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Nano-Scale Optomechanical Devices and Phononic Crystals for RF Signal Processing

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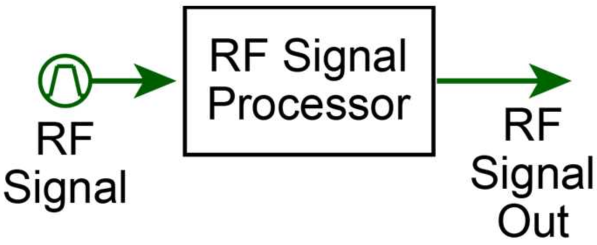
RF Signal Processing

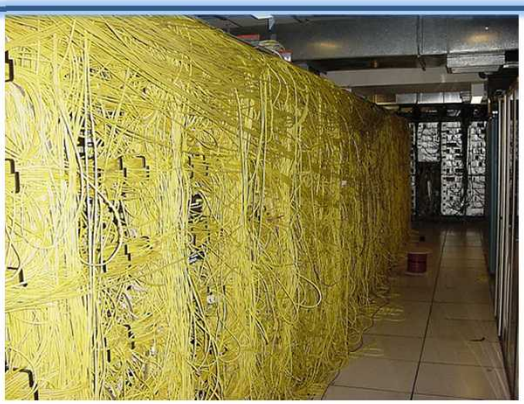
RF Electronics



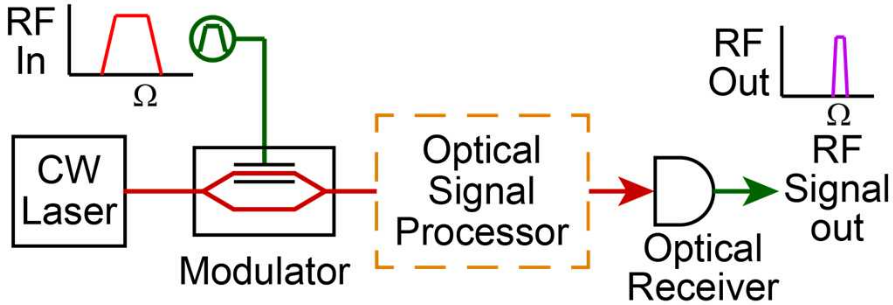
- Filters
- Time delay line
- Phase shifter
- Frequency converter
- Etc.

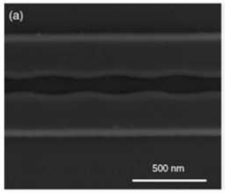
- Generally must be comparable in size to the RF wavelength
- SWaP increases with performance

RF Photonics

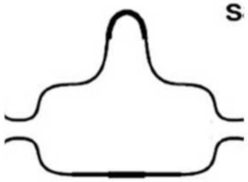


- Very large inherent bandwidth (>100THz)
- Integrated photonics could yield dramatic size and power reductions

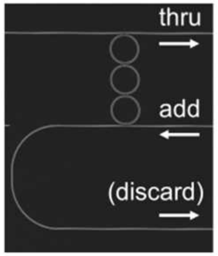




Bragg grating



Asymmetric MZI



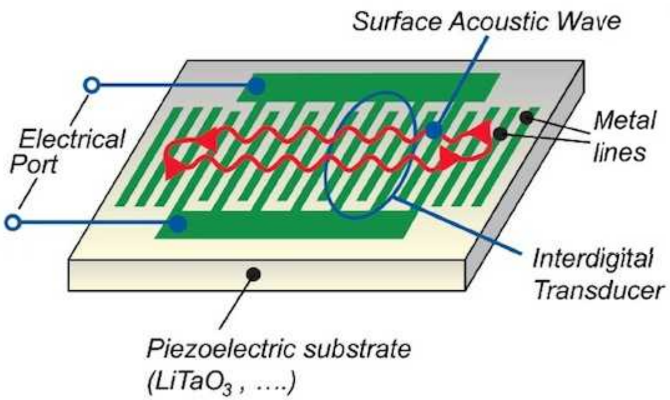
Ring resonator

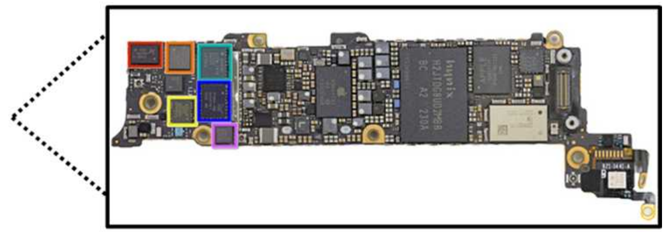
Whispering gallery mode resonator

RF MEMS

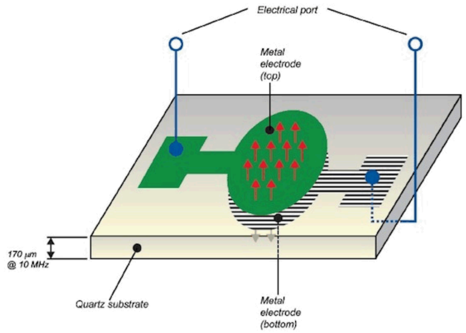
Acoustic (Phononics) Devices

SAW < 3GHz





Bulk Acoustic Wave (BAW) > 3GHz

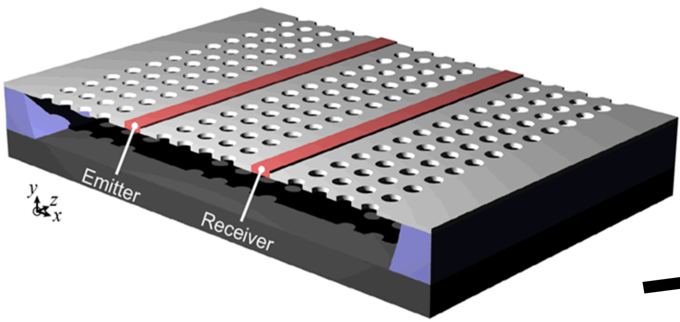


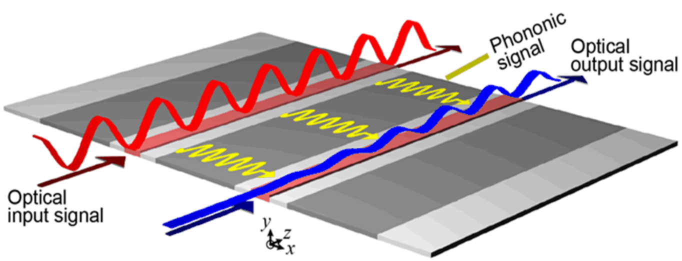
- Surface acoustic wave (SAW) devices:
  - Sound ~10,000x slower than light
  - Lifetimes 10^{-3} to 10^{-6} seconds
  - Low-frequency stability

