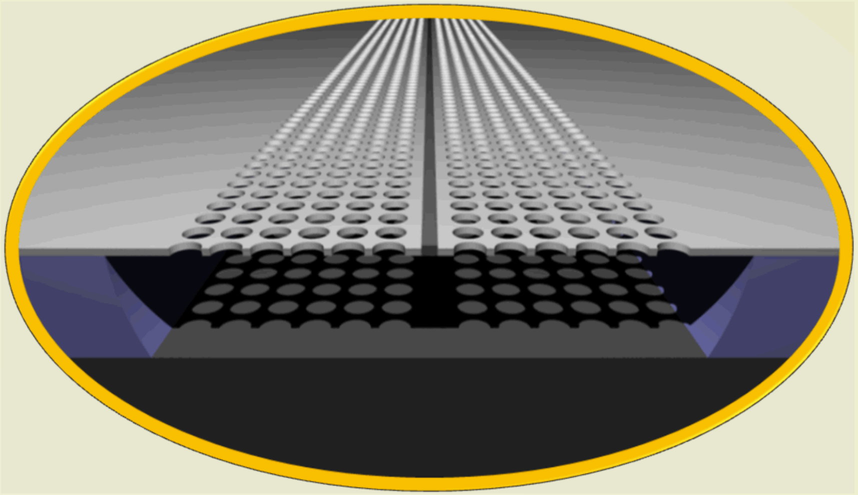
SAND2015-0919C

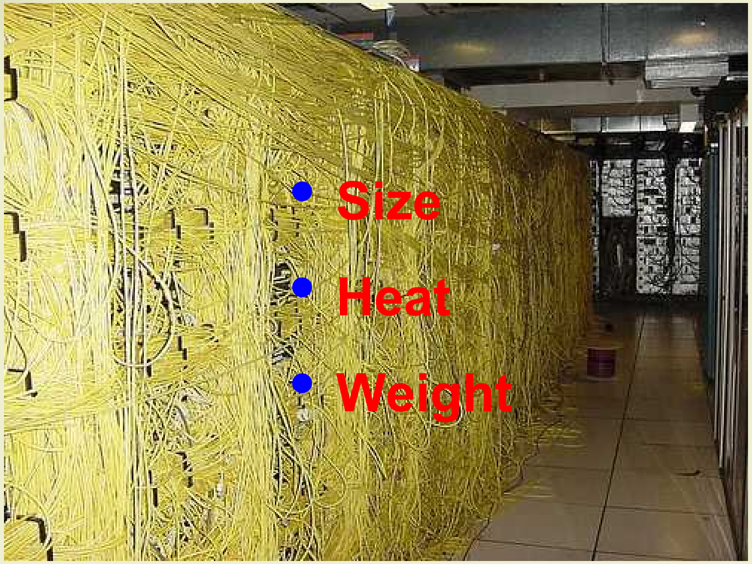


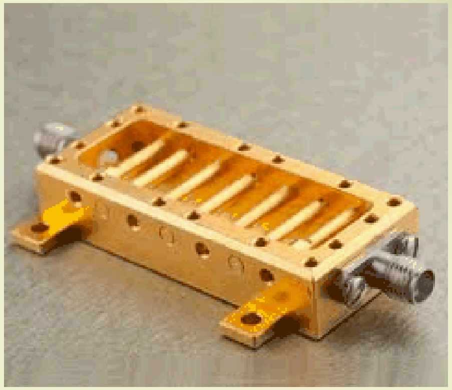
New nonlinear signal processing methods based on photon-phonon emitter-receiver

Heedeuk Shin[1], Jonathan A. Cox[2], Robert Jarecki[2], Andrew Starbuck[2], Zheng Wang[3], and Peter T. Rakich[1]

1. Department of Applied Physics, Yale University, New Haven, CT
2. Sandia National Laboratories, Albuquerque, NM
3. Department of ECE, University of Texas at Austin, Austin, TX

SPIE Photonics West 2015





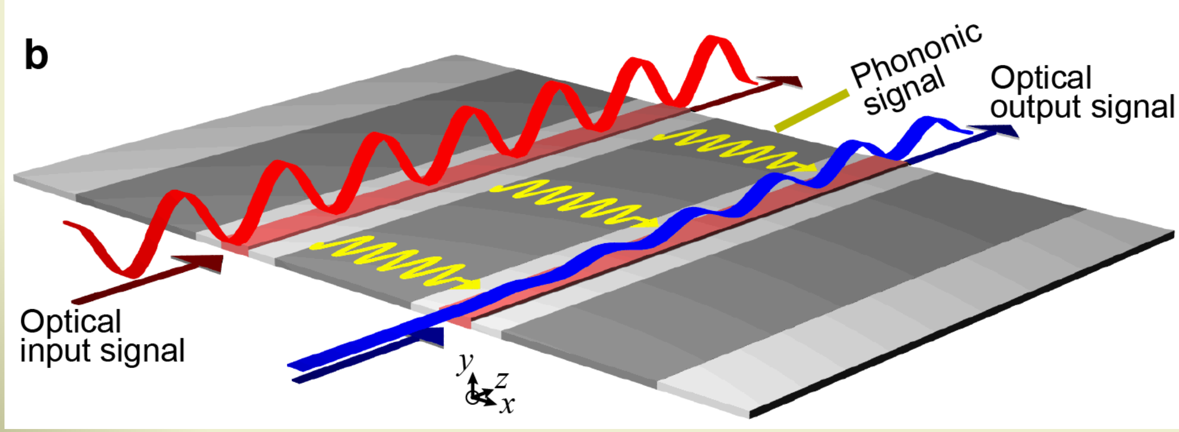
Yellow wall

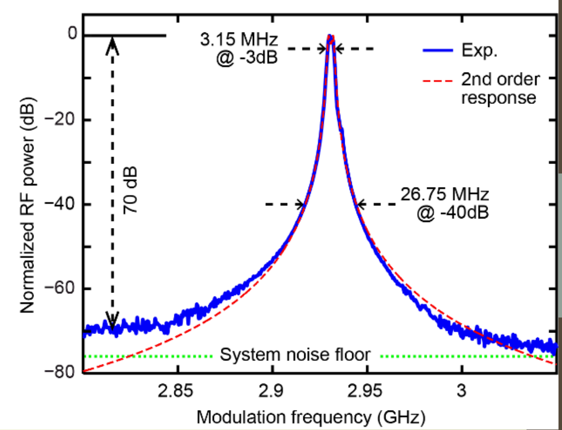
Signal In → Optical Transmitter →

→ → Signal Out

time delay
phase shift

Traveling-Wave Photon-Phonon Emitter-Receiver





Outline

1. Photon-phonon interaction & SBS

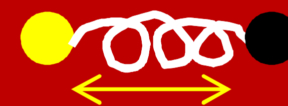
2. Brilloun Active Membrane

3. Photonic-phononic emitter-receiver

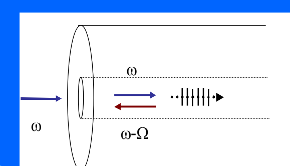
A phonon is an elementary vibrational mode in QM with the wave-particle duality.

Photon-phonon interaction

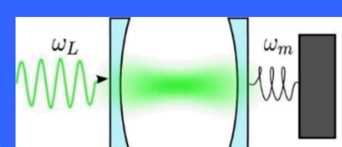
Raman scattering



Brillouin scattering



Opto-mechanics



Optically driven

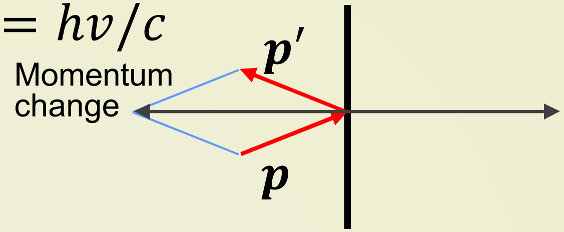
mechanical vibration

Yale

Optical Force 1: Radiation Pressure

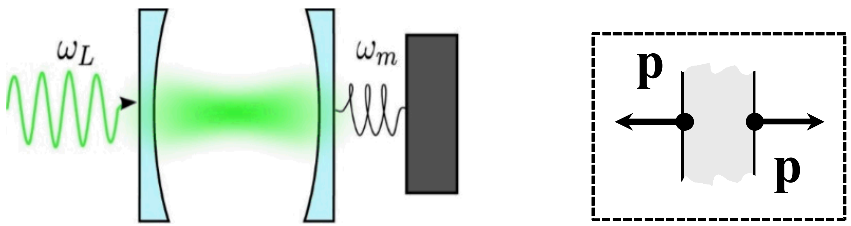
Radiation Pressure.

