Microwave-to-optics conversion using a mechanical oscillator in its quantum ground state

Moritz Forsch1,6, Robert Stockill1,6, Andreas Wallucks1, Igor Marinković7, Claus Gärtner1,2, Richard A. Norte1,3, Frank van Otten4, Andrea Fiore4, Kartik Srinivasan5 and Simon Gröblacher5*"n

Conversion between signals in the microwave and optical domains is of great interest both for classical telecommunication and for connecting future superconducting quantum computers into a global quantum network. For quantum applications, the conversion has to be efficient, as well as operate in a regime of minimal added classical noise. While efficient conversion has been demonstrated using mechanical transducers, they have so far all operated with a substantial thermal noise background. Here, we overcome this limitation and demonstrate coherent conversion between gigahertz microwave signals and the optical telecom band with a thermal background of less than one phonon. We use an integrated, on-chip electro-optomechanical device that couples surface acoustic waves driven by a resonant microwave signal to an optomechanical crystal featuring a 2.7 GHz mechanical mode. We initialize the mechanical mode in its quantum ground state, which allows us to perform the transduction process with minimal added thermal noise, while maintaining an optomechanical cooperativity >1, so that microwave photons mapped into the mechanical resonator are effectively upconverted to the optical domain. We further verify the preservation of the coherence of the microwave signal throughout the transduction process.

Research into novel quantum technologies is receiving significant attention for its potential to fundamentally transform how we receive, process and transmit information. In particular, major endeavours into building quantum processors and quantum simulators are currently underway. Many leading efforts, including superconducting qubits and quantum dots, share quantum information through photons in the microwave regime. While this allows for an impressive degree of quantum control, it also limits the distance the information can realistically travel before being lost. At the same time, the field of optical quantum communication has already seen demonstrations over distance scales capable of providing real-world applications. In particular, by transmitting information in the optical telecom band, fibre-based quantum networks operating on average one phonon. As our converter features a noise source containing less than one photon, optimizing the electromechanical cooperativity needs to be realized in order to suppress additional noise sources. To date there has been no demonstration of a system with mechanically mediated interfaces in both the microwave and optical domains that operates in the quantum ground state.

In this work, we demonstrate microwave-to-optics conversion with an electro-optomechanical device, which contributes less than one quantum of thermal noise. We cryogenically cool a gigahertz-frequency piezoelectric optomechanical crystal (OMC) device into its quantum ground state of motion. The low thermal occupation forms the basis for quantum control over mechanical states, with demonstrations including quantum-state preparation and entanglement between multiple mechanical degrees of freedom. Reaching this occupation regime is challenging because the absorption of optical photons has to be avoided, while at the same time a sufficiently strong optomechanical cooperativity needs to be realized in order to suppress additional noise sources. To this end there has been no demonstration of a system with mechanically mediated interfaces in both the microwave and optical domains.

Our microwave-to-optics converter consists of a one-dimensional OMC16, which is mechanically coupled to an interdigital transducer (IDT) through SAWs (see Fig. 1a). We fabricate the devices from a 250-nm-thick GaAs layer, on a 3 μm Al0.7Ga0.3As sacrificial layer, several experiments have recently demonstrated cooling of mechanical oscillators into the quantum ground state of motion. The low thermal occupation forms the basis for quantum control over mechanical states, with demonstrations including quantum-state preparation and entanglement between multiple mechanical degrees of freedom. Reaching this occupation regime is challenging because the absorption of optical photons has to be avoided, while at the same time a sufficiently strong optomechanical cooperativity needs to be realized in order to suppress additional noise sources. To this end there has been no demonstration of a system with mechanically mediated interfaces in both the microwave and optical domains.

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both epitaxially grown on a GaAs substrate. This material combines a large refractive index \( n_{GaAs} = 3.37 \) at \( \lambda = 1.55 \text{ nm} \) and a non-zero piezoelectric coefficient \( \epsilon_p = -0.16 \text{ C m}^{-2} \), with well-established fabrication processes. The optomechanical device, shown in the lower inset of Fig. 1a, is designed using finite-element modelling, such that the patterned nanobeam confines light in the telecom band, while at the same time exhibiting a co-localized mechanical breathing mode at \( \omega_m = 2\pi \times 2.7 \text{ GHz} \) (Fig. 1b). The electromechanical coupling in our device is due to the piezoelectric effect that allows for the excitation of travelling acoustic waves that drive the OMC\(^2\). The optomechanical coupling, on the other hand, is facilitated by the parametric coupling between the mechanical excitation and the intracavity photon number owing to the combination of photoelastic coupling and moving boundary conditions\(^3\). Both effects can intrinsically operate in a bi-directional and noiseless fashion. The device fabrication consists of a two-stage lithography process to define the IDT and then pattern the nanobeams, followed by a hydrogen fluoride etch to remove the AlGaAs sacrificial layer. A final deposition of 5 nm of AlO\(_x\) passivates the surfaces and reduces the effect of unwanted drive-laser absorption\(^4\) (see Supplementary Information for details). The lower inset of Fig. 1a displays a scanning electron micrograph of an optomechanical device, and an evanescently coupled waveguide that provides optical-fibre access to the confined optical mode\(^5\).

