Magnetic-free silicon nitride integrated optical isolator

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Integrated photonics enables signal synthesis, modulation and conversion using photonic integrated circuits (PICs). Many materials have been developed, among which silicon nitride (Si3N4) has emerged as a leading platform particularly for nonlinear photonics. Low-loss Si3N4 PICs have been widely used for frequency comb generation, narrow-linewidth lasers, microwave photonics and photonic computing networks. Yet, among all demonstrated functionalities for Si3N4 integrated photonics, optical non-reciprocal devices such as isolators and circulators have not been achieved. Conventionally, they are realized based on the Faraday effect of magneto-optic materials under an external magnetic field; however, it has been challenging to integrate magneto-optic materials that are not compatible with complementary metal–oxide–semiconductors and that require bulky external magnet. Here we demonstrate a magnetic-free optical isolator based on aluminium nitride (AlN) piezoelectric modulators monolithically integrated on low-loss Si3N4 PICs. The transmission reciprocity is broken by spatio-temporal modulation of a Si3N4 microring resonator with three AlN bulk acoustic wave resonators that are driven with a rotational phase. This design creates an effective rotating acoustic wave that allows indirect interband transition in only one direction among a pair of strongly coupled optical modes. A maximum of 10 dB isolation is achieved under 300 mW total radiofrequency power applied to three actuators, with minimum insertion loss of 0.1 dB. An isolation bandwidth of 700 MHz is obtained, determined by the optical resonance linewidth. The isolation remains constant over nearly 30 dB dynamic range of optical input power, showing excellent optical linearity. Our integrated, linear, magnetic-free, electrically driven optical isolator could be a key building block for integrated lasers and optical interfaces for superconducting circuits.
megahertz. Although nonlinear optics can work passively without active modulation, the main concern is the dynamic reciprocity that forbids light propagation in both directions with limited dynamic range of input optical power\(^4\).

Spatio-temporal modulation\(^{49-55}\), which breaks reciprocity by coupling two optical modes and prescribing phase matching condition by active modulation, stands out in terms of integration and applicability on nearly all optical materials. Schemes based on acousto-optic modulation (AOM) have recently been extensively developed due to their compatibility with low-loss PICs (for example, AlN\(^{54}\) and silicon\(^{55}\)). Thus far, only non-reciprocal sideband modulation is achieved, limited by the modulation efficiency and power handling capability of the interdigital transducers for generating surface acoustic waves. Here we demonstrate the first AOM-based optical isolator for Si\(_3\)N\(_4\) integrated photonics. Three AlN piezoelectric actuators are equidistantly placed along a Si\(_3\)N\(_4\) microring resonator, and generate high-overdrive bulk acoustic resonances (HBAR)\(^7\) to create an effective rotating acoustic wave that couples two optical modes only in the momentum-biased direction.

**Results**

**Device principle and design.** Our integrated optical isolator consists of three AlN piezoelectric actuators on top of a Si\(_3\)N\(_4\) microring resonator, as shown in Fig. 1a. The Si\(_3\)N\(_4\) PIC (blue) fully cladded with SiO\(_2\) was fabricated using the photonic Damascene process\(^8\), followed by monolithic integration of AlN actuators\(^{9,10}\). Figure 1d shows the fabrication process flow, and more details are found in Methods. The AlN thin film (green) with a piezoelectric coefficient of \(d_{33} = 3.9\) pm V\(^{-1}\) is sandwiched between the aluminium (top, yellow) and molybdenum (bottom, orange) electrodes. When the electrodes are microwave-driven, bulk acoustic waves are formed vertically in the substrate (that is, the HBAR mode) beneath the actuators. By contrast to previous work\(^3\), here we apply a silicon release process to create a suspended SiO\(_2\) membrane in which Si\(_3\)N\(_4\) microresonator is embedded. This release process enables tight confinement of HBAR modes inside the Fabry–Pérot acoustic cavity formed by the top and bottom SiO\(_2\)–air surfaces, and thus enhances the acousto-optic coupling through stress-optic effect\(^3\).

The Si\(_3\)N\(_4\) microresonator is designed to support two optical eigenmodes (a and b) at a frequency difference that matches a mechanical/acoustic resonant frequency, as shown in Fig. 1b. The microwave drives applied on the three AlN actuators create acoustic waves inside the mechanical cavity, which scatter light between modes a and b (that is, indirect interband transition). Figure 1c illustrates the \(\omega - k\) space, where \(k = 2\pi x / \lambda\) is wavenumber (the photon/phonon momentum is \(hk\), with the sign denoting the rotating direction along the microring, clockwise or counter-clockwise), and \(\omega\) is the angular frequency. To induce interband transition, energy and momentum conservations must be satisfied, known as the phase matching condition. With a non-zero phonon momentum \(k_m\), phase matching requires \(\Delta \omega_m = \omega_b - \omega_a = \Omega_m\) and \(\Delta k_m = k_b - k_a = -k_m\), where \(\Delta \omega_m\) is the optical frequency spacing, and the minus sign of
\(k_m\) indicates that the acoustic wave counter-propagates with the two co-propagating optical modes, as illustrated in Fig. 1a. We denote this direction of light transmission — where phase matching condition is fulfilled — as the forward direction in the following discussion.

