Workshop on Quantum Simulations and Quantum Devices 2019

Non-reciprocity in a multi-mode optomechanical microcavity

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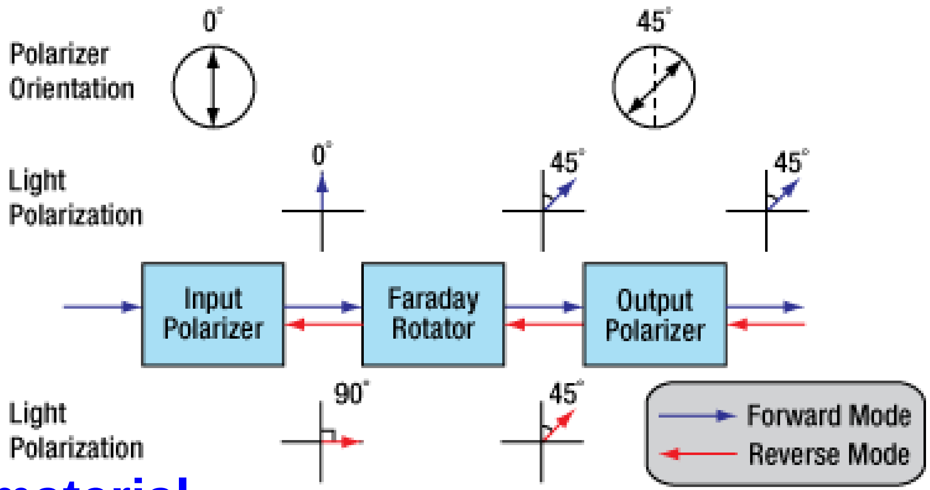
2019-11-23, Beijing

Outline

- **Introduction:**
  - **Non-reciprocity**
- **Experiment results:**
  - **Optomechanically induced Non-reciprocity**
  - **Isolator & Circulator & Directional amplifier**
  - **Synthetic magnetic field**
- **Summary**

Non-reciprocity

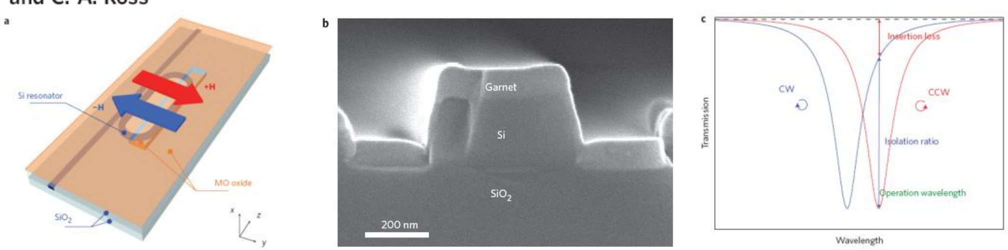


Isolator with magnetic material

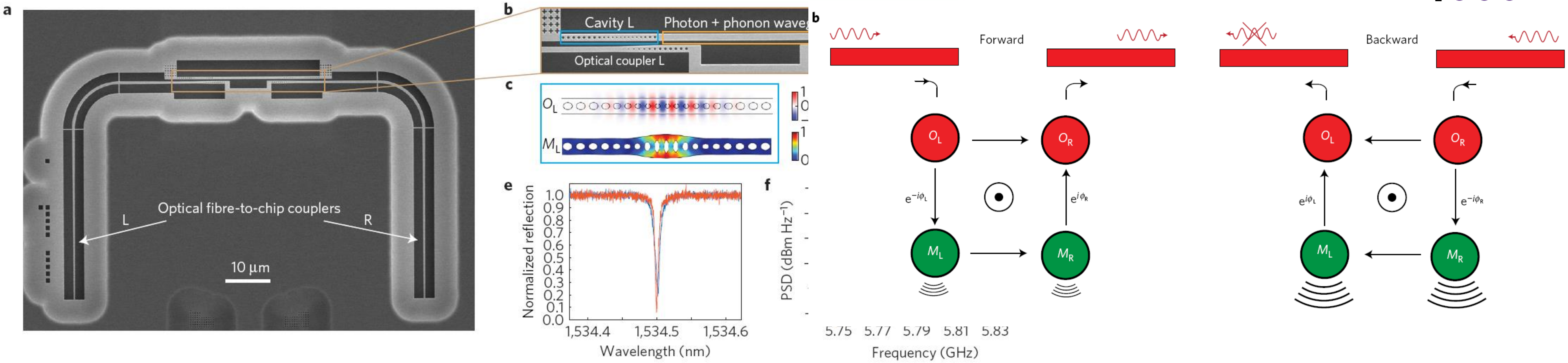
LETTERS
PUBLISHED ONLINE: 13 NOVEMBER 2011 | DOI: 10.1038/NPHOTON.2011.270
nature photonics

On-chip optical isolation in monolithically integrated non-reciprocal optical resonators

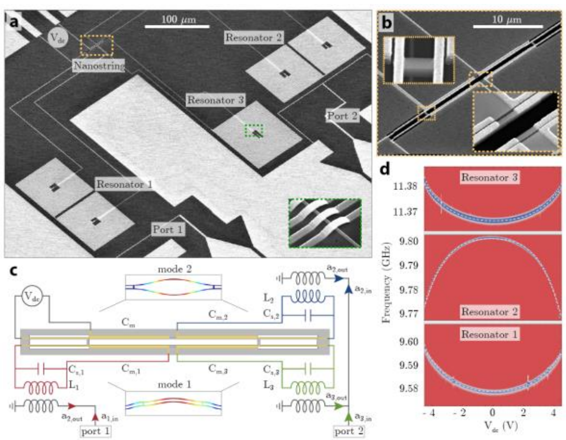
Lei Bi[1]*, Juejun Hu[2], Peng Jiang[1], Dong Hun Kim[1], Gerald F. Dionne[1], Lionel C. Kimerling[1] and C. A. Ross[1]*

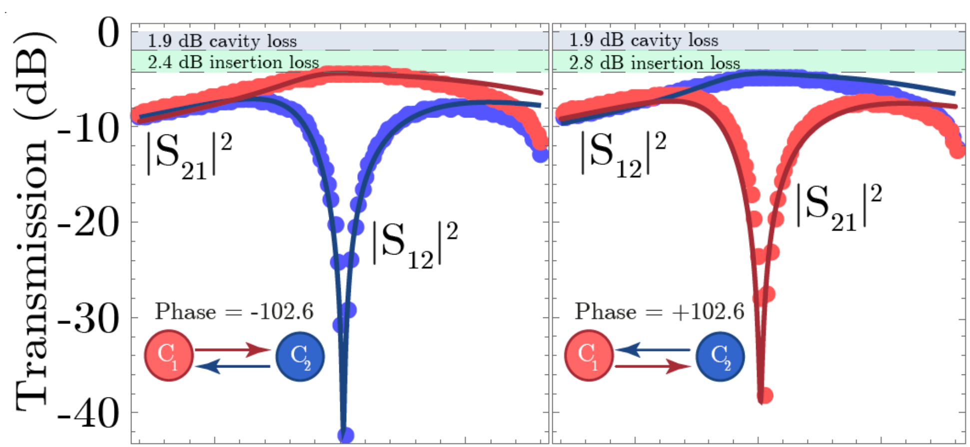


Non-reciprocity



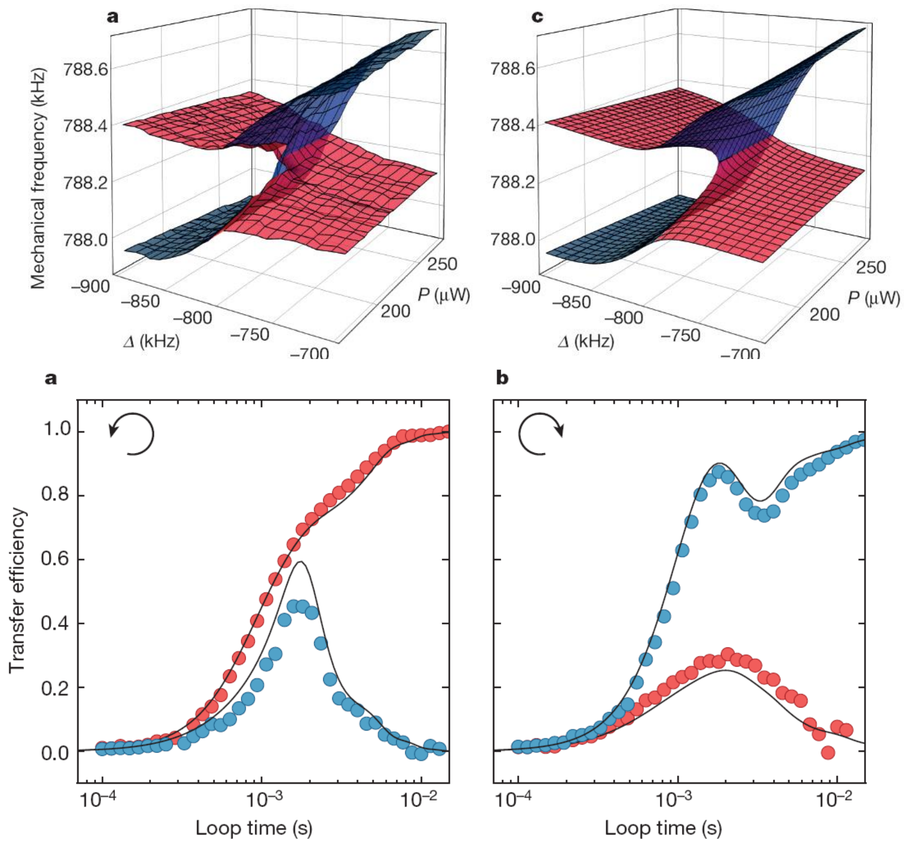
Fang, K. et al. Nature physics (2016).





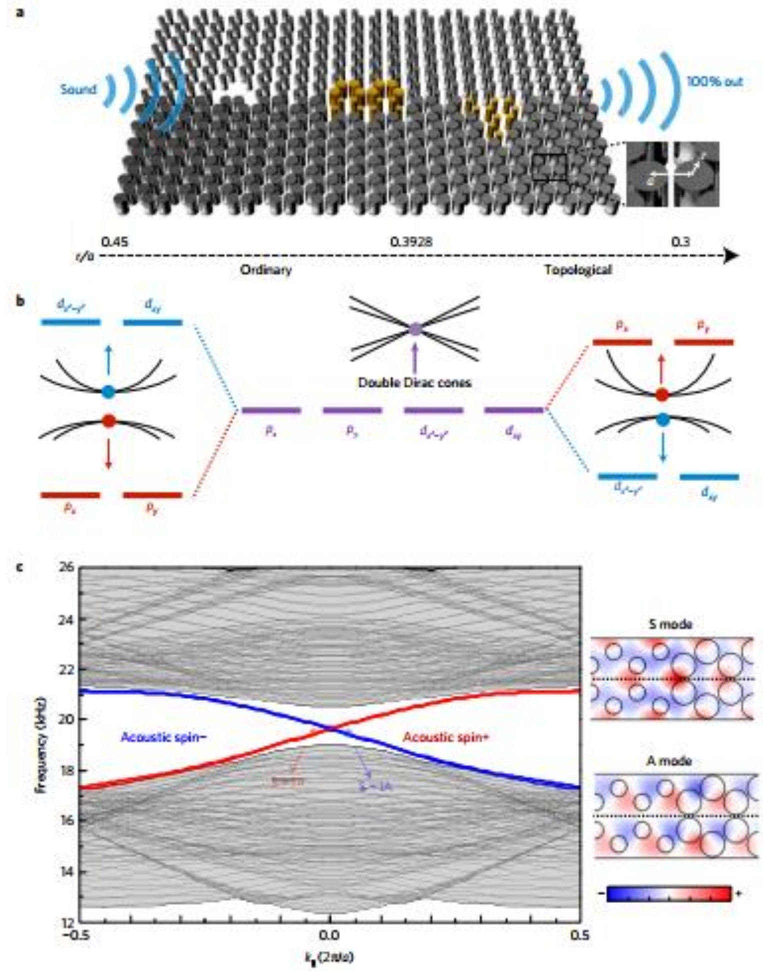
S. Barzanjeh et al, Nature Communications (2017).

Non-reciprocity



Topological operations

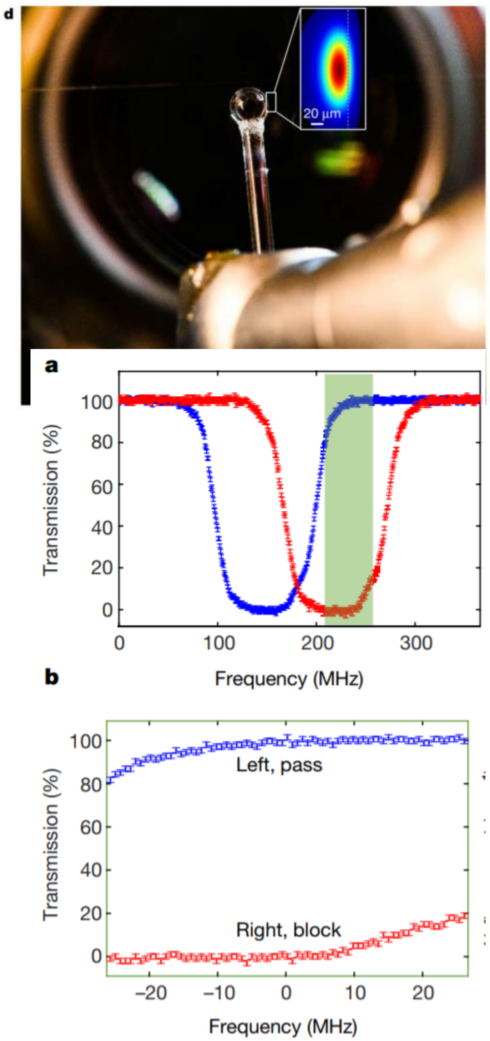
H. Xu et al, Nature (2016).



Acoustic Topological insulator

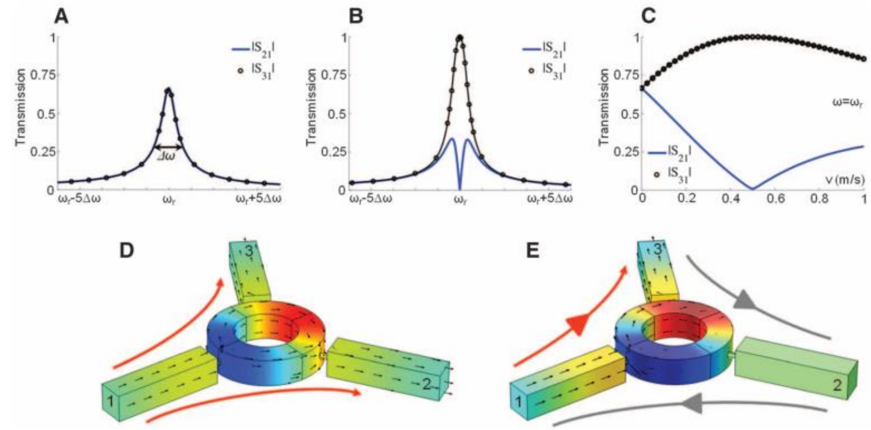
C. He et al, Nature Physics (2016).

