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Millikelvin temperature cryo-CMOS multiplexer for scalable quantum device characterisation

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Abstract
Quantum computers based on solid state qubits have been a subject of rapid development in recent years. In current noisy intermediate-scale quantum technology, each quantum device is controlled and characterised through a dedicated signal line between room temperature and base temperature of a dilution refrigerator. This approach is not scalable and is currently limiting the development of large-scale quantum system integration and quantum device characterisation. Here we demonstrate a custom designed cryo-CMOS multiplexer operating at 32 mK. The multiplexer exhibits excellent microwave properties up to 10 GHz at room and millikelvin temperatures. We have increased the characterisation throughput with the multiplexer by measuring four high-quality factor superconducting resonators using a single input and output line in a dilution refrigerator. Our work lays the foundation for large-scale microwave quantum device characterisation and has the perspective to address the wiring problem of future large-scale quantum computers.

1. Introduction

Quantum computing technology is a subject of intense research and development. Numerous groups have already demonstrated quantum processors containing several tens of quantum bits (qubits) with unprecedented gate fidelities [1–4]. A path forward is being explored both in the near-term noisy intermediate-scale quantum computer direction with up to a few hundreds of qubits on a chip [5, 6], as well as in the direction of a fully fault-tolerant quantum computer with projected millions of qubits [7, 8].

To scale up quantum processors, several technological challenges still need to be solved in terms of device fabrication [9–11], high-performance control electronics [12, 13] and system integration [14–16]. For example, current implementations require each qubit to have at least one control line between room temperature (RT) electronics and the base plate in a dilution refrigerator [14, 16]. This is not a scalable strategy for devices containing thousands of qubits, due to spatial limitations and the limited cooling power of dilution refrigerators [17].

Furthermore, state-of-the-art quantum devices exhibit large parameter variations [10, 11]. In frequency crowded multiqubit systems, this can lead to an accidental spectral overlap and consequently reduce quantum gate and process fidelities [18]. To improve device reproducibility, the fabrication process is migrating from laboratory environments to industrial-level 200 mm/300 mm fabrication facilities [10]. Equipment developed for mature semiconductor technologies in these facilities offer low variability,
Figure 1. Cryo-CMOS multiplexer for microwave signal routing. (a) Schematic of a large-scale characterisation platform for QDUT or a multiqubit processing platform. Cryo-CMOS multiplexer and demultiplexer reduce the number of required input and output RF lines from the RT to the base temperature stage (0.01 K) of a dilution refrigerator. (b) Photograph of a PCB containing the CMOS-multiplexer device. (c) Micrograph of the cryo-CMOS multiplexer chip. (d) Simplified circuit schematic of the multiplexer. RF1–RF4 are the four input RF ports, RFC is the common RF output port, A–D are DC or low frequency select lines for the multiplexer. (e) Chip layout showing spatial configuration of the CMOS multiplexer device. Protective IO ring (blue, cyan) surrounds the digital control logic core and switch transistors. RF ports and CMOS control lines are denoted at the edge: D0, D1, LE low frequency control lines are used for the parallel interface and CLK, SI, PS, LE for the serial control interface. All ports without a label are connected to $V_{ss}$ (ground).

near-atomic scale precision and production of a large number of devices, enabling statistical-level electrical characterisation [19]. The latter provides a valuable insight into the material properties at room and cryogenic temperatures, as well as enables further development of fabrication processes [19, 20]. However, massive characterisation of quantum devices at cryogenic temperatures is limited by a non-scalable number of required input and output lines in a dilution refrigerator [17].

To alleviate the wiring problem and increase characterisation throughput, a multiplexing scheme is needed at the base temperature of the dilution refrigerator (figure 1(a)) [17]. In such a scheme, a user interface and classical computing/control platform communicates with the control and readout electronics using minimal number of lines. Control electronics based on cryo-CMOS technology can be placed at the 1–4 K stage in the refrigerator to improve noise performance and lower latency for feedback and feedforward experiments [12, 13]. Control electronics sends the signals to the millikelvin stage using a small number of lines, where multiplexers and demultiplexers distribute them to many individual quantum devices for increasing characterisation throughput, or to address a single multiqubit chip for quantum information processing applications.

