

Broadband parametric amplification for multiplexed SiMOS quantum dot signals

Victor Elhomsy^{1,*}, Luca Planat¹, David J. Niegemann¹, Bruna Cardoso-Paz¹, Ali Badreldin¹, Bernhard Klemt¹, Vivien Thiney¹, Renan Lethiecq¹, Eric Eyraud¹, Matthieu C. Dartailh¹, Benoit Bertrand², Heimanu Niebojewski², Christopher Bäuerle¹, Maud Vinet², Tristan Meunier¹, Nicolas Roch¹, and Matias Urdampilleta^{1,†}

¹ *Université Grenoble Alpes, CNRS, Grenoble INP, Institut Néel, 38042 Grenoble, France*

² *Université Grenoble Alpes, CEA, Laboratoire d'électronique des technologies de l'information (Leti), F-38000 Grenoble, France*

 (Received 12 March 2025; revised 13 August 2025; accepted 28 August 2025; published 24 December 2025)

Spins in semiconductor quantum dots hold great promise as building blocks of quantum processors. Trapping them in SiMOS transistorlike devices eases future industrial-scale fabrication. Among the potentially scalable readout solutions, gate-based dispersive radio-frequency reflectometry only requires the already existing transistor gates to read a quantum dot state, which alleviates the need for additional elements. In this effort toward scalability, traveling-wave superconducting parametric amplifiers significantly enhance the readout signal-to-noise ratio (SNR) by reducing the noise below that of typical cryogenic low-noise amplifiers, while offering a broad amplification band, essential to multiplex the readout of multiple resonators. In this work, we demonstrate a 3-GHz gate-based reflectometry readout of electron charge states trapped in quantum dots formed in SiMOS multigate devices, with SNR enhanced due to a Josephson traveling-wave parametric amplifier (JTWPA). The broad tunable 2-GHz amplification bandwidth combined with more than 10-dB ON-OFF SNR improvement of the JTWPA enables frequency and time-division-multiplexed readout of interdot transitions, and noise performance consistent with JTWPA characteristics at higher frequencies. In addition, owing to a design without superconducting loops and with a metallic ground plane, the JTWPA is flux insensitive and shows stable performance up to a magnetic field of 1.1 T at the quantum dot device, compatible with standard SiMOS spin-qubit experiments.

DOI: [10.1103/sj8d-x674](https://doi.org/10.1103/sj8d-x674)

I. INTRODUCTION

Since seminal proposals [1,2], spins trapped in semiconductor quantum dots have attracted a lot of attention given the prospect of their use as bits of information for quantum computation. The SiMOS industrial platform could implement this technology, with the hope of leveraging the well-established microelectronics foundry in order to scale from a few laboratory qubits up to a processor containing billions of them [3,4].

The readout part of a quantum algorithm must meet this scalability criterion. In semiconductor quantum dot spin-qubit experiments, spin-state readout relies on

spin-to-charge conversion techniques, where the charge susceptibility depends on the spin state of the qubit [5,6]. Such techniques can be realized by embedding the device in a radio-frequency (rf) resonator and probing the shift in resonance frequency due to a change in charge susceptibility of the quantum dot [7,8]. A scalable example of such techniques relies on using resonators connected to already-existing metallic gates and measuring a capacitance signal, when a nonzero charge susceptibility arises at a charge transition only if tunneling is allowed [9–22]. This method requires small rf power to avoid populating excited states, averaging out the signal with modulation, and heating. This *in situ* readout relieves the need for nearby reservoirs or additional charge sensors.

In such cryogenic semiconductor experiments, the amplitude of the signal of interest is so small that multiple amplification stages are needed between the output of the device and room-temperature readout electronics. Superconducting parametric amplifiers [23], which can be placed at the coldest stage of a cryostat, offer a typical (10–20)-dB gain and a noise temperature an order

*Contact author: elhomsy.victor@gmail.com

†Contact author: matias.urdampilleta@neel.cnrs.fr

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International](https://creativecommons.org/licenses/by/4.0/) license. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI.

of magnitude lower than typical semiconductor low-noise amplifiers operating at the 4-K stage [24–28]. Various approaches are being developed, either based on arrays of Josephson junctions or superconducting quantum interference devices (SQUIDs) [29–34], high-kinetic-inductance superconductors [35–41], semiconductors [42], hybrid devices [43], or graphene [44,45], with a trade-off between low bandwidth due to resonant processes, little material resilience to external magnetic fields or to incoming power, or an added noise further from the quantum limit.

Among these solutions, traveling-wave parametric amplifiers [46] seem more suitable to scale up qubit readout beyond the bandwidth constraints of resonant architectures, at the cost of a more complex nanofabrication and challenges in impedance and phase matching. Indeed, one way to tackle the scalability challenge is to have a single readout line and to perform parallel readout thanks to multiplexing [27,47–49]. Simultaneous multiplexed readout of semiconductor spin qubits requires large bandwidth, a high compression point, and magnetic field resilience, while keeping the noise level as low as possible. Besides, in this scalability context, typical circuit quantum electrodynamics resonators have dimensions of the same order as the signal wavelength. While meandering these structures can lower their footprint to a few mm^2 , it is challenging to make them smaller and unwanted harmonics can enter the experiment bandwidth due to their inherent one-dimensional shape [50,51]. This limits their on-chip integration when going to more and more qubits.

In this paper, we use a Josephson-junction-based traveling-wave superconducting parametric amplifier (JTWPA) to probe the impedance signal of quantum dots embedded in small-footprint lumped-element resonators. After presenting the setup and the JTWPA in Sec. II, we first characterize the JTWPA in the frequency regime corresponding to our experiments in Sec. III: we find nominal gain, bandwidth, and compression point compared to its usual regime of operation at higher frequencies. In Sec. IV, we characterize the noise performance of the readout and estimate a JTWPA added noise close to the quantum limit of an amplification process. Section V puts emphasis on the resistance of the JTWPA to the externally applied magnetic field at the position of the quantum dot device. In Sec. VI, after presenting the multigate SiMOS device, we demonstrate the interest in the JTWPA with regard to dispersive charge-susceptibility measurements at interdot charge transitions in double quantum dots (DQDs). Finally, we leverage its broadband gain to multiplex the readout of two interdot signals in Sec. VII and conclude in Sec. VIII.

II. SETUP AND DEVICE DESCRIPTION

The signal of interest in this work is the dispersive change in resonance frequency of a lumped-element

resonator in which our device is embedded, at the coldest stage (50 mK) of a homemade dilution refrigerator [see Fig. 1(a)]. A vector network analyzer (VNA) sends an rf tone of power P_{in} through successive stages of attenuation. On the cold plate, the tone goes through a feedline on the printed circuit board (PCB) where the device is glued. The device is connected to the feedline in a “hanger” geometry, through a bias tee combining low-frequency control electronics (gate voltages) and the rf tone of interest. After the feedline, the output signal goes through an isolator to protect the device from reflections of the JTWPA pump tone P_p . Then it goes through the JTWPA, a second isolator to protect the JTWPA from 4-K radiation, a high-electron-mobility transistor (HEMT) amplifier anchored at the 4-K stage, and further room-temperature amplifiers, and it is retrieved by the VNA to compute the scattering parameters.

The SiMOS chip is glued to a center square pad with silver paste, with 100 pads around it available for wire bonding [Fig. 1(b)]. The center pad (below the chip in the figure) is voltage controlled as well, enabling substrate polarization of the SiMOS device. The rf signals arrive at the back of the PCB through two eight-port connectors [Fig. 1(c)]. Twelve terminations serve to convey the rf signals directly to a front face pad for, e.g., fast gate pulses. The remaining four are inputs and outputs of two coplanar waveguides used as feedlines in reflectometry readout.

On each feedline, surface-mounted coupling capacitors couple the feedline to a front face pad, which needs to be wire bonded to an on-chip inductor. In Fig. 1(d), we take a closer look of the SiMOS chip, where we can see several spiral inductors corresponding to different devices. An enlargement of the red square in Fig. 1(d) is shown in Fig. 1(e), where we see four different six-gate devices. Each of them have three spiral inductors directly linked to SiMOS device gates and six additional bonding pads (the three remaining gates, the source, the drain, and the substrate).

To form the resonator, we integrate niobium superconducting spiral inductors directly on chip [52] in a post-CMOS fabrication process [53,54]. This forms an LC_p resonator due to the parasitic capacitance C_p from the PCB, the bonding pads, and the device structure. Patterning the inductor directly on chip enables us to reduce C_p compared to inductors fabricated on a separate chip and wire bonded to the device. This results in a resonance frequency closer to the range in which superconducting amplifiers operate. The principle of this readout method is to send P_{in} on a resonance flank, so that a small shift in resonance frequency will result in a sensitive variation of the transmitted signal through the feedline.

