Non-reciprocal frequency conversion and mode routing in a microresonator

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The transportation of photons and phonons typically obeys the principle of reciprocity. Breaking reciprocity of these bosonic excitations will enable the corresponding non-reciprocal devices, such as isolators and circulators [1–3]. Here, we use two optical modes and two mechanical modes in a microresonator to form a four-mode plaquette via radiation pressure force. The phase-controlled non-reciprocal routing between any two modes with completely different frequencies is demonstrated, including the routing of phonon to photon (MHz to MHz), photon to phonon (THz to MHz), and especially photon to photon with frequency difference of around 80 THz for the first time. In addition, one more mechanical mode is introduced to this plaquette to realize a phononic circulator in such single microresonator. The non-reciprocity is derived from interference between multi-mode transfer processes involving optomechanical interactions in an optomechanical resonator. It not only demonstrates the non-reciprocal routing of photons and phonons in a single resonator but also realizes the non-reciprocal frequency conversion for photons and circulation for phonons, laying a foundation for studying directional routing and thermal management in an optomechanical hybrid network.

Optical and acoustic non-reciprocal devices are the basic building blocks for information processing and sensing based on photons and phonons. For bosons, several methods can be used to achieve non-reciprocity, ranging from applying a magnetic field [2, 4], imposing rotational motion [5–8], optomechanical interactions [9–13], spatiotemporal modulations [14–20], and chiral interaction of atoms [21–23]. Magnetically induced non-reciprocity, as the most common mechanism, is challenging to integrate low-optical-loss magnetic materials on chip for optical devices [4] and typically produce milli-scale phononic devices because of weak non-reciprocal absorption [24, 25]. The optomechanical systems [26, 27], are one of the most promising candidates to realize magnetic-free non-reciprocity [28, 29], where the optical isolation and non-reciprocal control of phonons have been demonstrated respectively. Among them, one non-reciprocal mechanism is the use of phase matching conditions of traveling wave modes [28, 30–33]. Another mechanism is based on the gauge phase in the network of multiple modes, which highlights the phase control of non-reciprocity [10–12, 34–36]. Similar mechanisms have been applied to microwave photons in superconducting circuits [37–42]. Although the non-reciprocal mode conversion in superconducting circuits is demonstrated over a few gigahertz, applying the gauge phase mechanism to frequency dimension of optical photons and more modes in optomechanical systems will provide more non-trivial devices, such as phase-controlled non-reciprocal frequency conversion and phononic circulator.

FIG. 1. Schematic of the non-reciprocal routing in a microresonator. a. The control lasers enhance the optomechanical coupling and control the non-reciprocal transportation inside a microsphere. b–c. The typical two optical modes with frequencies ω1 and ω2 and two mechanical modes with frequencies ωm1 and ωm2 are used to establish a four-mode plaquette via optomechanical interactions, which is controlled by four red-detuned control fields. The non-reciprocal effects can be changed by tuning the control phase θ11, θ12, θ21 and θ22.

Here, we study the non-reciprocal routing of both photons and phonons in a microresonator, where two optical modes and two mechanical modes are exploited to form a closed loop of a four-mode plaquette, using the optomechanical interactions as shown in Figs. 1a-b. The four modes have completely different frequencies, i.e., 388
THz, 309 THz, 117 MHz, and 79 MHz, respectively. The non-reciprocal routing between any two nodes among these four modes is demonstrated, including the routing of phonon-phonon (MHz - MHz), photon-photon (THz - THz), and photon-phonon (THz - MHz). In general, the non-reciprocity results from the interference between two transportation paths engineered to connect the targeted nodes. The interference phase is governed by the phase of the control field, leading to a phase-controlled and flexible non-reciprocal routing. We demonstrate the phononic circulator simultaneously controlled by two independent phases when one more mechanical mode is introduced to such plaquette. The non-reciprocal frequency conversion opens new possibilities in communication and information processing, especially in the optical domain for wavelength-division-multiplexing (WDM) networks and quantum interface connecting separated systems operating at incompatible frequencies [43–45]. The phononic circulator holds great potential in thermal management, heat transfer, and phononics-based information processing [10].

