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Cryogenic electro-optic interconnect for superconducting devices

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Encoding information onto optical fields using electro-optical modulation is the backbone of modern telecommunication networks, offering vast bandwidth and low-loss transport via optical fibers [1]. For these reasons, optical fibers are also replacing electrical cables for short range communications within data centers [2]. Compared to electrical coaxial cables, optical fibers also introduce two orders of magnitude smaller heat load from room to milli-Kelvin temperatures, making optical interconnects based on electro-optical modulation an attractive candidate for interfacing superconducting quantum circuits [3-5] and hybrid superconducting devices [6]. Yet, little is known about optical modulation at cryogenic temperatures. Here we demonstrate a proof-of-principle cryogenic electro-optical interconnect, showing that currently employed Ti-doped lithium niobate phase modulators [7] are compatible with operation down to 800 mK—below the typical operation temperature of conventional microwave amplifiers based on high electron mobility transistors (HEMTs) [8,9]—and maintain their room temperature Pockels coefficient. We utilize cryogenic electro-optical modulation to perform spectroscopy of a superconducting circuit optomechanical system, measuring optomechanically induced transparency (OMIT) [10-13]. In addition, we encode thermomechanical sidebands from the microwave domain onto an optical signal processed at room temperature. Although the currently achieved noise figure is significantly higher than that of a typical HEMT, substantial noise reduction should be attainable by harnessing recent advances in integrated modulators [14-17], by increasing the modulator length, or by using materials with a higher electro-optic coefficient [18,19], leading to noise levels on par with HEMTs. Our work highlights the potential of electro-optical modulators
for massively parallel readout for emerging quantum computing [3–6] or cryogenic classical computing [20] platforms.

**FIG. 1.** Principle of a cryogenic electro-optical interconnect for readout of superconducting devices. a, Simplified schematic of a conventional readout of a device under test (DUT) in a dilution fridge using a cryogenic HEMT amplifier. The dashed box indicates an optional quantum-limited pre-amplifier not used in this work. The devices are interrogated by input microwave signals that are attenuated to reduce thermal noise, and amplified using an HEMT amplifier at 3 K. b, Principle of a cryogenic electro-optic readout scheme using an electro-optical phase modulator. The DUT is interrogated using the same microwave input line, but the microwave signals are converted to the optical domain at 3 K, reducing thermal load. c, Conducted heat through a typical cryogenic coaxial cable and optical fiber, between room temperature and 3 K. d, Schematic cross-section of a $z$-cut LiNbO$_3$ electro-optic phase modulator. e, Microscope photo of the commercial phase modulator used in the experiment, showing the coupling region between fiber and LiNbO$_3$ chip.

Optical modulators are ubiquitous in our information society and encode electrical signals in optical carriers that can be transported over fiber. Initially only used for long-haul communications, optical fiber links are now also replacing electrical cables for short range communications within data centers [21–23]. This is motivated by the high power consumption of electrical interconnects that spurred the development of optical interconnects based on silicon photon-
ics [22]. Such interconnects may also be used in the future for on-board chip-to-chip communication [24, 25].

A similar challenge is foreseeable in superconducting quantum circuits, where recent advances [3–5] have highlighted the potential associated with scaling superconducting qubit technology [26]. Currently, significant efforts are underway to scale the number of qubits [27]. As a result, one of the challenges that future progress in superconducting circuits will face is to massively increase the number of microwave control and readout lines while preserving the base temperature and protecting qubits from thermal noise.

Figure 1a shows a prototypical measurement chain of a single superconducting device-under-test (DUT) that operates at the 15 mK stage of a dilution refrigerator. Coaxial cables are used to transmit output signals to the room temperature as well as to send control signals to the cold stages of the fridge. To read out GHz microwave signals, a high electron mobility transistor (HEMT) amplifier with low-added-noise \( n_{\text{add}} \sim 10 \text{ quanta}/(s \cdot \text{Hz}) \) is typically employed that operates at the 3 K stage and amplifies the DUT output signal for further processing outside the cryostat. Although HEMTs are not quantum-limited [8, 9], the development of Josephson junction-based preamplifiers [28–31] that operate at the 15 mK stage have allowed near-quantum-limited microwave amplification.

