decay. (d) Linewidth and maximum detuning as a function of excitation power extracted from the solutions of the rate equation. Excitation powers are normalized to the saturation power  $P_{\text{sat}} = 1.01 \mu\text{W}$ , derived as detailed in the SM [20].

significantly improved agreement between experiment and theory, capturing the signal increase on the low-energy side in the upward- and downward-scan directions. The bias-dependent measurements indicate a quadratic Stark shift, further justifying the use of this model. However, we observe that the parameters from the bias-dependent measurement deviate from the parameters in the simulation, suggesting that while the model effectively captures the general trends, it may not fully account for complex effects within the QD. For more details on the rate-equation model and the adjustment with a quadratic Stark shift we refer to the SM [20]. In common with the linear Stark shift approach the stationary solutions of the rate-equation model give three solutions in the fold-over region [between 1.335 40 and 1.335 66 eV in Fig. 1(b)] of which only two are stable, corresponding to the observed PC signal in upward- and downward-scan directions. The manual fit of the rate-equation solution provides access to the linewidth and resonance of the QD and the maximum detuning by the internal hole gas. For the quadratic solution shown in Fig. 1(b), the linewidth  $\Gamma$  is 20  $\mu\text{eV}$ , the original resonance  $v_0$  is 1.335 31 eV, and the maximum detuning  $\delta v_{\text{max}}$  is 350  $\mu\text{eV}$ . A visual schematic of the undisturbed QD signal and its detuning by the internal hole gas is given in Fig. 1(c).

The analysis of an excitation-power-dependent PC study of the same QD is presented in Fig. 2. The PC spectra at

excitation powers of 7 and 39  $\mu\text{W}$ , shown in Fig. 2(a) and Fig. 2(b), respectively, reveal significant changes with increasing power. As the PC signals for upward and downward scans reveal a strong hysteresis at 7  $\mu\text{W}$ , a clear decline of this effect is visible for 39  $\mu\text{W}$ . However, in this case the differences in amplitude and linewidth between the upward and downward scans become less pronounced. In Fig. 2(c) we plot the hysteresis (peak PC energy difference between the upward and downward scan directions) as a function of increasing excitation power in units of the saturation power,  $P_{\text{sat}}$ . The saturation power for this QD, derived from fits shown in the SM [20], is 1.01  $\mu\text{W}$ . The data show a clear decline in hysteresis with increasing power which can be well approximated by an exponential decay (fit in red), although the physical mechanism behind this behavior is not yet fully understood.

The black lines in Fig. 2(a) and Fig. 2(b) represent the solutions of the rate-equation model, with the dashed lines indicating unstable solutions analogous to those in Fig. 1(b). By the manual fit of these solutions to the data, we again extract the linewidth  $\Gamma$  and the maximum detuning  $\delta\nu_{\text{max}}$  presented in Fig. 2(d). The linewidth initially broadens with power before stabilizing, which is indicative of power broadening typically observed in a two-level system [26]. Additionally, the maximum detuning decreases with increasing power, suggesting a reduction in the number of trapped holes in the hole gas. According to the suggested model the maximum detuning is given by the maximum number of holes  $n_{\text{hmax}}$  trapped in the hole gas:

$$\delta\nu_{\text{max}} = -\delta\nu_1 n_{\text{hmax}} + \delta\nu_2 n_{\text{hmax}}^2, \text{ with} \quad (1)$$

$$n_{\text{hmax}} = P_{\text{ionize}} \frac{\gamma_{\text{abs}}}{\gamma_{\text{esc}}}. \quad (2)$$

The proportionality factors  $\delta\nu_{1/2}$  define the shift of the resonance by the internal hole gas, and the relation between them mainly influences the curvature in the signal rise on the low-energy side of such a QD spectra. In Eq. (2),  $\gamma_{\text{abs}}$  is the photon absorption rate,  $P_{\text{ionize}}$ , the ionization probability of a generated electron-hole pair, and  $\gamma_{\text{esc}}$  the escape rate of carriers out of the hole gas. The observed behavior suggests a power dependence in at least one of these parameters. The photon absorption rate is naturally linked to the excitation power until saturation is reached, but the increasing excitation should enhance  $n_{\text{hmax}}$  and lead to an increase of  $\delta\nu_{\text{max}}$ . The observed decline is prominent at saturation and suggests a decline in the ionization probability or an enhanced escape rate. However, a distinction cannot be given without independent measurements. Nevertheless, an excitation power beyond  $P_{\text{sat}}$  reduces the influence of the charge-driven feedback loop, thereby reducing the hysteresis.

