Experimental realization of optomechanically induced non-reciprocity

Zhen Shen\textsuperscript{1,2}, Yan-Lei Zhang\textsuperscript{1,2}, Yuan Chen\textsuperscript{1,2}, Chang-Ling Zou\textsuperscript{1,2,3,*}, Yun-Feng Xiao\textsuperscript{4}, Xu-Bo Zou\textsuperscript{1,2}, Fang-Wen Sun\textsuperscript{1,2}, Guang-Can Guo\textsuperscript{1,2} and Chun-Hua Dong\textsuperscript{1,2,*}

Non-reciprocal devices, such as circulators and isolators, are indispensable components in classical and quantum information processing in integrated photonic circuits\textsuperscript{1}. Aside from these applications, the non-reciprocal phase shift is of fundamental interest for exploring exotic topological photonics\textsuperscript{2}, such as the realization of chiral edge states and topological protection\textsuperscript{3,4}. However, incorporating low-optical-loss magnetic materials into a photonic chip is technically challenging\textsuperscript{5}. In this study we experimentally demonstrate non-magnetic non-reciprocity using optomechanical interactions in a whispering gallery microresonator, as proposed in a previous work\textsuperscript{6}. Optomechanically induced non-reciprocal transparency and amplification are observed and a non-reciprocal phase shift of up to 40° is also demonstrated\textsuperscript{7}. The underlying mechanism of optomechanically induced non-reciprocity has great potential for all-optical controllable isolators and circulators, as well as non-reciprocal phase shifters in integrated photonic chips.

In recent years, there has been growing interest in the realization of non-reciprocal photonic devices without magnetic materials. To create genuine non-reciprocal devices, it is necessary to break the Lorentz reciprocity\textsuperscript{7}. The methods that have been used in the attempt to achieve this goal primarily rely on two mechanisms: the effect due to a moving medium or reference frame, and the non-linear optical effect. The Sagnac effect utilizes the first mechanism and can induce a non-reciprocal phase shift for a photon that is propagating in a rotating non-inertial frame of reference\textsuperscript{8}. The sound analogue of isolation due to a circulating fluid medium was reported\textsuperscript{9}, however, the optical Sagnac effect requires a long optical path, which is not suitable for a photonic chip. Based on the non-linear optical effect, the non-reciprocity of a photon can be achieved by interacting with travelling wave excitations or equivalent spatiotemporal modulations\textsuperscript{10–12}. For example, a directional travelling acoustic wave can only efficiently couple with light that propagates forwards or backwards due to Brillouin scattering, which leads to time-reversal symmetry breaking of light\textsuperscript{13–15}. A similar effect can also be realized with a directional photon–photon interaction in a nonlinear microring resonator\textsuperscript{16}. However, the energy conservation and momentum matching conditions must be satisfied for all of the modes involved, resulting in challenges for dispersion engineering and fabrication of the photonic structures. There are also efforts to create an optical isolator via Kerr-like nonlinearity-induced bistability, but the performance for a single-photon-level signal and isolation from weak backward noise are under debate\textsuperscript{17}.

In this Letter, we report the experimental demonstration of optomechanically induced non-reciprocity in a silica microsphere resonator. In this approach\textsuperscript{6}, an optical mode dispassively couples with a symmetric radial breathing mechanical mode. A signal photon can only be affected when it propagates in the same direction as the driving laser. The non-reciprocity can also be realized through Brillouin-scattering\textsuperscript{14,15}, where two optical modes couple with a travelling acoustic mode. The triply resonant process can enhance the light–acoustic interaction, while it is hard to fulfill the momentum and energy conservation conditions for two optical modes with the given mechanical mode in practice. In contrast, the underlying mechanism of optomechanically induced non-reciprocity can be generalized to any travelling optical wave resonator with mechanical vibration. It can be operated with many optical modes in a broad wavelength range and can readily be implemented in current integrated photonic chips\textsuperscript{18,19}. With the mechanical vibrations being cooled to their ground states, applications in the quantum regime—such as single-photon isolators and circulators—also become possible.