The presence of coaxial cables introduces additional heat load from room temperature into the cold stages of the refrigerator, which poses significant barrier to the scalability of such systems [27]. In contrast, optical fibers have superior thermal insulation, reducing the heat load per line by two orders of magnitude (Fig. 1b). Optical fibers additionally exhibit ultralow signal losses, \( \sim 0.2 \text{ dB/km} \), compared to \( \sim 3 \text{ dB/m} \) at GHz frequencies for coaxial lines (compensated by the HEMT amplification). Note also that thermal noise is completely negligible at optical frequencies. Optical fibers could therefore provide a solution to scaling the number of lines without the concomitant heating. For this approach, a critical component are transducers that convert input microwave signals to the optical domain, which are compatible with low temperature operation and are sufficiently efficient to ensure low noise conversion of microwave to optical signals. Indeed, substantial efforts are underway to create quantum-coherent interfaces between the microwave and optical domains [32]. To date, quantum coherent conversion schemes based on piezo-electromechanical [33, 34], magneto-optical [35], and optomechanical [36–40] coupling
have been developed. In addition, schemes based on cavity electro-optics [41] have been demonstrated using bulk [42–44] or integrated [45–47] microwave cavities coupled via the Pockels effect to an optical cavity mode. Yet, all these schemes have in common that they transduce narrowband microwave signals to the optical domain. While this ability is critical for future quantum networks, an optical replacement for the currently employed HEMT amplifiers may be required for scaling control lines. One route is therefore to use broadband optical modulators as already used today in telecommunication networks. While this approach may yield lower conversion efficiency compared to systems employing narrowband resonant cavities, continued improvements in design, and new material systems, can render it competitive, especially given its relative simplicity.

Here we explore this potential and replace the HEMT amplifier with a LiNbO$_3$-based optical phase modulator (PM), the workhorse of modulator technology, in order to directly transduce the DUT microwave output signal onto sidebands around the optical carrier field (Fig. 1b), detectable using standard homodyne or heterodyne detection schemes at ambient temperatures. To illustrate the principle of the readout, we consider the operating principle of a PM. Optical PMs are based on the Pockels effect (Fig. 1d) and induce a phase shift on the input optical field $E_{\text{in}}(t)$, proportional to the voltage $V(t)$ applied on the input microwave port of the device,

$$E_{\text{out}}(t) = E_{\text{in}}(t)e^{-i\pi V(t)/V_\pi} \approx E_{\text{in}}(t)[1 - i\pi V(t)/V_\pi],$$

(1)

where the half-wave voltage $V_\pi$ is the voltage at which the phase shift is $\pi$, and typical $V(t) \ll V_\pi$ is assumed. The relation between microwave (field operator $\hat{b}$) and optical (field operator $\hat{a}$) photon flux spectral densities [48], $\bar{S}_{bb}$ and $\bar{S}_{aa}$ respectively, can be written as (see Appendix)

$$\bar{S}_{aa}[\omega_{\text{opt}} \pm \omega_{\text{MW}}] = G \times (\bar{S}_{bb}[\omega_{\text{MW}}] + n_{\text{add}})$$

(2)

where $\omega_{\text{MW}}$ and $\omega_{\text{opt}}$ are the microwave signal and optical carrier frequencies, $n_{\text{add}}$ is the added noise of the transducer (referred to the input), and the transduction gain $G$ is the number of transduced optical photons per microwave input photon, given by (see Appendix):

$$G = P_{\text{opt}} \frac{\omega_{\text{MW}}}{\omega_{\text{opt}}} \frac{\pi^2 Z_0}{2V_\pi^2}$$

(3)
FIG. 2. Cryogenic characterization of a LiNbO₃ phase modulator. 

a, Experimental setup for low temperature characterization of the phase modulator. b, Plot of $V_\pi$ vs. frequency at 800 mK. c, Characterization of $V_\pi$ at 5 GHz vs. temperature from room temperature to 800 mK. d, Measurement of heating due to optical dissipation when the phase modulator is mounted on the 800 mK flange. Plot of the steady state temperature vs. input laser power of the 3 K, 800 mK, and 15 mK flanges. e, Experimental setup for phase shift keying detection. RF signal from waveform generator is directly applied on a phase modulator. After homodyne detection the electrical signal is recorded on a fast oscilloscope. f, Eye-diagram of an optical signal phase-modulated at a rate of 5 GBaud, the bit error ratio is $5 \times 10^{-5}$.

