

Highly Efficient Homodyne Cryogenic Readout Link Based on a Silicon-Organic Hybrid (SOH) Phase Modulator

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Abstract We demonstrate a homodyne cryogenic optical egress link utilizing a silicon-organic hybrid (SOH) phase modulator. With our approach, we achieve a record-low total net energy dissipation of less than 10 fJ/bit per net bit at a temperature of 3.6 K and a data rate of 40 Gbit/s. © 2025 The Author(s)

Introduction

Cryogenic egress links are key to advanced computing concepts that leverage the various advantages of superconducting electronic circuits and quantum devices. Examples comprise rapid single-flux-quantum (RSFQ) arithmetic logic units, that have demonstrated clock speeds of up to 50 GHz [1], or superconducting quantum interferences devices (SQUID), which are at the core of recent quantum computers with qubit counts beyond 1000 [2]. A key challenge of such increasingly complex cryogenic systems is the communication interface to the room-temperature environment, which currently mainly relies on radio-frequency (RF) cables. These cables are lossy, offer only limited bandwidth, and lead to heat bridges that increase the thermal load of the cryogenic system. In contrast, optical links based on silica fibers combine ultra-low propagation loss with virtually unlimited bandwidth, while reducing the parasitic passive thermal load by two orders of magnitude [3]. Optical cryogenic egress links, however, require optical transmitters that can operate at lowest temperatures with ultra-low power dissipation and drive voltage levels on the millivolt level [4]. Over the previous years, a series of different modulator technologies has been explored in optical egress links, and the dissipated electrical per-bit energy $W_{\text{bit,e}}$ has been used as figure of merit to benchmark efficiency [3],[5]–[7],[10]–[16]. More specifically, cryogenic signaling with peak-to-peak drive-voltage swings of only 5 mV_{pp} has been demonstrated in thin-film lithium niobate (TFLN) Mach-Zehnder modulators (MZM) with superconducting electrodes, resulting in an electrical energy dissipation $W_{\text{bit,e}}$ of only 0.125 fJ/bit [5]. However, these devices feature comparatively large footprints with lengths of the order of 10 cm. Even lower drive-voltage swings down to 4 mV_{pp} have been achieved with spoked silicon micro-ring modulators (MRM), co-integrated with a cryo-compatible 28 dB CMOS amplifier [6]. The amplifier, however, leads to a comparatively large electrical energy dissipation of $W_{\text{bit,e}} \approx 50$ fJ/bit. Indium phosphide (InP) MRMs have been demonstrated with drive-voltage swings of 10 mV_{pp} without additional RF amplifiers, resulting in an impressive $W_{\text{bit,e}}$ of only 0.01 fJ/bit, but the data rates were limited to

1 Gbit/s [7]. Another interesting device class is based on organic electro-optic materials, combined with either silicon photonic waveguides [8] or plasmonic structures [9]. Silicon-organic hybrid (SOH) MZM have been shown to work with 230 mV_{pp} drive voltage swings, corresponding to an energy dissipation of $W_{\text{bit,e}} \approx 2$ fJ/bit [10]. Plasmonic-organic hybrid (POH) MZM have been demonstrated at voltage swings of 96 mV_{pp} and much lower energy dissipations of $W_{\text{bit,e}} \approx 0.23$ fJ/bit, enabled by ultra-small device capacitances [11]. However, just like all the aforementioned demonstrations, these experiments relied on rather high optical power levels of the order of 10 mW that were coupled to the MZM and that were not counted towards the overall heat load. In fact, only a few publications [7],[11] explicitly state and benchmark the optical energy dissipation – a particularly problematic aspect for MZM and ring modulators, which are subject to inherent optical modulation losses and for which the electrical energy dissipation can be minimized at the expense of its optical counterpart. For a full picture of the thermal load of cryogenic transmitters, it is therefore necessary to consider and minimize the full energy dissipation, comprising optical and electrical contributions alike, and to focus on modulator concepts that are particularly suitable in this respect.

