

Superfluid-Cooled Transmon Qubits under Optical Excitation

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Microwave-to-optical quantum state transfer enables the interconnection of remote superconducting quantum processors via optical-fiber links. Achieving high conversion efficiency necessitates an intense optical pump, yet direct optical exposure of superconducting circuits often degrades their performance. Efficient and fast thermalization of superconducting qubits is therefore essential. To achieve this, we immerse a laser-illuminated transmon qubit in superfluid helium-4 and investigate its behavior. We observe that the qubit recovers significantly faster in superfluid helium than in vacuum, with an improvement in power handling by over 10 dB. This enhanced cooling capacity supports higher optical pump powers, shortening recovery times after high-power optical pulses. These findings open a promising pathway for future efficient implementation of microwave-to-optical quantum transduction devices.

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I. INTRODUCTION

The scalability of superconducting quantum processors [1–5] in large-scale networks hinges on efficient microwave-to-optical quantum transduction [6–12], allowing long-distance communication over optical fibers [13]. Achieving high efficiency requires a strong optical pump to drive the nonlinear processes within transducers under the condition that fragile quantum states are preserved across the electro-optic interface. One approach to minimize the light-induced backaction on superconducting qubits involves placing transducers and qubits on separate chips with one or more rf isolators in between [9,11]. While effective at reducing the impact of emitted thermal microwave photons from the transducer, a large number of isolators not only introduce significant insertion loss but also consume valuable dilution refrigerator space and add significant heat load, limiting scalability. Alternatively, integrating both the superconducting qubit and the transducer on the same chip reduces the footprint. However, it directly exposes the qubit to optical photons [6], resulting

in several deleterious effects. These include quasiparticle generation [14–18], pair-breaking phonon production [19–21], and localized heating in the superconductor caused by low-energy phonons. To accelerate the recovery of circuits after laser illumination, it is beneficial to utilize superconducting materials with inherently short quasiparticle lifetimes on the nanosecond scale. Notable examples include niobium (Nb) [22–26] and niobium nitride (NbN) [27–30]. Additionally, incorporating normal-metal reservoirs within the chip can improve the pair-breaking phonon down-conversion rate [20,21], effectively dispersing energy into low-energy phonons that can no longer break Cooper pairs. Despite progress in suppressing quasiparticle generation and pair-breaking phonon production, mitigating localized heating in the superconductor remains a persistent challenge, requiring further innovation in thermal management strategies.

The limited cooling capacity at millikelvin temperatures restricts both the optical pump power that can be applied and the rate with which qubits can be controlled and read out. In this context, high-capacity cooling is essential and superfluid helium-4 (⁴He) stands out as an ideal coolant choice. Appearing below its lambda transition temperature of 2.17 K at saturated vapor pressure, superfluid ⁴He exhibits unique properties. With remarkable thermal conductivity and high specific heat enabled by nonclassical transport effects [31–34], superfluid ⁴He is widely used as a coolant in advanced superconducting technologies, such as superconducting cavities for particle accelerators [35,36]. In addition, helium immersion cells have proven effective in enhancing thermalization of sensitive quantum

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devices such as two-dimensional electron systems [37,38] and superconducting circuits [39,40] at millikelvin temperatures. However, the zero-viscosity property of superfluid ^4He allows it to penetrate through microscopic holes [41–43], making the integration of optical fibers into a superfluid-tight package challenging [44–46].

In this paper, we examine how superfluid encapsulation can lead to a dramatic improvement of thermal behavior when light is directly coupled to the chip via an optical fiber in the case of a thin-film superconducting transmon qubit. This configuration simulates heating induced by the optical power in a transduction device and its packaging, allowing us to investigate the time dynamics of the properties of the qubit after laser illumination by applying laser pulses in both vacuum and superfluid ^4He . We perform one-tone-spectroscopy and Rabi-oscillation measurements in the presence of laser pulses to characterize the qubit readout and control. In vacuum, the one-tone-spectroscopy time dynamics reveals that following laser illumination, the cavity resonance shifts but does not fully recover in the 2-ms repetition period. Similarly, the Rabi-oscillation time dynamics shows that the excited-state population P_e remains below 0.5 for the first tens of microseconds after the laser pulse, indicating increased energy-relaxation rates due to quasiparticle transport across the junction [47,48]. In contrast, the performance of the circuit recovers significantly faster in superfluid ^4He under identical conditions: while the cavity resonance still shifts, it fully recovers between laser pulses and P_e is capable of reaching 1 immediately after the laser pulse, indicating that T_1 has largely recovered. Additionally, we examine power-handling capabilities in both vacuum and superfluid ^4He and observe an improvement of over 10 dB in superfluid ^4He for both one-tone spectroscopy and Rabi-oscillation measurements. These findings demonstrate that superfluid ^4He effectively thermalizes thin-film superconducting transmon-qubit systems at cryogenic temperatures, achieving an order-of-magnitude improvement in pair-breaking photon power handling. For future quantum transduction devices, superfluid immersion offers the potential for significantly higher optical pump powers and faster circuit recovery and thus promises enhanced quantum transduction efficiency and faster qubit control and readout.