where $P_{opt}$ is the power of the optical carrier at the output of the PM, and $Z_0$ its input microwave impedance. In this experiment, we employ a commercial (Thorlabs LN65S-FC), $z$-cut traveling wave Ti-doped LiNbO₃ PM with specified bandwidth of 10 GHz and $V_\pi = 7.5$ V at 10 GHz (Fig. 1c). We use a 1555 nm fiber laser as the optical source. The typical incident optical power on the PM is 15 mW. The optical transmission of the PM was reduced during the first cooldown, and measured at 23%. Additional details on the cryogenic optical setup are given in the Appendix.

Previous works investigated the temperature dependence of the electro-optic coefficient and refractive index of congruent LiNbO₃ at low frequencies down to 7 K [49]. Commercial $x$-cut LN modulators were also tested down to 10 K, showing a slight change in $V_\pi$ from its room temperature value [50, 51]. Ref. [52] discusses the behavior of LiNbO₃ modulators with superconducting electrodes down to 4 K.

To date, however, such modulators have not been used in a dilution refrigerator to directly read out a superconducting device.
Characterization.

To characterize the electro-optic behavior of the device at cryogenic temperatures, we mount the PM on the 800 mK flange of the dilution fridge. We directly drive the microwave port of the PM at frequency $\omega_{MW}$ using a microwave source outside the fridge, generating sidebands around the optical carrier frequency (Fig. 2a). The half-wave voltage $V_\pi$ is determined from the modulation depth $MD$, defined as the ratio of the power in one of sidebands to the power in the carrier,

$$V_\pi = \pi \sqrt{\frac{Z_0 P_{MW}}{2 MD}},$$

where $P_{MW}$ is the power at the microwave input port of the PM. We measure $MD$ by beating the output optical signal with a local oscillator (LO) with frequency $\omega_{opt} + \omega_{MW}/2 + \delta$, generating two closely-spaced beatnotes at $\omega_{MW}/2 \pm \delta$, due to the carrier and the high-frequency sideband. Using Eq. (4) we extract $V_\pi$ by sweeping the microwave power and measuring $MD$. Figure 2c shows $V_\pi$ at 5 GHz monitored as the fridge is cooled down from room temperature to 800 mK, and Fig. 2b shows $V_\pi$ at different frequencies at 800 mK. Importantly, $V_\pi$ does not change substantially from the room temperature value.

To investigate the effect of heating caused by optical dissipation in the PM, we measured the steady state temperature of different flanges of the dilution fridge when the PM is mounted on the 800 mK flange. The results are shown in Fig. 2d. In the Appendix, by comparing to a calibrated heater, we show that these temperature increases can be attributed to optical power loss within the PM package (and not, e.g., light leakage into the fridge volume). This allows quantitative comparison with, e.g., heat dissipation due to a HEMT, and suggests reduced heat load in high optical transmission devices.

To further assess the performance of the PM at 800 mK, we also performed a basic telecommunication experiment shown in Fig. 2e. An arbitrary waveform generator (AWG) directly drives the PM with a pseudo-random bit sequence at a rate of 5 GBaud. We beat the optical phase-modulated carrier output with its reference arm, effectively forming a Mach-Zehnder interferometer whose average transmission is tuned to the quadrature point by adjusting the laser frequency, and detect the electrical signal on the oscilloscope. Figure 2f shows an eye diagram obtained from $8 \times 10^5$
samples. The open eye diagram features no error bits, hence the upper bound on bit error ratio is limited by total amount of measured samples and can be estimated to be $5 \times 10^{-5}$ with 95% confidence level [53]. These measurements clearly demonstrate that the cryogenic modulator still functions at 800 mK.
Having established the cryogenic modulation properties, we next carry out a cryogenic interconnect experiment, where the microwave output of a DUT is read out optically. As an example system we employ a superconducting electromechanical device in the form of a mechanically-compliant vacuum gap capacitor parametrically coupled to a superconducting microwave resonator (Fig. 3a–e). These devices have been employed in a range of quantum electromechanical experiments, such as cooling the mechanical resonator to its quantum ground state [54], strong coupling between mechanical and microwave modes [13], squeezing of mechanical motion [55], and demonstration of the quantum entanglement in the mechanical motion [56, 57], as well as implementing mechanically mediated tunable microwave non-reciprocity [58] and quantum reservoir engineering [59]. The microwave resonance (frequency $\omega_c \simeq 2\pi \times 8.2$ GHz and linewidth $\kappa \simeq 2\pi \times 3$ MHz) is coupled to the mechanical resonance (frequency $\Omega_m \simeq 2\pi \times 6$ MHz and linewidth $\Gamma_m \simeq 2\pi \times 10$ Hz) of the capacitor via electromechanical coupling [60] (Fig. 3d). The electromechanical coupling rate is $g = g_0 \sqrt{n_{cav}}$, where $g_0 \simeq 2\pi \times 150$ Hz is independently characterized [61] and $n_{cav}$ is intracavity microwave photon number, proportional to the microwave pump power. The system is inductively coupled to a microwave feed-line, enabling us to pump and read out the microwave mode in reflection.

