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

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Overview

- Motivation: Nano-scale optomechanical systems
- Demonstration of large optomechanical transduction
- Time-domain characterization using ultrafast pulses
- RF filtering using phononic crystals

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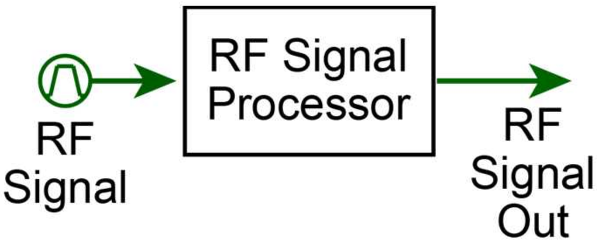
RF Signal Processing

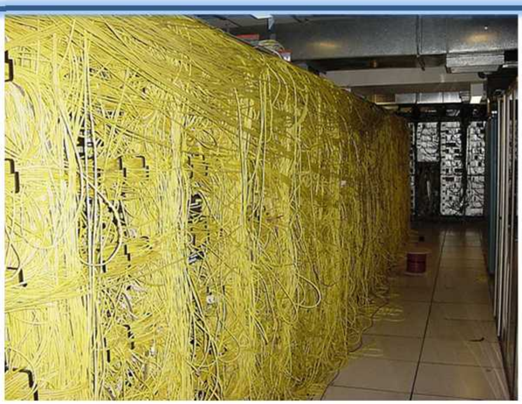
RF Electronics



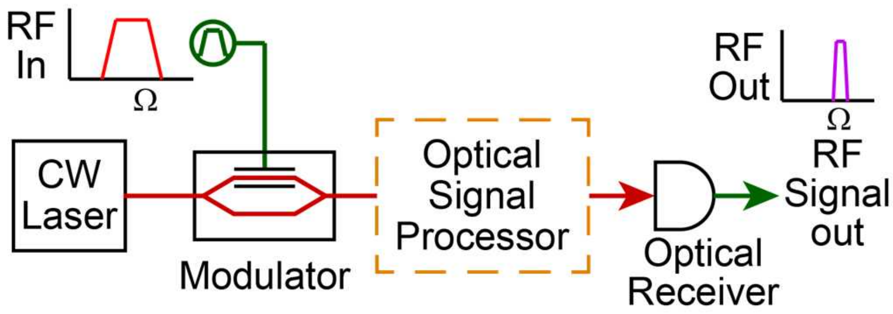
- Filters
- Time delay line
- Phase shifter
- Frequency converter
- Etc.

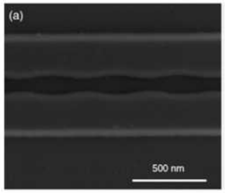
- Generally must be comparable in size to the RF wavelength
- SWaP increases with performance

RF Photonics

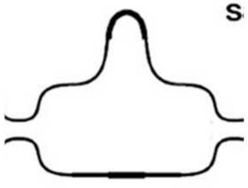


- Very large inherent bandwidth (>100THz)
- Integrated photonics could yield dramatic size and power reductions

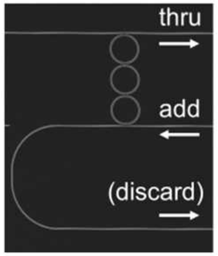




Bragg grating



Asymmetric MZI



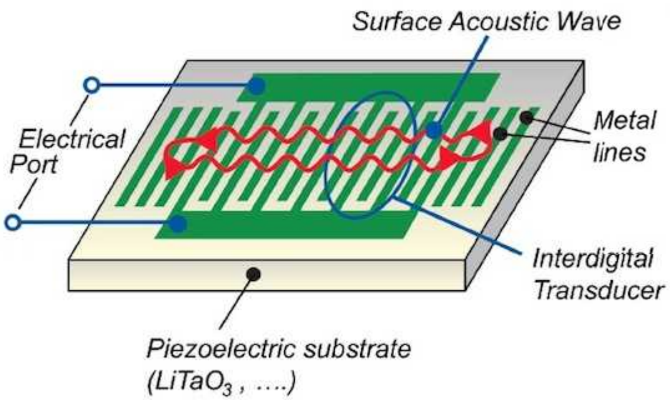
Ring resonator

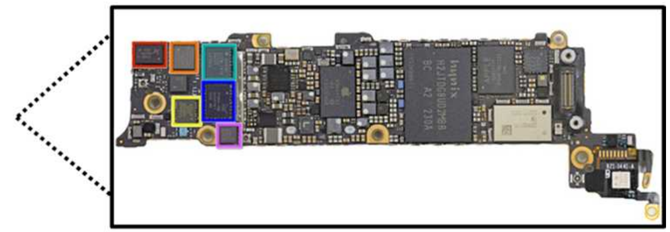
Whispering gallery mode resonator

RF MEMS

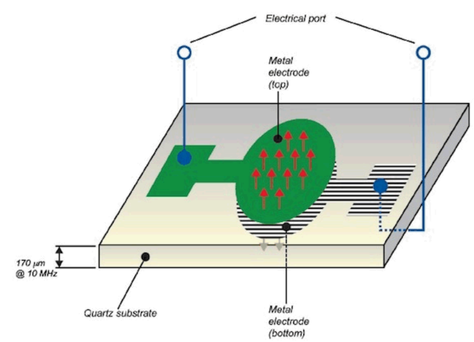
Acoustic (Phononics) Devices

SAW < 3GHz





Bulk Acoustic Wave (BAW) > 3GHz

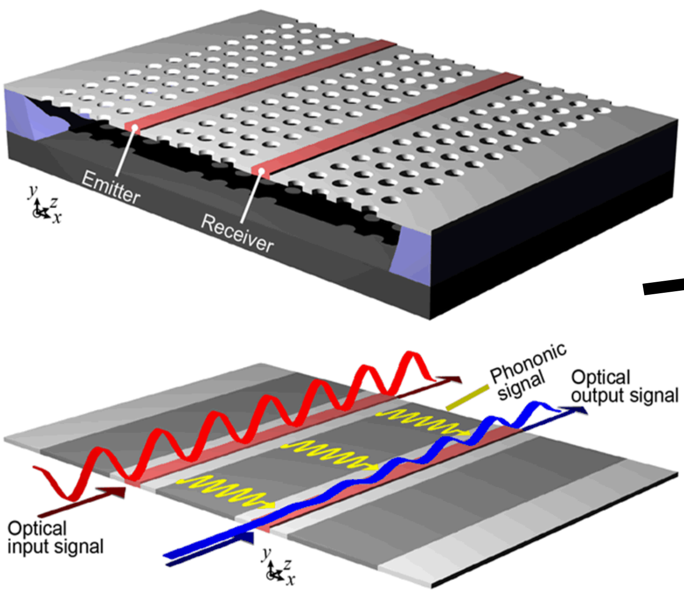


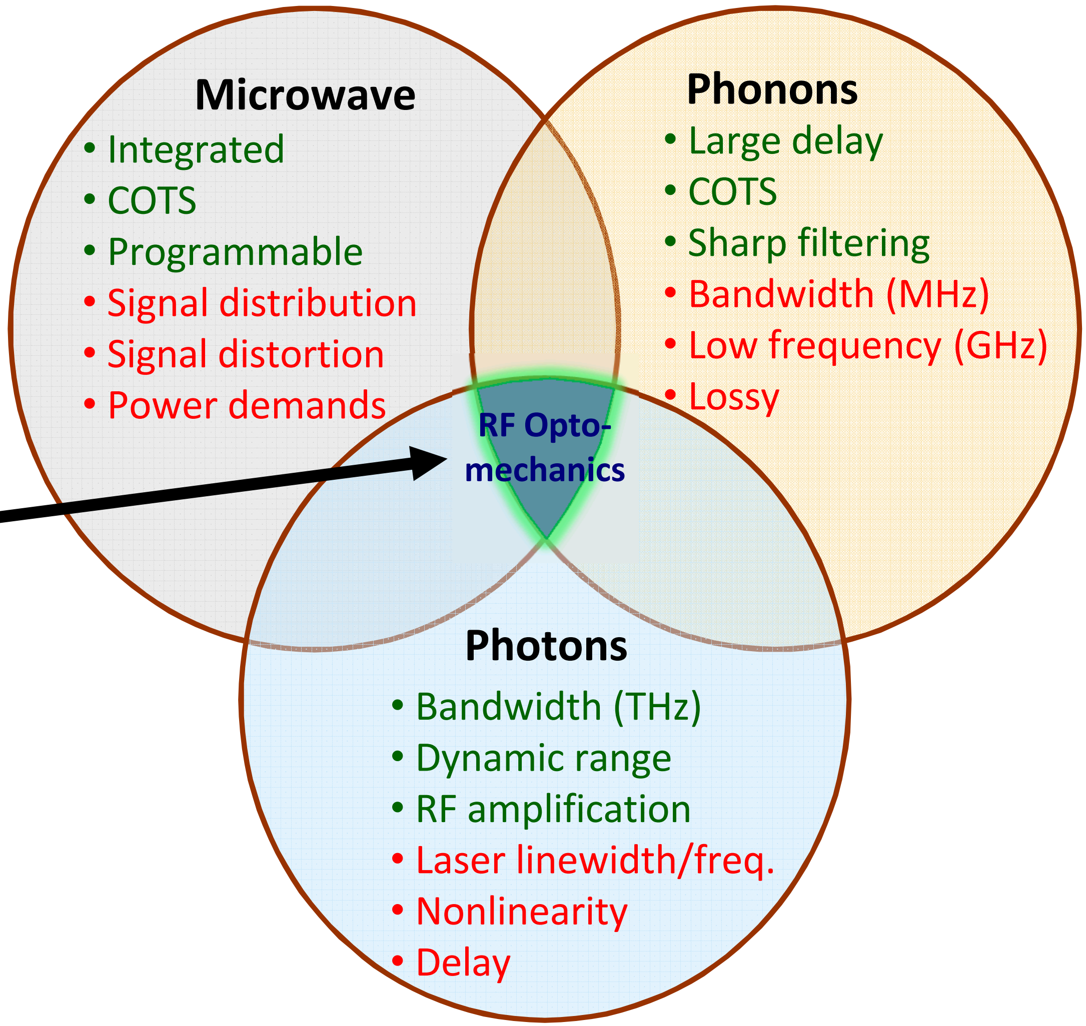
- Surface acoustic wave (SAW) devices:
  - Sound ~10,000 x slower than light
  - Lifetimes 10^{-3} to 10^{-6} seconds
  - Low-frequency stability

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

Signal Processing with Optomechanics

Photonic-Photonic RF Platform





Overview

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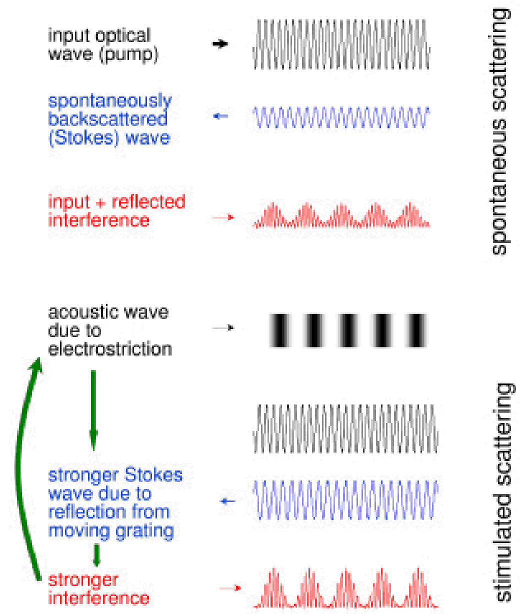
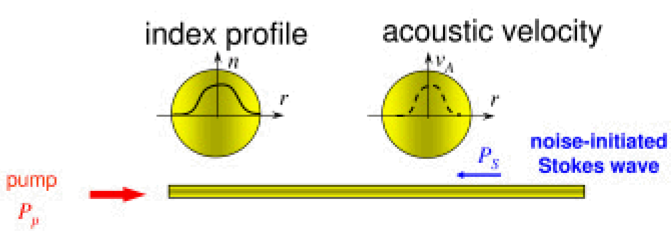
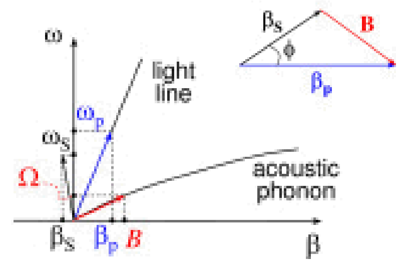
Stimulated Brillouin Scattering (SBS)