The main figure of merit of such a readout protocol is the signal-to-noise ratio (SNR), which quantifies the contrast in the rf signal between zero and nonzero charge

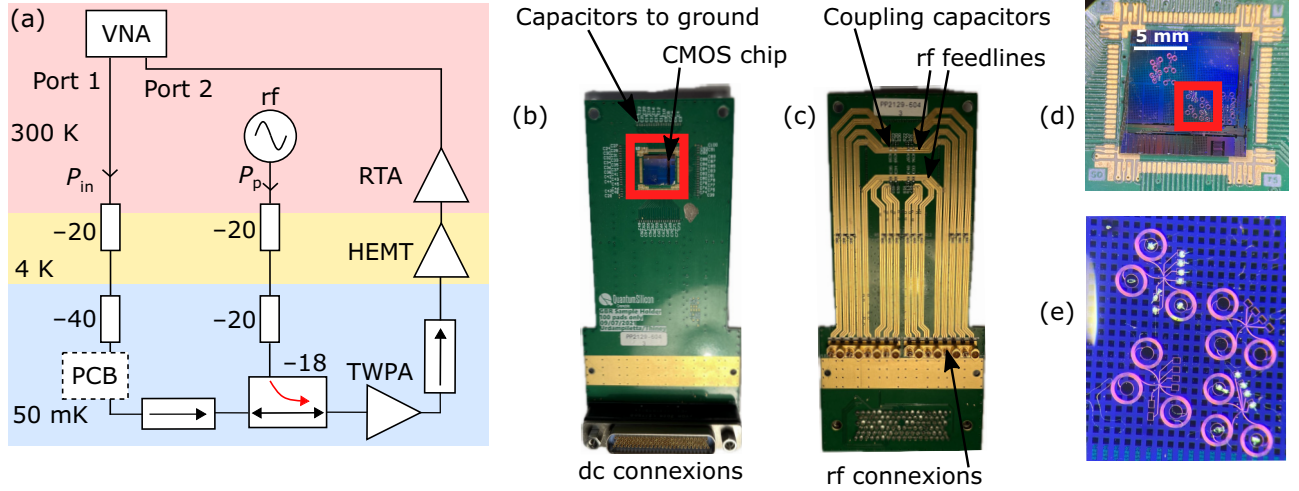


FIG. 1. (a) A description of the setup for Josephson traveling-wave parametric amplifier (JTWPA) characterization. A vector network analyzer (VNA) sends an rf tone in the dilution refrigerator through successive stages of attenuation. A second rf source provides energy to the JTWPA via a directional coupler with the pump tone P_p . P_{in} goes through a printed-circuit-board (PCB) feedline coupled to the readout resonator (containing the SiMOS device) and an isolator to protect the device from pump reflection. The resulting rf signal is amplified by the JTWPA, then goes through a second isolator that prevents reflected 4-K radiation from disturbing the JTWPA. It is then amplified by the high-electron-mobility transistor (HEMT) amplifier anchored to the 4-K stage and by room-temperature amplifiers (RTAs). It is retrieved by the VNA to compute the scattering parameters. (b),(c) The front and back faces of the PCB. The rf tones enter and leave through the back face, travel through feedlines, and are coupled to the front face with coupling capacitors. On the front face, these tones are connected to the SiMOS chip with microbonds. (d) A closer view of the red square in (b): the SiMOS chip is glued on the front face in the middle of 100 bonding pads connected to rf and dc lines. (e) A closer view of the red square in (d) with four six-gate SiMOS devices (more details on the device are given in Sec. VI). The round features are the spiral inductors of the readout resonators. The background network of squares is the original bonding pads from the industrial CMOS process, before the academic postprocess used to fabricate on-chip inductors.

susceptibility in the SiMOS device. It can be written as

$$\text{SNR} = |\Delta T|^2 \frac{P_{in}}{P_n}, \quad (1)$$

where $|\Delta T|^2$ is the shift in rf transmission due to charge degeneracy ($T = \sqrt{I^2 + Q^2}$), P_{in} is the input rf power, and P_n is the noise power. $|\Delta T|^2$ can be enhanced with a better resonator quality factor or to a better coupling between gates and quantum dots [55]. In our context, P_{in} is limited by power broadening, when the rf modulation becomes larger than the interdot linewidth and averages it out. In practice, tunnel couplings in the range of a few tens of microelectronvolts limit P_{in} to about -100 dBm and depend on the resonator quality factor and on the gate lever arms.

P_n contains the information on the noise that hinders signal readout. In the case of an amplification chain, it is dominated by the added noise of the first amplifier [56]. This is the cornerstone of readout performance and in our case this amplifier will be the JTWPA.

The JTWPA used here consists of a chain of single aluminum Josephson junctions, the characteristic heights of which are periodically modulated [see Figs. 2(a) and 2(b)]. It is a single-junction adaptation of the SQUID-based

amplifier described in Refs. [33,57], which gives details on the fabrication process and a quantitative description of the amplification phenomenon. The chip containing the JTWPA is depicted at the center of Fig. 2(c), wire bonded to a copper PCB and mounted into a copper box. Thermal anchoring is ensured by fixing the JTWPA to a copper cold finger screwed on the cold plate. This cold finger is about 10 cm long, to place the JTWPA as far as possible from the center of the coil used to generate the magnetic field meant to lift the degeneracy of spin states of electrons trapped in the transistor device. Except for some turns of aluminum tape around the copper box, we do not use any other protection against magnetic field.

III. JTWPA PERFORMANCE AT THE INTEGRATED RESONATOR FREQUENCIES

Superconducting parametric amplifiers are usually designed to operate in the (4–12)-GHz range [23,46]. In contrast, usual semiconductor spin-qubit experiments using rf reflectometry happen below 1 GHz because of the parasitic capacitance arising from bonding pads when using surface-mounted inductors or inductors patterned on a separate chip: the spiral inductor gives a few tens of nanohenry and the parasitic capacitance lies between

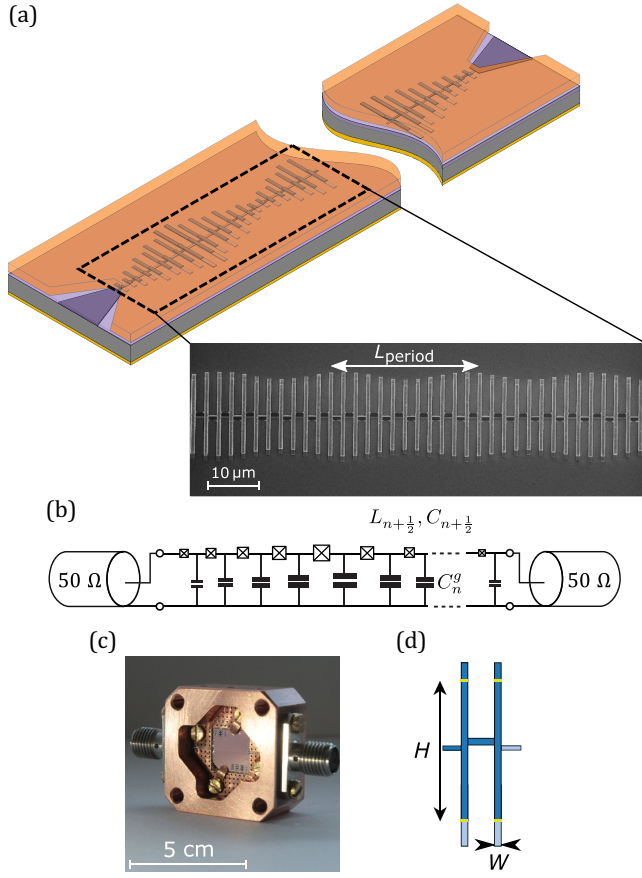


FIG. 2. The Josephson traveling-wave parametric amplifier (JTWPA), adapted from Ref. [33]. (a) A schematic of the JTWPA. An array of aluminum Josephson junctions is fabricated on top of a silicon substrate. They are then covered by a thin atomic-layer-deposition- (ALD) grown alumina layer (purple) and a thick copper layer (orange), used as a top ground to enforce impedance matching. Below, we show an SEM image of three periods of a spatially modulated array of junctions. (b) An electrical sketch of the JTWPA. Crosses in squares represent Josephson junctions, consisting of a capacitor and a nonlinear inductor in parallel. (c) A photograph of the sample. The chip is the square in the middle, anchored to a PCB in a copper case. (d) A schematic of two successive Josephson junctions. Here, only the junction height H (the overlap between the top and bottom aluminum layers) is modulated in space, not its width W .

0.5–1 pF. Patterning the inductor on chip as described in the last section has enabled to go higher in frequency and to reach the (2–4)-GHz range.

