

High-efficiency microwave photodetection by cavity-coupled double quantum dots with single-cavity-photon sensitivity

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We present a superconducting cavity-coupled double quantum dot (DQD) photodiode that achieves a maximum photon-to-electron conversion efficiency of 25% in the microwave domain. With a higher-quality-factor cavity and improved device design to prevent photon leakages through unwanted pathways, our device measures microwave signals down to the 100-aW power level and achieves sensitivity to probe microwave signals with one photon at a time in the cavity. We analyze the photodiode operation using the Jaynes-Cummings input-output theory, identifying the key improvements of stronger cavity-DQD coupling needed to achieve near-unity photodetection efficiency. The results presented in this work represent a crucial advancement toward near-unity microwave photodetection efficiency with single-cavity-photon sensitivity.

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I. INTRODUCTION

The investigation of microwave photons interacting with solid-state quantum systems plays a central role in advancing quantum information processing, quantum communication, and precision measurements for quantum computing [1–4]. In this domain, an intriguing approach involves integrating a superconducting cavity with semiconductor quantum dots (QDs) [5–7]. The QDs, characterized by their discrete energy levels, offer a unique platform for exploring fundamental quantum optics effects while simultaneously allowing electron transport and realizing key elements for quantum technology [8–10]. Here, a double quantum dot (DQD) system is particularly important because of its gate-voltage-controlled tunnel-coupled energy levels [5,6]. Extensive research has been performed to investigate the interaction of microwave photons with

DQDs [11–16]. This includes studies of photon-assisted electron tunneling for applications related to microwave photodetection [16–18] and photon emission during electron tunneling demonstrating on-chip maser operation [13,19]. While superconducting circuits have been used to demonstrate near-unity photodetection efficiency in the microwave domain [20–22], such advancements with semiconductor QDs are encouraging, especially due to their gate-voltage-controlled discrete energy levels that offer energy selectivity for the incident photons and integration into existing semiconductor technology [23,24]. Another promising approach for photodetection involves superconducting hot-electron nanobolometers, which provide higher bandwidth and do not require spectral tuning, unlike semiconductor QD-based systems [25]. However, these bolometer detectors typically operate in the infrared and terahertz regimes, where photon energies are more than an order of magnitude higher than for 4–8-GHz-frequency microwave photons. Therefore, the remarkable advancements made in these fields are not yet directly relevant to the present study focusing on low-frequency gigahertz photons.

Recent experiments by Khan *et al.* [17] demonstrated a cavity-coupled semiconductor DQD as a microwave photodetector with 6% photoconversion efficiency. As

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compared to the results presented in Ref. [17], in this work and in Refs. [26,27], we have (i) improved the internal losses of the resonator by changing the resonator material from Al to Nb, (ii) minimized photon leakages by adding large capacitive filters on the dc lines, and (iii) lowered the coupling losses using one-port resonator geometry instead of the two-port geometry. While Ref. [26] focused on studying the energetics of microwave absorption during photon-assisted electron tunneling and Ref. [27] the energy conversion efficiency, here we investigate the improvements to the photodetection efficiency thanks to these aspects.

We demonstrate a superconductor-semiconductor hybrid device achieving a maximum photodetection efficiency of 25% operating down to the 100-aW input power level. We note that for studies of photon statistics and quantum sensing, it is crucial that the detector (i) achieves near-unity efficiency and (ii) can be operated with one (or fewer) photons in the cavity [28,29]. Our work advances these goals by showing photodiode operation with a single cavity photon. We analyze the device operation using the Jaynes-Cummings input-output theory and suggest future improvements to achieve near-unity photodetection efficiency by increasing the cavity-DQD coupling strength, potentially by introducing a high-impedance resonator [30,31]. We also investigate the dynamics of microwave-photon-assisted electronic transport in an asymmetrically tunnel-coupled DQD photodiode and characterize the performance parameters of our device.

II. DEVICE AND EXPERIMENTAL DETAILS

Our hybrid device consists of a semiconductor nanowire DQD dipole-coupled to a superconducting coplanar waveguide (CPW) cavity, Fig. 1(a) [17,26,27]. We use a polytype InAs nanowire with zinc blende and wurtzite crystal structures grown using metal-organic vapor phase epitaxy [32]. The electrons are confined within zinc blende islands due to a conduction band offset of approximately 120 meV between the two crystal phases [33,34]. The nanowire, typically 100 nm in diameter, consists of 100-nm-long zinc blende sections forming the dots and 20-nm-long wurtzite barriers. The plunger gate voltages V_L and V_R tune the energy levels ε_L and ε_R and change the carrier occupancies N and M of the left and right dots, respectively. The one-port half-wavelength ($\lambda/2$) CPW cavity, made of a 100-nm-thick sputtered Nb film, Fig. 1(b), directly connects to the drain (D) lead of the DQD. The DQD is located at the voltage antinode of the cavity mode, as depicted in Fig. 1(a). The other end of the cavity connects to a microwave input port via a 400- μm -long finger capacitor, Fig. 1(c). The cavity has a characteristic resonance at $\omega_r/2\pi = 6.716$ GHz. The measurements are performed in a dilution refrigerator at an electronic temperature of $T_e \approx 60$ mK. The same device has been used previously in Refs. [26,27].