To demonstrate the electro-optical readout technique, we perform two-tone spectroscopy and measure optomechanically induced transparency (OMIT) [10–12] (Fig. 3) on the electromechanical sample, by applying a microwave pump tone on the lower motional sideband (red-detuned by $\Omega_m$ from the cavity resonance) and sweeping a second probe tone across the resonance. The strong pump damps the mechanical motion, resulting in a wider effective mechanical linewidth, $\Gamma_{eff} = \Gamma_m + 4g^2/\kappa$. The microwave pump modifies the cavity response due to the electromechanical coupling, resulting in a transparency window of width $\Gamma_{eff}$ that appears on resonance, which we observe by the probe (Fig. 3g). We performed an OMIT experiment for different pump powers and observed the mechanical resonance via the transparency feature. In order to electro-optically read out the coherent response, the optical output is detected in a balanced heterodyne detector, using a frequency-shifted local oscillator (Fig. 3g). Note that this scheme allows resolving spectroscopic features finer than the laser linewidth (Fig. 3h). To compare the optical and HEMT readouts, the
FIG. 4. Electromagnetic readout of an incoherent microwave spectrum of a superconducting electromechanical system. a, Frequency-domain picture: a microwave tone pumps the electromechanical system on the upper motional sideband, inducing a parametric instability and generating mechanical sidebands equally spaced around the tone by the mechanical resonance frequency $\Omega_m$. The phase modulator transfers the microwave spectrum on the optical signal, which is subsequently mixed with a local oscillator (LO) and detected via heterodyne detection. b, Level scheme showing electromechanically induced parametric instability. A blue-detuned pump photon scatters into an on-resonance photon and generates a phonon in the mechanical oscillator and causes anti-damping. At pump power above a certain threshold induces instability in the mechanical oscillator. c, Measured power spectral densities of the microwave pump (central peak) and mechanical sidebands detected by the HEMT (blue) and optical (orange) readouts. d, Enlargement of the gray-shaded area in c, showing the power spectral densities of the on-resonance mechanical sideband.

reflected signal is split and measured simultaneously using both techniques (Fig. 3a). Figure 3c shows the OMIT results, with excellent agreement between the optical and HEMT readouts. At high pump powers, when $g \sim \kappa$, we observe mode splitting as a result of strong coupling and mode-hybridization between the mechanical and microwave modes [13].

