Control of Coherent Information by Mixing Light and Sound in Photonic Circuits

SAND2015-9147C

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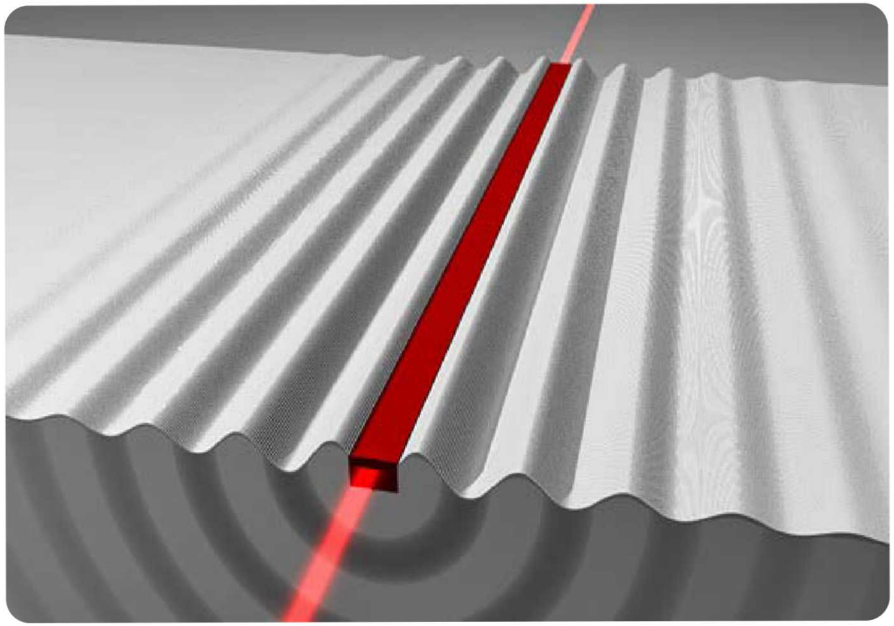
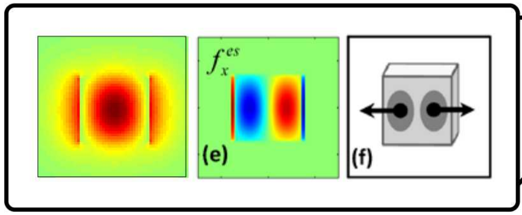
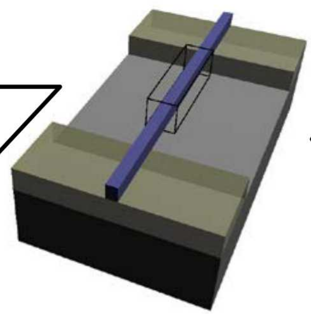


Topic: Light-Sound Coupling

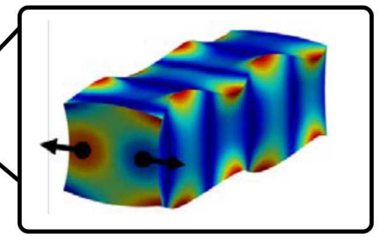
Physics of Stimulated Brillouin Scattering (SBS) at Nanoscales.

Electrostriction + Radiation Pressure





10-40 GHz Phonons

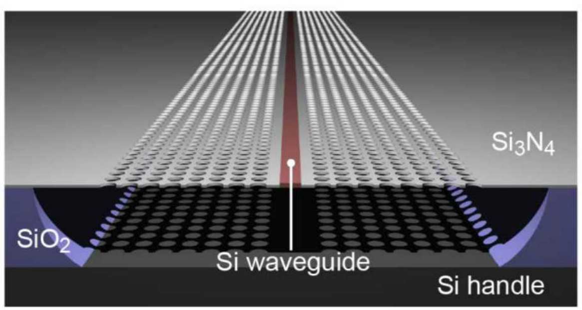


Radically enhanced SBS.

