Electrical control of surface acoustic waves

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Acoustic waves at microwave frequencies are widely used in wireless communication and are potential information carriers in quantum applications. However, most acoustic devices are passive components, and the development of phononic integrated circuits is limited by the inability to control acoustic waves in a low-loss, scalable manner. Here we report the electrical control of gigahertz travelling acoustic waves at room temperature and millikelvin temperatures. We achieve phase modulation by tuning the elasticity of a lithium niobate acoustic waveguide via the electro-acoustic effect. This phase modulator is then used to build an acoustic frequency shifter based on serrodyne phase modulation, and phase modulators in a Mach–Zehnder interferometer configuration are used to create an electro-acoustic amplitude modulator. By tailoring the phase matching between acoustic and quasi-travelling electric fields, we achieve reconfigurable non-reciprocal modulation with a non-reciprocity of over 40 dB. To illustrate the potential of the approach in quantum applications, we show that our electro-acoustic modulator can provide coherent modulation of single-phonon-level acoustic waves at 50 mK.

A phononic integrated circuit requires several essential functionalities, including low-loss waveguiding of acoustic waves, efficient transduction from and to electromagnetic waves at microwave frequencies, and dynamic routing and modulation of travelling acoustic waves. Integrated acoustic waveguides have been used for suspended structures, two-dimensional phononic crystals and high-acoustic-velocity substrates, whereas efficient transduction between acoustic waves and electromagnetic waves can be achieved using piezoelectric coupling with microwaves and optomechanical coupling with light. However, the development of acoustic integrated circuits is limited by the absence of techniques capable of the active control of the phase, amplitude, frequency and non-reciprocity of acoustic waves in a low-loss and scalable manner.

Previous approaches to control on-chip acoustic waves based on acoustic four-wave mixing require large acoustic powers due to the weak nonlinearity of the elastic response of most materials. Directional amplification and manipulation of sub-GHz acoustic waves have been demonstrated using electrical amplifiers and semiconductor acousto-electric effects. However, these rely on the thermal excitation of charge carriers in semiconductors, which inevitably induces loss and noise in the acoustic signals and makes them incompatible with the cryogenic temperatures needed in quantum applications. Furthermore, strategies to achieve acoustic non-reciprocity using nonlinear materials, circulating fluids, water-submerged phononic crystals, deformed water-air interfaces and optomechanics are limited to acoustic frequencies below a few megahertz and are thus unsuitable for applications that require microwave acoustic frequencies. Approaches using ferromagnetic materials require a magnetic field and are therefore inconvenient for co-integration with superconducting circuits or spins in solids.

In this Article, we report the electrical control of the fundamental degrees of freedom of GHz acoustic waves on an integrated lithium niobate (LN) platform. The modulation of acoustic waves is enabled by the electro-acoustic effect (also known as the third-order piezoelectric effect), which is used to tune the elasticity of an LN acoustic waveguide, and thus the phase velocity of the travelling acoustic wave, by applying an electric field. We create an electro-acoustic phase modulator that operates at a carrier frequency of around 2.5 GHz. The phase modulator can be used as an acoustic frequency shifter by applying a repeated linear voltage ramp—analogous to serrodyne frequency shifting used in optics—with an efficiency of 92% at room temperature. We also show that phase modulators in a Mach–Zehnder configuration can be used to build an electro-acoustic amplitude modulator. By applying a quasi-travelling electric field using multiple electrodes across the waveguide and adjusting the phase of the modulating signal at each electrode, non-reciprocal acoustic phase modulation can be achieved, with a non-reciprocity higher than 40 dB. To illustrate the potential of our approach in quantum applications, we show that it can provide the coherent modulation of single-phonon acoustic waves at 50 mK and that the modulation adds less than one noise phonon to the system.