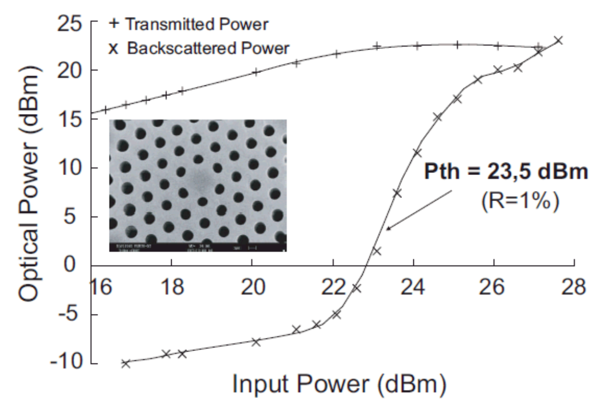
- Backward SBS typically seen in optical fiber
  - Third-order nonlinear optical process
  - Mediated by electrostriction
  - Strong confinement of longitudinal acoustic modes allows for long-range interactions





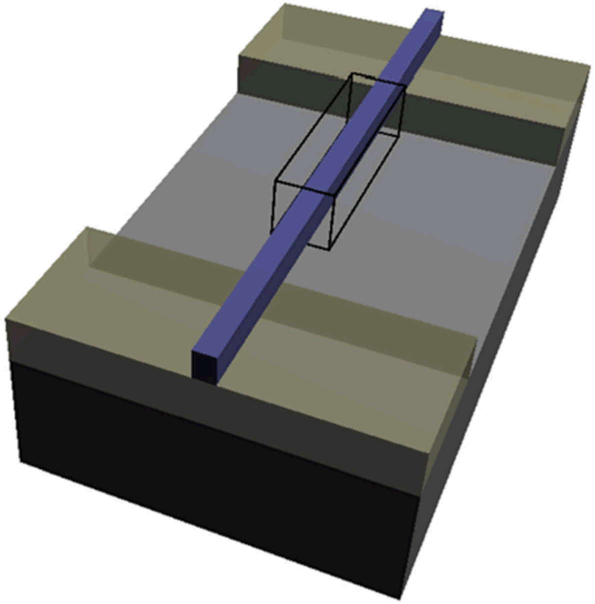


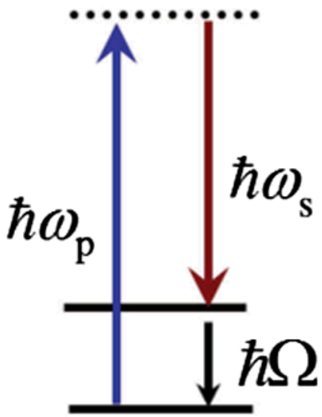
- Forward SBS recently observed in photonic crystal fiber
  - Transverse acoustic confinement enables new coupling mechanisms

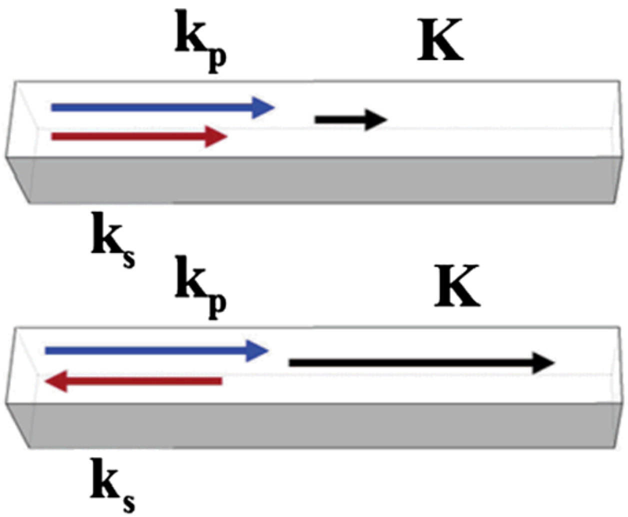


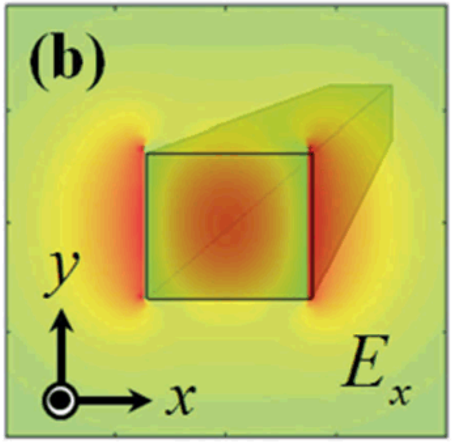
SBS in Nanophotonic Waveguides

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



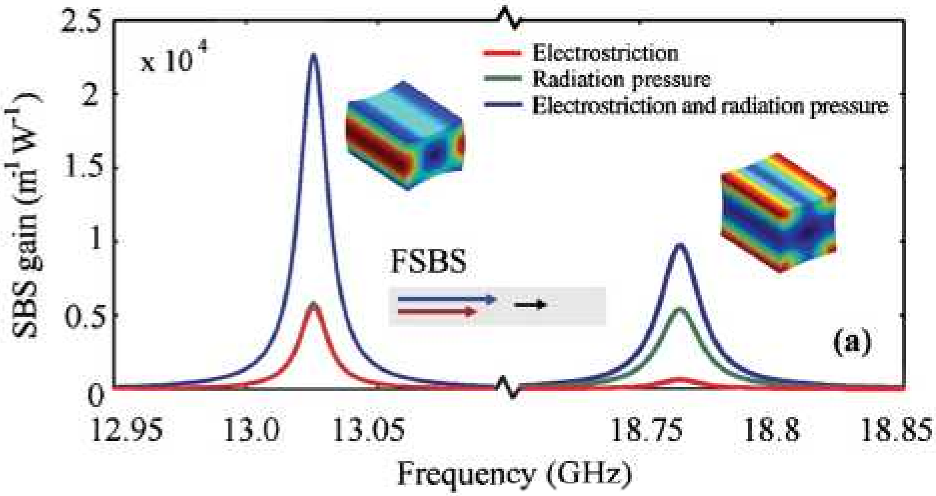


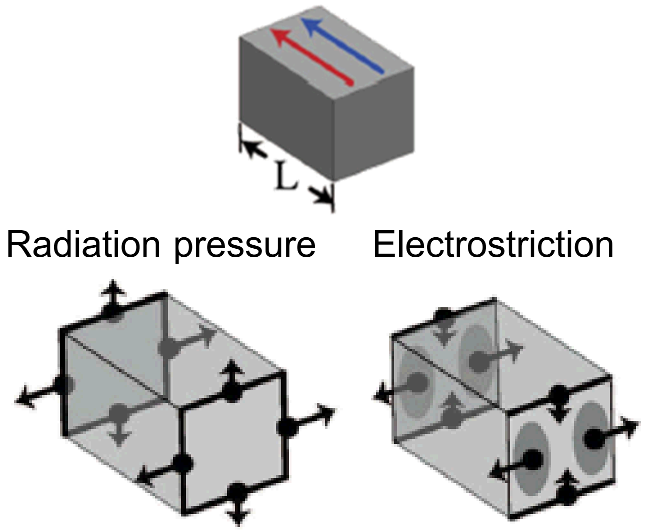


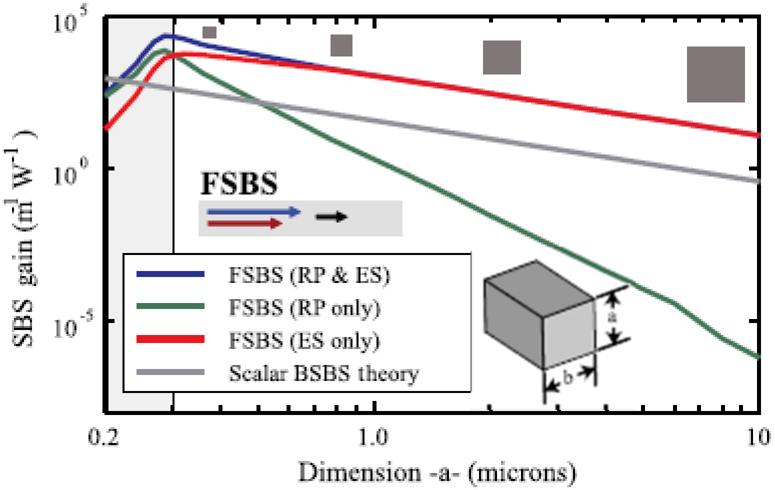


Enhancement of SBS

- 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 ~$4 \cdot 10^3 m^{-1}W^{-1}$



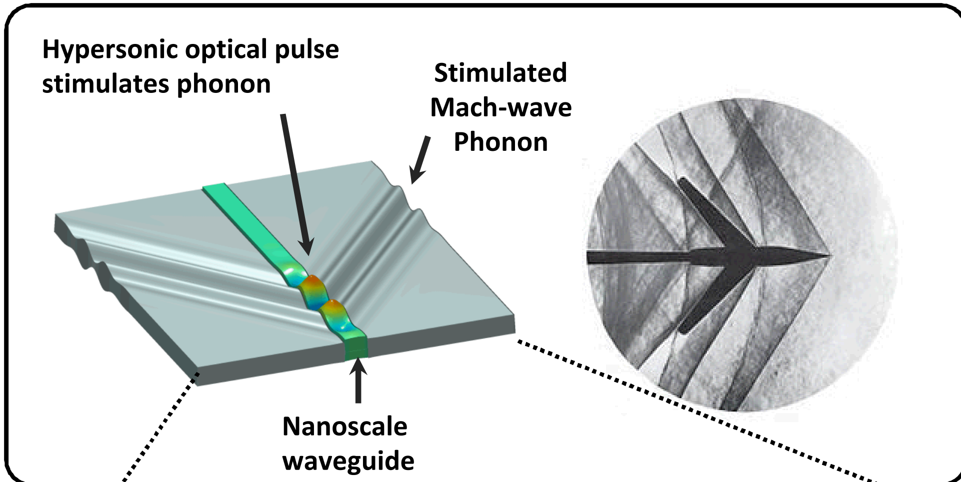


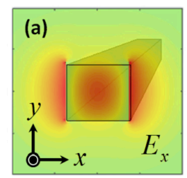


Rakich, *et al.*, *Phys. Rev X* **2**, 011008 (2012)

Stimulated Mach-Wave Phonon Emission

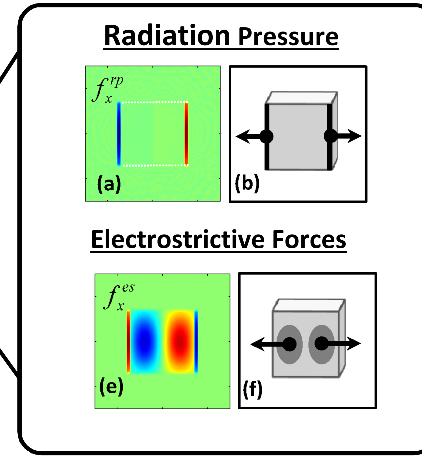
New Physics: Stimulated Mach-wave Phonon Emission