While a single vertical HBAR mode from one AlN actuator carries zero in-plane momentum, an effective acoustic wave rotating along the microring is generated by driving three actuators coherently with phases of \((0^\circ, 120^\circ, 240^\circ)\), that is, a 120° phase difference between the two adjacent actuators, as illustrated in Fig. 1a. In the forward direction, the two optical modes are coupled via the rotating acoustic wave, which can be described by simplified coupled-mode theory (CMT) equations:\(^a\)

\[
\frac{d}{dt} \hat{a} = -(i\Delta_a + \frac{\kappa_a}{2}) \hat{a} - igb e^{2\alpha t} \hat{a}^* + \sqrt{\kappa_{a,\text{in}}} \hat{d}_{\text{in}}
\]

(1)

\[
\frac{d}{dt} \hat{b} = -(i\Delta_b + \frac{\kappa_b}{2}) \hat{b} - ig\hat{a} e^{-i\Delta t}
\]

(2)

where \(\hat{a}(\hat{b})\) is the intracavity amplitude, \(\kappa_a(\kappa_b)\) is the total loss rate of mode \(a(b)\), \(\kappa_{a,\text{ex}}\) is the external coupling rate of mode \(a\). These equations of motion are transformed under the rotating-wave approximation referenced to the input laser frequency \(\omega_0/2\pi\), thus \(\Delta_a = \omega_a - \omega_0\) (\(\Delta_b = \omega_b - \omega_0\)) is the relative detuning between the laser frequency and the optical resonant frequency of \(a(b)\); \(\Omega_a/2\pi\) is the microwave drive frequency, which can be slightly detuned from the mechanical resonant frequency \(\Omega_{m,a} / 2\pi\). Mode \(a\) is probed by the input light with amplitude \(\hat{d}_{\text{in}}\), and its optical transmission/isolation is studied in the following analysis.

In the forward direction, the two optical modes undergo interband transition with a scattering rate \(\Gamma = \text{go} \sqrt{\pi}, \) where \(g_0\) is the single photon-phonon coupling rate describing the optomechanical interaction strength, and \(n\) is the steady-state intracavity photon number; \(C = 4g_0^2|\kappa_a|\kappa_b\) is the photon–photon cooperativity, which measures the ratio of scattering rate to optical losses. Strong coupling requires \(C \gg 1\), which can induce Rabi oscillation and mode splitting. The latter results in a transparency window on the resonance in the light transmission, which can be calculated from equations (1) and (2) as:

\[
T|_{\Delta_a = 0} = \left\| \frac{\hat{d}_{\text{out}}}{\hat{d}_{\text{in}}} \right\|_{\Delta_a = 0}^2 = \left[ 1 - \frac{2\kappa_{a,\text{ex}}}{\kappa_a(1 + C)} \right]^{-2}
\]

(3)

In the forward direction, \(C \gg 1\) and \(T|_{\Delta_a = 0} = 1\). This transparency can be understood intuitively as the impedance mismatch between the bus waveguide and the microresonator which results from the increasing effective intrinsic loss due to the scattering to the other optical mode \(b\). In the backward direction where the three-wave phase matching is not fulfilled, interband transition is prohibited, leading to \(C \approx 0\) and \(T|_{\Delta_a = 0} = 0\) in the critical coupling regime \((\kappa_a = 2\kappa_{a,\text{ex}})\). Consequently, the microresonator remains critically coupled and its light transmission is not affected by the presence of the acoustic wave. This non-reciprocal transmission between the forward \((T = 1)\) and backward \((T = 0)\) directions is the basic of our optical isolator.

Meanwhile, in the forward direction, a single modulation sideband is generated in mode \(b\), which is frequency-shifted by \(\Omega_{m,b} / 2\pi\), relative to \(\omega_b/2\pi\). The mode conversion efficiency \(\eta\) is:

\[
\eta|_{\Delta_b = 0} = \left\| \frac{\hat{b}_{\text{out}}}{\hat{d}_{\text{in}}} \right\|_{\Delta_b = 0}^2 = \frac{\kappa_{a,\text{ex}} \kappa_{b,\text{ex}}}{\kappa_a \kappa_b} \frac{4C}{(1 + C)^2}
\]

(4)

Equations (3) and (4) are derived assuming that the microwave drive \(\Omega_a\) matches \(\Delta_0\), that is \(\Omega_a = \Delta_0\). A detailed derivation of these equations and general cases with a frequency mismatch — which were used for subsequent fitting with experiments — are provided in Methods. This non-reciprocal sideband generation has been demonstrated in previous studies in the \(C < 1\) regime\(^{35,35}\).