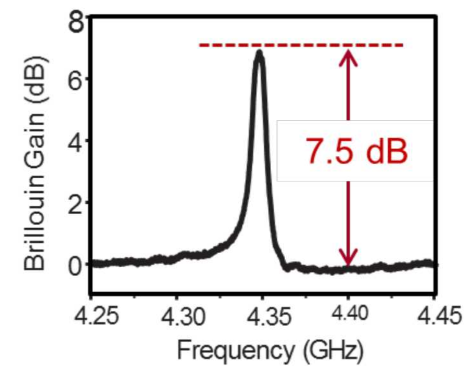
New Understanding:

- Origins of optical forces at nanoscale.
- New mechanisms for photon-phonon coupling

Experimental Realizations of Forward-SBS in Silicon.

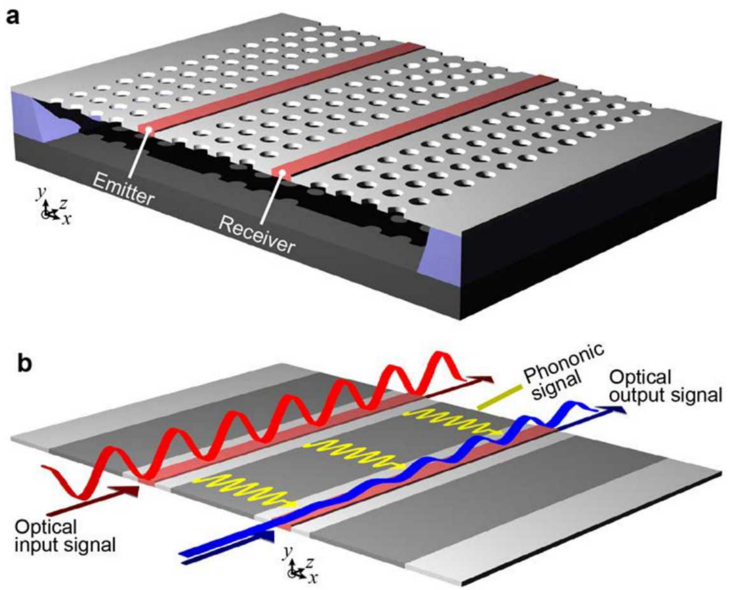


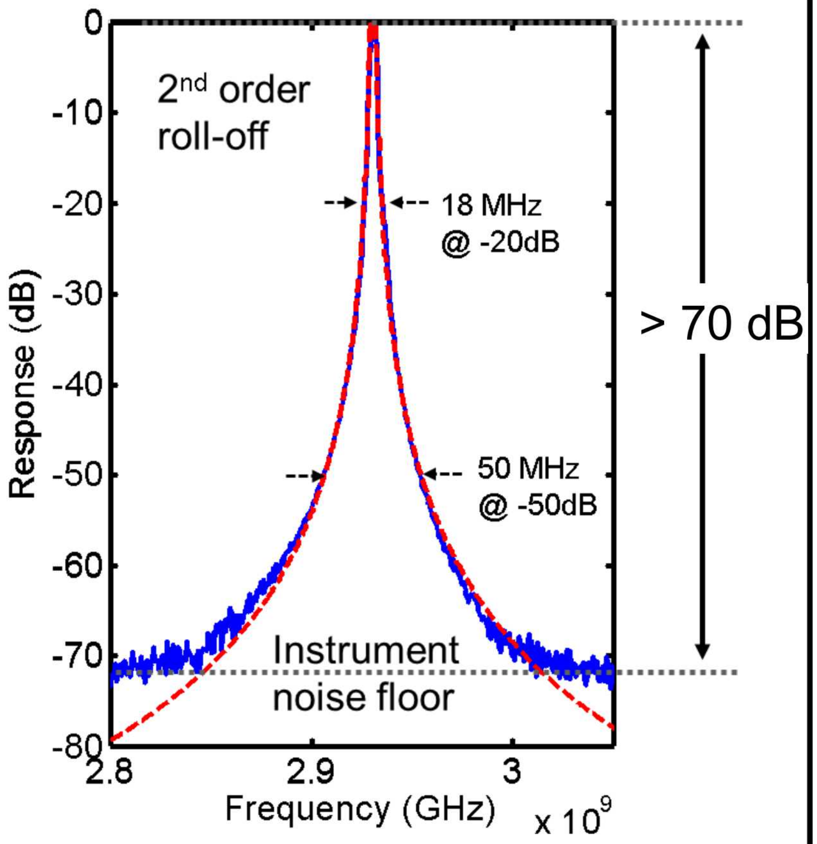
- First demonstration of stimulated Brillouin scattering in silicon.
- Tailorable nonlinear susceptibilities.
- High power signal amplification via traveling-wave photon-phonon coupling in silicon!