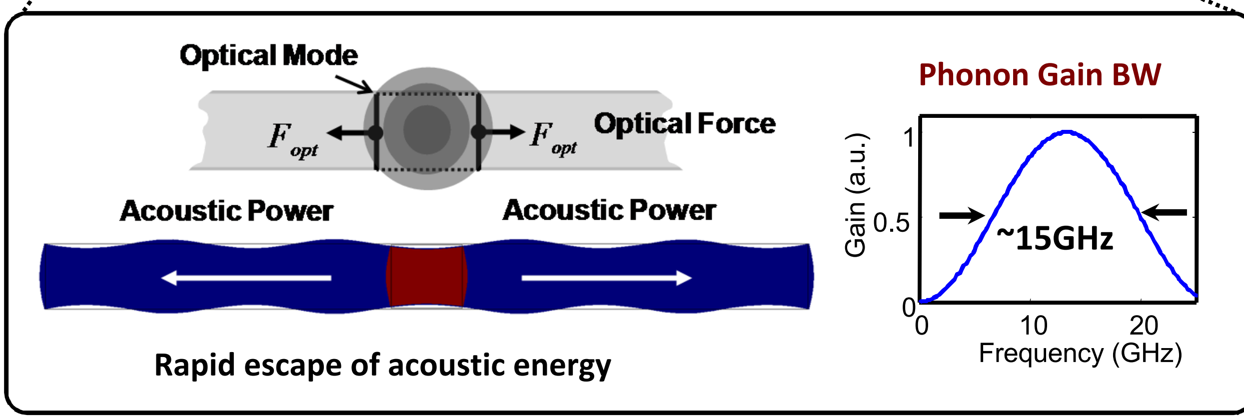


300nm x 300nm

Enhanced optical forces



Result: Ultra-Broadband Stimulated Phonon Emission

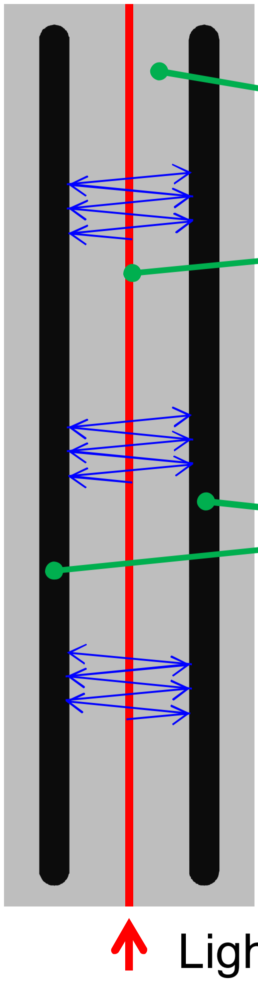


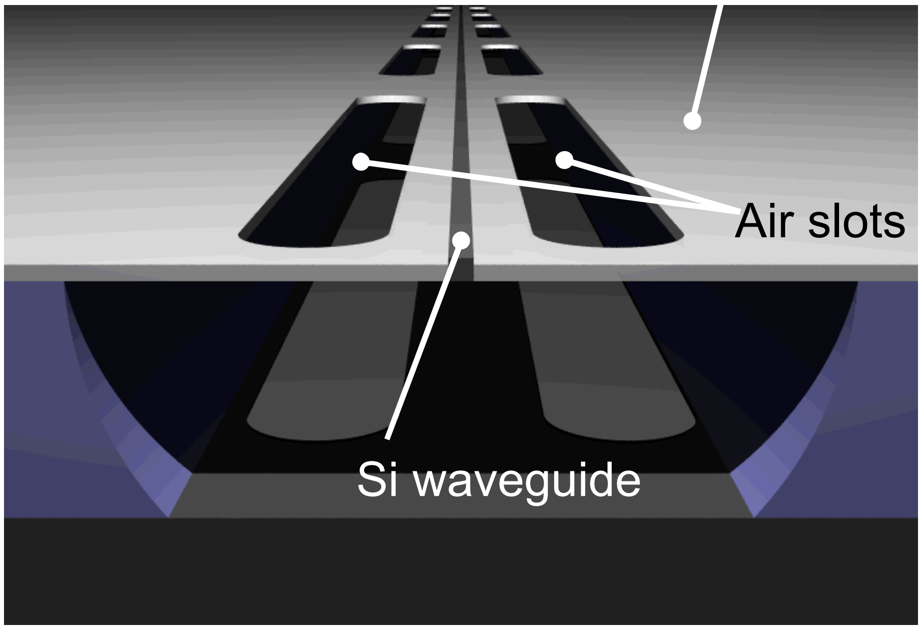
Mach-wave emission:

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

Chip-Scale SBS Structures

Brillouin-active membrane and waveguide



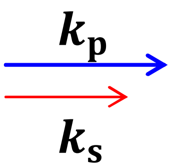


- Reducing phonon dissipation
- Photonic waveguide (silicon)
- Phononic waveguide (SiN between slots)
- Strong photon-phonon **confinement**

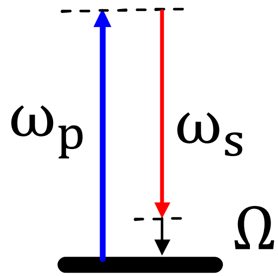
Shin, *et al.*, *Nat. Comm.* **4**, 1944 (2013)

Forward SBS

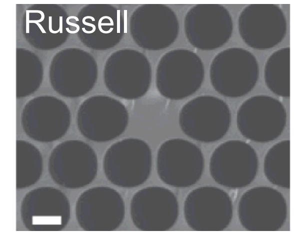
- **Co-propagation**
- **Structure dependent resonant frequency**



$$\vec{K} = k_p - k_s \ll k$$



Strong forward SBS



Nature Phys. **5**, 276 (2009)

Chip-Scale SBS Amplification

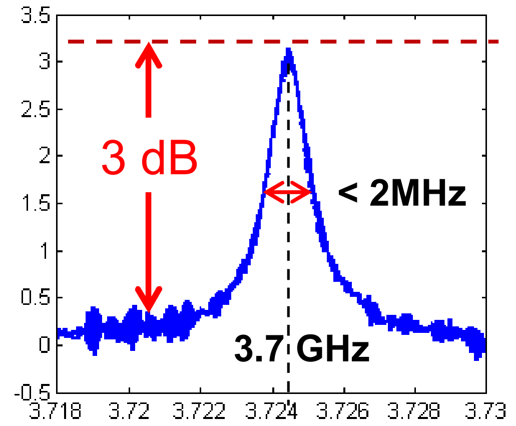
Phononic Crystal BAM waveguide

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

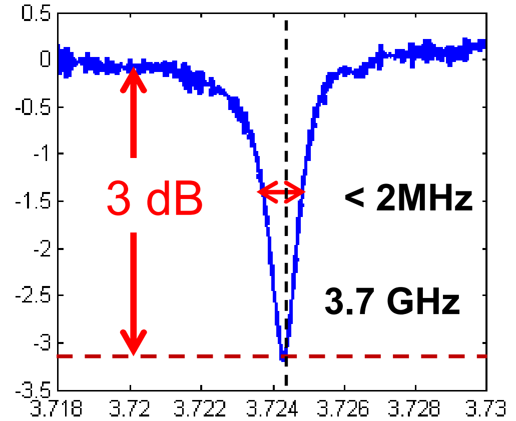
Results:

- High power handling ➔ 300mW
- Brillouin nonlinearity ➔ 10x Kerr
- Gain ➔ 175 dB/W-cm

Stokes: Amplification

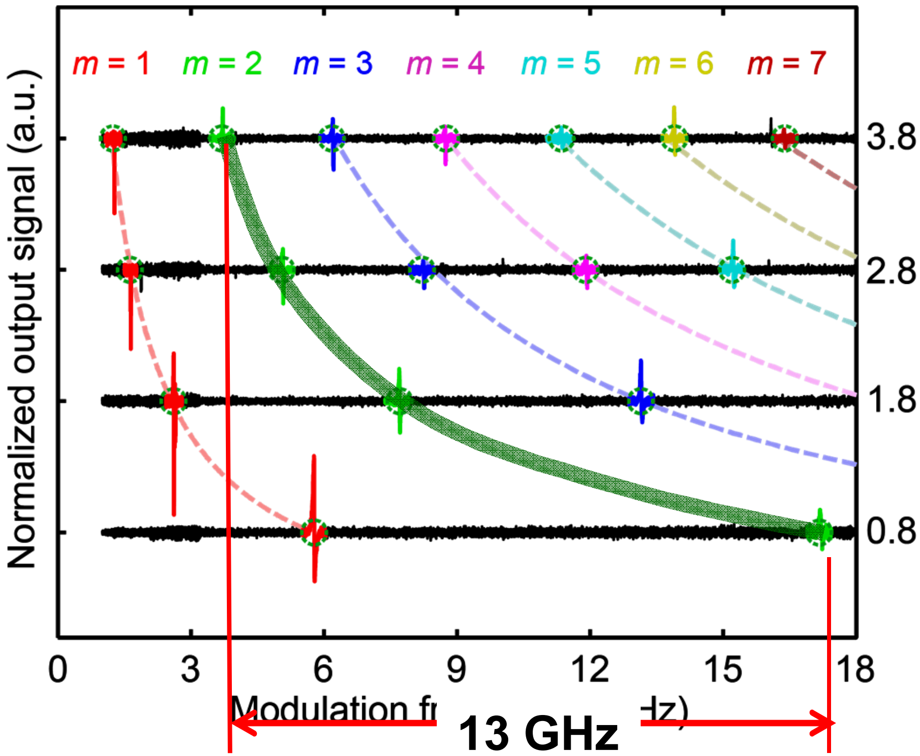


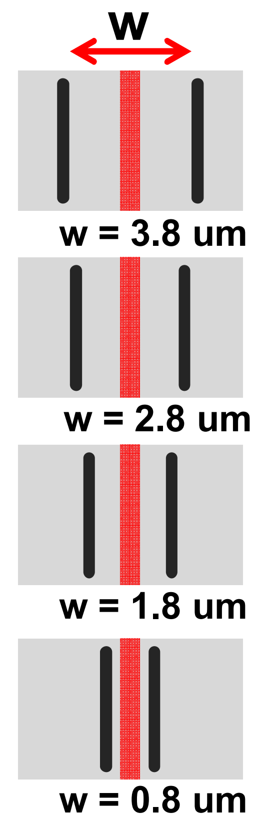
Anti-Stokes: Depletion



Tailorable SBS Nonlinearity

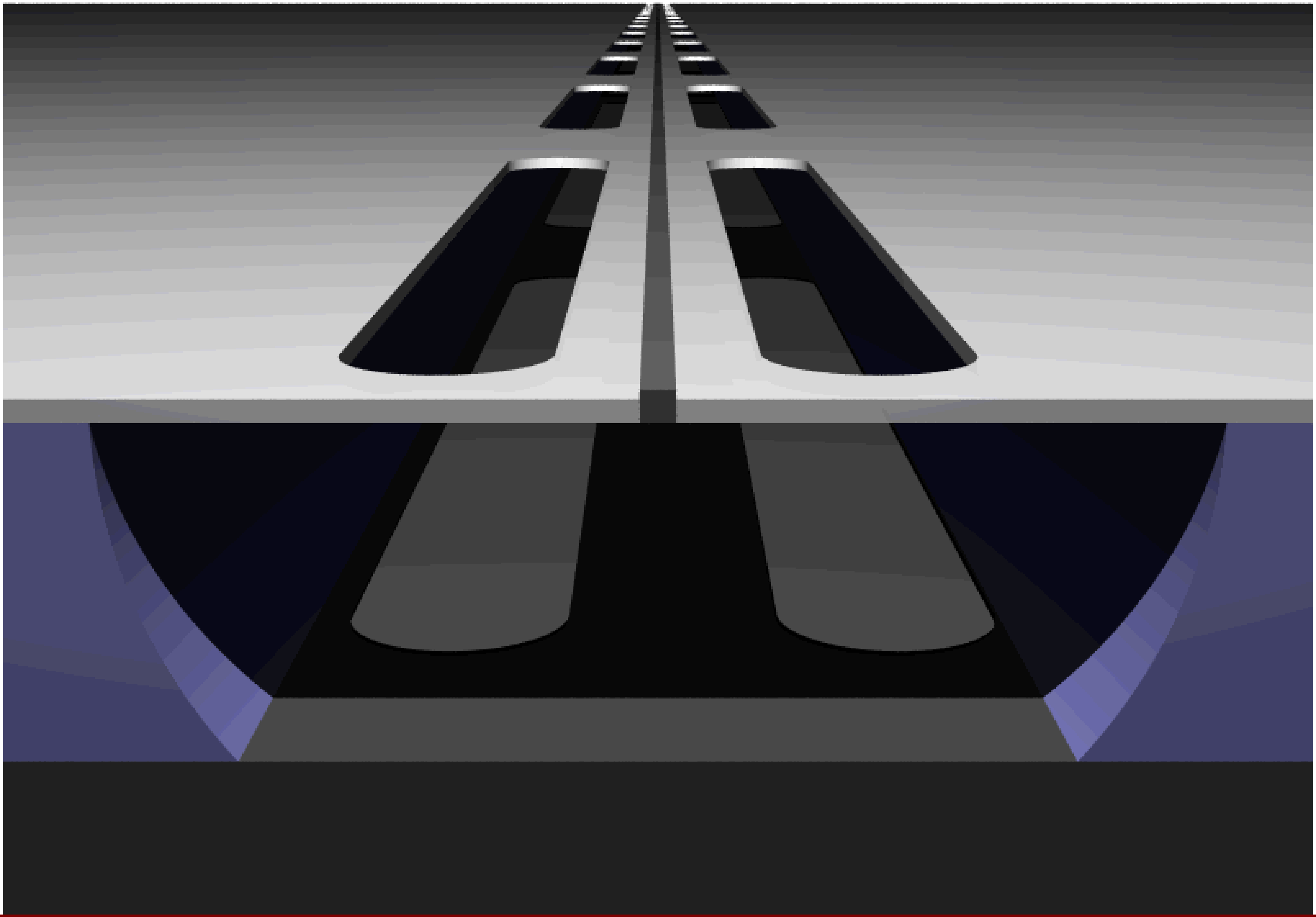
Phonon spectrum changes with phononic cavity dimensions