In cavity-coupled QD devices, undesired photon leakages through the dc gate lines often lead to a low quality factor of the cavity [17,35,36]. A plausible approach to mitigate such effects is to introduce on-chip low-pass

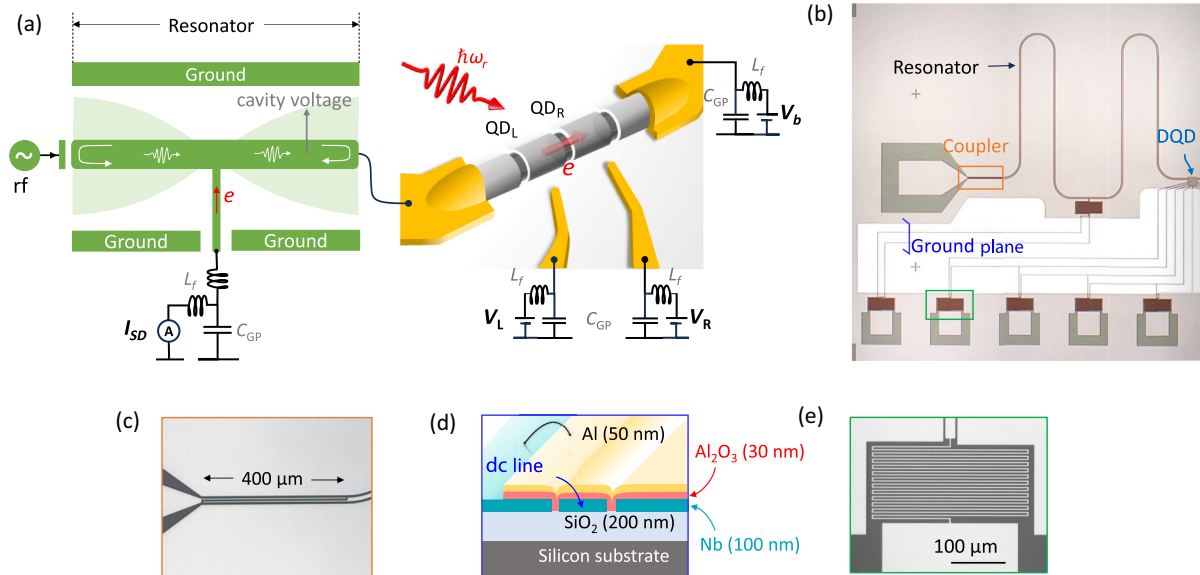


FIG. 1. (a) Schematic illustration of the hybrid device, comprising a semiconductor nanowire double quantum dot (DQD) coupled to a coplanar waveguide cavity. The photocurrent of the device is measured by utilizing the cavity voltage node at the midpoint of the cavity. (b) Optical microscope image of the chip showing the one-port cavity and indicating the input port, ground plane on the dc lines, and location of the DQD. (c) Input coupler of the cavity. (d) Schematic cross-sectional view showing the layered structure of the ground plane capacitor on the dc lines and (e) an inductive filter integrated into a dc line.

capacitive and inductive filtering [37–39]. In our device, we address this by depositing a 30-nm-thick Al_2O_3 layer followed by a 50-nm-thick Al layer on the dc lines. See the bright-shaded area that appears in Fig. 1(b) and the schematic cross-sectional view in Fig. 1(d). The Al layer is then wire-bonded to the ground plane of the device. With this design, the capacitance of a dc line to the ground increases to $C_{\text{GP}} \approx 600$ pF. Thus, the impedance of the dc line, for a high-frequency signal, reduces to $Z_{\text{line}} \approx 40$ m Ω , which is more than 3 orders of magnitude smaller than the cavity impedance $Z_r \approx 58$ Ω . Under this condition, only $2Z_{\text{line}}/(Z_r + Z_{\text{line}}) \lesssim 0.1\%$ of the microwave power may transmit into a single dc line. Additionally, we have integrated on-chip inductive (L_f) filters, Fig. 1(e). These modifications allow us to obtain a maximum internal quality factor of $Q_{\text{int}} = \omega_r/\kappa_{\text{int}} = 9200$ for a similar device with the DQD tuned to a very small tunnel coupling regime. Here, ω_r is the cavity resonance frequency and κ_{int} denotes the internal losses of the cavity. However, for our current device, we have $Q_{\text{int}} = 5150$ with the DQD tuned to a Coulomb-blockade regime.