In Fig. 3(a), we show the transmission $|S_{21}|^2$ of the setup, comparing JTWPA ON and OFF. The JTWPA-OFF transmission shows the dips of the three resonators, around 3.465, 3.655, and 3.525 GHz, respectively. The JTWPA-ON transmission shows different zones, which are better understood by looking directly at the gain (the difference between the ON and OFF curves) [see Fig. 3(b)]. The sine-wave pattern of the height of the Josephson junctions

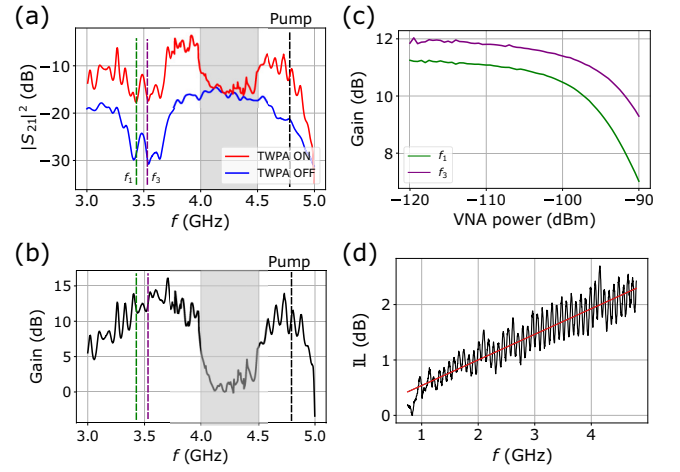


FIG. 3. The characteristics of the JTWPA. (a) The transmission $|S_{21}|^2$ through the whole rf setup. The blue curve, with JTWPA OFF (i.e., the pump rf source output OFF), shows the three resonances of the resonators around 3.465, 3.655, and 3.525 GHz. We have pinpointed in purple and green the two frequencies relevant for the Sec. VII multiplexing measurements. The red curve, with JTWPA ON, adds the JTWPA gain to the blue curve. We have pinpointed the pump tone at 4.76 GHz. (b) The JTWPA gain as a function of the incoming rf frequency [the difference between the JTWPA-ON and -OFF curves of (a)]. (c) The compression point: the JTWPA gain as a function of the rf power at the input of the JTWPA, for the two frequencies pinpointed in (a). (d) The JTWPA insertion loss. The blue curve shows measured data and the orange line is a fit to $IL = 0.46 \times f [\text{GHz}] + 0.08$.

induces a modulation of the wave impedance along the JTWPA, resulting in a stop band of propagation [33]. It appears here after 5 GHz. The transmission gap around 4.3 GHz is the symmetric of this photonic gap compared to the pump frequency, sent at 4.73 GHz (the rf source for the pump is tuned at -5.5 dBm). It can be explained as follows. As this TWPA relies on a four-wave-mixing amplification process, two pump photons at frequency f_p are converted to one signal photon at frequency f_s and one idler photon at frequency f_i , verifying $f_s + f_i = 2f_p$. These three tones must be able to copropagate along the JTWPA to enable signal amplification. However, at signal frequencies lying in the gray area, corresponding idler tones fall in the propagation stop band and cannot propagate, so no signal amplification is possible in the gray area.

The area of interest for us lies below 4 GHz: the JTWPA gives between 12- and 15-dB bare ON-OFF gain over 0.5 GHz, and is tunable over a broad 2-GHz band up to the gap, by tuning the pump frequency and power. This contrasts with resonant Josephson amplifiers that need to be finely tuned near resonance. The wiggles in the gain profile come from impedance mismatch between the JTWPA and the rf circuitry connected to it.

In Fig. 3(c), we show the JTWPA gain as a function of the rf power at the JTWPA input, for frequencies $f_1 = 3.465$ GHz and $f_3 = 3.525$ GHz, in the same pump configuration as for Figs. 3(a) and 3(b). These correspond to optimal reflectometry working points to read interdot charge transitions in (T_1/B_1) and (T_3/B_3) DQDs, as will be illustrated in Sec. VII. Both curves lose 1 dB around -100 dBm. This gain compression point is 2–3 orders of magnitude higher than those of typical resonant Josephson parametric amplifiers and enables multiplexed readout of these two interdot transitions.

An important point to emphasize here is that in our setup, the “JTWPA-OFF” curves are obtained simply by not pumping the JTWPA while measuring. However, we do not remove it from the chain. This implies that the data with JTWPA OFF are artificially degraded due to the JTWPA insertion loss. To account for this, we have estimated the insertion loss in a different setup, in the frequency window between the low-frequency cutoff of the isolators and the JTWPA photonic gap. We have measured the full rf transmission through the cryostat, first with a $50\text{-}\Omega$ short on the cold plate, then by replacing the short by the JTWPA pump OFF. We plot the difference between these measurements in Fig. 3(d). A linear fit gives a slope of 0.46 dB GHz^{-1} .

IV. SYSTEM NOISE AND JTWPA ADDED NOISE

To assess the noise performance of the JTWPA-enhanced measurement, we perform the following measurement on a similar device, with a resonance frequency at $f = 2.911$ GHz. The setup is similar to that of the previous section, with the difference that we provide P_{in} with an external rf source tuned at f , and we measure the tone coming out of the cryostat with a spectrum analyzer (SA), with a $B = 300$ Hz resolution bandwidth. The usual way to represent these data is to offset them by the total amplification of the rf output line, as in Fig. 4(a). The estimation of the output line is discussed further in this section. As this has been obtained on a different device than before, and with a different pump configuration, it demonstrates how the JTWPA tunability can be adapted to different optimal readout frequencies. At the frequency at which the data in Fig. 4(a) have been taken, the insertion loss is 1.26 dB, from Fig. 3(d). We have taken this into account in the SA plot, by subtracting it from the JTWPA gain for the offset of the ON data, and by adding it to the line attenuation for the offset of the OFF data. Without JTWPA in the chain, the noise-floor OFF would be 9.41 K.

A convenient way to assess noise is to express it in terms of noise temperature. We can write the whole system noise power as [59,60]

$$P_n = G_{\text{out}} k_B T_{\text{sys}} B + S_n^{\text{SA}} B, \quad (2)$$

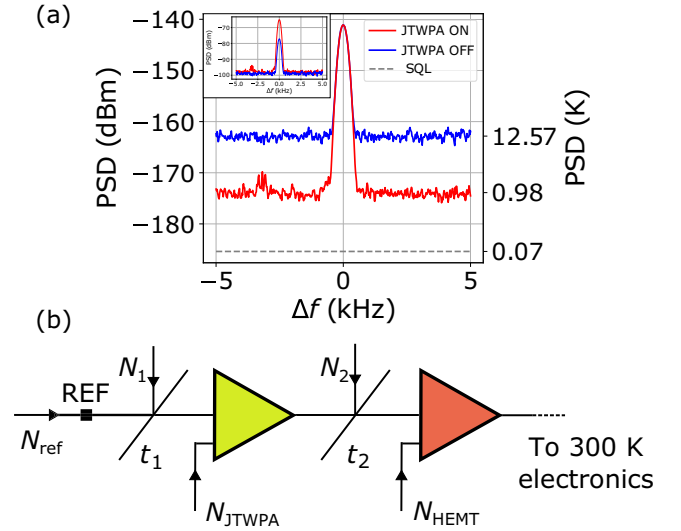


FIG. 4. (a) The spectrum-analyzer (SA) measurement of a tone sent at $f = 2.911$ GHz, JTWPA ON (red) and OFF (blue), offset by the amplification chain. The dashed gray line shows the standard quantum limit of added noise for an amplification process, for comparison with the noise floors. The inset shows the bare SA data without renormalization by the gain. (b) The model for noise estimation, adapted from Ref. [58]. N_{JTWPA} and N_{HEMT} are the added noise of the JTWPA and the HEMT. The rf circuitry before the JTWPA, and between the JTWPA and the HEMT, is modeled as lossy beam splitters of transmissivities $t_{1,2}$. $N_{1,2}$ are vacuum noise incoming at the beam splitters. “REF” is the reference point where we express the noise temperature: the output gain G_{out} in Eq. (2) is the sum of all gains and attenuations beyond this point.

where $G_{\text{out}} = +76.1 \pm 1$ dB is the full output gain after the device, $S_n^{\text{SA}} = -142 \text{ dBm Hz}^{-1}$ is the noise power density of the SA, and T_{sys} is the system noise temperature. The gain of the output chain is only estimated with constructor specifications as summarized in Table I. We realize that these numbers can differ from real performance, so the following quantities and JTWPA added noise cannot be asserted with good precision.

TABLE I. Estimation of the gain or attenuation of the different rf components in the output chain.

The rf component	Gain or attenuation (dB)
SMA before JTWPA (t_1)	−0.37
SMA after JTWPA (t_2^1)	−0.37
Isolator (t_2^2)	−0.2
SMA after isolator (t_2^3)	−0.13
SMA from 50 mK to HEMT (t_2^4)	−1.88
JTWPA	+10.8
HEMT	+36
300-K amplifiers (G_{RT})	+32.2

SMA means SubMiniature version A.

The noise-floor JTWPA ON on bare SA measurement reads $P_n = -97.8$ dBm [the average of the noise floor outside the peak in Fig. 4(a), inset]. From this, we calculate a system noise temperature of $T_{\text{sys}} = 0.98^{+0.3}_{-0.2}$ K. Expressed in terms of measurement quantum efficiency, we have $\eta = hf/k_B T_{\text{sys}} = 14\%$. This low value is explained by the limited JTWPA gain, which is not enough to overcome the subsequent HEMT added noise, by the high (4-K) HEMT added noise temperature compared to state-of-the-art HEMTs, and by additional losses in rf circuitry before the HEMT.

To disentangle these different contributions, and to investigate the JTWPA part in this limited measurement efficiency, we rely on the following model for noise estimation in an amplification chain [58], illustrated in Fig. 4(b). As the standard quantum limit of noise added by an amplification process is conveniently given by half a quantum of energy at the frequency of interest [61], the following discussion expresses noise in numbers of quanta.

