LETTER

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Nonreciprocal control and cooling of phonon modes in an optomechanical system

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Mechanical resonators are important components of devices that range from gravitational wave detectors to cellular telephones. They serve as high-performance transducers, sensors and filters by offering low dissipation, tunable coupling to diverse physical systems, and compatibility with a wide range of frequencies, materials and fabrication processes. Systems of mechanical resonators typically obey reciprocity, which ensures that the phonon transmission coefficient between any two resonators is independent of the direction of transmission[1,2]. Reciprocity must be broken to realize devices (such as isolators and circulators) that provide one-way propagation of acoustic energy between resonators. Such devices are crucial for protecting active elements, mitigating noise and operating full-duplex transceivers. Until now, nonreciprocal phononic devices[3–11] have not simultaneously combined the features necessary for robust operation: strong nonreciprocity, in situ tunability, compact integration and continuous operation. Furthermore, they have been applied only to coherent signals (rather than fluctuations or noise), and have been realized exclusively in travelling-wave systems (rather than resonators). Here we describe a scheme that uses the standard cavity-optomechanical interaction to produce robust nonreciprocal coupling between phononic resonators. This scheme provides about 30 decibels of isolation in continuous operation and can be tuned in situ simply via the phases of the drive tones applied to the cavity. In addition, by directly monitoring the dynamics of the resonators we show that this nonreciprocity can control thermal fluctuations, and that this control represents a way to cool phononic resonators.

Jinuk Kim

Journal Club 2019-06-04

Jack Harris

Biography

2000: PhD, UC Santa Barbara

(Thesis : High Sensitivity Magnetization Studies of Semiconductor Heterostructures)

2001-2004: Postdoctoral Researcher(Wolfgang Ketterle group)

2001- : Professor at Yale, Departments of physics and applied physics.

Research interest

Optomechanics

Persistent Current

https://harrislab.yale.edu/sites/default/files/files/CV17.pdf

Persistent Currents in Normal Metal Rings

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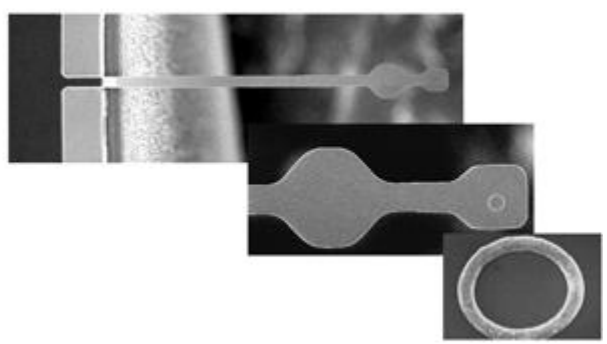
Quantum mechanics predicts that the equilibrium state of a resistive metal ring will contain a dissipationless current. This persistent current has been the focus of considerable theoretical and experimental work, but its basic properties remain a topic of controversy. The main experimental challenges in studying persistent currents have been the small signals they produce and their exceptional sensitivity to their environment. We have developed a technique for detecting persistent currents that allows us to measure the persistent current in metal rings over a wide range of temperatures, ring sizes, and magnetic fields. Measurements of both a single ring and arrays of rings agree well with calculations based on a model of non-interacting electrons.



PHYSICAL REVIEW LETTERS **122**, 153601 (2019)

Editors' Suggestion Featured in Physics

Quantum Optomechanics in a Liquid

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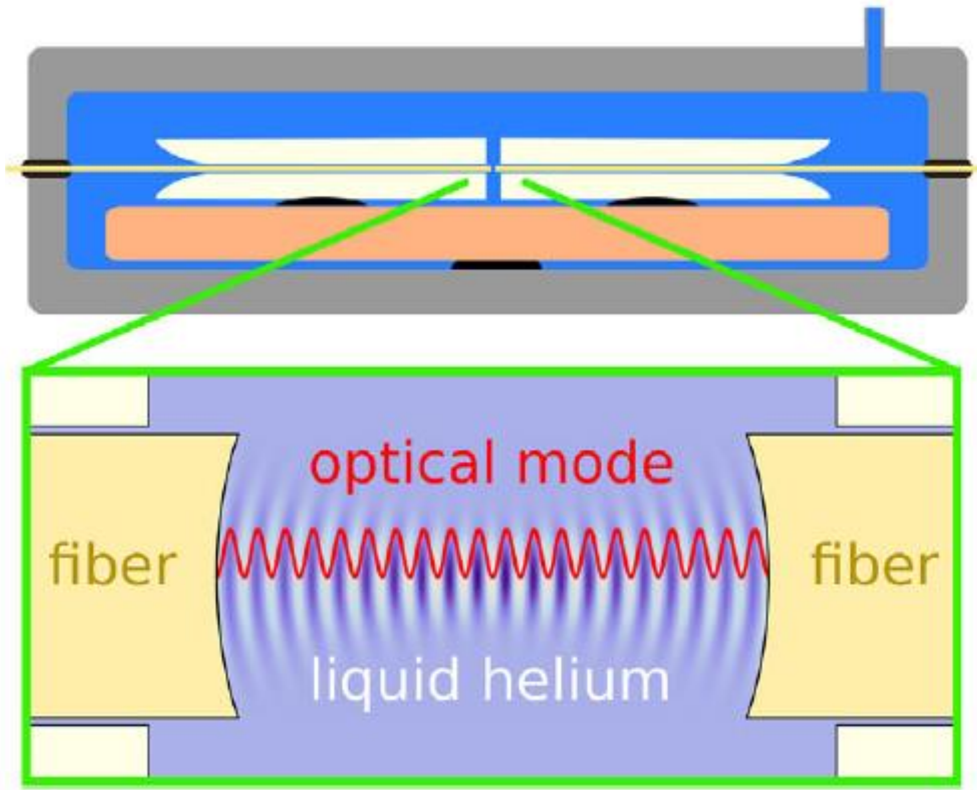
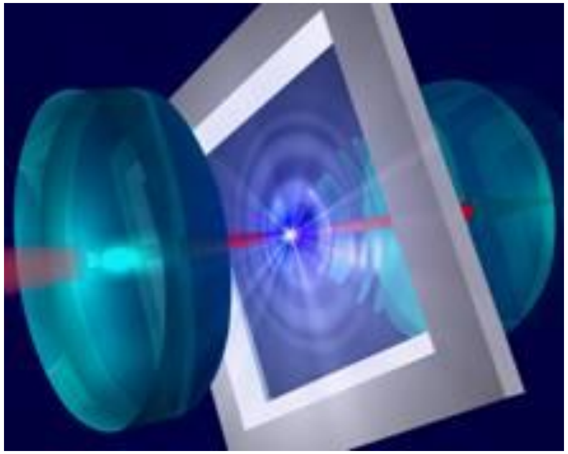