Non-reciprocity

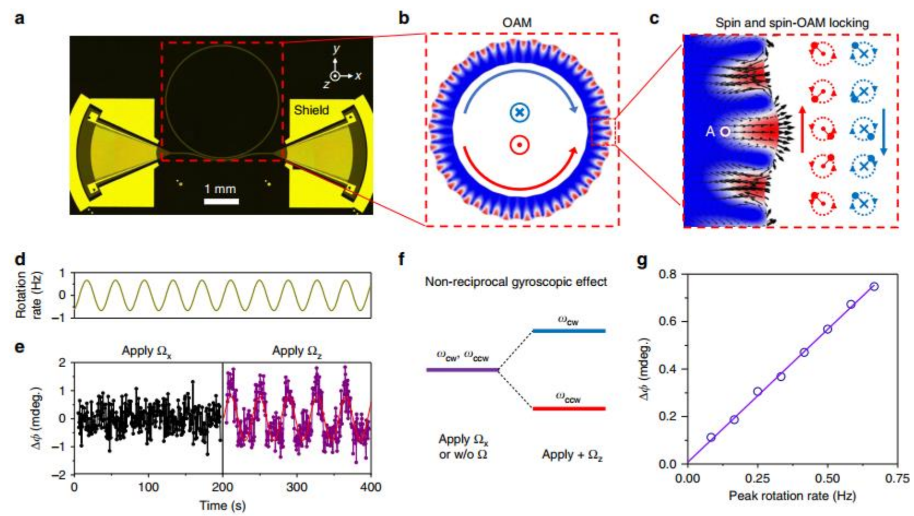


Spinning Microresonator

S. Maayani et al. Nature (2018).

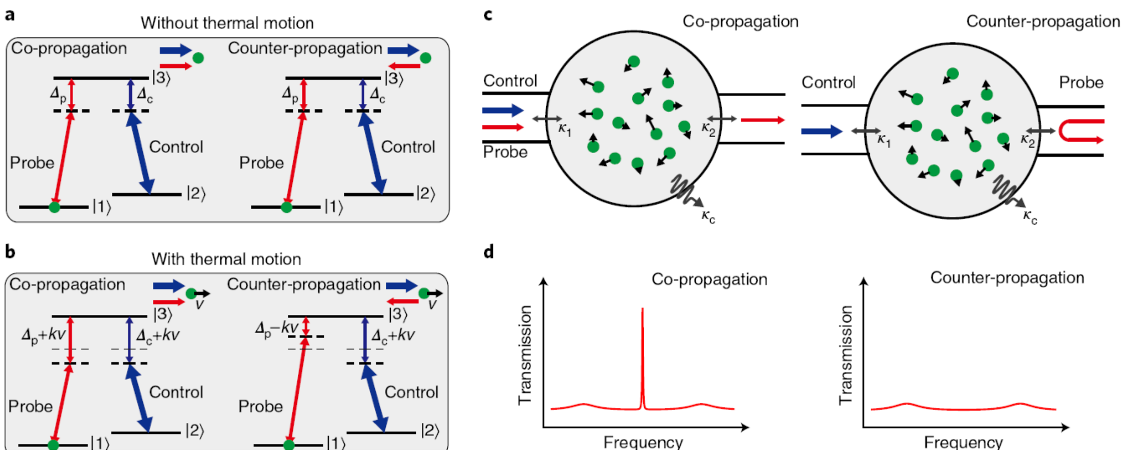


Science **343**, 516-519 (2014).



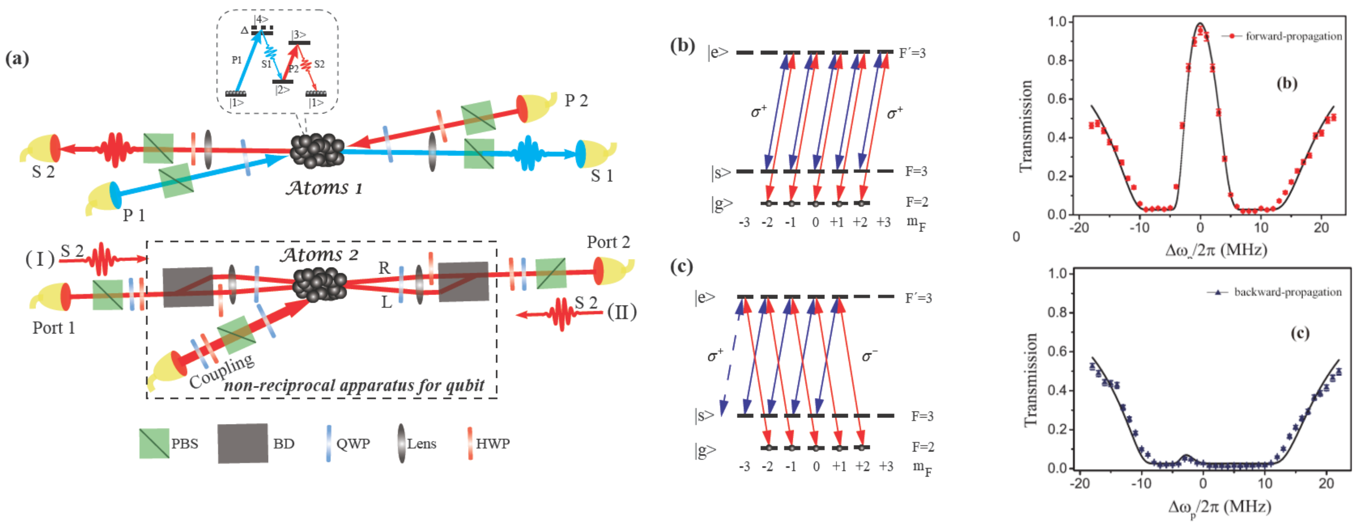
Nature Commutations **10**, 2743 (2019)

Non-reciprocity



Nature Photonics (2018).

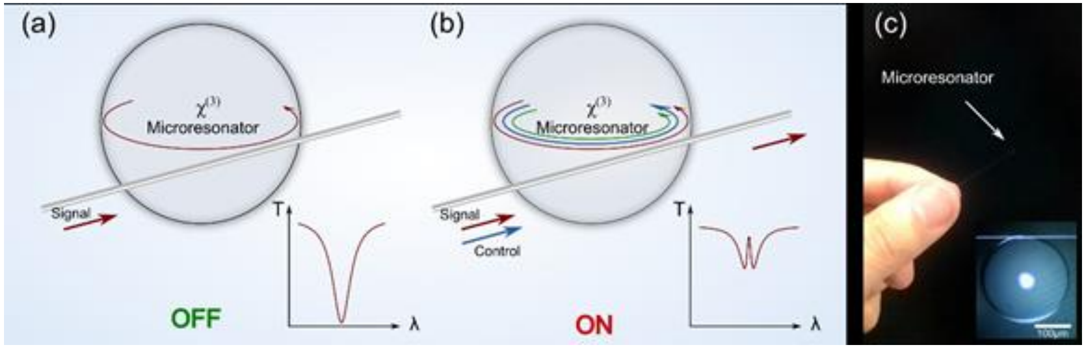
Thermal-motion-induced non-reciprocal quantum optical system



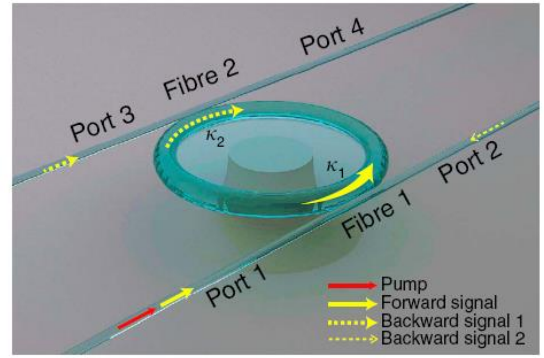
arXiv: 1908.09242v1 (2019).

Quantum non-reciprocity based on cold atomic ensembles

Non-reciprocity



Light: Science & Applications [5, e16072 (2016)].

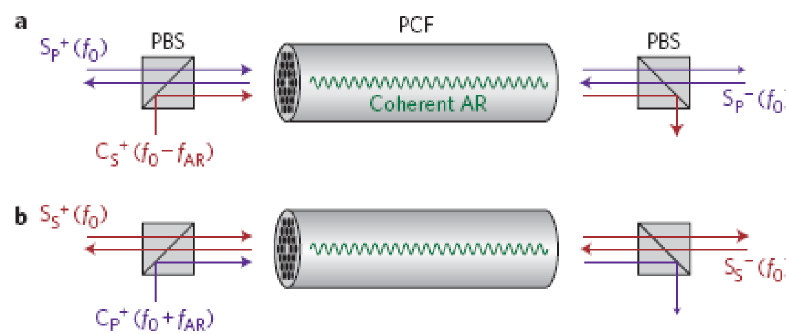


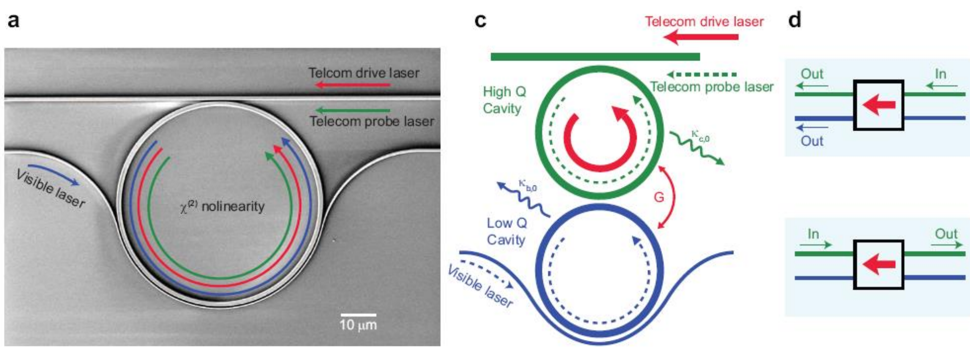
X. Jiang, et al, Nature Communications (2016).

nature photonics | ARTICLES
PUBLISHED ONLINE: 14 AUGUST 2011 | DOI: 10.1038/NPHOTON.2011.180

Reconfigurable light-driven opto-acoustic isolators in photonic crystal fibre

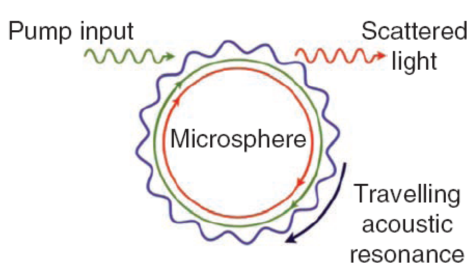
M. S. Kang*, A. Butsch and P. St. J. Russell

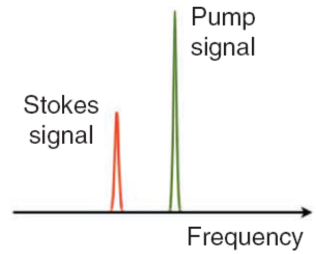


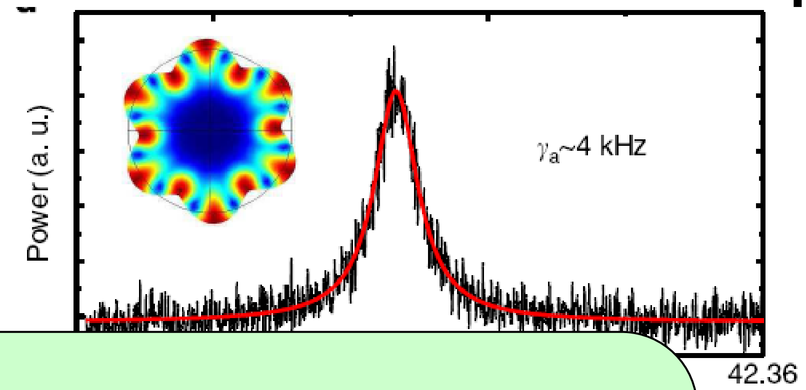


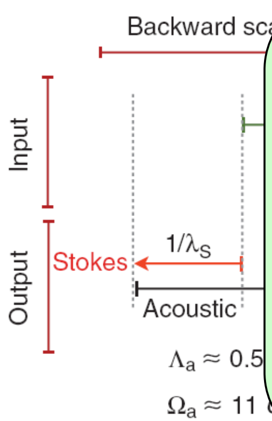
X. Guo, C. Zou, H. Jung, H. Tang, **Physical Review Letters** 117, 123902 (2016).

Non-reciprocal Brillouin scattering induced transparency

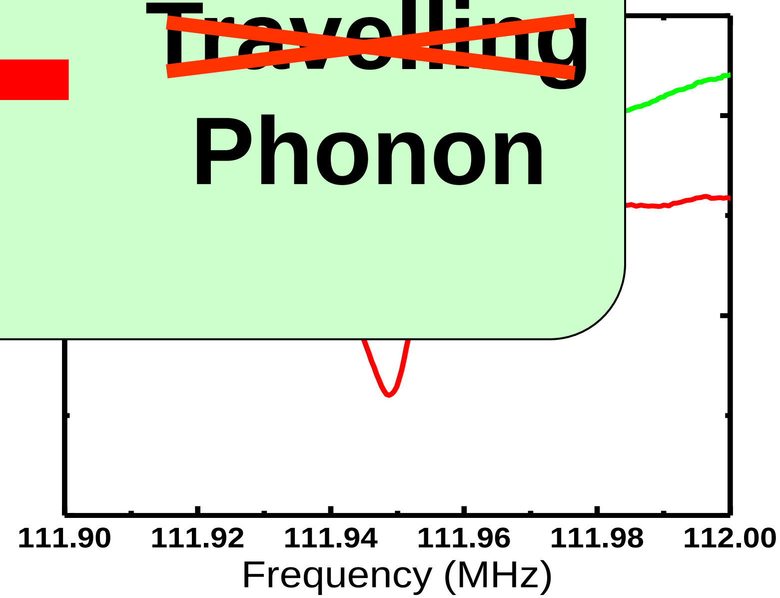








Resonator Travelling Photon + ~~**Travelling**~~ **Phonon**

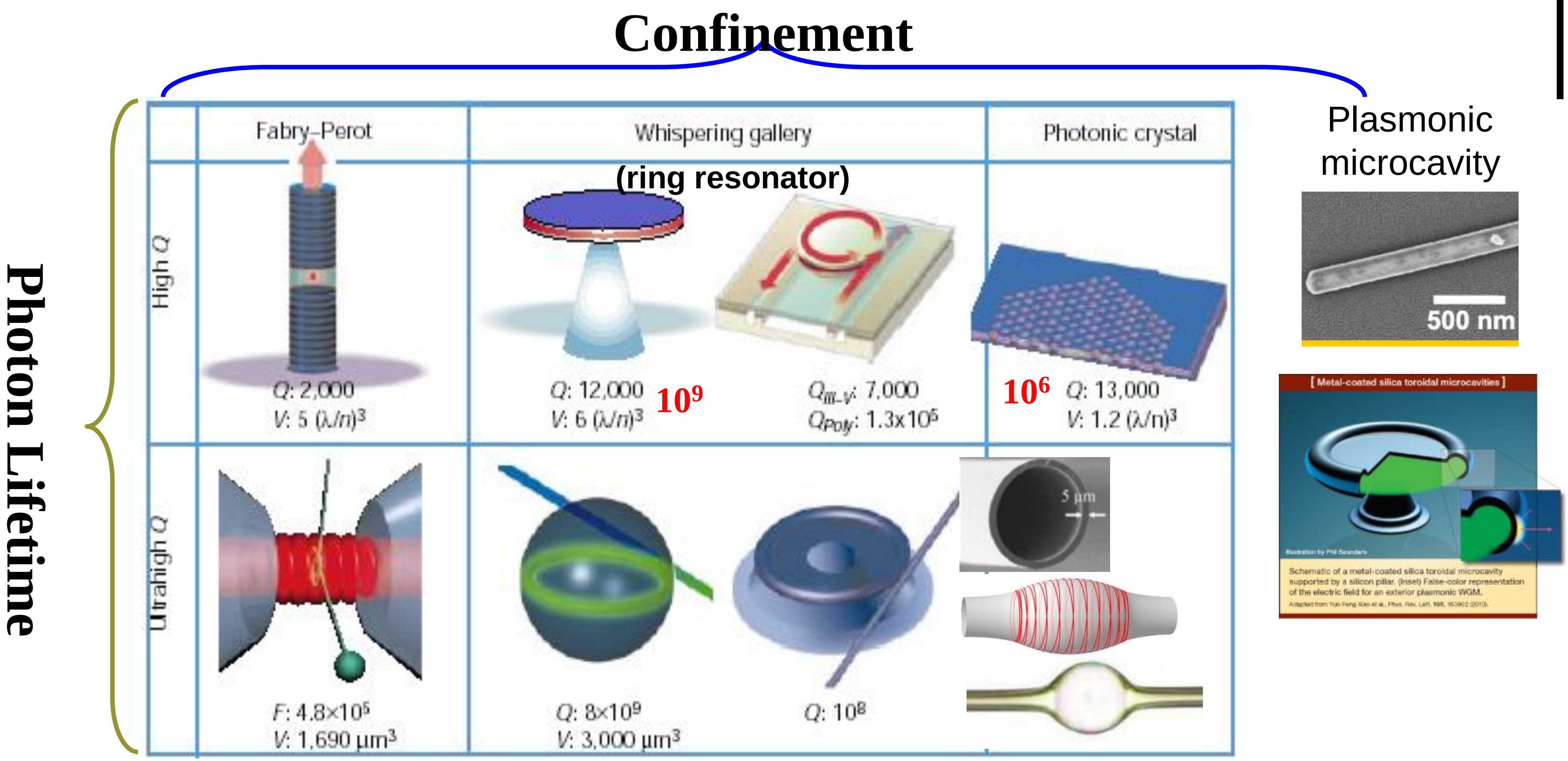


- *Energy match*
- *Momentum match*

C.-H. Dong, et al, Nature Communications **6**, 6193 (2015).