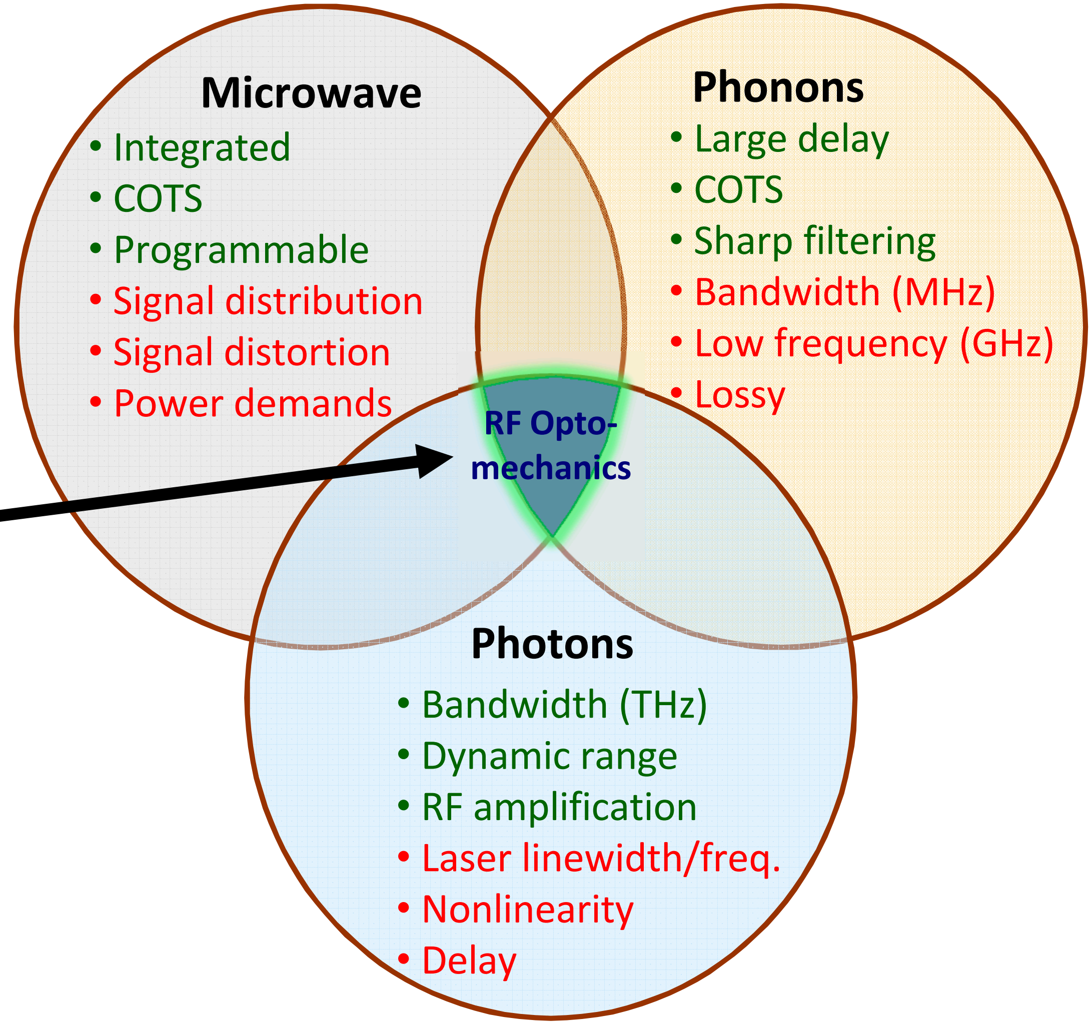
Example: Narrow-band filtering and compact signal delay routinely achieved with SAW technology

Signal Processing with Optomechanics

Photonic-Photonic RF Platform

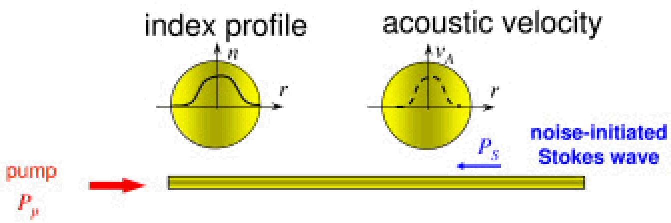


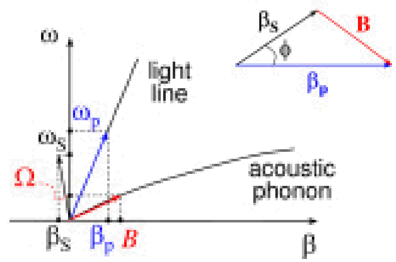


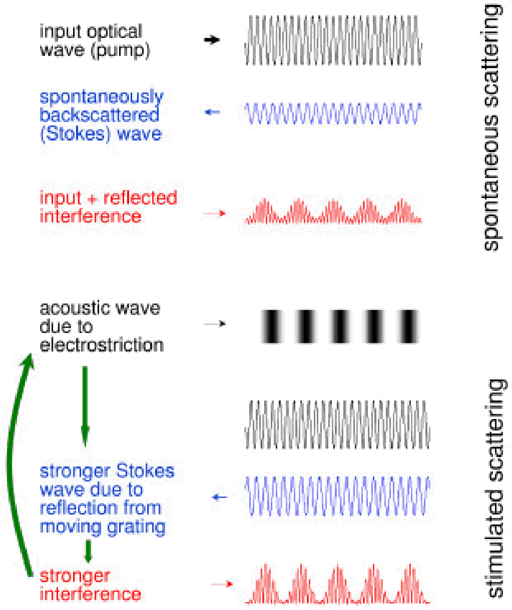


Stimulated Brillouin Scattering (SBS)

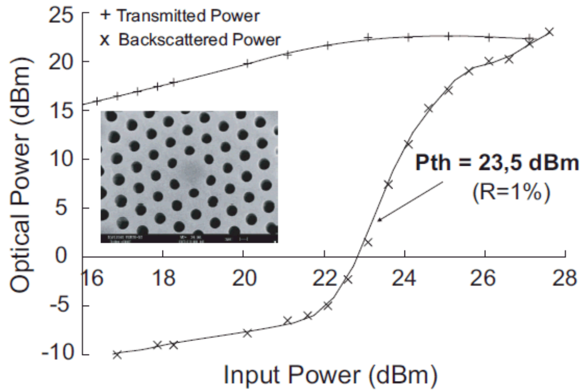
- Backward SBS typically seen in optical fiber
  - Third-order nonlinear optical process
  - Mediated by electrostriction
  - Strong confinement of longitudinal acoustic modes allows for long-range interactions





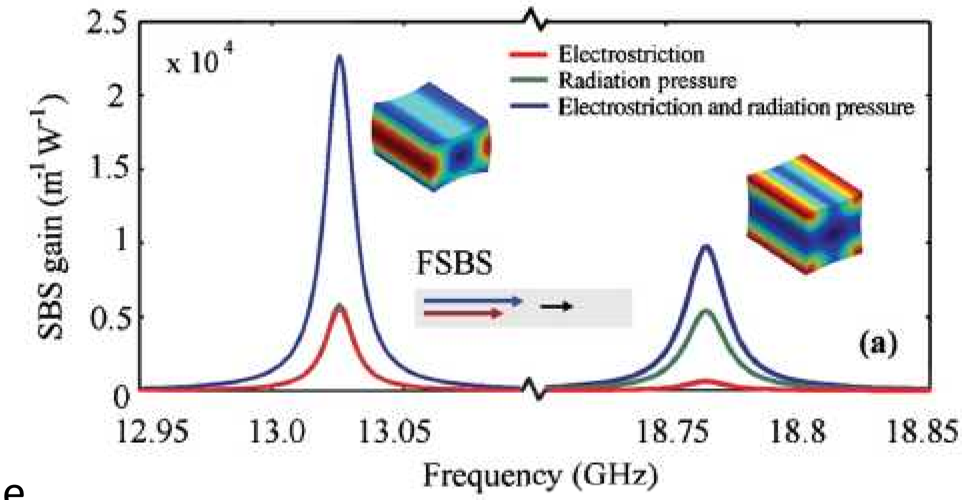


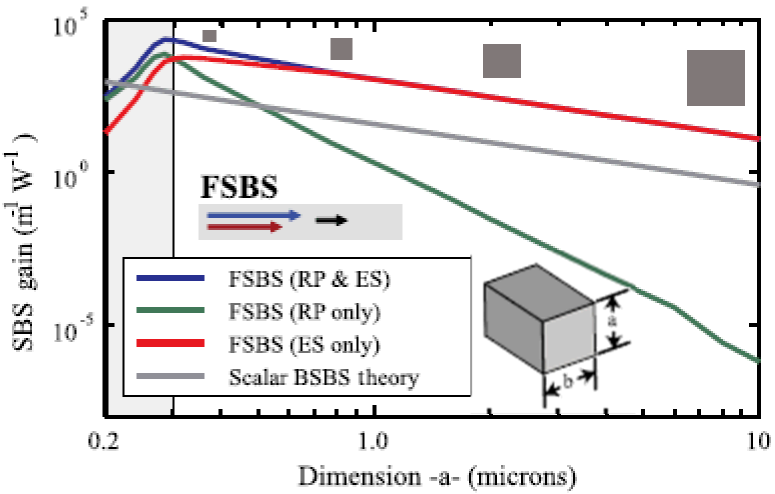
- Forward SBS recently observed in photonic crystal fiber
  - Transverse acoustic confinement enables new coupling mechanisms