Electro-acoustic modulator

The electro-acoustic effect is a parametric process that occurs at both room temperature and millikelvin temperatures and is analogous to an electrical field and a quasi-travelling electric field, which consists of a series of static and quasi-travelling electric fields. The quasi-travelling electric fields are generated by applying a repeated linear voltage ramp, which is used to tune the elasticity of an LN acoustic waveguide and thus the phase velocity of the travelling acoustic wave, by applying an electric field. The phase modulator can be used as an acoustic frequency shifter by applying a repeated linear voltage ramp—analogous to serrodyne frequency shifting used in optics—with an efficiency of 92% at room temperature. We also show that phase modulators in a Mach–Zehnder configuration can be used to build an electro-acoustic amplitude modulator. By applying a quasi-travelling electric field using multiple electrodes across the waveguide and adjusting the phase of the modulating signal at each electrode, non-reciprocal acoustic phase modulation can be achieved, with a non-reciprocity higher than 40 dB. To illustrate the potential of our approach in quantum applications, we show that it can provide the coherent modulation of single-phonon acoustic waves at 50 mK and that the modulation adds less than one noise phonon to the system.
the waveguide is oriented along a 30° angle with respect to the crystal Z axis (coordinates indicated). The out-of-focus dark lines are scratches on the back side of the chip, which do not affect the device. The modulation length of the device is 1 mm, whereas the devices with different modulation lengths are used throughout this work. b, Cross-section of the acoustic waveguide in the modulation region. The normalized displacement-field intensity (blue shading) shows the simulated fundamental acoustic mode. The displacement field is exaggerated for visualization. The arrows indicate the simulated electric-field direction and magnitude due to a bias voltage on the modulation electrodes. c, False-coloured scanning electron microscopy image of the acoustic waveguide. d, Measured propagation loss of the acoustic waveguide as a function of temperature. The error bars indicate the maximum and minimum losses measured.

Fig. 1 | LN electro-acoustic platform. a, Optical micrograph of the fabricated device. The bright regions are aluminium (Al). The etched SiN layer (showing dark boundaries) is used to define the acoustic waveguide and regions where the IDTs are fabricated. IDTs are used to excite and detect the acoustic waves. The device is on an X-cut LN substrate, and the acoustic waveguide is at a 30° angle with respect to the crystal Z axis (coordinates indicated). The out-of-focus dark lines are scratches on the back side of the chip, which do not affect the device. The modulation length of the device is 1 mm, whereas the devices with different modulation lengths are used throughout this work. b, Cross-section of the acoustic waveguide in the modulation region. The normalized displacement-field intensity (blue shading) shows the simulated fundamental acoustic mode. The displacement field is exaggerated for visualization. The arrows indicate the simulated electric-field direction and magnitude due to a bias voltage on the modulation electrodes. c, False-coloured scanning electron microscopy image of the acoustic waveguide. d, Measured propagation loss of the acoustic waveguide as a function of temperature. The error bars indicate the maximum and minimum losses measured.

to the electro-optic effect used to control the phase and amplitude of optical signals. This effect results in a change in the elasticity of a solid due to an applied electric field, which causes a change in the phase velocity of travelling acoustic waves. The electro-acoustic effect is characterized by the third-order piezoelectric tensor d. The change in elastic constants Δc due to the applied electric field E is given by Δc_i=ε_i,j,k,d_{ijk}E_j, where i, j, and k can take values from 1 to 3, corresponding to the crystal's X, Y, and Z directions, respectively, and d_{ijk} is subject to the material symmetry (see Methods). However, since this electro-acoustic effect is relatively weak, bulk components show small phase changes[15] and are unsuitable for practical applications. Here we overcome this limitation by confining the acoustic wave to a wavelength-scale acoustic waveguide and placing the modulation electrodes closely across the waveguide. This drastically enhances the electrical-–acoustic interaction and therefore allows a full π phase shift to be achieved.

Our electro-acoustic modulators are fabricated on an X-cut LN substrate (Fig. 1a). The acoustic waveguide is formed by creating a 10 μm slot inside a thin silicon nitride (SiN) film deposited on the top of LN (Fig. 1b,c). Since the acoustic velocity (index) of SiN is smaller (larger) than that of LN, a Rayleigh-type acoustic mode is confined (Fig. 1b). Interdigital transducers (IDT) are used to electrically excite and detect microwave acoustic waves. The pitch of the IDT finger electrodes is 650 nm and equal to the half-wavelength of the acoustic waves at 2.5 GHz. To optimize the transduction efficiency, the width of the IDT (75 μm) is designed to be larger than the acoustic waveguide (10 μm), and tapered waveguide structures are used to couple the wave into the acoustic waveguide. Importantly, the waveguide is oriented along a 30° angle with respect to the crystal Z axis, as this direction features the smallest acoustic velocity on the X-cut surface and thus provides the best acoustic-wave confinement (Extended Data Fig. 1). Finally, aluminium electrodes are deposited on the SiN layer and used to apply the electric field needed for acoustic-index modulation. Low loss is critical for realizing large-scale phononic integrated circuits. We measure the propagation loss of the acoustic waveguide at different temperatures down to 1 K (Fig. 1d). At room temperature (300 K) and under a vacuum, the acoustic propagation loss is a = 17 dB cm⁻¹. It decreases with lower temperatures to a = 5 dB cm⁻¹ at the temperature of liquid nitrogen (77.0 K) and a < 1 dB cm⁻¹ at 1.3 K. These values are consistent with those measured using acoustic cavities on LN[21,26]. Phonon-phonon and thermoelastic dissipations[27,28] are the likely sources of loss at temperatures above 1 K.