$$\boldsymbol{p} = \hbar\boldsymbol{k} = hv/c$$

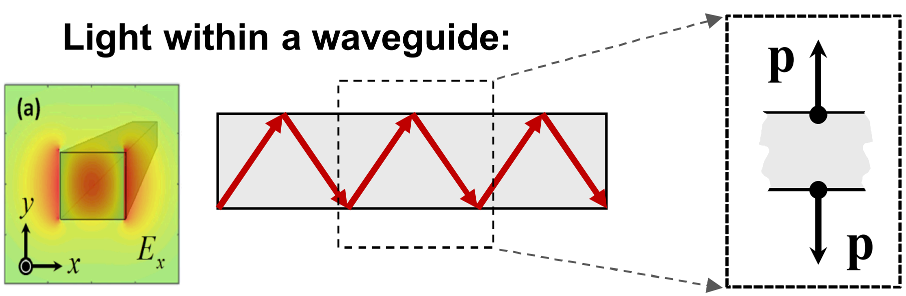


Radiation Pressure

Light within a cavity:



Light within a waveguide:



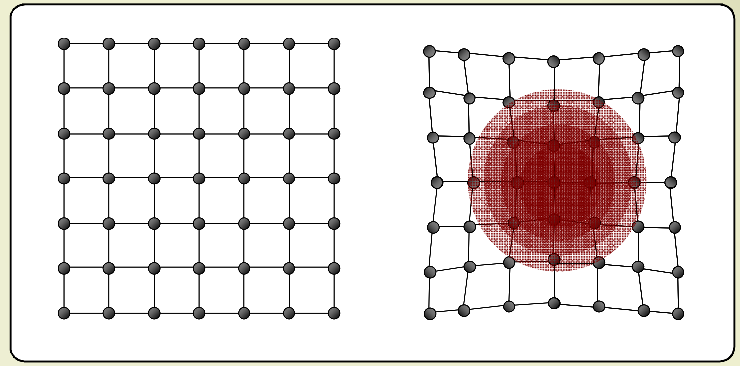
1. **Large at nanoscales.**
2. **Force localized to boundary.**
3. **Entirely depends on geometry.**

P. T. Rakich, et al., *Optics Letters* **36**, 217 (2011).
P. T. Rakich, et al., *Physical Review X* **2**, 011008 (2012).
W. Qiu, et al., *Optics Express* **21**, 31402 (2013).

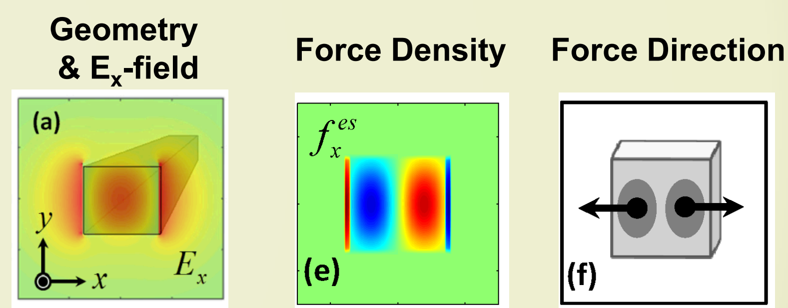
Optical Force 2: Electrostrictive Force

Electrostriction:

Dynamic response of media to light.



1. **Force distributed within volume.**
2. **Directed outward or inward.**
   - **Sign of p_{ijkl} constants**
3. **Depends on material.**
   - **Increases as n^4.**
   - **proportional to p_{ijkl} constants**



Net SBS effect

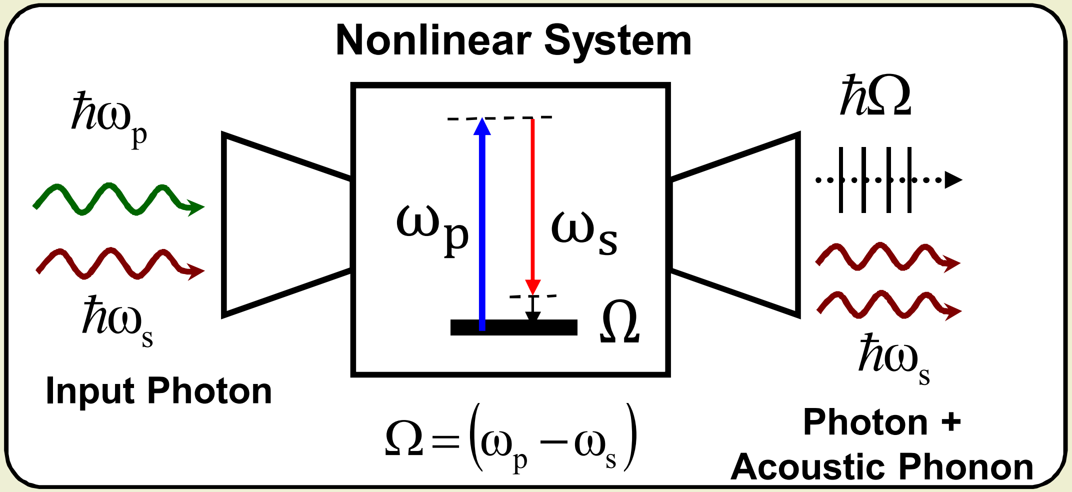
$$\propto \left(f^{ES} + f^{RP}\right)^2$$

SBS: Stimulated Brillouin scattering

P. T. Rakich, et al., *Optics Letters* **36**, 217 (2011).
P. T. Rakich, et al., *Physical Review X* **2**, 011008 (2012).
W. Qiu, et al., *Optics Express* **21**, 31402 (2013).

Stimulated Brillouin Scattering

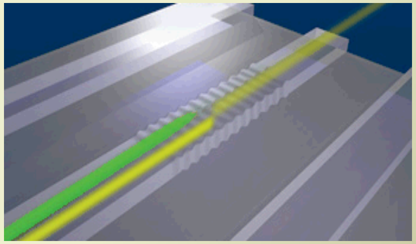
Light scattering from acoustic waves (phonons)



1. **Coupling between photons and acoustic phonons.**
2. **Absorbing a pump photon (ω_p).**
3. **Creating a Stokes photon (ω_s) and a GHz frequency phonon (Ω).**

Applications: narrow band amplifier, sensor, SBS laser, slow/fast light, etc.

Phase matching conditions ?

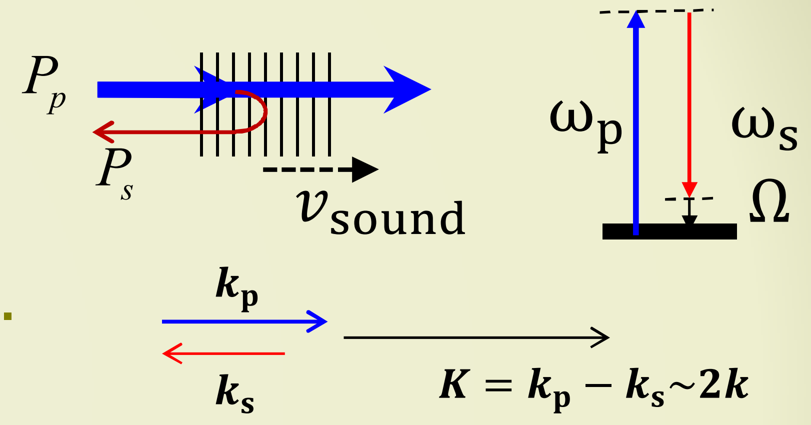


Kabakova, et al., OPN, Feb. 2015

SBS Phase matching condition - 1

Backward SBS

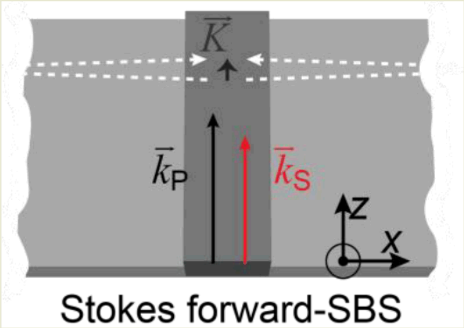
- **Light is scattered backward.**
- **Strong effect in optical fibers.**