Theoretical model

The hybrid plaquette includes two optical modes and two mechanical modes in the microresonator, as shown in Figs. 1b–c. The bosonic operators $c_1$ and $c_2$ denote two optical whispering-gallery modes with resonance frequencies of $\omega_1$, $\omega_2$ and dissipation rates of $\kappa_1$, $\kappa_2$, respectively. The bosonic operators $m_1$ and $m_2$ denote two mechanical modes with resonance frequencies of $\omega_{m1}$, $\omega_{m2}$ and dissipation rates of $\gamma_1$, $\gamma_2$. We focus on achieving non-reciprocal routing between any two nodes of these four modes, that is, the bosonic excitations in one mode can be unidirectionally converted to another mode. A total of six pairs transportation ($m_1$-$m_2$, $c_1$-$c_2$, $c_1$-$m_2$, $c_2$-$c_1$, $c_2$-$m_1$, $c_1$-$m_1$) for $j$, $k \in \{1, 2\}$ should be respectively considered. Due to the symmetry, we select three pairs of nodes ($m_1$-$m_2$, $c_1$-$c_2$, $c_1$-$m_1$) for experimental verification, showing that the non-reciprocal routing can be implemented between phonon-phonon, photon-photon, and photon-phonon in the plaquette, where the non-reciprocal mechanism can be fully described by the general theory of symmetry breaking between the two optomechanical coupling paths.

Here, we only theoretically describe the non-reciprocal routing of $m_1$-$m_2$ in detail (other non-reciprocal routings are discussed in the Supplemental Material). When the cavity mode $c_1$ is driven by two optical tones with frequencies of $\omega_{c1}$ and $\omega_{c2}$, the phonon of one mechanical mode up-converts to the optical mode $c_1$ and then down-converts to the other mechanical mode. As this process of frequency conversion features reciprocity, the cavity mode $c_2$ is introduced by the second pair of tones with frequencies of $\omega_{c1}$ and $\omega_{c2}$, to form another path of optically mediated frequency conversion simultaneously. Based on the path interference, the hopping phases controlled through external drives in such a plaquette give rise to the non-reciprocal routing [37–39]. In the frame rotating at the frequencies $\omega_{jk}$, the linearized Hamiltonian can be written as ($h = 1$)

$$H = \sum_{j,k=1,2} G_{jk} \left[ c_j^\dagger m_k e^{i(\delta_{jk} t + \theta_{jk})} + c_j m_k^\dagger e^{-i(\delta_{jk} t + \theta_{jk})} \right],$$

(1)

where the driving fields are around the red sideband of the cavity with the detuning $\delta_{jk} = \omega_j - \omega_{jk} - \omega_{mk}$. And the counter-rotating terms can be neglected in the weak coupling regime $G_{jk} \ll \omega_{mk}, |\omega_{m2} - \omega_{m1}|$. $G_{jk} = g_{jk}/\sqrt{n_{jk}}$ is the effective optomechanical interaction strength with the vacuum optomechanical coupling rate $g_{jk}$ and the total number of intracavity photons $n_{jk}$, and $\theta_{jk}$ is the relative phase set by driving fields.

For the interference of the two conversion paths, the effective phase $\delta_{jk} t + \theta_{jk}$ determines the non-reciprocity and conversion efficiency. For the non-reciprocal transportation between two mechanical modes, we set the cavity detunings $\delta_{11} = \delta_{12} = -\delta$ and $\delta_{21} = \delta_{22} = \delta$. And we define the transmission $T_{ab} = |b_{out}/a_{in}|^2$ with $a, b \in \{m_1, m_2, c_1, c_2\}$. The ratio $\eta$ (See the Supplemental Material) of backward to forward transmission reads

$$\eta = \frac{T_{m_1 \rightarrow m_2}}{T_{m_2 \rightarrow m_1}} = \left| \frac{G_{11} G_{22} e^{-i\theta_1 \chi_1(\omega) + G_{21} G_{22} \chi_2(\omega)}}{G_{11} G_{12} e^{i\theta_1 \chi_1(\omega) + G_{21} G_{22} \chi_2(\omega)}} \right|^2,$$