Optical Readout of an Incoherent Microwave Spectrum

Next, we employ our scheme to directly read out optically the power spectral density of a microwave signal emitted by the DUT. For this, we drive the mechanical oscillator into self-oscillation by pumping the system on its upper motional sideband, $\omega_{\text{pump}} = \omega_c + \Omega_m$, inducing a parametric instability [60, 62-64]. The output microwave spectrum features strong sidebands around the microwave pump, at integer multiples of the mechanical frequency (Fig. 4a,b). Figure 4c shows these mechanical signals obtained simultaneously using both our optical readout and
the HEMT amplifier. We use the known properties of the HEMT to estimate the transduction gain $G$ [Eq. (2)] of our optical readout. The blue trace in Fig. 4c shows the HEMT output referred back to its input using its known added noise, $n_{\text{add}}^{\text{HEMT}} \simeq 8 \text{ quanta/}(s \cdot \text{Hz})$, characterized independently. This calibration yields the HEMT input signal $S$, which is equal to the PM microwave input. The noise in the optically detected spectrum, referred to the optical output of the PM, is dominated by the optical shot noise, $1 \text{ quanta/}(s \cdot \text{Hz})$, for our $G \ll 1$. In this calibration, we can obtain $G$ from the optical spectrum containing the transduced microwave signal $GS$. The orange trace in Fig. 4c shows the optical noise spectrum referred to the microwave input, and Fig. 4d shows a zoom-in of a single sideband. In this calibration, the signal areas in both measurements are equal to $S$. Further explanation of this calibration is given in the appendix. This yields $G = 0.9 \times 10^{-7}$, in good agreement with the theoretical value $G^{\text{theory}} = 3.5 \times 10^{-7}$ obtained from Eq. (3) using the measured output optical power, $P_{\text{opt}} = 1.1 \text{ mW}$ (optical efficiency of 5%, including losses in fiber connectors and heterodyne detection setup). We note that the frequency widening of the optically detected sidebands, observed in Fig. 4d, is due to fluctuations in the LO frequency, caused by the limited bandwidth of the locking setup in conjunction with using a minimal resolution bandwidth (RBW) of 1 Hz in the spectrum measurement. The integrated sideband power, however, is conserved. Improving the LO locking setup can reduce this effect.

The added noise in the transduction process is (see Appendix)

$$n_{\text{add}} = \frac{1}{2G} + n_{\text{th}}^{\text{MW}} + \frac{1}{2},$$

(5)

where $n_{\text{th}}^{\text{MW}}$ is the average occupation of the thermal photonic bath due to the microwave fields. This gives $n_{\text{add}} \approx 6 \times 10^6$. The noise floor of the optical measurement in Fig. 4c is 60 dB above the HEMT readout. This is due to the very small gain $G \sim 10^{-7}$, caused by the large $V_\pi$ and the limited optical power. However, there is much room for improvement in these parameters. Ref. 18 reported a $V_\pi$-length product of 0.45 V cm in a BaTiO$_3$-based modulator, thus $V_\pi \sim 50 \text{ mV}$ can be realized in a $\sim 10 \text{ cm}$ device, possibly using low-loss superconducting electrodes [47, 52]. The optical power can be increased arbitrarily in principle, however one needs to consider optical losses (mainly at the fiber-to-chip interfaces) that lead to heating. Considering a device with an improved optical transmission of 66% [65] and incident power of 15 mW, yields $P_{\text{opt}} \sim 10 \text{ mW}$. 
This scenario achieves $G \sim 5 \times 10^{-2}$ [Eq. (3)], with $n_{\text{add}} \approx 20$ at 3 K, competitive with HEMT performance, while the heat load of 5 mW is half that of a typical cryogenic HEMT.

It is worth mentioning that many experiments utilize a near-quantum-limited pre-amplifier at the 15 mK stage (Fig. 1a,b). In this case, the noise added in the second amplification stage, referred to the input, is $\sim (G_{PA} G)^{-1}$ (see Appendix), where $G_{PA} \sim 10^3$ is the pre-amplifier gain [28–31]. Thus, $G \gtrsim G_{PA}^{-1}$ suffices to preserve near-quantum-limited amplification (See Appendix).

Conclusions

We have demonstrated the viability of LiNbO$_3$ devices, currently-employed in the telecommunication market, as electro-optical interconnects in cryogenic platforms used in superconducting quantum technologies, in particular as viable alternative to HEMT amplifiers with the potential of reduced heat load. By interfacing a commercial PM to a circuit-electromechanical system that was previously used to perform quantum experiments, we implemented an electro-optical readout of this system. In addition, we quantified the gap between conventional microwave amplifiers and the electro-optical alternative. It is feasible that this gap be closed in the near future, by improved devices with lower $V_\pi$, resulting in a near-quantum-limited broadband microwave-to-optical interconnect.