III. RESULTS

To characterize the transport properties of the DQD, we begin by measuring the charge stability diagram around $(N, M) \leftrightarrow (N + 1, M + 1)$ charge occupations with a bias voltage of $V_b = 1$ mV, Fig. 2(a). The applied bias enables electron tunneling across the DQD, forming finite bias triangles (FBTs) at the triple points [34,40,41]. The black arrow in Fig. 2(a) indicates the detuning (δ) axis. The level detuning, $\delta = \varepsilon_R - \varepsilon_L$, tunable by the gate voltages, determines the energy gap $E_q = (\delta_r^2 + 4t^2)^{1/2}$ of the hybridized DQD levels $|g\rangle$ and $|e\rangle$ [35], where t denotes the tunnel coupling between the dot levels. Here, $|g\rangle$ and $|e\rangle$ denote the hybridized ground and excited states of the DQD, respectively. The FBTs exhibit distinct features of charge tunneling via the excited states of the QDs, as indicated by blue arrows in Fig. 2(a). We also observe cotunneling lines appearing along one edge of the hexagonal stability pattern [12,34].

Next, we measure the rf reflectance (R) with $\omega = \omega_r$ across the plunger gate space within the dashed square outlined in Fig. 2(a). The measured result with input power $P_{\text{in}} = 1$ fW is shown in Fig. 2(b). We observe two distinct absorption lines in the interdot charge-transfer region with $R \approx 0$. As shown in previous studies [17,18,35], photon-assisted tunneling of an electron is energetically permissible when the DQD energy gap E_q matches the photon energy $\hbar\omega_r$. Therefore, the DQD at $\delta = \pm\delta_r$ introduces an additional loss channel to the cavity photon mode, resulting in the observation of two absorption lines in Fig. 2(b). Further, to realize the cavity-DQD interactions, in Fig. 2(c), we present the measured reflectance R as a function of drive frequency $\omega/2\pi$ across the charge-transfer

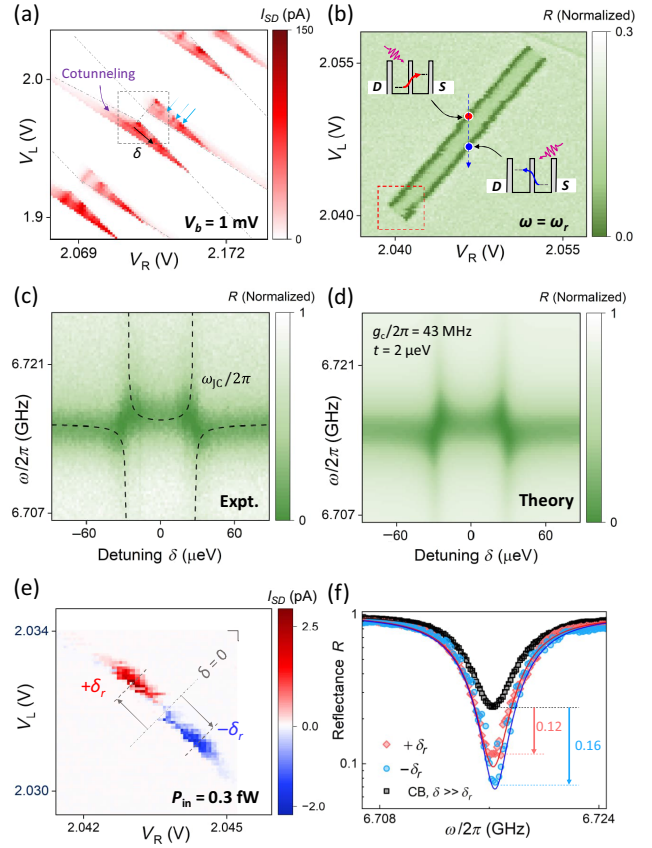


FIG. 2. (a) Charge stability diagram of the double quantum dot (DQD) showing finite bias triangles at charge triple points with $V_b = 1$ mV and without an rf drive. (b) Measured rf reflectance R with $\omega = \omega_r$ as a function of plunger gate voltages V_L and V_R with $V_b = 0$ and $P_{\text{in}} = 1$ fW. Two distinct lines appear due to the DQD absorption at $\pm\delta_r$. (c) The measured rf spectra across the interdot charge-transfer line and (d) rf spectra theoretically fitted using the Jaynes-Cummings model. The dashed lines in panel (c) show the lowest two transition energies of the Jaynes-Cummings Hamiltonian, Eq. (2). (e) Photocurrent measurement across the plunger gate space with $P_{\text{in}} = 0.3$ fW and drive frequency 6.716 GHz. (f) Measured reflectance as a function of drive frequency with the DQD tuned to photodetection points at $\pm\delta_r$ at the charge triple points with finite photocurrent and the Coulomb blockade (CB) regime $\delta \gg \delta_r$ when $I_{SD} = 0$, showing insights into cavity photon dissipation due to DQD absorption.

line along the blue-dashed arrow in Fig. 2(b). The corresponding theoretical result is shown in Fig. 2(d), which we discuss in Sec. IV.