J. Kim, et al Nat. Phys. **11**, 275 (2015).

Optical microcavity – an important platform



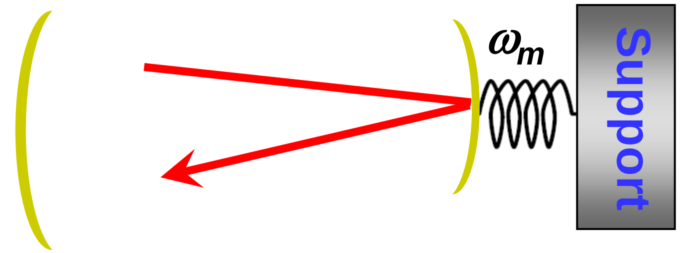
1. FP-type microcavity
2. Whispering gallery microcavity
3. Photonic crystal microcavity
4. Plasmonic microcavity

K. J. Vahala Nature ***424****, 839*

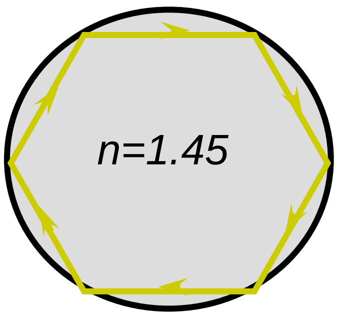
Ultrahigh Q, very small V

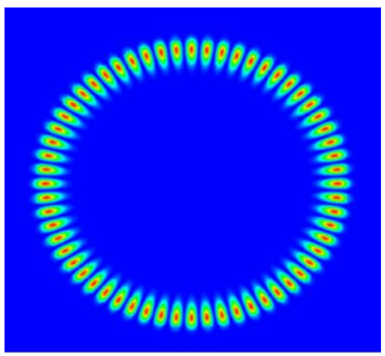
Cavity Optomechanics

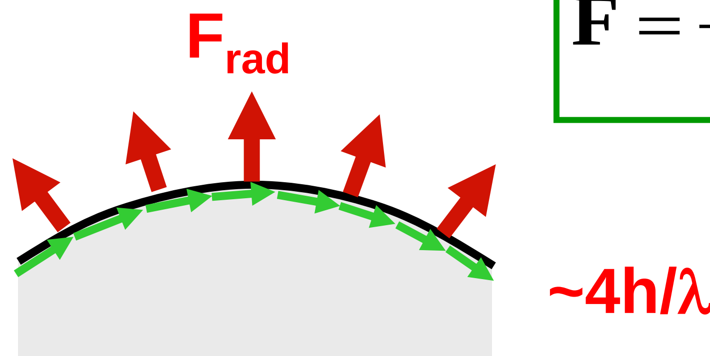
A laser beam of 1 *Watt* generates a radiation pressure force about a few *nano-Newtons*.



$$\mathbf{F} = \frac{d\mathbf{p}}{dt}$$



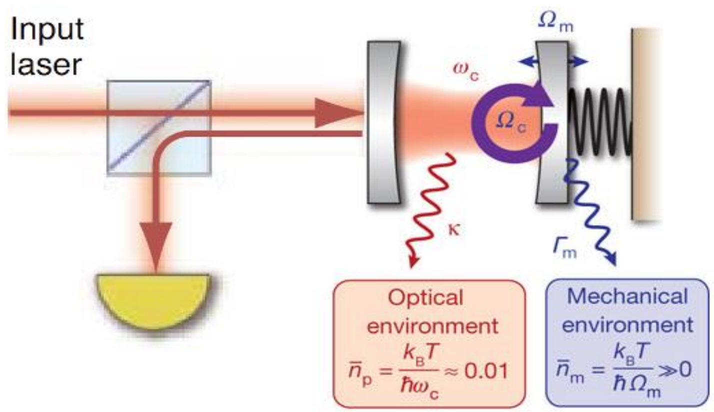


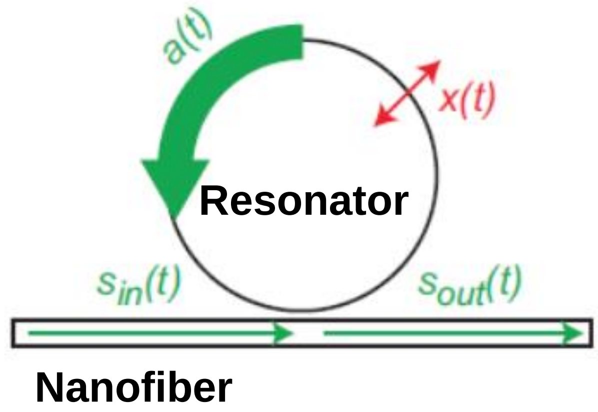


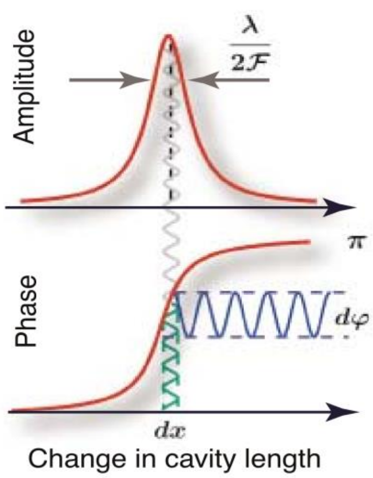
Q~10^8, τ~50ns, Round ~10^5

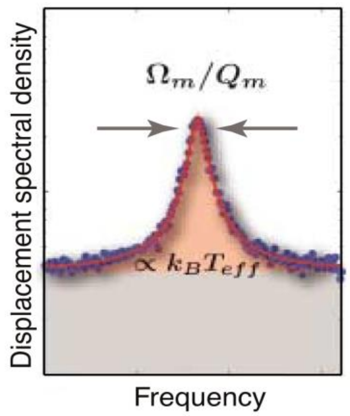
Cavity enhanced radiation pressure

Cavity Optomechanics



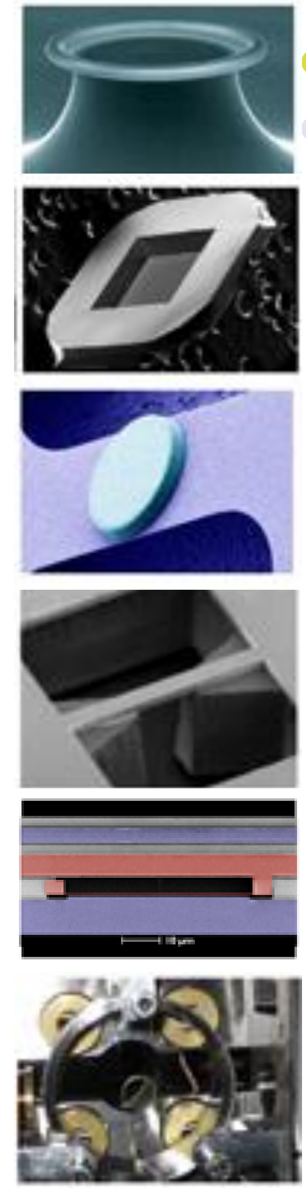






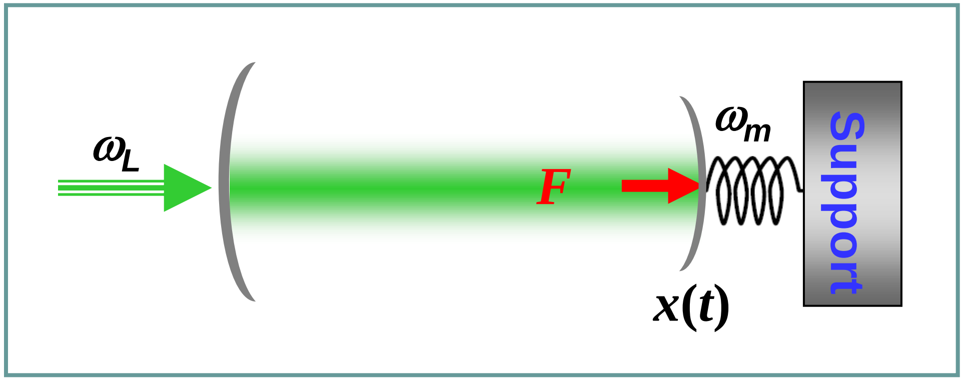
For reviews, see for example:

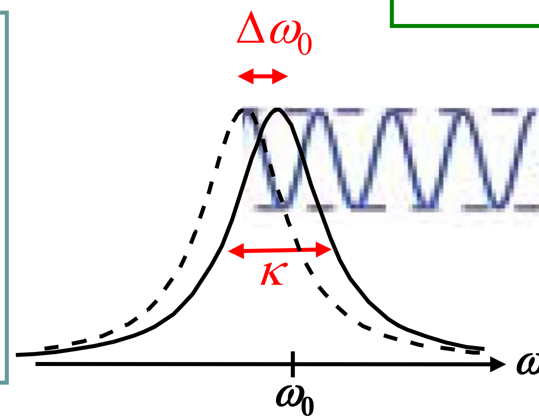
- Science **321**, 1172 (2008).
- Physics **2**, 40 (2009).
- Nature Photonics **4**, 211 (2010).
- Physics Today **65**, 29 (2012).



Interaction between optical and mechanical modes

$$\Delta\omega_0(t) = -\omega_0 \frac{x(t)}{L}$$





Optomechanical coupling:

- **Circulating optical field exerts a radiation pressure force on the mirror.**
- **The mirror displacement induces a change in the optical resonance frequency.**
- **Strong effects of optomechanical coupling can be observed, if $\Delta\omega$ is large compared with κ.**

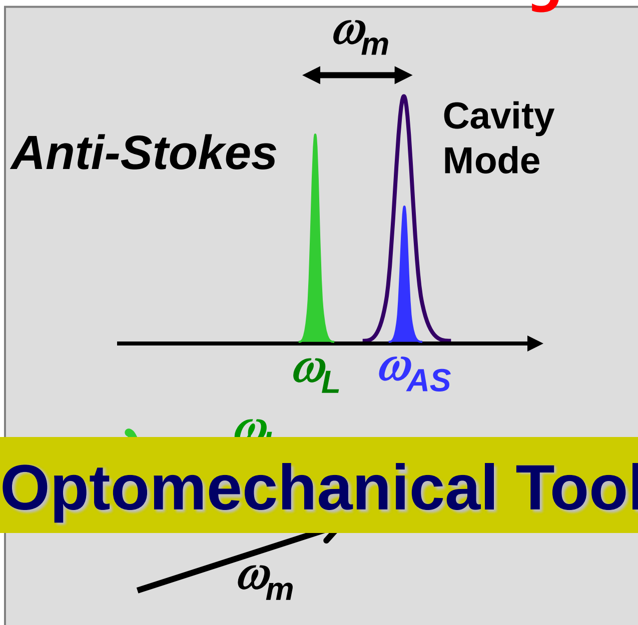
Dykman (1978); Law, PRA 51, 2573 (1995).

Interaction between optical and mechanical modes

$$H_{\text{int}} = \hbar G(e^{-iW_l t}\hat{a}^{\dagger}\hat{b} + e^{iW_l t}\hat{a}\hat{b}^{\dagger}) + \hbar G(e^{iW_l t}\hat{a}\hat{b} + e^{-iW_l t}\hat{a}^{\dagger}\hat{b}^{\dagger})$$

$\hat{a}$ **: Optical mode** $\hat{b}$ **: Mechanical mode** $G = g\sqrt{n_c}$ ***Effective coupling rate***

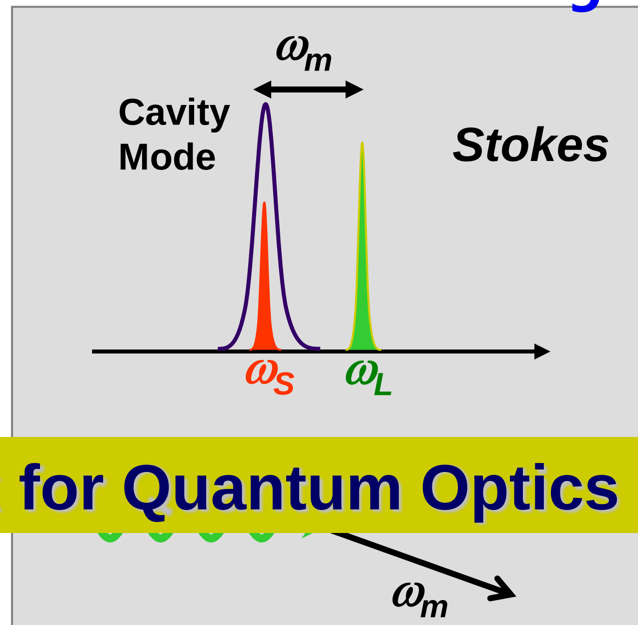
Red detuning



Converts phonons to photons and vice versa.

Cooling

Blue detuning



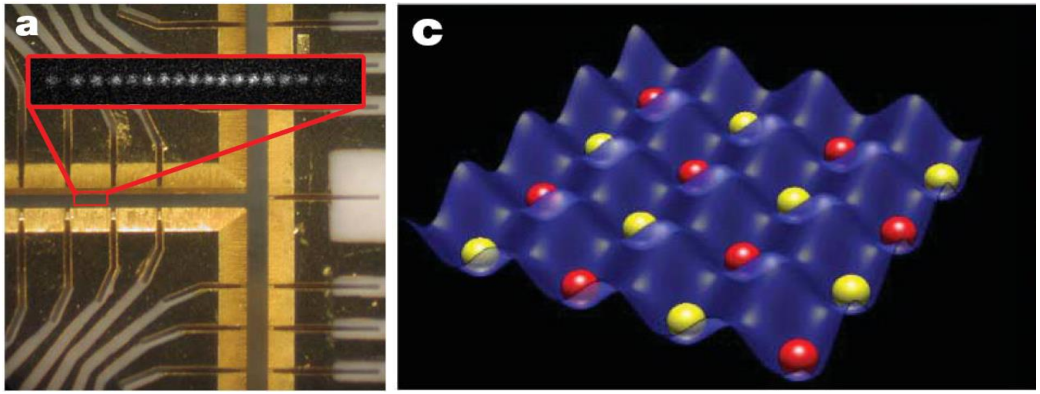
Similar to parametric down conversion.