Phase modulation of acoustic waves

We measure the performance of a 1-cm-long electro-acoustic phase modulator by inputting an acoustic wave at a carrier frequency of f₀ ≈ 2.5 GHz and detecting the phase and amplitude of the modulated acoustic wave (Fig. 2a). The insertion loss of the device, measured from a microwave signal applied to one IDT and detected after the other, is 10 dB at cryogenic temperatures. This loss is dominated by the tapers that guide the acoustic waves to the waveguide and the symmetric IDTs that bidirectionally excite and collect acoustic waves, which result in a 3 dB loss at each IDT. The insertion loss could be further reduced by employing unidirectional IDTs[15]. At room temperature, the insertion loss increases by 25 dB due to a higher propagation loss and a lower efficiency of IDTs (Extended Data Fig. 2). We used transmission-mode microwave impedance microscopy (TMIM)[40,41], a scanning probe technique that coherently measures the profiles of travelling acoustic waves near the
The phase change linearly increases with the amplitude of the modulating signal (Extended Data Fig. 3). When the peak-to-peak voltage ramp (serrodyne) with $V_{pp} = 2.528 \text{ GHz}$, and $V_{pp} = 53 \text{ V}$, the peak transmission frequency shifts to $1.3 \text{ K}$, the peak transmission frequency shifts to $135 \text{ V}$ (Extended Data Fig. 3) as the material properties vary with temperature. Despite the increased $V_e$ at cryogenic temperatures, an important figure of merit for the modulator—the product of its half-wave voltage $V_e$, length $L$ and propagation loss $\alpha$ (that is, $V_e L \alpha$)—is reduced by a factor of 7 (from 900 to 120 V dB) at 1.3 K owing to the reduced propagation loss compared with room temperature. The $V_e$ value of the phase modulator could be further reduced by a factor of 2 by using narrower acoustic waveguides, which is possible using materials with higher acoustic contrast. In addition, we measure the 3 dB bandwidth to be $110 \text{ KHz}$ and observe zero modulation at $f_{mod} = 336 \text{ KHz}$ when the period of the modulating signal matches the travelling time of the acoustic wave (Extended Data Fig. 4).

Next, we demonstrate two proof-of-concept applications—electro-acoustic frequency comb and acoustic frequency shifting. By driving the phase modulator with a 10 kHz sinusoidal signal of output of the modulator waveguide. We observe an $\pi/2$ phase shift in the acoustic wave when a d.c. bias voltage is applied to the modulator electrode (Fig. 2b). This measurement of the travelling-wave profile confirms that the acoustic wave is being directly modulated.

To reliably measure the half-wave voltage $V_e$ of the modulator, we apply a sinusoidal signal at $f_{mod} = 10 \text{ KHz}$ on the phase modulator electrode and analyse the output by a real-time spectrum analyser. The phase change linearly increases with the amplitude of the modulating signal (Extended Data Fig. 3). When the peak-to-peak voltage $V_{pp} = 53 \text{ V}$, at a $\pi$-phase change in the received acoustic wave is observed at room temperature, inferring $V_e = 53 \text{ V}$. At 1.3 K, the peak transmission frequency shifts to 2.532 GHz, and $V_e$ increases to 135 V (Extended Data Fig. 3) as the material properties vary with temperature. Despite the increased $V_e$ at cryogenic temperatures, an important figure of merit for the modulator—the product of its half-wave voltage $V_e$, length $L$ and propagation loss $\alpha$ (that is, $V_e L \alpha$)—is reduced by a factor of 7 (from 900 to 120 V dB) at 1.3 K owing to the reduced propagation loss compared with room temperature. The $V_e$ value of the phase modulator could be further reduced by a factor of 2 by using narrower acoustic waveguides, which is possible using materials with higher acoustic contrast. In addition, we measure the 3 dB bandwidth to be $110 \text{ KHz}$ and observe zero modulation at $f_{mod} = 336 \text{ KHz}$ when the period of the modulating signal matches the travelling time of the acoustic wave (Extended Data Fig. 4).
$V_{pp}^c = 2.3V_g$, we generate 19 equidistant-frequency comb lines centred at $f_c = 2.483$ GHz (Fig. 2c). The frequency comb coherently generates new frequencies and could be useful for short acoustic pulse generations and frequency-domain information processing. Additionally, the ability to modulate over a full $2\pi$ phase allows us to demonstrate acoustic frequency shifting using a serrodyne approach. Specifically, by applying a repeating linear voltage ramp signal at a frequency of 1 kHz and $V_{pp}$ of $2V_g$, the modulated acoustic wave experiences an approximately linear phase ramp in time, which results in a shift in frequency of the acoustic wave. We measure the on-chip frequency-shift efficiency, defined as the ratio of the detected acoustic power at the shifted frequency and the power of the unmodulated acoustic wave, of 92% (Fig. 2d). The carrier suppression of our frequency shifter is 21 dB.