We now turn to measure the photocurrent I_{SD} as a function of V_L and V_R with input power $P_{\text{in}} = 0.3$ fW and bias $V_b = 0$. Figure 2(e) shows the measured result. We observe two distinct resonant features of positive (I_{SD}^+) and negative (I_{SD}^-) photocurrent at $+\delta_r$ and $-\delta_r$, respectively. We also observe a factor of 1.5 higher photocurrent at the positive detuning than at the other operation point. Such effects can be attributed to the asymmetric tunnel

rates at the left (Γ_L) and right (Γ_R) QD-lead barriers of the DQD [27]. To probe the corresponding cavity photon dissipation due to the DQD absorption (κ_{DQD}), we record the reflectance spectra when operating the device at $\pm\delta_r$ with photocurrent $I_{SD} \neq 0$ and in the Coulomb blockade regime with $\delta \gg \delta_r$ and $I_{SD} = 0$. Figure 2(f) shows the measured results. The measured $R(\omega = \omega_r)$ changes by $\Delta R^+ = -0.12$ ($\Delta R^- = -0.16$) when operating the device at $+\delta_r$ ($-\delta_r$). Note that the observed $I_{SD}^+ > I_{SD}^-$ in Fig. 2(e) would suggest a larger absorption at $+\delta_r$. However, contrary to this expectation, Fig. 2(f) shows an opposite behavior: a lower photon dissipation at $+\delta_r$ than at $-\delta_r$. This indicates the role of competing processes contributing to the photodiode operation, which we discuss in detail below.

Next, we tune the DQD level detuning to $\pm\delta_r$ at the charge triple point and measure I_{SD} as a function of P_{in} , Fig. 3(a). The corresponding photodetection efficiency, $\eta_{\text{PD}} = I_{SD}\hbar\omega_r/eP_{\text{in}}$, at the two operation points is shown in Fig. 3(b). Note that the electron tunnel rate shown on the right-hand side in Fig. 3(a) demonstrates that the photon-to-electron conversion takes place at megahertz-level rates. The I_{SD} in the low-drive limit, $P_{\text{in}} < 1$ fW, increases linearly with P_{in} . In this linear response regime, we obtain the photon-to-electron conversion efficiency, $\eta_{\text{PD}}^- = 15\% \pm 2\%$ at $-\delta_r$. At $+\delta_r$, the photoconversion efficiency becomes $\eta_{\text{PD}}^+ = 25\% \pm 2\%$, which surpasses recent results for the similar cavity-coupled DQD device of Ref. [17] fourfold and outperforms the results of Ref. [27] by a factor of 2. Another crucial advancement here is the ability to operate the device with an input power of 100 aW, which is at least an order of magnitude lower than the power levels at which previous devices were operated [17,27,42]. We note that at $P_{\text{in}} = 100$ aW, the number of photons stored in the cavity reaches $n_c = 2C_rQ_L^2Z_rP_{\text{in}}/Q_{\text{ex}}\hbar\omega_r = 1.35$ [26], where $Q_L = 1300$ ($Q_{\text{ex}} = 1720$) is the loaded (external) quality factor and $C_r = 540$ fF is the total capacitance of the cavity. The cavity photon numbers n_c for different input powers are also shown in Fig. 3. Increasing the input power $P_{\text{in}} > 30$ fW decreases the photoresponse, Figs. 3(a) and 3(b). In this regime, multiple-photon absorption processes typically contribute to photon-assisted tunneling, where the cavity-photon field modulates the interdot tunneling rate [43,44]. Investigation of such multiphoton processes is beyond the scope of our present discussion.

IV. DEVICE PARAMETERS

We now turn to fit the measured results of Fig. 2 using the Jaynes-Cummings input-output theory model [17,18,27,35,45] to obtain the device parameters. We begin by fitting the interaction of the cavity photons and the DQD of Fig. 2(c), which can be described by [30]

$$|R(\omega)| = |\kappa_c A(\omega) - 1|^2, \quad (1)$$

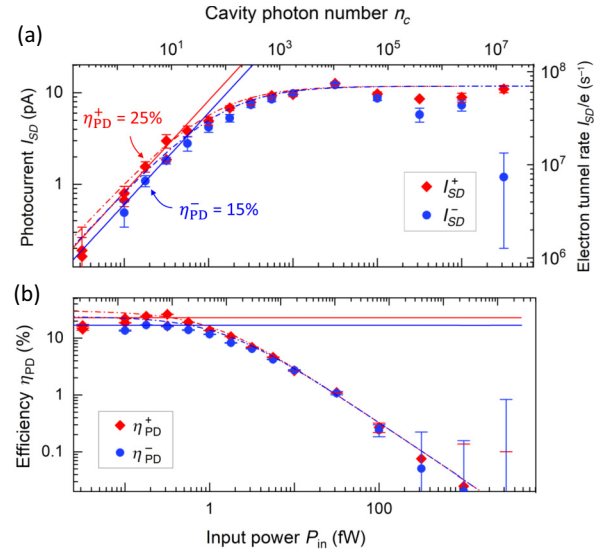


FIG. 3. (a) Photocurrent recorded at $\pm\delta_r$ and (b) corresponding photodetection efficiency as a function of input microwave power P_{in} . The electron tunneling rate I_{SD}/e contributing to the measured signal is also shown on the right-hand side of panel (a). The device achieves a maximum photoconversion efficiency of 25%. The solid (dashed-dotted) lines show the theoretically fitted results in the low-power (high-power) regime.

