A path towards attojoule cryogenic communication

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Abstract *Photonic integration technologies are key to scale-up superconducting quantum computers. Here, we identify suitable classical optical links to control and read out the qubits in cryostats and resolve the power dissipation issue of superconducting computing platforms. Recent results and future solutions are shown. ©2022 The Author(s)*

A major bottleneck

The end of the roadmap for scaling down CMOS technology has led to unsustainable growth of power consumption (e.g. 13 MW in Summit [1]) in data centres and high-performance computers (HPC). This has resulted in renewed interest in cryogenic computing schemes that offer extreme power efficiency, even taking the cooling power into account [2]. Furthermore, several companies and public consortia have recently invested heavily in the promising concept of quantum computation using superconducting circuits [3]. However, an important bottleneck for scaling up any cryogenic computing technology is the data transfer between the cryogenic electronics and the conventional information processing equipment required at room temperature. With a seamless high-bandwidth data link, the emerging technologies could leverage the vast transistor count of CMOS, rather than compete against it. In this vision, the cryogenic coprocessors would play a role similar to today's GPUs, which assist CPUs in tasks like matrix multiplication that are an integral part of modern HPC, including machine learning.

CMOS itself can also be used in cryogenic environments, allowing lower operating voltages and thus lower power consumption [4], but more dramatic gains in energy efficiency are possible using single flux quantum (SFQ) technology [2]. The latter, and its variants such as energy-efficient SFQ (eSFQ), represent bits as short (~ 1 ps) pulses produced by switching processes in superconducting tunnel junctions called Josephson junctions. The typical energy of these pulses is only 0.2 aJ and they can be processed at speeds exceeding 100 GHz [5].

Quantum computing (QC) is still in its infancy, but there the most prominent approach is also based on superconducting Josephson junction technology. Here, the need for a high-bandwidth data bus arises from the large number of control and readout operations required to implement quantum error correction. Although cutting-edge realisations [6] still rely on radio-frequency (RF) cables for the control and readout of the quantum bits (qubits), this approach is not sustainable because the heat load from these coaxial cables is already near the limits of state-of-the-art (SoA) cryogenic technology. In the long term, the number of qubits will grow dramatically (≈ 10^6 qubits), and thus entirely new concepts for transmitting the control and readout signals will be required. Integrating low-level CMOS [4] or SFQ [7] components directly in the cryogenic environment partially alleviates this problem, but the complex classical processing associated with surface code based error correction is still likely to require the processing power and memory capacity of conventional CMOS technology, meaning that a large amount of data must be transferred from and to a classical supercomputer with ultra-high energy efficiency. For all the above reasons, optoelectronic solutions [8] hold the promise of record-breaking data rates and low dissipation to support development and exploitation of superconducting computing platforms.

Cryogenic optical transceivers

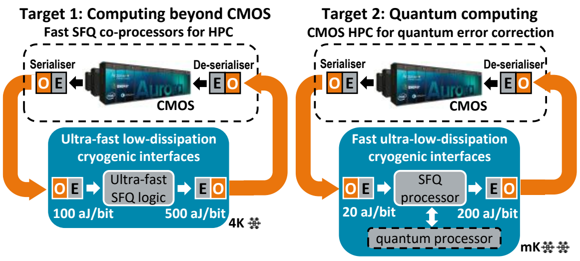

Fig. 1: Two main application targets.

The attojoule cryogenic communication challenge has been picked up by the aCryComm project. In this project cryogenic optical

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transceivers are developed to address two scenarios: superconducting classical logic (like SFQ) operated at or near liquid helium temperature (T = 4.2 K), and superconducting quantum computing operated at < 100 mK, typically used (see Fig. 1).

Challenges of data exchange in a cryostat

Conventionally, information between room-temperature equipment and superconducting electronics is transmitted through coaxial RF cabling. Because cooling power quickly diminishes with decreasing temperature, diligent mechanical design and a careful choice of materials is required to strike a suitable balance between bandwidth and heat conduction. This is because both bandwidth and heat conduction in conventional cabling depend on resistivity, which does not apply to optical fibres. Still, scaling conventional RF cabling up to a few hundred cables is possible, and in fact implemented in cryostats used for SoA qubit experiments [6]. The question of transmitting data from 4 K to a mK stage requires separate consideration, because superconducting cables are an option, ensuring low thermal conductivity. Nevertheless, optical fibres have the long-term potential of providing even more bandwidth for the same footprint, thanks to their extremely high-bandwidth, small diameter, and negligible cross-talk.