II. METHODS

In Fig. 1(a), we show the layout of the qubit chip used in this work, which comprises four transmon qubits on a silicon substrate: two single-junction qubits and two flux-tunable qubits. The Josephson junctions are Al/AIO_x/Al junctions. The capacitors and the readout cavities are made from Nb. This chip is flip-chip bonded to a second chip, which contains etched cavities lined with Nb to provide microwave mode isolation around all of the active circuit elements on the qubit devices. Fabrication details can be

found in Refs. [49,50]. We focus on the single-junction qubit without direct control lines marked in Fig. 1(a). Both cavity readout and qubit-drive pulses are sent through the transmission line. In Fig. 1(c), we show its Rabi oscillation measured in vacuum. The position of the optical fiber relative to the qubit under test is also depicted in Fig. 1(a). The optical wavelength is fixed at 1550 nm. The qubit chip is placed in a superfluid-tight copper cell with two rf and one optical-fiber feedthroughs [Fig. 1(d)], where the rf feedthroughs use an indium seal and the optical one is sealed with Stycast epoxy (2850FT). The helium-cell design and packaging details are similar to those shown in Refs. [51,52]. As shown in Fig. 1(b), the cell is thermally anchored to the mixing chamber of a dilution refrigerator, operating at 50 mK. ^4He is introduced through a thin stainless-steel capillary line on top of the cell.

III. RESULTS

A. One-tone spectroscopy

We begin by examining the time dynamics of the one-tone spectroscopy following a laser pulse in both vacuum and superfluid ^4He . We illustrate the pulse configuration in Fig. 2(a). The laser-pulse peak power P_{peak} is swept and the delay T_d between the laser pulse and the qubit readout is varied while the laser-pulse width and repetition period are fixed at 5 μs and 2 ms, respectively. In this setup, a parametric amplifier was not used, so relatively long readout windows (9.6 μs) were required to achieve a sufficient signal-to-noise ratio. Instead of capturing a full time-dynamic heat map of the one-tone spectroscopy, we monitor the amplitude at the cavity resonant frequency measured without laser power and track its change over time, similar to a T_1 measurement of a qubit. In Figs. 2(b) and 2(c), we illustrate the time dynamics of the amplitude in vacuum and in superfluid ^4He , respectively. Each trace represents averaged data collected as the delay T_d varies, where negative T_d values indicate that the cavity readout window occurs before the laser pulse. Shaded areas indicate the 95% confidence interval of the data mean value and each trace corresponds to a different P_{peak} .

In vacuum [Fig. 2(b)], when $P_{\text{peak}} = -50$ dBm, the amplitude remains stable regardless of whether the laser pulse is on or off. When $P_{\text{peak}} = -40$ dBm, a peak appears during the laser pulse, suggesting a resonance-frequency shift. Following the pulse, the amplitude decays exponentially but it does not fully return to the baseline measured with $P_{\text{peak}} = -50$ dBm, indicating that the heat generated by the laser pulse does not fully dissipate in the 2-ms repetition period. The repetition period is 3 orders of magnitude longer than the cavity-photon lifetime, effectively ruling out influence from the cavity ring-down process on the measured time dynamics. With a further increase of P_{peak} to -30 dBm, the laser-induced heating is more pronounced, causing a larger peak during the