with

$$A(\omega) = \frac{\tilde{\Gamma}_0/2 - i(\omega - \omega_q)}{[\kappa/2 - i(\omega - \omega_r)][\tilde{\Gamma}_0/2 - i(\omega - \omega_q)] + g_c^2}.$$

Here, $\tilde{\Gamma}_0$ is the decoherence rate of the DQD in the interdot charge-transfer region, g_c is the cavity-DQD coupling constant, $\omega_q = E_q/\hbar$ is the DQD qubit frequency, and $\kappa = \kappa_c + \kappa_{\text{int}}$ denotes the total losses in the cavity. Figure 2(d) shows the theoretically fitted result with tunnel coupling t , cavity-DQD coupling g_c , and decoherence rate $\tilde{\Gamma}_0$ being the fitting parameters. With the fitted values of g_c and δ_r , the dashed lines in Fig. 2(c) show the lowest two transition energies of the Jaynes-Cummings Hamiltonian, which is given by [35,46,47]

$$\omega_{\text{JC}} = \frac{(\omega_q + \omega_r)}{2} \pm \frac{1}{2} \sqrt{(\omega_q - \omega_r)^2 + 4g_c^2}. \quad (2)$$

The above fitting procedure yields $t = 2 \pm 1$ μeV (correspondingly, $\delta_r = 27.5$ μeV) and $g_c/2\pi = 43 \pm 4$ MHz, and $\Gamma_0/2\pi = 2600 \pm 200$ MHz is the decoherence rate when tunneling in and out the DQD is suppressed. In Fig. 2(c), the spectral response of the cavity in the Coulomb blockade regime ($\delta \gg \delta_r$) provides the input-coupling losses $\kappa_c/2\pi = 3.9$ MHz and internal losses of the cavity $\kappa_{\text{int}}/2\pi = 1.3$ MHz [17]. Note that these loss parameters also define the quality factors of the cavity $Q_L = \omega_r/(\kappa_c + \kappa_{\text{int}})$ and $Q_{\text{ex}} = \omega_r/\kappa_c$.

Moving on, the photocurrent $I_{SD}^{\pm}$ in the low-power linear-response regime is given by [17,27,45]

$$I_{SD}/e\dot{N} = \frac{\kappa_c}{\kappa} \frac{4\kappa_{\text{DQD}}\kappa}{(\kappa_{\text{DQD}} + \kappa)^2} \frac{\Gamma_{0e}}{(\Gamma_{0e} + \gamma_-)} p_f, \quad (3)$$

where $\dot{N} = P_{\text{in}}/\hbar\omega_r$ is the input photon flux and $p_f = (\Gamma_{gL}\Gamma_{Re} - \Gamma_{gR}\Gamma_{Le})/\Gamma_{0e}\Gamma_{g0}$ is the directivity of the photocurrent between the source (S) and drain (D) reservoirs. Here the tunnel-in rate from S to the ground state $|g\rangle$ is denoted as $\Gamma_{gL} = \Gamma_L \cos^2(\theta/2)$, and the tunnel-out rate from the excited state $|e\rangle$ to D is $\Gamma_{Re} = 2\Gamma_R \cos^2(\theta/2)$, with $\theta = \cos^{-1}(-\delta_r/\hbar\omega_r)$ being the mixing angle. Similarly, for the other two rates, $\Gamma_{gR} = \Gamma_R \sin^2(\theta/2)$ and $\Gamma_{Le} = 2\Gamma_L \sin^2(\theta/2)$. The factor of 2 appearing for the out-tunneling rates Γ_{Re} and Γ_{Le} accounts for the spin degeneracy of the dot levels [48,49]. Figures 4(a) and 4(b) schematically illustrate the tunnel-in and -out rates for the two operation points. The total tunnel rate into $|g\rangle$ (out of $|e\rangle$) is denoted by $\Gamma_{g0} = \Gamma_{gL} + \Gamma_{gR}$ ($\Gamma_{0e} = \Gamma_{Le} + \Gamma_{Re}$).