Phonons Enable *Nonlocal* Interactions:

Traveling-Wave Phonon Emit-Receive Functionalities.





New Paradigm for RF-Photonic Signal Processing:

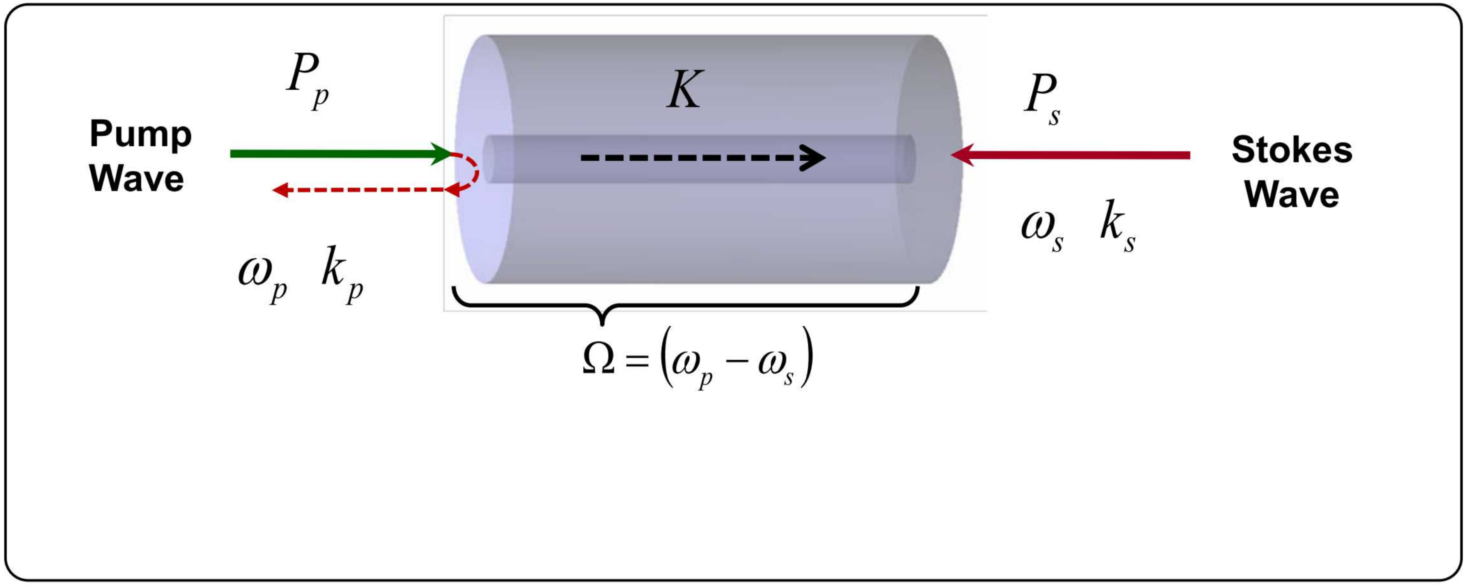
- **Phonons mediated information transfer between distinct waveguides.**
- **Flexible new signal processing approaches.**

Outline of Presentation:

1. Introduction and Background
2. Light scattering and nonlinearity
3. Optical forces at nanoscales
4. Stimulated light scattering in nanophotonics
5. Novel signal processing applications

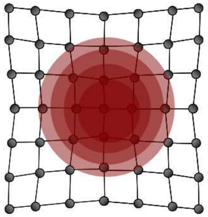
Stimulated Brillouin Scattering (SBS) in Fibers:

How does backward-SBS work?