Heating

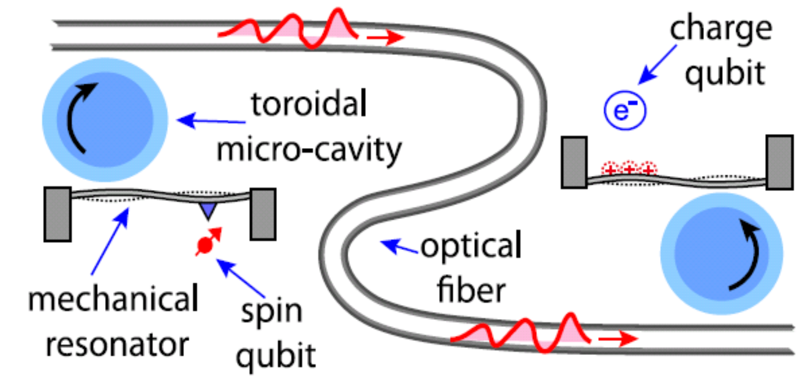
Optomechanical Tool Box for Quantum Optics

PRL **107**, 133601 (2011); PRA (2010), PRL **97,** 243905 (2006)

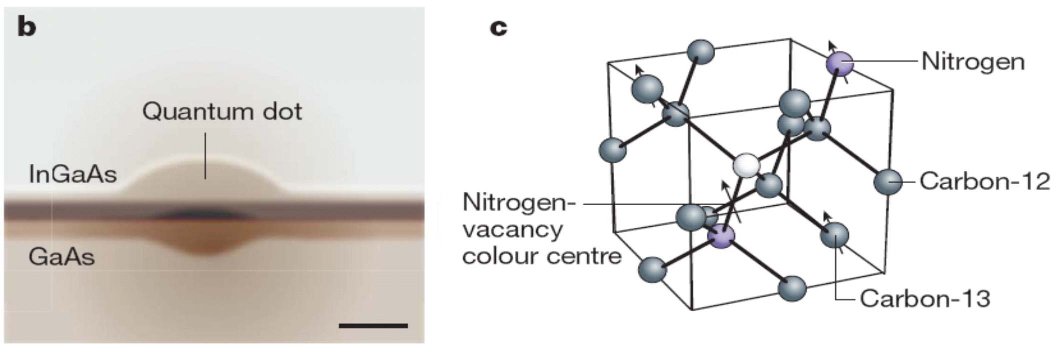
Interfacing Different Quantum Systems



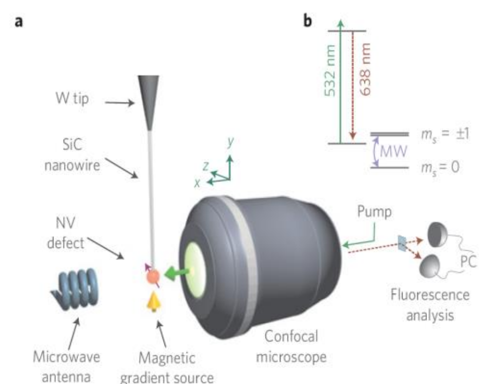
Nature **464, 45 (2010)**



K. Stannigel, et al PRL (2010).



Nature **453, 1043 (2008)**

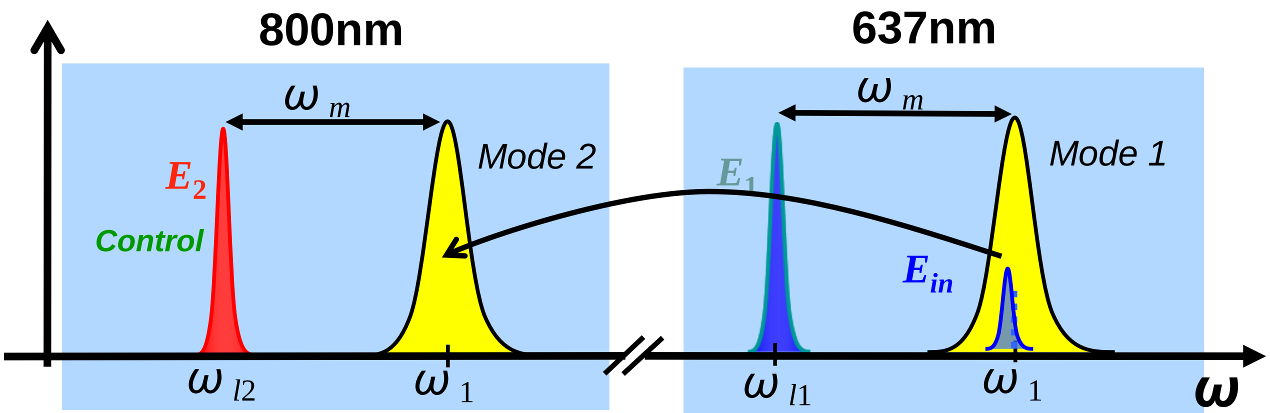


O. Arcizet,et al Nature Physics (2011).

Different types of quantum systems couple to photons with different wavelengths.

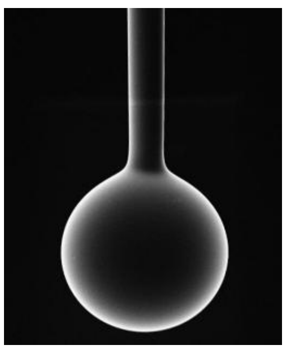
- ***Take advantage of unique properties of optomechanical systems to interface different types of quantum systems.***

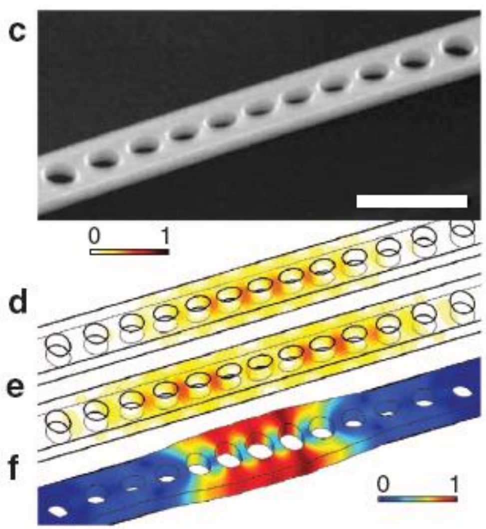
Wavelength conversion

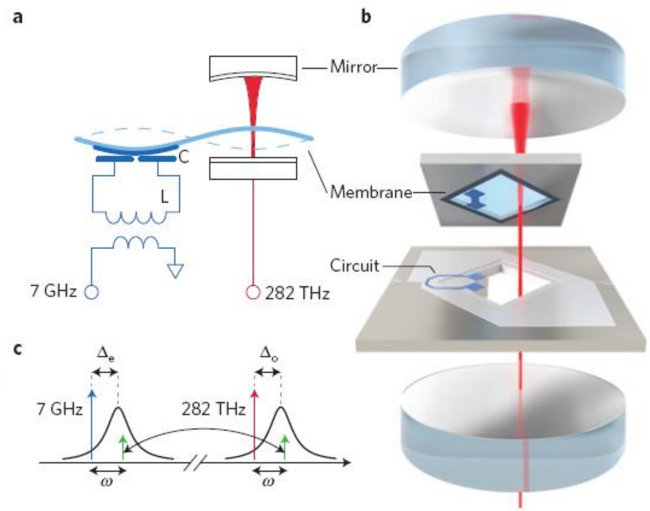


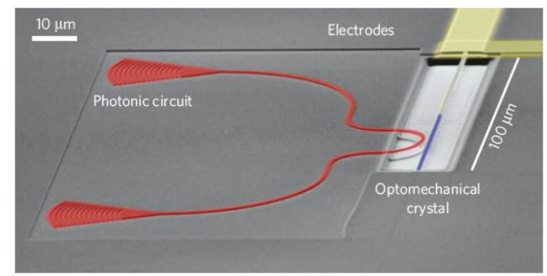
Wang PRL 108, 153603 (2012);
Tian, PRL 108, 153604 (2012).
J. Hill, Nat. Commun. 3, 1196 (2012).
Y. Liu, PRL 110, 223603 (2013).
J. Bochmann, Nature Phys. 9, 712 (2013).
R. W. Andrews, Nature Phys. 10, 321 (2014).

C.-H. Dong, Science 338, 1609 (2012).









Photon – phonon - microwave

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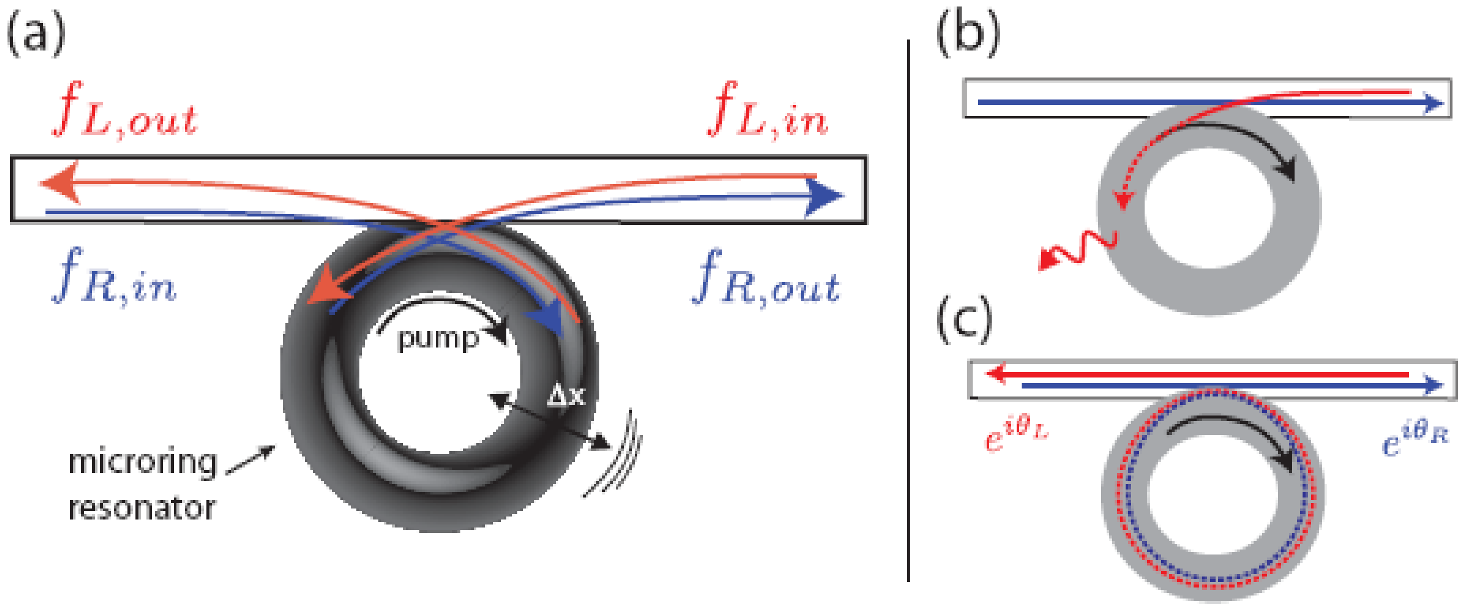
  - **Synthetic magnetic field**
- **Summary**

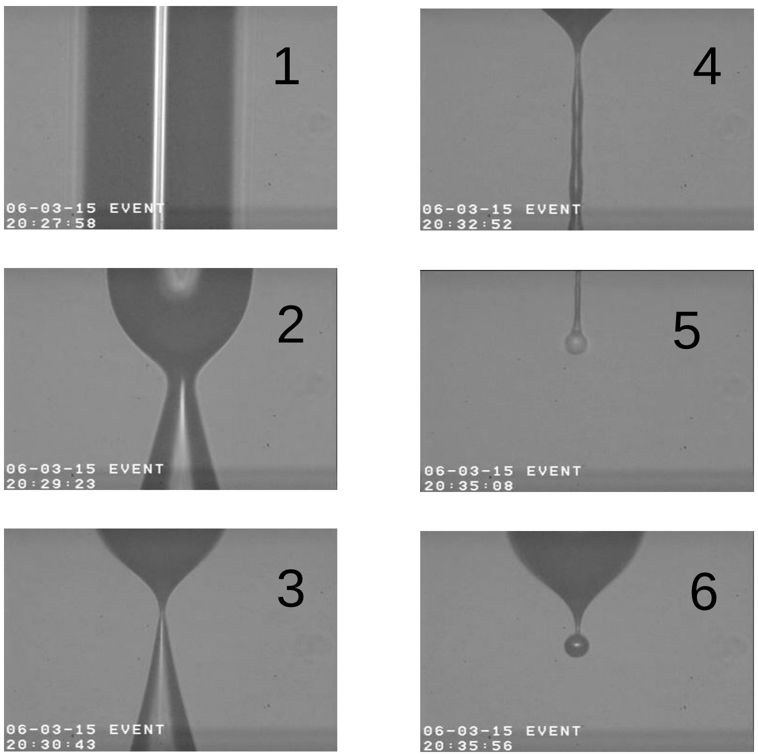
Optomechanically induced non-reciprocity in microring resonators

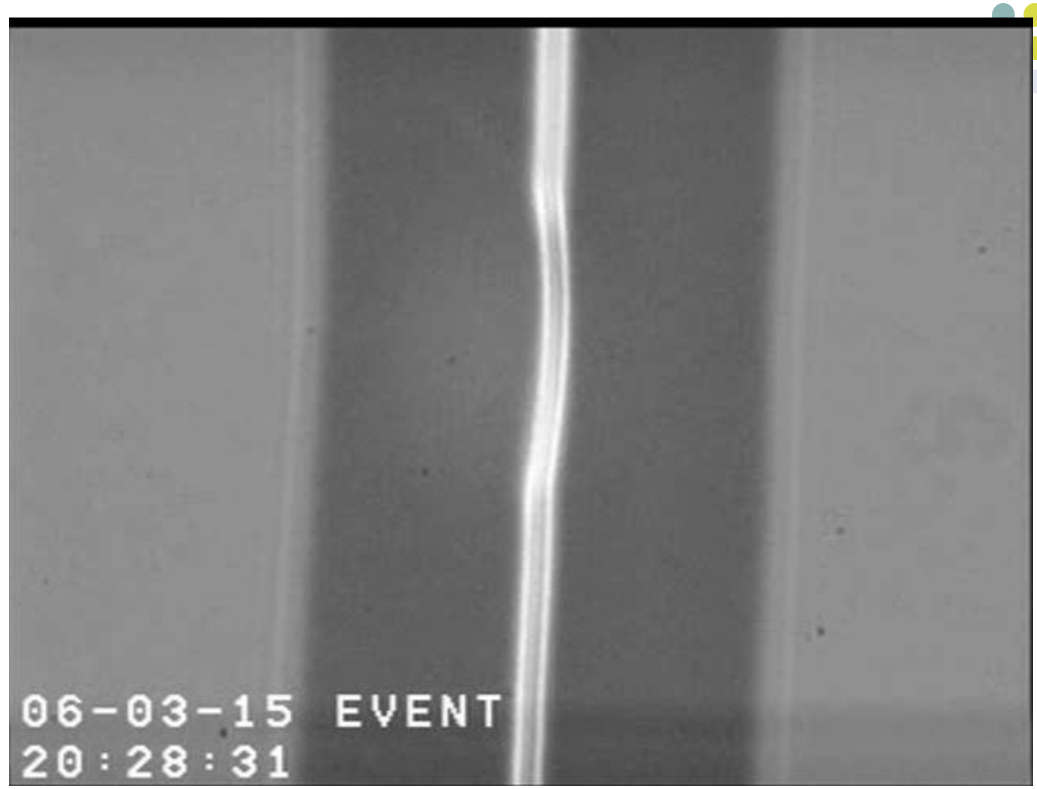


$$H_{om-lin} = -\Delta(a_R^\dagger a_R + a_L^\dagger a_L) + \omega_m b^\dagger b + (G_R a_R^\dagger + G_R^* a_R)(b^\dagger + b)$$

Hafezi, M. & Rabl, P. Optomechanically induced nonreciprocity in microring resonators. Opt. Express **20**, 7672 (2012).