In the strong-drive limit, the photocurrent reads [27,45]

$$I_{SD}/e = \frac{16\kappa_c\dot{N}g_c^2(\Gamma_{gL}\Gamma_{Re} - \Gamma_{gR}\Gamma_{Le})}{16\kappa_c\dot{N}g_c^2(\Gamma_{0e} + 2\Gamma_{g0}) + \Gamma_{g0}\tilde{\Gamma}\kappa^2(\Gamma_{0e} + \gamma_-)}. \quad (4)$$

With the values of t , g_c , κ_c , and κ_{int} already obtained using Figs. 2(c) and 2(d), we here fit $I_{SD}^{\pm}$ in the linear (non-linear) response regime of Fig. 3(a) using Eq. (3) [Eq. (4)]. The solid (dash-dotted) lines show the theory results in the low-power (high-power) regime, which yields $\Gamma_L/2\pi = 12$ MHz, $\Gamma_R/2\pi = 1100$ MHz, interdot relaxation rate $\gamma_-/2\pi = 23$ MHz, and dephasing rate $\gamma_\phi/2\pi = 1800$ MHz. We find a large Γ_R when compared to Γ_L and γ_- , which causes the asymmetry in the photodiode operation. We also calculate $\kappa_{\text{DQD}}^+/2\pi = 0.8$ MHz and $\kappa_{\text{DQD}}^-/2\pi = 1$ MHz, where $\kappa_{\text{DQD}} = 4g_c^2/\tilde{\Gamma}$ and $\tilde{\Gamma} = \Gamma_{0e} + \gamma_- + 4\gamma_\phi$.

With the above-calculated κ_{DQD}^+ and κ_{DQD}^- values, the solid red and blue lines in Fig. 2(f) show the theoretically predicted rf reflectance curves at $\pm\delta_r$, which are given by [17]

$$R(\omega) = \frac{(\kappa_{\text{int}} + \kappa_{\text{DQD}} - \kappa_c)^2 + 4(\omega - \omega_r)^2}{(\kappa_{\text{int}} + \kappa_{\text{DQD}} + \kappa_c)^2 + 4(\omega - \omega_r)^2}. \quad (5)$$

The theoretical results in Fig. 2(f) are in excellent agreement with experimental data and correctly reproduce the asymmetry of the cavity photon dissipation at the two operation points.

We note that the dephasing rate γ_ϕ , calculated at a charge triple point using Figs. 3(a) and 2(f), is about a factor of 3 higher than that obtained across an interdot transition using Figs. 2(c) and 2(d). This increase in γ_ϕ at the charge triple point may be attributed to the activation

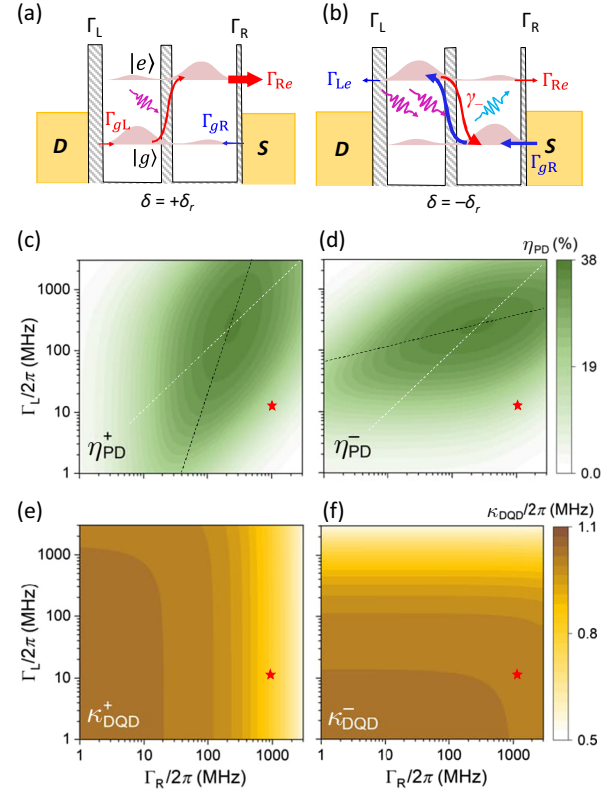


FIG. 4. (a),(b) Schematic diagrams showing the tunneling-in and -out rates for the two operation points, highlighting the asymmetry in device operation. Theoretical predictions of quantum efficiency at the low-power limit of Eq. (3) under varying tunnel couplings Γ_L and Γ_R , showing the potential for optimizing photoconversion efficiency at (c) $+\delta_r$ and (d) $-\delta_r$. (e),(f) The corresponding cavity photon dissipation due to double quantum dot (DQD) absorption. The star marks in (c)–(f) show the operation point of the present experiment. The white dashed lines in panels (c),(d) show the efficiency of a symmetrically tunnel-coupled DQD photodiode.

of two-level fluctuators nearby or within the DQD when current flows between the source and drain leads of the DQD.