Figure 1a schematically illustrates a travelling wave optomechanical system that consists of a whispering gallery microresonator that is evanescently coupled with a tapered fibre\textsuperscript{20–22}. The travelling wave nature of the microresonator produces a rise in the degenerate clockwise (CW) and counter-clockwise (CCW) travelling-wave whispering-galley modes, which can also be represented by the orbital angular momenta \( m \) and \( -m \), respectively. Similarly, the mechanical modes in such an axial symmetric geometry have an

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1State Key Laboratory for Mesoscopic Physics and School of Physics, Peking University, Beijing 100871, China. *e-mail: clzou321@ustc.edu.cn; chunhua@ustc.edu.cn

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red lines are the results of calculations using the parameters $\omega_{m}/2\pi = 88.54$ MHz, $\kappa/2\pi = 15$ MHz, $\gamma_{m}/2\pi = 22$ kHz and $C_{CW} = 1.5$, respectively. The emission power spectra in the OMIT response are obtained using co- and counterpropagating signal pulses. The incident driving power is 10 mW. The solid red lines are the results of calculations using the parameters $\omega_{m}/2\pi = 88.54$ MHz, $\kappa/2\pi = 15$ MHz, $\gamma_{m}/2\pi = 22$ kHz and $C_{CW} = -0.8$, respectively.

orbital angular momentum $m_{b}$, here $m_{b} = 0$ represents the breathing vibration mode, where the equator of the sphere expands and compresses uniformly. The variation of the cavity radius leads to the modification of the resonant frequency of all of the optical modes, which can be described by the dispersive optomechanical interaction Hamiltonian:

$$H_{int} = g_{o}(a_{CW}^\dagger a_{CW} + a_{CCW}^\dagger a_{CCW})(b + b^\dagger)$$

(1)

where $a_{CW(CC)}$ and $b$ denote the Bosonic operators of the CW(CC) optical mode and mechanical mode, respectively; $g_{o}$ is the single-photon coupling rate, which corresponds to the optical cavity frequency shift per phonon excitation. For such an interaction, the CW and CCW modes are independently coupled with mechanical mode. Only when the driving and signal optical fields are coupled to the same optical mode can the driving field stimulate the coherent interaction between signal photons and phonons. Thus the CW(CC) driving field can only stimulate the interaction between a phonon and a CW(CC) signal photon, as shown in Fig. 1b. This relation between the driving signal directions can also be interpreted by the conservation of orbital angular momentum $m_{s} - m_{d} = m_{b} = 0$, where $m_{s}$ and $m_{d}$ denote the momentum for the signal photon and driving laser, respectively. As a result, the directional driving field breaks the time-reversal symmetry and leads to non-reciprocal transmittance for the signal light; the copropagating signal photons can be coherently coupled with phonons, while the coupling between counterpropagating photons and the phonon is negligible.

The experimental demonstration of the optomechanically induced non-reciprocity is performed using the set-up shown in Fig. 2a. The driving laser excites the CW optical mode, while either CW or CCW signal photons are sent to the cavity (see Supplementary Information for more details with regard to the experimental set-up). In a sphere with a diameter of approximately 36 µm, we choose a high-quality-factor whispering-gallery mode near 780 nm (optical mode linewidth $\kappa/2\pi = 15$ MHz). The radial breathing mechanical mode in this sphere has a frequency of $\omega_{m}/2\pi = 88.54$ MHz and an optomechanical mode linewidth of $\gamma_{m}/2\pi = 22$ kHz.

Figure 2b shows the two configurations of the driving field. For the driving field that is red-detuned from the cavity mode by $\omega_{m}$, an effective phonon–phonon beam-splitter-like interaction ($a_{CW}^\dagger b + a_{CW} b^\dagger$) would lead to coherent conversion and induce a transparent window in the cavity field spectrum. In this study, we send a short drive laser and signal pulse (duration $\tau_{s} = 18$ µs) to measure the transient optomechanical coupling while avoiding thermal instability in the microsphere. The experimental result in Fig. 2c shows a sharp transparency window for copropagating signal photons, demonstrating the destructive interference between the signal field and the optical field generated from the anti-Stokes scattering process. Conversely, the spectrum of the counterpropagating signal in Fig. 2d does not show such an effect, which is indicative of optomechanically induced non-reciprocity. The spectra still agree with the theoretical predictions of the steady-state intracavity field:

$$a_{CW}(\delta) = \frac{-\sqrt{G_{m}G_{s}}}{i\delta - \frac{\kappa}{2(1 - 2\delta/\gamma_{m})}}$$

(2)

$$a_{CCW}(\delta) = \frac{-\sqrt{G_{m}G_{s}G_{CCW}}}{i\delta - \frac{\kappa}{2}}$$