We model the rf circuit between the device and the JTWPA, and the rf circuit between the JTWPA and the HEMT, as lossy beam splitters with respective transmissivities $t_1 = -0.37$ dB and $t_2 = t_2^1 + t_2^2 + t_2^3 + t_2^4 = -2.58$ dB (these quantities are defined in Table I). In this situation, the whole system consisting of the two amplifiers and two beam splitters is equivalent to one amplifier with total gain and added noise:

$$G_T = t_1 t_2 G_{\text{JTWPA}} G_{\text{HEMT}},$$

$$N_T = \frac{1}{G_T - 1} [t_1 (G_{\text{JTWPA}} - 1) G_{\text{HEMT}} (N_{\text{JTWPA}} + 1) + (G_{\text{HEMT}} - 1) (N_{\text{HEMT}} + 1)] - 1. \quad (3)$$

We make the approximation that the gain of the HEMT is high enough to discard the added noise coming from further components of the amplification chain. Thus, the noise measured by the SA renormalized by the amplification chain up to point “REF” in Fig. 4(b) is this total added noise N_T plus the incoming noise N_{ref} at point “REF.” The attenuators on the signal and pump lines render the room-temperature thermal noise negligible, so we take $N_{\text{ref}} = 0.5$ photon, accounting for quantum vacuum fluctuations of a bosonic bath. $N_{\text{sys}} = k_B T_{\text{sys}}/hf$ is computed from Eq. (2), with $G_{\text{out}} = G_T \times G_{\text{RT}}$ and G_{RT} the gain of the room-temperature circuitry. Finally, writing $N_{\text{sys}} = N_T + N_{\text{ref}}$ and isolating the JTWPA added noise, we find $N_{\text{JTWPA}} = 0.46$ energy quantum, on the order of the quantum limit of added noise for a linear amplifier: $(G_{\text{JTWPA}} - 1)/(2G_{\text{JTWPA}})$ [62]. The absence of precise estimation of the gains and attenuations implies that we cannot assert this number precisely but, rather, as a validation that the JTWPA operates in a regime with ultralow added noise. This JTWPA added noise performance can be explained

partly by the reduced dielectric losses when going to lower frequencies.

V. MAGNETIC FIELD RESILIENCE

In the context of semiconductor spin qubits, quantum dots in these SiMOS devices are meant to trap individual electrons to coherently manipulate their spins. In such experiments, a magnetic field is needed to lift the degeneracy of spin states [5,52]. In Fig. 5(a), we show the SNR improvement of the JTWPA with respect to an externally applied magnetic field at the position of the SiMOS device B_{QD} . The reported magnetic field is the one felt by the device at the center of an external coil, not the one felt by the JTWPA. We see that for fields up to 1.1 T, the SNR improvement stays in a [10 dB; 13 dB] window, and begins to drop for higher fields. The pump has been tuned only once, at the beginning of the ramp.

In order to understand this resilience and the shape of this plot better, we have conducted an additional experiment with the SiMOS device removed and the JTWPA positioned right below the superconducting coil, so that we can estimate the magnetic field that it feels more precisely. We have first ensured that at least 10 dB gain is still achievable at the same frequency at which the magnetic field resilience is investigated in last paragraph, despite the change of setup.

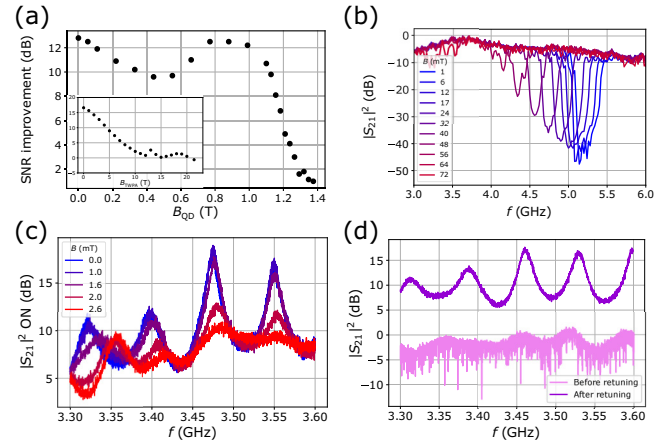


FIG. 5. The JTWPA magnetic field resilience. (a) The JTWPA SNR improvement as a function of the externally applied magnetic field at the position of the quantum dot device. We see a resilience of the JTWPA noise performance up to 1.1 T felt by the device. The inset shows the same quantity measured in a different setup, with the JTWPA right below the coil that generates the magnetic field: the reported field is the one felt by the JTWPA. (b) The JTWPA transmission pump OFF while ramping up the magnetic field. (c) The JTWPA transmission pump ON for small magnetic field steps. (d) The JTWPA transmission pump ON, after losing the gain due to a magnetic field ramp up to 26 mT for a given pump tuning (light violet) and after retuning the pump at this same magnetic field value (dark violet).

In Fig. 5(b), we show the transmission with JTWP OFF while ramping up the magnetic field. We note a displacement and closing of the photonic gap. This time, the field mentioned in the legend is the one felt by the JTWP itself. This has been observed in Ref. [63], where the authors have specifically investigated the behavior of a similar JTWP in a magnetic field. The gap closing suggests that a non-negligible part of the field is in plane, transverse to the long side of the junctions. The complete closing occurs around 50 mT, an order of magnitude higher than in the above-cited reference. This is consistent with the present JTWP installation, with most of the field parallel to the long side of the junctions.

We have then tested the SNR-improvement resilience to the magnetic field in this configuration [see the inset of Fig. 5(a)]. We insist that in the inset, the x -axis B_{JTWP} gives the field felt by the JTWP this time, not by the quantum dot device. The SNR improvement decays smoothly while the JTWP magnetic field is ramped up to 10 mT. This absence of gain is observed up to 22 mT. Going to higher fields induces a superconducting-to-normal transition of the JTWP. This first suggests that the SNR-improvement drop in the main panel of Fig. 5(a) is not induced by a superconductivity breakdown but, rather, by the fact that the optimal pump parameters change with the field. Indeed, they depend strongly on the gap position and we have just seen that the gap is displaced when the field varies.

To illustrate this point further and understand the qualitative difference between Fig. 5(a) and its inset, we measure the gain profile on a reduced band, for different but close values of the magnetic field. The results are shown in Fig. 5(c). For example, we can see that the gain on the 3.48-GHz peak decreases steadily with the field. On the other hand, sitting around 3.33 GHz, the gain first drops and then rises again, because the gain profile is displaced, similarly to the main panel of Fig. 5(a).

To confirm this point one step further and conclude on the JTWP magnetic field resilience, we investigate the possibility of retuning the pump after the gain profile is completely lost when varying the magnetic field. In Fig. 5(d), we show the gain profile at 26 mT: on the light-violet curve, we have kept the initial pump settings and the gain is completely lost. The dark-violet curve is taken after retuning the pump parameters to account for the gap displacement. This suggests that as long as the photonic gap is present to help fulfill phase matching for the amplification process, the pump can be retuned and the gain profile recovered.

This resilience of the JTWP to the magnetic field is explained by the single-junction nature of the JTWP, compared to SQUID-based amplifiers, which are highly sensitive to magnetic flux, and also by the nonsuperconducting metallic top ground. This mu-metal-free, easy to implement, magnetic field resilience encourages the use of JTWPs in usual semiconductor spin-qubit experiments.

VI. SNR IMPROVEMENT

We can now turn to charge-susceptibility measurements of charge states in SiMOS devices with the help of the JTWP. The corresponding setup is described in Fig. 6(a). It is the same as in Fig. 1(a), except that the rf input tone is generated by an rf source similar to the pump tone, not by a VNA. It is split in two at room temperature to serve as a local oscillator for I - Q demodulation of the rf output. The I and Q quadratures are then low-pass filtered and read by a homemade analog-to-digital converter (ADC, not shown in the figure). We have also schematized the PCB and on-chip components to illustrate where the readout resonators are connected to the SiMOS devices.

The devices studied in this work are based on silicon nanowire transistors from 28-nm fully depleted silicon-on-insulator (FD-SOI) technology [64]. On top of a 10-nm-thick and 80-nm-wide nanowire, we deposit 6 nm of SiO₂ gate dielectric, 5 nm of TiN, and 50 nm of poly-Si metal for the gate layer. In the device depicted in Fig. 6(a), three pairs of split gates are deposited, with 40-nm gate width, 40-nm gate pitch, and 40-nm split-gate separation. The gate pitches are filled with SiN spacers. The device is then buried in 200 nm of SiO₂, with tungsten vias to connect the gates and the reservoirs of the transistor. We have connected one readout resonator per pair of split gates. In this case, they are on gates T₁, T₂, and B₃.

At cryogenic temperatures, the gates of the device can be used to trap individual charges in the active channel of the transistor. With more and more positive gate voltage, electrons accumulate in “corner dots” due to the wrap-around shape of the gate [64]. When an electron can tunnel between the dots below two gates, the charge of the system is degenerate, which creates a capacitive shift of resonance frequency. The transmitted I - Q signal on these “interdot” charge-transition lines is different from regions of stable charge occupancy. In Fig. 6(b), we show a comparison of the rf transmitted signal modulus $|T|$ between JTWP ON and OFF, at a gate-voltage configuration in which an electron is able to tunnel between dots formed under T₃ and B₃. The actual dc voltage applied on a gate is the sum of two signals: one digital-to-analog converter (DAC) output gives the coarse operating point, while another DAC output is divided by 50 to scan around this point. The axis labels on the interdot plots are these fine DAC outputs and the actual voltage span seen by the gate is divided by 50.