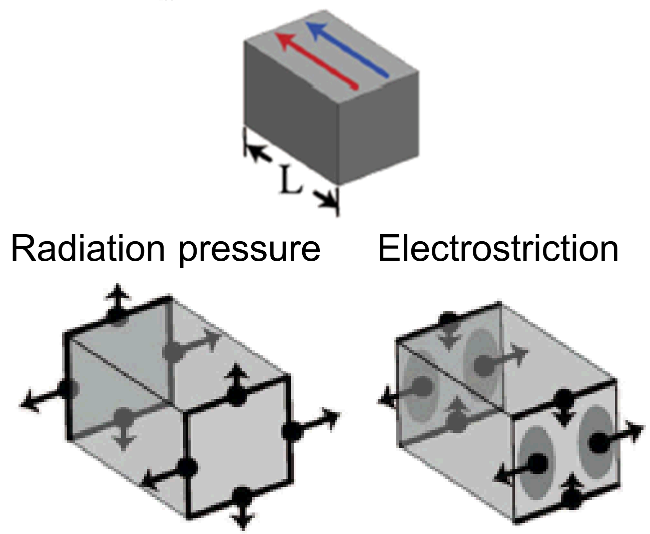


Enhancement of SBS

- Combination of electrostriction and radiation pressure more than double optomechanical forces
- Microscale SBS theory under-predicts nanoscale optomechanical forces
  - Nanoscale geometric effects
  - Different photoelastic coefficients
- Nanoscale forces 100x larger than microscale prediction ➔ SBS gain ~$4{\cdot}10^{3} m^{-1}W^{-1}$



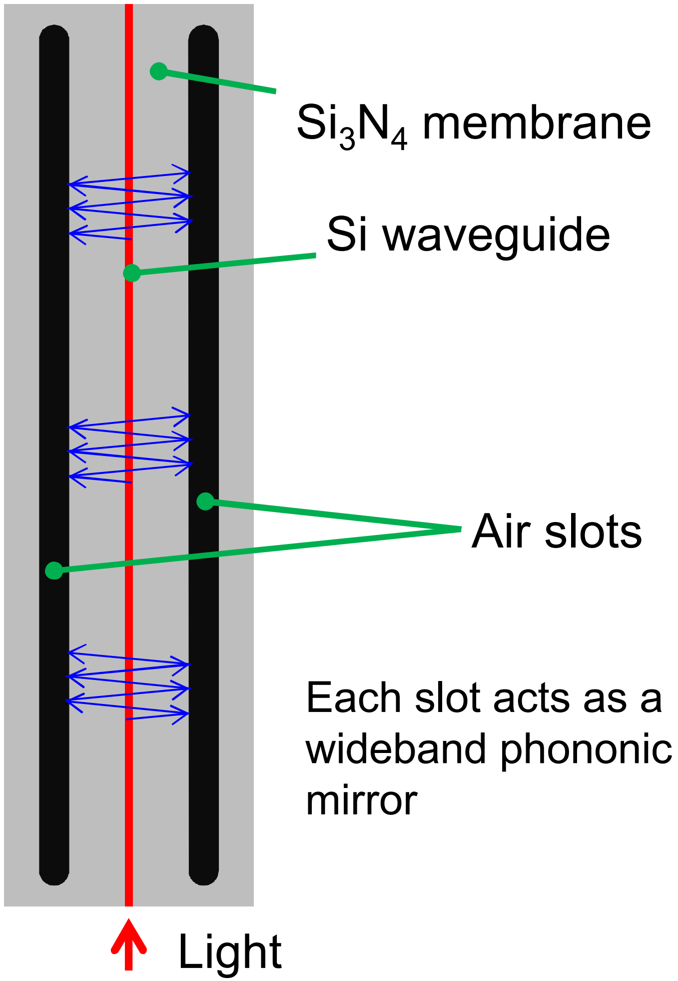


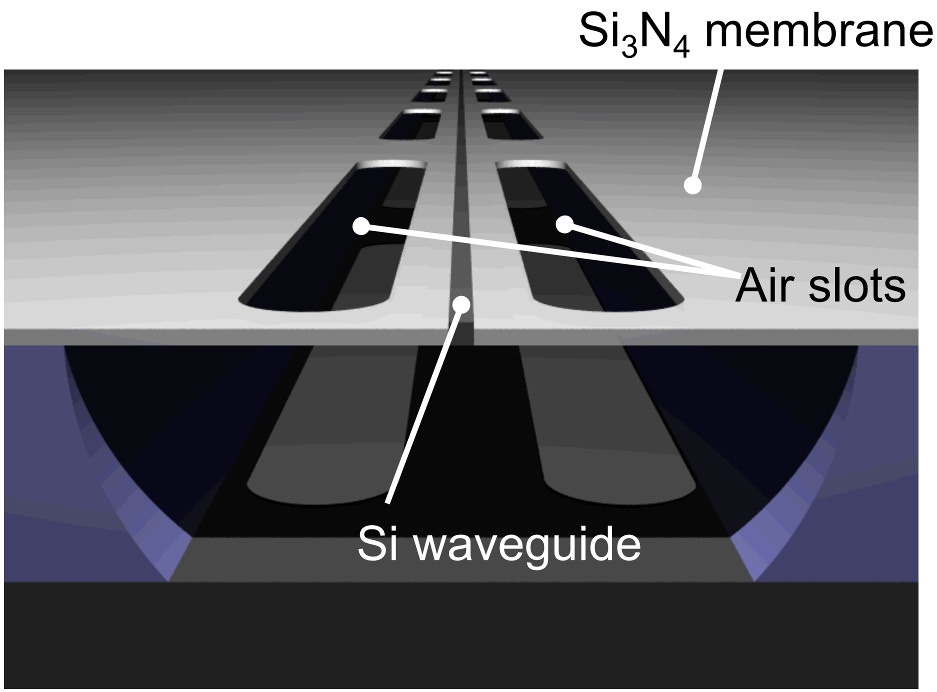


Rakich, *et al.*, *Phys. Rev X* **2**, 011008 (2012)

Chip-Scale SBS Structures

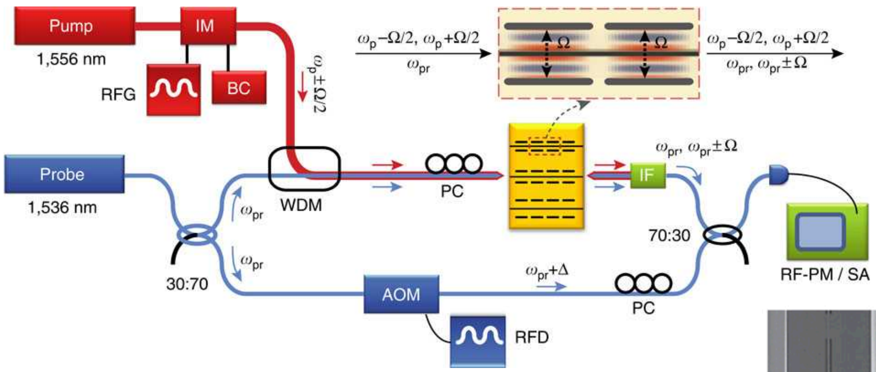
Brillouin-active membrane and waveguide

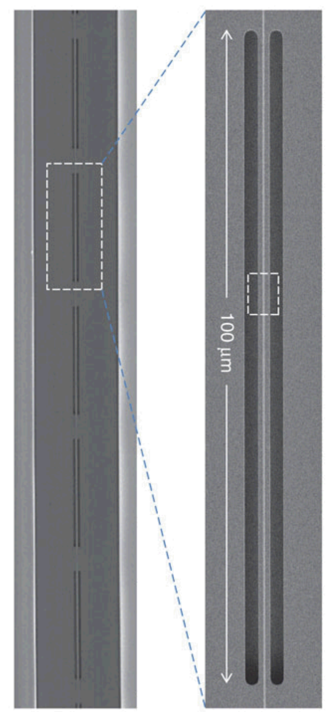




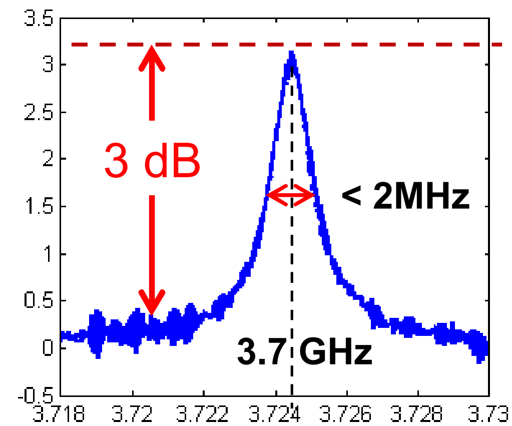
- Reducing phonon dissipation
- Photonic waveguide (silicon)
- Phononic waveguide (SiN between slots)
- Strong photon-phonon **confinement**