Several approaches to signal multiplexing at millikelvin temperatures have already been explored, however, they do not satisfy the necessary requirements needed for scalable quantum device characterisation or multiqubit control, related to frequency range, insertion loss, isolation and heat dissipation. Commonly used devices for multiplexing signals over a large frequency range are electro-mechanical switches [21–23]. Despite high microwave isolation between ports and no heat dissipation in the idle state, the large physical size and strong Joule heating during state change does not make it suitable for scalable device characterisation [22]. Routing microwave signals at millikelvin temperatures without heat dissipation was demonstrated with nanowires [24] and Josephson-junction devices [25–27], however, these devices have limited bandwidth (<2 GHz) [25, 26] and low dynamic range [24]. Very low heat dissipation during switching and no dissipation in idle state was achieved with a phase change switch [28]. Possible creation of infrared radiation due to high local peak temperatures of 1350 K and high insertion loss make phase change switch less suitable for quantum device characterisation. FET transistors based on CMOS [29] or HEMT [30] technology were also used for microwave signal multiplexing, but their implementation exhibited limited bandwidth (~20 MHz) [29] and high (>10 dB) insertion loss in the 4–8 GHz frequency range [30]. Scalable DC characterisation was recently demonstrated with CMOS technology. DC multiplexers were either cointegrated with device under test (DUT) [29, 31, 32], built as a separate unit with off-the-shelf CMOS components [20] or with custom designed CMOS chips [19]. Scalable qubit control electronics was recently demonstrated for spin qubits [33–37], however, high-frequency and high-performance signal multiplexers required for microwave device characterisation and qubit control for superconducting qubit technology have not yet been demonstrated.
Here, we report on a custom designed proof-of-principle cryo-CMOS multiplexer for scalable quantum device characterisation. The multiplexer can be controlled with a parallel or serial interface, has a large bandwidth (DC-10 GHz), very low insertion loss (1.6 dB at 6 GHz), high isolation (34 dB at 6 GHz), nanosecond switching times and moderate heat dissipation (36.2 µW) at millikelvin temperatures. We demonstrate the use of the multiplexer by characterising intrinsic microwave loss in four superconducting lumped-element resonators (LERs) with intrinsic Q-factors ranging from $10^4$ to $7 \times 10^6$ at microwave powers corresponding to a single photon in a resonator. The demonstrated scheme simulates short-loop scalable characterisation of microwave loss sources introduced by different fabrication steps. This is critical for fabrication process development of high-performance superconducting qubits. We verify that the residual heat dissipation does not influence measured resonator performance. The demonstrated technology paves the way to scalable quantum device characterisation of resonators [38], microwave kinetic inductance detectors [39], quantum-limited amplifiers [40], as well as superconducting [41] and spin qubits [42]. This work also explores the interaction between cryo-CMOS electronics and superconducting qubits with a perspective of cryo-CMOS-controlled time-division multiplexing of multiqubit control signals.

2. Cryo-CMOS multiplexer

A single-pole-4-throw (SP4T) reflective CMOS multiplexer is custom-designed using standard TSMC 28 nm HPC + technology and optimized for low microwave insertion loss and high isolation between input and output ports (figure 1). The multiplexer device is designed to operate over a wide frequency range, from DC to 10 GHz (figure A1 in supplementary material A (https://stacks.iop.org/QST/7/015004/mmedia)), and a wide temperature range. All four input RF ports can be selectively connected or disconnected from the common RF port (RFC) using four pairs of series and shunt switch NMOS transistors, as shown in the simplified circuit schematics in figure 1(d).

A series-shunt switch topology [43] is chosen to increase the isolation despite a small increase in insertion loss caused by the shunt switch transistor. The optimal insertion loss and isolation is realized with minimum length and optimized width of NMOS transistors. The optimal width is chosen such that the ‘on’-state resistance ($R_{on} < 10 \, \Omega$) of the switch is small compared to the 50 $\Omega$ transmission line impedance, while keeping an acceptably low ‘off’-state capacitance ($C_{off} < 50 \, \text{fF}$). To further reduce the insertion loss of the device, a 450 pH inductor is added to the common RF port (RFC) to match the output impedance of the on-chip switches to the 50 $\Omega$ impedance of the transmission line (figure 1(d)). Since signal absorption at un-selected ports is not needed for presented application, a reflective switch topology is chosen to maintain low insertion loss in the signal path. The control logic core and large switching transistors are protected by a surrounding input–output (IO) ring, shown in blue and cyan in figure 1(e), which provides protection against electrostatic discharge (ESD). The digital logic and the surrounding IO ring are designed with the standard (RT) libraries. No design optimization is made for cryogenic operations.