To quantify the improvement in SNR provided by the JTWP, we represent the interdot feature in the I - Q plane in Fig. 6(c). To do so, we toggle between the two positions in the stability diagram corresponding to a fixed charge (point “1” in the figure) and to a charge-degeneracy point on an interdot signal (point “2”). We bin these I - Q data and fit them to a two-dimensional double-Gaussian curve (see Appendix A). The SNR is then computed as the ratio of the distance between the Gaussian centers (signal S)

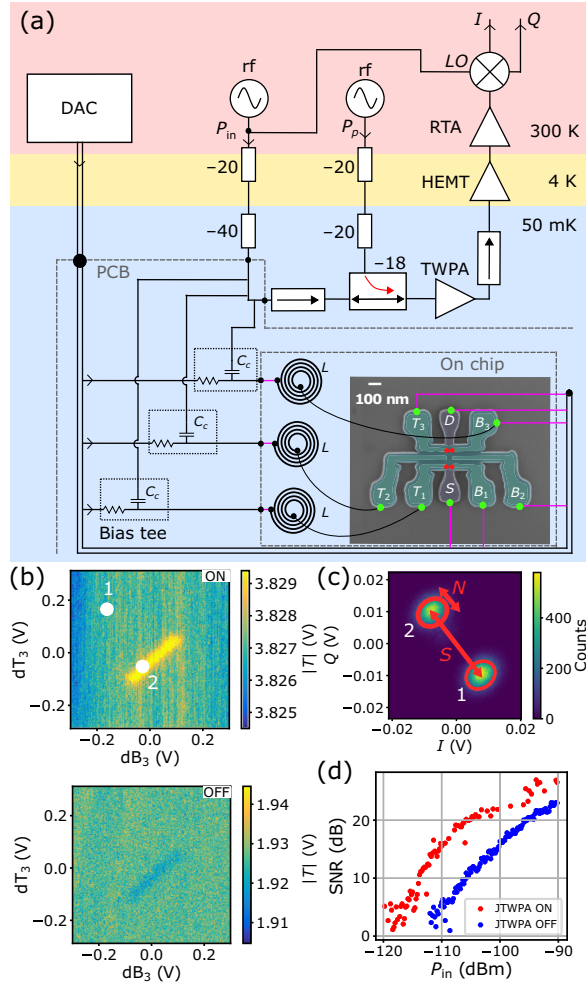


FIG. 6. The JTWPA SNR improvement of rf dispersive measurements of interdot charge transitions. (a) The setup adaptation: an rf source at room temperature provides the readout input tone. It is split in two at room temperature to serve as local oscillator for I - Q demodulation of the rf output. The dc voltages for gate and electron reservoirs of the SiMOS device are provided by a DAC via tungsten vias (green), either directly or through bias tees on the PCB for gates connected to a resonator. The rf readout tones are conveyed to SiMOS gates through PCB feedlines, coupling capacitors C_c , wire bonds (violet), and spiral inductors postprocessed on chip. (b) The rf output signal at a charge transition between the two quantum dots below gates T_3 and B_3 . Here, we show only the transmission-modulus quadrature. Point 1 is a gate-voltage point of charge stability. Point 2 is a gate-voltage configuration enabling electron tunneling. This tunneling possibility adds a capacitance signal in the resonator, shifting the resonance frequency and thus giving a different transmission amplitude. (c) The I - Q plot of the rf output signal. The data at positions 1 and 2 of (a) are binned in a two-dimensional histogram. The two resulting blobs are fitted to tilted Gaussians. The signal S is defined as the distance between their centers, the noise N is the Gaussian half width at half maximum, and $\text{SNR} = S/N$. (d) The SNR computed as explained in (c) on a different device, and studied as a function of the input power offset by the input line attenuation P_{in} up to the JTWPA input, comparing JTWPA ON (red) and OFF (blue).

and the mean extension of these Gaussian bells (noise N). In this representation, the effect of the JTWPA is a better separation of the Gaussians, without enlarging them.

To show evidence of reproducibility and applicability of the JTWPA characteristics of the previous section on this signal of interest, we have repeated the experiment described in Fig. 6(b) on a similar device consisting of only one pair of split gates. The resonance frequency of the corresponding resonator was 3.32 GHz, similar to the device described above. We have retuned the JTWPA pump frequency and power to maximize the gain at this readout position, giving a pump frequency of 4.921 GHz and power -6.83 dBm. In Fig. 6(c), we show SNR data computed from I - Q plots as described just above, for power coming into the device from -120 dBm to -90 dBm. We first verify $\text{SNR} \propto P_{in}$ as in Eq. (1). This plot contains different zones. Below -110 dBm, the JTWPA makes the signal stand out from the noise, when there is no consistent SNR value for JTWPA-OFF data. Between -110 dBm and -100 dBm we get around 10 dB SNR improvement, again consistent with the two other devices studied in this work. This performance finally drops off after around -100 dBm. This SNR-improvement saturation is consistent with standard compression-point measurements shown in Fig. 3(c) for the three-split-gate device. This result illustrates that the direct measurements of the JTWPA characteristics are found to be unchanged when the amplifier is used in typical semiconductor quantum dot experiments. In particular, it can be noted here that up to this point, we have reproduced a stable ON-OFF SNR improvement of around $+10$ dB over three similar SiMOS devices, with resonance frequencies ranging from 2.911 GHz to 3.525 GHz.

VII. MULTIPLEXED READOUT

Finally, we investigate multiplexed readout of two interdot charge transitions. Going back to the three-split-gate device, we first implement frequency multiplexing of the readout of an interdot charge transition in the DQD below T_1 and B_1 , and of an interdot transition in the DQD below T_3 and B_3 . The experimental setup differs from the one described in Fig. 6(a) at room temperature: here, the rf source is used to generate a 3.46-GHz carrier frequency. A second source is used to generate two modulation signals at $f_1^m = 5$ MHz and $f_3^m = 50$ MHz, which are then added together and mixed with the carrier signal due to a single-sideband modulator (SSB). The resulting signal is then sent into the cryostat. It is worth noting here that the tone separation is limited by the SSB (5–50)-MHz IF bandwidth, forcing us to work at nonoptimal frequencies for reflectometry. The output rf signal from the cryostat is first down-converted by the carrier frequency, and the resulting signal is demodulated at f_1^m and f_3^m .

In Fig. 7(a), we show both interdots measured simultaneously. B_1 and T_3 are fast swept together along the y

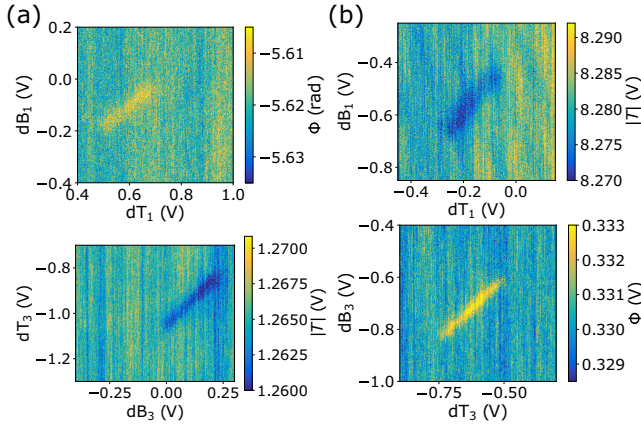


FIG. 7. The multiplexed readout of two interdot charge transitions. The top panels show the (B_1, T_1) transition and the bottom panels show the (B_3, T_3) transition. We only show the cleanest quadrature between the modulus and the phase. (a) Frequency-division-multiplexing data. (b) Time-division-multiplexing data.

axis, and T_1 and B_3 (the two gates connected to an rf circuit) are stepped together along the x axis. The top panel shows the phase of the signal demodulated at f_1^m with the interdot corresponding to (T_1/B_1) DQD, and the bottom panel shows the modulus of the signal demodulated at f_3^m with the interdot corresponding to (T_3/B_3) DQD. We always measure both the transmission modulus and phase, but the figure shows only the quadrature containing the cleanest signal (for the complete measurement data, see Appendix B). Beside the SSB bandwidth constraint, the quality of this frequency-multiplexed signal is mainly limited because of the quality factor of the resonators, which degrades the SNR and additionally creates crosstalk between the two signals of interest. Also, both tones must be 3 dB lower than individual ones, in order to work at maximum P_{in} but stay below JTWPA compression.

Another alternative to perform multiple readout while maintaining the total power below compression is to perform time rather than frequency multiplexing. In Fig. 7(b), we show interdot transitions below (T_1/B_1) (top panel, measured at $f_1 = 3.385$ GHz) and below (T_3/B_3) (bottom panel, measured at $f_3 = 3.565$ GHz). Again, we have kept only the best quadratures. Both maps are taken together in an alternating fashion: for each point, we toggle between 2 ms at a gate-voltage configuration corresponding to a point on the T_1/B_1 map and input frequency f_1 while T_3/B_3 are at 0 V, and 2 ms on the T_3/B_3 map and input frequency f_3 while T_1/B_1 are at 0 V, with f_1 and f_3 the optimal reflectometry frequencies for both transitions. We toggle between f_1 and f_3 due to a fast-gated rf switch. We retrieve both interdot features with the JTWPA ON during all the duration of experiments, with no need to retune the pump parameters. This has been enabled by the broad 500-MHz band of JTWPA gain in this pump configuration, and opens

the pathway toward multiplexing of a larger number of resonators.

VIII. CONCLUSIONS

In this paper, we have demonstrated the convenient and reproducible use of a superconducting traveling-wave parametric amplifier based on single Josephson junctions (JTWPA) in dispersive gate-based rf readout of interdot charge transitions in SiMOS quantum dots.