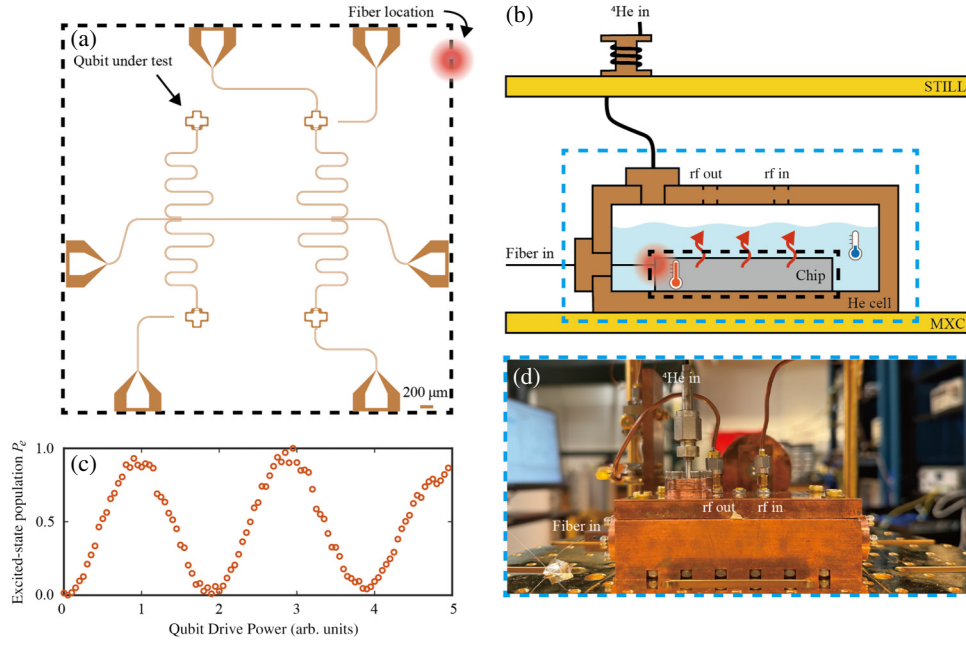


FIG. 1. (a) The qubit-chip layout. The chip contains four transmon qubits: two single-junction qubits (on the left) and two flux-tunable qubits (on the right). The qubit used in this work is the single-junction qubit located in the upper left corner, which has no direct control lines. The red spot in the upper-right corner of the chip indicates the location of the optical fiber. (b) A schematic of the experimental setup. “STILL” and “MXC” refer to the still plate and mixing chamber of the dilution refrigerator. The helium immersion cell, thermally anchored to the MXC, is equipped with two rf feedthroughs on top and an optical-fiber feedthrough on the side. ^4He is introduced through a thin capillary line that is thermally anchored at each stage of the dilution refrigerator. (c) Rabi oscillation measured in vacuum. (d) The helium immersion cell mounted in the dilution refrigerator.

pulse and a higher baseline afterward. If the first data point with $P_{\text{peak}} = -30$ dBm is compared to its corresponding value with $P_{\text{peak}} = -50$ dBm, there is a 11.8-dB baseline increase. We use a single-exponential decay model to fit the decay curves. The curves with $P_{\text{peak}} = -30$ dBm and $P_{\text{peak}} = -40$ dBm have time constants of 55 μs and 96 μs , respectively. The shorter time constant when $P_{\text{peak}} = -30$ dBm could be related to shorter quasiparticle lifetimes [22,53], higher phonon down-conversion rates, and a higher cooling power at higher temperatures. The inset sketch illustrates three selected points within a single trace at different T_d , capturing the one-tone spectroscopy before (I), during (II), and after (III) the laser pulse. From I to II, the resonance down-shifts with a reduction in quality factor Q . Between II and III, the resonance partially shifts back, with a partial Q recovery. The dashed line represents the probe frequency, illustrating the relative amplitude in each case.

In superfluid ^4He [Fig. 2(c)], when P_{peak} is set to -40 dBm, the peak during the laser pulse is suppressed. The difference between the baseline with $P_{\text{peak}} = -40$ dBm in Fig. 2(c) and that with $P_{\text{peak}} = -50$ dBm in Fig. 2(b) is due to the change of Q and the overall background when the device is immersed in superfluid ^4He . When P_{peak} is increased to -30 dBm and -20 dBm, a similar phenomenon can be observed: higher optical powers

produce greater-magnitude peaks during the laser pulse, followed by an exponential decay. However, the difference is that the baseline amplitudes after the decay are significantly lower than those in vacuum. For $P_{\text{peak}} = -30$ dBm, the baseline returns to the same level as that observed with $P_{\text{peak}} = -40$ dBm over the 2-ms period between laser pulses. With $P_{\text{peak}} = -20$ dBm, the baseline is slightly elevated, with an increase of 3.5 dB. These results indicate that superfluid ^4He effectively dissipates heat and enhances thermalization of the chip with an improvement in power handling of more than 10 dB. If we fit the decay curves for $P_{\text{peak}} = -20$ dBm and $P_{\text{peak}} = -30$ dBm using a single-exponential decay model, the fitted time constants are 117 μs and 72 μs , respectively. The longer time constants in superfluid ^4He compared to vacuum could be attributed to longer quasiparticle lifetimes and reduced phonon down-conversion rates, both enabled by faster thermalization to the base temperature following the laser pulse in superfluid ^4He . However, the longer time constant observed at the higher P_{peak} in superfluid ^4He runs counter to the observation in vacuum. This could be related to different quasiparticle and phonon dynamics when the device is immersed in superfluid ^4He . We have not fully understood the underlying mechanisms yet. Giving a definite explanation would require more data and a specialized setup, which could be done in future work.