V. DEVICE FOR NEAR-UNITY PHOTODETECTION EFFICIENCY

To gain further insights into the device operation and to identify potential improvements needed for near-unity photodetection efficiency, we now analyze each term of Eq. (3) individually [27]. The first term, κ_c/κ , and directivity p_f remain constant for the two detuning cases. For the present experiment, we have $\kappa_c/\kappa = 0.75$ and $p_f = 0.67$. The second term, $4\kappa_{\text{DQD}}\kappa/(\kappa_{\text{DQD}} + \kappa)^2$, describes how well κ_{DQD} matches the cavity losses κ . Here, the decoherence, $\tilde{\Gamma} = (\Gamma_{Le} + \Gamma_{Re}) + \gamma_- + 4\gamma_\phi$, plays a crucial role in the absorption process in terms of $\kappa_{\text{DQD}} = 4g_c^2/\tilde{\Gamma}$. For the positive detuning case of Fig. 4(a), $\tilde{\Gamma}$ is large because of the

larger Γ_{Re} , which leads to a smaller κ_{DQD}^+ and η_{PD}^+ than for the other operation point, Fig. 4(b). The fractional contribution in η_{PD} arising from this term is estimated to be 0.46 (0.55) at $+\delta_r$ ($-\delta_r$). Moving to the third term of Eq. (3), $\Gamma_{0e}/(\Gamma_{0e} + \gamma_-)$, which describes the competition between the tunneling out ($\Gamma_{0e} = \Gamma_{Le} + \Gamma_{Re}$) and unwanted interdot relaxation of a photoexcited electron. With Γ_R much larger than γ_- , in Fig. 4(a), electrons quickly tunnel out (Γ_{Re}) from $|e\rangle$ to S and thus, the effect of relaxation becomes negligible with $+\delta_r$, whereas, for the other operation point, Fig. 4(b), with $\Gamma_{Le} < \gamma_-$ and Γ_{gR} , a large number of photoexcited electrons relax to the ground state. Thus, the contribution arising from the third term predicts a larger η_{PD} with positive detuning, which in our case is 0.99 (0.61) at $+\delta_r$ ($-\delta_r$).

Thus, the second term showing the mismatch of κ and κ_{DQD} becomes the main reason for observing a photodetection efficiency below the 50% level. Additionally, the comparable κ_{int} and κ_c of the cavity, resulting in $\kappa_c/\kappa = 0.75$, causes another lowering of about 25% in η_{PD} . Therefore, it would be plausible to improve η_{PD} by (i) employing a high-impedance cavity with a strong cavity-DQD coupling enabling $\kappa_{DQD} = 4g_c^2/\Gamma = \kappa$ [30,31,37], (ii) increasing the input coupling (or reducing the internal losses) to achieve $\kappa_c \gg \kappa_{int}$, and (iii) optimizing the tunnel couplings of the DQD to obtain $p_f = 1$, as described below. Notably, our present photodiode closely aligns with criterion (ii), with $\kappa_c = 3\kappa_{int}$ and criterion (iii) with directivity $p_f = 0.67$.

We note that the third term has the biggest difference between the positive and negative detuning contribution and thus defines the asymmetry in photocurrent, with an effect opposing that of the second term. To further study how the asymmetry in the DQD influences $\eta_{PD}^\pm$, we perform theoretical calculations using Eq. (3) with varying tunnel couplings Γ_L and Γ_R while keeping all other parameters constant, Figs. 4(c)–4(f). The star marks in the four panels indicate our present device operation point. The dashed white lines in Figs. 4(c) and 4(d) indicate the symmetric photodiode operation with $\eta_{PD}^+ = \eta_{PD}^-$ and $\kappa_{DQD}^+ = \kappa_{DQD}^-$. The results of Figs. 4(c) and 4(d) indicate that η_{PD} of the present device could be increased by a factor of 1.5 by optimizing the tunnel couplings of the DQD. We note that the maximum photodetection efficiency of the device arises with $\Gamma_L = \Gamma_R \approx 10\gamma_-$. However, when Γ_L and Γ_R are much larger or lower than approximately $10\gamma_-$, the maximum photodetection efficiency can be obtained along an off-diagonal axis, marked with a black dashed line in Figs. 4(c) and 4(d). The slope of this line depends on the relaxation rate and interdot tunnel coupling. In this regime, to achieve a higher η_{PD} by minimizing the competing DQD relaxation process, it is advantageous to increase one of the tunnel rates at the cost of the other.