(3)

where $C_{CW} = (4|G_{CCW}|^{2}/(\kappa\gamma_{m}))$ is the cooperativity; $G_{CW} = \sqrt{N_{d}}\delta_{0}$ is the effective optomechanical coupling rate; $N_{d}$ is the CW driving...
intracavity photon number; $e_{s,\text{CW}}$ and $e_{s,\text{CCW}}$ are the weak signal amplitudes of the CW- and CCW-circulating optical modes, respectively; $\delta$ is the detuning between the signal and cavity field; and $\kappa_m$ is the coupling rate between the microfibre and the microsphere. For a critically coupled optical mode, the observed intracavity fields for the CW and CCW signal that correspond to non-reciprocal transmissions of the CW and CCW signals are 0 and 1 around $\delta \approx 0$, respectively.

For a driving field that is blue-detuned from the cavity mode by $\omega_m$ (that is, the driving frequency $\omega_d = \omega_c + \omega_m$), an effective photon–phonon pair generation process $(a_{\text{CW}}b^\dagger + a_{\text{CCW}}b)$ would lead to optomechanically induced amplification. Figure 2e,f presents the corresponding experimental results, which show non-reciprocal amplification of the signal. The sequences of driving laser and signal pulses are the same as before. Here, the experimental results are fitted to the modified transient intracavity field spectra because of the unsteady state optomechanical coupling even with an 18 µs driving pulse at the blue sideband:

$$a_{\text{CW}}(\delta) = \frac{-\sqrt{\kappa m}}{i\delta - \frac{\kappa}{2}(1 + C_{\text{CW}}/1 - i2\delta/\gamma_m)} [1 + F(\gamma_m)]$$

with the transient modification

$$F(t) = \frac{2C_{\text{CW}}\exp(i\delta t + (\kappa + \gamma_m)/4)}{1 - i2\delta/\gamma_m} \times \sinh \left[ \sqrt{(\kappa + \gamma_m)/4 - \kappa \gamma_m(1 + C_{\text{CW}})/2} \right]$$

where $F(t)$ is the modification factor at time $t$. In this study, $C_{\text{CW}} = \frac{1}{4} (\left| G_{\text{CW}} \right|^2) / (\kappa \gamma_m)$ has a negative sign, which would effectively narrow the linewidth of the cavity and amplify the intracavity signal.

To obtain a more quantitative analysis of the optomechanically induced non-reciprocity, the detailed spectra for different experimental conditions are shown in Fig. 3a. For blue detuning, the peak height increases and the linewidth decreases with the driving power. For red detuning, the transparent depth and linewidth both increase with the driving power. The intensity at $\delta = 0$ and the corresponding $C_{\text{CW}}$ are summarized and plotted in Fig. 3c. The intensity of the copropagating signal agrees with the prediction, while the counterpropagating signal is found to be independent of $C_{\text{CW}}$.

The non-reciprocal transmittance of the signal can also be inferred from the phase because $\arg(a_{\text{CW}}(\delta))$ in equation (2) varies with the detuning and $C_{\text{CW}}$. The measured phase is plotted in Fig. 3b; the difference between the copropagating and counterpropagating signal unambiguously shows the non-reciprocal phase shifter due to the optomechanical interaction. The extracted phases at $\delta = \pm \gamma_m$ that are plotted in Fig. 3d agree with the theory. The maximum phase shift achieved in the experiment is approximately 40°. The oscillations around the opacity peak in Fig. 3a and the corresponding phase response in Fig. 3b are observed due to the transient response of the optomechanical system25, as described by $F(t)$ (see Supplementary Information).

Optomechanically induced non-reciprocity is controllable using two oppositely propagating driving fields that excite the CW and CCW modes simultaneously. As a result of the interesting interplay between the three coupled modes (Fig. 1b), there is an optomechanically dark mode21 (that is, a superposition of the CW and CCW modes), which enables the conversion of optical fields from the