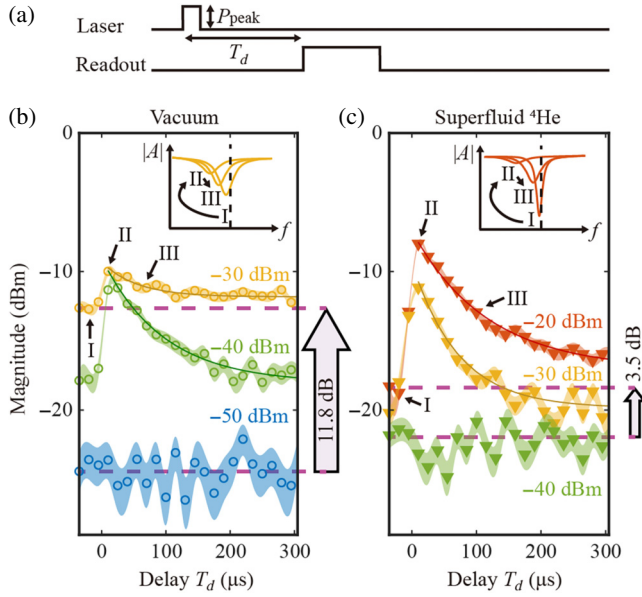


FIG. 2. (a) The pulse configuration for the one-tone-spectroscopy measurement. The laser-pulse peak power P_{peak} is varied and the delay T_d between the laser pulse and the cavity readout window is swept. The laser-pulse width and repetition period are fixed at 5 μs and 2 ms, respectively. (b),(c) The results in (b) vacuum and (c) superfluid ^4He as T_d is swept in 15- μs steps. In both cases, data points are measured at the resonant frequencies with no applied laser power and the solid colored lines represent single-exponential fits to the corresponding data. The shaded regions indicate the 95% confidence interval of the data mean value. The dashed purple lines denote baseline values from the first data point for selected power levels, showing an increase of 11.8 dB in (b) and 3.5 dB in (c). The insets illustrate sketched schematics of resonance shifts over time at delay points I, II, and III, with the vertical dashed lines indicating the probe frequencies. Power levels: blue, -50 dBm; green, -40 dBm; yellow, -30 dBm; red, -20 dBm.

The comparison between Figs. 2(b) and 2(c) not only highlights the excellent thermal performance of the superfluid ^4He but also helps reveal the possible underlying mechanisms during the process. The photoresponse of a superconducting circuit involves three main effects: quasiparticle generation [14–18], pair-breaking phonon production [19–21], and localized heating in the superconductor caused by low-energy phonons. In vacuum, when the laser pulse is turned on, the abrupt magnitude increase could be attributed to quasiparticle generation induced by direct light absorption in the superconductor. This process arises from the interaction between photons and Cooper pairs, leading to pair breaking. The timescale for this mechanism is extremely short, typically on the sub-nanosecond to nanosecond scale for Nb [54] and aluminum (Al) [55]. Another possible mechanism contributing to the abrupt magnitude change involves pair-breaking phonons. Pair-breaking phonons are emitted when quasiparticles

recombine. These phonons can break additional Cooper pairs or inelastically scatter, eventually down-converting to lower energies. In our measurements, the precise transition time is obscured by the 15- μs T_d sweep step and the 9.6- μs readout window. Consequently, we are unable to distinguish between these two contributing mechanisms within the constraints of our setup. However, the resonance frequency shift induced by the laser pulse should primarily originate from their influence on the qubit rather than the cavity itself. To support this, a similar measurement is performed on the same readout cavity, which is fully decoupled from the qubit by raising rf power. Under identical laser-pulse conditions as used in Fig. 2, the resonant frequency exhibited negligible shift, indicating that the observed frequency shift in Fig. 2 is predominantly due to changes in the qubit properties. When the laser pulse is turned off, in addition to quasiparticle and pair-breaking phonon dynamics, localized heating in the superconductor dissipates gradually, restoring thermal equilibrium. In superfluid ^4He , the existence of the peak with high laser power suggests that superfluid ^4He cannot suppress light-induced quasiparticle generation. The nearly full recovery of the resonance before the next laser pulse indicates fast thermalization of the system facilitated by superfluid ^4He . This occurs at the extended area of the superconductor-helium interface compared to the superconductor-substrate interface, as it provides an additional pathway for phonons to escape from the superconductor. Moreover, considering that the exceptionally high thermal conductivity of superfluid ^4He ensures rapid dissipation and thermalization of the transmitted heat, either the quasiparticle recombination rate or the phonon down-conversion rate could be the limiting factor of the recovery. Specifically, if the recovery is limited by quasiparticle recombination, given that Al has a relatively long quasiparticle lifetime [53,56,57] compared to Nb [22–26], quasiparticles generated in the Al/ AlO_x /Al junction are the possible limiting factor.