To assess our electro-acoustic modulator for quantum applications, we demonstrate the coherent modulation of single-phonon-level acoustic waves at 50 mK (Methods and Extended Data Fig. 5). We attenuate the input microwave signal so that the mean phonon number of the field in the acoustic waveguide is much less than one. The basic functionalities of the electro-acoustic modulator are preserved at low temperatures: symmetric sidebands are observed when applying a 10 Hz sinusoidal modulation signal (Fig. 2e) and serrodyne frequency shifting, with an efficiency of 94.8%, is realized by applying a repeating linear voltage ramp at 10 Hz for $V_{pp} = 2V_g$ (Fig. 2f). Importantly, we experimentally verify that the modulation process adds less than one noise phonon (Extended Data Fig. 6).

Amplitude modulation of acoustic waves

We achieve the amplitude modulation of acoustic waves by constructing an acoustic Mach–Zehnder interferometer in the push–pull configuration (Fig. 3a). The input acoustic wave is equally split between two Mach–Zehnder interferometer arms. As the electric fields applied over the waveguides are in opposite directions, the induced elasticity changes are also with opposite signs, and thus, the two split waves experience opposite phase shifts as they propagate in each arm. The phase difference is controlled by the voltage applied to the electrodes. When the two waves recombine, the acoustic interference yields amplitude modulation. The maximum output amplitude occurs when the phase difference between the two paths is zero (no voltage applied) or an even integer number of $\pi$, whereas the minimum amplitude occurs when the phase difference is an odd integer number of $\pi$. We measure $V_g = 29$ V at a quasi-d.c. frequency (100 Hz) for an 8-mm-long acoustic Mach–Zehnder modulator. The extinction ratio between the maximum and minimum output power is over 15 dB (Fig. 3b), likely limited by the fabrication imperfection of the Y-splitter or the existence of higher-order modes in the waveguide. When the modulator is biased at the quadrature point (that is, 50% transmission), the amplitude of the output acoustic waves follows the small input signal accordingly (Fig. 3c).

Non-reciprocal modulation of acoustic waves

To achieve the non-reciprocal transmission of acoustic waves, we employ a quasi-travelling electric field to break the symmetry of counterpropagating acoustic waves. By separating the modulation electrode into three segments, we can control the wavenumber (momentum) of the quasi-travelling electric field by adjusting the relative phase of the modulating signals applied to each electrode (Fig. 4a). This approach enables non-reciprocal acoustic phase modulation when the quasi-travelling modulating signal is phase matched with the travelling acoustic wave in one direction but mismatched in the opposite direction (Fig. 4b and Supplementary Video 1). Maximum non-reciprocity occurs when the signals applied to each succeeding modulation electrode segment are phase delayed by 120° and when the modulation frequency matches the total travelling time of the acoustic wave, that is, $1f_{mod} = 3t_0$, where $t_0$ is the time for the acoustic wave to travel through one electrode segment. In this case, the forward-propagating acoustic wave always experiences the same phase modulation when it traverses the electrodes and thus results in the maximum modulation. On the other hand, the backward-propagating wave effectively experiences a full ($2\pi$) modulation cycle, which results in no net phase change. To implement this concept, we fabricate such a non-reciprocal acoustic modulator with an overall electrode length of 1 cm and apply
The measured non-reciprocal phase modulator has an overall modulation length of 1 cm, which is evenly divided into three segments. The acoustic non-reciprocity can be adjusted by the relative phase of the signals applied to the modulation electrodes (Fig. 4c).