The multiplexer can be controlled by either a parallel or a serial interface. The parallel interface requires $\log_2(N) + 1$ digital interface lines, where $N$ is the number of multiplexer ports, and a serial interface requires only four digital interface lines independent of the number of multiplexer ports. However, the serial interface programing time scales linearly with the number of ports ($t = N \cdot t_{clk}$, where $t_{clk}$ is the clock period), which can become noticeable for large number of ports. The number of digital interface lines in the multiplexer is significantly smaller than the number of lines $(N + 1)$ required to operate a mechanical switch, especially for large $N$ [21, 22]. In addition to reducing the number of RF lines between room and base temperature plates in a dilution refrigerator, parallel and serial interfaces therefore also drastically reduce the number of digital interface lines. This makes cryo-CMOS multiplexers ideal for large-scale device characterisation or for distributing signals to a large quantum computing processor.

We highlight that the small physical chip size ($1.12 \times 1.12 \, \text{mm}^2$) and compact design of presented cryo-CMOS multiplexer (figure 1) allows to allocate more available refrigerator space to quantum DUT (QDUT), thereby further increasing characterisation throughput. The size of the printed circuit board (PCB), currently set by the size of five SMP connectors, can be further reduced in future designs using multi-port RF connectors or adding QDUTs on the same PCB.

3. Cryo-CMOS multiplexer characterisation

The presented cryo-CMOS multiplexer operates over a wide temperature range between RT and 32 mK. The lowest temperature is the base temperature of the dilution refrigerator with fully powered multiplexer attached to the base plate. We have thermally cycled multiplexers between RT and millikelvin temperatures...
more than 10 times and did not observe any performance degradation in terms of insertion loss or isolation. Microwave properties of a multiplexer device are characterised at both room and 32 mK temperature. Characterisation at cryogenic temperature is limited to the 4–8 GHz bandwidth by a bandpass filter and an HEMT amplifier mounted on the output line in the dilution refrigerator (figure A2(a) in supplementary material A). The insertion loss is measured as a $S_{21}$ scattering parameter through the multiplexer input port RF4 and output port RFC with RF4 port internally connected to RFC (‘on’ state). Isolation is measured between the same ports, but with all input ports internally shunted (‘off’ state).

RT and low-temperature insertion loss measurements agree well with the RT and $-40^\circ C$ insertion loss simulations as shown in figure 2(a). We note that $-40^\circ C$ is the lowest temperature at which available transistor models are specified. 1–2 dB discrepancy between RT measurements and simulations come from losses in PCB and packaging which are not included in simulations. The insertion loss at 32 mK ranges between 1 and 3 dB with $\sim 1.6$ dB at 6 GHz. Similarly, both room- and low-temperature measurements of the isolation agree well with RT and $-40^\circ C$ simulations. The low-temperature isolation ranges between 30 and 40 dB with $\sim 34$ dB at 6 GHz (figure 2(c)). Comparable microwave properties confirm that the device performs nominally over a wide operation temperature range down to millikelvin temperatures. In fact, the insertion loss reduces by $\sim 0.9$ dB at 6 GHz between room and 32 mK temperature. This is attributed to higher conductance of the copper transmission lines on the chip and PCB at low temperatures. The insertion loss is relatively constant in the 4–8 GHz frequency range with reduced performance expected above 10 GHz due to the SMP PCB mount connector and bond wires on the PCB (figure A1 in supplementary material A). Isolation shows a noticeable frequency dependence resulting in $\sim 10$ dB reduction between 4 and 8 GHz, which is within the experimental uncertainty independent of temperature. This behaviour is attributed to the frequency dependent signal leakage through the parasitic capacitance of the series switch transistors in the ‘off’ state.