In this paper, we demonstrate an optical egress link with a drive voltage of 141 mV_{pp} at a record-low overall per-bit energy dissipation W_{bit} of 7.17 fJ/bit, comprising $W_{\text{bit,e}} = 2.49$ fJ/bit on the electrical and $W_{\text{bit,o}} = 4.68$ fJ/bit on the optical side. Our demonstration relies on an SOH phase modulator that does not suffer from any inherent modulation loss. The signals are detected by a room-temperature coherent homodyne IQ receiver, and the data is extracted by dedicated digital signal-processing (DSP) techniques that compensate for phase drifts along the link. We test the devices, estimate the electrical and optical energy dissipation for both cases, and benchmark our results to previously reported optical egress links. We further extract the energy dissipation W'_{bit} per net bit, which considers the reduction of the usable bit rate by the forward error correction (FEC) overhead and which also amounts to a record-low value of $W'_{\text{bit}} = 8.6$ fJ/bit.

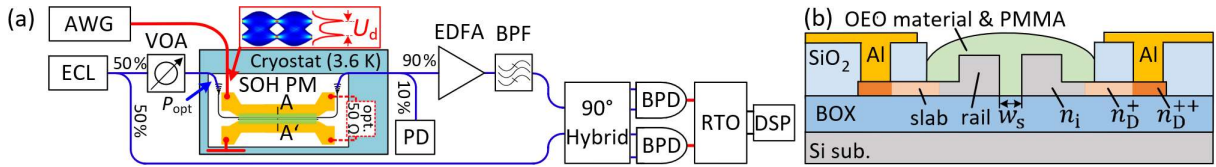


Figure 1: Concept of the coherent optical egress link and of the underlying SOH phase modulator (PM). **(a)** Egress link comprising the cryogenic SOH PM and a room-temperature (RT) coherent receiver. Light from an ECL is split into a signal and LO path, and a variable optical attenuator (VOA) is used to adjust the power level coupled to the PM in the cryostat. The PM drive signal (peak-to-peak voltage swing U_d at SOH PM) is derived from an arbitrary-waveform generator (AWG). The device can be terminated by an optional 50 Ω resistor. 10 % of the outcoupled light is tapped to a monitor PD, while the remainder is amplified by an EDFA. At the coherent receiver, a 90° hybrid and a pair of balanced photodetectors (BPD) coupled to a real-time oscilloscope (RTO) are used to detect the signal. After DSP, the BER is calculated. **(b)** Cross-section of the SOH PM as indicated by A – A' in (a). The device contains slabs that are in contact with the Si rails of the slot waveguide on one end while connecting to a metal (aluminum, Al) transmission line at the other end. In contrast to conventional slot-waveguide devices, the rails and the directly adjacent areas of the slabs are left undoped (n_i), which leads to decreased modulation efficiency, but minimizes optical losses due to free-carrier absorption (FCA) – in analogy to recently demonstrated resistively-capacitively coupled SOH MZM [18]. The slot is slot filled with OEO material mixed with PMMA.