Appendix

Quantum mechanical model for a phase modulator. In the following, we derive a simple quantum description of the phase modulator to establish the quantum limits in transducing the input microwaves. The central assumption is that the linear regime stays valid, for sufficiently low input microwave powers. As such, the scattering equations linking inputs to output should be identical in both quantum and classical cases. We can use the known classical regime as a starting point, with the output optical field amplitude $\hat{a}_{\text{out}}$ expressed as a function of the input optical field $\hat{a}_{\text{in}}$ as

$$\hat{a}_{\text{out}} = e^{-i\pi V/V_\pi} \hat{a}_{\text{in}} \approx (1 - i\pi V/V_\pi) \hat{a}_{\text{in}},$$

(A.1)
where $V$ is the classical voltage applied at the input and the half-wave voltage $V_{\pi}$ is the voltage at which the phase modulator applies a phase shift of $\pi$. For the quantum model, the classical fields are replaced by their quantum equivalent. The microwave input becomes $\hat{V} = \sqrt{\hbar \omega_{MW} Z_0} (\hat{b} + \hat{b}^\dagger) / \sqrt{2}$ with $\hat{b}$ the annihilation operator for the microwave field at frequency $\omega_{MW}$ traveling on a transmission line of impedance $Z_0$. The optical input is $\hat{a}_{in} = \alpha e^{-i \omega_{opt} t} + \delta \hat{a}_{in}$, where $\alpha$ is the amplitude of the coherent carrier field of frequency $\omega_{opt}$, with $|\alpha|^2 = P_{opt} / \hbar \omega_{opt}$, and $\delta \hat{a}_{in}$ carries the quantum fluctuations of the input optical field. Inserting the expressions in Eq. (A.1), we can compute $\delta \hat{a}_{out} = \hat{a}_{out} - \alpha e^{-i \omega_{opt} t}$, the quantum fluctuations of the output optical field, given by

$$\delta \hat{a}_{out} = \delta \hat{a}_{in} - i \sqrt{G} e^{-i \omega_{opt} t} (\hat{b} + \hat{b}^\dagger)$$

(A.2)

with the transduction gain $G$ given by Eq. (3).

To understand the implications of Eq. (A.2) for the quantum noise in the transduction, we compute the power spectral density of the output optical field,

$$S_{\delta a \delta a}^{\text{out}}[\omega_{opt} + \omega_{MW}] = S_{\delta a \delta a}^{\text{in}}[\omega_{opt} + \omega_{MW}] + G (S_{\delta b \delta b}[\omega_{MW}] + S_{\delta b \delta b}^\dagger[-\omega_{MW}]).$$

(A.3)

The first term corresponds to the added quantum noise due to the input optical field. The second term contains contributions from the microwave frequency $\omega_{MW}$, including both the signal and noise. The third term contains added microwave noise at frequency $-\omega_{MW}$, composed of thermal and quantum noise components, respectively $n_{\text{th}}^{MW} + 1/2$. Thus Eq. (A.3) can be simplified to

$$S_{\delta a \delta a}^{\text{out}}[\omega_{opt} + \omega_{MW}] = G S_{\delta b \delta b}[\omega_{MW}] + G \left( n_{\text{th}}^{MW} + \frac{1}{2} \right) + \frac{1}{2}.$$ 

(A.4)

We emphasize two limiting cases. When $G \ll 1$, as in our experiment, the added noise is dominated by the input optical quantum noise, the last term in Eq. (A.4). In the opposite limit, $G \gg 1$, the added noise is dominated by the microwave input noise, and the signal-to-noise ratio is independent of $G$. In any case, the added noise referred to the input is given by Eq. (5).

**Calibration of the transduction gain.** Figure 5 illustrates the procedure of experimentally characterizing the transduction gain of our electro-optic transducer. The microwave signal is split equally into two parts $S$, fed to the HEMT amplifier and the PM respectively (Fig. 5a). The HEMT
added noise is characterized independently to be $n_{\text{add}}^{\text{HEMT}} = 8 \text{ quanta/(s} \cdot \text{Hz)}$. We infer $S$ from the spectrum of the HEMT amplified signal, referring the noise floor to $n_{\text{add}}^{\text{HEMT}}$ (Fig. 5b). In the PM branch, the added noise of the transduction is given by Eq. (5). The spectrum is detected using a balanced heterodyne detector, which adds $1/2 \text{ quanta/(s} \cdot \text{Hz)}$ of noise (Fig. 5c). We can safely neglect $G(n_{\text{MW}} + 1/2)$ and consider the noise floor of the spectrum referred to the input of the heterodyne detector, i.e. $1 \text{ quanta/(s} \cdot \text{Hz)}$. This allows us to calculate $G$, and finally obtain $G$ with knowledge of $S$ from the HEMT measurement.