B. Rabi-oscillation measurement

The one-tone-spectroscopy measurements suggest that superfluid ^4He significantly enhances the readout performance of a laser-illuminated qubit. Building on this, we aim to assess the extent to which superfluid ^4He improves qubit control under similar conditions. To explore this, we examine the time dynamics of Rabi oscillations following laser illumination in both vacuum and superfluid ^4He . The pulse configuration is shown in Fig. 3(a). In the time-dynamics measurements, T_d is varied while P_{peak} and the laser-pulse width are set to -40 dBm and 100 ns, respectively. We also fix the qubit-drive frequency. This laser-pulse duration is kept short to minimize its impact on the readout cavity and isolate the direct influence on the qubit itself. The laser-pulse repetition period is 2 ms

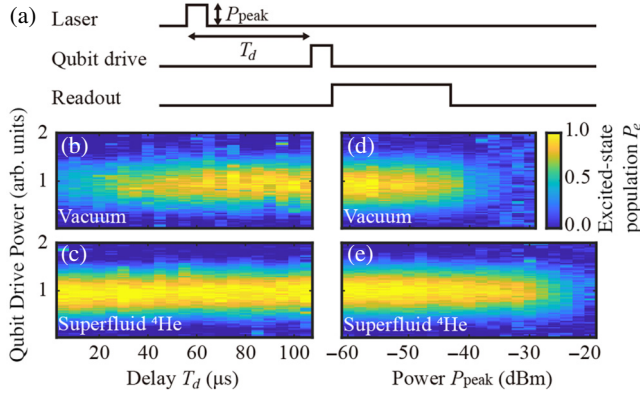


FIG. 3. (a) The pulse configuration for Rabi-oscillation measurement. The laser pulse is repeated every 2 ms in vacuum and 1 ms in superfluid ^4He . The qubit readout occurs immediately following the qubit-drive pulse with a 32-ns pulse width. (b),(c) Results in (b) vacuum and (c) superfluid ^4He as T_d is varied with a 5- μs step. For (b) and (c), P_{peak} and the laser-pulse width are fixed at -40 dBm and 100 ns, respectively. (d) Results in vacuum as P_{peak} is swept from -60 dBm to -30 dBm with a 2-dB step. (e) Results in superfluid ^4He as P_{peak} is swept from -60 dBm to -20 dBm with a 2-dB step. For (d) and (e), T_d and the laser-pulse width is fixed at 4 μs and 100 ns, respectively. (b)–(e) are measured column by column.

in vacuum and 1 ms in superfluid ^4He due to the cooling effect when the device is immersed in superfluid ^4He .

In Fig. 3(b), we present a time-dynamics heat map measured in vacuum, where each column represents a Rabi-oscillation measurement taken at a specific T_d . The first column, corresponding to $T_d = 5$ μs , shows that P_e is significantly suppressed immediately after the laser pulse. Approximately 20 μs after the laser pulse, P_e begins to increase. Extracting the time evolution of P_e at the π -pulse point along the horizontal axis in Fig. 3(b) yields the red dots shown in Fig. 4. An exponential fit to these data reveals a time constant of about 35 μs . Notably, although P_e is initially reduced, the Rabi-oscillation rate remains constant throughout the process, indicating that the qubit frequency does not shift following the laser illumination.

In contrast to the behavior in vacuum, the time dynamics in superfluid ^4He remains remarkably stable after the laser pulse, as shown in Fig. 3(c): both P_e and the Rabi-oscillation rate stay constant. To further test the effectiveness of the superfluid ^4He , we perform a Rabi-oscillation measurement just 1 μs after the laser pulse, finding no degradation in P_e and no change in the oscillation rate. In short, the results in superfluid ^4He show that the qubit is resilient to laser illumination, even with a doubled laser repetition rate. The time dynamics observed in vacuum versus superfluid ^4He suggest that localized heating in the superconductor is the primary source of loss in the Josephson junction under this laser configuration, highlighting the exceptional heat-dissipation properties of superfluid ^4He .