For the first-generation device presented in Ref. [17], photon dissipation caused by resonator internal losses, an

unnecessary additional port, and photon leakage through the dc gate lines reduced the photodetection efficiency. In this next-generation device, we have added large capacitive filters to the dc lines, minimizing photon leakage through these lines (see Sec. II). Additionally, we replaced the Al resonator used in Ref. [17] with a Nb resonator to reduce losses likely caused by impurities and vortices. With these improvements, we achieve $\kappa_{int}/2\pi = 1.3$ MHz, 4 times lower than the $\kappa_{int}/2\pi = 5.8$ MHz reported in Ref. [17]. Furthermore, we have a one-port over-coupled resonator ($\kappa_c \gg \kappa_{int}$), as compared to the two-port under-coupled resonator used in Ref. [17]. This allows us to improve the η_{PD} by increasing the first term of Eq. (3), κ_c/κ , from 0.28 to 0.75. The second, third, and fourth terms in Eq. (3) depend on the tunnel couplings— Γ_L , Γ_R , and t . We here tune these tunnel couplings to achieve a factor of 1.5 improvement in the third term, describing the competition between the unwanted DQD relaxation γ_- and the wanted tunneling-out rate Γ_{0e} , as compared to the results presented in Ref. [17]. This improvement is obtained at the cost of a slight reduction (from 0.8 to 0.67) in the fourth term that describes the directivity of the DQD.

VI. PERFORMANCE PARAMETERS

The η_{PD} calculated as the ratio of the photoelectron tunnel rate I_{SD}/e to the incident photon flux $P_{in}/\hbar\omega_r$, accounts for cavity photon losses, cavity-DQD coupling, and the efficiency of moving an electron from S to D when a photon is absorbed by the DQD. Thus, η_{PD} corresponds to the external quantum efficiency of the device.

On the other hand, the internal quantum efficiency η_{IQE} can be obtained by the ratio of the photon-assisted tunnel rate I_{SD}/e to the photon absorption rate by the DQD, $R_{abs} = \kappa_{DQD}n_c$. In other words, η_{IQE} describes how successfully an electron is transferred from S to D once a photon is absorbed by the DQD. Therefore, η_{IQE} explains the losses due to the interdot relaxation of electrons and electrons lost due to the less-than-unity directivity of the photodiode, p_f . In the linear response regime, we obtain $\eta_{IQE} = I_{SD}/(e\kappa_{DQD}n_c) = 75\% \pm 8\%$ at $+\delta_r$ and $\eta_{IQE} = 36\% \pm 10\%$ at δ_r . Remarkably, the DQD, as a photon-to-electron conversion engine at $+\delta_r$, achieves an internal quantum efficiency close to unity.

Another key performance parameter is the so-called noise-equivalent power (NEP), which describes the lowest input power needed to achieve a unity signal-to-noise ratio [50]. According to the definition, $NEP = P_{min}/\sqrt{B}$, where B is the bandwidth and $P_{min} = \delta I_{SD}/\mathbb{R}$ is the lowest input power needed for the unity signal-to-noise ratio in the detector [51–53]. Here δI_{SD} is the current noise of the measured signal in the low-power regime with $P_{in} \approx P_{min}$, and $\mathbb{R}$ the responsivity, which we calculate according to $\mathbb{R} = \Delta I_{SD}^+/\Delta P_{in} = e\eta_{PD}/\hbar\omega_r = 9000$ A/W. To estimate

the inherent current noise of our photodetector, we consider shot noise at a diminishing input signal. We observe no leakage current without the applied photon signal in the photodetector operation point within the 40-fA noise level of the current preamplifier. Therefore, the dark current is below $I_{SD} = 40$ fA. The corresponding shot noise is then less than $\delta I_{SD} = \sqrt{2eI_{SD}B}$, leading to an upper-limit estimate of $NEP = 10$ zW/ $\sqrt{\text{Hz}}$. In our measurements, however, the current preamplifier noise of $\delta I_{SD} = 40$ fA with the bandwidth of $B = 5$ Hz dominates over the shot noise. Therefore, in practice, the achieved NEP has a higher value of $NEP = \delta I_{SD}/R\sqrt{B} = 2$ aW/ $\sqrt{\text{Hz}}$. This value is close to the recently reported NEP value of a superconducting microwave detector [21]. As proposed in Ref. [21], reducing the amplifier noise would improve the operation performance and yield a lower NEP value closer to the inherent limitations of the device.

VII. CONCLUSIONS

In conclusion, our present study demonstrates experimental insights into microwave-photon-assisted electron tunneling in an asymmetrically tunnel-coupled DQD photodiode. Using a high-quality-factor cavity, on-chip filtering to prevent photon leakages, and an optimally chosen operation point to obtain near unity directivity, we achieved a photon-to-electron conversion efficiency of 25% with an input power level down to 100 aW. The device attains a maximum responsivity of 9000 A/W and a noise-equivalent power of 2 aW/ $\sqrt{\text{Hz}}$, facilitating efficient photon-to-electron conversion with a single microwave photon in the cavity. Together with a high-speed charge-sensing scheme, our work demonstrating continuous high-efficiency microwave photodetection could potentially be useful in solid-state quantum tomography [54,55], quantum metrology [56], and research in astronomy [57,58] where the detection of weak microwave signals is of critical need.

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DATA AVAILABILITY

The data that support the findings of this article are available from the authors upon reasonable request.

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