The acoustic non-reciprocity can be adjusted by the relative phase of the signals applied to the modulation electrodes (Fig. 4c). We observe a maximum non-reciprocity of over 40 dB in the modulator sideband power. Furthermore, we sweep the modulation frequency and relative phase delay of the applied voltages on the three electrodes. We observe the maximum modulation when the travelling acoustic wave and modulating signal are phase matched and zero modulation when they are phase mismatched by any positive integer number of \(2\pi\) phases (Extended Data Fig. 7). With additional filters and couplers, acoustic isolators and circulators could be implemented based on our frequency shifter and non-reciprocal phase modulator.

**Fig. 4 | Non-reciprocal phase modulation of acoustic waves.** a. Schematic of the device used for non-reciprocal phase modulation. The modulation electrode is separated into three segments with independently controlled voltages \((V_1, V_2, V_3)\). GND, ground. The acoustic travelling time through each segment is \(t_0\). The voltage applied on each segment of the electrodes is progressively delayed by 120°. For forward-propagating acoustic waves, the phase accumulated in each segment is the same and results in net modulation. For backward-propagating acoustic waves, the accumulated phase in each segment is different and can be designed to result in a net zero phase shift. b. Measured acoustic phases acquired for both forward- and backward-propagating acoustic waves. d. Measured modulation sideband power of the forward- and backward-propagating acoustic waves for varying phase delays between the voltages applied to the electrodes. The dashed line indicates the operating condition in c showing a non-reciprocity of >40 dB. The modulation frequency is \(f_{\text{mod}} = 1/(3t_0) = 336\,\text{kHz}\) in c and d. The measurements are at room temperature. The measured non-reciprocal phase modulator has an overall modulation length of 1 cm, which is evenly divided into three segments.

By using nanofabrication methods with a resolution of tens of nanometres, the operating frequency of our devices could be increased to tens of gigahertz, covering the millimetre-wave bands used in fifth-generation communication technology\(^2\). We expect the half-wave voltage \(V_{1/2}\) to quadratically decrease with higher frequency, as both width of the acoustic waveguide and acoustic wavenumber scale linearly with frequency. Our devices may find application in emerging acoustically mediated quantum networks that connect different solid-state systems and thus enable hybrid quantum networks that leverage the distinct functionalities of each system for quantum computing, communication and sensing\(^2\). In particular, phase modulation is necessary for the control of coherent interactions and entanglement between solid-state systems, dynamical routing and synchronization for addressability and error mitigation, compensating environmental changes (such as local temperature drifts) and for compensating unavoidable detuning between quantum systems.

**Conclusions**

We have reported an integrated electro-acoustic platform for the electrical control of the phase, amplitude and frequency of the on-chip travelling GHz acoustic waves at room temperature and cryogenic temperatures. Phase modulation is achieved by tuning the elasticity of an LN acoustic waveguide via the electro-acoustic effect. The phase modulators are then used to create an electro-acoustic frequency comb, acoustic frequency shifter, electro-acoustic amplitude modulator and non-reciprocal phase modulator with non-reciprocity over 40 dB. Taken together, our electro-acoustic platform contains the fundamental elements for acoustic signal processing and the manipulation of phononic quantum information. Compared with previous approaches, our electro-acoustic modulators offer advantages in terms of cryogenic-temperature compatibility, modulation efficiency, simplicity in fabrication and scalability.

**Methods**

**Design of electro-acoustic modulators.** The IDTs are optimized for maximum transduction between acoustic and electrical waves at 2.5 GHz. The aperture of the IDT is 75 µm, the pitch of the finger electrode is 650 nm and the number of finger-electrode pairs per IDT is 25. The maximum transmission between two IDTs at 2.5 GHz is ~8 dB at room temperature, with ~6 dB resulting from the symmetric design of the IDTs (~3 dB per IDT).

The adiabatic taper that connects an IDT to an acoustic waveguide is 400 µm long. The insertion loss per acoustic taper is about 5 dB at room temperature, as extracted from the measured transmission of devices with and without the tapered structure.

\(X\)-cut LN substrates are used for all the devices. The direction of the acoustic waveguide is at an angle of 30° with respect to the crystal Z axis (Fig. 1a). This direction features the slowest phase velocity of the surface acoustic wave using \(X\)-cut LN and thus leads to a well-confined acoustic mode for the waveguide (Extended Data Fig. 1). The modulating electric field applied across the waveguide is mainly in the crystal Y direction. As most strain field of the guided acoustic mode is in the \(X-Z\) component (corresponding to index 5 in the Voigt notation), our device employs a non-zero electro-acoustic modulation coefficient \(d_{31}\) = \(d_{32}\).
Device fabrication. A 400-nm-thick SiN layer is deposited using plasma-enhanced chemical vapour deposition on the X-cut LN substrate. The SiN layer is patterned using a direct-write lithography tool (Heidelberg Instruments MLA150) and etched using reactive ion etching with carbon tetrafluoride, sulfur hexafluoride and hydrogen gases. The metal layer is patterned using electron-beam lithography (Eloinx ELS-F125) with a polymethyl methacrylate resist. A 115-nm-thick aluminium layer is deposited using electron-beam evaporation, followed by lift-off in 1-methyl-2-pyrrolidone for more than 3 h at 80°C.