Data input

On the OE conversion side, we are tackling the challenging task to combine the SoA of single photon detection with the SoA of high-speed detectors. Superconducting nanowire single-photon detectors (SNSPDs) have reached unprecedented quantum efficiency (exceeding 90% [9]) but their detection rate is typically limited below 1 GHz [10]. Within aCryComm, we try to push the bandwidth of the SNSPDs further. On the other hand, the SoA of non-single photon high-speed photodetectors (PD) is represented by uni-traveling-carrier photodiodes, exceeding 300 GHz bandwidth. However, being diodes, they can hardly be operated at cryogenic temperatures, due to carrier freeze-out. A competing emerging technology is plasmonic PDs, that have recently exceeded 100 GHz [11], and are naturally suited for nanoscale miniaturization and for cryogenic operation, as they don't rely on dopants. We are presently characterising SoA art plasmonic detectors inside cryostats as well optimising their design for that environment.

We stress that SFQ circuits typically have input and output impedances of only a few ohms, meaning relatively large working currents (10÷100 μA) and sub-mV voltages. This is an issue for OE converters based on photodiodes and EO converters based on light emitters, since the photon energy sets the natural voltage scale to about 1 V. Instead, typical currents through SNSPDs are comparable to typical SFQ currents, and the rising edge of an SNSPD pulse is sharp (~ 100 ps), approaching the natural time scale of low-critical-current-density SFQ circuits. Indeed, readout of SNSPDs by superconducting logic has been proposed and demonstrated [12] and involved inherently long and relatively slow (≈ 100 MHz) SNSPDs, therefore not suitable to drive SFQ circuits at full speed. Our highest priority is instead to achieve the ultimate high speed of this type of detectors, even at the cost of reduced detection efficiency. We are therefore working on different strategies to shorten the nanowires while preventing their well-known latching issues [13].

Data output: a first approach

The EO conversion side is even more challenging for the existing technologies. The low signal levels of the electrical output of SFQs (10^1÷10^3 μV) together with the high-speed requirements call for EO interfaces which can operate with mV (or lower) driving voltages and ~ 0.1÷1 aJ energy per bit levels. Electro-optic modulation beyond 100 GHz have been demonstrated by several modulator concepts, but plasmonic modulators offer unprecedented small footprint, low power consumption and low driving voltages, due to enhanced interaction between the optical field and electro-optic material. SoA plasmonic modulators have reached modulation bandwidths up to 500 GHz [14] and power consumption in the sub-fJ/bit range [15], with driving voltages < 1 V. In the aCryComm project, we are developing further plasmonic modulators to enable high speed and (ultra) low-power consumption at cryogenic temperatures. The best plasmonic modulators reported to date, rely on the Pockels effect in polymers with EO coefficients up to 1000 pm/V [16] for bulk and up to 230 pm/V when integrated in a slot on a chip [17]. Even stronger Pockels effect (r_{42} = 700 pm/V) have been found in barium titanate (BTO) in plasmonic modulators [18]. Nevertheless, experiments at 4 K showed a significant 70% reduction of the nonlinear coefficient of BTO [19,20], whereas some EO polymers measured at 7 K had only about 10% decrease [21], suggesting that some polymeric materials may maintain most of their optical properties in this temperature range. The performance and durability of electro-optic materials in the mK regime, instead, remain mainly unexplored. Beside the challenges and unknowns, one good news of working at cryogenic temperatures is that the propagation losses of the plasmonic modes can be significantly reduced [36–38], which allows longer devices, and therefore lower driving voltages and power consumption, getting closer to SFQ requirements. We are presently characterising a first generation of plasmonic modulators optimised for cryogenic use, with a focus on energy, voltage compatibility and speed.