Optomechanics with micro-membrane



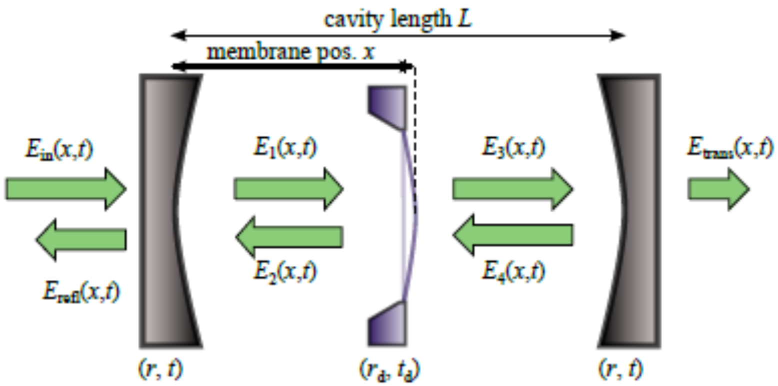
- Radiation pressure in the quantum engine
- Optical control of microstructures
- Mechanical control of non-classical light

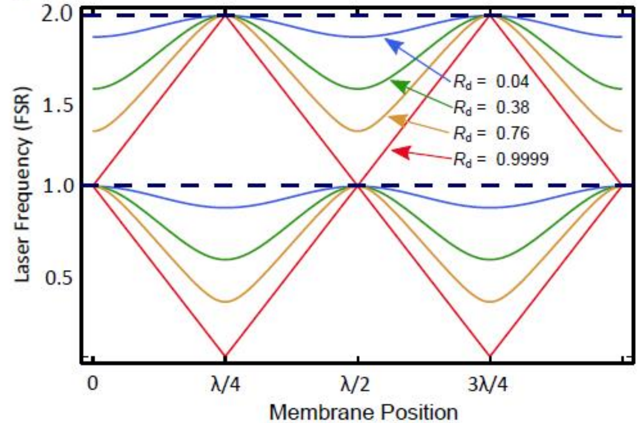
Si_3N_4 membrane

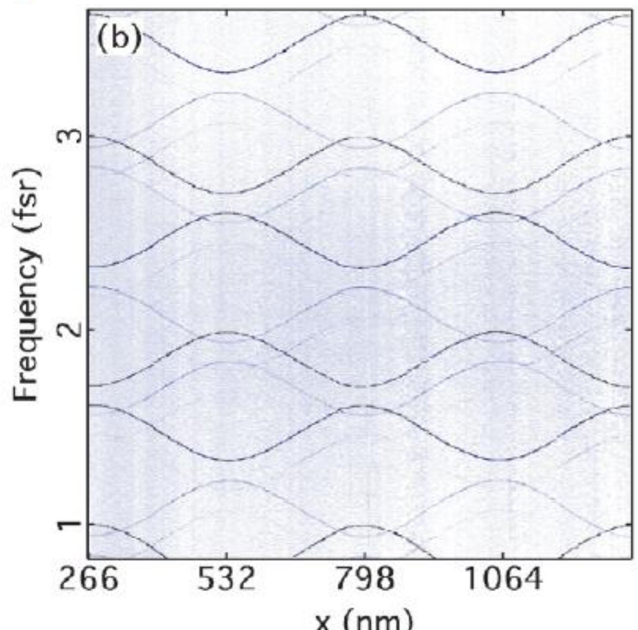
1mm square, 50nm thick

https://harrislab.yale.edu/gallery/photo-gallery-0

Dispersion by membrane







- Resonance frequency shift

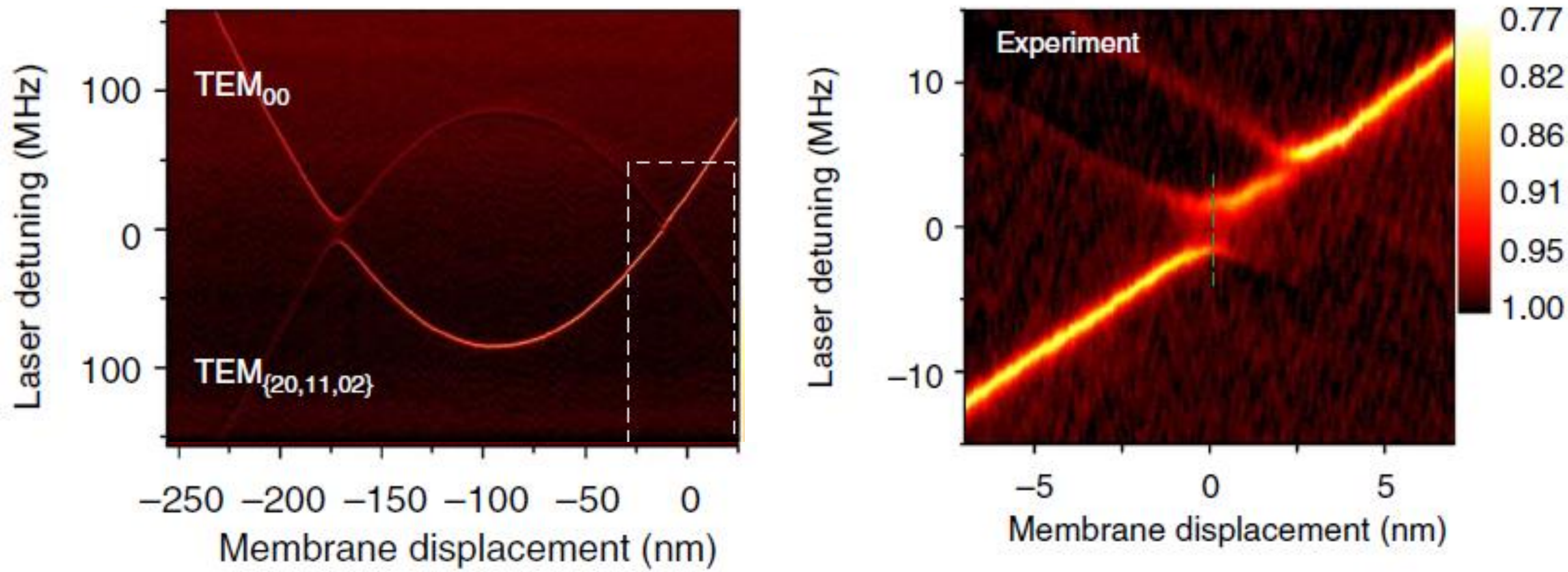
$$\Delta\omega = \frac{c}{2L}\left[2\arg(r_d) \ + 2\cos^{-1}\left(|r_d|\cos\left(\frac{2\pi}{\lambda\,/\,2}x\right)\right)\right]$$