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**Figure 3** | Optomechanically induced non-reciprocal transmission and phase shift. **a**, The typical emission power from the microcavity with the copropagating (circles for OMIT and squares for OMIA) and counterpropagating (triangles) signals. **b**, The corresponding phase responses at different driving powers. The solid lines are the results of calculations using $C_{\text{CW}} = -0.74$, -0.5, 0, 0.35 and 1.9. **c**, The spectral depth of the transparency window or spectral peak of the opacity peak as a function of $C_{\text{CW}}$. The lines in **d** represent the theoretically expected values.
CW mode to the CCW mode. To test the optical mode conversion, we fixed the CW driving power at 10 mW and varied the CCW driving power from 0 to 18 mW, while the input signal coupled only to the CW mode. As shown in Fig. 4b, the excitation of the CW mode increases with increasing \( C_{\text{CCW}} \) and the OMIT dip for this mode vanishes and is accompanied by a spectral broadening of the dip. There is light reflected from the system with a bandwidth smaller than 100 kHz; its peak power at \( \delta = 0 \) also increases with \( C_{\text{CCW}} \). The theoretical model predicts that \( a_{\text{CCW}} \propto ((1 + C_{\text{CCW}})/(1 + C_{\text{CW}} + C_{\text{CCW}})) \) and \( a_{\text{CW}} \propto ((\sqrt{(C_{\text{CW}}C_{\text{CCW}})})/(1 + C_{\text{CW}} + C_{\text{CCW}})) \) for the CW signal, which agrees with the experimental results shown in Fig. 4c. Compared with the CCW signal, for which \( a_{\text{CCW}} \propto ((1 + C_{\text{CW}})/(1 + C_{\text{CW}} + C_{\text{CCW}})) \) and \( a_{\text{CW}} \propto ((\sqrt{(C_{\text{CW}}C_{\text{CCW}})})/(1 + C_{\text{CW}} + C_{\text{CCW}})) \), the copropagating intracavity excitation and transmission are non-reciprocal if \( C_{\text{CW}} \neq C_{\text{CCW}} \), while the signal reflection is always reciprocal. Therefore, the system behaves as a controllable narrowband reflector with non-reciprocal transmittance, which might be interesting for future studies.

To summarize, optomechanically induced non-reciprocity is experimentally demonstrated for the first time. The underlying mechanism of the non-reciprocity demonstrated in this study is actually universal and can be generalized to any travelling wave resonators with a mechanical oscillator, such as an integrated disk-type microresonator coupled with a nanobeam. Given that higher cooperativity and cascading of the optical devices have been reported in a photonic integrated chip, optomechanically induced non-reciprocity has applications for integrated photonic isolators and circulators, which will play important roles in a hybrid quantum Internet.

**Methods**

Methods and any associated references are available in the online version of the paper.

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Author contributions
C.-H.D. and C.-L.Z conceived the experiments, Z.S., C.-H.D. and Y.C. prepared microsphere, built the experimental set-up and carried out measurements. Y.-L.Z and Z.S. performed the numerical simulation and analysed the data, Y.-F.X., X.-B.Z. and F.-W.S. provided theoretical support. C.-H.D. and C.-L.Z. wrote the manuscript with input from all co-authors. C.-H.D., C.-L.Z. and G.-C.G. supervised the project. All authors contributed extensively to the work presented in this Letter.

Additional information
Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to C.-L.Z. and C.-H.D.

Competing financial interests
The authors declare no competing financial interests.
Methods

Device and set-up. A silica microsphere was fabricated using a CO$_2$ laser. The tapered fibre was obtained by melting a standard SMF-28 silica fibre using a hydrogen flame. The silica microresonator and tapered fibre were kept in a clean chamber to avoid contamination. The high-quality-factor optical mode with very weak backscattering was chosen for the experiments, which were performed at room temperature. For more details, see Supplementary Information.

Measurement. To demonstrate the non-reciprocal effect, a signal field with a frequency $\omega_s$ excited the optical mode resonantly or near-resonantly. As shown schematically in Fig. 2a, the direction of the signal field is switchable by the double circulators, while the right-propagating driving laser is maintained. The signal was generated from the blue sideband of one weak laser beam, whose frequency was far away from that of the driving field. Optical emissions from the cavity mode, which are directly proportional to the respective intracavity intensity, were measured as a function of the detuning between the signal and weak laser frequency via a special heterodyne-detection technique. To avoid heating induced by the strong driving fields and to enable measurements of the behaviour of the mechanical mode, we used 18 $\mu$s driving and signal pulses. The shift in the cavity resonance induced by the Kerr effect can be compensated by changing the locking frequency. To probe the transient behaviour, emission spectra and the phase response were obtained via time-gated detection through the network analyser with a resolution bandwidth of 1 MHz and gate delay time of 16.5 $\mu$s. For more details on these processes see Supplementary Information.