Device measurements. The devices are mounted and bonded to a printed circuit board. The transmission spectra of the devices are measured using a vector network analyser (Keysight N5224A). For the modulation experiments, a microwave signal generator drives one IDT using a single-frequency tone around 2.5 GHz, and a real-time spectrum analyser (R&S; Tektronix RSA3303B) is connected to the other IDT. The RSA not only measures the power spectrum of the acoustic wave received by the IDT but also demodulates the signal to provide real-time in-phase and quadrature data that are converted to the phase and amplitude of the received signal. The microwave signal generator and RSA are synchronized by a 10 MHz clock. An arbitrary waveform generator is used to provide low-frequency modulation signals and a 20-kHz bandwidth voltage amplifier (Falco Systems, WMA-005) is used to provide 20 times voltage amplification when necessary. For non-reciprocal phase modulation, a four-channel arbitrary waveform generator (Tabor WS8104A-DST) is used to generate the three synchronized modulating signals with various phase delays.

Low-temperature measurements. Two low-temperature setups are used in this work (the data are shown in Fig. 1 and Extended Data Figs. 2 and 3). We use a closed-cycle cryostat (ICE Oxford) that reaches a base temperature of −0.8 K. The temperature, transmission (S21) and half-wave voltage of the devices are continuously monitored as the cryostat cools from room temperature. These measurements are repeated as the cryostat warms up. The cable losses are independently calibrated during a separate cooldown. To characterize the propagation loss of the surface acoustic waves, the transmission of two acoustic waveguides with different lengths is measured and compared. These waveguides are fabricated on the same chip, packaged on the same printed circuit board and connected using identical cables.

For the data shown in Fig. 2e,f and Extended Data Fig. 6, a 50 mK measurement setup is used (Extended Data Fig. 5). Our device is mounted on the mixing chamber plate of a dilution fridge (Bluefors) with a base temperature below 50 mK. The microwave input signal to the IDT of the electro-acoustic modulator is attenuated such that the mean phonon number on the 1-cm-long acoustic waveguide is less than one. The readout line includes a circulator, high-electron-mobility transistor amplifier at 4 K and two room-temperature low-noise amplifiers. The output signal is recorded using an RSA. The detection bandwidth of the RSA is set to 78 MHz to realize a high signal-to-noise ratio, but this detection bandwidth limits the span to 50 Hz. To detect the spectrum in this configuration of the RSA, the modulation signal is set to 10 Hz. The RSA signal is supplied by a function generator followed by a high-voltage amplifier (Trek 2210). A controlled and isolated thermal source, consisting of a heater, temperature sensor and 30 dB attenuator, is installed on the input line before the electro-acoustic modulator to calibrate the readout gain and added noise. We vary the temperature of this thermal source from 100 mK to 6.7 K and measure the output noise spectral density. By comparing the measured noise spectral density on the RSA against the calibrated thermal noise source, we extract a total readout gain of 91.49 dB, consistent with the specifications of the amplifiers and cables used.

We investigate the noise performance of our electro-acoustic modulator at 50 mK (Extended Data Fig. 6) by measuring the noise floor near the carrier frequency in three situations: (1) no signal is applied to the electro-acoustic modulator, (2) only the carrier microwave signal is applied and (3) both carrier microwave and modulation signal are applied. When no signal is applied (situation 1), we measure a noise phonon number of Nn.cac = 64.3 ± 0.39 quanta s−1 Hz−1, which is mainly from the high-electron-mobility transistor amplifier. When applying the carrier microwave signal (situation 2), we measure Nn.cac = 64.23 ± 0.36 quanta s−1 Hz−1. We further apply the modulation signal (situation 3) and observe Nn.cac = 64.32 ± 0.37 quanta s−1 Hz−1. As no observable differences (within error) in noise are measured, we conclude that our electro-acoustic modulation adds negligible noise and is thus suitable for quantum applications. This result agrees with the fact that our electro-acoustic modulation is a parametric process.