The excitation-power-dependent PC measurements allow further insights into the underlying charge dynamics. For a generated exciton state the electron tunnels out of the QD preferentially due to its small effective mass, leaving a single hole behind. As a result, the power-dependent linewidth gives the typical electron tunneling time and the power-dependent peak PC amplitude the hole tunneling time [26–28]. Accordingly, the PC response of a single QD under resonant excitation can be described with a simple two-level system

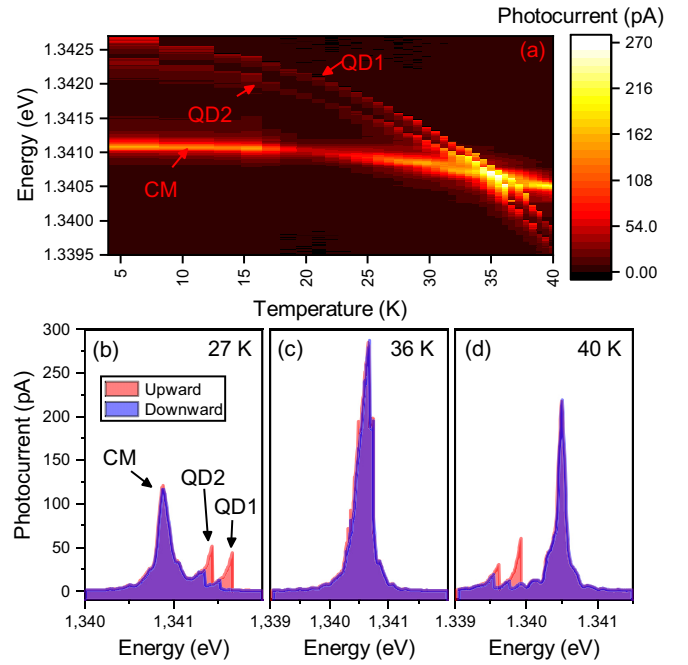


FIG. 3. (a) Temperature-dependent PC scan of the electrically contacted QD micropillar in upward direction at an excitation power of 700 nW. The two QDs are tuned into resonance with the CM around 36 K. PC scan in upward (red) and downward (blue) direction of QD1 and QD2 blueshifted (b) at 27 K, in resonance (c) at 36 K, and redshifted (d) at 40 K to the CM.

rate-equation approach [29] as

$$I(P) = \frac{e}{2\tau_h} \frac{\alpha P}{\alpha P + \left(\frac{1}{\tau_h} + \frac{1}{\tau_r}\right)}, \quad (3)$$

with the electron charge  $e$ , the hole tunneling time  $\tau_h$ , the radiative emission time  $\tau_r$ , the excitation power  $P$ , and a proportionality factor  $\alpha$  accounting for stimulated emission processes. A plot of the peak PC amplitude and linewidth as a function of laser excitation intensity with the relevant fits is given in the SM [20]. We determine a hole tunneling time of  $(582 \pm 21)$  ps and electron tunneling time of  $(13.4 \pm 1.5)$  ps with a linewidth at zero excitation power  $\Gamma_0$  of  $(25 \pm 3)$   $\mu\text{eV}$ . Typical tunneling times on similar devices are in the range between 300 ps and 1 ns for the slower hole tunneling and in the range of several picoseconds for the faster electron tunneling times [15,26,28], with a strong dependency on the externally applied bias voltage and the built-in voltage of the device [30].