(2)
where \( \theta = \theta_{12} - \theta_{21} - \theta_{22} \). \( \omega \) is the detuning between the signal and mode resonance, and \( \chi^{-1}_j = \kappa_j/2 - i (\omega + (-1)^j \delta) \) is the optical susceptibility with \( j \in \{1, 2\} \). Obviously, we have the ratio \( \eta = 1 \) when \( \theta = n \pi \) with \( n = 0, \pm 1, \pm 2, \ldots \), which means that there is no non-reciprocity for any detuning \( \delta \) and frequency \( \omega \). When the cooperativities for all four optomechanical couplings are equal \( (C = C_{jk} = 4G_{jk}^2/\kappa_j \gamma_k) \), we can obtain the perfect non-reciprocity, i.e., \( \eta = 0 \) or \( \eta = \infty \), where the phase satisfies
\[
\tan(\theta) = \pm \frac{\delta (\kappa_1 + \kappa_2) + \omega (\kappa_1 - \kappa_2)}{\kappa_1 \kappa_2 / 2 - 2 (\delta^2 - \omega^2)}.
\]
(3)

In a practical experimental system, \( \kappa_1 \neq \kappa_2 \) and the non-reciprocity still exists when \( \delta = 0 \). However, we usually choose an appropriate \( \delta \) in the experiment for an optimized non-reciprocity. In addition, due to the symmetry of four-mode plaquette, the cavity detunings should be changed as \( \delta_{11} = \delta_{21} = -\delta \) and \( \delta_{12} = \delta_{22} = \delta \) for the photon-photon non-reciprocity. For the adjacent conversion in such plaquette, i.e., phonon-phonon conversion, the cavity detunings as mentioned before are all satisfied for the non-reciprocal routing (see Supplementary Material for more details).

**Experimental realization**

To experimentally demonstrate the non-reciprocal routing between any two nodes in the four-modes plaquette, a silica microsphere with a diameter of approximately 40 \( \mu \)m is used in our experiment, where we choose two whispering-galley modes with resonance frequency \( \omega_1/2\pi = 387.56 \) THz (near 774 nm), damping rates \( \kappa_1/2\pi = 7 \) MHz and \( \omega_2/2\pi = 308.93 \) THz (near 971 nm), \( \kappa_2/2\pi = 27 \) MHz, respectively. The two radial breathing mechanical modes have frequencies of \( \omega_{m_1}/2\pi = 79 \) MHz and \( \omega_{m_2}/2\pi = 117 \) MHz with dissipation rates of \( \gamma_1/2\pi = 9 \) kHz and \( \gamma_2/2\pi = 28 \) kHz, respectively (see Supplementary Material for more details regarding the setup).

Figure 2 shows the demonstrated experiment of non-reciprocal routing between the two mechanical modes, where the resonator is driven with four control fields \( (CT_{11}, CT_{12}, CT_{21}, CT_{22}) \) with powers \( (P_{11}, P_{12}, P_{21}, P_{22}) = (1.8, 3.5, 1.1, 4.5) \) mW that correspond to the cooperativities \( (C_{11}, C_{12}, C_{21}, C_{22}) = (3.6, 0.46, 0.73, 1) \). The control fields are locked at a frequency detuning from the lower motional sidebands of \( \delta_{11}/2\pi = \delta_{12}/2\pi = -3 \) MHz and \( \delta_{21}/2\pi = \delta_{22}/2\pi = 3 \) MHz. Here, the control lasers are respectively modulated by the acoustic-optic modulators (AOMs) for pulse sequences to avoid thermal instability in the high-Q microresonator. And the four control tones are all phase-locked through the RF drives of AOMs, which can be varied continuously from \(-\pi\) to \(\pi\). As a first step, the phonons \( m_{1,\text{in}}(m_{2,\text{in}}) \) are prepared from the converted optical signal, which is resonant on the mode \( c_1 \) and converted by a red-detuned control tone \( CT_{11} \) (or \( CT_{12} \)) served as writing pulse \([43, 46, 47]\). Then all control tones are tuned on simultaneously for an interaction duration \( \tau = 5 \mu s \) to transfer the excitations from mode \( m_1 \) (or \( m_2 \)) to mode \( m_2 \) (or \( m_1 \)). Finally, a control pulse \( CT_{12} \) (\( CT_{11} \)) served as a readout pulse interacts with the converted mechanical excitations, converting the mechanical excitations back to an optical pulse at the cavity resonance, which corresponds to the retrieval process of the optomechanical light storage \([46, 47]\). Figure 2a shows the normalized power spectra of the mode \( m_{2,\text{out}} \) (or \( m_{1,\text{out}} \)) transferred from \( m_{1,\text{in}} \) (or \( m_{2,\text{in}} \)). The non-overlap transmittance unambiguously present phase-controlled non-reciprocal routing: with \( \theta = 0.27\pi \) the excitations prepared in mode \( m_1 \) is transferred to mode \( m_2 \) \( (T_{m_1 \rightarrow m_2} \approx 1.8\% \) but not vice versa, while with \( \theta = -0.27\pi \) the excitations prepared in mode \( m_2 \) is transferred to mode \( m_1 \) but not vice versa. The average phonon occupation \( N_{m_{2,\text{out}}} \) (or \( N_{m_{1,\text{out}}} \)) is estimated through the spectrally integrated area of the displacement power density spectrum of the mechanical excitation. We have used the thermal displacement power density spectrum and the corresponding average thermal phonon number, \( N_{m_{2,\text{in}}} \) (or \( N_{m_{1,\text{in}}} \)), to calibrate the measurement. The transmissions \( T_{m_1 \rightarrow m_2} \) and \( T_{m_2 \rightarrow m_1} \) are summarized and plotted in Fig. 2b as a function of the control phase \( \theta \) (see Supplementary Material for more details with regard to the measurement).