**Device characterization.** Figure 2a shows a false-coloured, top-view, scanning electron microscope (SEM) image of the fabricated device with three AlN actuators integrated onto a released Si₃N₄ microring resonator. The thickness of Al/AlN/Mo is 100/1,000/100 nm, respectively. The sulfur hexafluoride (SF₆) Bosch process was used to isotropically dry etch the silicon after opening the centre hole by oxide etching, allowing partial removal of the silicon substrate and the suspension of 5.4-μm-thick SiO₂ cladding. Figure 2b shows the optical microscope image highlighting the bus waveguide coupling region, the Si₃N₄ microring with a 118-μm-radius buried in the suspended SiO₂ membrane, and two AlN actuators. Figure 2c shows the simulated stress distribution of one HBAR mode within the SiO₂ membrane using finite element method. It can be seen that the HBAR mode is uniformly distributed under the AlN actuator and tightly confined in the SiO₂ membrane, allowing direct modulation of the optical mode propagating along the waveguide through photothermal and moving boundary effects.\(^{57,58}\)

We use the fundamental transverse electric (TE₀₀), that is, mode \(a\) and magnetic modes (TM₀₀, that is, mode \(b\) to realize interband transition assisted with the rotating acoustic wave. A quasi-square waveguide cross-section (810×820 nm²) is used, as shown in the inset of Fig. 2b. Figure 2c shows the simulated TM₀₀ and TE₀₀ mode profiles, which also include the slanted waveguide sidewalls. The transmission of polarization-tilted light through the optical microresonator, including a pair of TE₀₀ and TM₀₀ resonances, is shown in Fig. 2d. The TM₀₀ mode frequency is 3 GHz higher than that of the TE₀₀ mode at around 1,546 nm wavelength. The resonance line-width (total loss, \(\kappa_{a,b}/2\pi\)) is 0.68 and 1.16 GHz for the TE₀₀ and TM₀₀ modes, respectively.

Figure 2e shows the microwave reflection \(S_{11}\), where mechanical resonances are revealed. Only one actuator’s \(S_{11}\) is shown, as the others are similar. Three strong resonances are found at around 3.0, 3.4 and 3.8 GHz, which are due to the SiO₂ mechanical cavity with ~470 MHz free spectral range (FSR, determined by the SiO₂ cladding thickness). Besides, weak resonances with an FSR of ~19 MHz are observed, due to the HBARs in the thick silicon substrate formed under square signal probe pads which were not undercut\(^7\). However, only the HBARs confined in SiO₂ can efficiently modulate the optical mode because the HBARs in the silicon substrate have negligible overlap with the Si₃N₄ waveguide, which can be verified from the optomechanical S₂₁ response shown in Fig. 2e. \(S_{21}\) measures the ratio between the output light intensity modulation and the microwave drive power. Three actuators are measured individually. As the HBARs are mainly determined by the thickness of each layer that is highly uniform over the device scale, the HBAR frequencies of the three actuators show only sub-megahertz misalignment. A maximum of ~45 dB \(S_{21}\) is achieved, providing 20 dB improvement over a previously reported unreleased silicon HBAR AOM\(^1\). This is due to the considerably reduced mechanical mode volume and tighter HBAR confinement in the released SiO₂ membrane. The SiO₂ HBAR at 2.958 GHz is used in the following experiments to match the optical mode spacing. Furthermore, the signal cross-talk between the actuators is maintained below ~60 dB (see Supplementary Note 6), as the HBARs are tightly confined vertically beneath the actuator, and the centre etched hole prevents the transmission of any lateral mechanical modes.

**Optical isolation demonstration.** The experimental set-up is shown in Fig. 3a. Three radiofrequency (RF) signals are amplified and applied to each actuator, and the amplitudes and phases of each channel are controlled individually by each signal generator.
The TE$_{00}$ mode is excited by aligning the input light polarization using fibre polarization controllers (FPCs 1 and 2). The light propagation direction—forward or backward—is controlled by a $2 \times 2$ optical switch. The transmitted TE light and generated TM sideband are separated by a polarization beam splitter (PBS), which is a key reason why we use two modes of different polarizations. The laser wavelength is continuously scanned to probe the spectral response around the TE$_{00}$ resonance.

The RF phases are critical for phase matching. Figure 3b shows the transmission spectrum of TE light by sweeping the RF phases of signals 2 and 3 relative to signal 1 ($\phi_{21}$ and $\phi_{31}$), whereas the output RF power (20 dBm for each actuator) and light input direction are fixed. Note that reversing the sign of the RF phases changes the rotation direction of the acoustic wave. Non-reciprocity is seen from the disparate transmission by reversing the RF phases with respect to the origin ($0^\circ$, $0^\circ$). Strong mode splitting is induced under ideal phase setting ($\phi_{21}$, $\phi_{31}$) = ($120^\circ$, $-120^\circ$), while the original single resonance is maintained at ($\phi_{21}$, $\phi_{31}$) = ($-120^\circ$, $120^\circ$), as shown in Fig. 3d. When the RF phases deviate from the ideal values within $\pm 30^\circ$, non-reciprocity only slightly degrades, which allows large tolerance of phase fluctuations in practical applications. This behaviour and RF phase dependency are also revealed by finite-difference frequency-domain (FDFD) simulations, showing qualitative agreement with experimental data (see Supplementary Note 4).