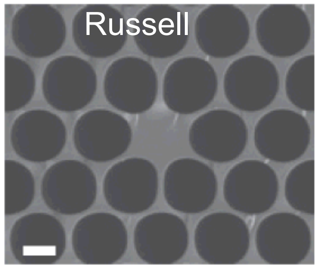
SBS Phase matching condition - 2

Forward SBS

- **Co-propagation**
- **Structure dependent resonant frequency**



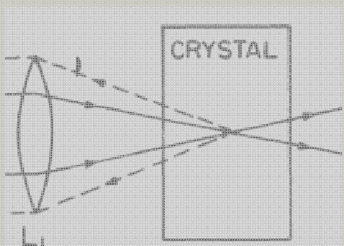
Strong forward SBS

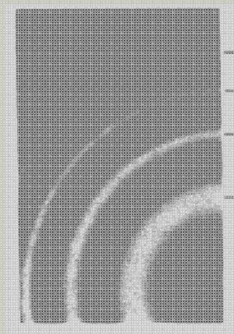


Kang, et al., Nature Phys. **5**, 276 (2009)

Timeline for SBS

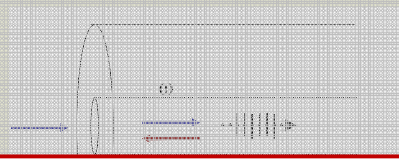
SBS in Bulk X-tal



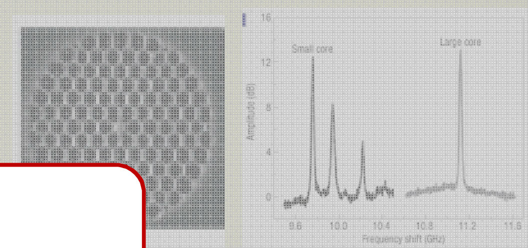


Chiao, PRL (1964)

SBS in Optical Fibers



SBS in Micro-Structured Fibers



e, Nat. Phys. (2006)

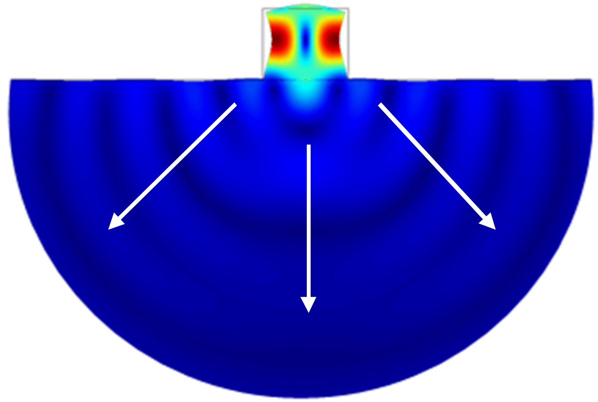
Macro →

Engineered

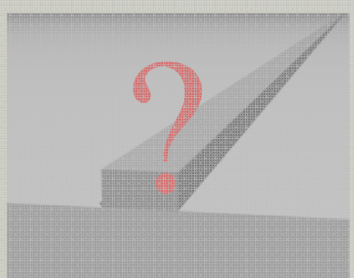
Trend: Brillouin interaction

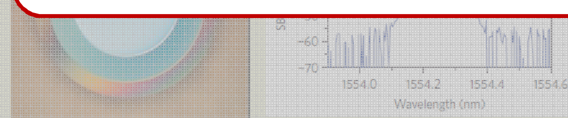
gth-scales

Phonon Dissipation



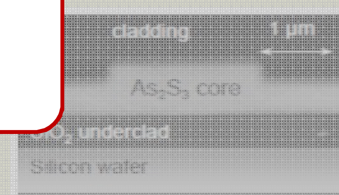
SBS in Silicon waveguide





Lee, Nat. Photonics (2012)

On-chip SBS



As_2S_3 waveguide

Pant, OE (2011)

↓ Waveguide ↓

Nano-structure ← Micro-structure

Trend: Photon-phonon waveguides at nanoscale can enhance SBS effects

Outline

1. Photon-phonon interaction & SBS

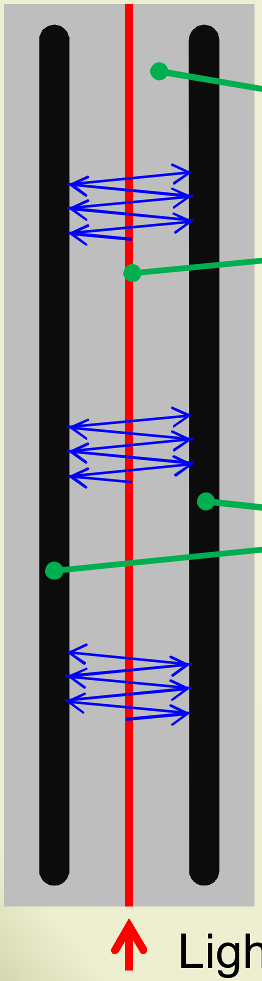
2. Brilloun Active Membrane waveguide

3. Photonic-phononic emitter-receiver

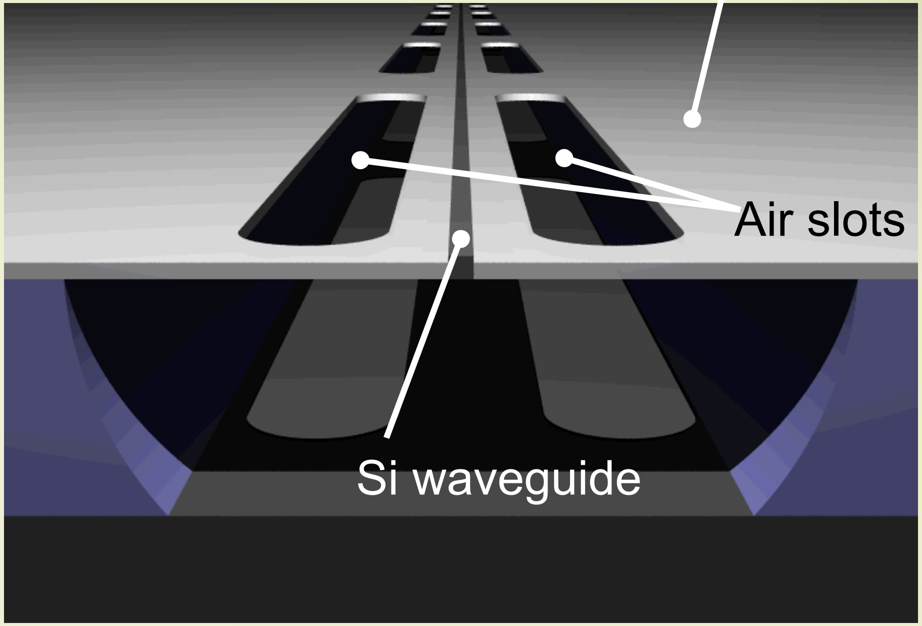
Yale

Creation of SBS in novel structure

Brillouin Active Membrane (BAM) waveguide



Each slot acts as a wideband phonon mirror.

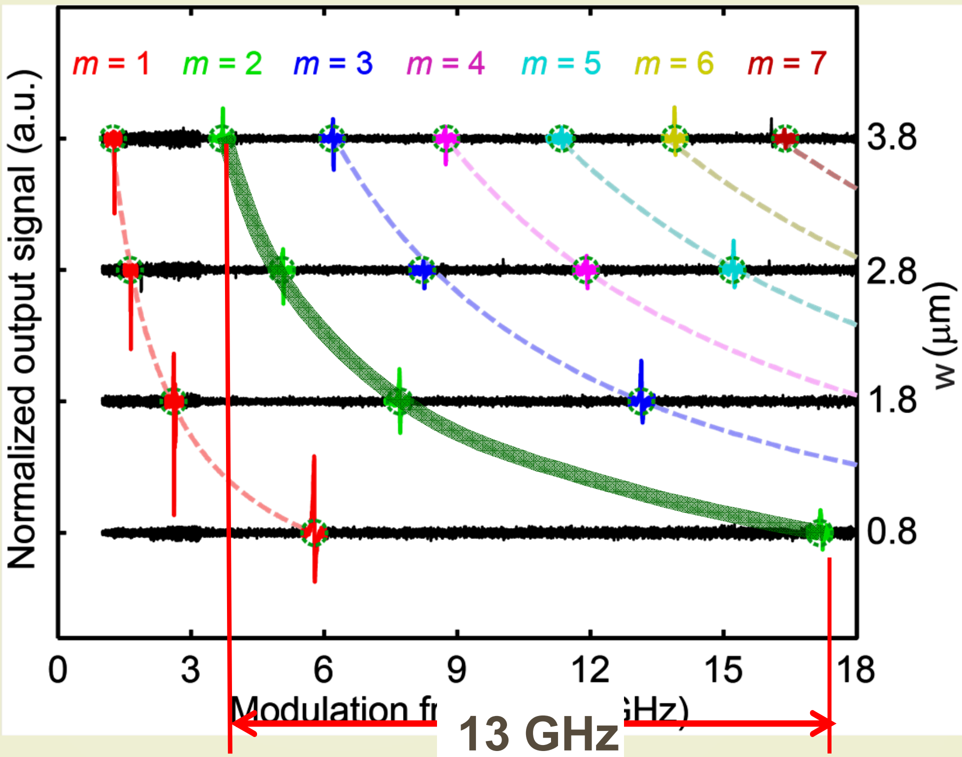


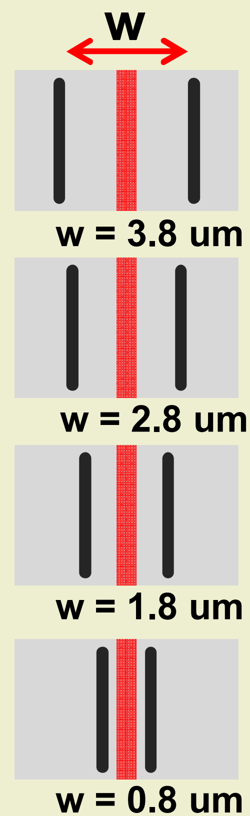
- Reducing phonon dissipation
- Photonic waveguide (silicon)
- Phononic waveguide (SiN between slots)
- Strong photon-phonon **confinement**

Shin, et al., Nature Comm. 4, 1944 (2013).