Therefore, isolation of more than 10 dB is demonstrated in each direction in a reconfigurable manner, that is, the direction of isolation can be switched by taking \( \theta \rightarrow -\theta \), as shown in Fig. 2c.

Next, we experimentally realize the non-reciprocal routing of photons between the two optical modes \( c_1 \) and \( c_2 \) through two mechanical modes instead of the reciprocal photons conversion via one mechanical mode \([30, 43]\). At this point, the detunings of the four control tones are tuned to a new configuration \( (\delta_{11}/2\pi = \delta_{21}/2\pi = -45 \) kHz, \( \delta_{12}/2\pi = \delta_{22}/2\pi = 45 \) kHz) to establish the asymmetric paths achieving non-reciprocity. The pulse sequence and the phase of the control field are generated similarly with the case of non-reciprocal conversion of phonons (see Supplementary Material for more details). The signal photons injected on resonance with one optical mode will be converted to the other one, while four control fields are synchronously to drive the mechanical motions. Frequency conversion in both directions, \( T_{c_1 \rightarrow c_2} \) and \( T_{c_2 \rightarrow c_1} \), are measured and compared for three different phases in Fig. 3a. At \( \theta = 0.73\pi \), we observe relatively high forward transmittance (6%) from cavity 1 to 2 and near-zero transmittance (0.1%) in the backward direction around zero detuning. Likewise, at the negative phase of \( \theta = -0.73\pi \) the transmission from cavity 1 to 2 is suppressed while the transmission from cavity 2 to 1 is
high. The peaks and dips with the linewidth of around $\sqrt{\gamma_1/\gamma_2}$ observed in Fig. 2a, highlight the two-path interference mediated by two mechanical modes. Isolation of more than 15 dB in both directions is demonstrated with a bandwidth of 17.7 kHz. Around $\theta = 0$, the frequency conversion is reciprocal and bidirectional. Figure 3b shows the transmission spectra as a function of probe detuning for the whole range of phases $\theta$, where isolation of more than 15 dB is demonstrated in both directions. Here, we neglect the mode coupling between clockwise (CW) and counter-clockwise (CCW) whispering-gallery modes because of the weak backscattering. Actually, the traveling wave cavity supports a pair of degenerate optical modes. The CW modes $c_1$ and $c_2$ can be coupled with the CCW modes due to the strong optical backscattering or nanoparticles [48]. Therefore, the model can be built including two paired optical modes. Finally, the non-reciprocal routing of bosonic excitations between the optical mode $c_1$ and the mechanical mode $m_1$ is demonstrated. The details of which are discussed in Supplementary Material. Due to the symmetry, the phase-controlled non-reciprocal routing between arbitrary two bosonic modes with ultra-high frequency difference can be implemented.