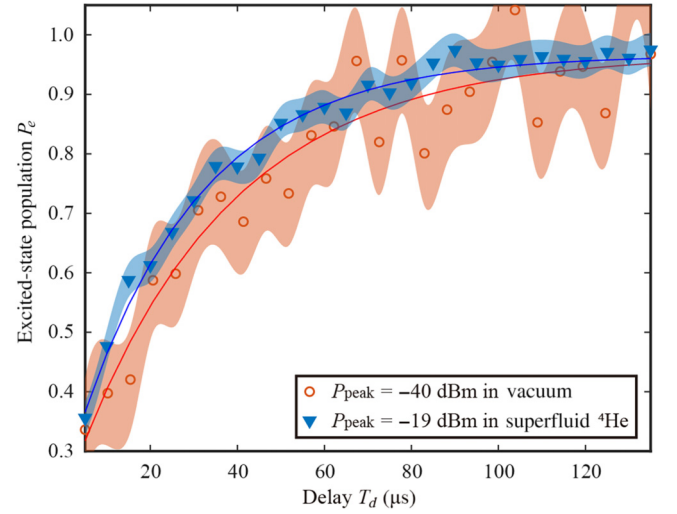


FIG. 4. The time evolution of P_e at the Rabi-oscillation π -pulse point in both vacuum (red) and superfluid ^4He (blue). The red data points are extracted from Fig. 3(b) with a qubit-drive π pulse, while the blue data points are measured with a qubit-drive π pulse as the delay T_d varies. For the red data points, the laser-pulse peak power P_{peak} is set to -40 dBm. For the blue data points, the effective P_{peak} is -19 dBm, taking the laser-pulse repetition period into account. The solid colored lines are single-exponential decay fittings to the corresponding data points. The shaded regions represent the 95% confidence interval of the data mean value. Note that the blue data points are measured with 6 times the averaging of the red data points.

In addition to the time-dynamics measurements, we vary P_{peak} to compare the power-handling capabilities of the system in both vacuum and superfluid ^4He . Here, T_d is fixed at 4 μs . The laser-pulse width is set to 100 ns, with a repetition period of 2 ms in vacuum and 1 ms in superfluid ^4He . In vacuum, as shown in Fig. 3(d), P_{peak} is swept from -60 dBm to -30 dBm. Initially, with lower P_{peak} , P_e remains stable. However, as P_{peak} approaches -50 dBm, P_e begins to degrade, becoming entirely suppressed when P_{peak} exceeds -40 dBm. Immersing the chip in superfluid ^4He significantly enhances its power-handling capability. As shown in Fig. 3(e), P_{peak} is swept from -60 dBm to -20 dBm and P_e remains stable even when P_{peak} is -40 dBm. P_e is only notably suppressed when P_{peak} exceeds -30 dBm. This more than 10-dB improvement in power handling in superfluid ^4He further confirms the exceptional heat-transport properties of superfluid ^4He . It is also worth noting that the Rabi-oscillation rate remains unchanged, as P_{peak} increases in both vacuum and superfluid ^4He .

At high P_{peak} , the amplitude of Rabi oscillations in superfluid ^4He still degrades. A plausible explanation is that the dominant loss mechanism changes—from localized heating in the superconductor to quasiparticles and pair-breaking phonons. To explore this further, we set $P_{\text{peak}} = -22$ dBm, where P_e is already suppressed with

$T_d = 4 \mu\text{s}$ in superfluid ^4He and measured the time evolution of P_e at the π -pulse point. The results, shown as blue dots in Fig. 4, reveal an exponential decay with a time constant of about $28 \mu\text{s}$, comparable to the time constant observed in vacuum. This similarity suggests that P_e degradation with high P_{peak} originates from the same underlying mechanism in both vacuum and superfluid ^4He , which could be related to quasiparticles and pair-breaking phonons near the Al/AIO_x/Al junction.