r_d : reflection coefficient of the membrane
x : position of the membrane

B. M. Zwickl, Doctoral dissertation (2011)

NJP, 10, 095008 (2008)

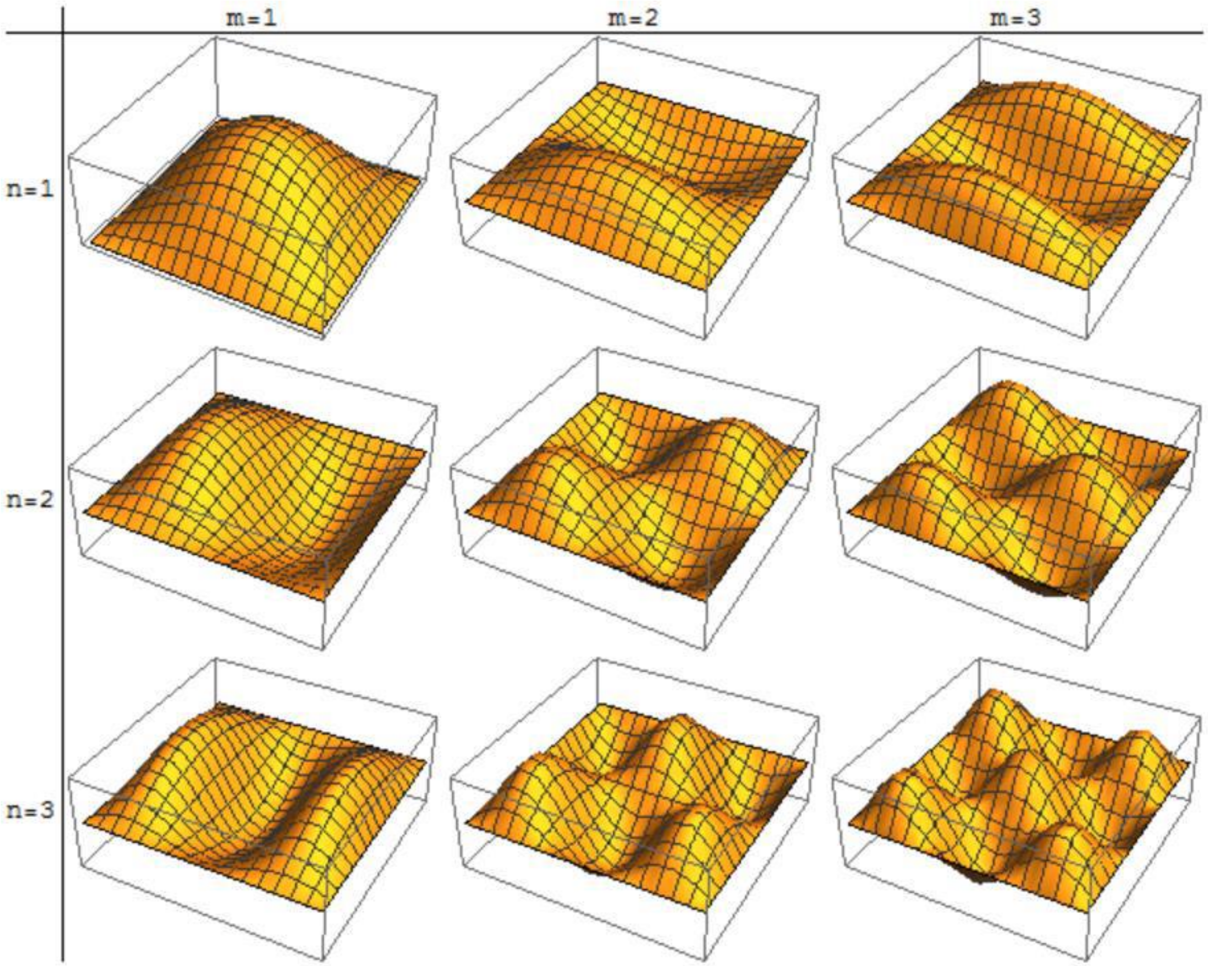
Avoided crossing of cavitymodes



- Interaction mediated by membrane
- The mechanical oscillator's Brownian motion is minimized by operating the device at 500mK

Nat. Commun. 6, 6232 (2015)