Tailorable SBS nonlinearity

By varying phononic waveguide dimension.

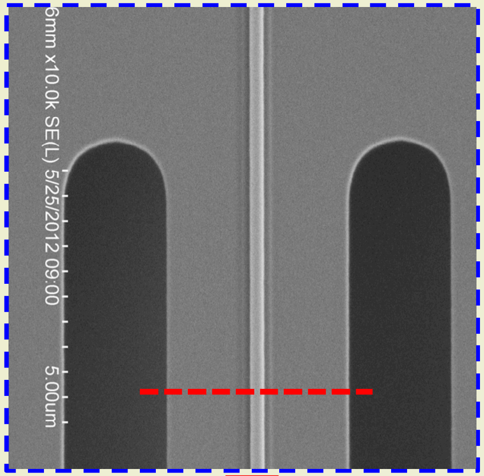


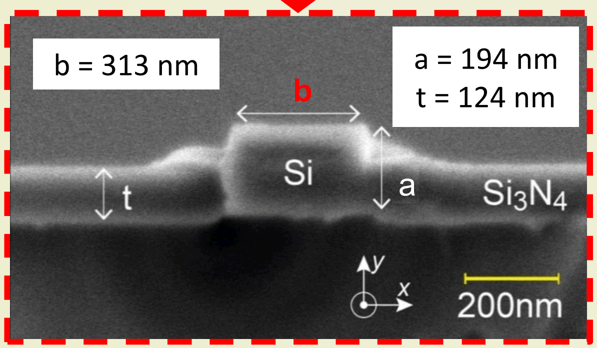


- As waveguide dimension increases, more guided modes are allowable.
- By lithographically varying waveguide dimension, the phononic resonant frequency is tuned by 13 GHz
- Unprecedented tailorability of nonlinearities

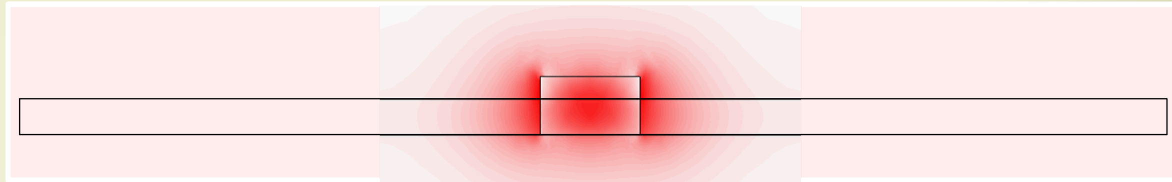
Nature Comm. 4, 1944 (2013).

Elastic wave displacement



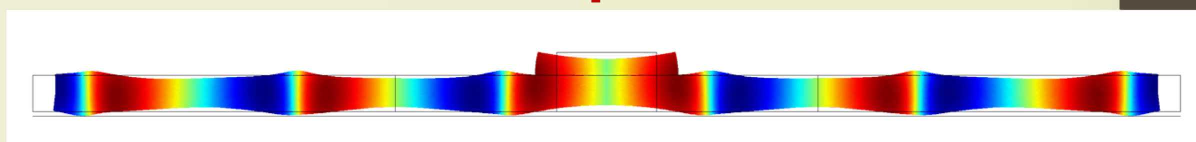


E-field distribution



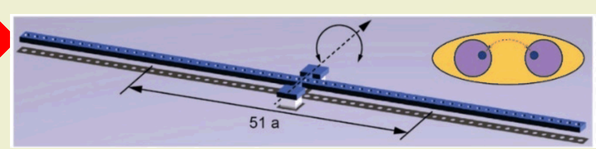
- **Photons are confined near the waveguide.**

Elastic wave displacement



- **Phonons are created in the optical waveguide.**
- **Phonons exists all over the membrane.**
- **Change at distinct place from pump light.**

Delocalized photon-phonon interaction.

➔ 

itter-receiver

Nat. Nanotech. 9, 913 (2014)
Nat. Nanotech. N&V, 9, 878 (2014)

Outline

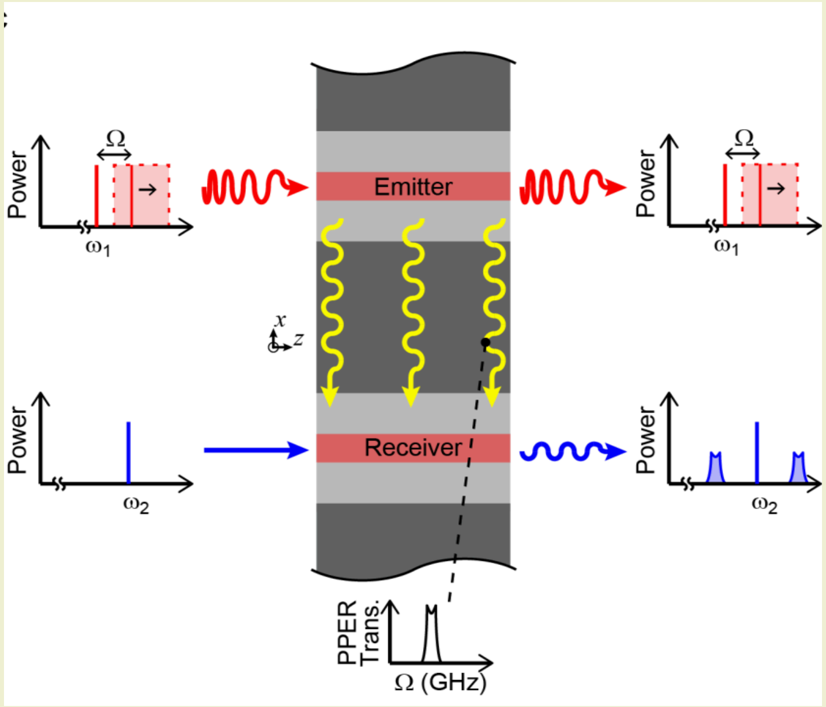
1. Photon-phonon interaction & SBS

2. Brilloun Active Membrane

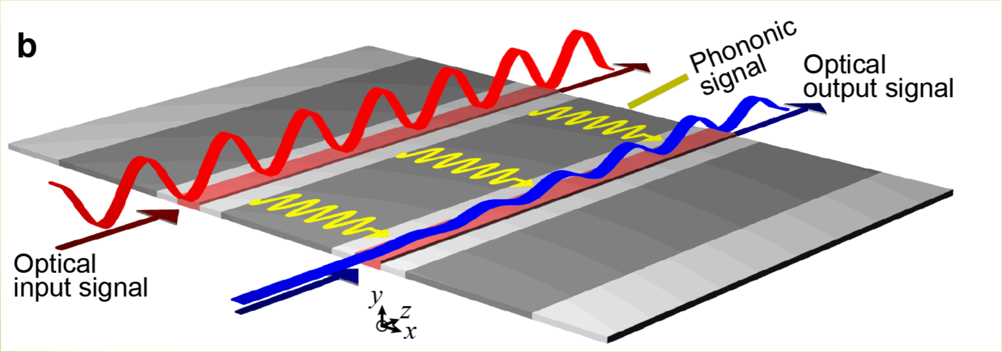
3. Photonic-phononic emitter-receiver

Traveling-wave photonic-phononic emitter-receiver (PPER)

Optical signals ➔ Phononic signals ➔ Phononic Filter ➔ Optical signals



- Dual channel BAM waveguides
- Selective information transduction between distinct waveguides
- Optical input signals ***emit*** phonons.
- Phonons with certain frequency range can be transferred to the ***receiver*** channel.
- Phonons impart a phase shift on the probe field.