#### IV. CAVITY EFFECTS

A central aspect of our work in which we go significantly beyond previous studies published, for instance in Ref. [13], is to examine the PC feedback loop response in the regime of cQED. For this purpose, we tune the QD resonance into the cavity mode (CM) by varying the temperature. Figure 3(a) shows temperature-dependent PC spectra for a scan in the upward-scan direction of the laser photon's energy at an excitation power of 700 nW. The measurement is performed on the same pillar examined in the previous section but on two

other QDs with energies close to the CM. At 27 K [Fig. 3(b)], the PC spectrum reveals two distinct QD signals (QD1 and QD2) that are blueshifted relative to the fundamental HE<sub>11</sub> mode. Both QDs experience the previously discussed effects of hysteresis and asymmetry, with the upward scan (red) displaying broader peaks and higher amplitudes compared to the downward scan (blue). The CM is most prominent in the spectrum with a symmetric Lorentzian shape and shows no signs of hysteresis. The observation of the photonic CM in a PC measurement is in the first place unexpected, but was reported in previous measurements on micropillar structures [15]. This observation can be attributed to two primary effects. First, QDs located near the cavity resonance may contribute to the cavity mode even if they are not directly visible in the photocurrent spectrum [16]. Second, nonresonant inverse cavity feeding mediated by phonons can couple off-resonant QDs to the cavity mode, allowing for indirect detection of the cavity resonance [31,32]. As the temperature is further increased to 36 K [Fig. 3(c)], the QDs are tuned into resonance with the CM. This tuning results in a significant increase in PC intensity, which is usually observed in photoluminescence experiments, where the Purcell effect enhances radiative emission for a QD state in resonance with the CM. In contrast, in a PC measurement, the enhanced radiative recombination is expected to reduce the photocurrent because of a competing relationship between tunnel and recombination rates. This mechanism was observed and described in single-QD PC experiments when exciting the micropillar from the side [15]. In the present case, the observed increase of PC in top excitation is attributed to the efficient coupling of the excitation laser in resonance with the CM, which overcompensates the Purcell-induced decrease of PC. Thus, tuning the QD into the cavity resonance results in both increasing the effective excitation power of the QD and decreasing the ionization probability due to the enhanced radiative emission. Consequently, we observe a reduction of hysteresis in resonance and a revival of hysteresis if the QDs are redshifted relative to the CM [Fig. 3(d)].

For a more quantitative evaluation of both effects on the hysteresis, we expand the model presented in Eq. (3) with a spectral detuning dependence of the radiative lifetime to account for cQED effects. In the weak coupling regime relevant for our system,  $\tau_r$  is reduced on resonance ( $\Delta = 0$ ) due to the Purcell effect:

$$\tau_r(\Delta) = \frac{\tau_{\text{bulk}}}{F_P \frac{\gamma_c^2}{4\Delta^2 + \gamma_c^2}} = \tau_{\text{eff}} \frac{4\Delta^2 + \gamma_c^2}{\gamma_c^2}. \quad (4)$$

The Purcell factor  $F_P$  and the spontaneous emission lifetime of the QD in the bulk material  $\tau_{\text{bulk}}$  are unknown to us and for simplicity are expressed in the single parameter  $\tau_{\text{eff}} = \tau_{\text{bulk}}/F_P$ . The linewidth of the CM  $\gamma_c$  is related to the  $Q$  factor, and  $F_P$  is proportional to the quotient of  $Q$  and the mode volume of the micropillar. From a Lorentzian fit to the CM, we determine a linewidth of  $(82.4 \pm 1.4) \mu\text{eV}$  with a  $Q$  factor of  $16260 \pm 276$ . We can further expand Eq. (3) by a detuning-dependent power term,

$$P(\Delta) = P_{\text{max}} \frac{\gamma_c^2}{4\Delta^2 + \gamma_c^2}, \quad (5)$$