- As the cavity width increases, more modes are allowed
- By lithographically varying the cavity width, the phononic resonant frequency can be tuned by 13GHz
- Unprecedented tailorability of nonlinearities

Fabrication Process



Overview

- Motivation: Nano-scale optomechanical systems
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- Time-domain characterization using ultrafast pulses
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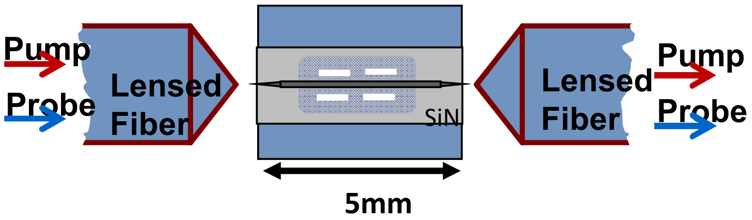
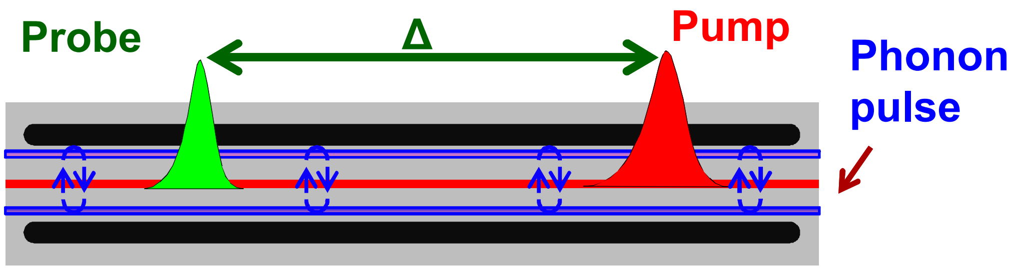
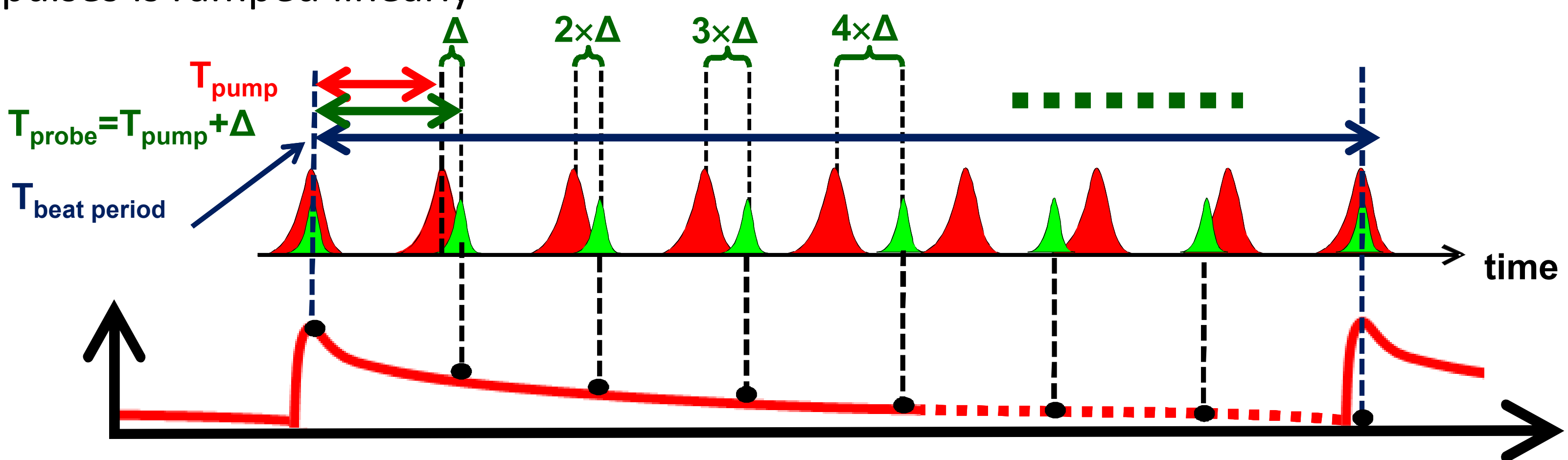
Asynchronous Optical Sampling (ASOPS)

- Transduction of laser pulses to phonon modes assess the viability of pulsed phonon devices





- In ASOPS, the repetition rate of pulsed pump (f_{pump}) and probe (f_{probe}) lasers are detuned by an offset frequency (f_{offset}) such that the time delay between consecutive pulses is ramped linearly

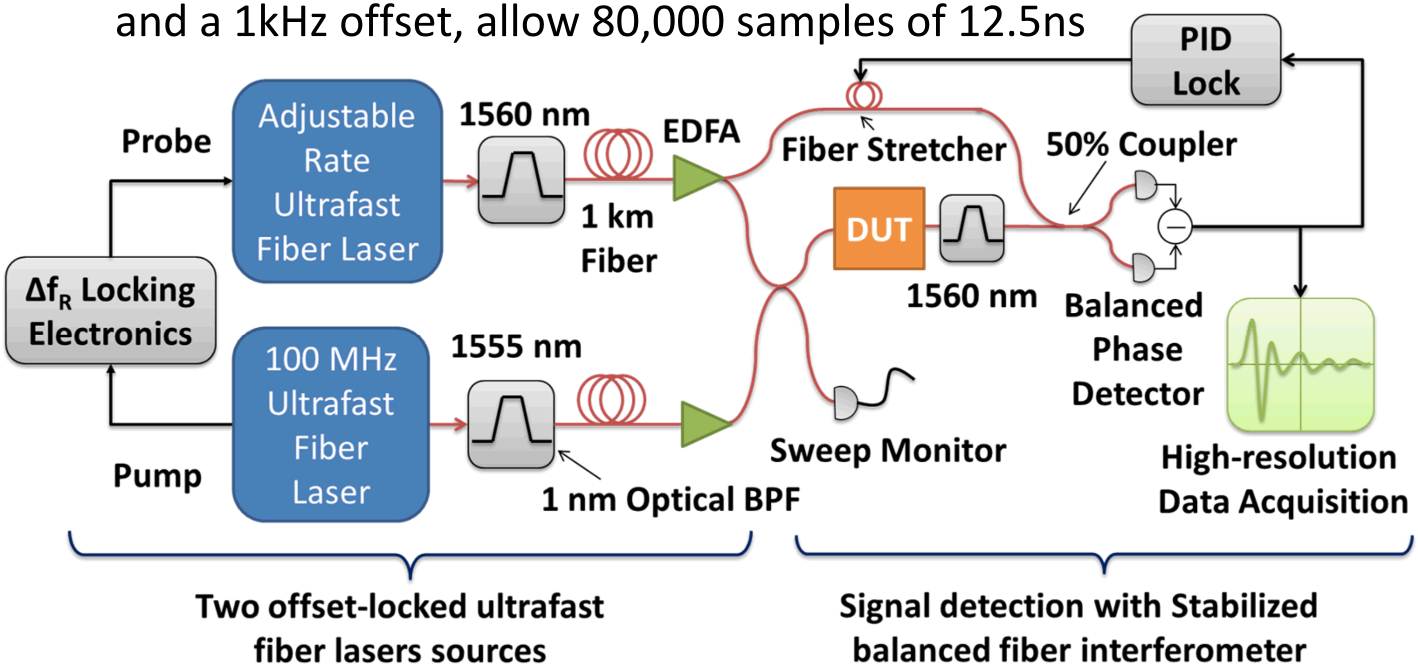


Waveform periodic with T_{beat} and with $N_{sample} = T_{pump}/\Delta$

- 100 MHz laser sources with 10kHz f_{offset} → $f_{optical}$ =1 THz without the need for mechanical delay lines

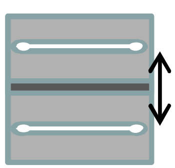
Experimental Setup

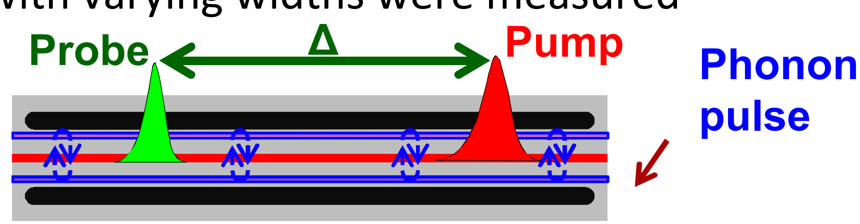
- Two ps fiber laser sources (pump and probe) locked with an 80MHz repetition rate and a 1kHz offset, allow 80,000 samples of 12.5ns



→ Sampling card and laser systems tightly synchronized enabling long-term averaging

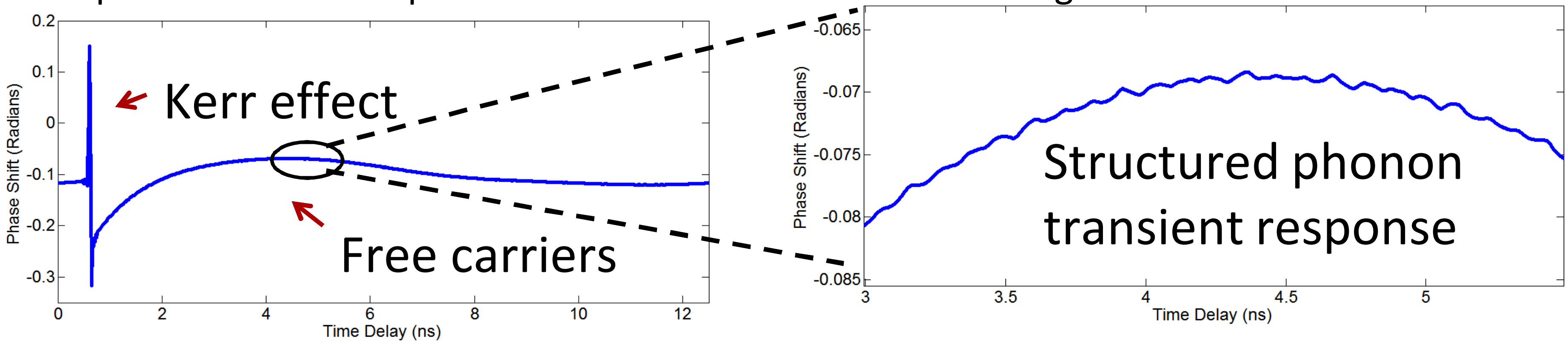
- The pump pulse generates a phonon pulse via optical transduction, which imparts a phase shift on the signal pulse that is measured in an interferometer having shot-noise-limited detection of a few μ-rad phase
- "Slot" waveguide devices with varying widths were measured



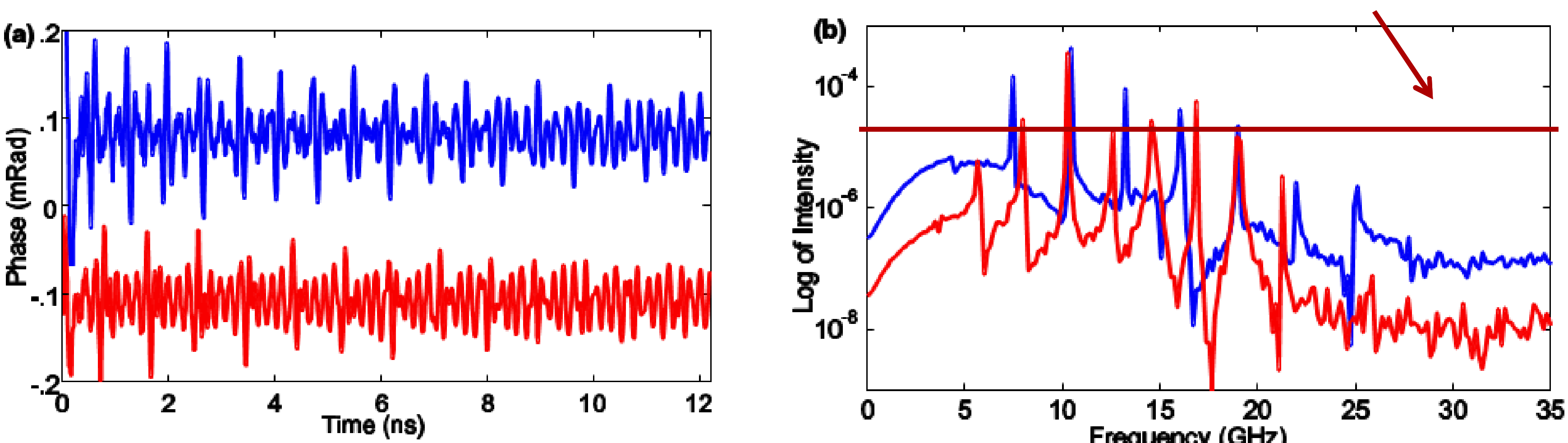


Advantages of Time-Domain Characterization

- Experimental data captures Kerr effect and free carrier background



- Convergence after 100,000 averages
- In the frequency domain, Kerr and free carrier effects dramatically limit dynamic range