Fundamental modes of the membrane



M. J. Underwood, Doctoral dissertation (2016)

Model Hamiltonian

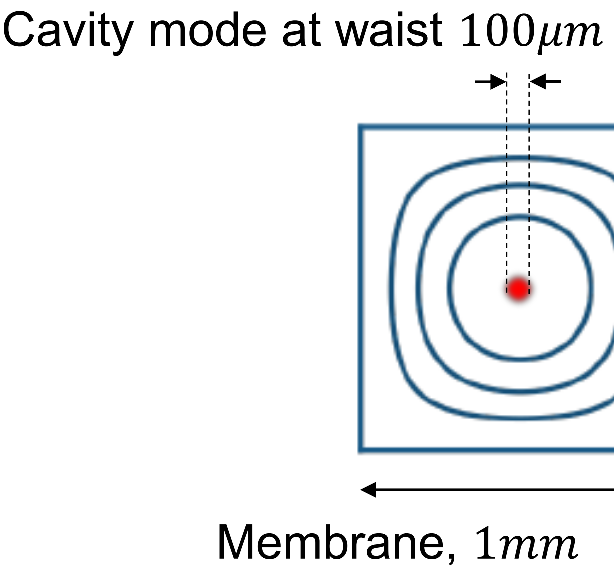
- Optomechanical hamiltonian

$$\hat{H} = \hbar\omega_M \hat{c}^\dagger \hat{c} + \hbar(\omega_c + Ax)\hat{a}^\dagger \hat{a}$$

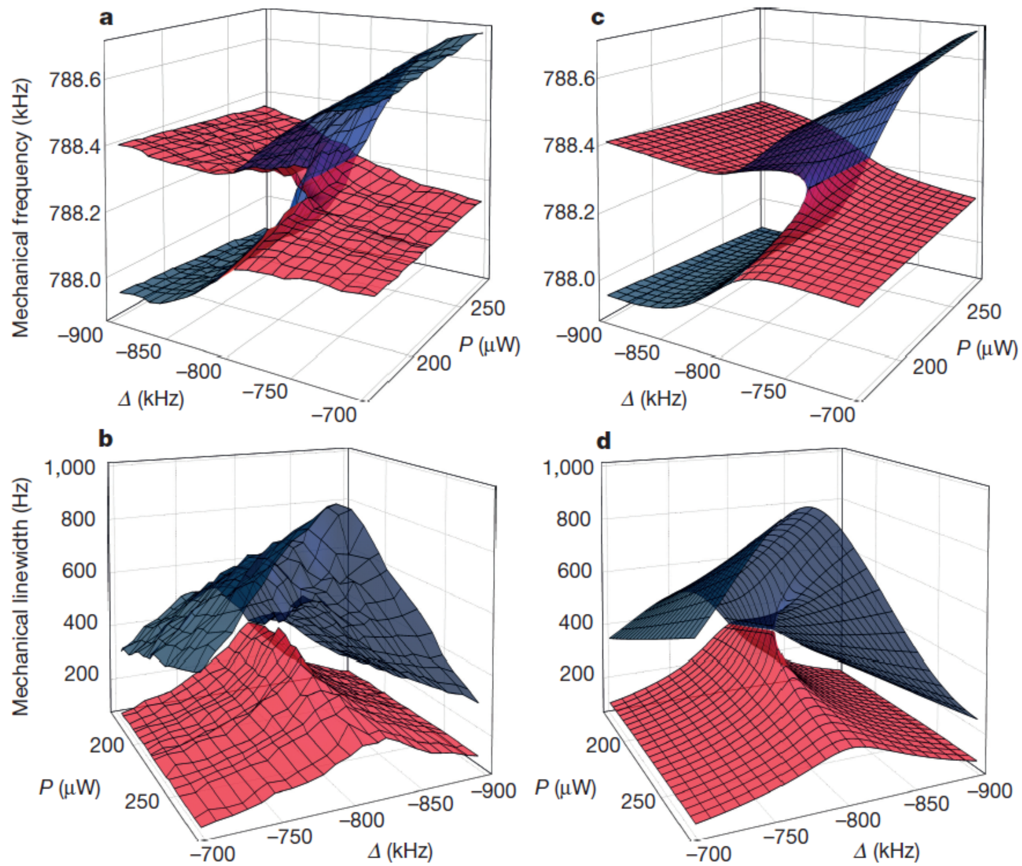
$$A \equiv \frac{d\Delta\omega}{dx} \qquad \Delta\omega = \frac{c}{2L}\left[2\arg(r_d) \; + 2\cos^{-1}\left(|r_d|\cos\left(\frac{2\pi}{\lambda\,/\,2}x\right)\right)\right]$$

$$\rightarrow \; \hat{H} \simeq \hbar\omega_M \hat{c}^\dagger \hat{c} + \hbar(\omega_c + A\hat{x})\hat{a}^\dagger \hat{a}$$

$$= \hbar\omega_M \hat{c}^\dagger \hat{c} + \hbar\big(\omega_c + A(\hat{c} + \hat{c}^\dagger)\big)\hat{a}^\dagger \hat{a}$$