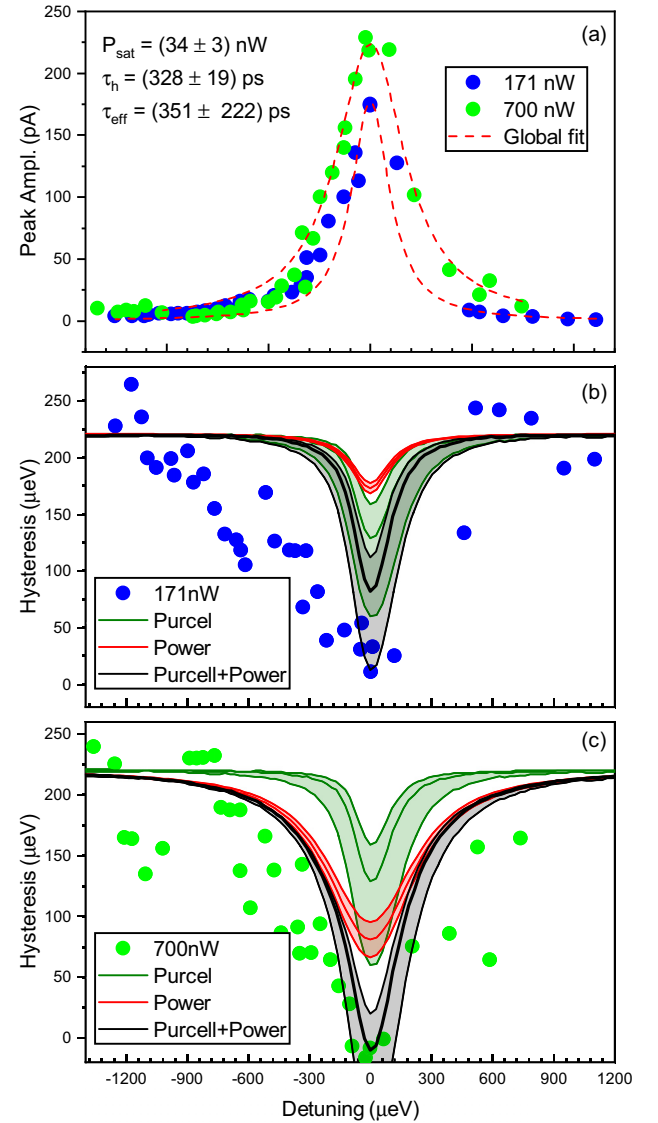


FIG. 4. (a) Peak PC amplitude over detuning for QD1 at 171 nW (blue) and 700 nW (green). The global fit of the datasets is shown by the dashed red line. The hysteresis for an excitation power of 171 nW (b) and 700 nW (c) over detuning from the cavity mode. The fitting parameters from (a) serve as basis for a simulation of the Purcell (green) and excitation power (red) impact on the hysteresis as discussed in the text. The sum of both effects is shown as black solid line. The respective errors are displayed as shaded error bands.

to model the transmission of the excitation-laser photons into the Lorentzian-shaped CM. Inserting Eq. (4) and Eq. (5) into the PC model from Eq. (3) gives the detuning-dependent PC signal. Figure 4(a) shows the peak PC amplitude of QD1 over the detuning from the CM, extracted from the temperature-dependent PC scans in upward direction for an excitation power of 171 nW (blue) and 700 nW (green). A global fit with the discussed model gives a hole tunneling time  $\tau_h = (328 \pm 19) \text{ ps}$ , a  $\tau_{\text{eff}} = (351 \pm 222) \text{ ps}$ , and a saturation power  $P_{\text{sat}} = 1/(\alpha\tau_h) = (34 \pm 3) \text{ nW}$ . If we assume a spontaneous emission time  $\tau_{\text{bulk}} = 1 \text{ ns}$ , the corresponding Purcell factor yields  $F_P = 2.85 \pm 1.80$ . The uncertainty in  $\tau_{\text{eff}}$  and the

related Purcell factor  $F_P$  are quite high. This may hint at insufficiencies in the fitting model. Especially, the influence of temperature variation, which is utilized to detune the QD but not represented in the model, might cause deviations via phonon-induced dephasing.

In the next step we use the derived parameters to determine the detuning-dependent influences of increasing excitation power, due to the spectral filter of the CM, and a decreasing ionization probability by the Purcell effect on the hysteresis. To estimate the excitation-power-dependent PC hysteresis, we use the results presented in the previous section to model the power dependency of the hysteresis for QD1 with the saturation behavior from Fig. 2(c). The impact of the Purcell enhancement is modeled by multiplying a detuning-dependent factor to the ionization probability in Eq. (1) and Eq. (2) by

$$P_{\text{ionize}}(\Delta) \propto \frac{1/\tau_h}{1/\tau_h + 1/\tau_r(\Delta)} \quad (6)$$