Data output: a second approach

We are also exploring a parallel approach for fast and low-energy EO interfaces, relying on directly modulated nanoscale light sources instead of the modulation of external light sources. In terms of high-speed and low energy per bit performance, vertical cavity surface emitting lasers (VCSEL) and distributed feedback (DFB) lasers present the current SoA of conventional directly modulated semiconductor light sources, with ~ 100 fJ/bit for modulation at 100 GHz. Our proposed solution is to exploit similar gain materials as in macroscopic lasers to create nanoscale light sources with subwavelength dimensions that can operate at cryogenic temperatures. Nanolasers and nanoLEDs based on metal-clad III-V semiconductor pillars are under extensive development for optical interconnects operating at room temperature [22], cryogenic operation requires completely different optical and electrical considerations. Doped regions must be carefully designed taking into account carrier freeze-out, and metal contacts are taken very close to the gain region, effectively acting also as a part of the optical cavity. In contrast to traditional macroscopic light emitters, a metal-clad semiconductor light source, has extremely small device volume (smaller than a cubic wavelength in the medium), which has a number of important consequences: (i) The cavity supports only one or a few optical modes in the gain band which increases the spontaneous emission coupling factor (β) to the lasing mode, reducing the lasing threshold. The extreme case of only one allowed mode with $\beta\rightarrow 1$ enables thresholdless lasing without a clear transition from spontaneous to stimulated emission [23]. (ii) A metal-clad semiconductor nanocavity has a low or moderate cavity quality factor yet it still provides strong Purcell enhancement of the emission owing to the ultra-small mode volume. Consequently, the device has short radiative lifetime of the excited state and short photon lifetime in the cavity mode, allowing ultrafast response in both LED and laser operation. To this end, the direct electrical modulation of InGaAs/InP based nanolasers has already been demonstrated for operation at 77 K [24]. (iii) The energy per bit for high speed operation scales down with the device volume [25]. In aCryComm, we are developing two parallel lines of technology: one using InGaAs/GaAs quantum dots as the gain medium for 950÷1100 nm wavelengths [26] and the other based on InGaAs/InP materials for the 1550 nm telecom band [27]. The metal-clad semiconductor nanolasers can potentially achieve modulation bandwidths exceeding 100 GHz [26]. We stress that the hybrid cavity mode becomes more and more plasmonic in nature when the volume is reduced, leading to the increase of lasing threshold as a result of losses in the metal. However, these losses become significantly lower when moving to cryogenic temperatures [28–30], which brings also a number of major advantages, such as a significant reduction of leakage current, and lower non-radiative losses in the semiconductor. We have here a unique opportunity to shrink the cavity to unprecedented small sizes, and to aim at a significant leap over the current SoA of electrically driven nano-light-sources in terms of both energy efficiency and modulation speed by exploiting the advantages brought by the cryogenic operation at 4 K and mK temperatures. This gives us also a chance to scale down the device volume to approach the quantum regime where the optical energy per bit is minimized down to the single photon level.

Conclusions

We presented our vision how to tackle the bottlenecks that are limiting the scalability of emerging superconducting technologies by introducing optical data buses to and from a cryostat. The proposed EO and OE devices and their interface to SFQ are a promising solution to allow for highest data rate transmission from and to the cryogenic environment.

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References

1. "Summit," https://www.olcf.ornl.gov/summit/
2. D. S. Holmes, A. L. Ripple, and M. A. Manheimer, "Energy-Efficient Superconducting Computing—Power Budgets and Requirements," IEEE Transactions on Applied Superconductivity **23**, 1701610–1701610 (2013) DOI: 10.1109/TASC.2013.2244634.
3. M. Mohseni, P. Read, H. Neven, S. Boixo, V. Denchev, R. Babbush, A. Fowler, V. Smelyanskiy, and J. Martinis, "Commercialize quantum technologies in five years," Nature News **543**, 171 (2017) DOI : 10.1038/543171a.
4. J. C. Bardin, E. Jeffrey, E. Lucero, T. Huang, O. Naaman, R. Barends, T. White, M. Giustina, D. Sank, P. Roushan,

K. Arya, B. Chiaro, J. Kelly, J. Chen, B. Burkett, Y. Chen, A. Dunsworth, A. Fowler, B. Foxen, C. Gidney, R. Graff, P. Klimov, J. Mutus, M. McEwen, A. Megrant, M. Neeley, C. Neill, C. Quintana, A. Vainsencher, H. Neven, and J. Martinis, "A 28nm Bulk-CMOS 4-to-8GHz <2mW Cryogenic Pulse Modulator for Scalable Quantum Computing," arXiv:1902.10864 [quant-ph] (2019).