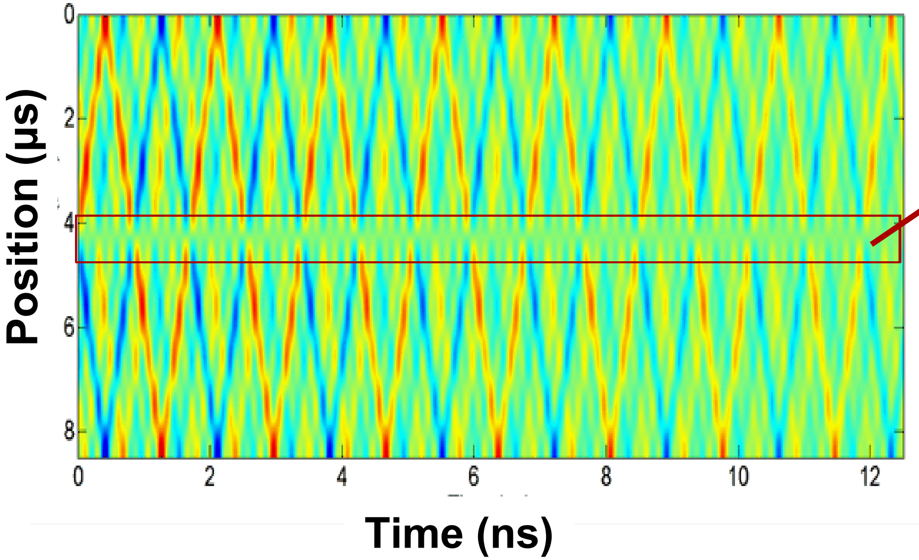


- We use signal processing to separate fast phonon oscillations from slow transients and the instantaneous Kerr effect

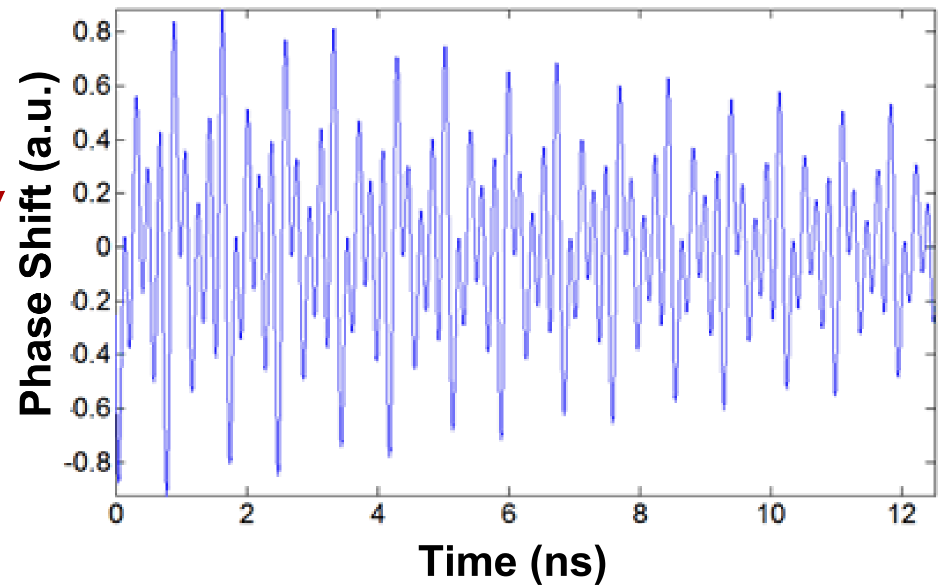
Simulation of Acoustic Pulses

- Simulated parametric pumping with side-wall reflections

Steady-State Displacement



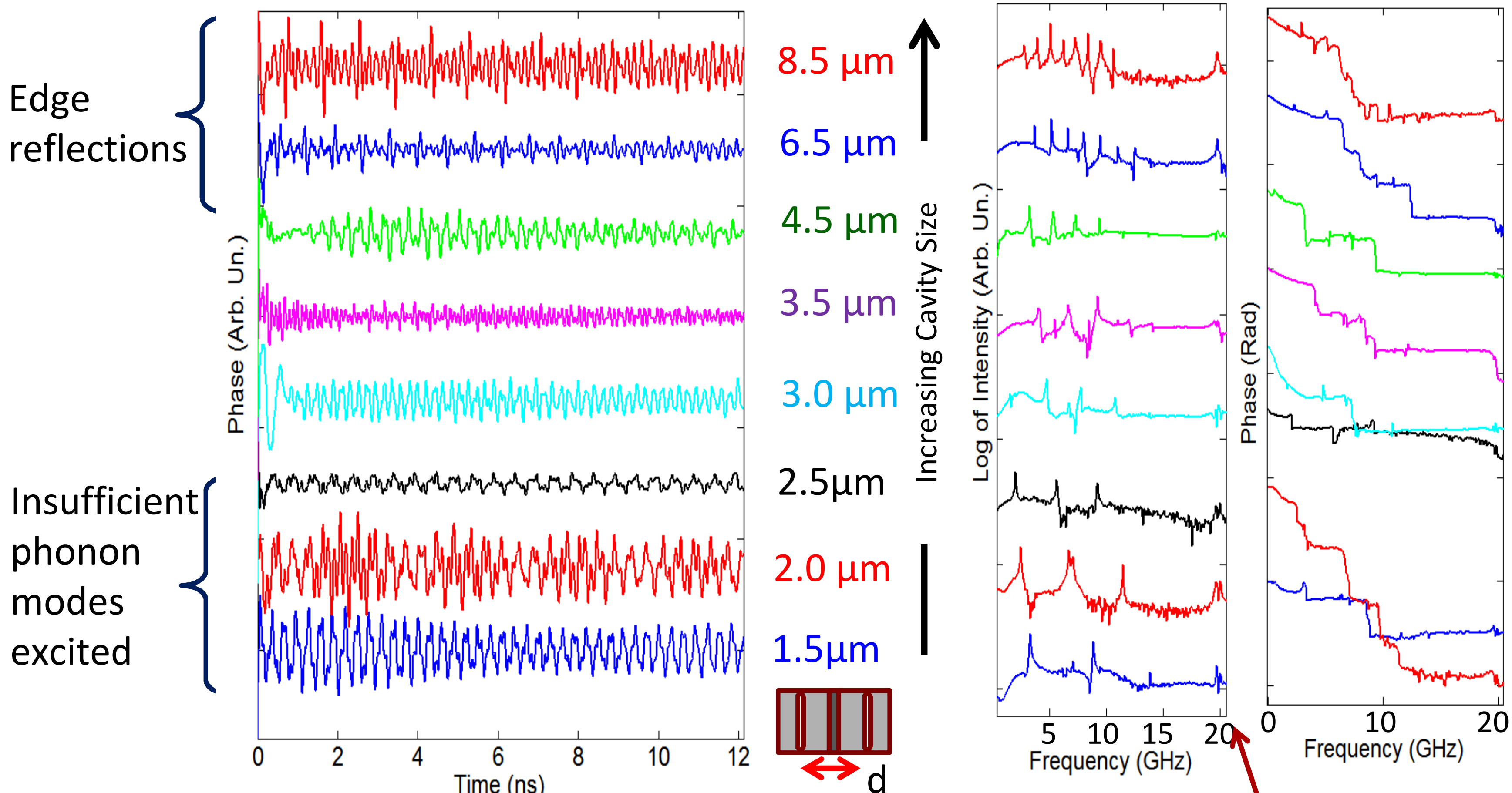
Phase Shift Imparted on the Waveguide



- Parametric pumping due to limited measurement window
- Large side-wall reflections indicate that optical delay with dual waveguide devices is feasible

Measurement of phonon impulse response

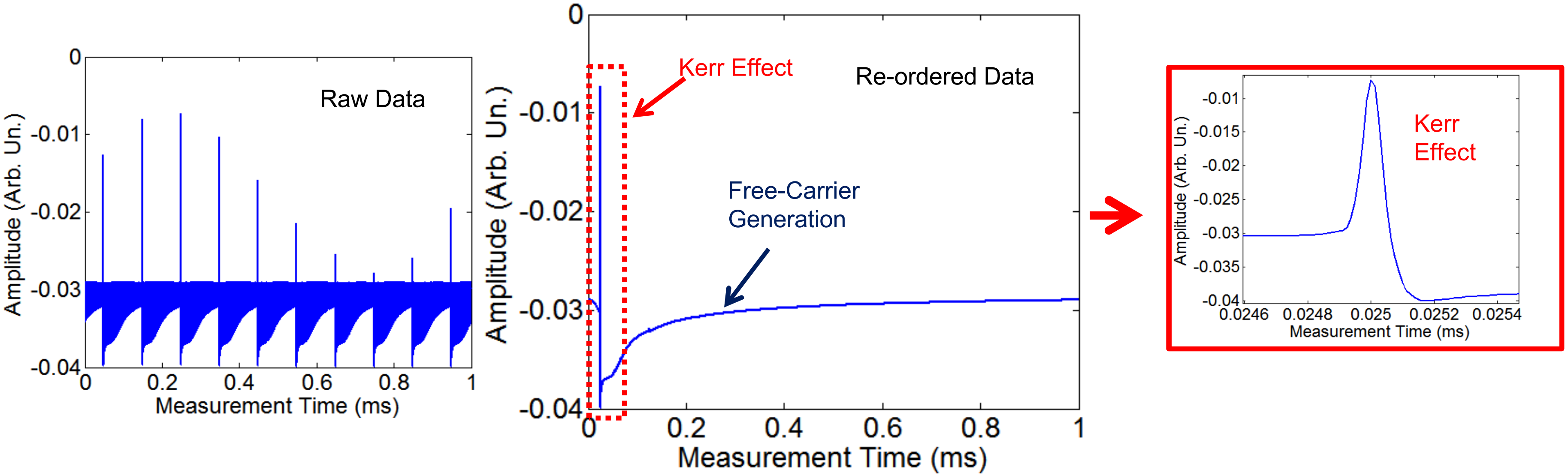
- Frequency domain (magnitude and phase) shows phonon spectrum



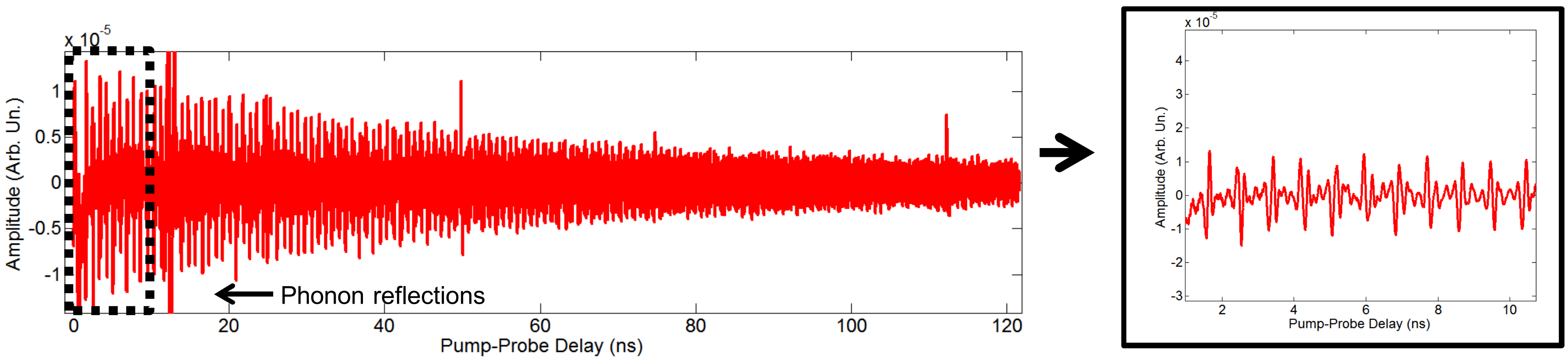
Frequency limitation from ps optical pulse duration

Interleaved ASOPS (I-ASOPS)

- Transient response dominated by optical Kerr effect and free carrier generation