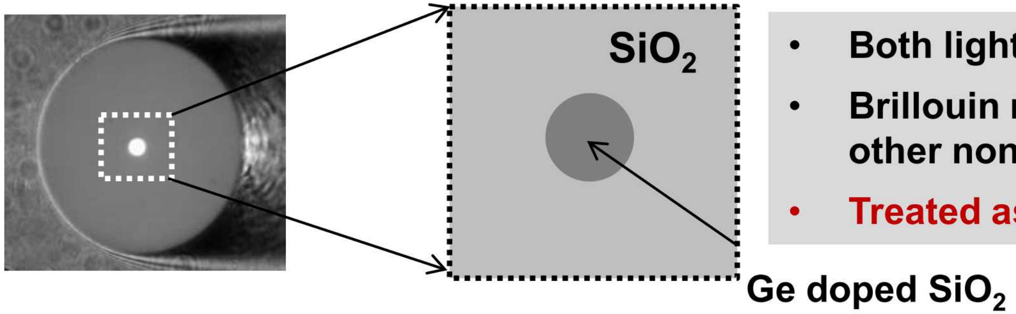


Electrostrictive forces compress medium

Electrostriction:



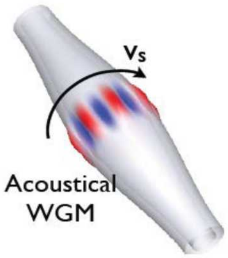
From dynamic material response.



- **Both light and sound are guided in silica core.**
- **Brillouin nonlinearities are 100x larger than any other nonlinearity in silica fiber.**
- **Treated as a bulk material nonlinearity.**

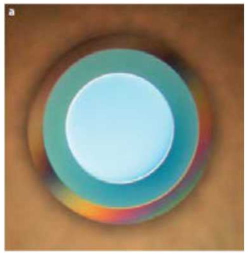
What can you do with Brillouin nonlinearities?

Science & technological impact of SBS?



Bahl Group

Carmon Group



Vahala Group

Slow and Fast Light

Y. Okawachi et al., *Physical review letters*, vol. 94, no. 15, p. 153902, 2005.

R. W. Boyd, "Slow and fast light: fundamentals and applications," Journal of Modern Optics, vol. 56, no. 18-19, pp. 1908-1915, Oct. 2009.

Narrow Band SBS Lasers

L. F. Stokes, M. Chodorow, and H. J. Shaw, "All-fiber stimulated Brillouin ring laser with submilliwatt pump threshold.," *Optics letters*, vol. 7, no. 10, pp. 509-11, Oct. 1982.

Non-Reciprocal Devices (i.e. isolators)

M. S. Kang, A. Nazarkin, A. Brenn, and P. S. J. Russell, *Nature Physics*, vol. 5, no. 4, pp. 276-280, Mar. 2009.

M. S. Kang, a. Butsch, and P. S. J. Russell, Nature Photonics, no. August, pp. 1-5, Aug. 2011.

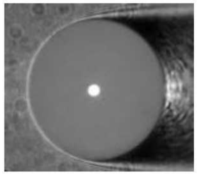
High Frequency Synthesis, Gyros, etc….

[2] Li, J., Lee, H. & Vahala, K. J.. Nature Communications 4, 1–7 (2013).

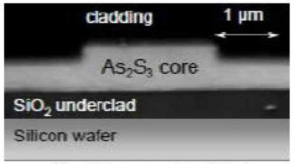
On Chip Brillouin Photonics

Eggleton, Benjamin J., Christopher G. Poulton, and Ravi Pant. *Advances in Optics and Photonics* 5.4 (2013): 536-587.

- Gross simplification of growing field….