The multiplexer is designed to operate at a supply voltage of $V_{dd} = 0.9$ V, however, it is important to study device performance also at reduced $V_{dd}$ in order to explore device limits and power dissipation. When lowering the supply voltage, both insertion loss and isolation degrade (figures 2(b) and (d)). At millikelvin temperature, the multiplexer stops operating at $V_{dd}(stop) = 0.475$ V at which point both isolation and insertion loss become 21.4 dB. At $V_{dd}(stop)$ the gate–source voltage of NMOS switching transistors falls
below their threshold voltage. At RT microwave properties degrade slower with lowering supply voltage and reach a lower $V_{dd,\mathrm{stop}}$ of $\sim 0.1$ V. RT simulations qualitatively agree with the measurements. Shallower measured sub-threshold slope likely results from a finite distribution of transistors’ threshold voltages on a physical device, which is not captured by simulations. The increase of $V_{dd,\mathrm{stop}}$ and stronger $V_{dd}$ dependent insertion loss and isolation at lower temperatures is in agreement with the increase of the threshold voltage and steeper subthreshold slope of NMOS transistors at lower temperatures [44, 45]. This is also indicated by simulations performed at $-40$ °C.

At $32$ mK, the cryo-CMOS multiplexer dissipates $36.2 \mu W$ at the nominal supply voltage of $V_{dd} = 0.9$ V (figure A3(b) in supplementary material A). This is responsible for a slightly elevated dilution refrigerator temperature of $32$ mK compared to $\sim 10$ mK when the multiplexer is powered off (figure A3(b) in supplementary material A). This static heat dissipation does not depend on the multiplexer state and no dynamic dissipation above the measurement uncertainty of $\sim 15$ nW can be observed during operational state switching when using either parallel or series control interface. The operational state switching frequency does not exceed $10$ mHz for the demonstrated application. We attribute the residual static dissipation to a small leakage in $126$ large clamping transistors in the protective IO ring (see figure 1(e)). To verify this claim, we independently measured current though two parallel ESD protection cells at $4$ K. The results show that ESD cell leakage directly scales with $I_{dd}$ measured though the multiplexer at low temperature, confirming our claim (see figure A3(a) in supplementary material A). We note that device simulations with foundry models at $-40$ °C yield approximately two orders of magnitude lower leakage current, in contrast to the experiment. The development of accurate CMOS transistor models at deep cryogenic temperatures is therefore needed and necessary to design and optimize future cryogenic CMOS devices.

To characterise the switching dynamics at millikelvin temperatures, we measured the switching time of the cryo-CMOS multiplexer. The signal rise time is $1.2$ ns at $6$ GHz and $1.8$ ns at $4$ GHz (figure A4 in supplementary material A). This rise time is mainly caused by the RC time constant of the NMOS switch transistor. With an optimized biasing circuit, the rise time can be further reduced without increasing the insertion loss in future designs.

4. Scalable millikelvin device characterisation

Reducing intrinsic microwave loss in superconducting quantum devices is essential for fabricating high-performing qubits with long coherence time [9]. To study microwave loss in materials, surfaces and interfaces and provide valuable experimental feedback for the fabrication process optimization, many samples must be characterised in a short amount of time. Here we use the cryo-CMOS multiplexer to demonstrate a proof-of-concept multidevice characterisation with a single RF input and a single RF output line in the dilution refrigerator. The characterization throughput is, therefore, increased compared to the scheme where each sample requires its own input and output line in a dilution refrigerator.

In the presented scalable cryogenic device characterisation scheme (figure 1(a) and figure A2(b) in supplementary material A) the cryo-CMOS multiplexer device connected to the input line is used for signal demultiplexing and device connected to the output line is used for signal multiplexing. In this configuration, we study microwave loss using four samples containing superconducting high-quality factor LERs fabricated with different process steps (table 1). Resonator are widely used as short-loop characterization vehicles for superconducting qubit devices, since their lifetime time is limited by the same dominant microwave losses as in qubits [46]. Qubit specific loss sources, such as quasiparticle tunnelling or two-level-system (TLS) defects inside a Josephson junction, are not captured by this method, however these are generally not limiting the performance of widely used transmon qubits [47]. A short-loop study can provide fast and reliable feedback necessary for rapid fabrication process development.