Light transmission of the generated anti-Stokes TM sideband is simultaneously measured as shown in Fig. 3c. It is normalized to the TE's input power, thus can be interpreted as conversion efficiency $\eta$. Figure 3b and 3c show similar patterns but with reversed colour rendering. Prominent splitting and TE–TM conversion are found at ($120^\circ$, $-120^\circ$), whereas TE–TM conversion is negligible at ($-120^\circ$, $120^\circ$). As the measured TM sideband results from mode coupling
and phase matching, it can be used as feedback signal for tuning and stabilizing the RF phases. From Fig. 3d, the optical isolation ratio between the clockwise (forward) and counter-clockwise (backward) directions is calculated as 9.3 dB, which is mainly limited by the level of critical coupling (−10.1 dB) of the optical microring (the current device is slightly undercoupled with 850 nm bus–microring gap). The isolation ratio can be improved in the future by fine tuning the bus–microring gap in the design and fabrication. We achieve 83% transmission on resonance corresponding to 0.8 dB insertion loss in the forward direction. We further note another device with 0.1 dB insertion loss (98% transmission), which shows higher modulation efficiency but less backward extinction due to the fact that the microring is more undercoupled with a wider gap (950 nm, see Supplementary Note 5).

Radiofrequency power dependency. The evolution of optical isolation with varying applied RF power is studied in Fig. 4 with fixed RF phases of (φ_21, φ_31) = (120°, −120°) and a drive frequency of 2.968 GHz. Figure 4a shows the measured forward and backward transmissions of the TE₀₀ mode, with the RF power (applied to each actuator) increased from 15 to 20 dBm. In the forward direction, initially the resonance depth decreases and the linewidth broadens with increasing RF power up to 16 dBm, resulted from the increasing intrinsic loss caused by the scattering to the TM₀₀ mode. Above 17 dBm, mode splitting appears, creating a transparency window at the original resonance frequency. In the backward direction, single-resonance profile remains, however, with slightly increasing linewidth due to the weak mode coupling as predicted and described by the Floquet theorem⁵². Figure 4c shows the isolation ratio between the clockwise and counter-clockwise directions as a function of RF power.
Fig. 4 | RF power dependency and anti-Stokes TM sideband generation. a. Optical transmission spectra of the TE light in the forward and backward directions, with increasing RF power from 15 to 20 dBm; $\Delta \lambda$ is the wavelength detuning of the input laser relative to the TE$_{00}$ mode $\lambda - \lambda_{TE,0}$, with $\lambda_{TE,0} = 1,544.1$ nm. b. Generated light of the anti-Stokes TM sideband in the forward direction, normalized by the input TE light power. The RF power increase is the same as a. The anti-Stokes sideband is blue-shifted relative to the input laser by the modulation frequency $2.968$ GHz ($\approx 24$ pm, $\lambda_{TE,0} - \lambda_{TE,0} = \Delta \lambda$). The fitted transmission using CMT is also shown in a and b. c, d. The conversion efficiency of the TM sideband at $\Delta \lambda = 0$ and the scattering rate $g$ as a function of RF power. Experimental data are grouped as low and high RF powers, fitted individually with CMT (solid lines) with different microwave drive to mechanical resonance detuning $\Delta \Omega = \Omega_\alpha - \Omega_\beta$. The horizontal grey dashed line in d marks the value of $g/2\pi = 460$ MHz when cooperativity $C = 1$. The vertical red and blue dashed lines in c and d mark the maximum conversion at each detuning. The error bars of each data point represent the standard deviation ($\sigma$) from five individual measurements. The dependence of isolation on RF power is shown in c with experimental data and exponential fitting. Note that the RF power in all of the panels is the power applied to each individual actuator, thus the total RF power consumption is three times (4.8 dB) higher.

ratio (black circles) at zero laser detuning relative to the TE$_{00}$ mode ($\Delta \lambda = 0$), which increases exponentially with the applied RF power and is finally limited by the backward extinction.

The mode splitting rate, which is two times of the interband scattering rate $g$, is extracted by fitting the resonance profile using the generalized equation (3) from CMT, with $g$ and $\Delta \Omega_\alpha$, as fitting parameters. Figure 4d shows that $g$ gradually increases with increasing RF power and sharply increases to a higher value at 18 dBm, above which $g$ continuously increases and finally saturates at 20 dBm. This behaviour is caused by the blue shift of the SiO$_2$ HBARs due to RF heating, as SiO$_2$ has a large positive temperature coefficient of elasticity of 188 ppm K$^{-1}$. The RF drive frequency $\Omega_\alpha$ is initially blue-detuned from the HBAR frequency $\Omega_\alpha$ at room temperature, that is, $\Omega_\alpha - \Omega_\alpha > 0$. As the RF power increases and the acoustic velocity in SiO$_2$ increases, $\Omega_\alpha$ approaches $\Omega_\alpha$ (that is, $\Omega_\alpha - \Omega_\alpha \rightarrow 0$) and more phonons are pumped into the mechanical cavity. This in turn increases the temperature, which further blue-shifts the HBAR. The thermal nonlinearity thus leads to an increase in $g$ at approximately 18 dBm. This transition is studied in Supplementary Note 7 with a fine sweep of RF power in 0.1 dBm steps.