- Re-ordered and processed data reveals phonon dynamics

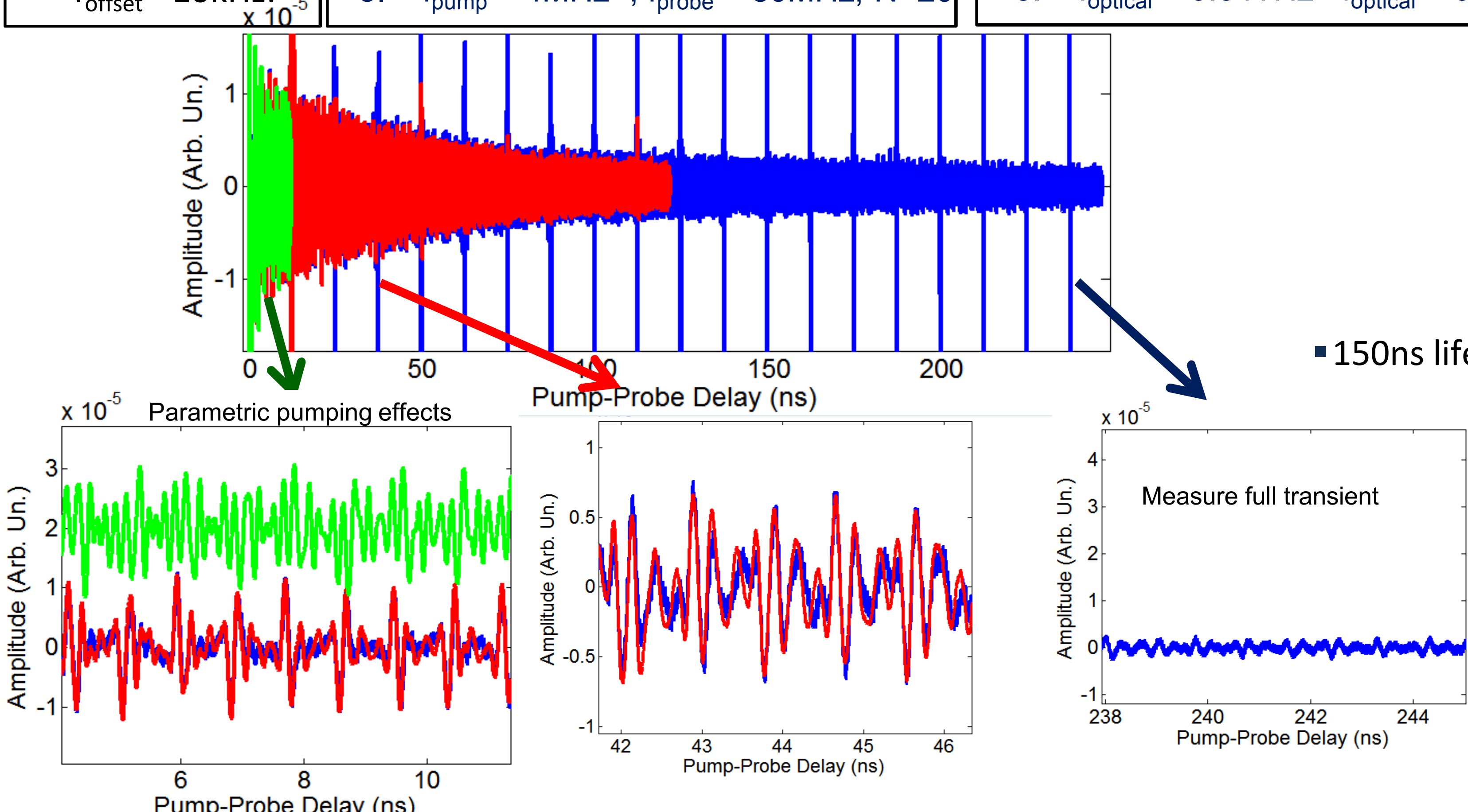


Comparison to ASOPS

- Measurement conditions with f_{offset} =10kHz:

1. f_{pump} = 80MHz, f_{probe} = 80MHz, N=1
2. f_{pump} = 8MHz , f_{probe} = 80MHz, N=10
3. f_{pump} = 4MHz , f_{probe} = 80MHz, N=20

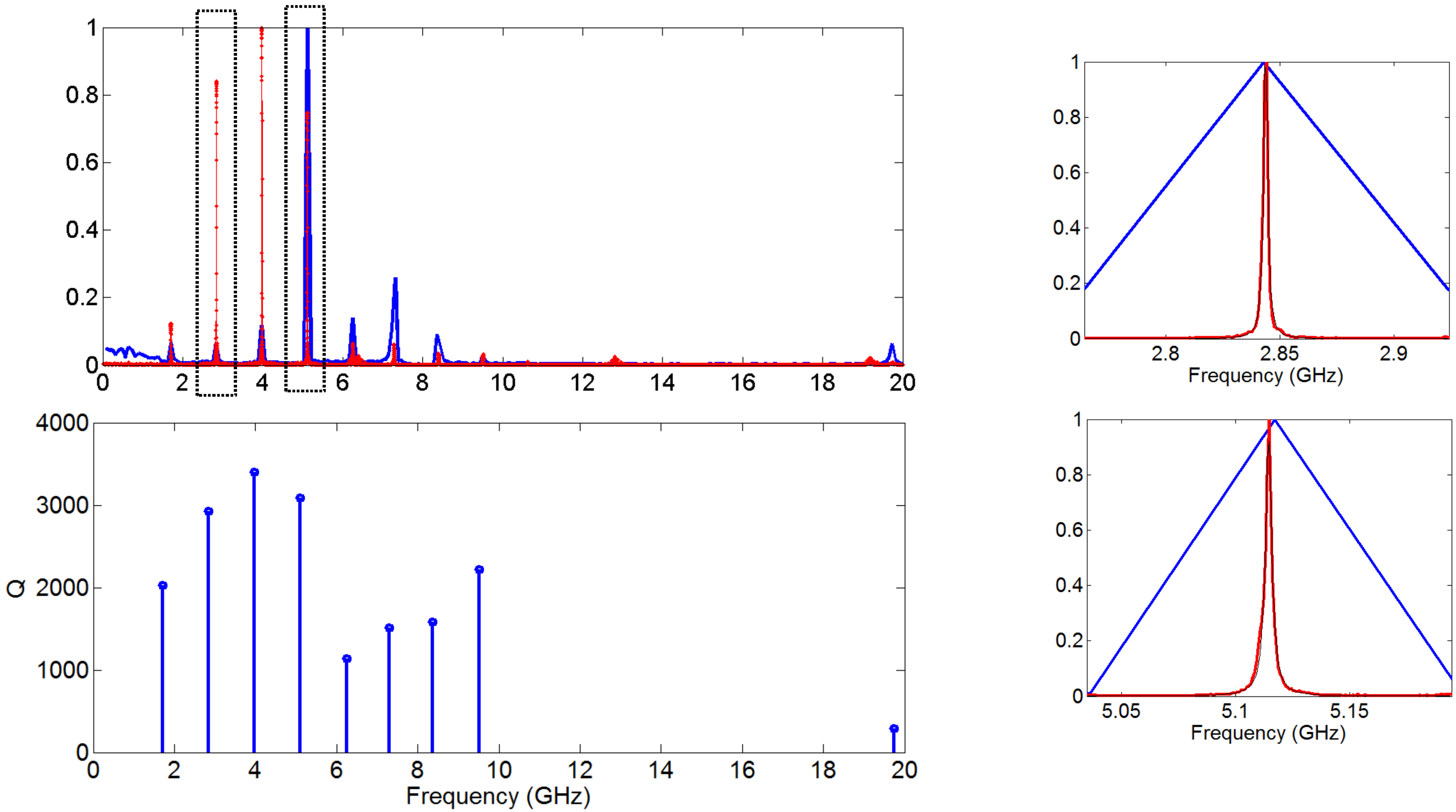
	I-ASOPS	ASOPS
1.		$f_{optical}$ = 0.64THz
2.	$f_{optical}$ = 0.64THz	$f_{optical}$ = 0.064THz
3.	$f_{optical}$ = 0.64THz	$f_{optical}$ = 0.032THz



- 150ns lifetime

- Longer measurement window afforded by I-ASOPS enables full measurement of transient without parametric pump ➔ Preserves timing resolution while increasing resolution bandwidth

Dramatically Enhanced Spectral Resolution



- Measure the spectral response and the excitation amplitudes with high resolution

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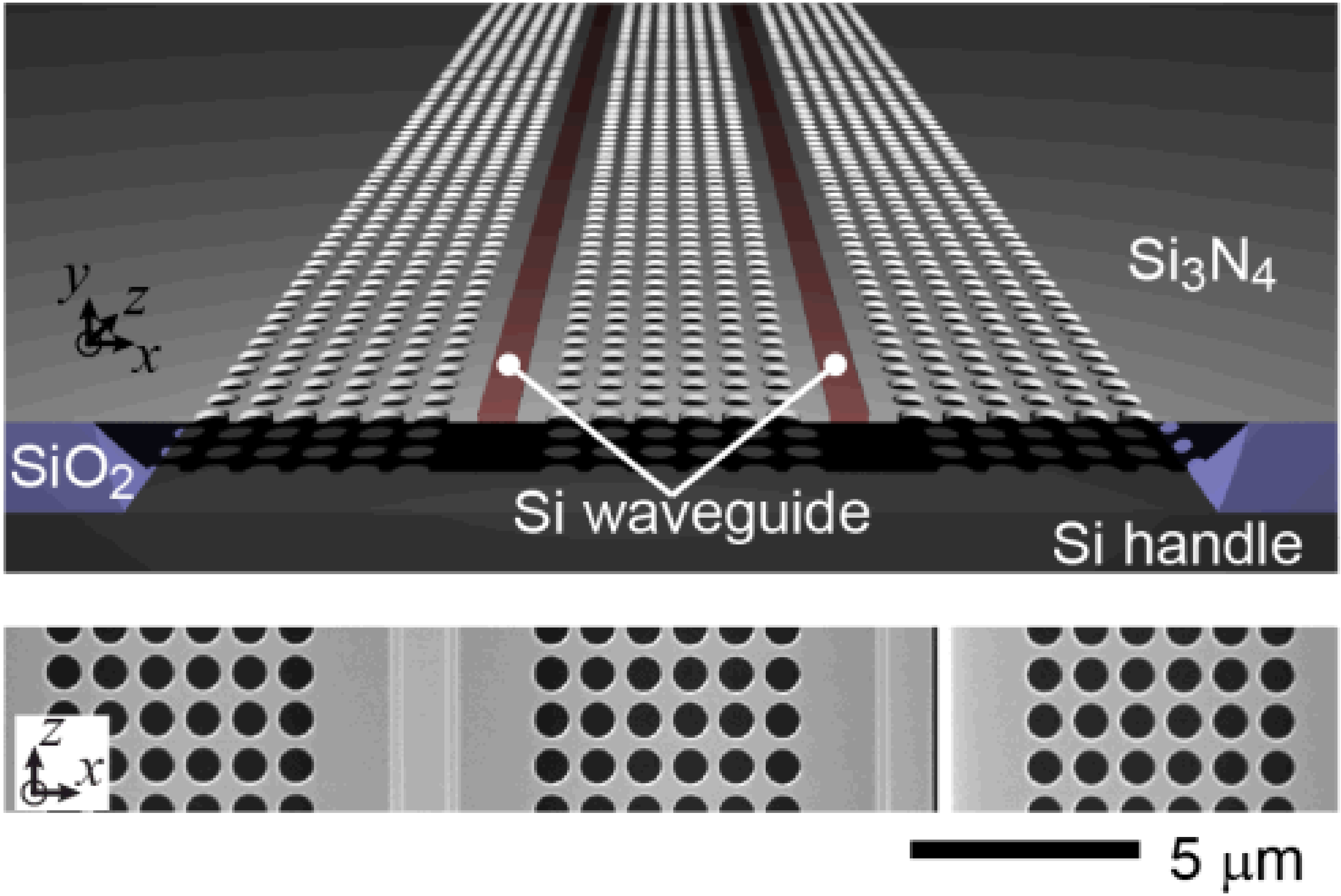
Photon-Phonon Emitter-Receiver (PPER)