The intrinsic microwave loss is characterised by the internal quality factor $Q_i$ of the resonator [9]. Samples are inserted and measured in high-purity superconducting aluminium 3D cavities, which enable fast sample exchange (see figure 3(a) and supplementary material A). Due to wireless coupling between LERs and the electric field of the 3D cavity’s fundamental mode, samples do not need to be glued or wire bonded. The superconducting 3D cavity ensures excellent shielding against external static and dynamic magnetic fields. It also provides a well-defined electromagnetic environment void of unwanted parasitic modes that typically lead to additional microwave losses in coplanar superconducting qubits and resonators [48, 49].

Each sample contains six LERs composed of a meander inductor and a dipole-antenna-shaped capacitor (figure 3(b)). The geometry of a capacitor and the LER position within the cavity determines the coupling between the LERs and the fundamental mode of the 3D cavity [50]. For the demonstration of proof-of-concept signal multiplexing, we present only a single LER at $4.8$ GHz on each sample. We also
choose four fabrication processes that yield samples with large spread in Q-factor values to test if cryo-CMOS multiplexers can be used for characterizing resonators in the full range of their performance parameters.

Transmission spectrum measurements through cryo-CMOS multiplexer and demultiplexer show that LERs exhibit nearly ideal Lorentzian line shapes at millikelvin temperatures (figure 3(d)). The resonances are slightly asymmetric due to the coupling to the 3D cavity mode offset by more than 2 GHz towards higher frequencies. Nevertheless, the transmission spectra can be well fitted using generalized Lorentzian line shape with a complex coupling quality factor (see supplementary material A). Setting the coupling quality factor $Q_c$ to be much larger than the highest expected internal $Q_i$ factor allows us to measure internal microwave losses ($1/Q_i$) originating from defects in the substrate and different interfaces.

Table 1. List of samples being measured with the CMOS multiplexers. Frequencies and measured low power Q-factors of resonators shown in figure 3 are listed in the right two columns.

| Sample name | Fabrication details | Resonator frequency (GHz) | Low power Q-factor |
|-------------|---------------------|---------------------------|--------------------|
| S1          | Nb on standard Si substrate ($1–100$ $\Omega$ cm) | 4.802 | $(12 \pm 2) \times 10^3$ |
| S2          | Nb on high resistivity substrate ($>3.3$ k$\Omega$ cm). Structures were in situ coated with 20 nm of SiNx in a deposition chamber | 4.815 | $(200 \pm 50) \times 10^3$ |
| S3          | Nb on high resistivity substrate ($>3.3$ k$\Omega$ cm) | 4.803 | $(1.5 \pm 0.5) \times 10^6$ |
| S4          | Nb on high resistivity substrate ($>3.3$ k$\Omega$ cm). Sample is cleaned with 5% wt. HF solution for 60 s, loaded in the fridge and cooled down in less than 20 min | 4.779 | $(7 \pm 2) \times 10^6$ |

Figure 3. LER device characterisation. (a) Photograph of an aluminium 3D cavity containing a sample with six LERs. (b) False-colour micrograph of an LER. Meander inductor and antenna-shaped capacitor are depicted in red and blue, respectively. Silicon substrate is shown in grey. (c) Cross-TEM micrograph of the metal–substrate–air interface. The cross-section location is indicated with a dashed line in panel (b). TLS defects are normally present at the interfaces, metal–air (NbO$_x$), substrate–air (SiO$_x$), substrate–metal or in the Si substrate [9]. (d) Magnitude of a transmission spectrum for the selected LER in sample S4 measured using CMOS demultiplexer–multiplexer configuration at high photon number powers. Grey solid line shows a fit described in supplementary material A. (e) Loaded quality factor of four samples measured using CMOS multiplexers as a function of drive power expressed in number of photons in the resonator. Data was fitted with equation (A1) in supplementary material A. Reference measurement results, obtained with unpowered CMOS multiplexers, are denoted with empty symbols.
on a device (figure 3(c)) by directly measuring loaded quality factor $Q_L$ (figure 3(d)), due to $1/Q_L = 1/Q_e + 1/Q_i \approx 1/Q_i$.