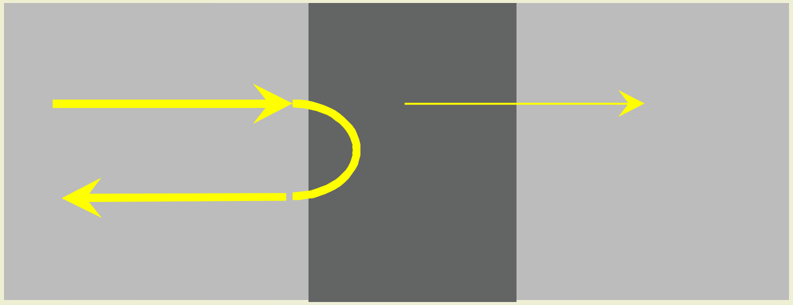


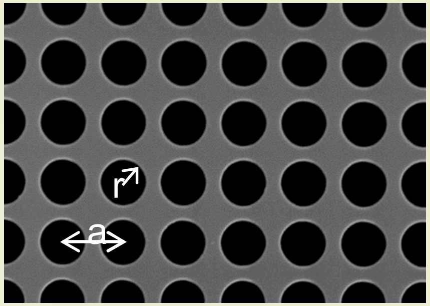
Yale

Lossy Phononic Mirror

Phononic mirrors with partial transmittance.

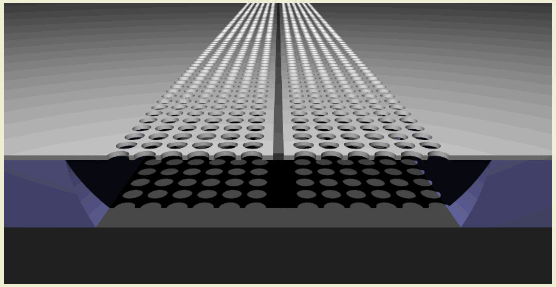
- Periodic pattern in 2D (square lattice)

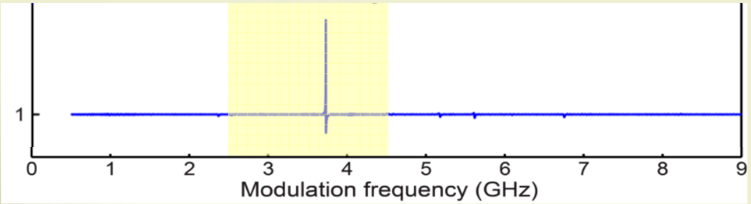




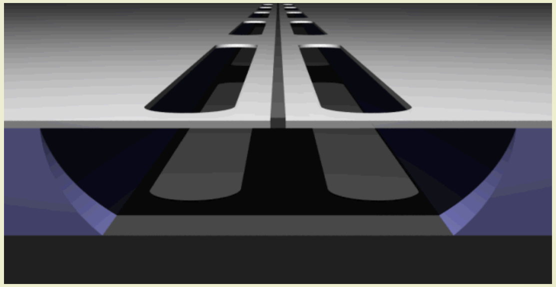
a = 1 μm
r = 0.385 μm

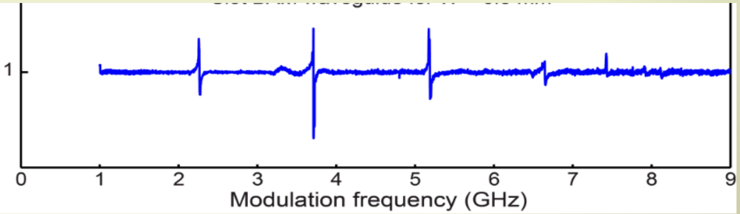
Phononic Bragg reflection



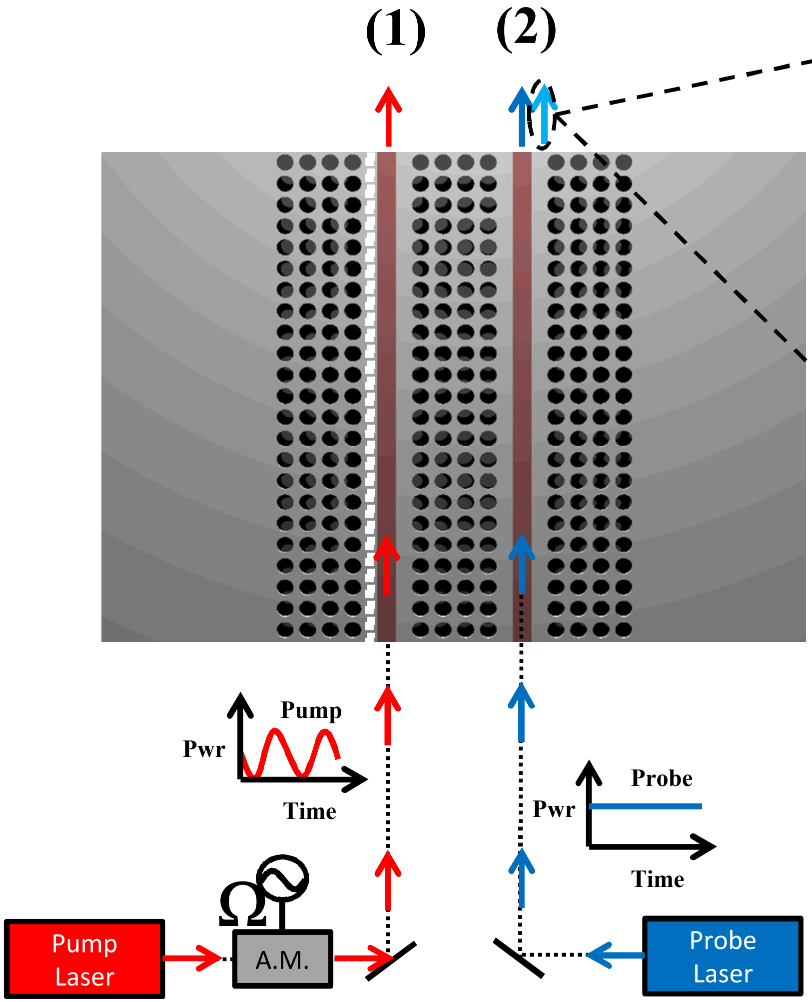


Impedance mismatching

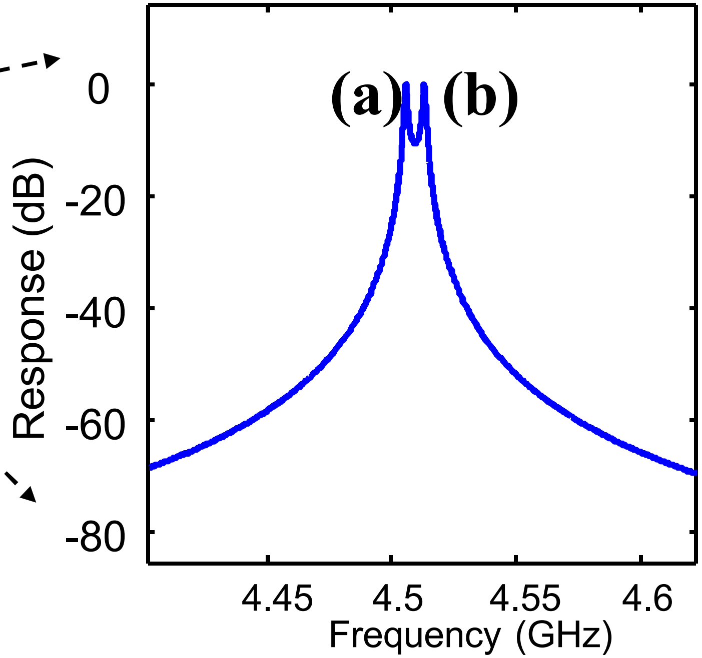




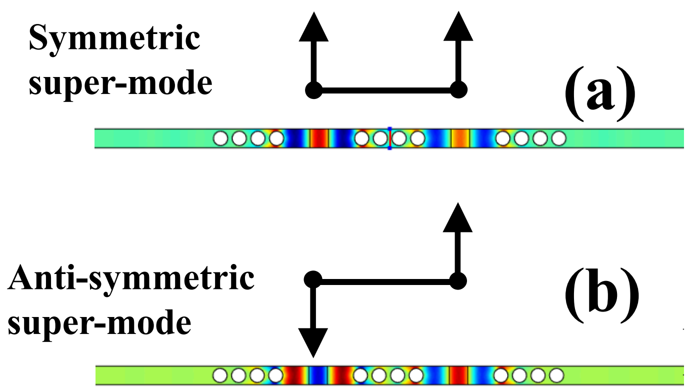
How does this PPER system work?