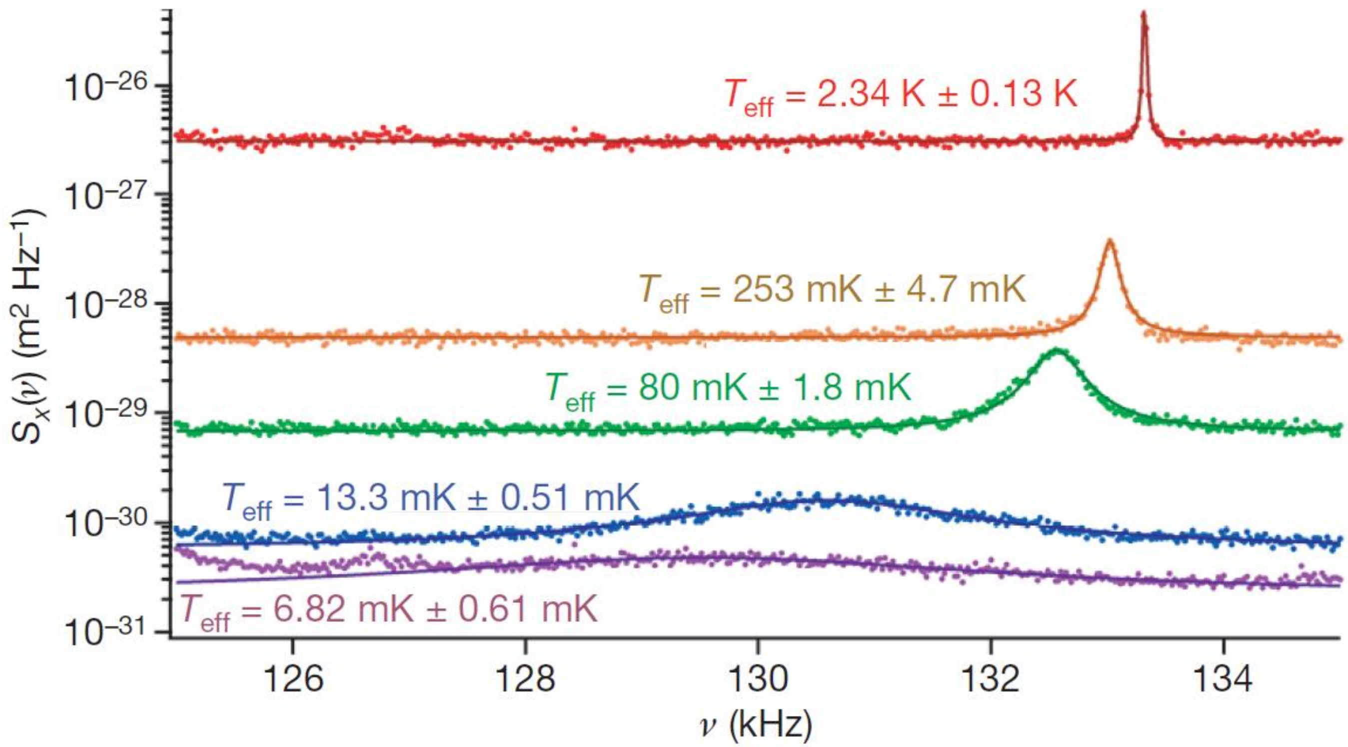
Avoided crossing of vibrational state



- Interaction mediated by photon
- An exceptional point of mechanical modes is observed

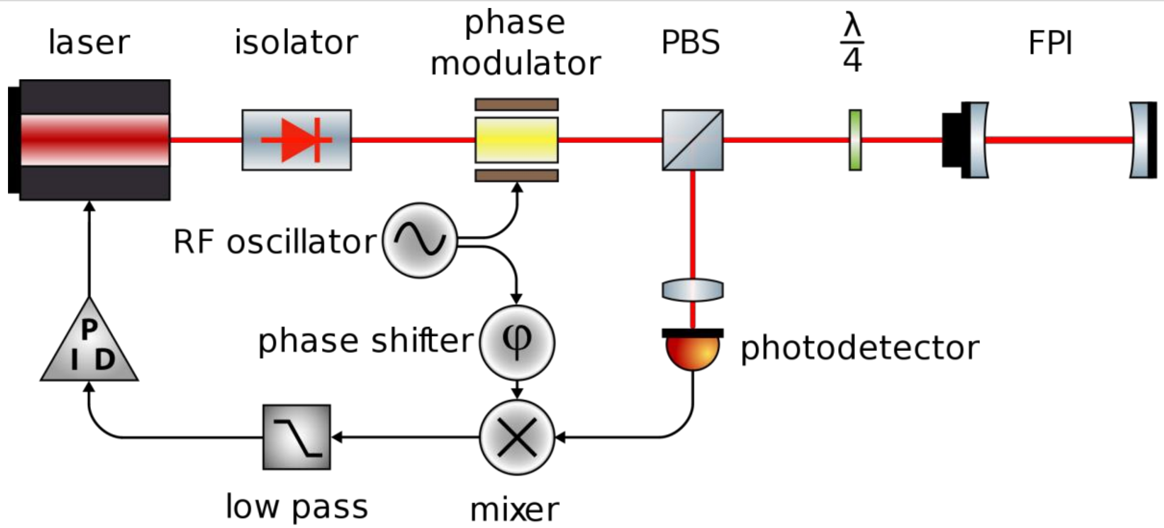
Nature 537 80 (2016)

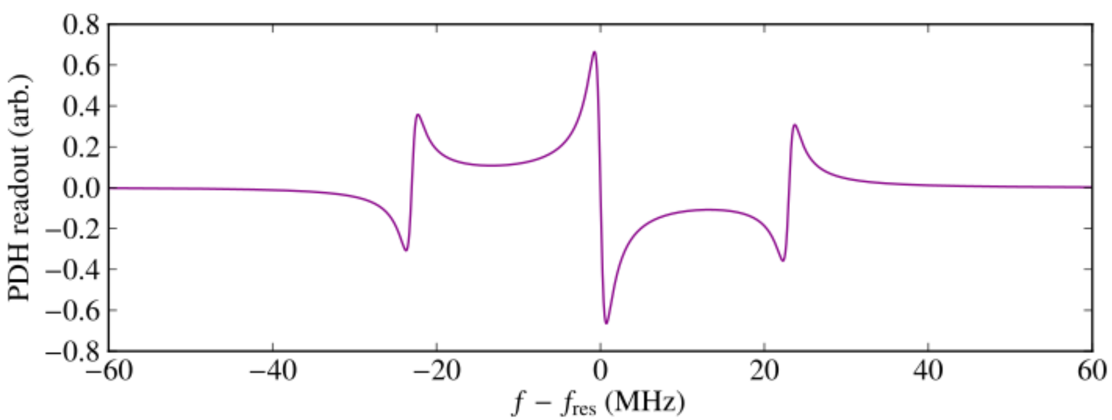
Laser cooling of the membrane



Nature 452, 72 (2008)