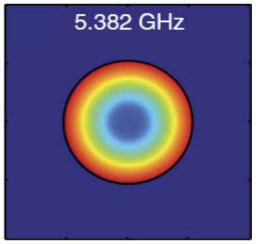


Russel



As_2S_3 waveguide

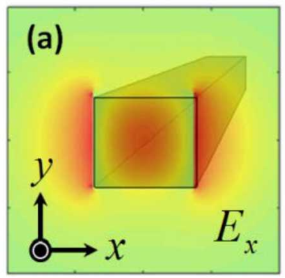
Eggleton Group



Sylvestre

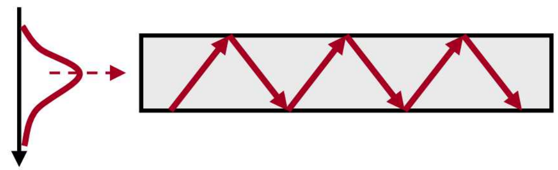
Nonlinear Enhancement in Silicon Photonics

Silicon Waveguide



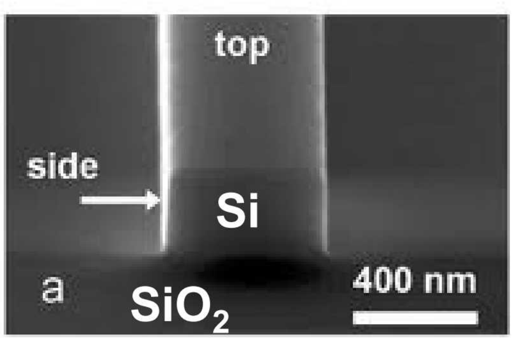
300nm x 300nm

Total internal reflection:



- **Sub-wavelength confinement.**
- **Wavelength = 1550 nm.**

Nanoscale Silicon Waveguide



Silicon: $n = 3.5$

Silica: $n = 1.45$

Intrinsic nonlinearities enhanced:

- **Stimulated Raman Scattering.**
- **Electronic Nonlinearities**
  - **Kerr Nonlinearities**
  - **Four Wave Mixing, etc.**

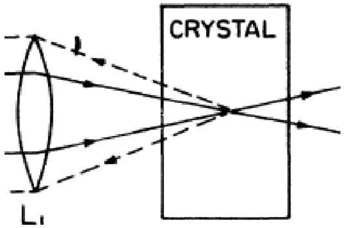
Timeline for Stimulated Brillouin Scattering:

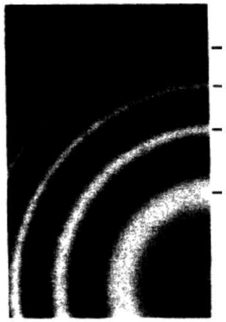
1. Bulk SBS with MASER (Chaio 1964)
2. Guided-wave SBS (Ippen, 1972)
3. Engineered SBS in fibers. (Russel 2007)

Macro → Micro

Micro → Nano

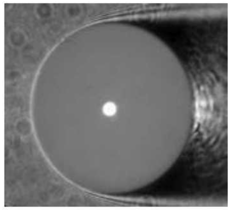
SBS in Bulk X-tal



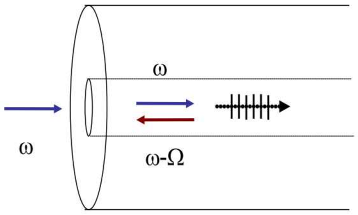


Chiao (1964)

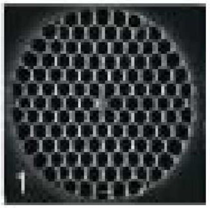
SBS in Optical Fibers

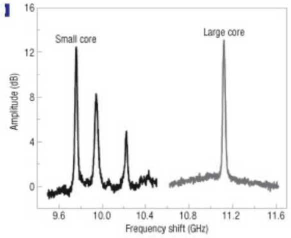


Ippen (1972)



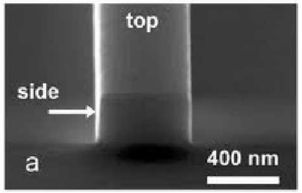
Micro-structured Fiber





Russel (2007)

SBS in Nanophotonics?



Q: What's needed to form strong SBS? A: Large optical forces & phonon confinement.