5. K. K. Likharev and V. K. Semenov, "RSFQ logic/memory family: a new Josephson-junction technology for sub-terahertz-clock-frequency digital systems," Applied Superconductivity, IEEE Transactions on **1**, 3–28 (1991) DOI: 10.1109/77.80745.
6. F. Arute, et al. "Quantum supremacy using a programmable superconducting processor," Nature **574**, 505–510 (2019) DOI: 10.1038/s41586-019-1666-5.
7. R. McDermott, M. G. Vavilov, B. L. T. Plourde, F. K. Wilhelm, P. J. Liebermann, O. A. Mukhanov, and T. A. Ohki, "Quantum–classical interface based on single flux quantum digital logic," Quantum Sci. Technol. **3**, 024004 (2018) DOI: 10.1088/2058-9565/aaa3a0.
8. F. Lecocq, F. Quinlan, K. Cicak, J. Aumentado, S. A. Diddams, and J. D. Teufel, "Control and readout of a superconducting qubit using a photonic link," Nature **591**, 575–579 (2021) DOI: 10.1038/s41586-021-03268-x.
9. J. Chang, J. W. N. Los, J. O. Tenorio-Pearl, N. Noordzij, R. Gourgues, A. Guardiani, J. R. Zichi, S. F. Pereira, H. P. Urbach, V. Zwiller, S. N. Dorenbos, and I. Esmaeil Zadeh, "Detecting telecom single photons with 99.5−2.07+0.5% system detection efficiency and high time resolution," APL Photonics **6**, 036114 (2021) DOI: 10.1063/5.0039772.
10. F. Beutel, H. Gehring, M. A. Wolff, C. Schuck, and W. Pernice, "Detector-integrated on-chip QKD receiver for GHz clock rates," npj Quantum Inf **7**, 40 (2021) DOI: 10.1038/s41534-021-00373-7.
11. Y. Salamin, P. Ma, B. Baeuerle, A. Emboras, Y. Fedoryshyn, W. Heni, B. Cheng, A. Josten, and J. Leuthold, "100 GHz Plasmonic Photodetector," ACS Photonics **5**, 3291–3297 (2018) DOI: 10.1021/acsphotonics.8b00525.
12. T. Ortlepp, M. Hofherr, L. Fritzsch, S. Engert, K. Ilin, D. Rall, H. Toepfer, H.-G. Meyer, and M. Siegel, "Demonstration of digital readout circuit for superconducting nanowire single photon detector," Optics Express **19**, 18593 (2011) DOI: 10.1364/OE.19.018593.
13. D.-K. Liu, S.-J. Chen, L.-X. You, Y.-L. Wang, S. Miki, Z. Wang, X.-M. Xie, and M.-H. Jiang, "Nonlatching Superconducting Nanowire Single-Photon Detection with Quasi-Constant-Voltage Bias," Appl. Phys. Express **5**, 125202 (2012) DOI: 10.1143/APEX.5.125202.
14. M. Burla, C. Hoessbacher, W. Heni, C. Haffner, Y. Fedoryshyn, D. Werner, T. Watanabe, H. Massler, D. L. Elder, L. R. Dalton, and J. Leuthold, "500 GHz plasmonic Mach-Zehnder modulator enabling sub-THz microwave photonics," APL Photonics **4**, 056106 (2019) DOI: 10.1143/APEX.5.125202.
15. W. Heni, Y. Fedoryshyn, B. Baeuerle, A. Josten, C. B. Hoessbacher, A. Messner, C. Haffner, T. Watanabe, Y. Salamin, U. Koch, D. L. Elder, L. R. Dalton, and J. Leuthold, "Plasmonic IQ modulators with attojoule per bit electrical energy consumption," Nat Commun **10**, 1–8 (2019) DOI: 10.1038/s41467-019-09724-7.
16. H. Xu, D. L. Elder, L. E. Johnson, W. Heni, Y. de Coene, E. D. Leo, M. Destraz, N. Meier, W. V. Ghinst, S. R. Hammond, K. Clays, J. Leuthold, L. R. Dalton, and B. H. Robinson, "Design and synthesis of chromophores with enhanced electro-optic activities in both bulk and plasmonic–organic hybrid devices," Mater. Horiz. (2021) DOI: 10.1039/D1MH01206A.