Pound-Drever-Hall locking

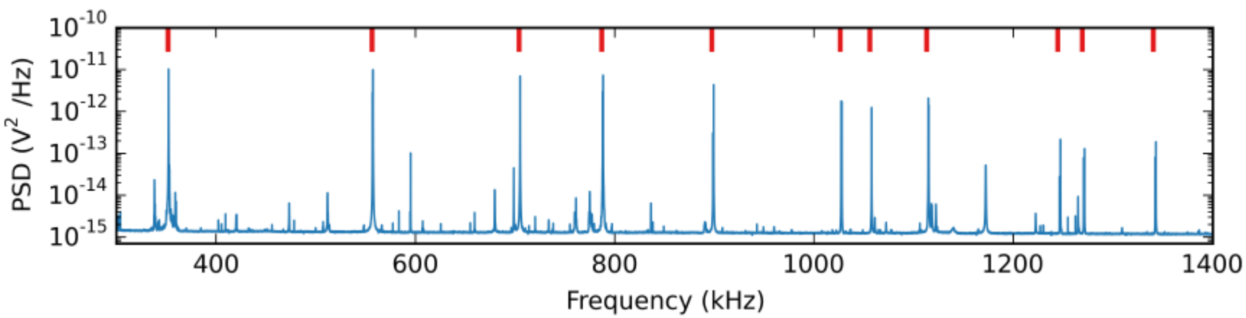


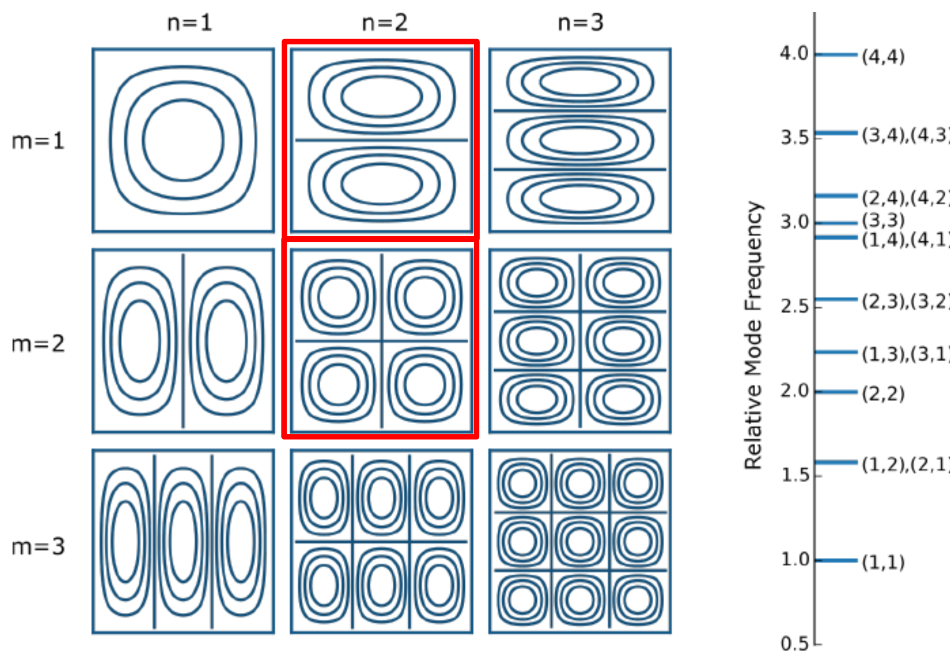


- Relative resonance frequency of the cavity modes can be measured by PDH technique
- Vibration of the membrane is recorded in the PDH signal

https://en.wikipedia.org/wiki/Pound%E2%80%93Drever%E2%80%93Hall_technique

Vibration of membrane





- Power spectral density of Brownian motion is obtained from PDH signal

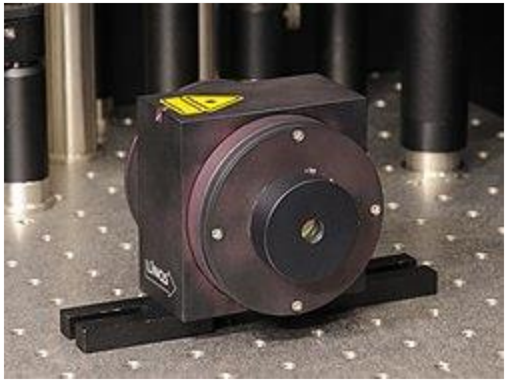
D. R. Mason, Doctoral dissertaion (2018)

Non-reciprocity

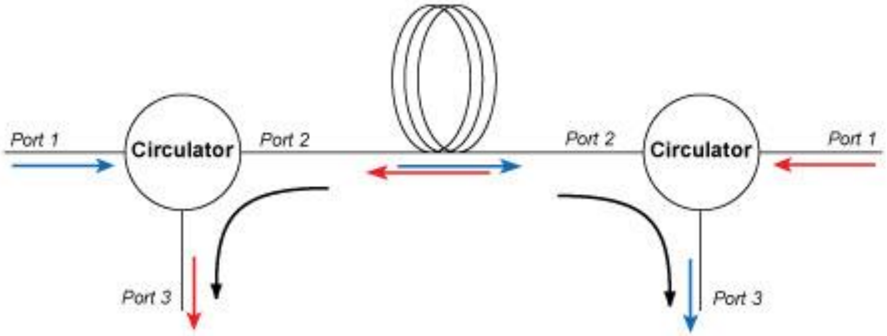
https://www.dictionary.com/browse/non-reciprocal