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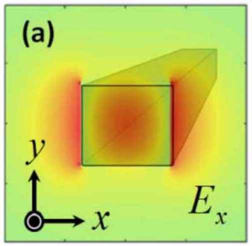
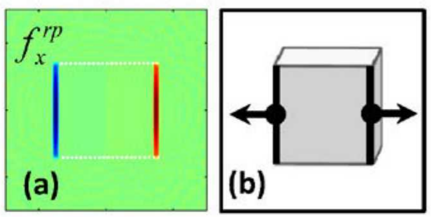
Optical Forces at Nano-scales

Silicon Waveguide.

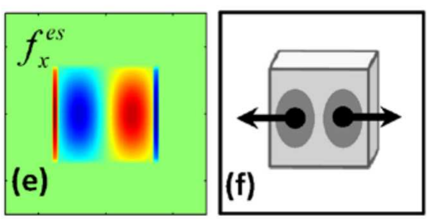


300nm x 300nm

Radiation Pressure



Electrostrictive Forces

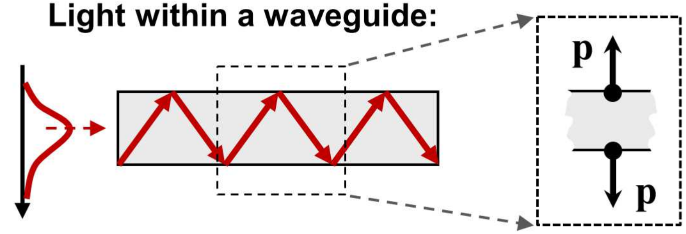


Both: Radically enhanced at nanoscales.

Radiation Pressure.

Radiation Pressure: Scattering from boundaries.

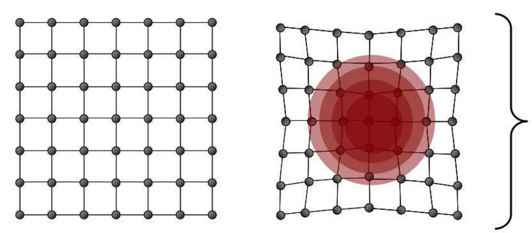
Light within a waveguide:



Entirely depends on geometry.

Electrostrictive Forces

Electrostriction: dynamic response of media to light.

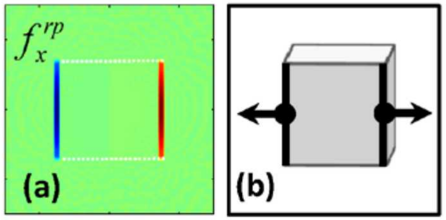


Depends primarily on material properties.

- **What factors dictate the magnitude of the force?**
- **How can we enhance forces and SBS?**

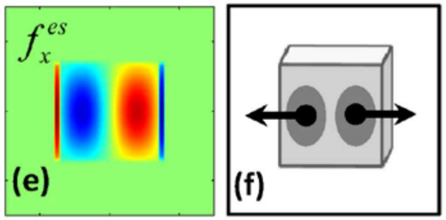
Nanoscales: The Neglected Optical Force Dominates!

Radiation Pressure



Rad. Pressure: $\bar{p}^{rp} = \frac{P_{opt}}{c \cdot A} \cdot (n_g - n_p) = \frac{P_{opt}}{c \cdot A} \cdot \alpha^{rp}$

Electrostrictive forces



Electrostriction: $\bar{p}^{es} \cong \frac{P_{opt}}{c \cdot A} \cdot n_g n^2 (p_{11} + 2p_{12}) / 2 = \frac{P_{opt}}{c \cdot A} \cdot \alpha^{es}$

Material	Symmetry	p_{11}	p_{12}	$p_{11} + 2p_{12}$	n	α^{rp}	α^{es}
Si	cubic	-0.09	+0.017	-0.056	3.5	-5	-1.7
Ge	cubic	0.27	0.235	0.74	4.2	-6.4	+40
GaAs	cubic	-0.165	-0.14	-0.445	3.4	-4.8	-12
Silica	amorphous	0.121	0.27	0.661	1.45	-0.89	+1.0
As_2S_3	amorphous	0.25	0.24	0.73	2.4	-2.8	+6.5
As_2Se_3	amorphous	-	-	-	2.8	-3.6	-

How Large are Forces?