The JTWPA offers more than 10 dB SNR improvement over a broad 2-GHz bandwidth, with ultralow added noise, comparable to its typical characteristics in usual working regimes for superconducting qubit experiments. We have demonstrated an advantage of using the JTWPA on interdot charge-transition signals in gate-defined corner dots in SiMOS structures over a 30-dB range of input power, and its reproducibility on three different devices. We have leveraged its broad amplification band together with a high -100 dBm 1 dB compression point to multiplex the readout of interdot charge transitions between two separate DQDs in the same multigate SiMOS device, in both the frequency and the time domain, measured with a method equivalent to gate-based rf reflectometry around 3 GHz, due to low-footprint lumped-element resonators postprocessed directly on the SiMOS chip. Additionally, we have shown the JTWPA magnetic field resilience up to 1.1 T felt by the quantum dot device, resulting simply from the single-junction nature of the superconducting chain, from its metallic top ground, and from its position and orientation in the cryostat. This lowers the cost and effort compared to usual mu-metal shielding necessary for SQUID-based amplifiers, and opens the pathway toward multiplexed spin-qubit readout in SiMOS devices. These results highlight the usefulness of such JTWPA in the context of semiconductor spin-qubit experiments, especially in the context of scalable quantum computation. This comes at the cost of additional lossy circuitry to link the JTWPA to the device and to the HEMT, resulting in a reduced overall measurement quantum efficiency.

Nevertheless, the signal quality and the measurement integration time do not compare with state-of-the-art semiconductor quantum dots experiments using lambda resonators and similar superconducting amplifier performance [27,32]. In order to bridge this gap, different elements need improvement. With further lumped-element resonator engineering, better quality factors would enable to reduce readout crosstalk and improve the dispersive-shift part of the SNR [55]. Working on the device design could give us a better understanding and control over the interdot transition rates [65], to which we could adapt the frequency and power of the rf readout method. In both regards, cointegration of lumped-element resonators and SiMOS devices on the chip will alleviate the need for bonding pads and wires, giving reduced resonator footprint

and parasitic capacitance. Finally, on the superconducting amplifier side, adapting the photonic gap position and depth could enable us to lower the attainable frequency regime and get to less uncharted bands for lumped-element rf resonators, where better quality resonances are routinely achieved.

ACKNOWLEDGMENTS

We acknowledge technical support from D. Dufeu, G. Bres, P. Carecchio, T. Crozes, D. Lepoittevin, L. Hutin, I. Pheng, L. Del Rey, J. Jarreau, C. Hoarau, and C. Guttin. We thank M. Nurizzo, B. Jadot, R. Maurand, and G. Le Gal for fruitful discussions, and J. Renard for his help with the cryogenic microwave setup. This research was supported by the European Union's Horizon 2020 program through the following projects: QuCube (Grant Agreement No. 810504), QLSI (Grant Agreement No. 951852) and Mosquito (Grant Agreement No. 688539).

H.N., B.B., and M.V. were responsible for the front-end fabrication of the SiMOS devices. B.K., V.T., and R.L. developed the postprocessing of the inductor and contacts on the SiMOS device. E.E. designed, fabricated, and installed the cryostat. L.P. developed and fabricated the JTWPAs for the purpose of this study. V.E. carried out the experiments with help from M.U., D.N., B.C., A.B., L.P., and M.D. The manuscript was written by V.E., with inputs from all the authors. M.U., N.R., and T.M. supervised and initiated the project.

The authors declare no competing financial or nonfinancial interest.

DATA AVAILABILITY

Data that support this study are available from the corresponding authors upon request.

APPENDIX A: I - Q PLANE SNR COMPUTATION

In this appendix, we explain the way in which we compute the SNR in the readout of interdot charge transitions (main Fig. 6). In the I - Q plane, we bin measurement points taken in a region of charge stability (the background of a stability diagram) and measurement points taken on an interdot charge transition, where the charge degeneracy adds a capacitance contribution to the resonance frequency and thus shifts the transmitted-signal I and Q output values. We obtain a histogram of two blobs, to which we can fit the following double-Gaussian-shaped curve:

$$f(i, q) = A_1 \times \exp[-(\cos(\theta_1)(i_1 - i) + \sin(\theta_1)(q_1 - q))^2 / (2\sigma_{1x})^2 - ((-\sin(\theta_1))(i_1 - i) + \cos(\theta_1)(q_1 - q))^2 / (2\sigma_{1y})^2] +$$

$$A_2 \times \exp[-(\cos(\theta_2)(i_2 - i) + \sin(\theta_2)(q_2 - q))^2 / (2\sigma_{2x})^2 - ((-\sin(\theta_2))(i_2 - i) + \cos(\theta_2)(q_2 - q))^2 / (2\sigma_{2y})^2]. \quad (\text{A1})$$

The fit parameters are:

- (1) (i_1, q_1) and (i_2, q_2) , the positions of the centers of the blobs
- (2) θ_1 and θ_2 , the tilt of the blobs compared to the I and Q axes
- (3) A_1 and A_2 , the amplitudes of the Gaussians
- (4) $(\sigma_{1x}, \sigma_{1y})$ and $(\sigma_{2x}, \sigma_{2y})$, the two-dimensional extensions of these Gaussians along the blob axes

The SNR quantifies the ease with which we can tell apart the two blobs. The signal is then computed as the distance between the Gaussian centers and the noise is their mean extension (we take the highest of both):

$$S = \sqrt{(q_1 - q_2)^2 + (i_1 - i_2)^2}, \quad (\text{A2})$$

$$N = \max\left(\frac{\sigma_{1x} + \sigma_{1y}}{2}, \frac{\sigma_{2x} + \sigma_{2y}}{2}\right) \quad (\text{A3})$$

$$\text{SNR} = S/N. \quad (\text{A4})$$

APPENDIX B: FREQUENCY-MULTIPLEXING COMPLETE DATA

In Fig. 7, we have chosen to show only the signal quadrature giving the best result for frequency-multiplexing purposes. Here, in Fig. 8, we show both quadratures (transmission modulus $|T|$ in the left panels and phase Φ in the right panels) of signals demodulated

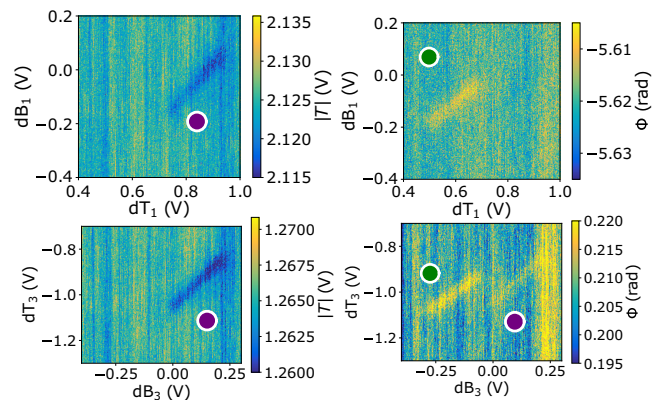


FIG. 8. The complete frequency-multiplexing data. The top panels show the signals demodulated at f_1^m in the main text, and the bottom panels those at f_3^m . The left panels show the transmission modulus and the right panels the phase. We pinpoint with green spots the interdot charge transition corresponding to (T_1/B_1) DQD and with purple spots the interdot charge transition corresponding to (T_3/B_3) DQD.

at both modulation frequencies (f_1^m in the upper panels and f_3^m in the lower panels). We pinpoint with green spots the interdot charge transition corresponding to the (T_1/B_1) DQD, and with purple spots the transition of (T_3/B_3) DQD.

We first get expected frequency-multiplexing results: the phase of the signal demodulated at f_1^m (top-right panel) contains the (T_1/B_1) interdot, and the modulus of the signal demodulated at f_3^m (bottom-left panel) contains the (T_3/B_3) interdot.

But we also get unwanted signals from these measurements. The modulus of the signal demodulated at f_1^m (top-left panel) contains the (T_3/B_3) interdot, while it should show the other interdot at this demodulation frequency. And the phase of the map demodulated at f_3^m (bottom-right panel) even shows both interdots at the same time. These parasitic signals most likely comes from leakage between resonators, given their poor quality factors while having similar resonance frequencies.