which reflects the competitive relation between radiative recombination and tunneling events. By implementing the detuning-dependent ionization probability into our rate-equation approach, we can simulate the hysteresis for a Purcell-enhanced radiative emission. More details on this simulation and a plot of the rate-equation model with the relevant data are given in the SM [20]. In Fig. 4 we plot the hysteresis measured at 171 nW [Fig. 4(b)] and 700 nW [Fig. 4(c)] over the detuning from the CM. Additionally, we plot the hysteresis induced by an excitation-power increase due to the spectral selectivity of the CM (red) and by the Purcell effect (green), estimated from the fitting parameters in Fig. 4(a). We see a nearly reversed Lorentzian trend of the measurement data demonstrating a close connection between hysteresis and cavity detuning. For both excitation powers the hysteresis nearly vanishes at zero detuning. Interestingly neither the power-induced decrease in hysteresis nor the Purcell-induced reduction explains this behavior alone, indicating that it is caused by a combination of both effects. Considering both effects (black line with gray error range), a reduction of the hysteresis to zero for an excitation power of 700 nW [Fig. 4(c)] and close to the observed reduction at 171 nW [Fig. 4(b)] is achieved. Nevertheless, a perfect agreement between measurement and simulation is not given. This may indicate an even stronger Purcell enhancement than observed from the fitting in Fig. 4(a). But also, a stronger power-induced hysteresis decline is a possibility, as our simulation is based on the measurements from a different QD. A clarification for the contribution of the Purcell effect could be achieved under sideexcitation, where the intensity at the QD would be constant irrespective of the detuning from the cavity.

## V. CONCLUSION

In this work, we presented single-QD PC studies in the cQED regime. Performing comprehensive bias-, temperature-, and excitation-power-dependent PC investigations of an electrically contacted QD-micropillar system we unveiled distinct features such as asymmetric PC line shapes and bistable behavior with hysteresis under resonant laser scans. The experimental observations are in very good agreement with a model that accounts for the charge-driven feedback

loop in single-QD PC spectroscopy driven by a quadratic Stark shift. In fact, the applied model allowed for an accurate representation of the line-shape asymmetry and hysteresis observed in the PC spectra, particularly capturing the gradual rise at lower energies and the sharp drop at higher energies. While the quadratic Stark shift model provides a significantly better fit than a simple linear approach, some deviations in the parameters suggest that additional effects, such as electrostatic shielding within the QD, may still need to be accounted for in future refinements of the model.

Furthermore, operating in the weak coupling regime of cQED we demonstrated that tuning the QD into resonance with the CM leads to a significant reduction in hysteresis, driven by a combination of the Purcell effect and an excitation-power-dependent reduction of the PC hysteresis. Here, due to light-matter interaction of the single QD with the coupled cavity mode, the Purcell effect enhances radiative recombination, which competes with nonradiative tunneling processes, leading to a pronounced reduction in hysteresis. The excitation-power induced decrease of the hysteresis is most prominent for excitation-power levels beyond the QD's saturation and contributes to the overall reduction of the PC hysteresis. The physical mechanism behind the power-induced decrease is unclear, but it likely relates to saturation effects in the ionization probability, the photon absorption rate, and the escape rate of trapped charge carriers.

Noteworthy, our sample is well suited for the built-in feedback stabilization described by Al-Ashouri *et al.* [14]. The smaller micropillar diameter (1.7 vs 15  $\mu\text{m}$  used in Ref. [14]) enhances lateral mode confinement, generating stronger local electric fields and requiring fewer holes to stabilize the QD's resonance frequency. This effect can potentially result in faster feedback dynamics and more efficient photon-noise suppression. Also, the Purcell effect narrows the QD linewidth in PC, a crucial parameter for performance of charge stabilization as identified by Al-Ashouri *et al.* [14]. Overall, our findings provide valuable insights into the interplay between QD charge dynamics and cavity effects, with important implications for the optimization of QD-based devices in quantum information technology and nanophotonics. Future work should aim at refining the model further, accounting for complex internal effects, and to better quantify the combined influence of excitation power and cavity interactions on device performance.

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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## DATA AVAILABILITY

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