Chip-Scale SBS Amplification

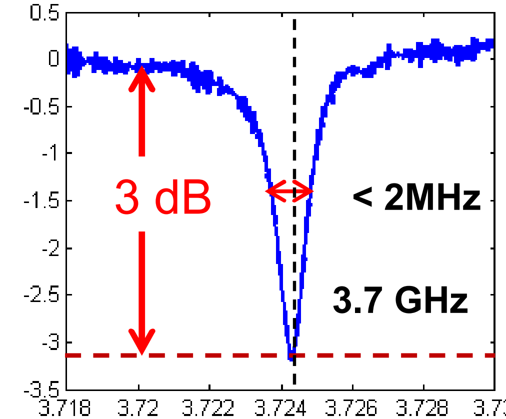




Stokes: Amplification



Anti-Stokes: Depletion



Phononic Crystal BAM waveguide

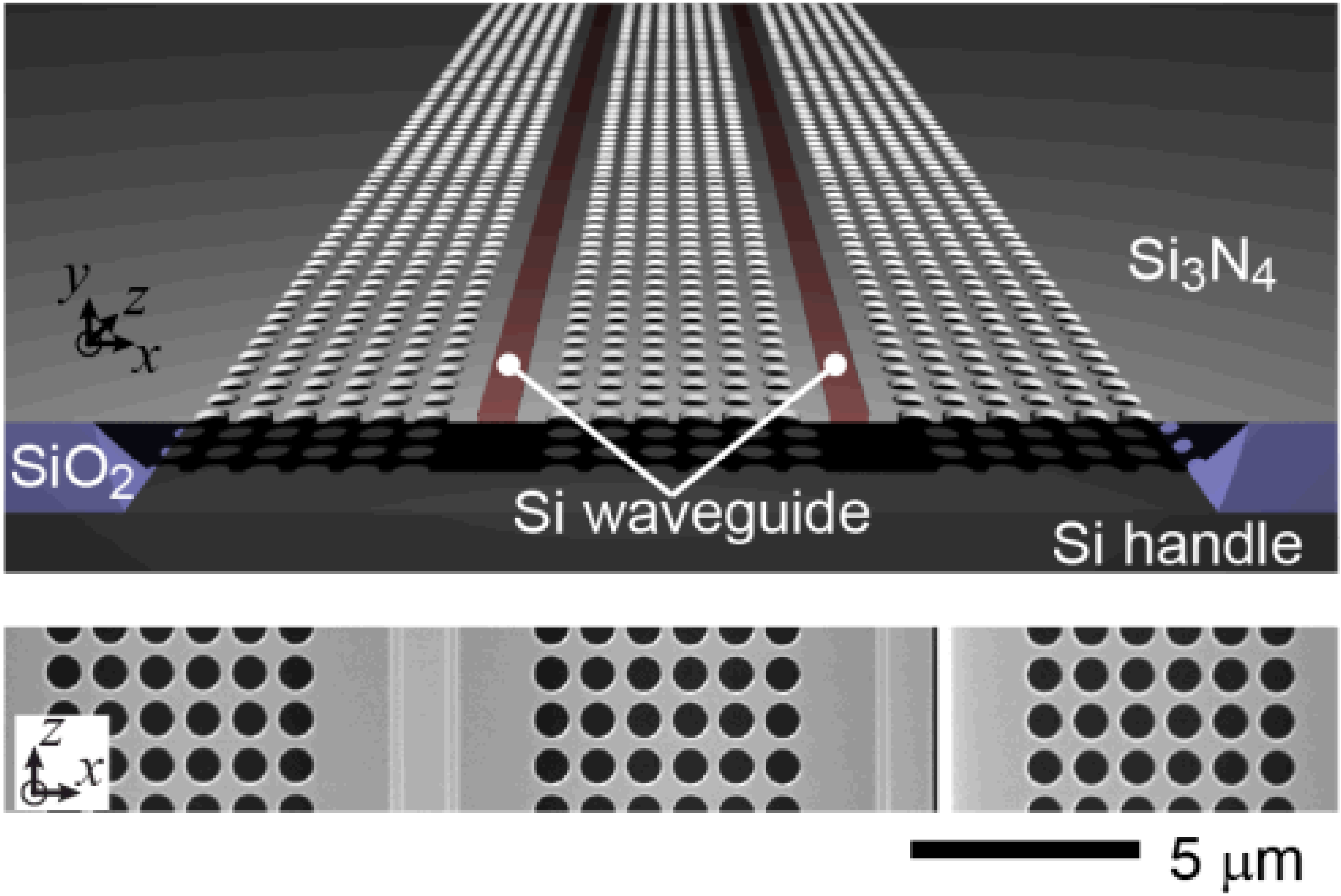
- Bragg reflection guides phonons
- Silicon waveguide ➔ 1um wide
- Low propagation loss ➔ ~0.5dB/cm

Results:

- High power handling ➔ 300mW
- Brillouin nonlinearity ➔ ~5x Kerr
- Gain ➔ 2750$W^{-1}m^{-1}$

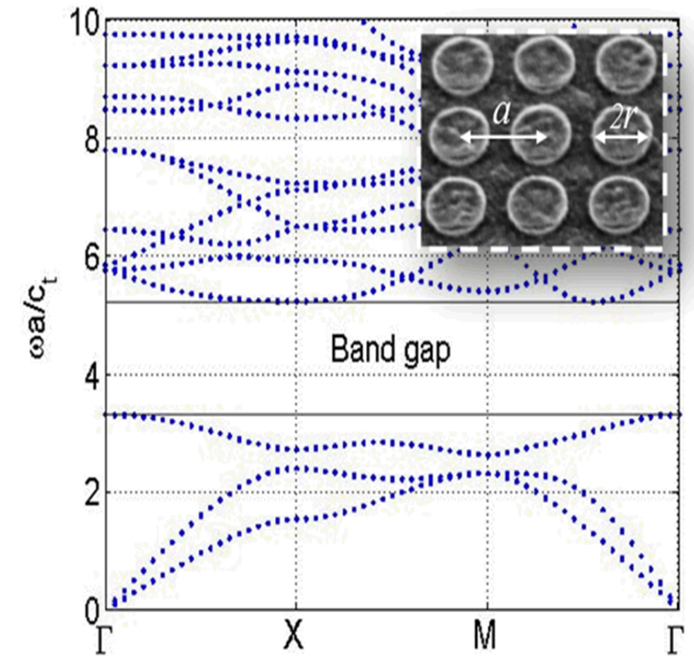
Shin, *et al.*, *Nat. Comm.* **4**, 1944 (2013)

Photon-Phonon Emitter-Receiver (PPER)