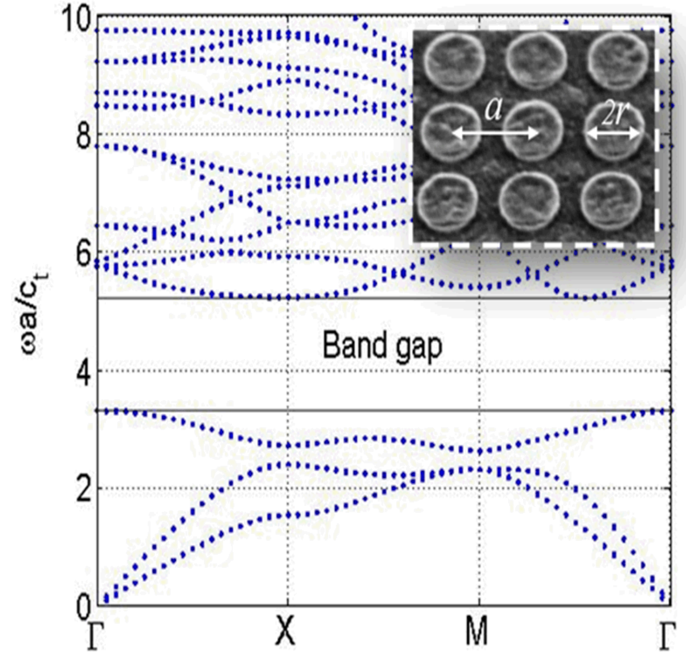


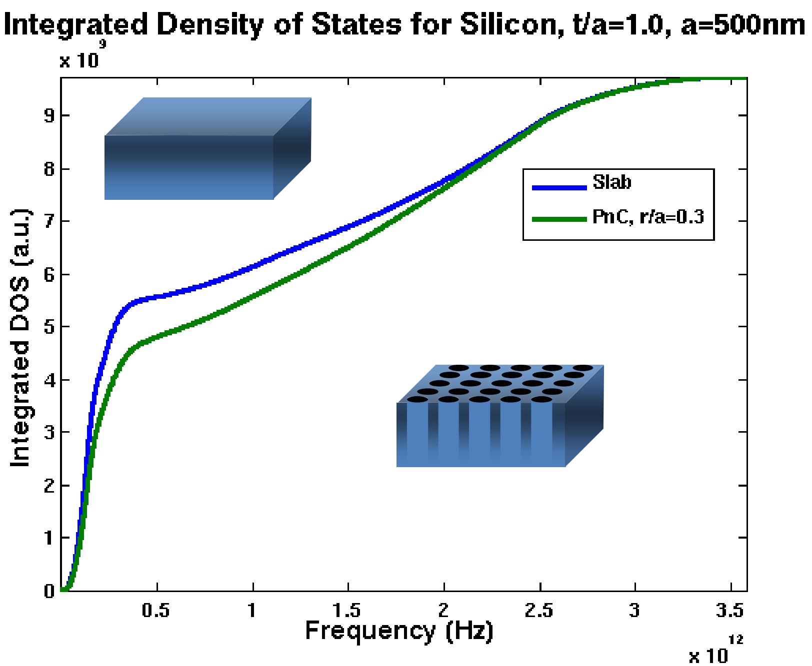
Photonic-phononic emitter-receiver (PPER)

Phononic Crystals (PnCs)

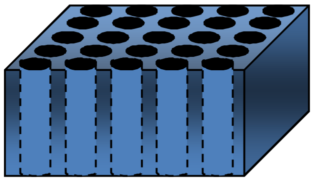
What are phononic crystals?

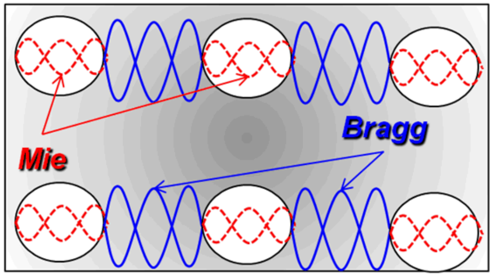
- Periodic arrangement of elastic scattering centers in a matrix material that exhibits both incoherent and Mie and Bragg resonant scattering
- Requires sufficient mechanical impedance mismatch

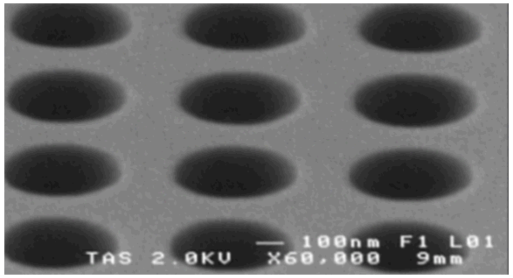




PnC

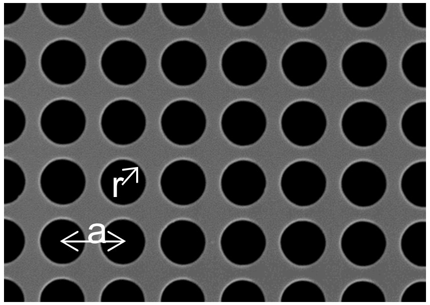




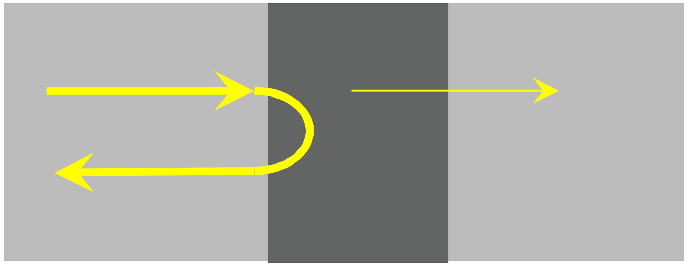


Phononic Crystals (PnCs)

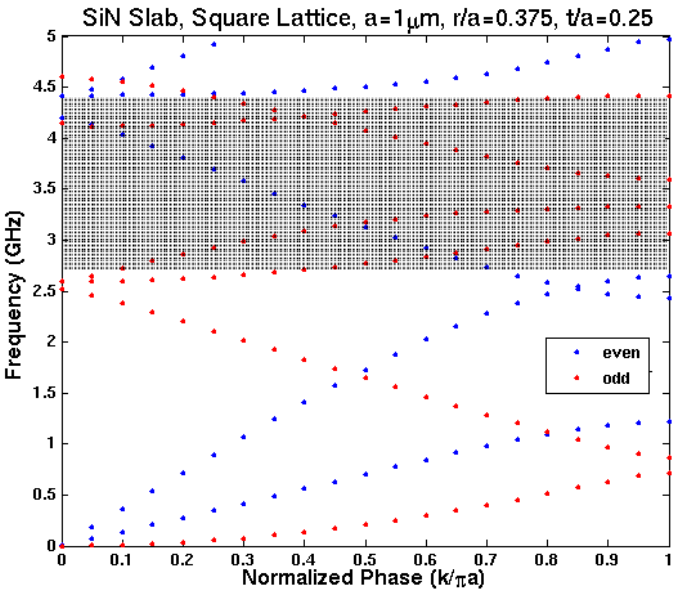
Square lattice PnC

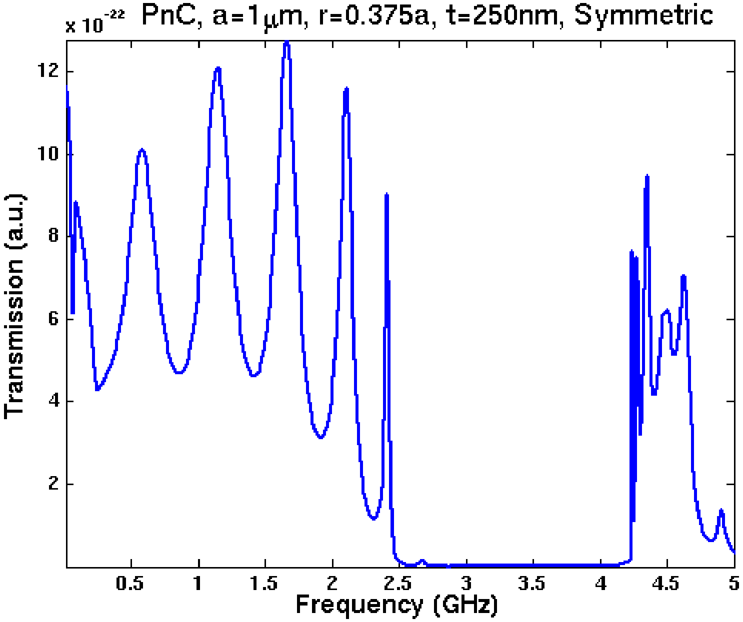


a = 1 μm
r = 0.385 μm

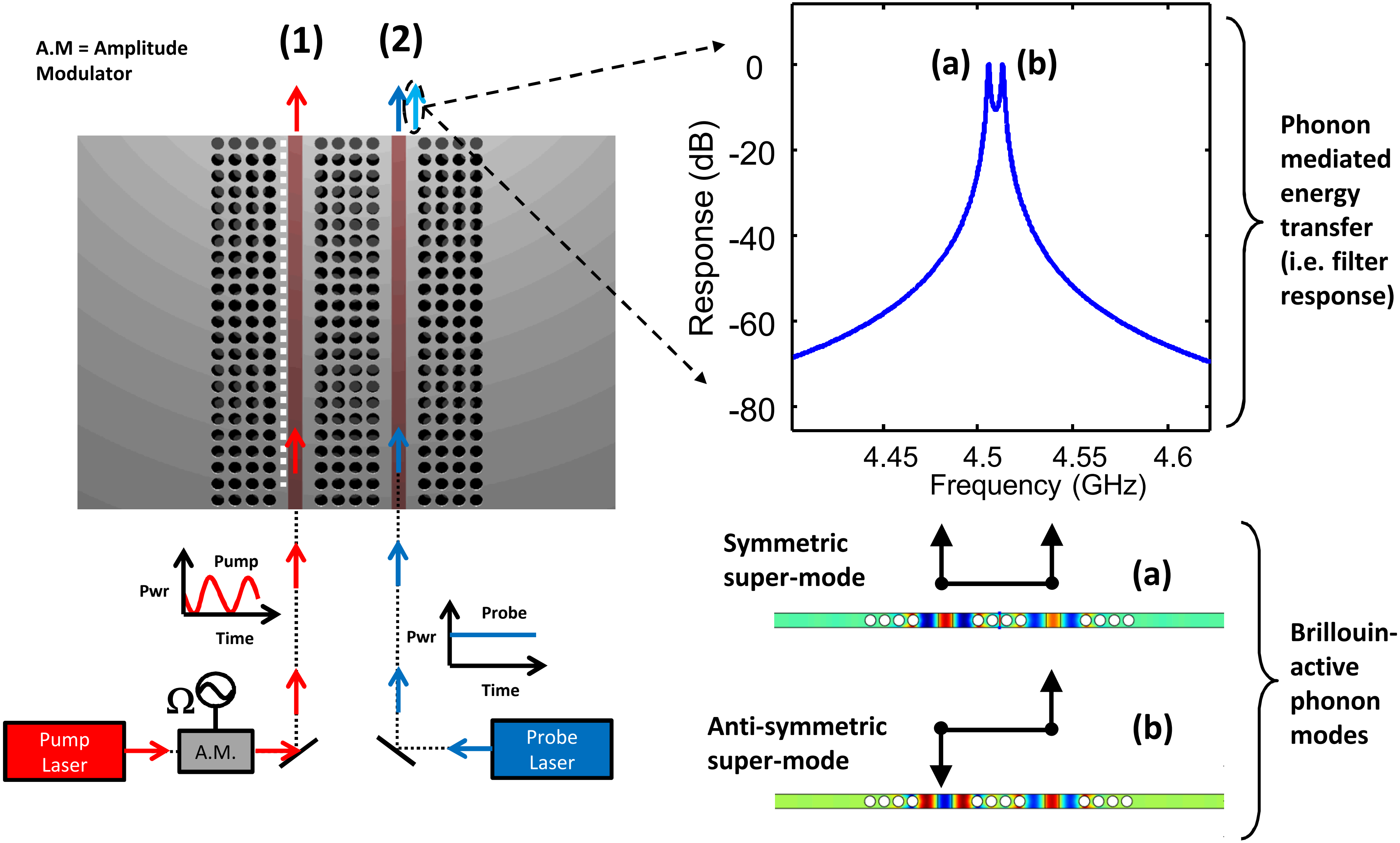


Khelif, et al., Phys. Rev. E 74, 046610 (2006).