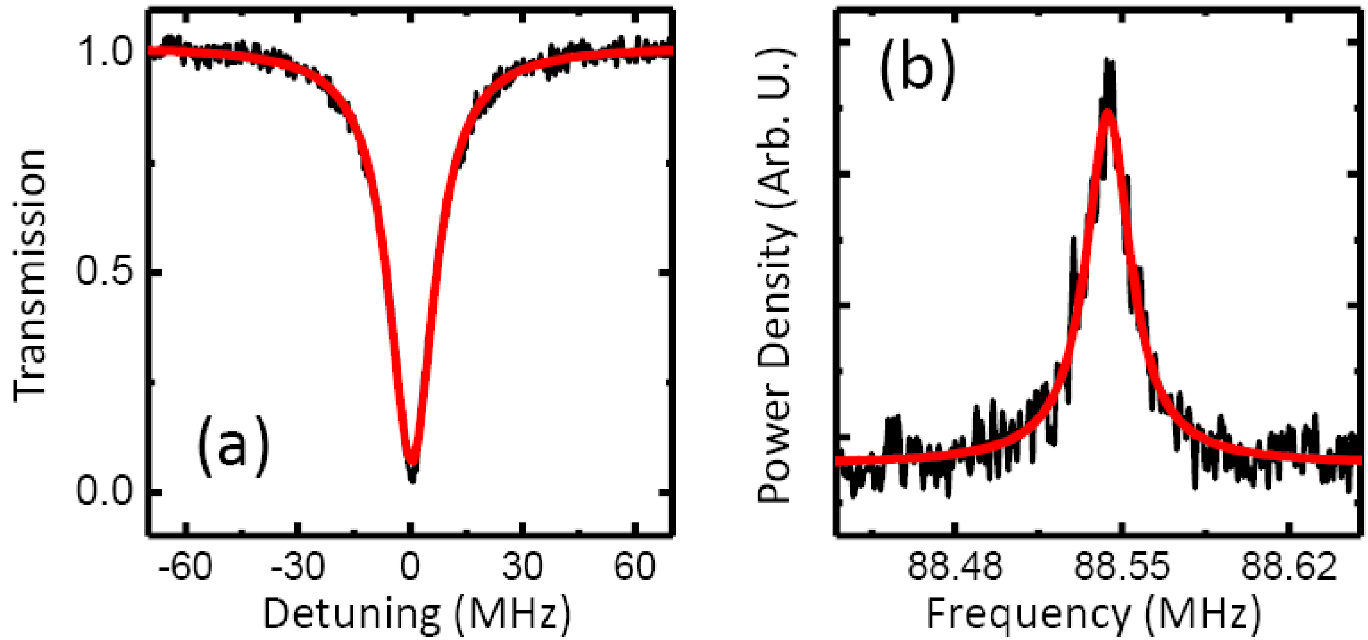
Fabrication of silica microsphere



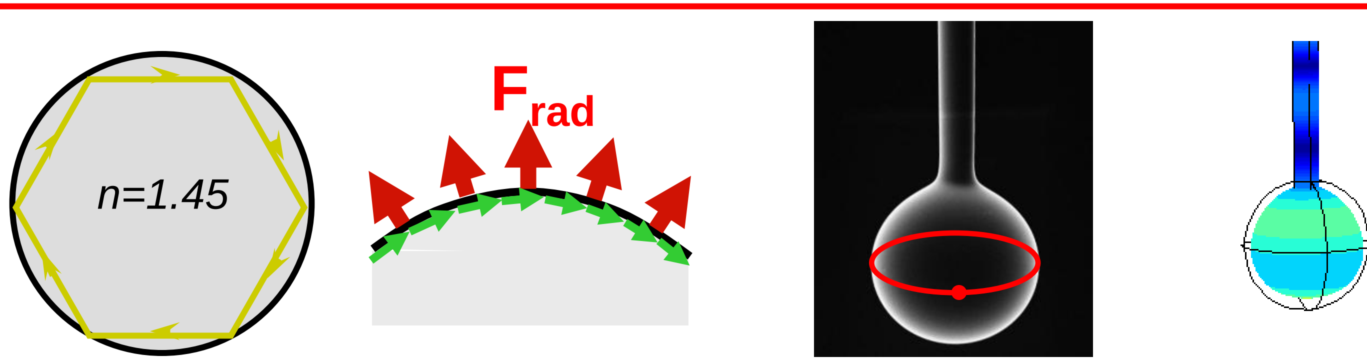


A CW CO_2 laser is focused on the fiber to fabricate the silica microsphere.

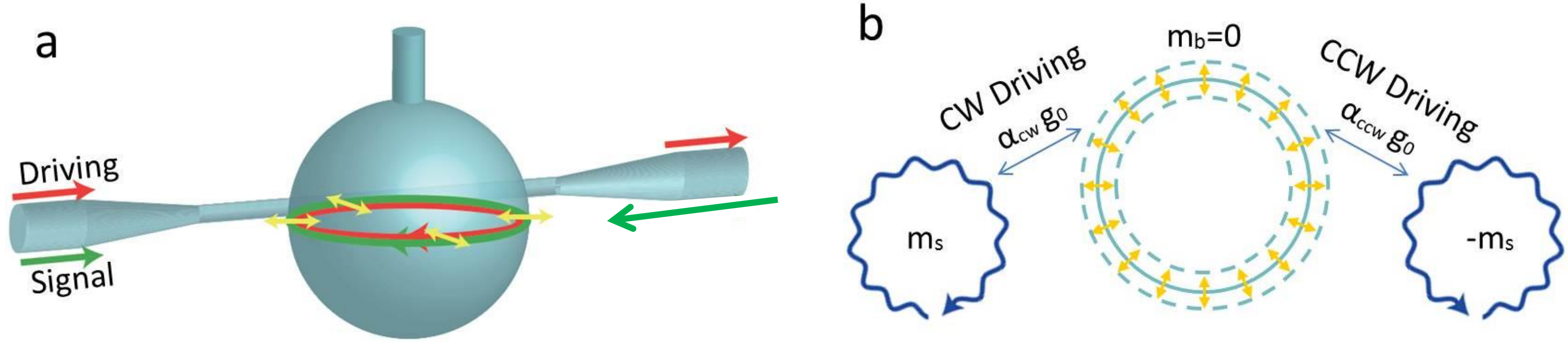
Optical and Mechanical modes

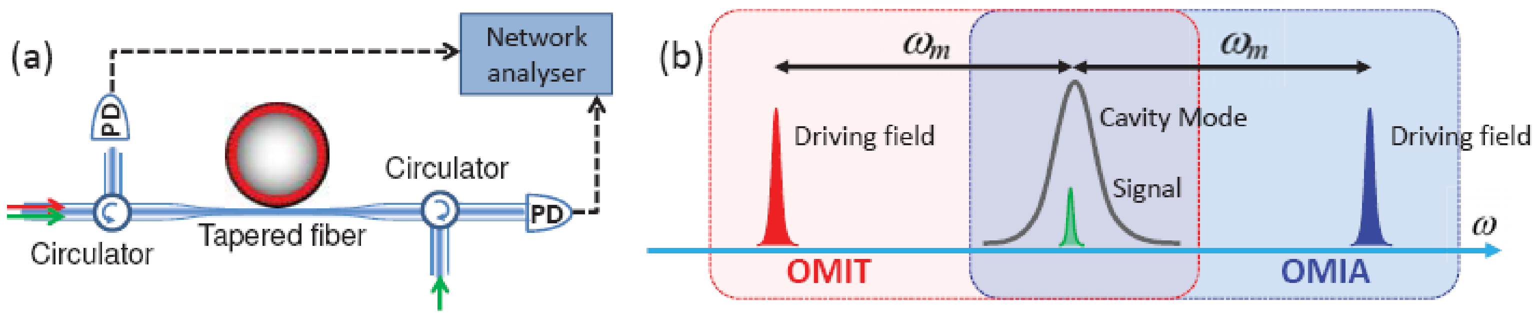


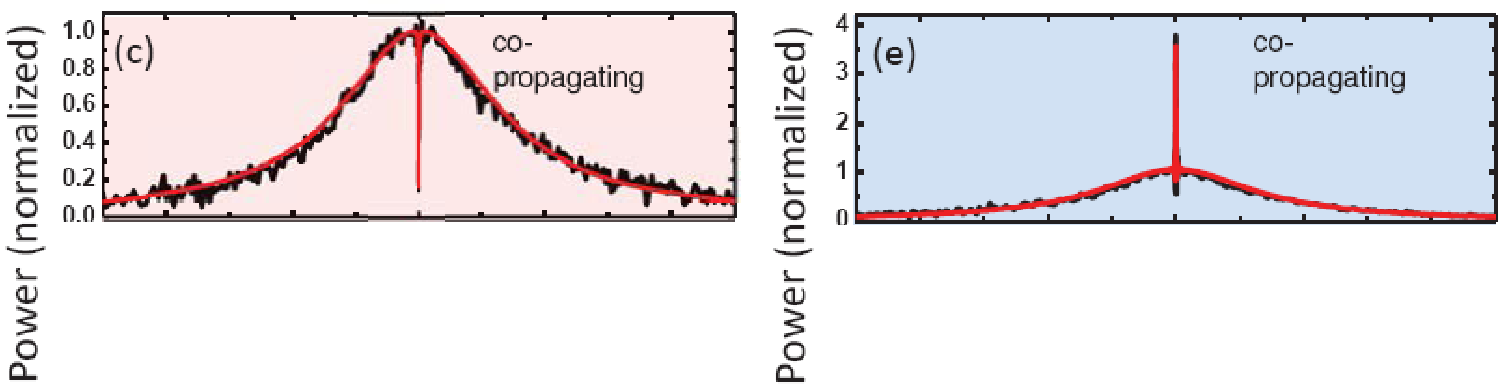
Optical $Q \sim 2.6 \times 10^7$ Mechanical $Q \sim 4 \times 10^3$



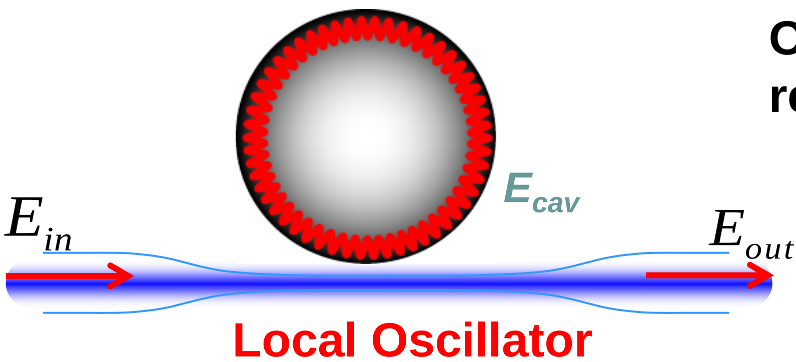
Non-reciprocity





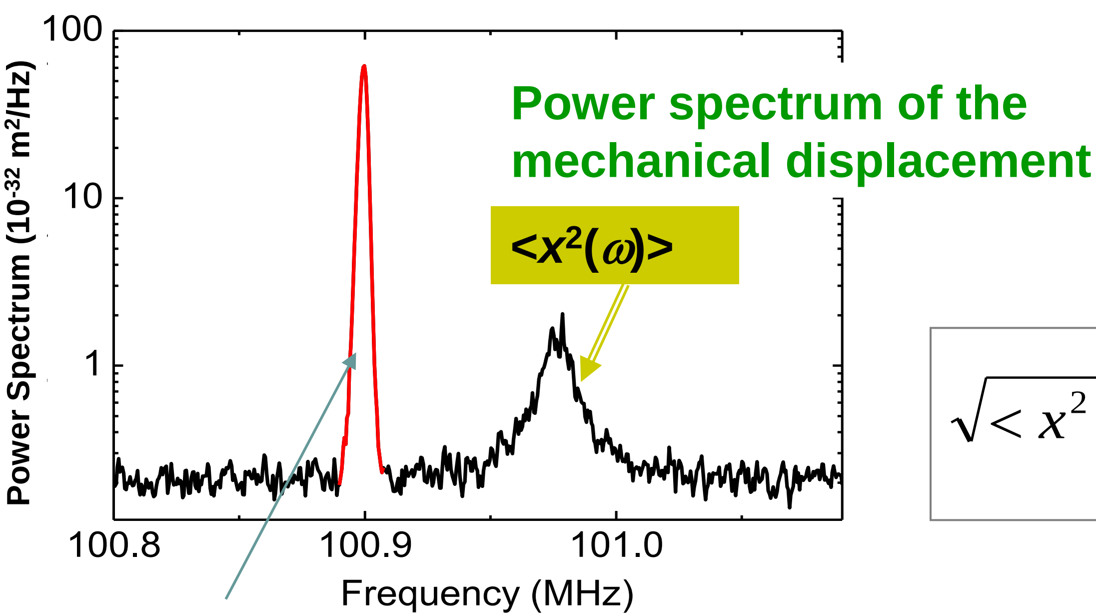


Homodyne Detection of the Mechanical Motion



Optical interference measures the relative phase of the optical field.