TMIM. The acoustic-wave profiles in the main text are directly imaged using TMIM14–16, which is implemented on a commercial atomic force microscopy platform Park XE-70. The IDT is driven by a continuous microwave input signal (Anritsu MSG9202A), which launches the propagating surface acoustic wave. During atomic force microscopy scanning, the customized cantilever probe (PrimeNano) picks up the GHz piezoelectric potential accompanying the acoustic wave. By using the same excitation frequency as the reference, the TMIM electronics demodulate the tip signal into a time-independent spatial pattern (Fig. 2b). Note that the TMIM image contains information on the phase of the propagating wave27. As a result, a lateral shift of the wave pattern indicates that the acoustic wave is modulated by the d.c.-bias electric field. Due to the charging effects at the interfaces between the layers, a higher d.c. bias voltage is required to achieve the same phase shift as that of a modulating signal at fmod = 10 kHz.

Measurement of modulation bandwidth. First, we measure the modulation bandwidth of the 1-cm-long phase modulator (Fig. 2). We apply weak signal modulation (V mod = 0.2 V) with varied frequencies and measure the modulation efficiency. The modulation efficiency is indicated by the first sideband power around 2.5 GHz, and a real-time spectrum analyser (RSA; Tektronix RSA3303B) connected using identical cables. For the data shown in Fig. 2e,f and Extended Data Fig. 6, a 50 mK noise floor is used (Extended Data Fig. 1). The RSA not only measures the power spectrum of the acoustic wave received by the IDT but also demodulates the signal to provide real-time in-phase and quadrature data that are converted to the phase and amplitude of the received signal. The microwave signal generator and RSA are synchronized by a 10 MHz clock. An arbitrary waveform generator is used to provide low-frequency modulation signals and a 20-kHz bandwidth voltage amplifier (Falco Systems, WMA-005) is used to provide 20 times voltage amplification when necessary. For non-reciprocal phase modulation, a four-channel arbitrary waveform generator (Tabor WS8104A-DST) is used to generate the three synchronized modulating signals with various phase delays.

LN electro-acoustic effect. Hook’s law states that the force on a spring is proportional to its displacement. The square of the resonant frequency of a mass-spring system is equal to the ratio of the spring proportionality constant to the mass. Thus, tuning the spring constant also varies the resonance frequency of the spring. Weakly excited acoustic waves in solids follow a generalized Hook’s law that relates stress σ and strain ε by an elasticity (stiffness) matrix C, which is a 6-by-6 matrix in Voigt notation. LN is of point group 3m, which has a three-fold rotation symmetry about its Z axis and mirror symmetry on its X axis. With vanishing components of C due to the symmetry of LN, the relation is

\[
\begin{pmatrix}
\sigma_1 \\
\sigma_2 \\
\sigma_3 \\
\sigma_4 \\
\sigma_5 \\
\sigma_6
\end{pmatrix} =
\begin{pmatrix}
0 & 0 & 0 & e_{11} & e_{12} & e_{13} \\
0 & 0 & 0 & e_{21} & e_{22} & e_{23} \\
0 & 0 & 0 & e_{31} & e_{32} & e_{33} \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0
\end{pmatrix}
\begin{pmatrix}
\varepsilon_1 \\
\varepsilon_2 \\
\varepsilon_3 \\
\varepsilon_4 \\
\varepsilon_5 \\
\varepsilon_6
\end{pmatrix}
\]
Coupling between travelling acoustic wave and bias electric field. An applied electric field affects the travelling acoustic wave by tuning the elasticity of the material. When the applied electric field is small, such tuning in elasticity can be treated by the perturbation theory. The wave equation for a guided acoustic mode is
\[ \Delta \omega = \frac{\omega}{k} r e^{i \Delta \omega} , \]
where \( \Delta \) is the mass density of the material, \( u \) is the displacement field and \( \omega \) is the angular frequency of the eigenmode at given wavenumber \( k \).

For a guided acoustic mode, the first-order shift in the eigenfrequency at the given wavenumber \( k \) due to the perturbation of elasticity \( \Delta \omega \) is given by
\[ \Delta \omega = \int \frac{d k}{d \omega} \frac{\omega}{k} r e^{i \Delta \omega} , \]
where \( v_g \) and \( v_p \) are the phase and group velocity of the guided acoustic mode, respectively. The overall acoustic phase change over length \( L \) due to the applied electric field is \( \Delta k L \).

Data availability

Source data are provided with the paper. Other data that support the findings of this study are available from the corresponding authors upon reasonable request.