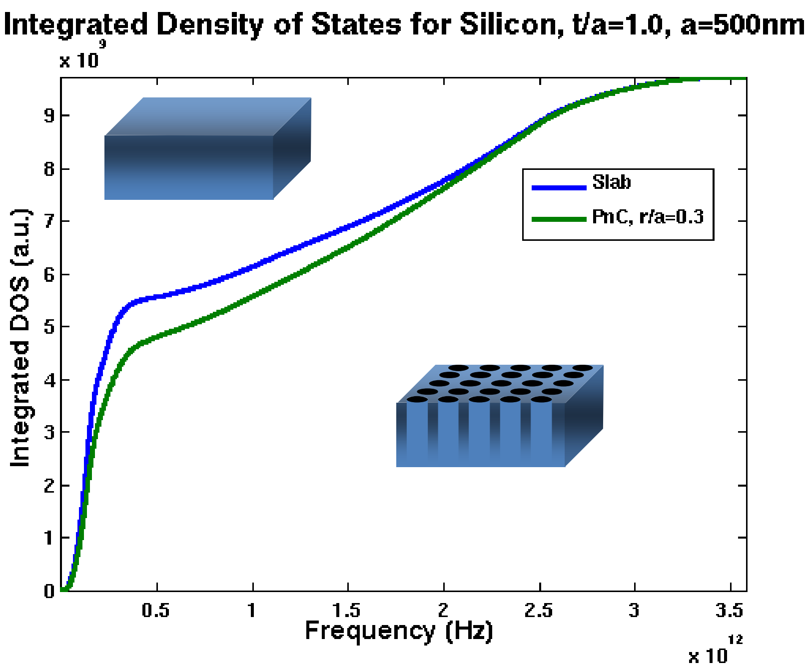
Photonic-phononic emitter-receiver (PPER)

Phononic Crystals (PnCs)

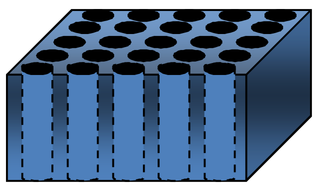


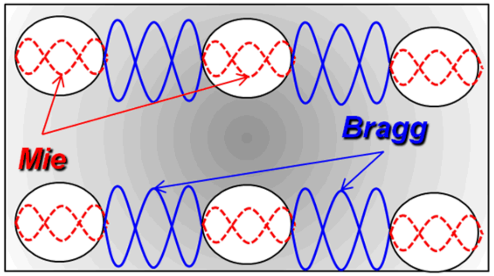
What are phononic crystals?

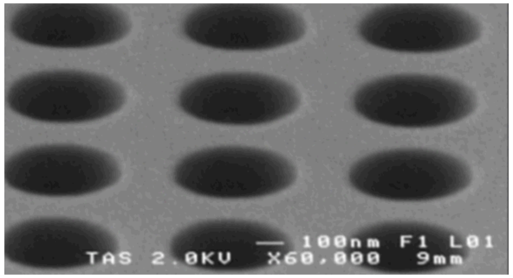
- Periodic arrangement of elastic scattering centers in a matrix material that exhibits both incoherent and Mie and Bragg resonant scattering
- Requires sufficient mechanical impedance mismatch



PnC

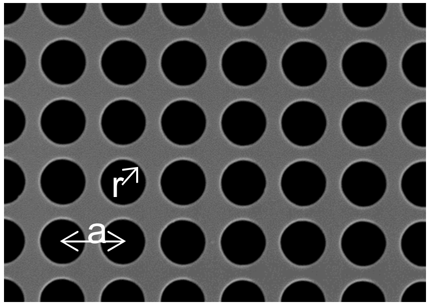




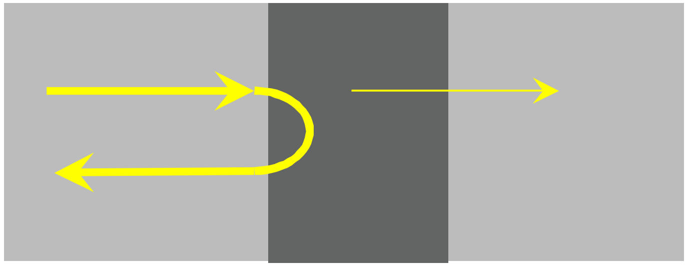


Phononic Crystals (PnCs)