Loaded quality factors are extracted by fitting power-dependent transmission spectra of the four samples (see supplementary material A). For convenience, we express the applied microwave power in terms of the number of microwave photons in an LER (see supplementary material A and C). We measure the power dependence of $Q_L$ down to a single-photon level power in the regime, where superconducting qubits and other quantum devices operate (figure 3(e)). At millikelvin temperatures and single-photon level powers, the dominant microwave loss is attributed to TLS material defects found predominantly in amorphous interfaces layers [9]. These exhibit a power-dependent loss due to the TLS nature of the defects. The combined loss is described by the following expression [9, 51]:

$$\frac{1}{Q_i} = \sum_i \frac{p_i \tan \delta_i}{\left(1 + \frac{n_i}{\pi c_i}\right)^{\beta_i}} + \frac{1}{Q_0}. \quad (1)$$

Here $p_i$ is the participation ratio of the $i$th loss component, which is equal to the amount of electric field energy stored in that region relative to the total electric-field energy of the system. $\tan \delta_i$ is the loss tangent of the $i$th component, $n_i$ is a number of photons in the resonators, $c_i$ is a critical number of photons in resonators above which the TLSs start to saturate, $\beta_i$ is an exponent dependent on the electric field distribution along the considered region [9] as well as the TLS–TLS interaction ($\beta = 0.5$ when interaction is absent) [9, 52], and $Q_0$ is power independent loss that can include residual dielectric, quasiparticle or radiation loss [9].

The four samples exhibit notably different power or photon number dependent quality factors, nevertheless, they can be well fitted with equation (1) using a single effective TLS component. The highest quality factor of $(7 \pm 2) \times 10^6$ at single photon level with the weakest power dependence is found for sample S4, where the native silicon and Nb oxides are removed by submerging the sample in hydrofluoric (HF) acid approximately 20 min before the cooldown. Remaining power dependent losses are likely attributed to the residual TLS losses in substrate–metal interface or high-resistivity silicon substrate [38, 53]. A lower, but still high-quality factor of $(1.5 \pm 0.5) \times 10^6$ is found in S3, where a combination of native surface oxides and the substrate limit the loss. To prevent native oxidation of surfaces exposed to air, a 20 nm layer of SiN$_x$ was in situ coated on top of the sample S2 immediately after etching. Despite the absence of metal oxides, the measured low-power quality factor of $(200 \pm 50) \times 10^3$ is lower than that of S3. Using equation (1), the simulated participation ratio of the SiN$_x$ layer ($p_{SiN_x} = 0.21\%$) and neglecting losses from the substrate and metal–substrate interfaces, we obtain a loss tangent $\tan \delta_{SiN_x} \approx 2.3 \times 10^{-3}$. The extracted loss tangent of SiN$_x$ is higher than what was published previously [54], likely due to the lower nitride deposition temperature used for our samples. The strongest power dependence and the lowest single photon quality factors of $(12 \pm 2) \times 10^3$ are found in S1. Here, a standard silicon substrate with $>1 \Omega$ cm resistance was used. Using a participation ratio of $p_{Si} = 0.917$ for the silicon substrate, we can extract the loss tangent of standard silicon wafer to be $\tan \delta_{Si} = (9 \pm 2) \times 10^{-5}$. Participation ratio simulation results and calculation details can be found in supplementary material B.

The residual power dissipation of CMOS multiplexers can increase the electron temperature of a sample and therefore increase static thermal photon population in LER. To verify whether the CMOS device dissipation affects resonator characterisation, we compare the presented results to reference quality factors measured through the multiplexer and the demultiplexer in an unpowered state ($V_{dd} = 0$). We note that the measurement uncertainty is larger especially at low photon numbers, due to an order of magnitude smaller signal to noise ratio resulting from 21.4 dB insertion loss of the unpowered multiplexer. Within the experimental uncertainty, the reference $Q$-factors follow the same power dependence as those measured through multiplexers (empty markers in figure 3(d)), even for S1 where the power dependence is largest and quality factors show a clear saturation at the single photon level powers. Since no discrepancy between measured and reference $Q_L$ can be observed down to the single photon level, we surmise that residual thermal occupation in the resonator must be less than ~1 photon.