$$I_{out} = |E_{cav} + E_{loc}|^2$$



Sensitivity

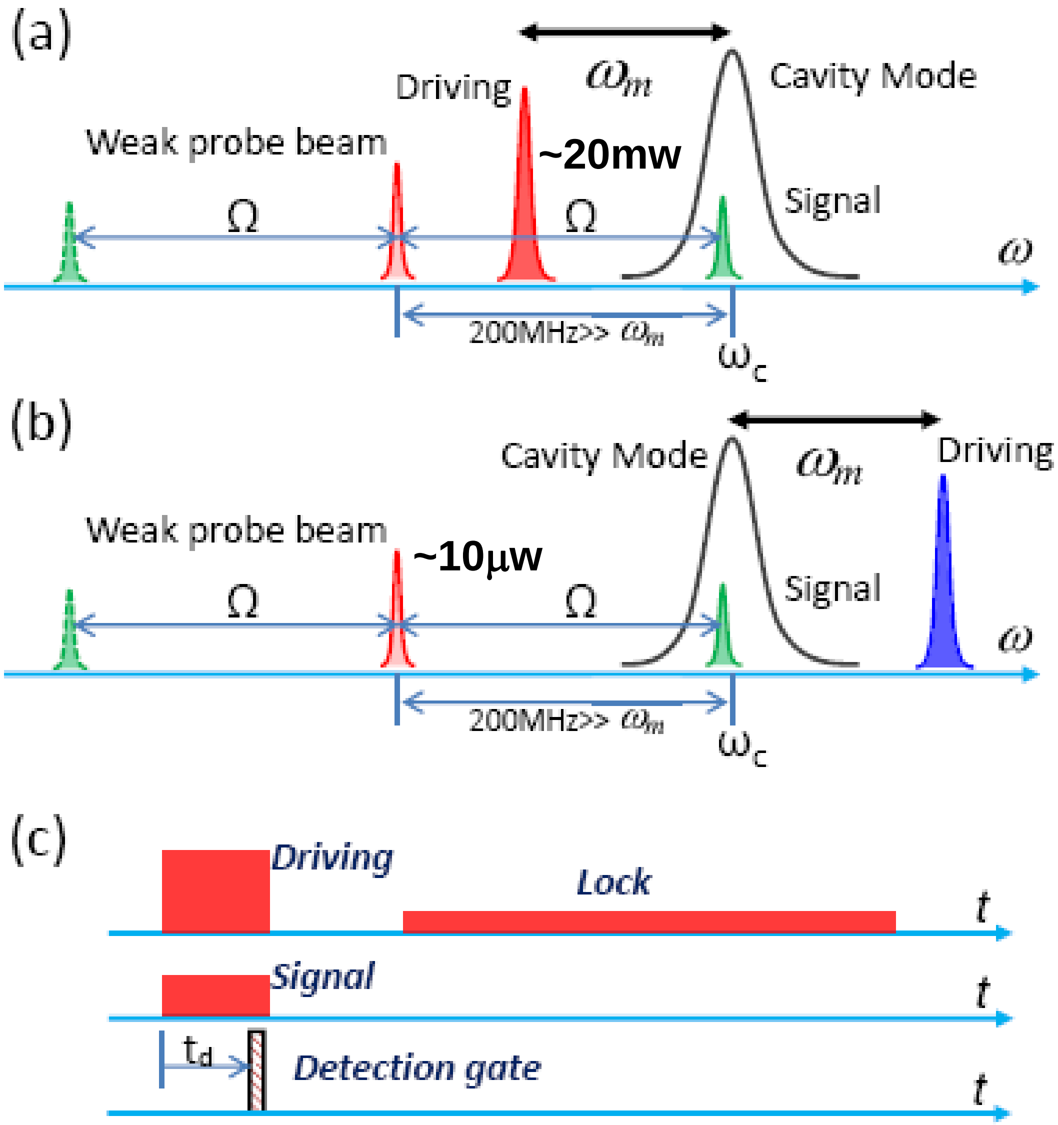
$$10^{-18} m/\sqrt{Hz}$$

$$\sqrt{< x^2 >} = \sqrt{\frac{k_B T}{m_{eff}\,\omega_m^2}} \sim 10^{-14}\ m$$

***T* = 300 K**
m*$_{eff}$ = 40 *ng

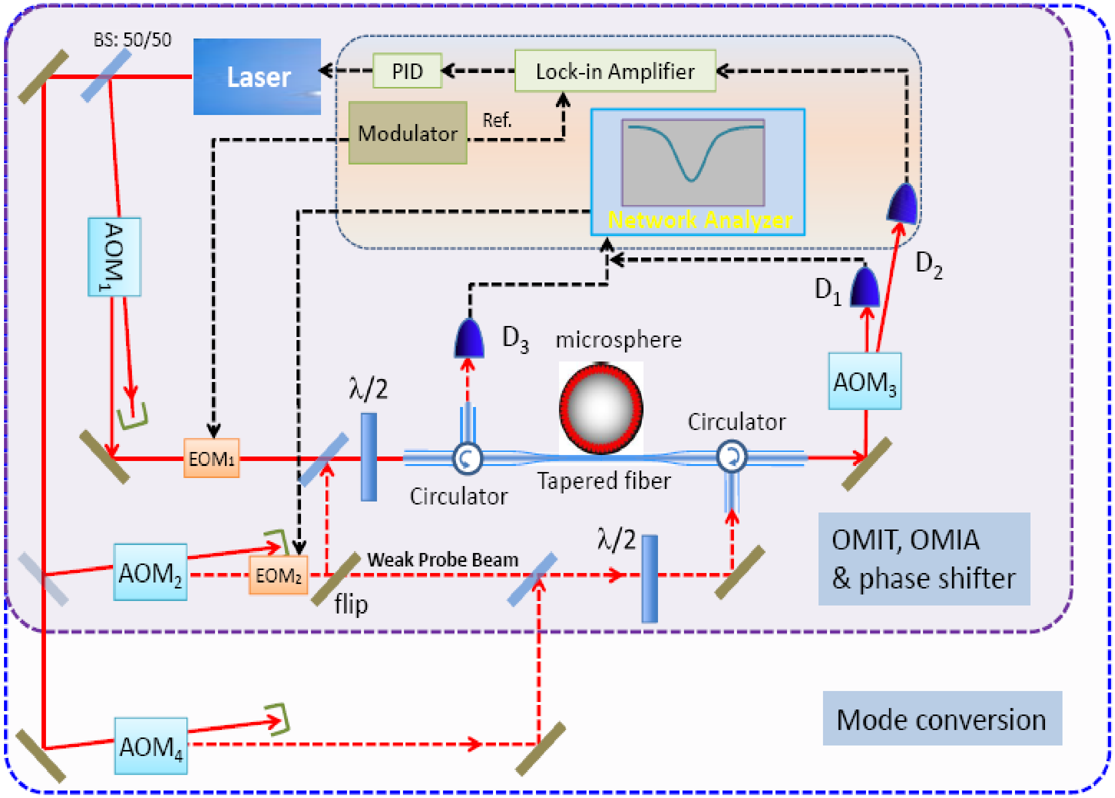
Calibration: Oscillating phase induced by an electro-optic modulator.

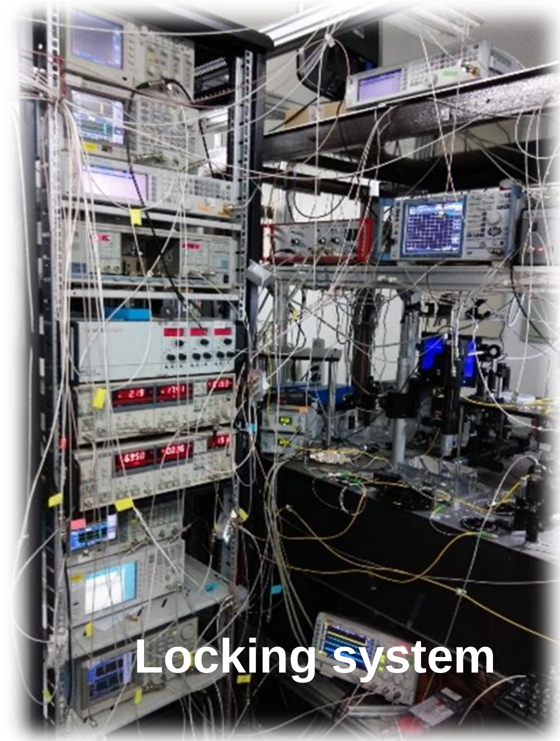
Spectral diagram and pulse sequences

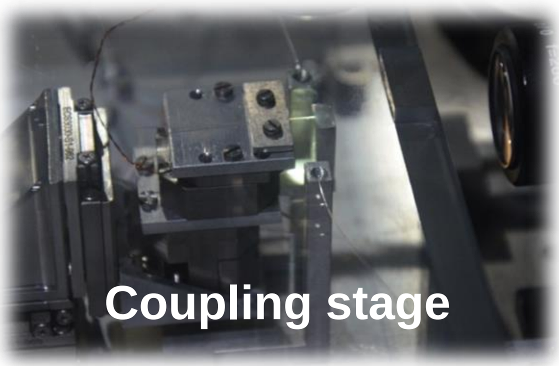


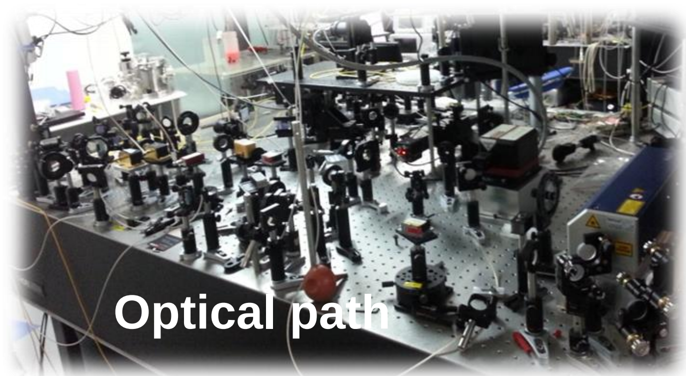
- **Lock the laser to the optical mode**
- **The probe beam generated by a weak laser far away resonance**
- **Gate detection method**
- **Avoid the thermal effect**

Setup for the experiment

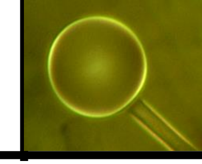




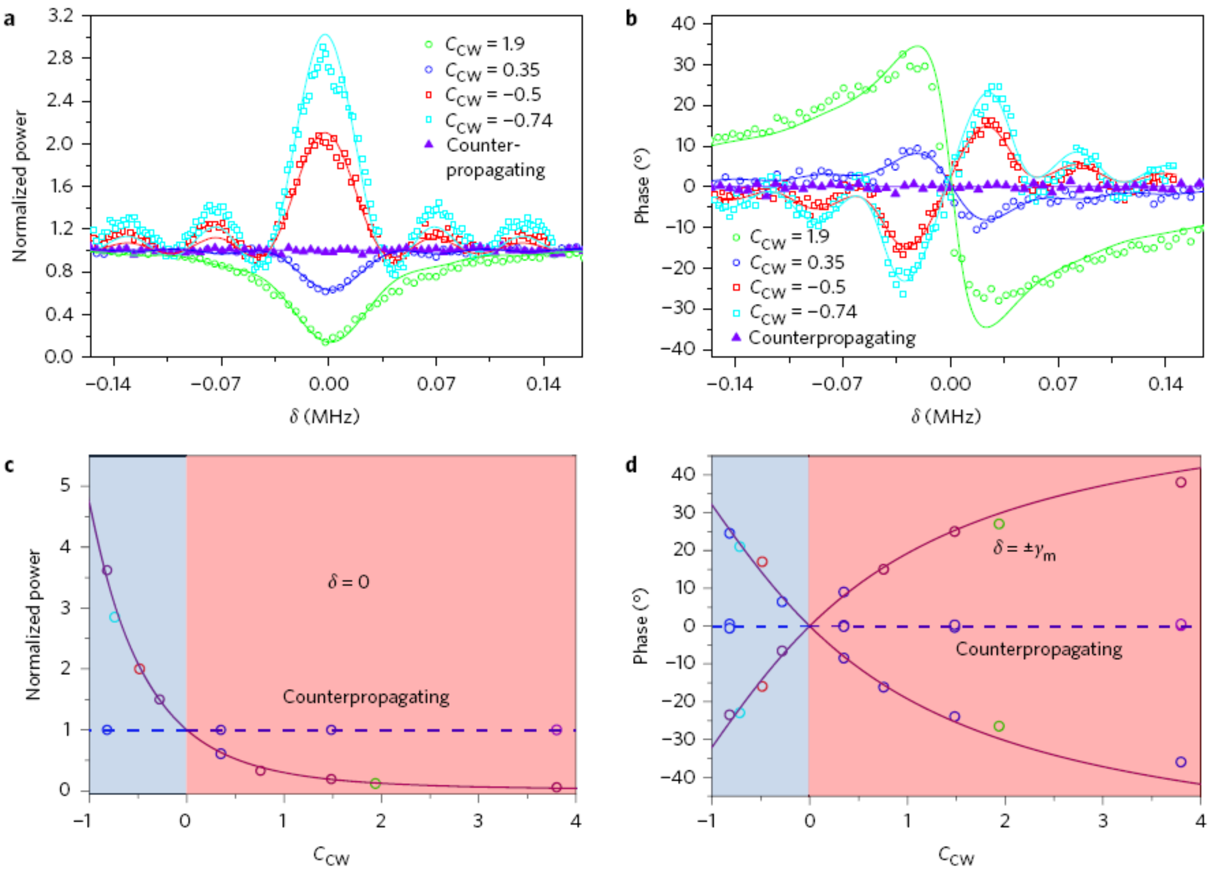


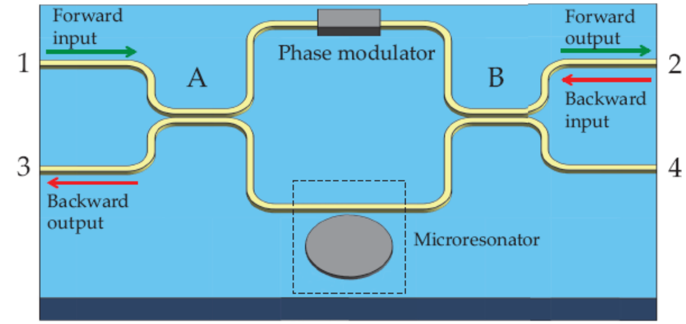


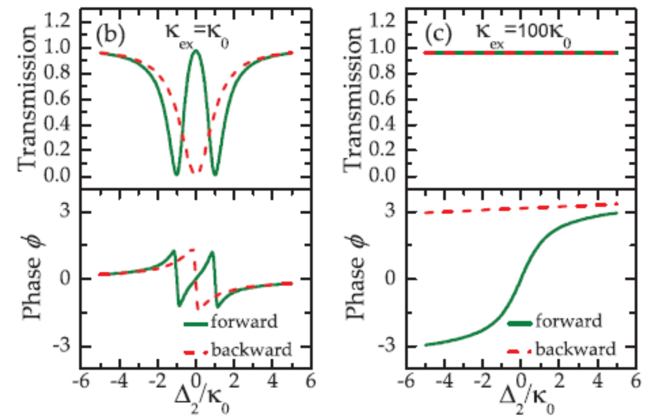
Non-reciprocal phase shifter



Transparency window **Phase shifter**



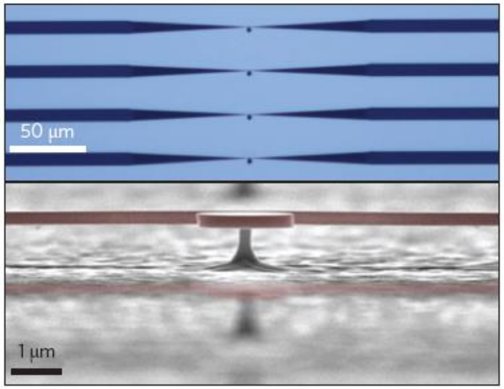




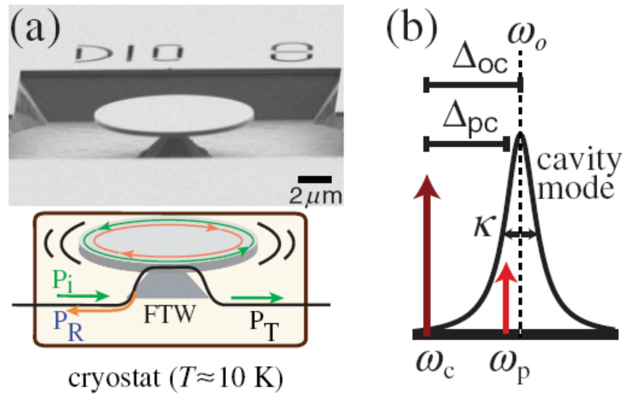
Wei Fu, et al, OE (2015).

Z. Shen, et al Experimental realization of optomechanically induced non-reciprocity, nature photonics **10**, 657 (2016).

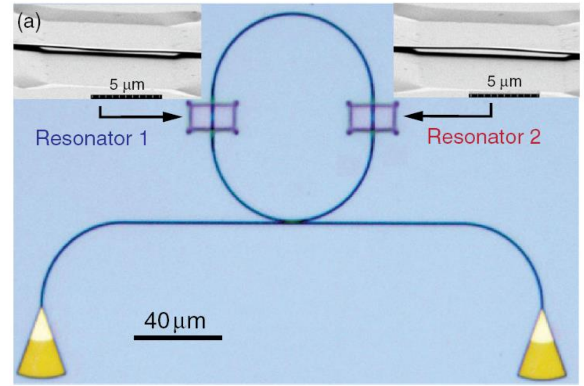
Integrated mechanical resonators



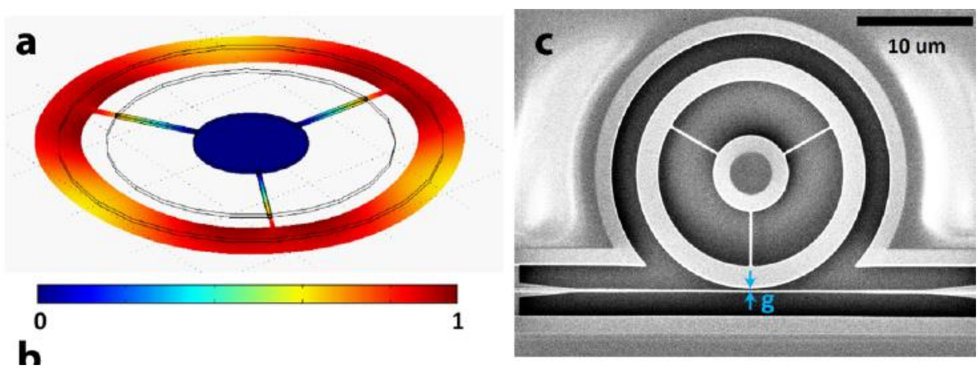
Nat. Nanotech. (2015).