With RF power above 20 dBm, the interband scattering rate $g$ saturates, indicating that the efficiency of pumping phonons into the cavity starts dropping. This is probably because $\Omega_\alpha$ becomes red-detuned to $\Omega_\alpha$, that is, $\Omega_\alpha - \Omega_\alpha < 0$; thus, nearly zero detuning can be derived for RF powers between 18 and 20 dBm. In this regime, the single-phonon optomechanical coupling strength $g/2\pi$ is estimated as 208 Hz, by fitting high RF power data (blue line) with $g = g_0 / \bar{\kappa}$, where $g_0$ is calculated by extracting the electromechanical coupling efficiency $k_{\text{eff}}^2 = 0.2\%$ from $S_{11}$ (see Supplementary Note 3). The low RF power region is fitted with $(\Omega_\alpha - \Omega_\alpha)/2\pi \approx 6$ MHz blue-detuning (red line). Another consequence of the RF heating effect is the drift of $\Delta \Omega_\alpha$. Figure 4a shows that the mode splitting evolves from symmetric (18 dBm) to asymmetric (20 dBm) with increasing RF power, and $\Delta \Omega_\alpha/2\pi$ is increased from 3 GHz to 3.3 GHz.

The spectrum of the anti-Stokes TM sideband is shown in Fig. 4b. The conversion efficiency $\eta$ at zero laser detuning to the TE$_{00}$ mode ($\Delta \lambda = 0$) is plotted in Fig. 4c. Similarly, each dataset with low and high RF power is fitted individually using equation (4) with the same RF driving detuning as used in Fig. 4d. It can be derived from equation (4) that the maximum value of $\eta$ is reached at $C = 1$. This can also be seen from Fig. 4b where the conversion starts to drop at centre due to the mode splitting when $C > 1$. A maximum of 8% ($\approx 11$ dB) of the TE$_{00}$ mode power is converted into the TM$_{00}$ sideband, which is mainly limited by the external coupling efficiency of the TE$_{00}$ mode ($k_{\text{ex}}/k_0 = 0.34$) and TM$_{00}$ mode ($k_{\text{ex}}/k_0 = 0.24$), see equation (4). At zero RF drive detuning (blue line), $C = 1$ is achieved with 14 dBm RF power applied on each actuator (18.8 dBm in total), and the system operates in the strong coupling regime at 20 dBm. The detuning not only reduces $g$ but increases the required RF power to achieve $C = 1$. In practice, the generated sideband can compromise the output signal purity. In our case, using optical modes with different polarizations enables the separation of different polarizations with high extinction ratio (>20 dB) using a PBS (see Supplementary Note 8). On the other hand, it is worth noting that the same device can work as a non-reciprocal frequency shifter and polarization rotator with 100% conversion achievable for strongly overcoupled devices (that is, $k_0 \approx \infty$). It could serve as a key building block in photonic quantum computing.66.
Detuning of optical mode spacing. As there is 380 MHz difference in FSR between the TE00 and TM00 modes (see Supplementary Note 2), their $\Delta \omega_{\text{FSR}}$ varies from pair to pair for different centre wavelengths. Here, the dependence of isolation performance on $\Delta \omega_{\text{FSR}}$ is studied in Fig. 5a under 20 dBm RF power. At $\lambda_0 = 1,542.58$ nm, $\Delta \omega_{\text{FSR}}$ is nearly equal to the driving frequency $\Omega_0$ and the mode splitting is symmetric. As the optical resonance linewidths are around the gigahertz level, TE00 and TM00 modes can still be coupled even with a frequency mismatch between $\Delta \omega_{\text{FSR}}/2\pi$ and $\Omega_0/2\pi$ on the order of 0.5 GHz. The mismatch leads to asymmetric mode splitting. Nevertheless, there is no prominent degradation of isolation within the measured range. The decrease of maximum isolation for shorter wavelength is caused by the reduction of extinction in the backward direction. This is because that shorter wavelength has smaller mode size and thus a weaker bus–microring external coupling rate $\kappa_{\text{sc}}$ that leads to undercoupling. A maximum of 9.5 dB isolation is achieved at 1,545.55 nm, which is even larger than the matched symmetric case due to its better critical coupling. The isolator can therefore work simultaneously for multiple centre wavelengths, which is important for optical communication using wavelength multiplexing$^3$. The wavelength range can be extended to cover the optical C-band by using pulley coupling scheme$^1$ to maintain critical coupling or slight overcoupling, and engineering the waveguide geometry to reach precise FSR match. On the other hand, thermal tuning to continuously shift the operating resonance can further increase the bandwidth.

Isolation of optical pulses. We further evaluate the optical isolator to demonstrate a unidirectional transmission of an optical pulse train to mimic (0, 1) data stream, as shown in Fig. 5b. The 100 ns pulse shows the quasi-static response, where the backward reflection is only 11% of the forward transmission. The bump at the pulse edge is caused by the limited bandwidth (~125 MHz) of the photodetector. The dynamic response is tested with 10 ns pulses, illustrating a vast contrast in the two directions. The isolation bandwidth can be inferred from the increasing isolation with increasing pulse duration, as revealed in Fig. 5c. A pulse of minimum 8 ns duration is measured, limited by the photodetector’s bandwidth. Over 8 dB isolation is maintained for pulses longer than 20 ns; however, the isolation drops exponentially when the pulse duration is shorter than 20 ns, which is ultimately limited by the photon lifetime of ~1.5 ns, corresponding to 680 MHz linewidth of the optical resonance.