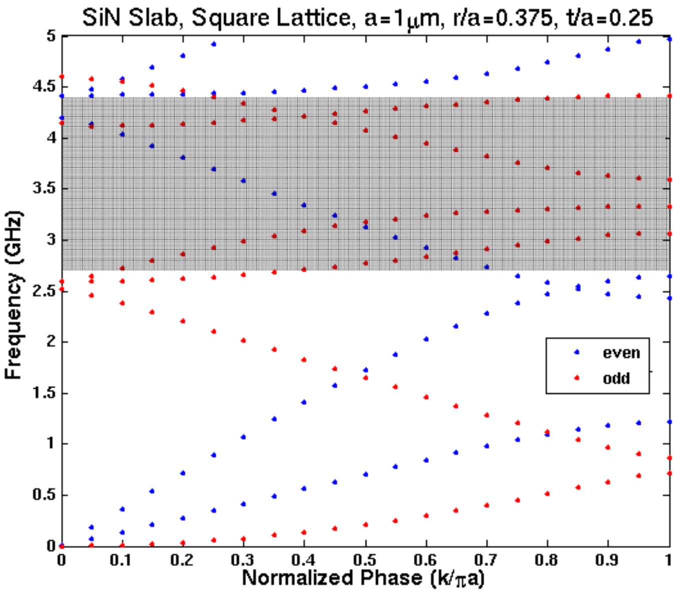
Square lattice PnC

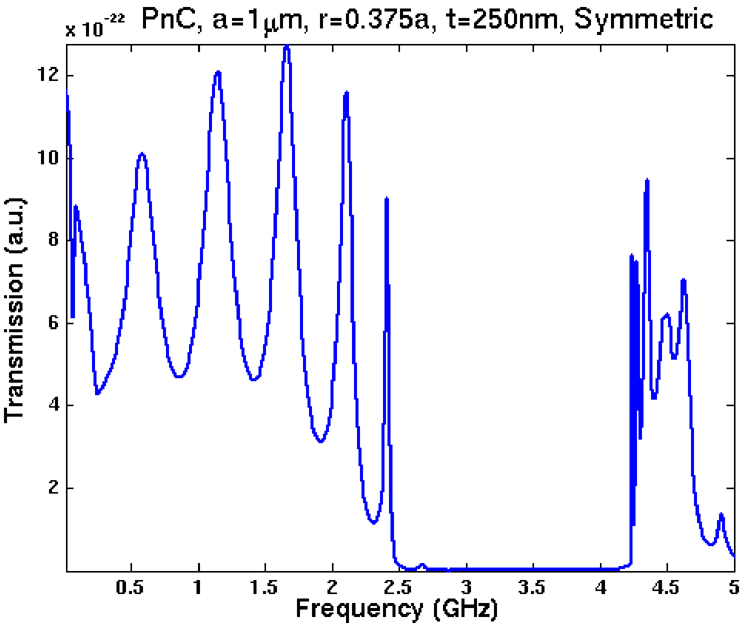


a = 1 μm
r = 0.385 μm

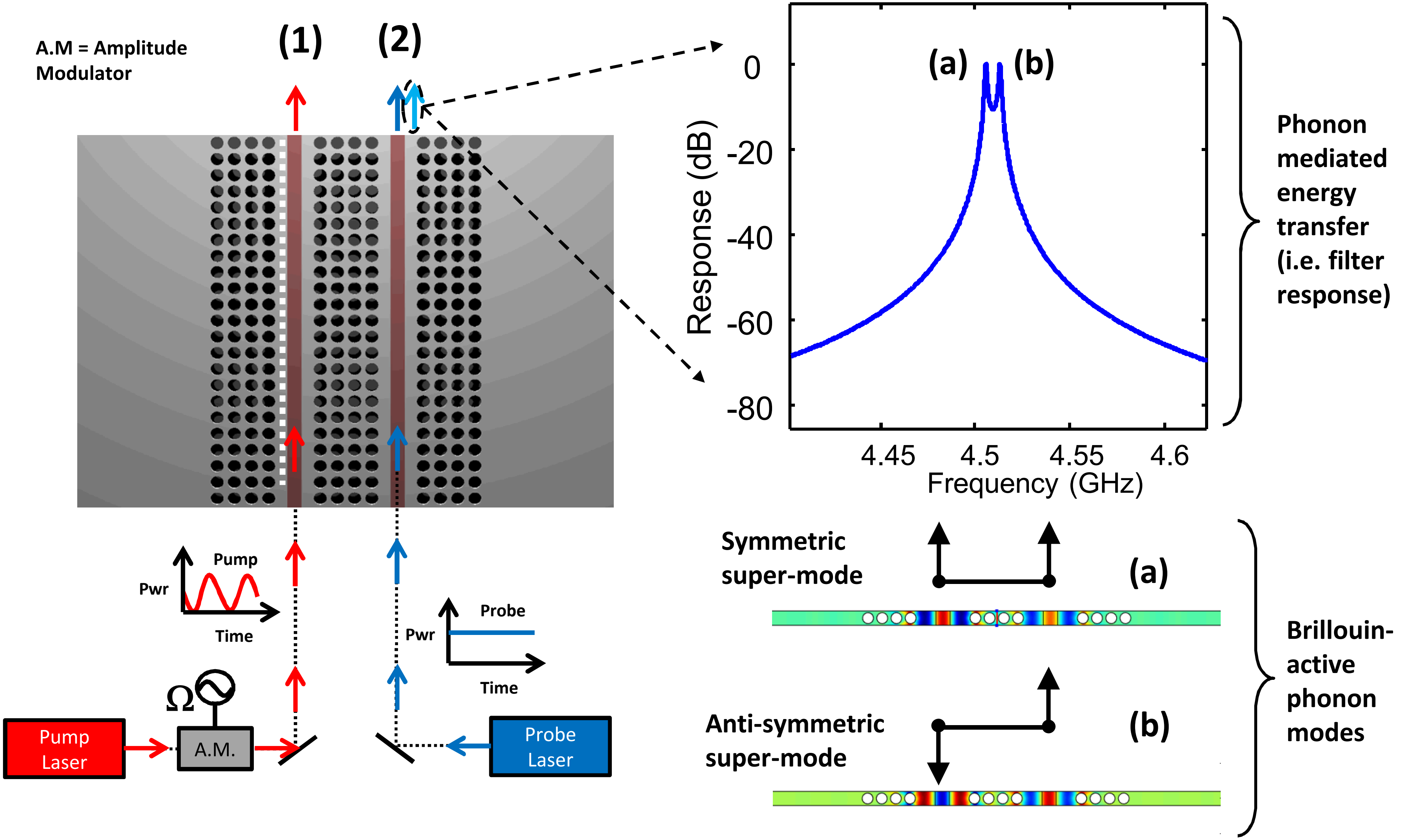


Khelif, et al., Phys. Rev. E 74, 046610 (2006)