IV. DISCUSSION AND CONCLUSIONS

When we perform the Rabi-oscillation measurement with laser pulses in superfluid ^4He , we observe significantly faster qubit recovery post laser illumination and a substantial improvement of over 10 dB in power handling, even with a doubled laser-pulse repetition rate compared to that used in vacuum. This enhancement opens up the feasibility of fabricating both the superconducting qubit and the optical transducer on a single chip, bringing added benefits for quantum system integration. When a combined qubit-transducer chip is immersed in superfluid ^4He , the superfluid not only helps stabilize qubit operations under optical pumping but also supports the microwave cavity in the transducer, maintaining stable performance even under high optical power [58,59]. This dual functionality of superfluid ^4He can improve transduction efficiency and yield higher transduction data throughput with shorter repetition period.

The time dynamics of Rabi oscillations reveal the effectiveness of superfluid ^4He in enhancing qubit control under optical excitation, indicating that superfluid ^4He could also stabilize qubit T_1 and T_2 following laser illumination. However, the $9.6\text{-}\mu\text{s}$ readout window poses limitations for examining such effects. This readout window would inadvertently average out any faster time dynamics. Future investigations could address this challenge by adding a parametric amplifier in the output line and shortening the readout window. Such research could deepen our understanding of how superfluid ^4He interacts with superconducting qubits under optical excitations, potentially enhancing the stability and resilience of quantum systems in optically active environments.

The analysis in the previous section shows that quasiparticle and pair-breaking phonon dynamics would slow down the circuit recovery post laser illumination. To enable qubit control and readout with short repetition periods following laser illumination, both the quasiparticle recombination rate and the phonon down-conversion rate need to be enhanced. Achieving faster quasiparticle recombination, potentially on the microsecond or even nanosecond scale, necessitates exploring alternative materials for Josephson junctions. Nb [22–26] and NbN [27–30] are promising candidates due to their nanosecond-scale quasiparticle lifetimes. Recent advancements have shown that

Nb/Al/AIO_x/Al/Nb [60] and NbN/AlN/NbN [61] Josephson junctions can be fabricated with T_1 and T_2 on the order of tens of microseconds, maintaining high performance while offering the potential for reduced recovery times. Moreover, the higher energy gap of Nb and NbN compared to Al can also mitigate the device sensitivity to thermal quasiparticles [62]. Furthermore, to increase the phonon down-conversion rate, incorporating normal-metal reservoirs or traps into the chip design has been demonstrated to effectively reduce the losses associated with pair-breaking phonons [20,21]. Implementing the methods outlined above would also accelerate the conversion of pair-breaking photons and phonons into localized heating in the superconductor. In such scenarios, the role of superfluid ^4He becomes even more crucial, as its efficient phonon-transport properties and exceptional thermal conductivity are vital for rapidly dissipating heat and maintaining thermal stability in the system.

The helium cell used in this work is compatible with larger qubit chips. The main packaging challenge arises from the increased number of rf and optical feedthroughs, which makes achieving a superfluid-tight seal more complex. The observed more than 10-dB power-handling improvement is also expected to hold for larger systems, as circuit recovery in this work appears to be limited by the quasiparticle and phonon dynamics rather than the localized heating in the superconductor. This suggests that the cooling capacity of superfluid ^4He is not saturated.

To summarize, the present study immerses a thin-film superconducting transmon-qubit chip in superfluid ^4He and performs time-dynamics measurements of one-tone spectroscopy and Rabi oscillations, comparing results in both vacuum and superfluid ^4He . The associated findings demonstrate that superfluid ^4He serves as an efficient coolant for quantum superconducting circuits, significantly enhancing thermal handling and supporting improved qubit performance under optical excitation. In the broader context of quantum information processing [63–65], the enhanced stability and power handling provided by superfluid ^4He could significantly advance hybrid quantum systems, making optically active superconducting devices more reliable for tasks such as photon-to-qubit state transduction [6–11,66] and scalable quantum network construction [67–69].