A.M = Amplitude Modulator



Phonon mediated energy transfer (i.e. filter response)



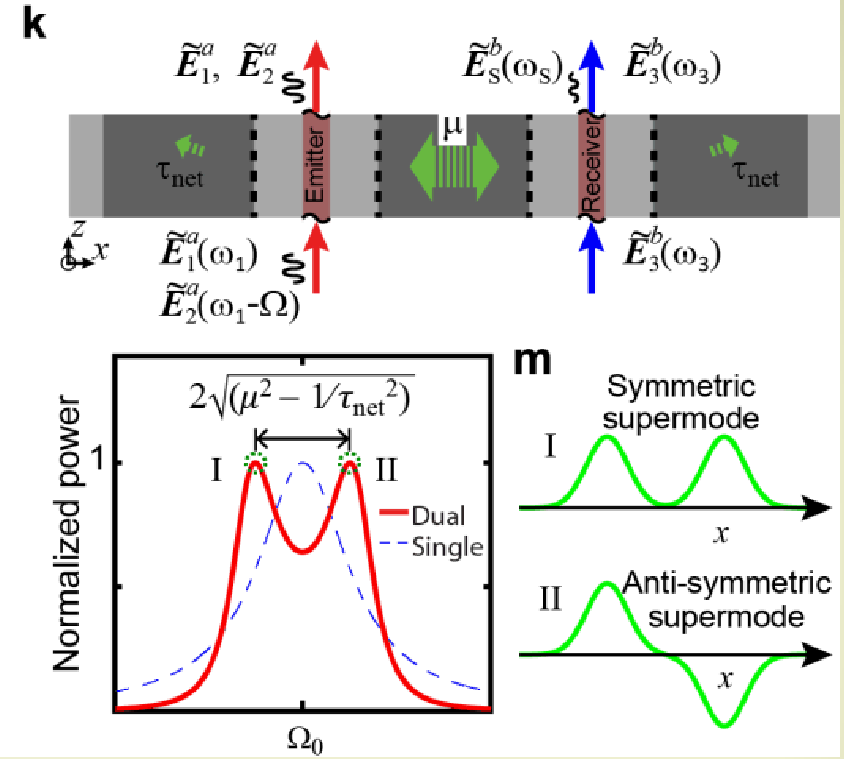
Brillouin-active phonon modes

Theoretical study of PPER system

Coupled mode theory

$$\frac{dc_a(t)}{dt} = -\left(i\Omega_0 + \frac{1}{\tau_{net}}\right)c_a(t) + i\mu c_b(t) + \eta(t)A_1A_2^*$$

$$\frac{dc_b(t)}{dt} = -\left(i\Omega_0 + \frac{1}{\tau_{net}}\right)c_b(t) + i\mu c_a(t)$$

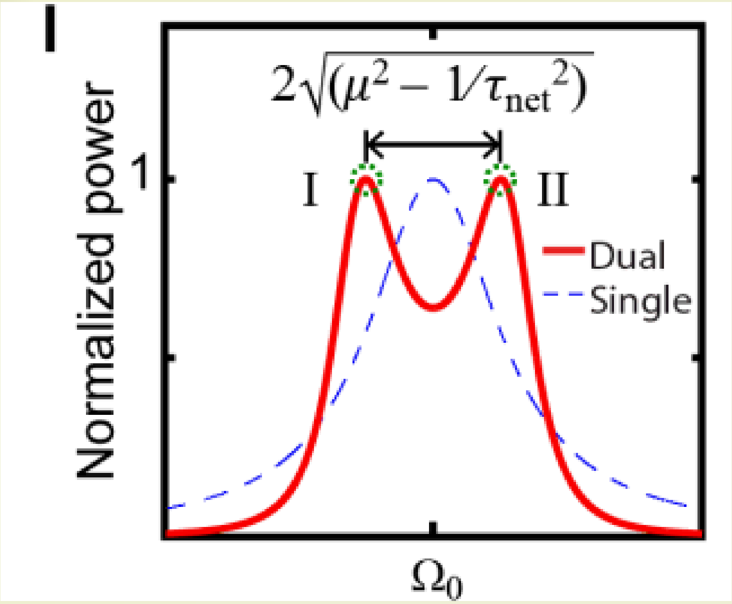


Nonlinear susceptibility
(or gain coefficient)

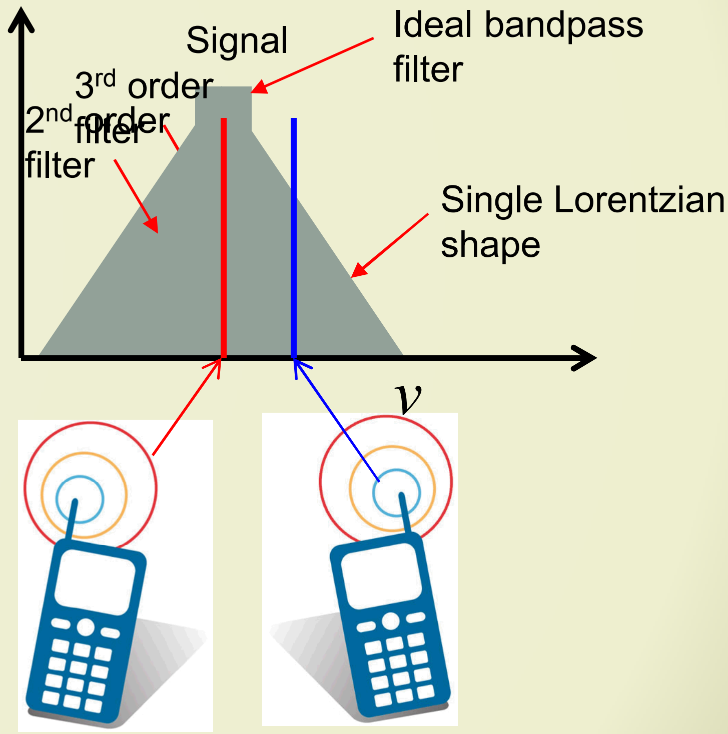
$$\gamma_{a\to b}(\Omega) = \left[\frac{\omega_3\tau_{net}}{2\Omega_0}\frac{\langle \mathbf{f}_n^a, \boldsymbol{e}_a\rangle\langle \boldsymbol{e}_b, \mathbf{f}_n^b\rangle}{\langle \boldsymbol{e}_a, \rho\boldsymbol{e}_a\rangle}\frac{2\mu/\tau_{net}}{\left[\Omega-\Omega_0-\sqrt{\mu^2-1/\tau_{net}^2}\right]\left[\Omega-\Omega_0+\sqrt{\mu^2-1/\tau_{net}^2}\right]}\right].$$