We perform an initial characterization of the device properties at room temperature with the set-up depicted in Fig. 1c, the results of which are presented in Fig. 1d. An \( S_1 \) measurement of the IDT shows a 10-MHz-wide microwave resonance centred at 2.76 GHz. The mechanical mode of the OMC is then measured by locking a laser onto the blue sideband \( (\omega_i = \omega_m + \omega_m) \) of the optical cavity resonance \( \omega_i (\omega_i = 2\pi \times 194.3 \text{ THz}) \), with a loaded optical quality factor \( Q_l = 3.3 \times 10^5 \) (see Supplementary Information), and monitoring the high-frequency noise in the reflected signal. The peak in the noise spectrum at 2.744 GHz corresponds to the thermally occupied mechanical mode \( (\sim 1 \times 10^3 \text{ phonons}) \) and has a linewidth of several megahertz. The small mismatch between the IDT and mechanical resonances of \( \sim 10 \text{ MHz} \) is a result of fabrication-based inhomogeneities. As we apply a radio-frequency (RF) tone to the IDT at the mechanical frequency \( \omega_m \), we observe an additional narrow peak on top of the thermal noise, corresponding to the transduced coherent signal from the IDT. The height of this peak is dependent on the RF power and the detuning from the mechanical resonance\(^2\).

The room-temperature characterization highlights that the large initial thermal occupation of the mechanical mode is a significant source of noise in this conversion process. Especially at low RF drive powers, the thermal noise dominates over the transduced signal\(^1\). By placing our device in a dilution refrigerator (base temperature \( \sim 20 \text{ mK} \)), we can in principle reduce the thermal occupation of the mechanical mode to \( n_{th} \approx 10^{-3} \). In practice, the achievable occupation is limited by residual heating through laser absorption and finite thermalization to the cryostat\(^2\). With the device cooled to millikelvin temperatures, we measure the actual thermal occupation of the mechanical mode by monitoring cavity-enhanced Stokes (blue sideband) and anti-Stokes (red sideband) scattering rates \( \Gamma_s \) and \( \Gamma_a \) respectively, when we drive the cavity with laser pulses detuned by \( \pm \omega_m \) (ref. \(^2\)). We suppress the reflected pump light through spectral filtering, such that only scattered photons on cavity resonance are detected by superconducting nanowire single-photon detectors (SNSPDs) as shown in Fig. 2a. Specifically, the rates we measure are set by \( \Gamma_s \propto n_{th} + 1 \) and \( \Gamma_a \propto n_{th} \) (ref. \(^2\)). Figure 2b shows a histogram of the single-photon count rates measured for 40-ns-long pulses set to the two detunings with a peak power of 107 nW at the device.
For this power, we find an optomechanical cooperativity of $C = 1.7$ (see Supplementary Information). We extract a thermal occupation of $n_{\text{th}} = 0.90 \pm 0.01$, confirming the initialization of the device close to its quantum ground state. This value is higher than the theoretical value set by the cryostat temperature, limited by residual heating of the structure during the laser pulse. A sweep of the pulse power reveals that lower occupations can be achieved (for example, $n_{\text{th}} = 0.36 \pm 0.03$; see Supplementary Information), at the cost of a lower conversion efficiency.

We now proceed to verify the conversion from microwave to optical telecom signals at millikelvin temperatures. Red-detuned ($\omega_l = \omega_c - \omega_m$) optical pulses, which realize an optomechanical state-swap, are sent into the OMC to read out the state of the mechanical mode, which is coherently excited by sweeping the frequency of an RF drive tone (1 $\mu$W) across the mechanical resonance (see Fig. 2c). The data are fitted with a Lorentzian, from which we extract a mechanical linewidth of $197$ kHz, corresponding to a mechanical lifetime of $\sim 0.8 \mu$s. HBT-type measurement of the photons emitted from our cavity with 7 nW of optical input power. The second-order correlations $g^{(2)}(\tau)$ are shown for a selection of the measured RF powers alongside a reference measurement with no RF drive, but high optical power (4.5 $\mu$W, bottom curve). The curves are offset for clarity. The bunching in the reference measurement results from absorption heating due to the laser drive, yielding a large thermal state of the mechanical resonator.