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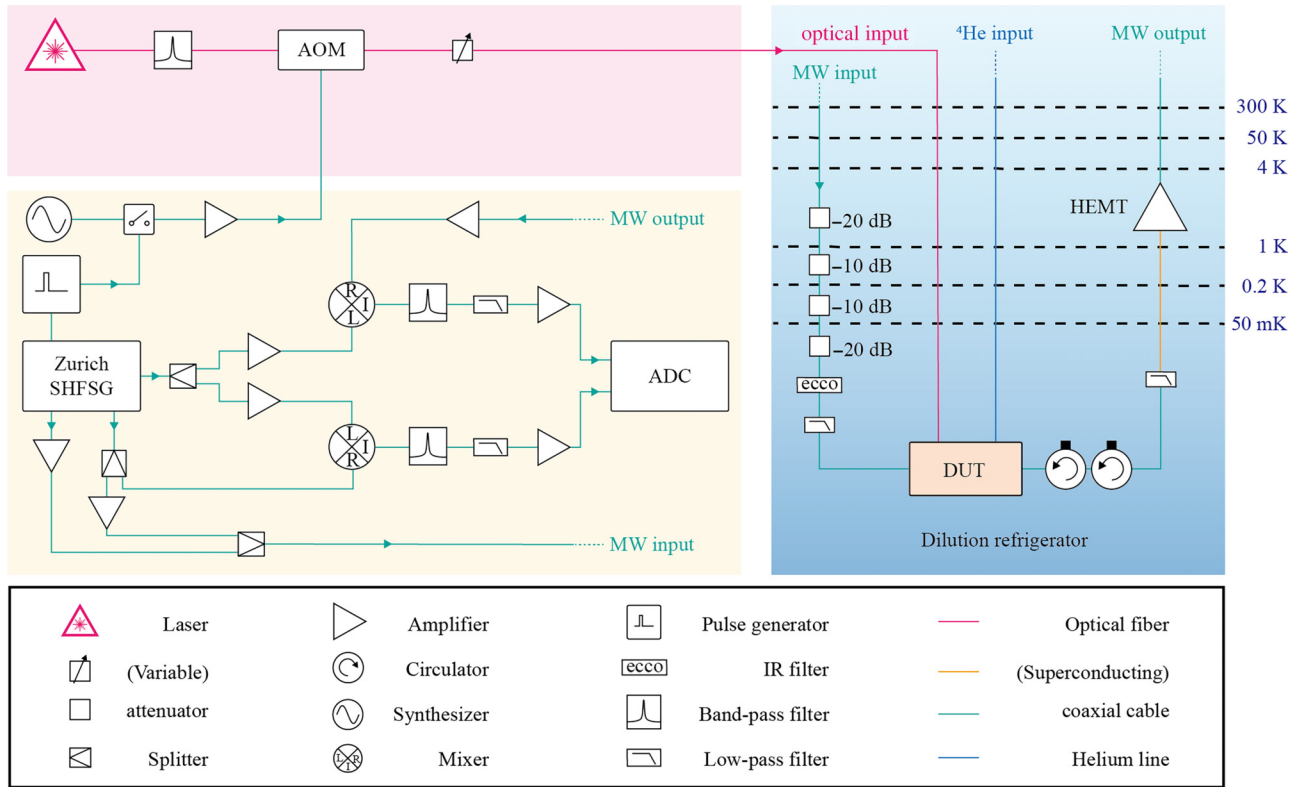


FIG. 5. The full measurement network. The entire measurement setup is divided into three sections: optical, rf, and dilution refrigerator. On the optical side, a tunable continuous-wave laser serves as the light source, operating at 1550 nm. Optical pulses are generated using an 80-MHz acousto-optic modulator (AOM), enabling precise control over the pulse width and repetition rate. These modulated pulses are delivered to the superconducting resonators via a fiber-coupled optical system. On the rf side, the qubit-drive and cavity-probe tones are generated by a Zurich Instruments SHFSG signal generator and sent to the device under test (DUT) through the input line. The transmitted signal is collected at the output port, amplified, and demodulated to 75 MHz using a mixer. A reference tone, split from the cavity-probe tone, is similarly demodulated to correct the phase drift in the system. Both signals are processed by an analog-to-digital converter (ADC) to extract the amplitude and phase information. The AOM, SHFSG, and ADC are synchronized to enable precise time-resolved measurements in response to laser pulses. Inside the dilution refrigerator, the microwave input line consists of 60-dB attenuators and filters to suppress the thermal noise. The microwave output line includes a high-electron-mobility transistor (HEMT) amplifier at the 4-K stage for signal amplification. ^4He is introduced through a commercial stainless-steel capillary line, extending from room temperature to the mixing chamber, with thermal anchoring at every plate for efficient heat sinking.

Dafei Jin, Xu Han, and Xinhao Li for discussion on the implementation of the helium cells and Jiacheng Xie for valuable discussions. The Air Force Research Laboratory (AFRL) discloses that this work is categorized as Approved for Public Release; Distribution Unlimited: PA# AFRL-2025-0655. Any opinions, findings, and conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the AFRL. We would like to thank Yuvraj Mohan and the Rigetti Quantum Foundry Services team for design support and device fabrication of the transmon studied in this work.

DATA AVAILABILITY

The data that support the findings of this paper are not publicly available upon publication because it is

not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

APPENDIX: EXPERIMENTAL SETUP

The full measurement-setup diagram as well as the description can be found in Fig. 5.

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