Cryogenic egress link with SOH phase modulator

A schematic of the coherent optical egress link based on a cryogenic SOH phase modulator and a room-temperature (RT) homodyne receiver is depicted in Fig. 1 (a). Light ($\lambda = 1555$ nm, $P = 14$ dBm) from an external-cavity laser (ECL) is equally split into a signal and local oscillator (LO) path. The power level in the signal path is adjusted by a variable optical attenuator (VOA, HP 8157A), and the light is then sent to the cryostat and coupled to the silicon-organic hybrid phase modulator (SOH PM) via a grating coupler (GC; 4.5 dB loss). The electrical drive signal is generated by an arbitrary-waveform generator (AWG, Keysight M8199B) and routed into the cryostat by RF cables. The drive signals are pre-distorted to compensate for frequency-dependent losses of the RF cable, but not of the PM. The drive signal with variable peak-to-peak voltage swing U_d is coupled to the SOH PM via an RF probe, and the device can optionally be terminated by a 50 Ω impedance via a second probe. For good thermal uniformity of the setup, the piezo-positioners (JPE CBS5) of the optical and electrical probes are mounted to the coldhead of the cryostat (TransMIT PTD-406C), resulting in a temperature of less than 3.6 K at the sample. After the PM, a fraction of 10 % of the light is tapped for monitoring the coupling losses and the power levels. The remainder is amplified to 20 dBm by an RT erbium-doped fiber amplifier (EDFA), followed by an optical bandpass filter (BPF) for noise suppression. The signal is fed to a coherent receiver along with the original optical carrier acting as LO tone. The receiver comprises a 90° optical hybrid, a pair of balanced photodiodes (BPD, Finisar BPDV2150RQ), and a real-time oscilloscope (RTO, Keysight DSOZ334A) to record the in-phase and quadrature component of the electrical signal. The signals are processed further offline (DSP), and unavoidable phase drifts between the signal and the LO path are compensated by phase tracking before demodulation and BER calculation. This obviates the need for active phase control, as used in previous experiments [3],[6]. The base structure of the SOH PM was fabricated by a commercial silicon photonic foundry and then combined with the organic electro-optic (OEO) material in a post-processing step [8]. The cross-section of the device in Fig. 2 (b) resembles that of a conventional slot-waveguide SOH phase shifter [8],[17],[18]

containing slabs that are in contact with the Si rails of the slot waveguide on one end while connecting to a metal (aluminum, Al) transmission line at the other end. However, in contrast to conventional slot-waveguide devices, the rails and the directly adjacent areas of the slabs are left undoped (n_i). This leads to a larger effective electrode spacing and hence to a decreased modulation efficiency, but minimizes optical losses due to free-carrier absorption (FCA) – in analogy to recently demonstrated resistively-capacitively coupled SOH MZM [19]. The two rails are separated by a 160 nm-wide slot, which is filled with the OEO material (SOXD123, SilOriX GmbH) mixed with Polymethylmethacrylate (PMMA) in a 1:1 ratio [20]. At 3.6 K we measure optical on chip losses of 8 dB, of which 7.6 dB originate from the 4.6 mm-long slot waveguide while the remaining 0.4 dB of loss are attributed to the strip-to-slot-converters [21] and the access strip waveguides. At 3.6 K, we measure a π -voltage U_π of (3.16 ± 0.4) V.

We use the setup in Fig. 1(a) to demonstrate data transmission from the 3.6 K-level to the RT environment using binary phase modulation. We start at a low data rate of $R_{\text{bit}} = 5$ Gbit/s, operating the SOH PM without termination resistor. In this case, the drive-voltage swing U_d that is effective at the device is twice the voltage measured by connecting the end of the RF cable to an oscilloscope with a 50 Ω input impedance. Figure 2 (a) shows the resulting bit error ratios (BER) as a function of the optical power P_{opt} measured in the fiber before the SOH PM, see Fig. 1 (a). The different colors and markers represent nine different drive voltages U_d , and the thresholds for different forward-error correction (FEC) schemes are indicated by dashed lines. If no error is found within our recordings of 500 000 symbols, the BER is set to 2×10^{-6} . For each measured BER below the 20 % SD FEC limit, we calculate and plot the total net energy dissipation per net transmitted bit in Fig. 2 (b), taking into account the electrical per-bit energy dissipation $W_{\text{bit,e}}$ as well as its optical counterpart $W_{\text{bit,o}}$ and the FEC overhead θ ,

$$\begin{aligned} W'_{\text{bit}} &= (1 + \theta)(W_{\text{bit,e}} + W_{\text{bit,o}}) \\ &= W'_{\text{bit,e}} + W'_{\text{bit,o}}. \end{aligned} \quad (1)$$

