

Cryogenic Silicon-Organic Hybrid Modulators for Readout of Superconducting Circuits

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Abstract

Superconducting electronics operating at 4 K and below offers significant advantages for a wide range of applications. Current systems use readout through RF cables with limited bandwidth and high thermal load. Optical fibers can offer high bandwidth and reduced thermal load. The key component is an efficient electro-optic (EO) modulator. We investigate the suitability of silicon-organic hybrid (SOH) modulators for cryogenic applications.

Introduction

Cryogenic electronics offers a promising high-performance, energy-efficient solution for energy-demanding AI-driven applications, potentially complementing or replacing current room-temperature technologies. In particular, superconducting electronics operating below 4 K provides significant advantages. Rapid single-flux-quantum (RSFQ) circuits, for instance, can achieve THz-range clock speeds with ultra-low switching energy, ideal for AI supercomputing [1]. Today, superconducting qubits lead the field [2], and RSFQ technology could be an optimal interface for qubit readout and control, paving the way toward scalable quantum processors.

One of the major challenges for scaling cryogenic circuits is implementing efficient readout and control lines to room-temperature back-end equipment. Current systems rely on coaxial radio frequency (RF) cables, which, however, conduct heat into the cryostat — a problem that worsens as circuit complexity and cable count grow. An optical fiber has two orders of magnitude lower thermal conductivity compared to a coaxial RF cable, and minimizes the thermal load [3] while providing the high bandwidth allowing to replace many RF cables using different signal multiplexing schemes.

For such an optical egress link, as depicted in Fig. 1(a), a highly efficient and broadband electro-optic modulator operating at cryogenic temperature is required. In such a link, the signals from cryogenic electronics are fed through RF cables to an EO modulator which resides at the 4 K stage of the cryostat. The upconverted signal in the optical domain is then transferred to a room temperature (RT) backend via an optical fiber. Recently, several EO modulators have been demonstrated operating at cryogenic temperatures, namely lithium niobate phase shifters [3] [4], plasmonic-organic hybrid (POH) Mach-Zehnder modulators (MZM) [5], and silicon MZM based on the optical DC Kerr effect [6]. Further, ring or racetracks modulators were tried based on the indium phosphide platform [7], on barium titanate [8], on silicon [9], [10], or on graphene [11]. With the POH MZM used in [5], line rates up to 128 GBd at temperatures down to 2.6 K could be demonstrated. However, POH MZM inherently feature high optical losses.

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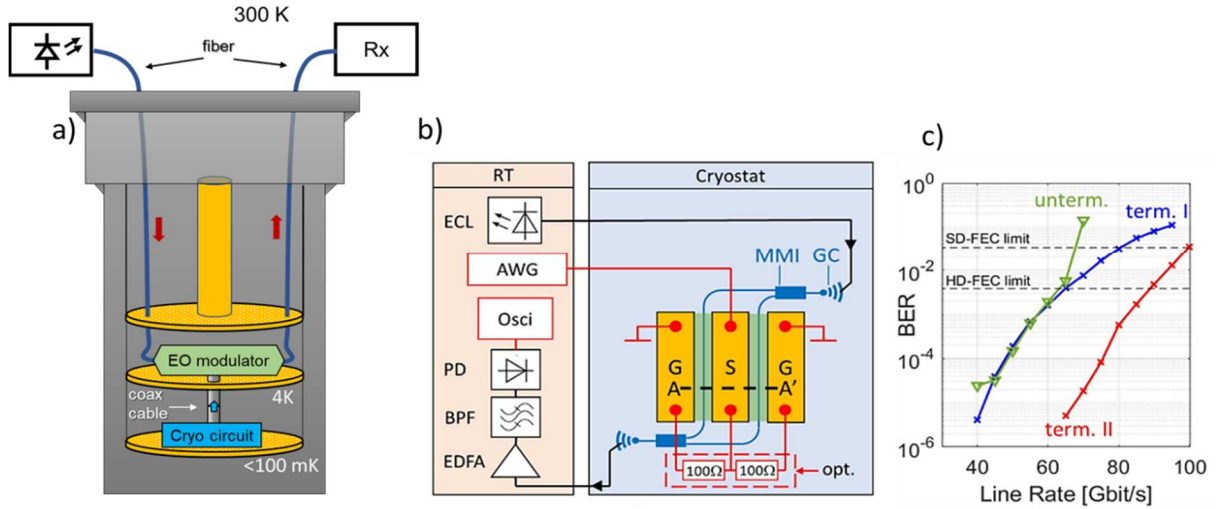