Optical power linearity. Dynamic reciprocity has been a well-known limitation for most optical isolators relying on optical nonlinearity, where the isolation degrades dramatically when light transmits
simultaneously in both directions and the optical power exceeds a certain threshold. In our work, with only electrical drives, the optical linearity is preserved as long as the intracavity photon number is smaller than the phonon number. As the phonon frequency is five orders of magnitude smaller than the photon frequency, theoretically it suggests maximum of 6 kW optical power for 20 dBm RF power in the experiment; however, the optical linearity of our isolator is nearly constant within several watts due to the Kerr nonlinearity of Si,N. The quasi-square waveguide cross-section used here has a normal group velocity dispersion and the optical microresonator has low optical Q<5×10^5, which suppress Kerr parametric oscillation. The linearity is experimentally verified in microwatt to milliwatt range, as shown in Fig. 5d. The optical isolation remains nearly constant within the measured range. The large variation at high optical power is mainly due to the optical thermal nonlinearity as the laser is swept across the optical resonance. Theoretically there is no limit on the lower bound of the optical power, thus our device can work for photonic quantum computing.

Discussion
We have demonstrated an integrated optical isolator by spatio-temporal modulation of a Si,N microring resonator via three AlN piezoelectric actuators. The device has been fully characterized in terms of RF phases, RF powers, optical spectra and optical powers, showing agreement with theoretical models and numerical simulations. Table 1 summarizes recently demonstrated, magnetic-free isolators (to the best of our knowledge), including our work. A comprehensive comparison with other experimental realizations is found in Supplementary Note 10.

Although promising progress has been made using nonlinear optics and synthetic magnetic field, most spatio-temporal modulation demonstrations are still in the non-reciprocal sideband modulation regime. In this work, the HBAR AOM helps to boost the optical cooperativity C beyond unity and enter strong coupling regime, thanks to the power handling capability and the tight acoustic confinement of our devices. We obtain 10 dB isolation with 300 mW total RF power applied on three actuators. Notably, a record-low insertion loss of 0.1 dB is achieved due to the intrinsic low loss of Si,N waveguides. In contrast to the scheme relying on nonlinear optics, the electrical drive used in our work largely preserves the optical linearity by separating RF driving and optical sensing in two different domains.

In the future, the isolation can be improved by optimizing the bus–microring coupling gap to reach perfect critical coupling or slight overcoupling. Furthermore, it has been demonstrated recently that perfect critical coupling in an initially overcoupled device can be achieved with a controllable manner. Using an overcoupled device with 600 nm coupling gap, we achieve 41 dB isolation and 1.9 dB insertion loss under 2 W total RF power (see Supplementary Note 9). The RF power consumption can be reduced to a few milliwatts by using microresonators of smaller radii to increase the piezo-optomechanical coupling efficiency, and scandium-doped AlN to increase the piezoelectric coefficient (see Supplementary Note 11). With these improvements, our electrically driven, magnetic-free optical isolators could be reliably incorporated as a key building block into current integrated opto-electronic systems.

Online content
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Table 1 | Comparison of monolithically integrated, magnetic-free optical isolator devices

| Year | Scheme | Structure | Material | Isolation | Insertion loss | Bandwidth | Power |
|------|--------|-----------|----------|-----------|---------------|-----------|-------|
| 2020 | Nonlinear optics | Ring | Si | 20 dB | 1.3 dB | 20 GHz | No drive |
| 2014 | Synthetic magnetic | MZI | Doped Si | 2.4 dB | N/A | 20 nm | 34 dBm |
| 2021 | Synthetic magnetic | Ring | AlN | 3 dB | 9 dB | 4 GHz | 16 dBm |
| 2021 | Synthetic magnetic | Ring | Doped Si | 13 dB | 1 dB | 2 GHz | -3 dBm |
| 2012 | Spatio-temporal | MZI | Doped Si | 3 dB | 70 dB | 200 GHz | 25 dBm |
| 2018 | Spatio-temporal | MZI | Si | 39 dB | N/A | 125 GHz | 90 mW |
| 2018 | Spatio-temporal | Ring | AlN | 15 dB | N/A | 1 GHz | 18 dBm |
| 2021 | Spatio-temporal | MZI | Si + AlN | 16 dB | N/A | 100 GHz | 21 dBm |
| This work | Spatio-temporal | Ring | Si,N + AlN | 10 dB | 0.1–1 dB | 0.7 GHz | 25 dBm |

*The isolation is the non-reciprocal response of modulation sideband. "Optical drive power, whereas others are electrical power.