When using a quantum-limited pre-amplifiers before the electro-optical transducer (not done in our experiment), we can model the readout chain as shown in Fig. 6b. The total added noise of the readout chain is

$$n_{\text{add}}^{\text{total}} = n_{\text{add}}^{\text{PA}} + \frac{n_{\text{add}}^{\text{HEMT}}}{G_{\text{PA}}} \simeq n_{\text{add}}^{\text{PA}} + \frac{1}{2G_{\text{PA}}} \quad \text{(A.5)}$$

Therefore when $G \simeq 1/G_{\text{PA}}$, the total added noise will be dominated by $n_{\text{add}}^{\text{PA}} \sim 1 \text{ quanta/(s} \cdot \text{Hz)}$ [28–31] and the readout will be near-quantum-limited.

**Experimental details and heating measurements.** We use a fiber-coupled lithium niobate PM from Thorlabs, model LN65S, used as-is with no modifications. Note that the minimum specified operating temperature is $0 \degree \text{C}$. The device sustained several cooldown-warmup cycles with reversible behavior in its optical transmission. We measured 25% reduction in the optical transmission at cryogenic relative to room temperature. The PM metallic box was tightly clamped to the
flange of the 800 mK or 3 K stage. We use a Bluefors LD-250 dilution refrigerator. The approximate available cooling powers of the \{15 mK, 800 mK, 3 K\} stages are \{12 \mu W, 30 mW, 300 mW\}.

Figure 2c shows the variation of \(V_z\) from room temperature to 800 mK, obtained during a cooldown of the dilution fridge and measured using the default thermometer on the 800 mK flange, located next to the heat exchanger, about 10 cm from the PM. In order to rule out possible temperature gradients, we mounted a calibrated thermometer next to the PM and monitored both thermometer readings during cooldown. Figure 7a shows the measured relative temperature difference, which is less than \(\sim 5\%\) throughout the cooldown. Note that this excludes pulse precooling and mixture condensation period when the temperature is unstable (shown for completeness in Fig. 7a).

Figure 2d shows the temperature increase of the 15 mK, 800 mK, and 3 mK stages of the dilution fridge as a function of the optical power incident on the PM, which is mounted on the 800 mK stage. We performed a simple measurement to verify that this temperature increase can be ascribed to light absorbed in the PM body (and not, e.g, light leakage into the fridge volume), corresponding to the optical transmission (insertion loss) of the PM. We used the calibrated 120 \Omega\ still heater built in the 800 mK stage to apply heat directly, we then repeated the measurement using optical input to the PM as the heating source (as in Fig. 2d). Figure 7a,b compares the results of this measurement, showing temperature increase in the 3 K and 800 mK stages (the latter recorded with the two separated thermometers) vs. dissipated power. In the case of optical heating, the dissipated power is computed directly from the incident power on the PM and its measured transmission of 23%.

Figure 7b,c shows the result of this measurement. The optical heating shows a temperature increase of 13.3 mK/mW (6.5 mK/mW) at the 800 mK (3 K) stage (Fig. 7b), while the resistive heating shows a temperature increase of 14.1 mK/mW (8.3 mK/mW) at the 800 mK (3 K) stage (Fig. 7b). Thus heating due to operation of the electro-optical interconnect is very similar to localized, resistive heating.
FIG. 7. **Heat dissipation and temperature gradients.** a, Relative temperature difference between PM box and heat exchanger, on 800 mK flange during a cooldown. The gray datapoints correspond to specific periods of pulse precooling and mixture condensation, where the temperature is unstable. b, Measurement of heating due to optical dissipation when the phase modulator is mounted on the 800 mK flange. c, Measurement of heating using a calibrated resistive heater mounted on the 800 mK flange.

**Data availability statement**

The code and data used to produce the plots within this paper will be available at a Zenodo open-access repository. All other data used in this study are available from the corresponding authors upon reasonable request.