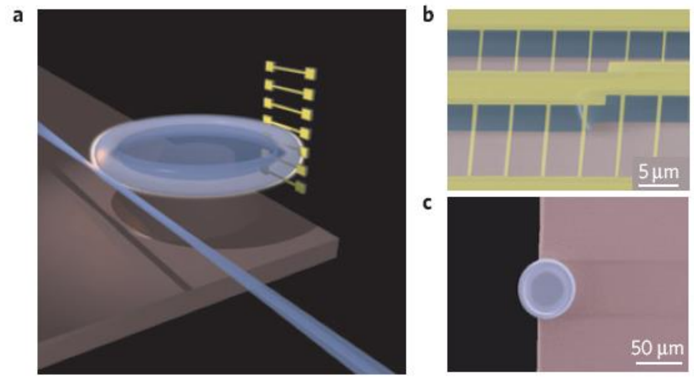
PRL 110, 223603 (2013)



Nat. Nanotech. (2011).



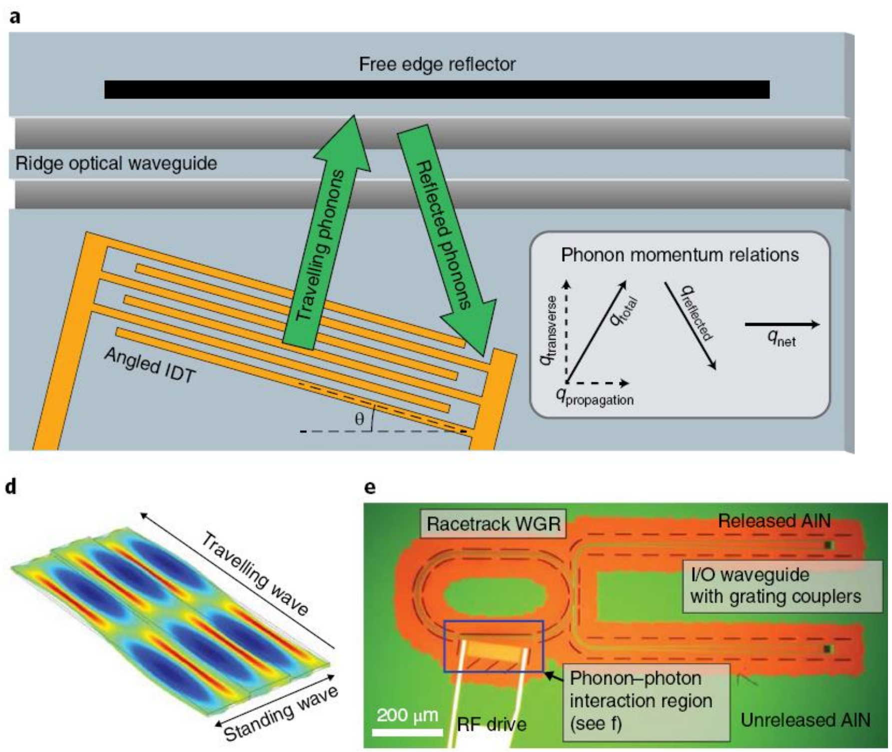
Nano. Lett. 15, 6116–6120 (2015).

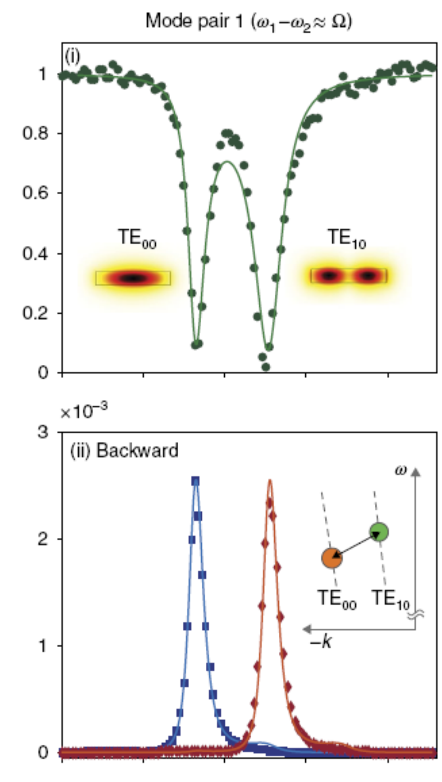


Nature *Physics* **5**, 909 (2009)

- Our idea of the non-reciprocity is actually universal and can be realized to any travelling wave resonators with a mechanical oscillator, such as an integrated disk-type microresonator coupled with a nanobeam.
- **Operated in a broaden wavelength.**

Non-reciprocity

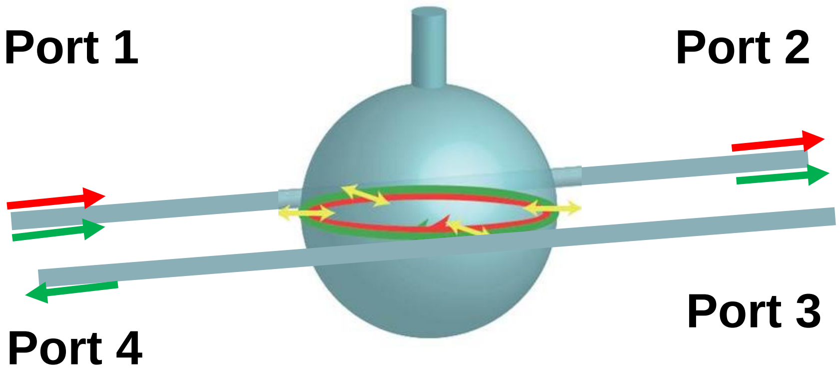


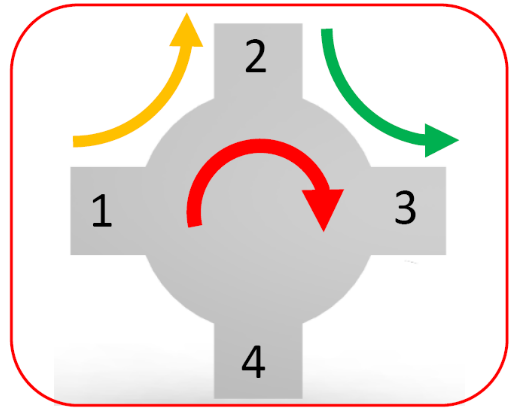


The demonstrated mode conversion asymmetry up to 15 dB and efficiency as high as 17% over a bandwidth exceeding 1 GHz.

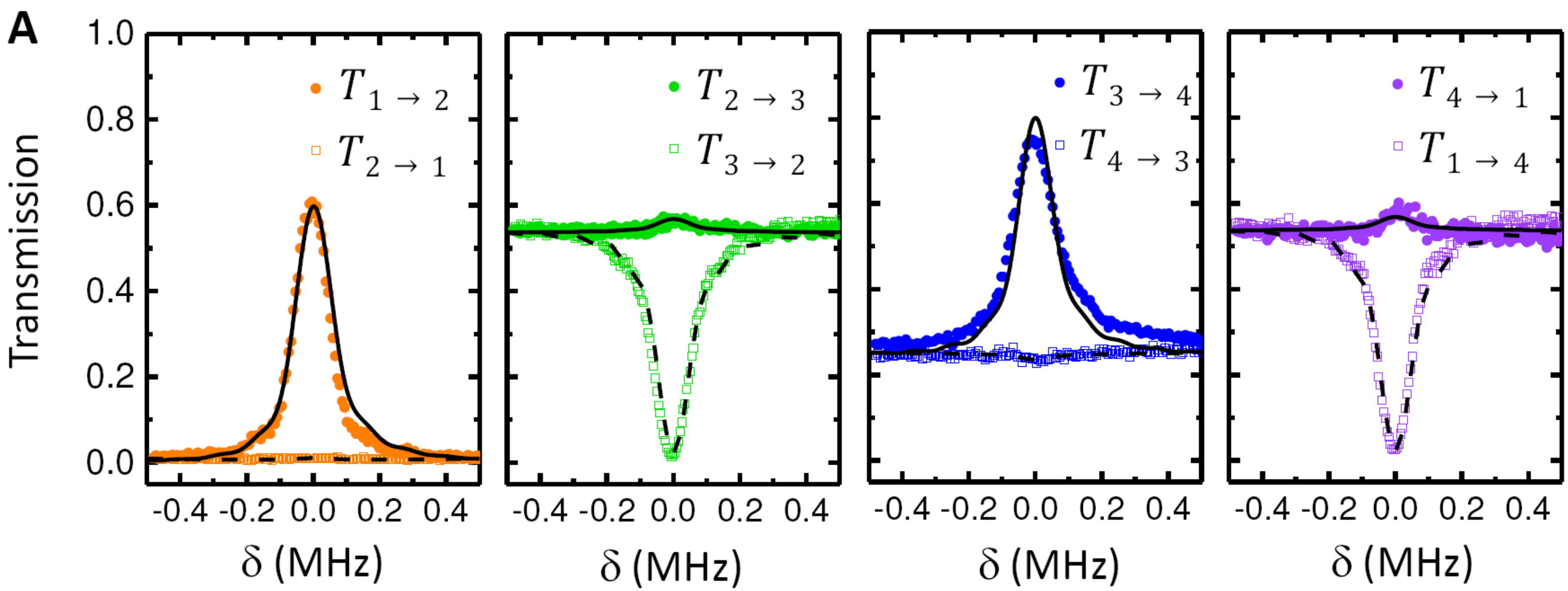
Gaurav Bahl et al, Nature Photonics **12**, 91 (2018).

Circulator



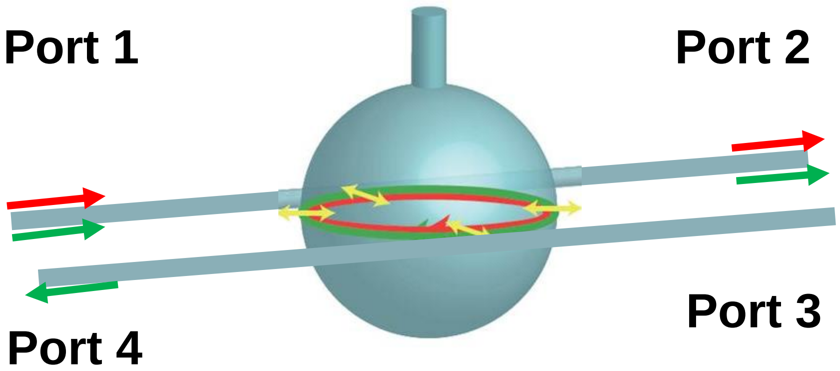


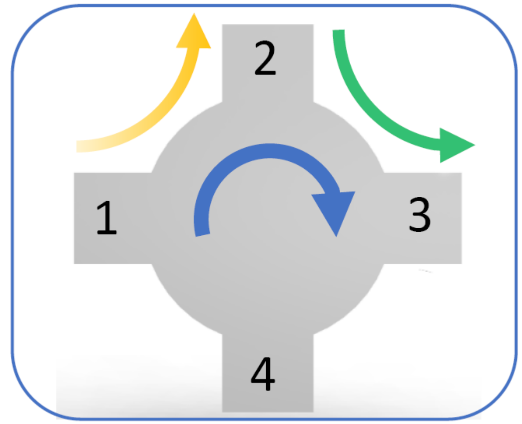
Red detuning



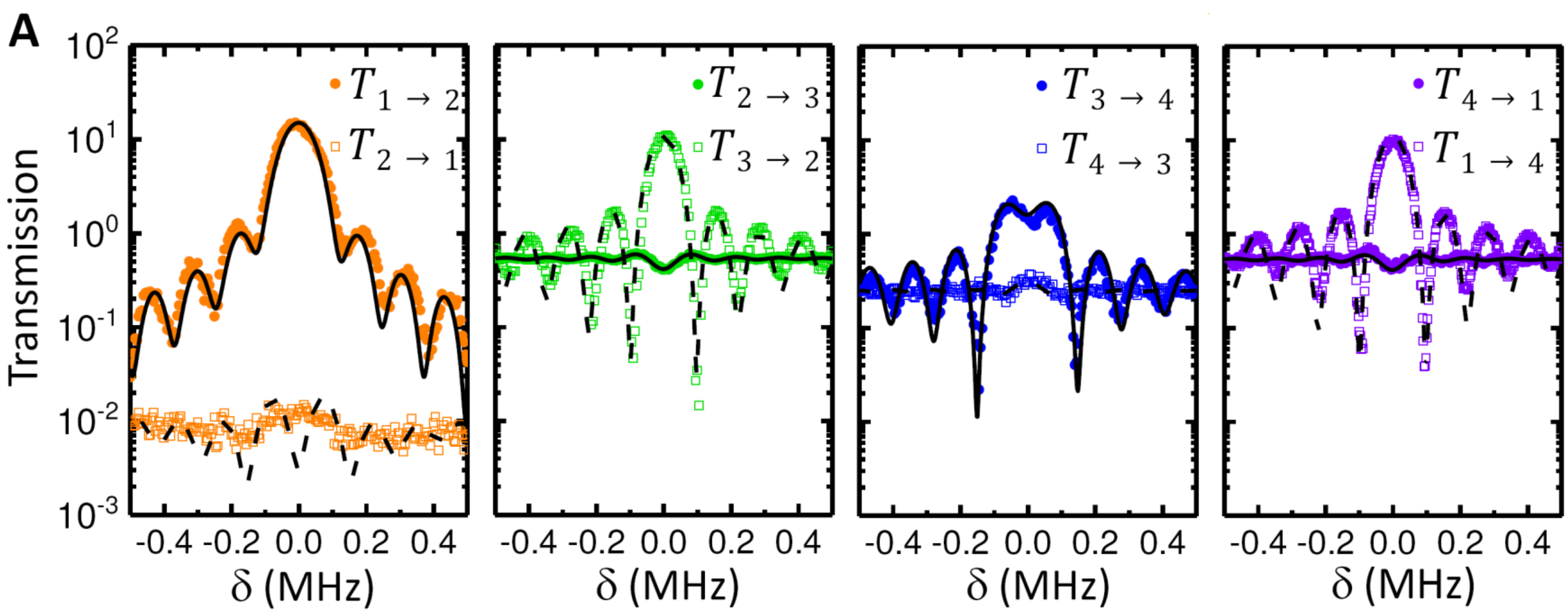
Z. Shen, Y Zhang, Y. Chen, *et al*, Nature Communications **9**, 1797 (2018).