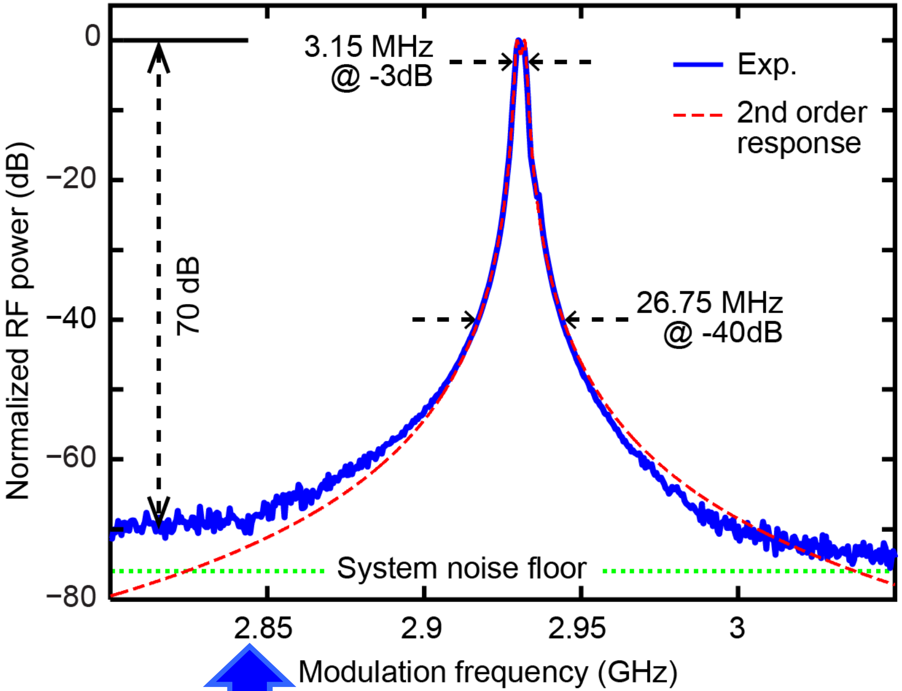


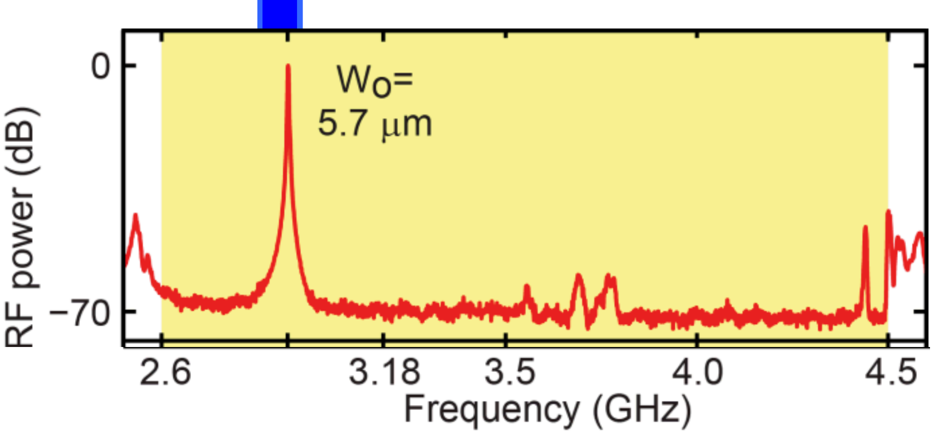


Dual-Waveguide PnC Cavity System



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

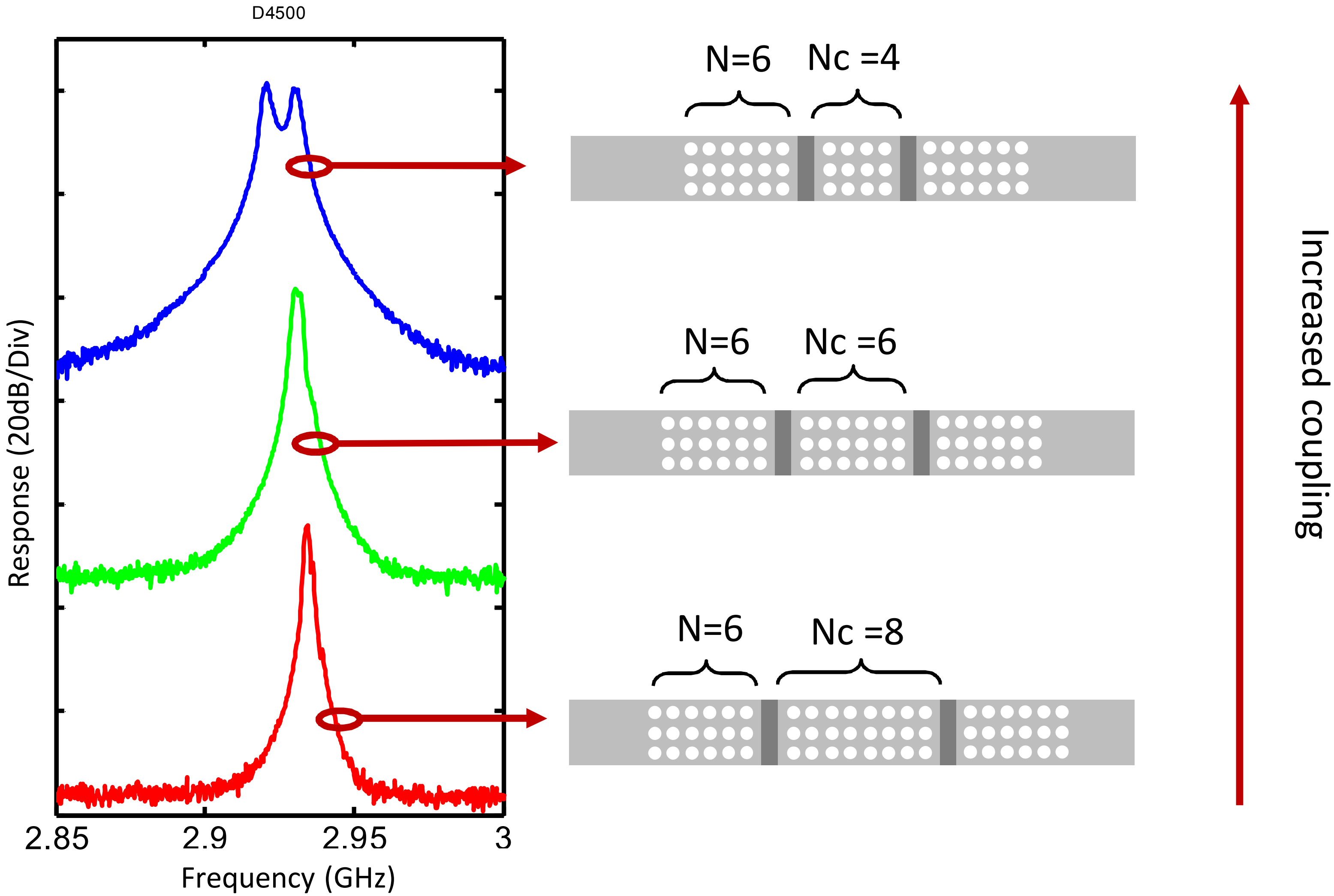
(110mW for 3dB/cm loss)

Wavelengths ➔ 1535nm and 1546nm

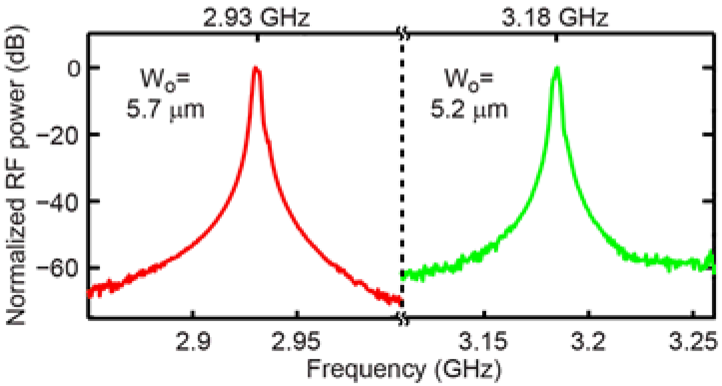
Laser bandwidth ➔ 5 MHz

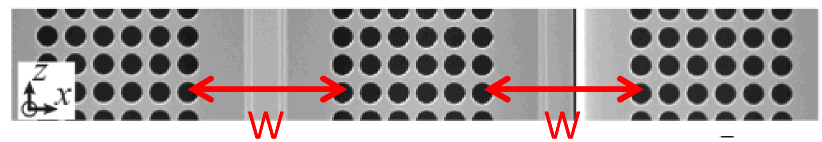
Shin, *et al.*, *Nat. Comm.* **6**, 6427 (2015)

PnC Engineering of Coupling Strength

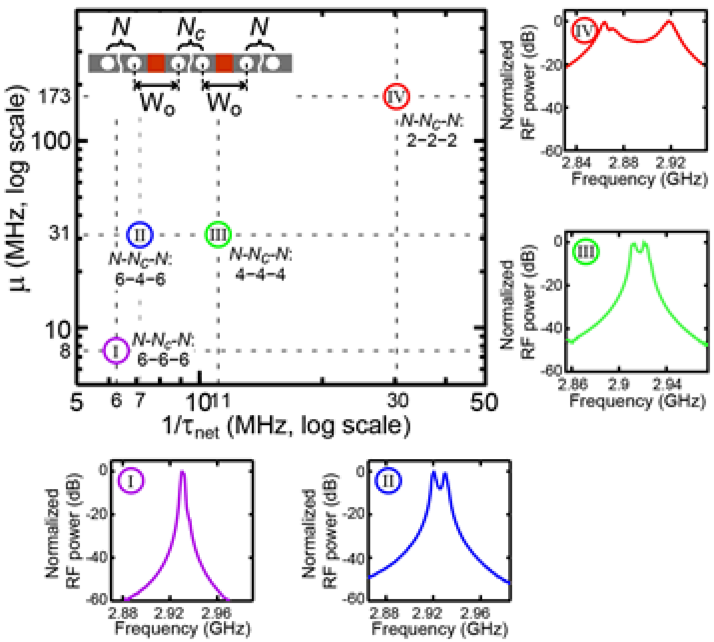


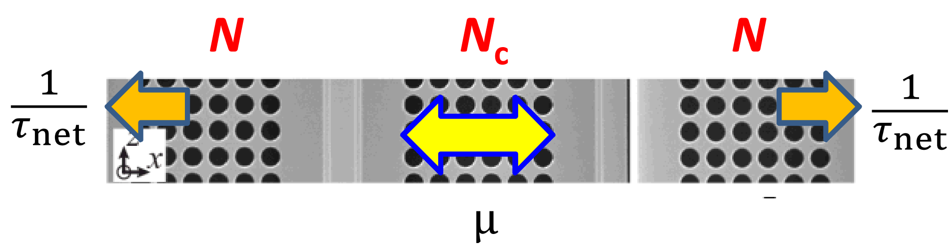
PPER Device RF Response





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





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

Comparison with RF Photonics

RF Photonic Filters Using All-Optical Methods

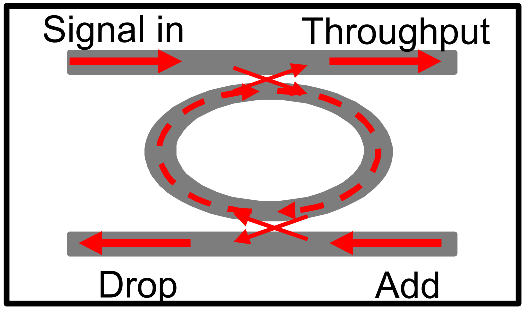
Asymmetric MZI

Whispering gallery mode resonator

Bragg grating

Ring resonator

Resonator-based RF photonic filters

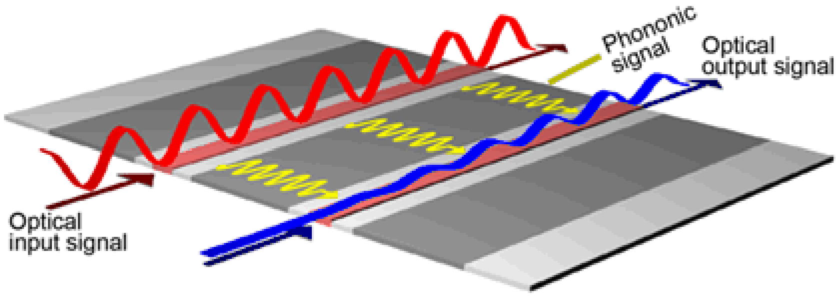


- Requires high optical Q (~10^8)
- Low power handling (optical nonlinearities)
- Requires narrow linewidth lasers
- Requires frequency locking
- First higher-responses difficult

Summary

- Demonstrated SBS gain values as large as $1000 m^{-1} W^{-1}$ in a 7mm-long device, equivalent to the SBS nonlinearity of more than a meter of conventional silica fiber

- Developed an I-ASOPS system enabling rapic time domain acquisition over long durations (ns-µs) with high (ps) temporal resolution and µrad sensitivity



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

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