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Methods

Device fabrication. The Si$_3$N$_4$ PIC is fabricated using the photonic Damascene process. The monolithic integration of piezoelectric AlN actuators on top of Si$_3$N$_4$ microresonators is illustrated in ref. 4. Films of 100 nm Mo and 1 μm AlN are sputtered on the wafer before throughput services (Plasma-Therm). The actuators are patterned by thick photoresist SPR220-4.5 and dry-etched using Cl$_2$ and BCl$_3$ in Panasonic E620 Etcher. The bottom molybdenum electrodes are patterned by photoresist AZ1518 and dry-etched using Cl$_2$ in the same etcher. Finally, the top 100 nm aluminium is deposited by an electron-beam evaporator and patterned using a standard lift-off process. The Al$_2$O$_3$ release process is shown in Fig. 1d. The centre release hole is patterned using photolithography, and SiO$_2$ is dry-etched to expose the silicon substrate. The silicon is then isotropically etched using the SF$_6$ Bosch process to undercut and suspend the SiO$_2$ membrane.

Design of Si$_3$N$_4$ waveguides for phase matching. From the microring’s resonant condition $k = 2π/e = m/R$, the momentum is related to the azimuthal order $m$ of the mode and the microring’s radius $R$. As the three actuators cover the entire microring, the generated rotating acoustic wave has an effective wavelength of 2πR, and thus the azimuthal order $m = 1$. The phase matching condition thus requires the azimuthal order difference $Δm = m - m = m = 1$ between the TE$_{00}$ and TM$_{00}$ modes. As the Si$_3$N$_4$ waveguide is fully cladded with SiO$_2$, a quasi-square waveguide cross-section (810 × 820 nm$^2$), as shown in Fig. 2b inset, is designed to have slightly different effective refractive indices for the two optical modes (see Supplementary Note 1). Here, phase matching requires the two optical modes to co-propagate, with the counter-propagating acoustic wave. In the final device used in the experiment, the azimuthal order difference is measured and calibrated (see Supplementary Note 2) to be around $Δm = 4$. Due to the discrete nature of the spatial modulation, there are higher-azimuthal-order Fourier components simultaneously excited that can fulfill phase matching at the expense of lower efficiency.

Measurement set-up. The electromechanical $S_{11}$ is measured by detecting the 100 nm aluminium is deposited by an electron-beam evaporator and patterned using a standard lift-off process. The Si$_3$N$_4$ release process is shown in Fig. 1d. The centre release hole is patterned using photolithography, and SiO$_2$ is dry-etched to expose the silicon substrate. The silicon is then isotropically etched using the SF$_6$ Bosch process to undercut and suspend the SiO$_2$ membrane.

Combination of two processes: (1) $a\hat{b}^c\hat{c}$, annihilation of a photon $\hat{a}$ and a phonon $\hat{b}$ and generation of one higher-frequency photon $\hat{c}$; (2) $a\hat{b}^\dagger\hat{c}^\dagger$, annihilation of one photon $\hat{a}$ and generation of a photon $\hat{c}$ and a phonon $\hat{b}$. Following an approach similar to ref. 5, the equations of motion for the average of the annihilation operators can be obtained by assuming resolved sidebands and rotating-wave approximation:

$$\frac{d}{dt} \langle a \rangle = -\left(\Delta_a + \frac{k_a}{2}\right) \langle a \rangle - ig_a \langle \hat{b} \rangle \langle \hat{c} \rangle + \sqrt{\kappa_{a,ex}} \langle \hat{c} \rangle$$

(6)

$$\frac{d}{dt} \langle \hat{b} \rangle = -\left(\Delta_b + \frac{k_b}{2}\right) \langle \hat{b} \rangle - ig_b \langle a \rangle \langle \hat{c} \rangle$$

(7)

$$\frac{d}{dt} \langle \hat{c} \rangle = -\left(\Delta_c + \frac{k_c}{2}\right) \langle \hat{c} \rangle - ig_c \langle a \rangle \langle \hat{b} \rangle + \sqrt{\kappa_{c,ex}} e^{-i\omega_c t}$$

(8)

where $\Delta_c/2\pi$ and $\Gamma_{c,ex}/2\pi$ are the total loss rate (11 MHz) of the mechanical mode and the external coupling rate (22 kHz) from the microwave channel to the HBAR phonons, and $\langle \hat{c} \rangle = \sqrt{P_c/\hbar \Omega_c}$ is the input microwave amplitude, where $P_c$ is the input RF power. Assuming that the optomechanical coupling (term $g_c \langle a \rangle \langle \hat{c} \rangle$ in equation (8)) has a much smaller contribution than the microwave drive, the mean intracavity amplitude of $\hat{c}$ at steady state is:

$$\bar{c} = \sqrt{\frac{\pi g_c^2}{\kappa_c^2}}$$

(9)

Measurement set-up. The electromechanical $S_{11}$ is measured by detecting the reflected microwave signal using a vector network analyser (VNA, Agilent E8364B), where the electrical signal is applied to the device through an RF GSG probe (Cascade ACP40-GSG-150). To measure the optomechanical $S_{21}$, a continuous wave (CW) light from a diode laser (Velocity Tunable Laser 6328) is edge-coupled into the chip using a lensed fibre and a fibre taper with around 50 μW power on chip. An RF signal of ~548 MHz power is applied from the port 1 of the VNA to drive the AlN actuator. The light intensity modulation is detected by a 12 GHz photodiode (New Focus 1544), whose output is sent back to port 2 of the network analyser.