Material	Pressure (Pwr = 100mW)
Si	~10^5 N/m^2
Ge	~10^6 N/m^2

5-50 People standing on chair

Material	Pressure (Pwr = 1kW)
Si	~5 x10^8 N/m^2
Ge	~10^{10} N/m^2

Stresses Approach Material Yield Strength

Yale

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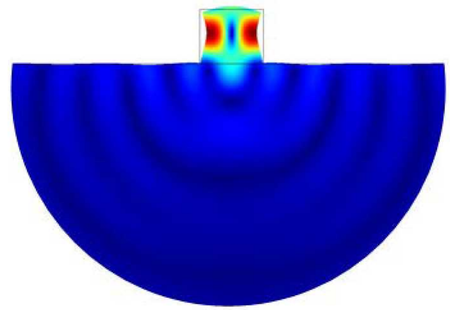
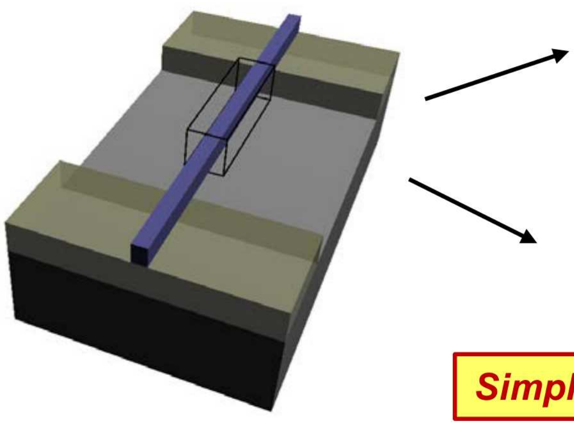
Q: Why hasn't SBS been observed in Silicon?

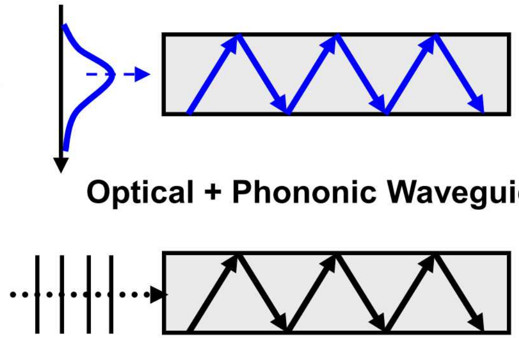
Silicon Waveguide

Problem: Rapid Dissipation



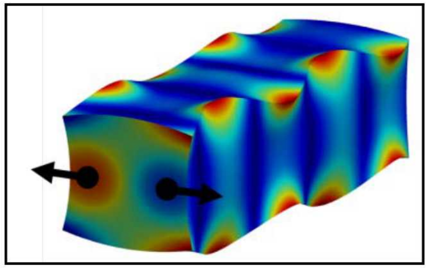
A: Requires control of the phonon modes.





Simplest Solution: Suspended Waveguide

photon-phonon coupling:

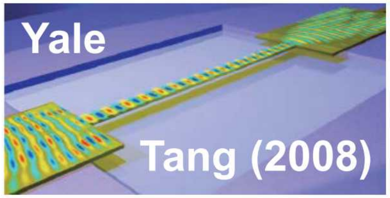


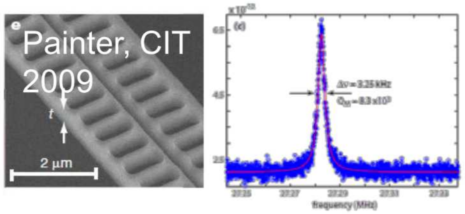
Efficient ultra-high frequency phonon emission.

Revised Paradigm for SBS at Nanoscales:

Yale

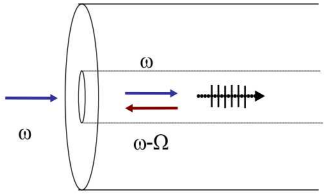
Optomechanics



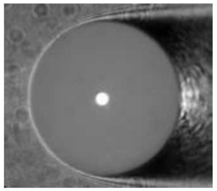


Nanoscales:
Radiation pressure mediated photon-phonon coupling.