Non-reciprocity

- *non-reciprocal* optics



Optical isolator



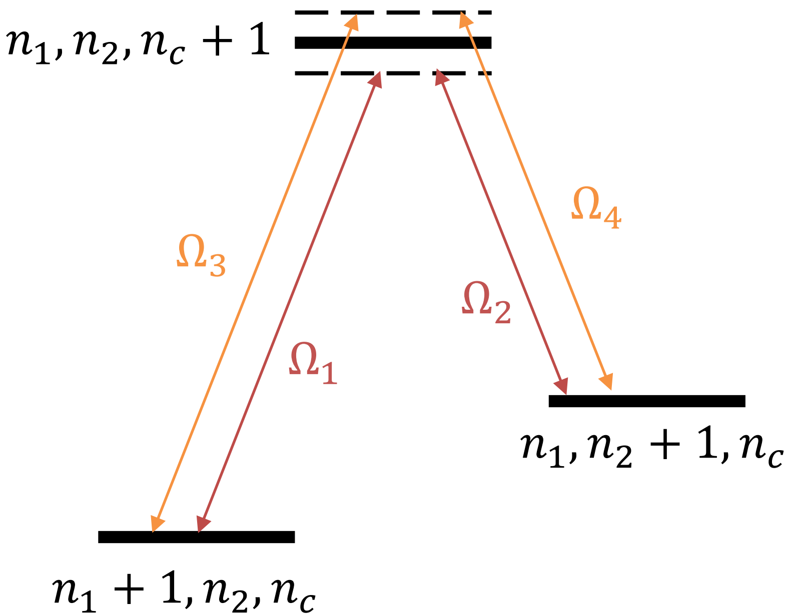
Optical circulator

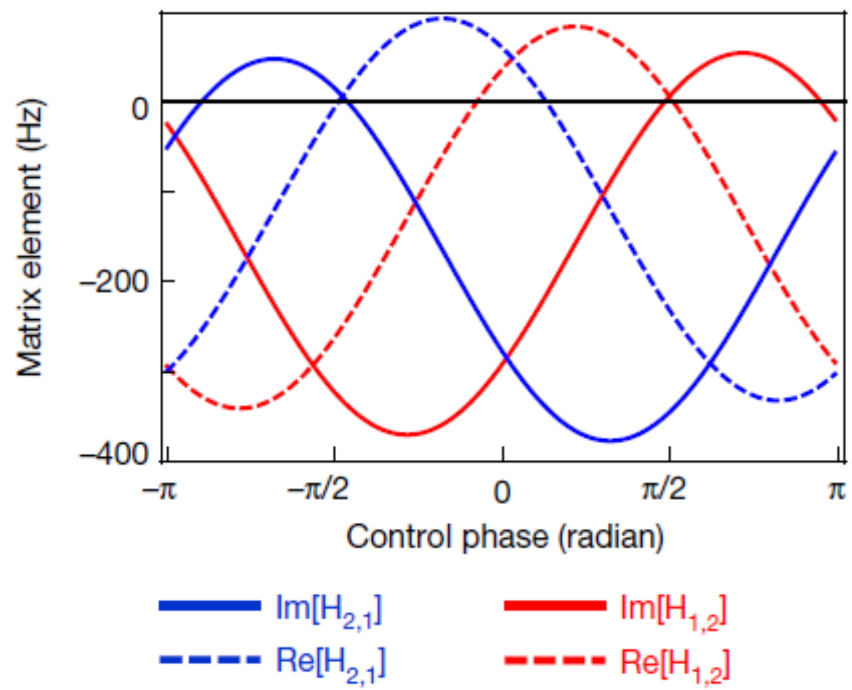
Changes in the properties of light passing through the device are not rever sed when the light passes through in the opposite direction.