Directional amplifier



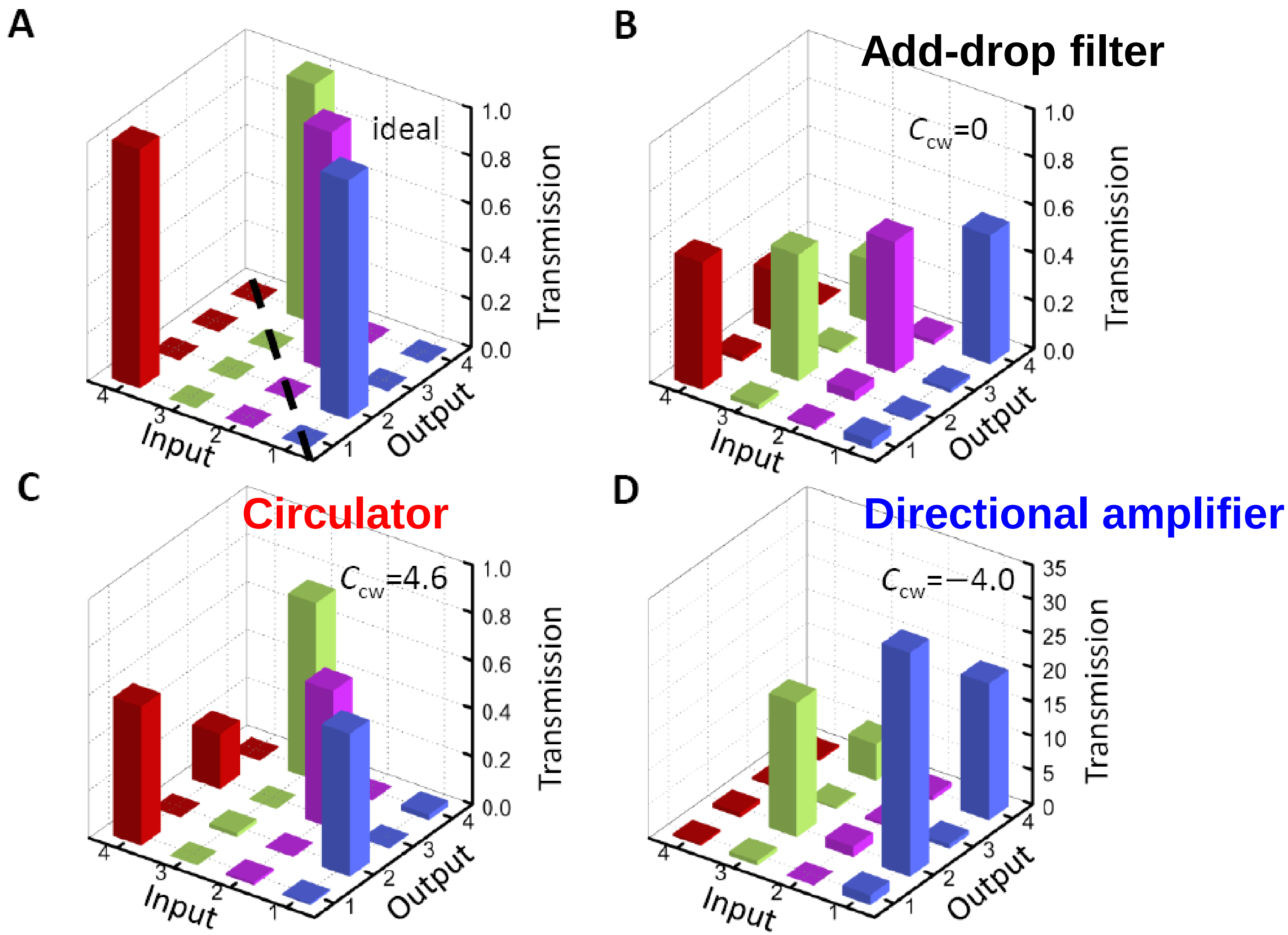


Blue detuning



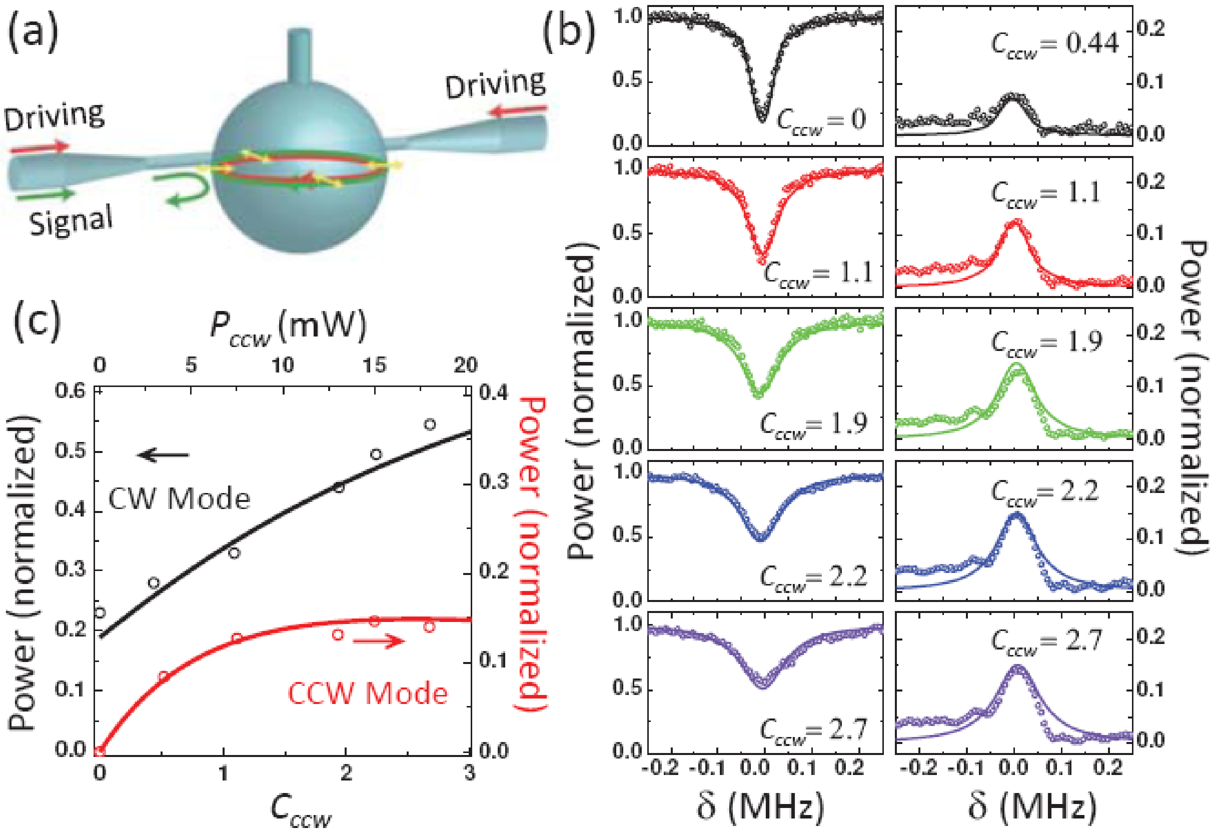
Z. Shen, Y Zhang, Y. Chen, *et al*, Nature Communications **9**, 1797 (2018).

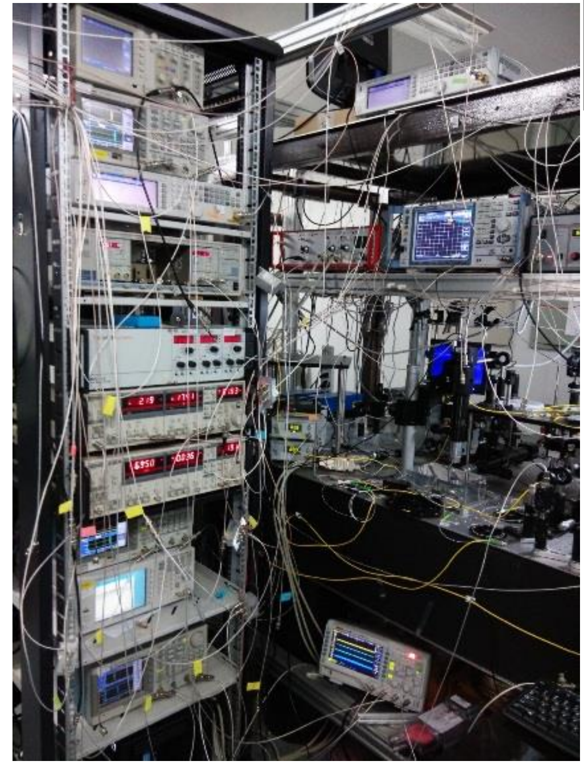
Reconfigurable optomechanical circulator and directional amplifier



Z. Shen, Y Zhang, Y. Chen, *et al*, Nature Communications **9**, 1797 (2018).

Controlled mode coupling

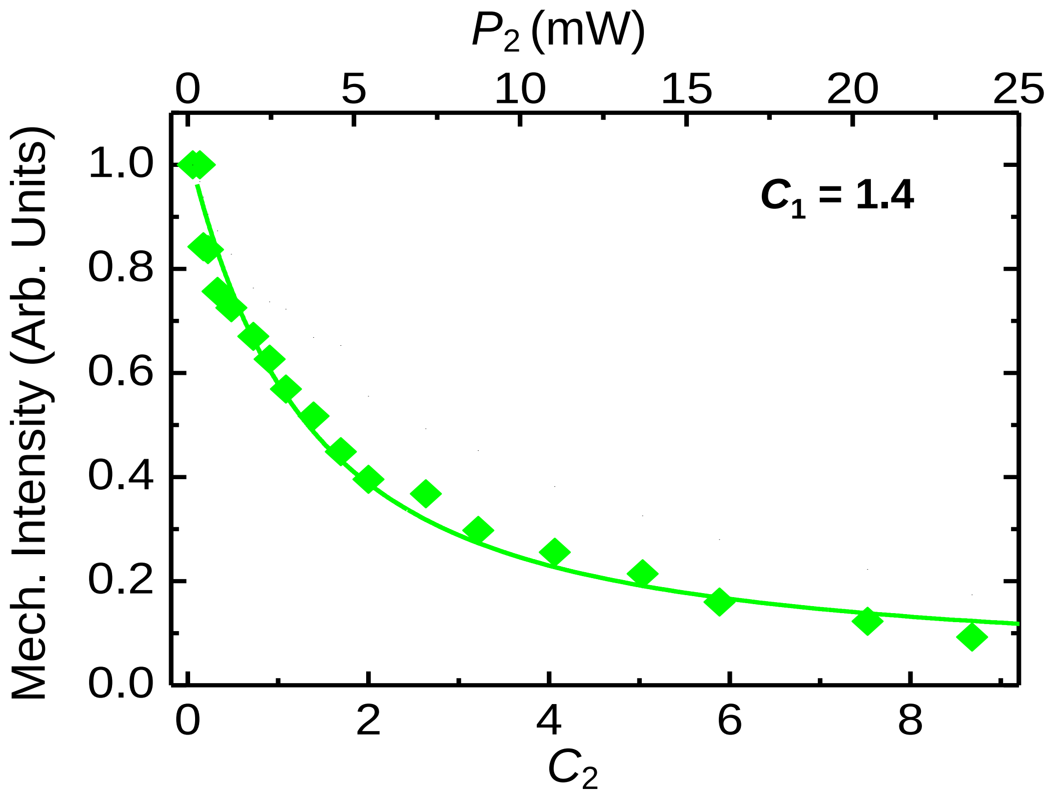


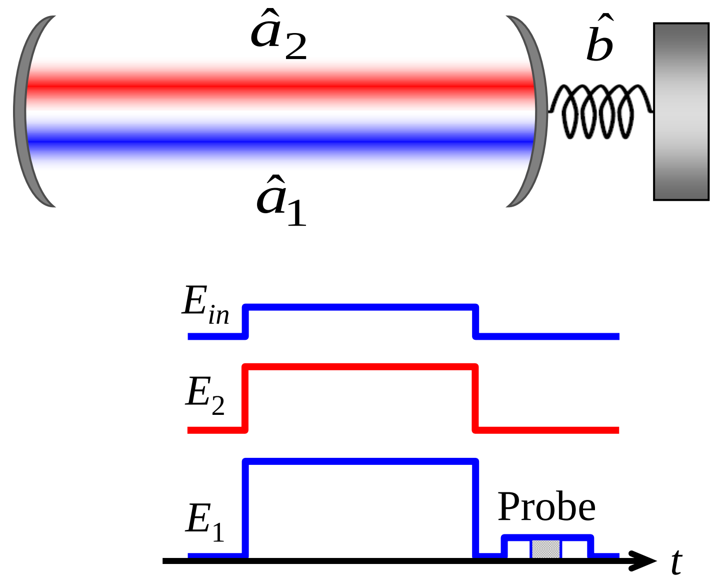


- ➢ Mode conversion between two oppositely propagating optical fields at the same wavelength → **Optomechanical dark mode**

Z. Shen, *et al* Nature Photonics (2016).

Optomechanical dark mode





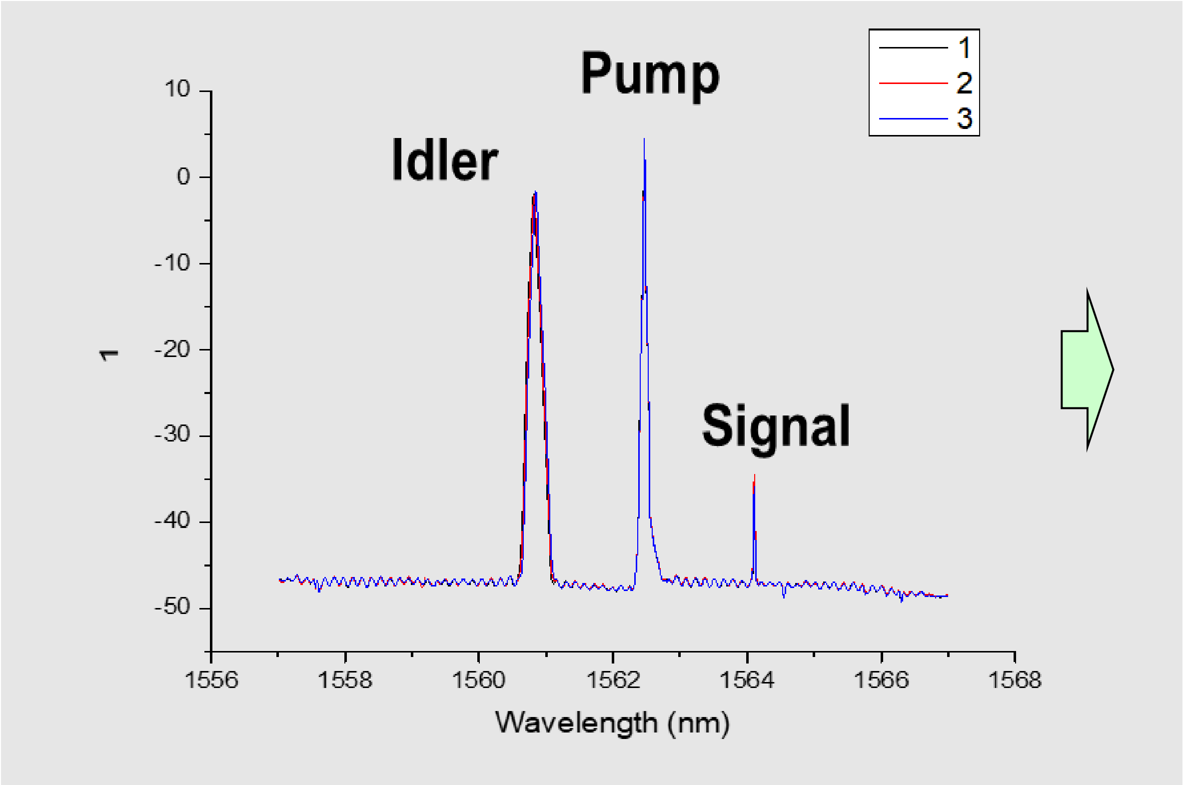
Phonons decreases as increasing the input power.

(1) The dark mode is a superposition of the two optical modes and is decoupled from the mechanical oscillator. **(2)** Optomechanical dark mode opens the possibility of using mechanically mediated coupling in quantum applications without cooling the mechanical oscillator to its motional ground state.

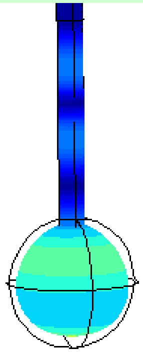
C. H. Dong *et al* Science (2012).

Future trend: Quantum source

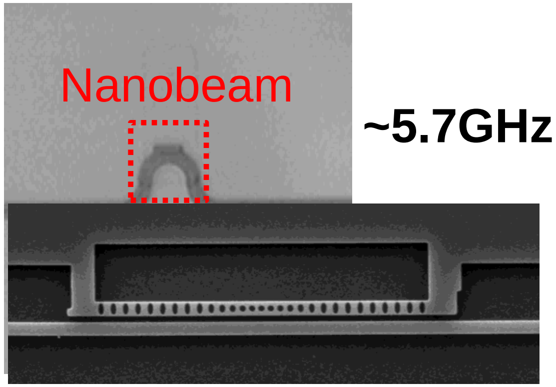
- **Cooling of a macroscopic mechanical oscillator to its motional ground state.**



Wavelength (nm)



~100MHz



~5.7GHz

Optomechanically induced non-reciprocity may play important roles in the quantum regime.

● ……

Summary

- Experimental realization of optomechanically induced non-reciprocity;
- We demonstrated the isolator and circulator based on the non-reciprocity;
- The coherent conversion between two optical modes via an optomechanical mode (To achieve the optomechanical dark mode using one laser).
- We got the Synthetic magnetic field in a mult-mode optomechanical microcavity.

Acknowledge

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Peking University

- Prof. Yunfeng Xiao

University of Oregon

- Prof. Hailin Wang

Thanks for your attention !