$$P_s^b = |\gamma_{a\to b}(\Omega)|^2 P_1^a\, P_2^a\, P_3^b\, L^2$$

Filters with the second order response function

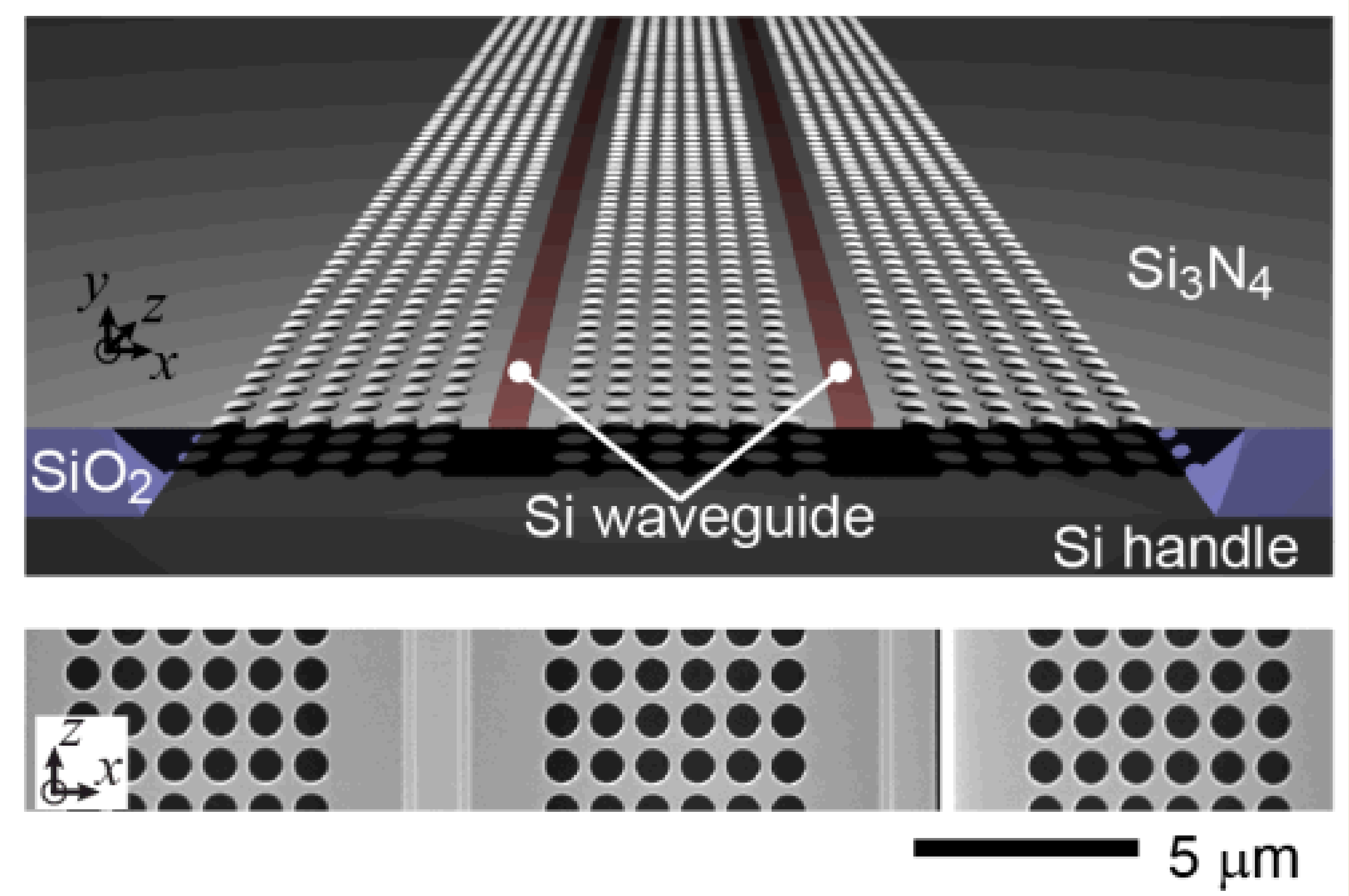


Second order response filter



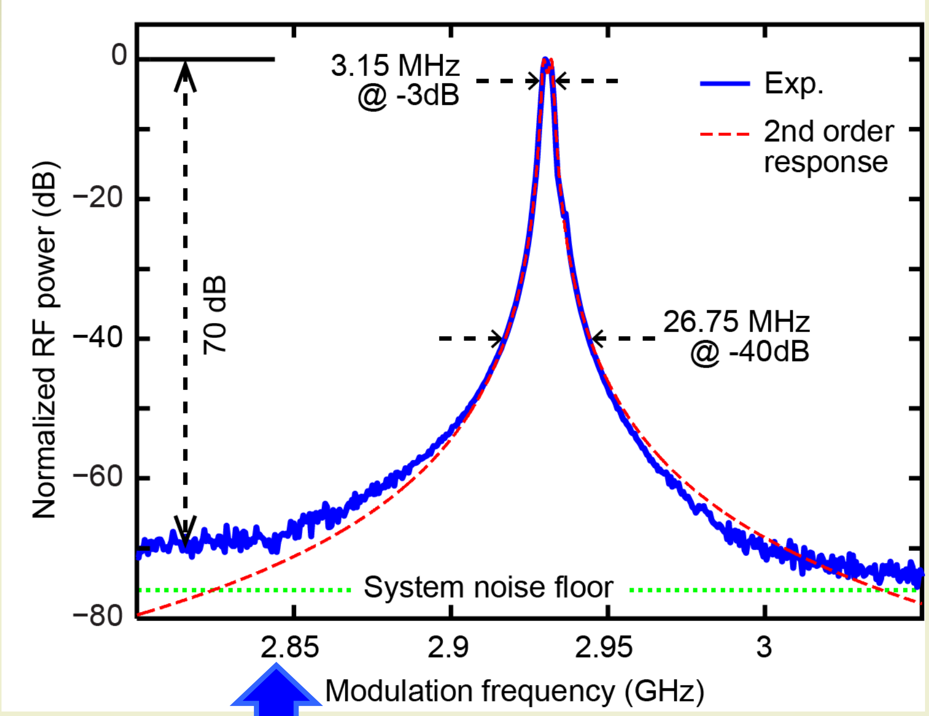
Sharp drop-off (high selectivity)

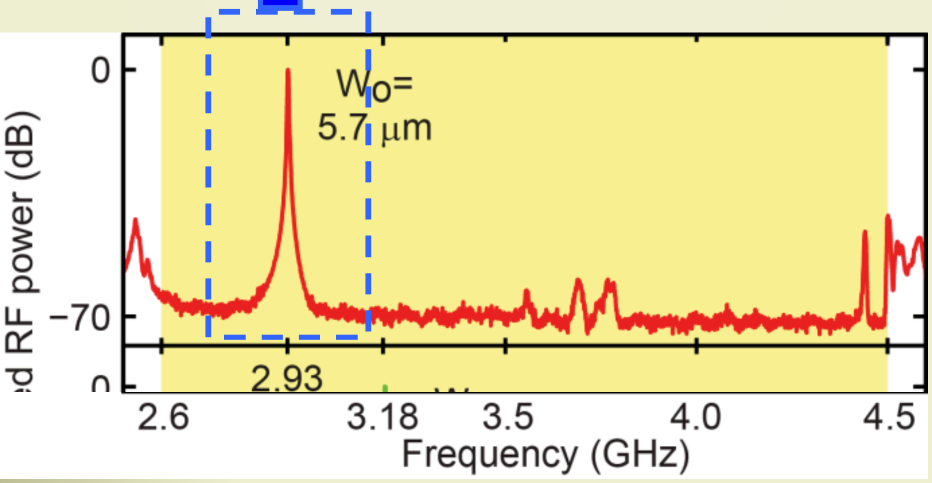
Traveling-wave photon-phonon emitter-receiver



Photonic-phononic emitter-receiver (PPER)

RF response of a PPER pair





Center frequency, f_o = 2.93 GHz

3-dB bandpass bandwidth, B = 3.15 MHz

Stopband attenuation, A > 70 dB

Rejection bandwidth, B_R = 1.9 GHZ

High power handling, 36 mW

(110 mW for 3 dB/cm loss)

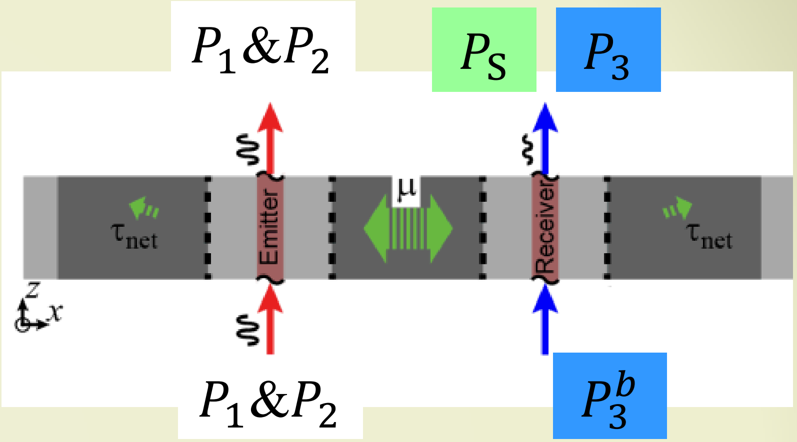
Laser bandwidth, 5 MHz

Wavelength 1535 nm & 1546 nm

Pump power dependence

- Peak signal conversion efficiency

$$\frac{\text{Created Stokes power}}{\text{Transmitted Probe power}} = \frac{P_s^b}{P_3^b}$$