-
- [1] D. Loss and D. P. DiVincenzo, Quantum computation with quantum dots, *Phys. Rev. A* **57**, 120 (1998).
 - [2] B. E. Kane, A silicon-based nuclear spin quantum computer, *Nature* **393**, 133 (1998).
 - [3] R. Maurand, X. Jehl, D. Kotekar-Patil, A. Corna, H. Bohuslavskiy, R. Laviéville, L. Hutin, S. Barraud, M. Vinet, M. Sanquer, and S. De Franceschi, A CMOS silicon spin qubit, *Nat. Commun.* **7**, 13575 (2016).
 - [4] M. F. Gonzalez-Zalba, S. De Franceschi, E. Charbon, T. Meunier, M. Vinet, and A. S. Dzurak, Scaling silicon-based quantum computing using CMOS technology, *Nat. Electron.* **4**, 872 (2021).
 - [5] J. M. Elzerman, R. Hanson, L. H. Willems van Beveren, B. Witkamp, L. M. K. Vandersypen, and L. P. Kouwenhoven, Single-shot read-out of an individual electron spin in a quantum dot, *Nature* **430**, 431 (2004).
 - [6] K. Ono, D. G. Austing, Y. Tokura, and S. Tarucha, Current rectification by Pauli exclusion in a weakly coupled double quantum dot system, *Science* **297**, 1313 (2002).
 - [7] R. J. Schoelkopf, P. Wahlgren, A. A. Kozhevnikov, P. Delsing, and D. E. Prober, The radio-frequency single-electron transistor (RF-SET): A fast and ultrasensitive electrometer, *Science* **280**, 1238 (1998).
 - [8] F. Vigneau, F. Fedele, A. Chatterjee, D. Reilly, F. Kuemmeth, M. F. Gonzalez-Zalba, E. Laird, and N. Ares, Probing quantum devices with radio-frequency reflectometry, *Appl. Phys. Rev.* **10**, 021305 (2023).
 - [9] K. D. Petersson, C. G. Smith, D. Anderson, P. Atkinson, G. A. C. Jones, and D. A. Ritchie, Charge and spin state readout of a double quantum dot coupled to a resonator, *Nano Lett.* **10**, 2789 (2010).
 - [10] J. I. Colless, A. C. Mahoney, J. M. Hornibrook, A. C. Doherty, H. Lu, A. C. Gossard, and D. J. Reilly, Dispersive readout of a few-electron double quantum dot with fast rf gate sensors, *Phys. Rev. Lett.* **110**, 046805 (2013).
 - [11] M. F. Gonzalez-Zalba, S. Barraud, A. J. Ferguson, and A. C. Betz, Probing the limits of gate-based charge sensing, *Nat. Commun.* **6**, 6084 (2015).
 - [12] A. C. Betz, R. Wacquez, M. Vinet, X. Jehl, A. L. Saraiva, A. J. Ferguson, M. Sanquer, and M. F. Gonzalez-Zalba, Dispersively detected Pauli spin-blockade in a silicon nanowire field-effect transistor, *Nano Lett.* **15**, 4622 (2015).
 - [13] M. G. House, T. Kobayashi, B. Weber, S. J. Hile, T. F. Watson, J. van der Heijden, S. Rogge, and M. Y. Simmons, Radio frequency measurements of tunnel couplings and singlet-triplet spin states in Si:P quantum dots, *Nat. Commun.* **6**, 8848 (2015).
 - [14] M. Urdampilleta, A. Chatterjee, C. C. Lo, T. Kobayashi, J. Mansir, S. Barraud, A. C. Betz, S. Rogge, and J. J. Morton, Charge dynamics and spin blockade in a hybrid double quantum dot in silicon, *Phys. Rev. X* **5**, 031024 (2015).
 - [15] M. F. Gonzalez-Zalba, S. N. Shevchenko, S. Barraud, J. R. Johansson, A. J. Ferguson, F. Nori, and A. C. Betz, Gate-sensing coherent charge oscillations in a silicon field-effect transistor, *Nano Lett.* **16**, 1614 (2016).
 - [16] J. van Der Heijden, T. Kobayashi, M. G. House, J. Salfi, S. Barraud, R. Laviéville, M. Y. Simmons, and S. Rogge, Readout and control of the spin-orbit states of two coupled acceptor atoms in a silicon transistor, *Sci. Adv.* **4**, eaat9199 (2018).
 - [17] I. Ahmed, A. Chatterjee, S. Barraud, J. J. Morton, J. A. Haigh, and M. F. Gonzalez-Zalba, Primary thermometry of a single reservoir using cyclic electron tunneling to a quantum dot, *Commun. Phys.* **1**, 66 (2018).
 - [18] A. Crippa, R. Ezzouch, A. Aprá, A. Amisse, R. Laviéville, L. Hutin, B. Bertrand, M. Vinet, M. Urdampilleta, T. Meunier, M. Sanquer, X. Jehl, R. Maurand, and S. De Franceschi, Gate-reflectometry dispersive readout and coherent control of a spin qubit in silicon, *Nat. Commun.* **10**, 2776 (2019).
 - [19] G. Zheng, N. Samkharadze, M. L. Noordam, N. Kalhor, D. Brousse, A. Sammak, G. Scappucci, and L. M. K. Vandersypen, Rapid gate-based spin read-out in silicon using an on-chip resonator, *Nat. Nanotechnol.* **14**, 742 (2019).
 - [20] A. West, B. Hensen, A. Jouan, T. Tanttu, C.-H. Yang, A. Rossi, M. F. Gonzalez-Zalba, F. Hudson, A. Morello, D. J. Reilly, and A. S. Dzurak, Gate-based single-shot readout of spins in silicon, *Nat. Nanotechnol.* **14**, 437 (2019).
 - [21] T. Lundberg, J. Li, L. Hutin, B. Bertrand, D. J. Ibberson, C. M. Lee, D. J. Niegemann, M. Urdampilleta, N. Stelmashenko, T. Meunier, J. W. A. Robinson, L. Ibberson, M. Vinet, Y.-M. Niquet, and M. F. Gonzalez-Zalba, Spin quintet in a silicon double quantum dot: Spin blockade and relaxation, *Phys. Rev. X* **10**, 041010 (2020).
 - [22] M. R. Hogg, P. Pakkiam, S. K. Gorman, A. V. Timofeev, Y. Chung, G. K. Gulati, M. G. House, and M. Y. Simmons, Single-shot readout of multiple donor electron spins with a gate-based sensor, *PRX Quantum* **4**, 010319 (2023).
 - [23] Jose Aumentado, Superconducting parametric amplifiers: The state of the art in Josephson parametric amplifiers, *IEEE Microw. Mag.* **21**, 45 (2020).
 - [24] J. Stehlik, Y. Y. Liu, C. M. Quintana, C. Eichler, T. R. Hartke, and J. R. Petta, Fast charge sensing of a cavity-coupled double quantum dot using a Josephson parametric amplifier, *Phys. Rev. Appl.* **4**, 014018 (2015).