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Figure 1

Principle of a cryogenic electro-optical interconnect for readout of superconducting devices. a, Simplified schematic of a conventional readout of a device under test (DUT) in a dilution fridge using a cryogenic HEMT amplifier. The dashed box indicates an optional quantum-limited pre-amplifier not used in this
work. The devices are interrogated by input microwave signals that are attenuated to reduce thermal noise, and amplified using an HEMT amplifier at 3K. b, Principle of a cryogenic electro-optic readout scheme using an electro-optical phase modulator. The DUT is interrogated using the same microwave input line, but the microwave signals are converted to the optical domain at 3 K, reducing thermal load. c, Conducted heat through a typical cryogenic coaxial cable and optical fiber, between room temperature and 3K. d, Schematic cross-section of a z-cut LiNbO3 electro-optic phase modulator. e, Microscope photo of the commercial phase modulator used in the experiment, showing the coupling region between fiber and LiNbO3 chip.

**Figure 2**

Cryogenic characterization of a LiNbO3 phase modulator. a, Experimental setup for low temperature characterization of the phase modulator. b, plot of $V_{\pi}$ vs. frequency at 800mK. c, Characterization of $V_{\pi}$ at 5 GHz vs. temperature from room temperature to 800mK. d, Measurement of heating due to optical dissipation when the phase modulator is mounted on the 800mK flange. Plot of the steady state temperature vs. input laser power of the 3K, 800mK, and 15mK flanges. e, Experimental setup for phase shift keying detection. RF signal from waveform generator is directly applied on a phase modulator. After homodyne detection the electrical signal is recorded on a fast oscilloscope. f, Eye-diagram of an optical signal phase-modulated at a rate of 5 GBaud, the bit error ratio is 5x10^-5.
Figure 3

Electro-optic readout of a coherent microwave spectrum of a superconducting electromechanical system. 

a, Experimental setup. Left: dilution fridge, right: optical setup. b, Electromechanical system used as a DUT. c, Optical micrograph of the LC resonator. d, Modal diagram of the electromechanical system. e, Scanning electron micrograph of the mechanically compliant capacitor. f, Coherent measurement of the electromechanical resonance for increasing microwave pump powers of (-20; 0; 5; 10; 15; 20)dBm at the source, from bottom to top respectively. The probe power is -20 dBm at the source. By increasing the pump power, the optomechanically induced transparency window emerges, and at stronger pump powers the modes get strongly coupled, leading to an avoided crossing effect. Blue lines correspond to HEMT readout and orange dots to optical readout. g, The frequency scheme for microwave tones, optical tones, and measured signal after heterodyning. h, High resolution measurement of the transparency window highlighted in f with the gray box. i, Level scheme of the optomechanical system. The pump tone is tuned close to red sideband transitions, in which a mechanical excitation quantum is annihilated (mechanical occupation nm -> nm - 1) when a photon is added to the cavity (optical occupation np -> np + 1), therefore coupling the corresponding energy eigenstates. The probe tone probes reflection in which the mechanical oscillator occupation is unchanged. The pump tone modifies the response of the cavity and creates a transparency window appears on resonance (OMIT).
Figure 4

Electro-optic readout of an incoherent microwave spectrum of a superconducting electromechanical system. a, Frequency-domain picture: a microwave tone pumps the electromechanical system on the upper motional sideband, inducing a parametric instability and generating mechanical sidebands equally spaced around the tone by the mechanical resonance frequency $\Omega_m$. The phase modulator transfers the microwave spectrum on the optical signal, which is subsequently mixed with a local oscillator (LO) and detected via heterodyne detection. b, Level scheme showing electromechanically induced parametric instability. A blue-detuned pump photon scatters into an on resonance photon and generates a phonon in the mechanical oscillator and causes anti-damping. At pump power above a certain threshold induces instability in the mechanical oscillator. c, Measured power spectral densities of the microwave pump (central peak) and mechanical sidebands detected by the HEMT (blue) and optical (orange) readouts. d, Enlargement of the gray-shaded area in c, showing the power spectral densities of the on-resonance mechanical sideband.
Figure 5

Illustration of the gain characterization procedure. a, Propagation of the DUT signal through the system. b, Power spectral density of the HEMT output. c, Power spectral density of the optical heterodyne detector.

Figure 6

Schematic signal flow when pre-amplifier is used.
Figure 7

Heat dissipation and temperature gradients. a, Relative temperature difference between PM box and heat exchanger, on 800mK flange during a cooldown. The gray datapoints correspond to specific periods of pulse precooling and mixture condensation, where the temperature is unstable. b, Measurement of heating due to optical dissipation when the phase modulator is mounted on the 800mK flange. c, Measurement of heating using a calibrated resistive heater mounted on the 800mK flange.