**Fig. 2** | Device characterization at millikelvin temperatures. **a**, A schematic of the cryogenic experimental set-up. The sample with the OMC and IDT, and a pair of SNSPDs, are placed inside the dilution refrigerator (at 20 mK and ~1K, respectively). We lock the laser on the red sideband of our cavity and filter residual reflected pump light from the cavity, detecting photons scattered on the cavity resonance. **b**, Sideband thermometry to extract the thermal occupation of the mechanical resonator. We find an occupancy $n_{\text{th}} = 0.90 \pm 0.01$, confirming the initialization of the device close to its quantum ground state. The bar graph shows the integrated counts for the red and blue sideband drives as well as the corresponding histograms (inset). The error bars are one standard deviation, owing to the shot noise resulting from photon counting. **c**, Mechanical characterization and initial conversion from the RF to the telecom band at millikelvin temperatures. We sweep the RF drive frequency with the laser locked at $\omega_l - \omega_m$ and monitor the count rate. The solid curve is a Lorentzian fit to the data, from which we extract a mechanical linewidth of $197$ kHz, corresponding to a mechanical lifetime of $\sim 0.8 \mu$s. **d**, HBT-type measurement of the photons emitted from our cavity with 7 nW of optical input power. The second-order correlations $g^{(2)}(\tau)$ are shown for a selection of the measured RF powers alongside a reference measurement with no RF drive, but high optical power (4.5 $\mu$W, bottom curve). The curves are offset for clarity. The bunching in the reference measurement results from absorption heating due to the laser drive, yielding a large thermal state of the mechanical resonator.
To demonstrate the potential of these devices as transducers of microwave to optical signals at the quantum level, we now operate both the RF driving and optical readout in a pulsed mode. We send a resonant RF pulse (1 μs long) to the IDT to excite our oscillator and access the mechanical state through a 40-ns-long red-detuned state-swap pulse. This allows us to minimize the effects of heating due to optical absorption. The pulsed experiment enables us to quantify the absolute number of coherent phonons added to our initial state by comparing the scattering rate in the presence of an RF drive ($I_{\text{RF}}$) to the scattering rate we obtain from the remaining thermal population ($I_{\text{th}}$) (inset in Fig. 3b). By measuring the photon rate with and without a resonant RF drive, we recover an RF-phonon conversion efficiency of $3.57 \times 10^{-10}$ phonons per RF photon.

Using the same HBT-type set-up as above, we detect the second-order correlation of the scattered photons, which allows us to compare the coincidences between detection events originating from the same ($\Delta t = 0$) or different ($\Delta t \neq 0$) pulse sequences. A selection of the histograms of these correlations is shown in Fig. 3a for various coherent phonon occupations ($n_{\text{coh}}$). The full set of $g^{(2)}(0)$ values for increasing coherent phonon occupation is shown in Fig. 3b. We expect the value of $g^{(2)}(0)$ to be determined by the ratio $n_{\text{coh}}/n_{\text{th}}$ (see the Supplementary Information). We extract this number from the relative count rate we recover with and without the RF pulse, $I_{\text{RF}} / I_{\text{th}}$, displayed in the inset of Fig. 3b. The dashed curve in Fig. 3b displays the expected $g^{(2)}(0)$ for our RF power sweep based on the theory for a displaced thermal state (see the Supplementary Information), which are in good agreement with our measured values. An increase in RF power results in a larger coherent displacement of the thermal state, which in turn leads to a decreased value for $g^{(2)}(0)$.

While our pulsed experiments clearly demonstrate conversion between a coherent state in the microwave and the telecom domain, they do not imply the retention of the input-state phase. To access the coherence of the transduction process, we use a modified version of the set-up (for a detailed sketch, see Supplementary Fig. 5). We split the red-detuned excitation laser into two branches of a phase-stabilized Mach–Zehnder interferometer, one of which contains our device and the other an amplitude electro-optic modulator. We drive both the IDT and the electro-optic modulator with a single RF source, such that a coherent transduction process results in a fixed phase relationship between the upconverted light in the two interferometer arms. We then mix the light on a beamsplitter, matching the photon rate in the two arms. Figure 4a displays the count rate at one output port of the Mach–Zehnder interferometer when we vary the phase of the interferometer for several coherent phonon occupations. We observe a clear interference pattern with a visibility of $44 \pm 3\%$ for powers corresponding to a coherent phonon occupation of $n_{\text{coh}} = 1.1$, which increases to $85 \pm 7\%$ as the coherent contribution dominates over the small thermal background. Figure 4b displays these experimentally retrieved visibilities for several coherent phonon occupations, showing the expected modelled behaviour assuming only thermal noise ($n_{\text{noise}} = n_{\text{th}}$, solid line), as well as additional incoherent noise sources ($n_{\text{noise}} = n_{\text{th}} + n_{\text{tot}}$, dashed line). These respective trends are given by $\sqrt{n_{\text{tot}} / (n_{\text{th}} + n_{\text{tot}})}$ and scaled by the maximally achievable interference visibility in our set-up of 90%. Here, $n_{\text{tot}}$ represents the equivalent noise figure for any other source than the thermal occupation of the resonator, including imperfections in the measurement set-up. We estimate the upper bound of these sources to be $n_{\text{tot}} \sim 2.5$. The main contributions to this remaining part are drifts of the interferometer free spectral range over the duration of the measurement, imperfect sideband resolution ($\delta f_{\text{side}} = 0.27$), and mechanical decoherence. With this measurement, we confirm the phase-preserving nature of the conversion process down to the single-phonon level.