Note that we do not consider energy dissipation by additional circuitry needed for the implementation of the FEC. For the calculation of $W_{\text{bit,o}}$, we consider the entire 17 dB optical loss in the cryostat, i.e.,

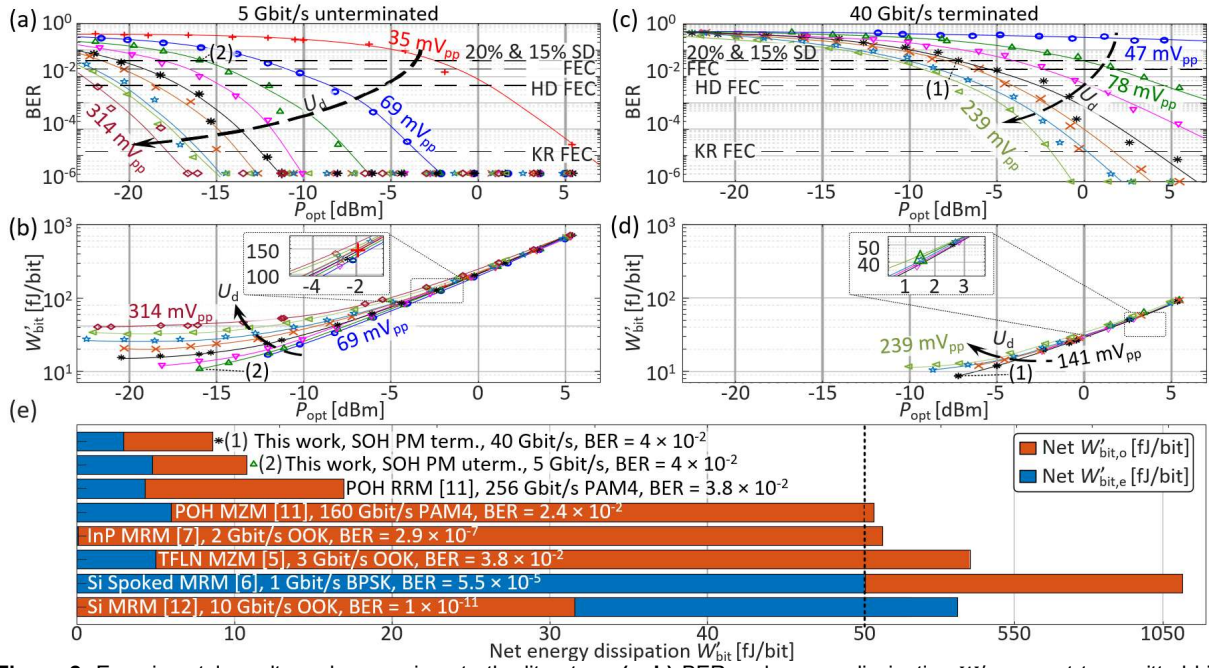


Figure 2: Experimental results and comparison to the literature. (a, b) BER and energy dissipation W'_{bit} per net transmitted bit vs. optical power P_{opt} for the unterminated SOH PM running at 5 Gbit/s. We use different drive voltages U_d of +35 mV_{pp}, 69 mV_{pp}, 104 mV_{pp}, 138 mV_{pp}, 173 mV_{pp}, 208 mV_{pp}, 243 mV_{pp}, 276 mV_{pp} and 314 mV_{pp}. The black dashed lines are the thresholds for soft-decision (SD) FEC with 20% or 15% overhead, hard-decision (HD) FEC and KR FEC. For recordings with a BER below the 20% SD FEC limit, the dissipated energy W'_{bit} per net transmitted bit is calculated. (c, d) BER and energy dissipation W'_{bit} vs. optical power P_{opt} for the unterminated SOH PM running at 40 Gbit/s. The drive voltages U_d are 47 mV_{pp}, 78 mV_{pp}, 110 mV_{pp}, 141 mV_{pp}, 173 mV_{pp}, 206 mV_{pp}, and 239 mV_{pp}. (e) Comparison of the lowest W'_{bit} from Subfigures (b) and (d) to the total energy dissipation per net bit for previously reported cryogenic egress links [5]–[7], [11], [12], distinguishing optical and electrical contributions. The values of 8.6 fJ/bit and 10.8 fJ/bit for the terminated and unterminated SOH PM are well below the numbers achieved by competing concepts.