- [25] S. Schaal, I. Ahmed, J. A. Haigh, L. Hutin, B. Bertrand, S. Barraud, M. Vinet, C.-M. Lee, N. Stelmashenko, J. W. A. Robinson, J. Y. Qiu, S. Hacoen-Gourgy, I. Siddiqi, M. F. Gonzalez-Zalba, and J. J. L. Morton, Fast gate-based readout of silicon quantum dots using Josephson parametric amplification, *Phys. Rev. Lett.* **124**, 067701 (2020).
- [26] F. J. Schupp, F. Vigneau, Y. Wen, A. Mavalankar, J. Griffiths, G. A. C. Jones, I. Farrer, D. A. Ritchie, C. G. Smith, L. C. Camenzind, L. Yu, D. M. Zumbühl, G. A. D. Briggs, N. Ares, and E. A. Laird, Sensitive radiofrequency readout of quantum dots using an ultra-low-noise SQUID amplifier, *J. Appl. Phys.* **127**, 244503 (2020).
- [27] D. De Jong, C. G. Prosko, D. M. Waardenburg, L. Han, F. K. Malinowski, P. Krogstrup, L. P. Kouwenhoven, J. V. Koski, and W. Pfaff, Rapid microwave-only characterization and readout of quantum dots using multiplexed gigahertz-frequency resonators, *Phys. Rev. Appl.* **16**, 014007 (2021).
- [28] G. A. Oakes *et al.*, Fast high-fidelity single-shot readout of spins in silicon using a single-electron box, *Phys. Rev. X* **13**, 011023 (2023).
- [29] M. A. Castellanos-Beltran, K. D. Irwin, G. C. Hilton, L. R. Vale, and K. W. Lehnert, Amplification and squeezing of quantum noise with a tunable Josephson metamaterial, *Nat. Phys.* **4**, 929 (2008).
- [30] R. Vijay, M. H. Devoret, and I. Siddiqi, Invited review article: The Josephson bifurcation amplifier, *Rev. Sci. Instrum.* **80**, 111101 (2009).
- [31] N. Bergeal, F. Schackert, M. Metcalfe, R. Vijay, V. E. Manucharyan, L. Frunzio, D. E. Prober, R. J. Schoelkopf, S. M. Girvin, and M. H. Devoret, Phase-preserving amplification near the quantum limit with a Josephson ring modulator, *Nature* **465**, 64 (2010).
- [32] C. Macklin, K. O'Brien, D. Hover, M. E. Schwartz, V. Bolkhovskiy, X. Zhang, W. D. Oliver, and I. Siddiqi, A near-quantum-limited Josephson traveling-wave parametric amplifier, *Science* **350**, 307 (2015).
- [33] L. Planat, A. Ranadive, R. Dassonneville, J. P. Martínez, S. Léger, C. Naud, O. Buisson, W. Hasch-Guichard, D. M. Basko, and N. Roch, Photonic-crystal Josephson traveling-wave parametric amplifier, *Phys. Rev. X* **10**, 021021 (2020).
- [34] A. Fadavi Roudsari, D. Shiri, H. Renberg Nilsson, G. Tancredi, A. Osman, I.-M. Svensson, M. Kudra, M. Rommel, J. Bylander, V. Shumeiko, and P. Delsing, Three-wave mixing traveling-wave parametric amplifier with periodic variation of the circuit parameters, *Appl. Phys. Lett.* **122**, 5 (2023).
- [35] S. Chaudhuri, D. Li, K. D. Irwin, C. Bockstiegel, J. Hubmayr, J. N. Ullom, M. R. Vissers, and J. Gao, Broadband parametric amplifiers based on nonlinear kinetic inductance artificial transmission lines, *Appl. Phys. Lett.* **110**, 152601 (2017).
- [36] S. Goldstein, N. Kirsh, E. Svetitsky, Y. Zamir, O. Hachmo, C. E. M. de Oliveira, and N. Katz, Four wave-mixing in a microstrip kinetic inductance travelling wave parametric amplifier, *Appl. Phys. Lett.* **116**, 152602 (2020).
- [37] M. Malnou, M. R. Vissers, J. D. Wheeler, J. Aumentado, J. Hubmayr, J. N. Ullom, and J. Gao, Three-wave mixing kinetic inductance traveling-wave amplifier with near-quantum-limited noise performance, *PRX Quantum* **2**, 010302 (2021).
- [38] D. J. Parker, M. Savytskyi, W. Vine, A. Laucht, T. Duty, A. Morello, A. L. Grimsmo, and J. J. Pla, Degenerate parametric amplification via three-wave mixing using kinetic inductance, *Phys. Rev. Appl.* **17**, 034064 (2022).
- [39] W. Vine, M. Savytskyi, A. Vaartjes, A. Kringhøj, D. Parker, J. Slack-Smith, T. Schenkel, J. C. McCallum, B. C. Johnson, A. Morello, and J. J. Pla, *In-situ* amplification of spin echoes within a kinetic inductance parametric amplifier, *Sci. Adv.* **9**, eadg1593 (2023).
- [40] M. Xu, R. Cheng, Y. Wu, G. Liu, and H. X. Tang, Magnetic field-resilient quantum-limited parametric amplifier, *PRX Quantum* **4**, 010322 (2023).
- [41] M. Khalifa and J. Salfi, Nonlinearity and parametric amplification of superconducting nanowire resonators in magnetic field, *Phys. Rev. Appl.* **19**, 034024 (2023).
- [42] A. E. Kass, C. T. Jin, J. D. Watson, G. C. Gardner, S. Fallahi, M. J. Manfra, and D. J. Reilly, An rf quantum capacitance parametric amplifier, *arXiv:2304.13227*.
- [43] D. Phan, P. Falthansl-Scheinecker, U. Mishra, W. M. Strickland, D. Langone, J. Shabani, and A. P. Higginbotham, Gate-tunable, superconductor-semiconductor parametric amplifier, *Phys. Rev. Appl.* **19**, 064032 (2022).
- [44] G. Butseraen, A. Ranadive, N. Aparicio, K. Rafsanjani Amin, A. Juyal, M. Esposito, K. Watanabe, T. Taniguchi, N. Roch, F. Lefloch, and J. Renard, A gate-tunable graphene Josephson parametric amplifier, *Nat. Nanotechnol.* **17**, 1153 (2022).
- [45] J. Sarkar, K. V. Salunkhe, S. Mandal, S. Ghatak, A. H. Marchawala, I. Das, K. Watanabe, T. Taniguchi, R. Vijay, and M. M. Deshmukh, Quantum-noise-limited microwave amplification using a graphene Josephson junction, *Nat. Nanotechnol.* **17**, 1147 (2022).
- [46] M. Esposito, A. Ranadive, L. Planat, and N. Roch, Perspective on traveling wave microwave parametric amplifiers, *Appl. Phys. Lett.* **119**, 120501 (2021).
- [47] M. Jerger, S. Poletto, P. Macha, U. Hübner, E. Il'ichev, and A. V. Ustinov, Frequency division multiplexing readout and simultaneous manipulation of an array of flux qubits, *Appl. Phys. Lett.* **101**, 042604 (2012).
- [48] E. Jeffrey, D. Sank, J. Y. Mutus, T. C. White, J. Kelly, R. Barends, Y. Chen, Z. Chen, B. Chiaro, A. Dunsworth, A. Megrant, P. J. J. O'Malley, C. Neill, P. Roushan, A. Vainsencher, J. Wenner, A. N. Cleland, and J. M. Martinis, Fast accurate state measurement with superconducting qubits, *Phys. Rev. Lett.* **112**, 190504 (2014).
- [49] A. Ruffino, T.-Y. Yang, J. Michniewicz, Y. Peng, E. Charbon, and M. F. Gonzalez-Zalba, A cryo-CMOS chip that integrates silicon quantum dots and multiplexed dispersive readout electronics, *Nat. Electron.* **5**, 53 (2022).
- [50] M. J. Rahim, T. Lehleiter, D. Bothner, C. Krellner, D. Koelle, R. Kleiner, M. Dressel, and M. Scheffler, Metallic coplanar resonators optimized for low-temperature measurements, *J. Phys. D: Appl. Phys.* **49**, 395501 (2016).
- [51] M. S. Khalil, F. C. Wellstood, and K. D. Osborn, Loss dependence on geometry and applied power in superconducting coplanar resonators, *IEEE. Trans. Appl. Supercond.* **21**, 879 (2011).
- [52] D. J. Niegemann, V. El-Homsy, B. Jadot, M. Nurizzo, B. Cardoso-Paz, E. Chanrion, M. Dartiaill, B. Klemm, V. Thiney, C. Bäuerle, P.-A. Mortemousque, B. Bertrand, H. Niebojewski, M. Vinet, F. Balestro, T. Meunier, and

- M. Urdampilleta, Parity and singlet-triplet high-fidelity readout in a silicon double quantum dot at 0.5 K, *PRX Quantum* **3**, 040335 (2022).
- [53] B. Klemm, V. Elhomsy, M. Nurizzo, P. Hamonic, B. Martinez, B. Cardoso Paz, C. Spence, M. C. Dartiailh, B. Jadot, E. Chanrion, V. Thiney, R. Lethiecq, B. Bertrand, H. Niebojewski, C. Bäuerle, M. Vinet, Y.-M. Niquet, T. Meunier, and M. Urdampilleta, Electrical manipulation of a single electron spin in CMOS using a micromagnet and spin-valley coupling, *npj Quantum Inf.* **9**, 107 (2023).
- [54] C. X. Yu, S. Zihlmann, J. C. Abadillo-Uriel, V. P. Michal, N. Rambal, H. Niebojewski, T. Bedecarrats, M. Vinet, É. Dumur, M. Filippone, B. Bertrand, S. De Franceschi, Y.-M. Niquet, and R. Maurand, Strong coupling between a photon and a hole spin in silicon, *Nat. Nanotechnol.* **18**, 741 (2023).
- [55] F. E. von Horstig, D. J. Ibberson, G. A. Oakes, L. Cochrane, N. Stelmashenko, S. Barraud, J. A. W. Robinson, F. Martins, and M. F. Gonzalez-Zalba, Multi-module microwave assembly for fast read-out and charge noise characterization of silicon quantum dots, *Phys. Rev. Appl.* **21**, 044016 (2024).
- [56] D. M. Pozar, *Microwave Engineering* (John Wiley & Sons, Hoboken, New Jersey, 2011).
- [57] L. Planat, E. Al-Tavil, J. P. Martínez, R. Dassonneville, F. Foroughi, S. Léger, K. Bharadwaj, J. Delaforce, V. Milchakov, C. Naud, O. Buisson, W. Hasch-Guichard, and N. Roch, Fabrication and characterization of aluminum squid transmission lines, *Phys. Rev. Appl.* **12**, 064017 (2019).
- [58] A. Blais, A. L. Grimsmo, S. M. Girvin, and A. Wallraff, Circuit quantum electrodynamics, *Rev. Mod. Phys.* **93**, 025005 (2021).
- [59] C. Braggio, G. Cappelli, G. Carugno, N. Crescini, R. Di Vora, M. Esposito, A. Ortolan, L. Planat, A. Ranadive, N. Roch, and G. Ruoso, A haloscope amplification chain based on a traveling wave parametric amplifier, *Rev. Sci. Instrum.* **93**, 094701 (2022).
- [60] R. Di Vora *et al.*, Search for galactic axions with a traveling wave parametric amplifier, *Phys. Rev. D* **108**, 062005 (2023).
- [61] C. M. Caves, Quantum limits on noise in linear amplifiers, *Phys. Rev. D* **26**, 1817 (1982).
- [62] A. A. Clerk, M. H. Devoret, S. M. Girvin, F. Marquardt, and R. J. Schoelkopf, Introduction to quantum noise, measurement, and amplification, *Rev. Mod. Phys.* **82**, 1155 (2010).
- [63] L. M. Janssen, G. Butseraen, J. Krause, A. Coissard, L. Planat, N. Roch, G. Catelani, Y. Ando, and C. Dickel, Magnetic field dependence of a Josephson traveling-wave parametric amplifier and integration into a high-field setup, *Phys. Rev. Appl.* **22**, 054018 (2024).
- [64] S. De Franceschi, L. Hutin, R. Maurand, L. Bourdet, H. Bohuslavskyi, A. Corna, D. Kotekar-Patil, S. Barraud, X. Jehl, Y.-M. Niquet, M. Sanquer, and M. Vinet, in *2016 IEEE International Electron Devices Meeting (IEDM)* (IEEE, San Francisco, California, 2016), pp. 13-4.
- [65] H. Niebojewski, B. Bertrand, E. Nowak, T. Bédécarrats, B. Cardoso Paz, and L. Contamin, in *2022 IEEE Symposium on VLSI Technology and Circuits (VLSI Technology and Circuits)* (IEEE, Honolulu, Hawaii, 2022).