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\[ \Delta \omega = \int \frac{d k}{d \omega} \frac{\omega}{k} r e^{i \Delta \omega} , \]
where \( \Delta \omega / k \) is the change in wavenumber \( \Delta k \) at certain

Author contributions

I.S.: conceptualization, methodology, investigation, formal analysis, visualization, writing (original draft). D.Z.: methodology, investigation, writing (original draft). M.C.: writing (review and editing). L.S.: conceptualization, methodology, investigation, formal analysis, visualization.

Competing interests

M.L. is involved in developing LN technologies at HyperLight Corporation. President and Fellows of Harvard College has a patent pending (Application number: PCT/
US21/60426) on the electro-acoustic modulators, in which M.L. and L.S. are listed as inventors. The other authors declare no competing interests.

Additional information

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Extended Data Fig. 1 | Simulated acoustic phase velocities for varying directions on X-cut LN. The direction is defined by the angle respective to the crystal Z axis. The electromechanical coupling coefficient $k^2 = 2 (v_0 - v_m)/v_0$, where $v_0$ and $v_m$ are the phase velocities when the top surface is free and electrically shorted, respectively. The direction of the waveguide used in our device is 30°, as indicated by the dash line.
Extended Data Fig. 2 | Measured transmission spectra of the acoustic modulator at temperatures of 300 and 1.3 K. The results indicate a 25 dB improvement in peak transmission at low temperature. The frequency shift of the spectrum is due to the temperature dependent elasticity of LN.
Extended Data Fig. 3 | Measured Peak-to-peak acoustic phase changes due to sinusoidal modulating signals of varying peak-to-peak voltage ($V_{\text{pp}}$) at room and cryogenic temperatures. The sinusoidal modulating signals are of the frequency $f_{\text{mod}} = 10\, \text{kHz}$. Linear fits show $V_\pi$ of 53 $V$ at room temperature (300 K) and 135 $V$ at 1.3 K, respectively. The same device is measured as that in Fig. 2.
Extended Data Fig. 4 | Modulation bandwidth of the 1-cm-long electro-acoustic phase modulator. The modulation efficiency is indicated by the first sideband power due to the phase modulation. The measured 3-dB bandwidth is 110 kHz. The modulation approaches zero at $f_{\text{mod}} = 336$ kHz when the acoustic traveling time through the modulator equals $1/f_{\text{mod}}$. The same device is measured as that in Fig. 2.
Extended Data Fig. 5 | Fifty millikelvin measurement setup. The electro-acoustic modulator is mounted on a mixing plate of a dilution fridge with a base temperature below 50 mK. The input microwave signal is provided by a signal generator and, to ensure negligible contribution of thermal noise, passed through attenuators at various temperature stages of the fridge before going into our device. The output microwave signal from the modulator passes through a circulator, a high-electron-mobility transistor (HEMT) amplifier at 4 K, two low-noise amplifiers at room temperature, and is finally detected by a real-time spectrum analyzer (RSA). The modulation signal is provided by a function generator. A controlled and thermally isolated thermal source, which consists of a heater, temperature sensor, and a 30 dB attenuator, is installed in the microwave line before our electro-acoustic modulator to calibrate the gain and added noise in the output/readout line.
Extended Data Fig. 6 | Noise measurement of the electro-acoustic modulator at 50 mK. Total noise power spectrum density near $f_c$ when (1) no signal is applied to the electro-acoustic modulator (black), (2) only the carrier microwave signal is applied (blue), and (3) both the carrier microwave and modulation signals are applied (red). The total noise power $N_{\text{tot}} = N_{\text{dev}} + N_{\text{add}}$, where $N_{\text{dev}}$ is the noise of the electro-acoustic modulator and $N_{\text{add}}$ is the added noise from the readout chain. $N_{\text{add}}$ is mainly determined by the high-electron-mobility transistor (HEMT) at the 4 K stage. The electro-acoustic modulation adds negligible noise and is thus suitable for quantum phononics. The same device is measured as that in Fig. 2. The error bars indicate the standard deviation of measured noise power spectrum density.
Extended Data Fig. 7 | Phase matching between a traveling acoustic wave and a quasi-traveling electric field. The modulation sideband power is measured with varied modulation frequency and phase delay between the three electrodes. The maximum modulations that satisfy the phase matching condition are indicated by the red line. The condition for the maximum nonreciprocity in phase modulation is indicated by the black dots, as the counter propagating acoustic waves experience opposite phase delays compared to the propagating waves. The sideband power is normalized to the unmodulated carrier acoustic wave power. The measured date is from the same device as in Figs. 4C and 4D, which consists of three electrodes with overall modulation length of 1 cm.