$W_{bit,o} = (1 - 10^{-1.7}) \times P_{opt}/R_{bit}$. In the unterminated operation mode, $W_{bit,e}$ depends on the capacitance $C = 370$ fF of the SOH PM, $W_{bit,e} = CU_d^2$ [21]. A minimum overall energy dissipation of $W'_{bit} = 147$ fJ/bit is found for $U_d = 104$ mV_{pp} and $P_{opt} = 25$ μW (-16 dBm). Note that, for a certain required signal quality, lower drive voltages and lower electrical energy dissipation $W_{bit,e}$ can be achieved only by increasing the optical power – a finding that underpins the importance of considering the overall energy dissipation $W_{bit} = W_{bit,e} + W_{bit,o}$ rather than just the electrical part $W_{bit,e}$. In a second step, we operate the device with a 50 Ω termination such that $W_{bit,e} = (U_d/2)^2/(R_{bit}/50 \Omega)$ [21]. We use a higher data rate of $R_{bit} = 40$ Gbit/s, limited by the bandwidth of the device. Figure 3 (a) and (b) show the BER and net per-bit energy dissipation W'_{bit} as function of the optical input power P_{opt} for different drive voltages U_d . If no error is found in the 1 million recorded symbols, the BER is set to 1×10^{-6} . For a drive voltage of $U_d = 141$ mV_{pp} and an optical power of $P_{opt} = 190.5$ μW (-7.2 dBm), we find the lowest net per-bit energy consumption W'_{bit} of 8.6 fJ/bit, labeled (1) in Fig. 2 (c) and (d). Lower drive voltages can only be achieved by for higher optical power, increasing the overall per-bit energy dissipation.

Benchmarking of the results

To benchmark our results against other results from the literature, we extracted the optical, the electrical and the minimum overall energy dissipation per net bit $W'_{bit,o}$, $W'_{bit,e}$, and $W'_{bit} = W'_{bit,o} + W'_{bit,e}$, respectively, from selected publications and illustrate them

as bar charts – the results are shown in Fig. 2 (e). The electrical and optical power dissipation per net bit are calculated in analogy to Eq. (1). We find that the overall per-net-bit energy dissipations W'_{bit} of 8.6 fJ/bit and 10.8 fJ/bit for the terminated and unterminated SOH PM, respectively, are well below the numbers achieved by competing devices. The closest competitor is a POH ring modulator with a per-net-bit energy dissipation of $W'_{bit} = 16.9$ fJ/bit [11]. For completeness, we added information on modulation format, BER and data rate. Note that most experiments with exception of [6], [7] and [12] have been conducted at rather high BER $> 10^{-3}$. Note also, that the optical energy dissipation is significantly larger than its electrical counterpart – supporting again the importance of considering the full energy dissipation.

Summary and outlook

We demonstrate an optical cryogenic egress link with a record-low overall energy dissipation of 8.6 fJ per net transmitted bit, comprising both electrical and optical contributions. Our demonstration relies on a silicon-organic hybrid (SOH) phase modulator operated at 3.6 K in combination with a coherent homodyne detector and associated phase-tracking algorithms at the room-temperature receiver side. We evaluate the performance of our link for different drive voltages and optical power levels. While our experiment clearly shows the potential of compact SOH-based phase modulators for cryogenic egress links, it still leaves room for future improvements of the device design, that could further reduce the electrical as well as the optical energy dissipation.

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