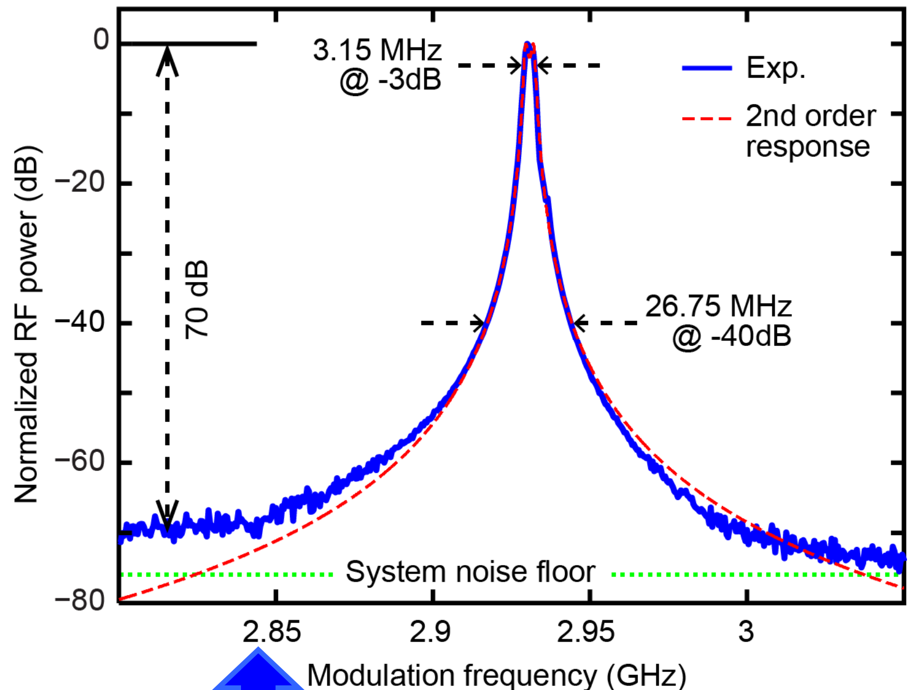


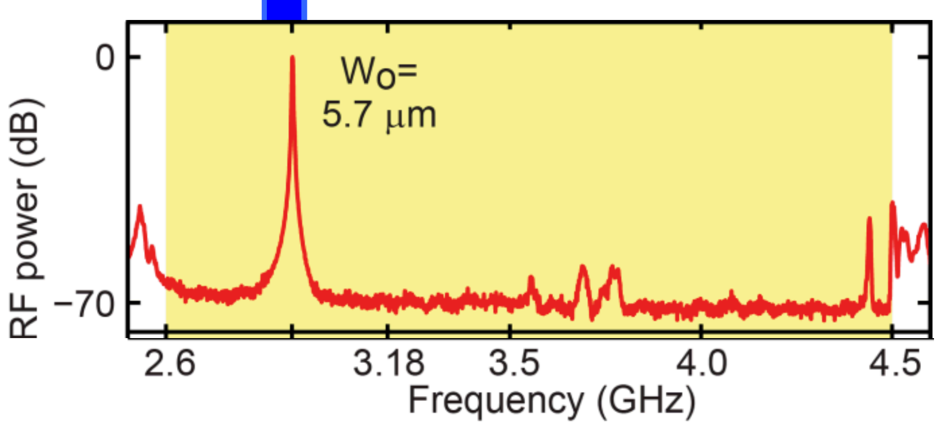


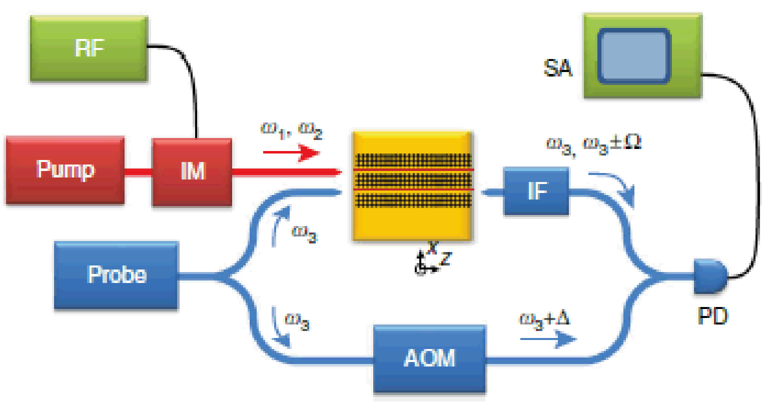
Dual-Waveguide PnC Cavity System



PPER Device RF Response







Center frequency, f_o = 2.93GHz

3-dB bandpass bandwidth, B = 3.15MHz

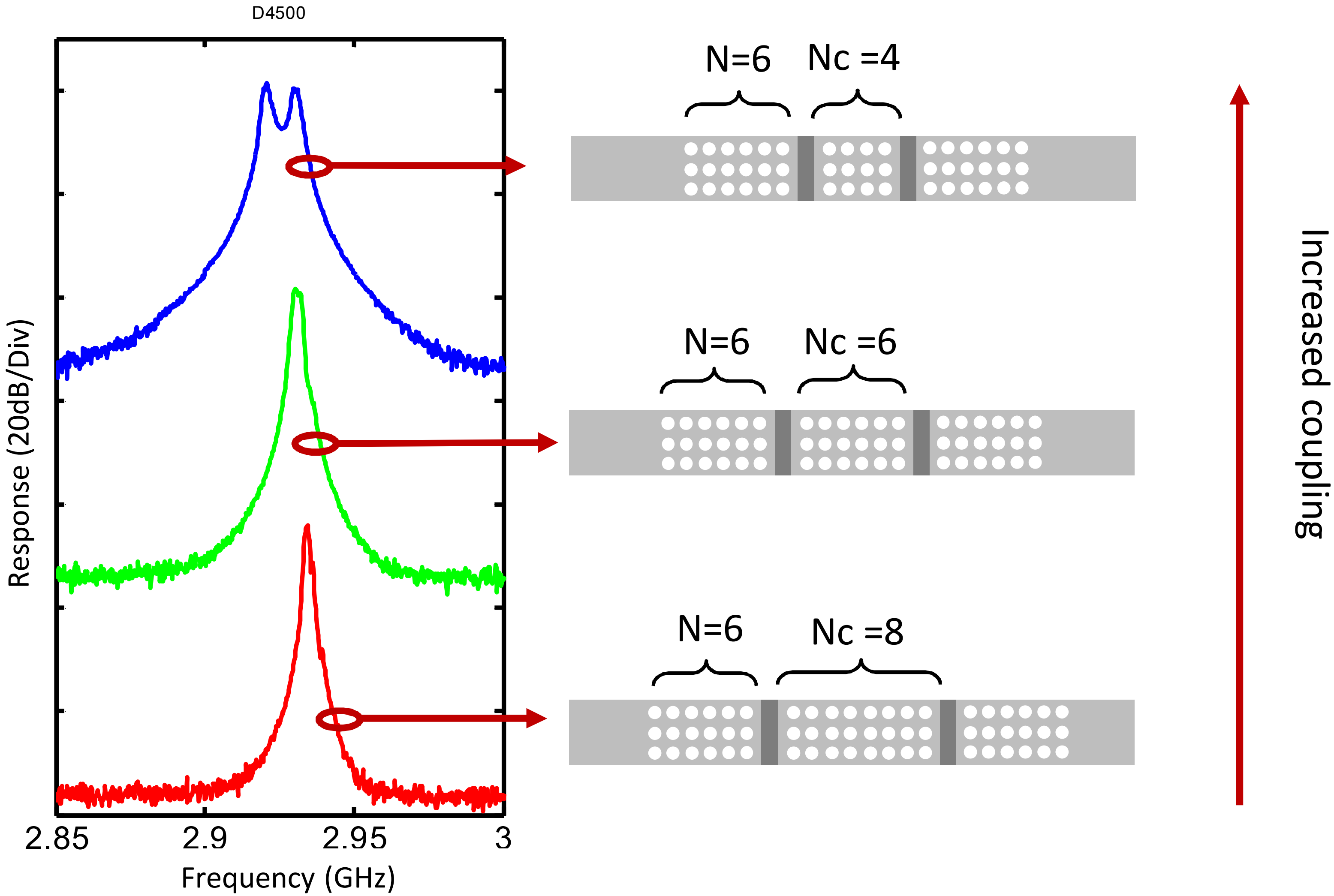
Stopband attenuation, A > 70dB

Rejection bandwidth, B_R = 1.9GHZ

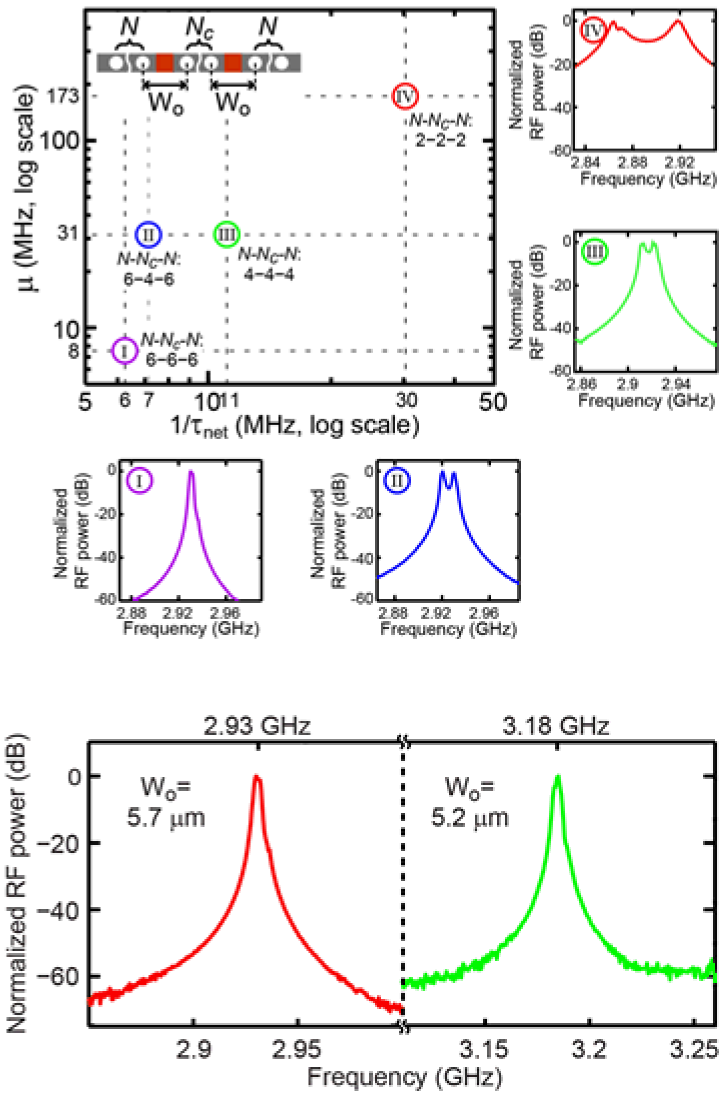
High power handling, 36mW (110mW for 3dB/cm loss)

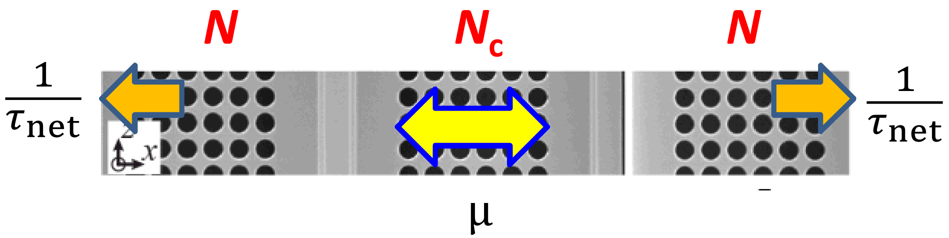
Shin, *et al.*, *Nat. Comm.* **6**, 6427 (2015)

PnC Engineering of Coupling Strength

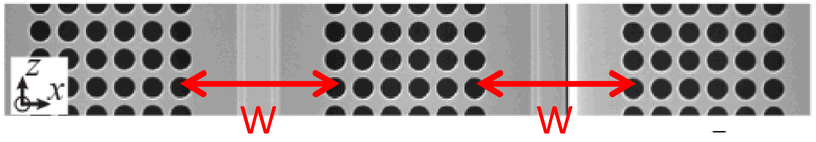


PPER Device RF Response





- Peak separation and/or bandwidth tuned by varying the number of PnC hole layers



- Center frequency tuned by changing the phononic cavity width, W

Comparison with RF Photonics

RF Photonic Filters Using All-Optical Methods

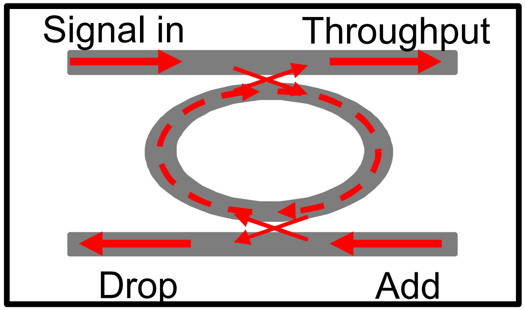
Asymmetric MZI

Whispering gallery mode resonator

Bragg grating

Ring resonator

Resonator-based RF photonic filters



- Requires high optical Q (~10^7)
- Low power handling (optical nonlinearities)
- Requires narrow linewidth lasers
- Requires frequency locking
- Higher-order filter responses difficult

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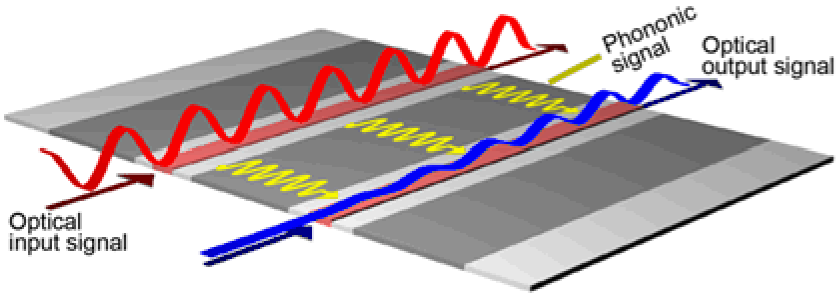
Summary