17. W. Heni, C. Haffner, D. L. Elder, A. F. Tillack, Y. Fedoryshyn, R. Cottier, Y. Salamin, C. Hoessbacher, U. Koch, B. Cheng, B. Robinson, L. R. Dalton, and J. Leuthold, "Nonlinearities of organic electro-optic materials in nanoscale slots and implications for the optimum modulator design," Optics Express **25**, 2627 (2017) DOI: 10.1364/OE.25.002627.
18. A. Messner, F. Eltes, P. Ma, S. Abel, B. Baeuerle, A. Josten, W. Heni, D. Caimi, J. Fompeyrine, and J. Leuthold, "Plasmonic Ferroelectric Modulators," Journal of Lightwave Technology **37**, 281–290 (2019) DOI: 10.1109/JLT.2018.2881332.
19. F. Eltes, J. Barreto, D. Caimi, S. Karg, A. A. Gentile, A. Hart, P. Stark, N. Meier, M. G. Thompson, J. Fompeyrine, and S. Abel, "First cryogenic electro-optic switch on silicon with high bandwidth and low power tunability," in *2018 IEEE International Electron Devices Meeting (IEDM)* (2018), p. 23.1.1-23.1.4 DOI: 10.1109/IEDM.2018.8614511.
20. F. Eltes, G. E. Villarreal-Garcia, D. Caimi, H. Siegwart, A. A. Gentile, A. Hart, P. Stark, G. D. Marshall, M. G. Thompson, J. Barreto, J. Fompeyrine, and S. Abel, "An integrated optical modulator operating at cryogenic temperatures," Nat. Mater. **19**, 1164–1168 (2020) DOI: 10.1038/s41563-020-0725-5.
21. D. h. Park, V. Yun, J. Luo, A. k.-Y. Jen, and W. n. Herman, "EO polymer at cryogenic temperatures," Electronics Letters **52**, 1703–1705 (2016) DOI: 10.1049/el.2016.1406.
22. R.-M. Ma and R. F. Oulton, "Applications of nanolasers," Nature Nanotechnology **14**, 12 (2019) DOI: 10.1038/s41565-018-0320-y.
23. M. Khajavikhan, A. Simic, M. Katz, J. H. Lee, B. Slutsky, A. Mizrahi, V. Lomakin, and Y. Fainman, "Thresholdless nanoscale coaxial lasers," Nature **482**, 204–207 (2012) DOI: 10.1038/nature10840.
24. S. H. Pan, S. S. Deka, A. El Amili, Q. Gu, and Y. Fainman, "Nanolasers: Second-order intensity correlation, direct modulation and electromagnetic isolation in array architectures," Progress in Quantum Electronics **59**, 1–18 (2018) DOI: 10.1016/j.pquantelec.2018.05.001.
25. C.-Z. Ning, "Semiconductor nanolasers and the size-energy-efficiency challenge: a review," AP **1**, 014002 (2019) DOI: 10.1117/1.AP.1.1.014002.
26. P. Qiao, C.-Y. Lu, D. Bimberg, and S. L. Chuang, "Theory and experiment of submonolayer quantum-dot metal-cavity surface-emitting microlasers," Optics Express **21**, 30336 (2013) DOI: 10.1364/OE.21.030336.
27. C.-Y. Fang, F. Vallini, A. El Amili, A. Tukiainen, J. Lyytikäinen, M. Guina, and Y. Fainman, "Development of Efficient Electrically Pumped Nanolasers based on InAlGaAs Tunnel Junction," in *Conference on Lasers and Electro-Optics* (OSA, 2018), p. SW4Q.4 DOI: 10.1364/CLEO_SI.2018.SW4Q.4.
28. J.-S. G. Bouillard, W. Dickson, D. P. O'Connor, G. A. Wurtz, and A. V. Zayats, "Low-Temperature Plasmonics of Metallic Nanostructures," Nano Letters **12**, 1561–1565 (2012) DOI: 10.1021/nl204420s.
29. S. V. Jayanti, J. H. Park, A. Dejneka, D. Chvostova, K. M. McPeak, X. Chen, S.-H. Oh, and D. J. Norris, "Low-temperature enhancement of plasmonic performance in silver films," Opt. Mater. Express, OME **5**, 1147–1155 (2015) DOI: 10.1364/OME.5.001147.
30. L. Sun, C. Zhang, C.-Y. Wang, P.-H. Su, M. Zhang, S. Gwo, C.-K. Shih, X. Li, and Y. Wu, "Enhancement of Plasmonic Performance in Epitaxial Silver at Low Temperature," Sci Rep **7**, 8917 (2017) DOI: 10.1038/s41598-017-09402-y.