The described four-mode plaquette can achieve flexible expansion, for example by parametrically coupling a third mechanical mode $m_3$ to the optical modes, as shown in Fig. 4a. This five-mode plaquette is established in another silica microsphere with $\omega_{m_1}/2\pi = 75.3$ MHz, $\omega_{m_2}/2\pi = 76.4$ MHz and $\omega_{m_3}/2\pi = 112.7$ MHz (see Supplemental Material for more details). Similar to the four-mode case, we use six control fields with frequencies slightly detuned from the lower motional sidebands of the resonances to form the closed-loop. The powers of the control fields are $(P_{11}, P_{12}, P_{13}, P_{21}, P_{22}, P_{23}) = (4.8, 1.6, 4.2, 3.4, 1.6, 1.7)$ mW corresponding to the cooperativities $(C_{11}, C_{12}, C_{13}, C_{21}, C_{22}, C_{23}) = (1.6, 1.3, 1.3, 1.1, 0.86, 0.76)$. For an experimental demonstration of the phase-controlled phononic circulator, we measure the isolation $I_{ij} = 10\log(T_{m_i\rightarrow m_j}/T_{m_j\rightarrow m_i})$ ($i, j \in \{1, 2, 3\}$) versus the control phases, as shown in Fig. 4b. Unlike the four-mode case, where the non-reciprocal conversion is achieved by varying only one control phase, in the phononic circulator, at least two independent control phases ($\theta_{11}$ and $\theta_{12}$ in our experiment) need to be tuned to change the phase difference of the three pairs of interference paths. As both $\theta_{11}$ and $\theta_{12}$ dominantly affect the transportation between mode $m_1$ and mode $m_2$, $I_{12}$ has a significant change in the diagonal direction, while $I_{23}$ ($I_{13}$) changes dominantly upon $\theta_{12}$ ($\theta_{11}$) varying, which is in agreement with intuition and theory (see Supplementary Material for more details). Figure 4c plots the $I_{sum} = I_{12} + I_{23} + I_{31}$, where we see phononic circulation in the forward direction $I_{sum}$ of up to 35 dB at $\theta_{11}, \theta_{12} = (-0.7, 0.1)\pi$ or in the backward direction $I_{sum} = -33.3$ dB at $\theta_{11}, \theta_{12} = (0.7, -0.1)\pi$. Via a simple change in the control fields, the direction of circulator is reversed, demonstrating the great flexibility of our device.

Beyond the five-mode model, our demonstration can be scaled to the two-dimensional hybrid network by exploiting more optical and mechanical modes in the same microcavity, while each link couples one optical mode and one mechanical mode. Indeed, the transmission of photons between CW and CCW optical modes can also achieve non-reciprocal conversion mediated by one mechanical mode [12]. Because of the demonstration of non-reciprocal transportation between any two modes, we can control the propagation of the bosonic excitations along the designated route (Supplementary Fig. S6). The expansion of the network in a single microcavity provides a potential platform for studying topological photonics/phononics and quantum many-body physics, without the requirement of fabricating massive identical microstructures.

In conclusion, we have experimentally demonstrated the non-reciprocal routing of phonon-phonon, photon-phonon, and photon-phonon simultaneously in a single microresonator. The non-reciprocal routing is controlled by adjusting the frequency and phase of the control field. Among them, the optical non-reciprocal frequency conversion can reach 6% efficiency and 15 dB isolation, and
more than 15dB isolation for the phonon non-reciprocal conversion and circulation. These results can be applied to information processing and thermal management, and also lay a foundation for the directional routing of signals in a hybrid network.

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Author contributions
Z.S. C.-L.Z. and C.-H. D. conceived and designed the experiment. Z.S., Y.C. and C.H.D. prepared the samples, built the experimental setup and carried out experiment measurements. Y.-L.Z. Y.-F. X. and C.-L.Z. provided theoretical support and analysed the data. Z.S., C.-H.D. and C.-L.Z. wrote the manuscript with inputs from all authors. C.-H.D. and G.-C.G. supervised the project. All authors contributed extensively to the work presented in this paper.

Additional information
Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at. Correspondence and requests for materials should be addressed to C.-H.D. (chunhua@ustc.edu.cn).

Competing financial interests
The authors declare no competing interests.
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