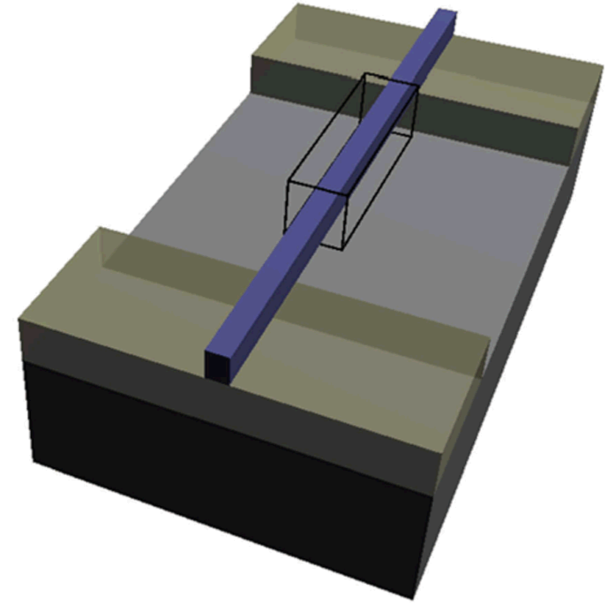
- Demonstrated SBS gain values as large as >2000$m^{-1}W^{-1}$ in a 7mm-long device, equivalent to the SBS nonlinearity of more than a meter of conventional silica fiber

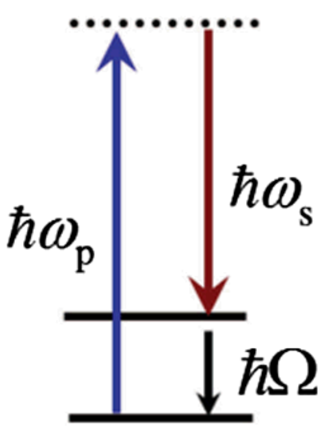


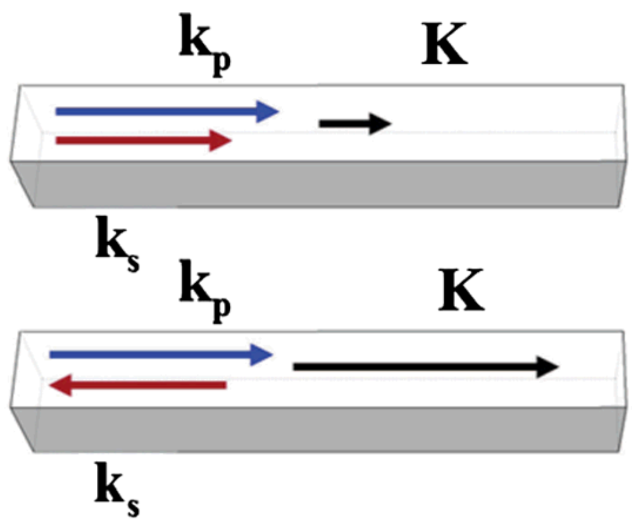
- Demonstrated chip-scale, agile RF filtering with MHz linewidths, GHz bandwidth, and >70dB of dynamic range

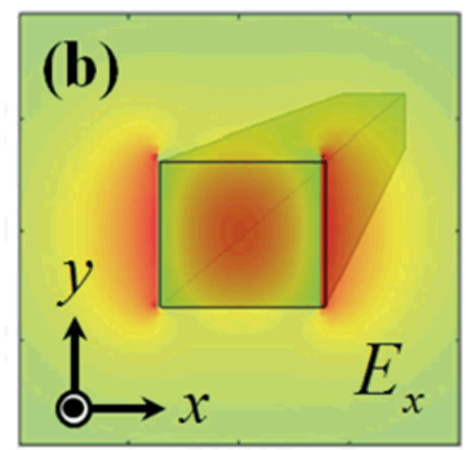
SBS in Nanophotonic Waveguides

- Nano-scale photonic waveguides
- Tight optical mode confinement ➔ Strong interaction with waveguide boundaries
- Mediated by both electrostriction and radiation pressure



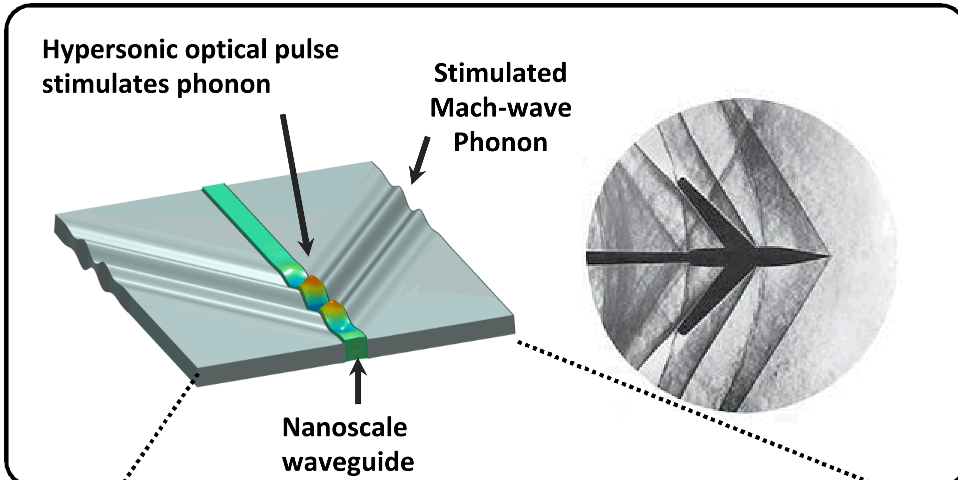


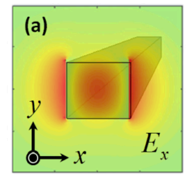




Stimulated Mach-Wave Phonon Emission

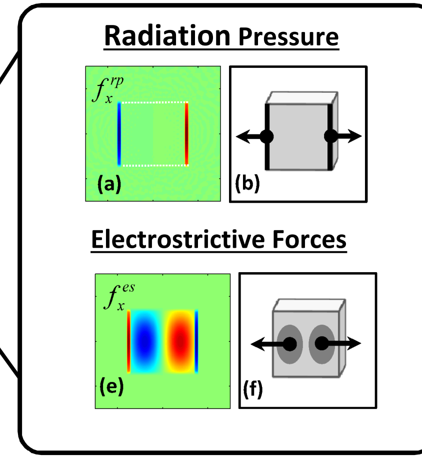
New Physics: Stimulated Mach-wave Phonon Emission



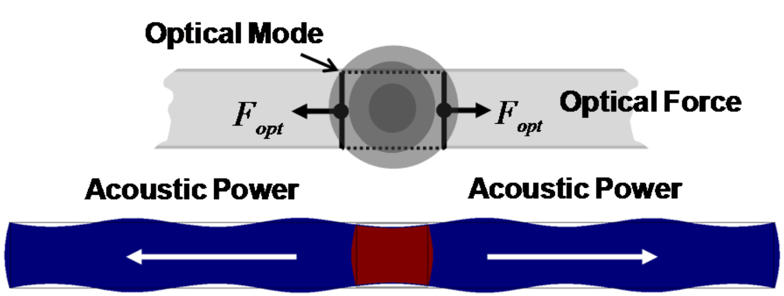


300nm x 300nm

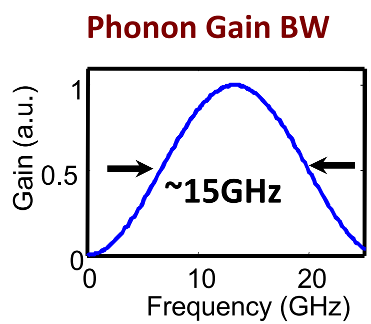
Enhanced optical forces



Result: Ultra-Broadband Stimulated Phonon Emission



Rapid escape of acoustic energy



Mach-wave emission:

- New chip-scale signal processing platform
- Wide-band and narrow-band parametric processes