Fig.1. Concept of a cryogenic optical egress link. (a) Light is coupled from a laser operating at RT through a fiber into the cryostat and into the EO modulator. Another fiber connects the EO modulator to receiver electronics (Rx) operating at RT. (b) Schematic of a cryogenic data transmission experiment. An SOH MZM operates at 11 K. A test signal, applied to an SOH MZM, is generated at RT by an arbitrary waveform generator (AWG). A laser carrier is supplied from an external-cavity laser (ECL) to the MZM using grating couplers (GC) for the input and the for modulated output light. The output signal is boosted by an erbium-doped fiber amplifier (EDFA). A bandpass filter (BPF) is used to reduce out-of-band amplified spontaneous emission (ASE) noise from the EDFA. The signal is converted back to the electrical domain by beating the optical sidebands with the laser carrier on a high-speed photodiode (PD), and its outcome is recorded by a real time oscilloscope (Osci.). (c) Measured BER vs. line rate for a terminated (term. I) and an unterminated (unterm.) MZM RF transmission line. The “term II” depicts the BER vs. line rate dependence after doubling the drive voltage (adapted from [17]).

Cryogenic Silicon-Organic Hybrid Electro-Optical Modulator

The silicon organic hybrid (SOH) EO platform [12], combining the highly efficient EO organic materials with low optical loss [13] [14], is well suited for cryogenic applications. For a resistively-coupled SOH MZM, the issue of carrier freeze-out in the silicon contact slabs must be addressed as it can significantly limit the bandwidth of the device. The high doping of the slabs beyond $5 \times 10^{18} \text{ cm}^{-3}$ [15] helps to mitigate the freeze-out. Another issue is that an organic electro-optic material which is dispensed on the silicon photonic chips experiences high tensile stress on cooldown, which eventually causes the formation of cracks resulting in an increased optical loss due to scattering. In the first demonstration of an SOH MZM at cryogenic temperatures, the EO organic material JRD1 was mixed with polymethylmethacrylate (PMMA) in a 1:1 ratio [16] which helped to reduce the stress in the dispensed film. A π -voltage-length product $U_{\pi}L$ of 2 Vmm was measured at temperatures of 4 K, and a line rate of 50 Gbit/s could be achieved. The cryo-compatible SOH MZM with $U_{\pi} = 0.9 \text{ V}$ was demonstrated in [17], using PerkinamineTM Series 5 in amorphous polycarbonate (APC). Line rates of up to 140 Gbit/s using PAM4 format were demonstrated with a 1 mm long device at a temperature of 11 K [17]. The device was based on a multi-level doping scheme, with dopant concentrations close to degeneracy near the slot waveguide, and well beyond degeneracy further away from it. The data transmission experiments were conducted using the setup shown schematically in Fig. 1(b). The data rates reached 100 Gbit/s, Fig. 1(c), and the bit-error ratio (BER) stayed below the threshold for soft decision forward error correction (SD-FEC) with 20 % coding overhead. The green curve (unterm.) corresponds to the unterminated, i.e., open-ended device, without the optional circuit “opt.” in Fig. 1(b). The performance of the terminated (red curve) and the unterminated device was similar up to line rates of 65 Gbit/s. At a higher line rate, the high frequency components of the modulating control signal propagating along the RF line in the SOH MZM are reflected back from the open end, thereby causing an increased BER for the unterminated device. By doubling the drive voltage, line rates of up to 100 Gbit/s were achieved with a BER below the SD-FEC limit. The dashed lines in Fig. 1(c) correspond to the hard-decision FEC and the SD-FEC limits.

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