The three-wave mixing process (two optical modes $\hat{a}$ and $\hat{b}$, and one mechanical mode $\hat{c}$) can be described by the quantum interaction Hamiltonian:

$$\hat{H}_I = ig_b \langle \hat{b} \rangle \langle \hat{c} \rangle + \hat{c} \langle \hat{b} \rangle$$

(5)

assuming that phase matching is fulfilled and $\hat{a}$ has a smaller frequency than $\hat{b}$. Under these conditions, the optomechanical interaction can be understood as the combination of two processes: (1) $a\hat{b}^c\hat{c}$, annihilation of a photon $\hat{a}$ and a phonon $\hat{b}$ and generation of one higher-frequency photon $\hat{c}$; (2) $a\hat{b}^\dagger\hat{c}^\dagger$, annihilation of one photon $\hat{a}$ and generation of a photon $\hat{c}$ and a phonon $\hat{b}$. Following an approach similar to ref. 5, the equations of motion for the average of the annihilation operators can be obtained by assuming resolved sidebands and rotating-wave approximation:

$$\frac{d}{dt} \langle a \rangle = -\left(\Delta_a + \frac{k_a}{2}\right) \langle a \rangle - ig_a \langle \hat{b} \rangle \langle \hat{c} \rangle + \sqrt{\kappa_{a,ex}} \langle \hat{c} \rangle$$

(6)

$$\frac{d}{dt} \langle \hat{b} \rangle = -\left(\Delta_b + \frac{k_b}{2}\right) \langle \hat{b} \rangle - ig_b \langle a \rangle \langle \hat{c} \rangle$$

(7)

$$\frac{d}{dt} \langle \hat{c} \rangle = -\left(\Delta_c + \frac{k_c}{2}\right) \langle \hat{c} \rangle - ig_c \langle a \rangle \langle \hat{b} \rangle + \sqrt{\kappa_{c,ex}} e^{-i\omega_c t}$$

(8)

where $\Delta_c/2\pi$ and $\Gamma_{c,ex}/2\pi$ are the total loss rate (11 MHz) of the mechanical mode and the external coupling rate (22 kHz) from the microwave channel to the HBAR phonons, and $\langle \hat{c} \rangle = \sqrt{P_c/\hbar \Omega_c}$ is the input microwave amplitude, where $P_c$ is the input RF power. Assuming that the optomechanical coupling (term $g_c \langle a \rangle \langle \hat{c} \rangle$ in equation (8)) has a much smaller contribution than the microwave drive, the mean intracavity amplitude of $\hat{c}$ at steady state is:

$$\bar{c} = \sqrt{\frac{\pi g_c^2}{\kappa_c^2}}$$

(9)

By inserting equation (11) into equations (6) and (7), we obtain equations (1) and (2) in the main text. Due to the modulation, the frequency of mode $\hat{b}$ is shifted by $\Omega_b$ in the rotating frame of $\hat{a}$, where the polarization will change as we switch the MEMS optical switch, the optical modes are selected by rotating the polarization controller until that only TE mode resonances are observed. This process is repeated for both directions. It is worth noting that, although the polarization will change as we switch the MEMS optical switch, the polarization right before the PBS will be the same, since the optical switch itself is a reciprocal device. During the experiments, the RF phases are actively adjusted to compensate the drift of RF phases due to the thermal heating and HBAR resonance shift. The RF phases are calibrated by comparing the transmission spectrum with numerical simulations.

For measuring isolation of optical pulses, the input light before the optical switch is modulated by an electro-optic intensity modulator (Lucent 2623CSA), and the input pulse is generated by a function generator (Agilent 33250A). The 100 ns (10 ns) pulse has a repetition rate of 4 MHz (5 MHz). Supplementary Video 2 shows the experimental demonstration. To measure the optical linearity, an erbium-doped fibre amplifier (EDFA-1-B) is used before the optical switch to increase the optical power to above 100 μW.

Derivation of coupled mode equations. The three-wave mixing process (two optical modes $\hat{a}$ and $\hat{b}$, and one mechanical mode $\hat{c}$) can be described by the quantum interaction Hamiltonian:

$$\hat{H}_I = ig_b \langle \hat{b} \rangle \langle \hat{c} \rangle + \hat{c} \langle \hat{b} \rangle$$

(5)

assuming that phase matching is fulfilled and $\hat{a}$ has a smaller frequency than $\hat{b}$. Under these conditions, the optomechanical interaction can be understood as the
Author contributions
H.T. and J.L. designed the devices. J.L., H.T. and R.N.W. developed the process and fabricated the samples, with the assistance from J.H. H.T. performed the experiment and simulations, and analysed the data. A.S. performed the experiment on the overcoupled device with the assistance from T.B. H.T. and J.L. wrote the manuscript, with input from others. S.A.B and T.J.K supervised the collaboration.

Competing interests
The authors declare no competing interests.

Additional information
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