$$P_s^b = |\gamma_{a\to b}(\Omega)|^2 P_1^a\ P_2^a\ P_3^b\ L^2$$

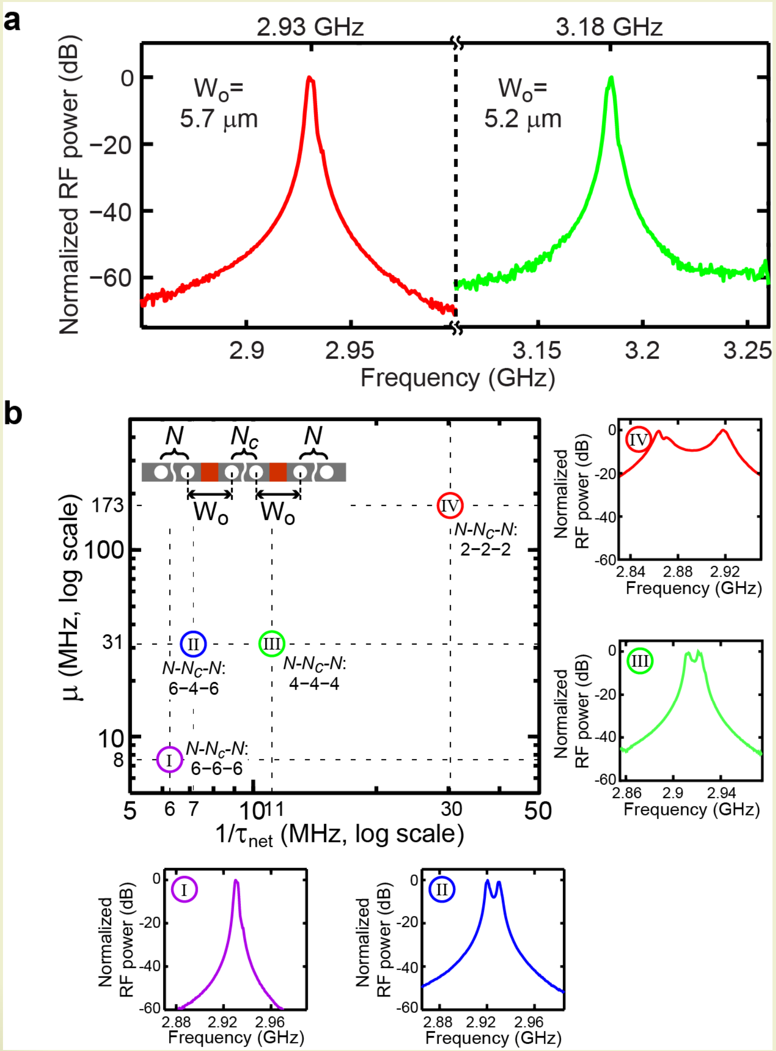
Scalable conversion efficiency

$\frac{P_s^b}{P_3^b} \propto Length^2$ $\frac{P_s^b}{P_3^b} \propto gain^2$ $\frac{P_s^b}{P_3^b} \propto Pump\ power^2$ $\frac{P_s^b}{P_3^b}$

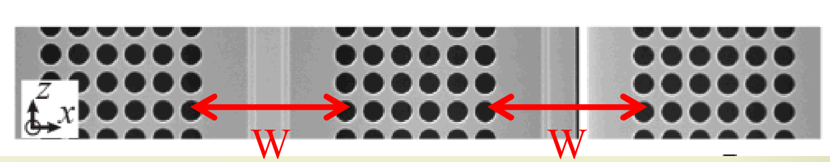
$L = 7$ mm $G = 800\ \mathrm{m^{-1}W^{-1}}$ $P_1^a = P_2^a = 3.5$ mW 0.01%

$P_1^a = P_2^a = 36$ mW 1%

Engineering RF response of a PPER pair



- Desired center frequency



- By changing the phononic waveguide dimension, W.
- Peak separation varies with the number of PnC hole layers between two waveguides by changing phononic coupling ratio.
- Bandwidth varies with the number of outer PnC hole layers by changing phonon lifetime.

Comparison with all-optical photonic filters

RF Photonic Filters by All-optical methods

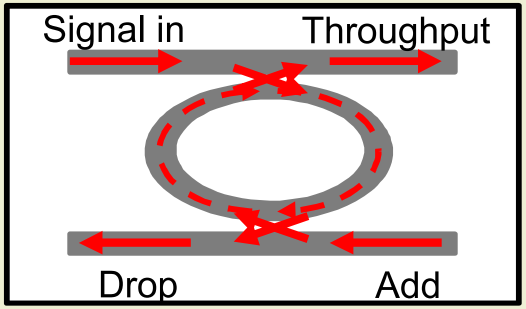
Asymmetric MZI

Whispering gallery mode resonator

Bragg grating

Ring resonator

- Resonator based optical filters

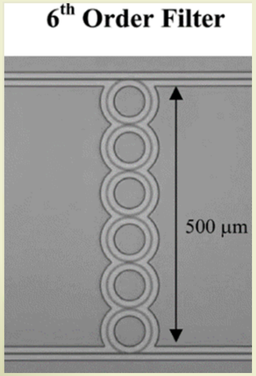


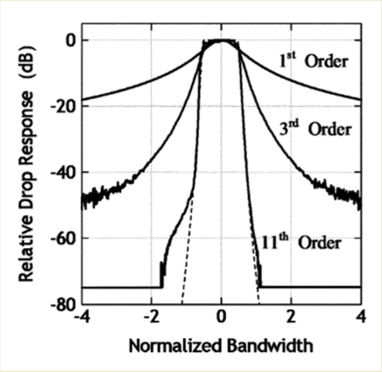
Requires high optical Q (~10^8).

Low power handling.

Requires frequency locking.

First order response.





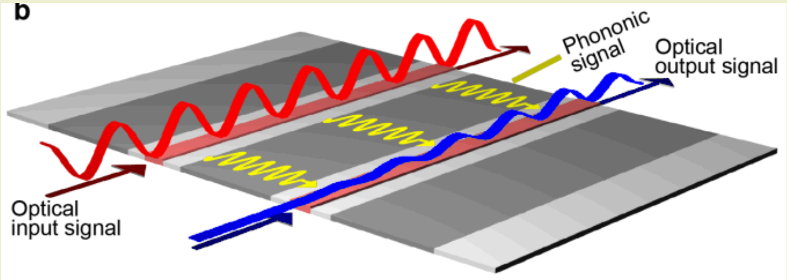
Higher order response.

Difficult to fabricate coupled ring resonators.

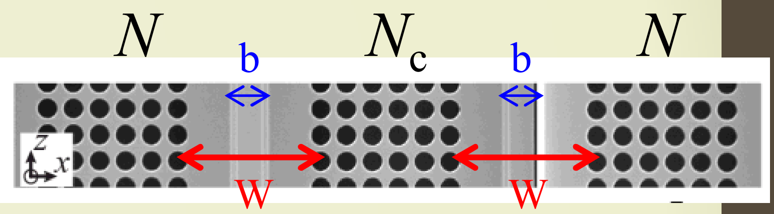
Low power handling & frequency locking.

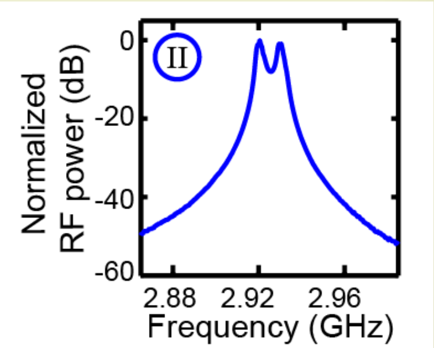
IEEE Phot. Tech. Lett. 16, 2263 (2004)

PPER as an RF photonic filter



- Wavelength (and bandwidth) insensitivity
- High power handling
- Independent control of photonic and phononic modes
- Narrow bandwidth (high selectivity) with high Q factor
- Multiport system with 2nd order response function
- High dynamic range
- Compatible with CMOS technologies

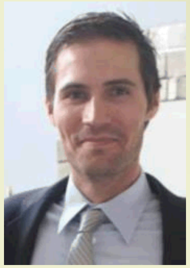




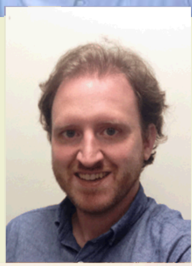
H. Shin, J. Cox, R. Jarecki, A. Starbuck, Z. Wang, and P.T. Rakich, "Control of coherent information via on chip photonic-phononic emitter-receivers," Accepted to Nature Communications (ArXiv:1409.0580 [physics.optics])

Thank you

- Prof. Peter T. Rakich

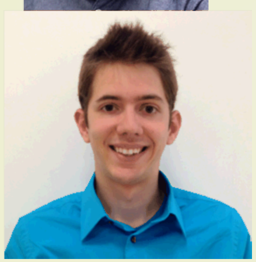


- Dr. Ryan Behunin



- Dr. William Renninger

- Prashanta Kharel



- Eric Kittlaus

- Erik Stassen

Yale | Sandia National Laboratories | UT ECE | DARPA — Bridging the Gap, Powered by Ideas | LDRD — Laboratory Directed Research & Development

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. This work was supported by the DDRE under Air Force Contract No. FA8721-05-C-000.