To measure the effective temperature of a resonator connected to a cryo-CMOS multiplexer, we measure an ac Stark shift of a transmon qubit coupled to a coplanar waveguide resonator [55]. At the operating supply voltage of $V_{dd} = 0.9$ V, the ac Stark shift of a qubit corresponds to a mean photon number of 2.2 photons in the resonator (see supplementary material D). This is in agreement with the power dependent quality factor measurement presented above. The average photon number in a resonator corresponds to an electron temperature of 0.83 K. We can conclude that the residual heat dissipated by the CMOS multiplexers does not influence the high-$Q$ factor resonator characterisation.
5. Discussion

The presented cryo-CMOS multiplexer is a proof-of-concept device designed for scalable characterisation. The SP4T multiplexer has a modular circuit design and can be expanded to any number of input RF ports. In the current implementation the assembled multiplexer physical size is set by the RF PCB mount connectors, as can be seen in figure 1(b). When scaling to a large number of multiplexer ports, static and dynamic heat dissipation will remain unchanged, since both number of ESD cells and simultaneous transistor switching do not scale with the number of ports in this application. RF crosstalk between closely spaced RF pins on a large-scale cryo-CMOS chip could increase, however, increasing the chip size or using vertical interconnect such as flip-chip technology is commonly used to alleviate this problem. When considering the entire scalable cryogenic device characterization setup, most of the space would be taken by individual device sample holders (figure 3(a)) needed for shielding against environmental noise. To further increase the measurement throughput, quantum devices could be mounted on a specially designed large samples holders with a common PCB containing cryo-CMOS multiplexers and several quantum devices while providing required shielding. Taking advantage of multilayer PCB wiring, daughter PCBs [19], or high-density flex line connections for dense signal routing and thermal management [15] would further aid the scaling process.

Current multiplexer implementation is not yet compatible with scalable high-fidelity qubit control or complete qubit characterisation, due to noticeable thermal radiation emanating from the multiplexer. However, based on the presented heat dissipation results, we can identify two possible directions that can substantially reduce thermal radiation of the cryo-CMOS multiplexer and with that open a path to scalable high-fidelity qubit control.

The first direction is to reduce the number of leaky ESD protection units in the design from currently 126 to the minimum safe value of 4. Assuming that majority of dissipation originates from the protection ESD circuits, reducing the number of ESD protection units by a factor of 31.5 would lower the heat dissipation from 36 μW to 1.1 μW. The estimated thermal population in the resonator would then be lowered from ~2 photon to ~0.06 photons, which is comparable to the residual thermal population in the state-of-the-art qubit devices [56]. This is a scalable solution since the residual thermal dissipation does not dependent on the number of multiplexer ports.

The second direction is to thermalize the signal at the output of the multiplexer by a well thermalized attenuator as it is typically done for signal input lines in a dilution refrigerator [14]. Due to a sufficient dynamic range of CMOS multiplexers the input signal power can be increased to compensate for the signal attenuation at the output. The attenuation can be either done by the off-the-shelf or custom designed cryo-attenuators [57] or by PCB-mounted attenuators. In the latter case thermal isolation between the ‘hot’ CMOS part of the PCB and ‘cold’ qubit part of the PCB can be achieved with superconducting high-density rigid-flex throughs [15].

A combination of the proposed two directions can lead to cascaded thermal radiation reduction by more than four orders of magnitude at the expense of a redesign of the circuit or additional microwave components. To go beyond this restriction and achieve even lower dissipation, other techniques are also worth exploring such as cryo-CMOS with optimized switching voltages [33], adiabatic switching [58], or using technologies such as FD-SOI CMOS [59] or superconducting SFQ electronics [60].

6. Conclusions

We present custom designed cryo-CMOS multiplexers with very low insertion loss and high isolation over a wide frequency range that are well suited for scalable characterisation of devices, such as superconducting resonators, quantum-limited amplifiers, microwave kinetic inductance detectors, and to an extend superconducting and spin qubit devices.

We emphasize that the presented cryo-CMOS multiplexers are designed and fabricated using a commercially available CMOS technology, and do not require additional technology development. Based on demonstrated nanosecond switching capabilities, high isolation, low insertion loss, and possibility to further reduce heat dissipation, we can conclude that cryo-CMOS multiplexers represent a viable solution for increasing the cryogenic characterisation throughput and can contribute to alleviating the wiring problem in future large-scale quantum computing systems.
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Data availability statement

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

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