$$\hat{H}/\hbar = \begin{pmatrix} \omega_1 & g_1 \\ 0 & \omega_2 \end{pmatrix}$$

https://www.dictionary.com/browse/non-reciprocal

Optically induced non-reciprocity



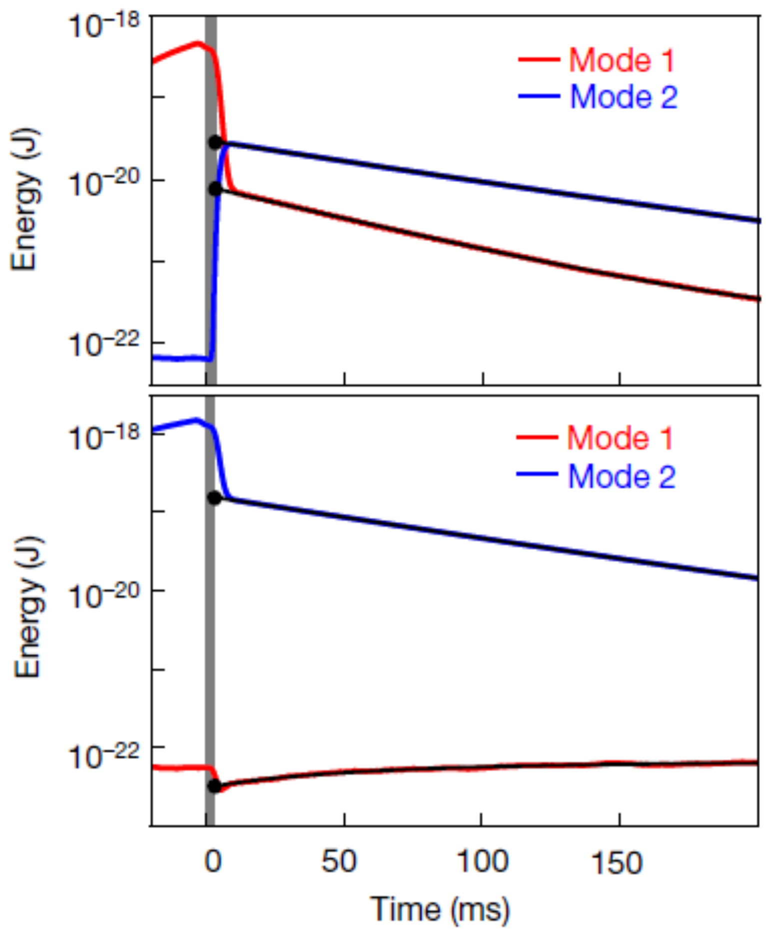


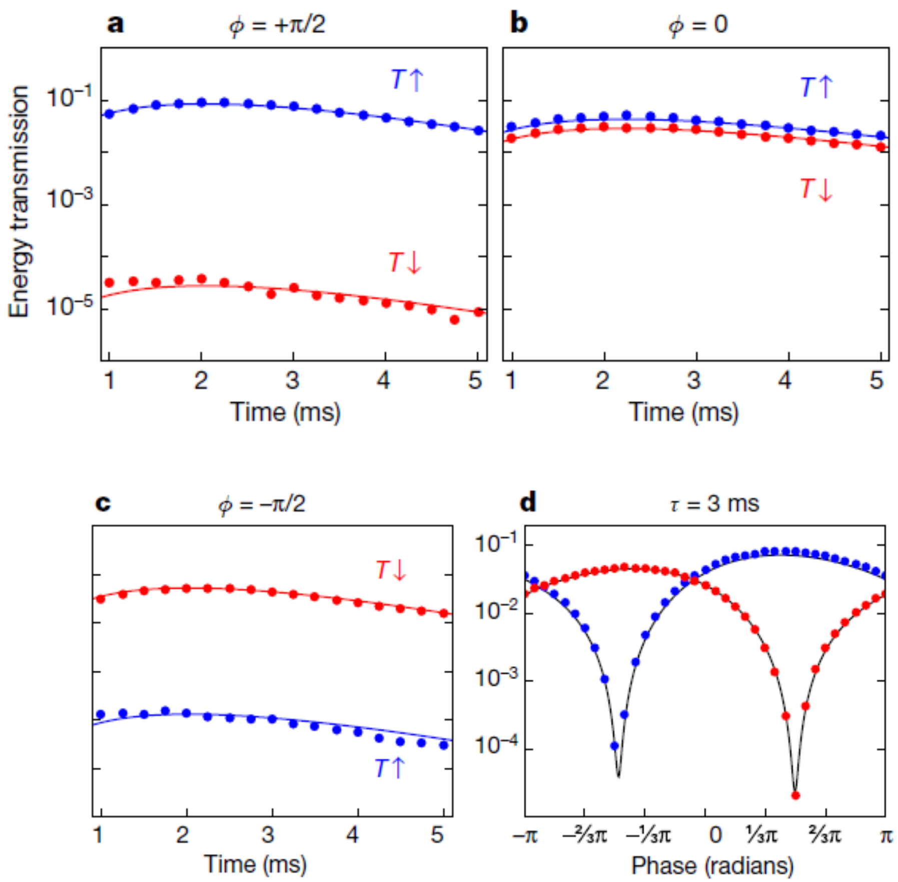
$$\hat{H}/\hbar = \begin{pmatrix} \omega_1 & H_{1,2} \\ H_{2,1} & \omega_2 \end{pmatrix}$$

n_1 , n_2: number of phonon

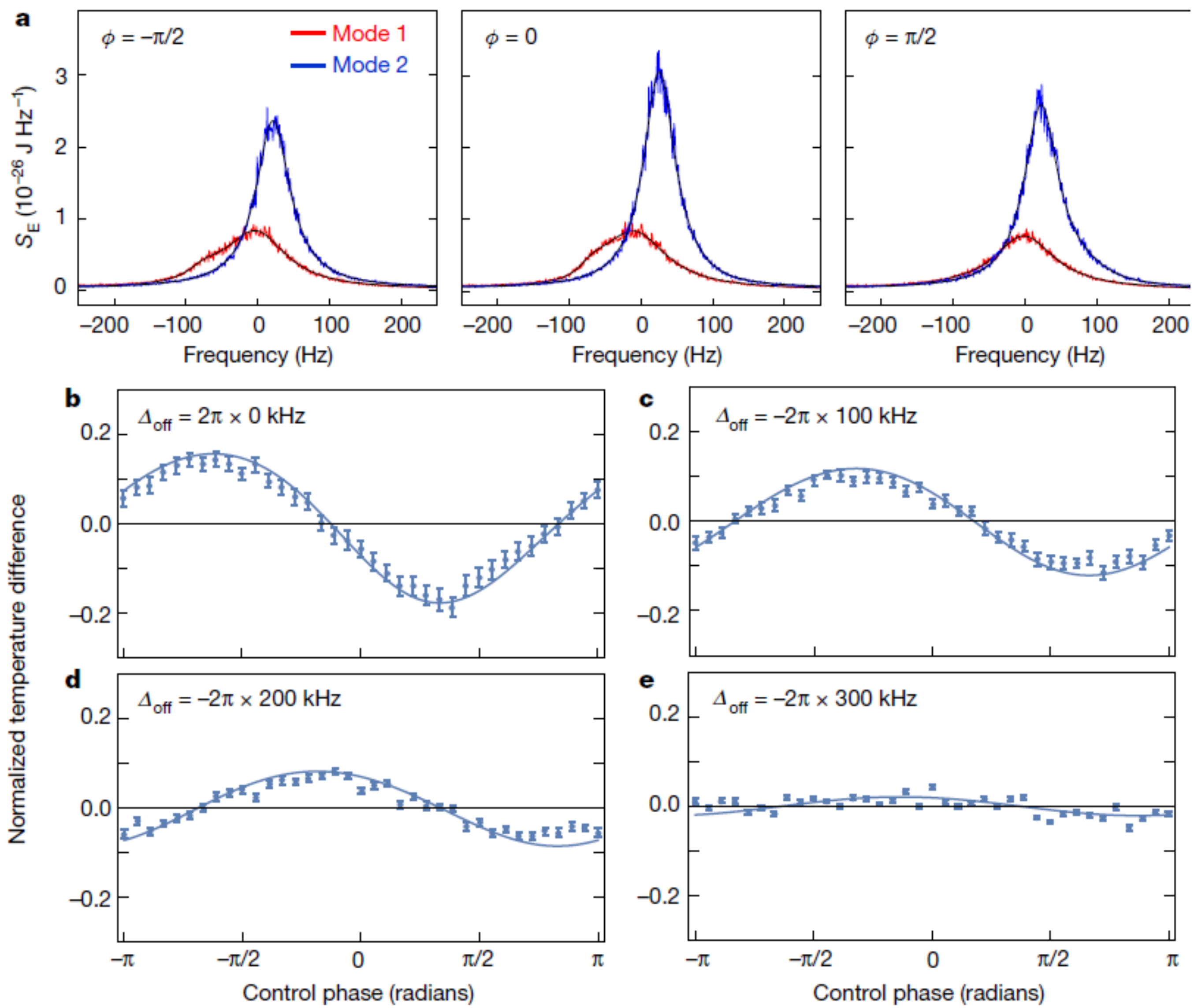
n_c : number of photon in the cavity

Optically induced non-reciprocity





Cooling by non-reciprocity



Supplementary Material

Real temperature