The total efficiency of our device is the product of two parts: the loading efficiency of the mechanical mode from the microwave side
(3.57 × 10⁻¹⁰, measured from the attenuator output at the mixing chamber to the excitation of phonons in the mechanical mode) and the optical readout efficiency of the mechanical mode (1.55 × 10⁻⁴). The latter one can itself be separated into two parts: \( \eta_{\text{th}} = p_t \times \eta_{\text{det}} \), with \( \eta_{\text{det}} = 1.41 \times 10^{-3} \) (see Supplementary Information). The state-swap probability \( p_s = 1.1\% \) is a function of the power with which the optical readout is performed and can be increased through improvements with respect to optical absorption. Note that the current performance of our device is already sufficient to read out a non-classical state of the mechanical mode. The low loading efficiency of the mechanical mode can be attributed to the design and size of the electromechanical transducer. We estimate the efficiency of transferring a SAW from the IDT (150 μm wide) into a single, narrow (~1 μm), suspended beam to be less than 2.5 × 10⁻⁶. Additional contributions arise from the difference in the polarizations of the incoming SAW and the mechanical mode, the discrepancy between the IDT and mechanical frequencies, and the large electrical impedance of the IDT. These factors can be improved by tailoring the size and design of the electromechanical transducer specifically to the purpose of exciting the breathing mode of a single nanobeam. While the small-scale piezo-resonator required to mode-match the nanobeam will necessitate careful electrical impedance matching, the required network falls into the range accessible with coplanar resonator technology. The relatively small optomechanical state-swap probability and detection efficiency reported here, on the other hand, can be circumvented with post-selection techniques routinely used in quantum optics experiments.

We have demonstrated faithful conversion of a microwave to an optical signal with only a small added thermal contribution due to the ground state occupation of the mechanical resonator. Furthermore, these measurements show our ability to detect the displacement amplitude of the initial state in our mechanical resonator down to one phonon (corresponding to our lowest measured RF power), marking a crucial benchmark for applications in the quantum regime. The device used for this experiment is a fully integrated, on-chip hybrid electro-optomechanical system with a mechanical mode as the transducer. We cool this mode to its quantum ground state using a dilution refrigerator, which allows us to operate directly at the quantum noise limit. This work allows for the on-chip integration of a single-photon RF source, such as a superconducting qubit, which paves the way for building a true quantum network over large distances, based on superconducting nodes. The device we consider here is specifically suited towards heralded entanglement generation between remote superconducting qubits, a protocol that is described in ref. 21.

While we demonstrate quantum-limited noise performance in the readout of the mechanical state, the conversion efficiency is currently limited by low microwave-phonon excitation efficiency. We note that this is not a fundamental limit but rather a result of design choices for this proof-of-principle demonstration. The material itself imposes some limitations on the efficiency, such as the remaining absorption heating and the relatively low piezoelectric coupling. However, demonstrations of coherent coupling between superconducting qubits and SAWs in GaAs (refs. 35, 45) suggest that the latter are highly suitable choices for noise-free carriers of quantum information. Importantly, our system is already operating in the range of optical drive strengths expected for mediating efficient conversion. In particular, the optomechanical cooperativity of \( C \approx 1.7 \) (see Supplementary Information) is sufficient for efficiently converting gigahertz phonons into telecom photons.

Note added in proof: During the submission process, we became aware of a related work demonstrating a GaAs OMC in the low thermal occupation regime.

Data availability
The data represented in the figures are available as Supplementary information files. All other data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

Online content
Any methods, additional references, Nature Research reporting summaries, source data, statements of code and data availability and associated accession codes are available at https://doi.org/10.1038/s41567-019-0673-7.

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