Microscales:
Electrostrictively mediated photon-phonon coupling.

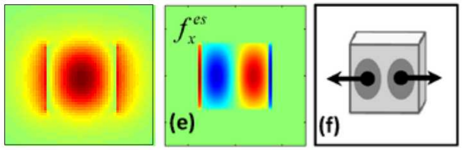


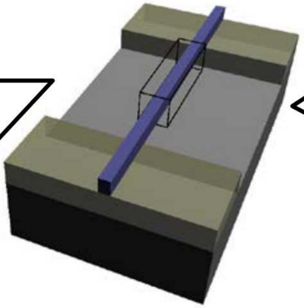
Fiber-SBS



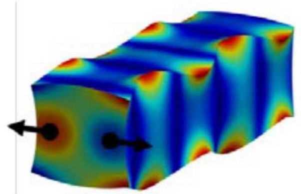
Result: Giant Enhancement of Stimulated Brillouin Scattering at Nanoscales

Electrostriction + Radiation Pressure





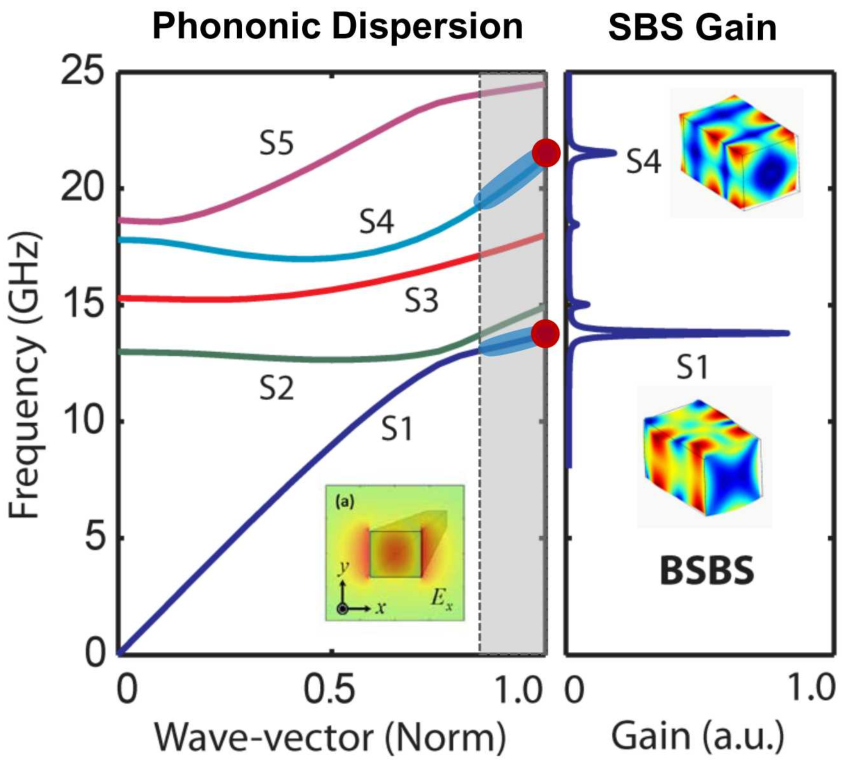
10-40 GHz Phonons



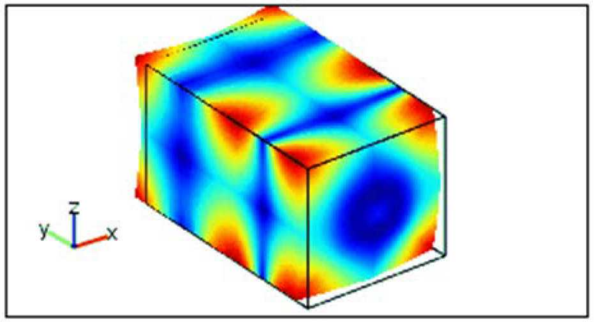
Radically enhanced SBS.

- No longer *bulk* nonlinearity.
- Geometry introduces new nonlinearities.

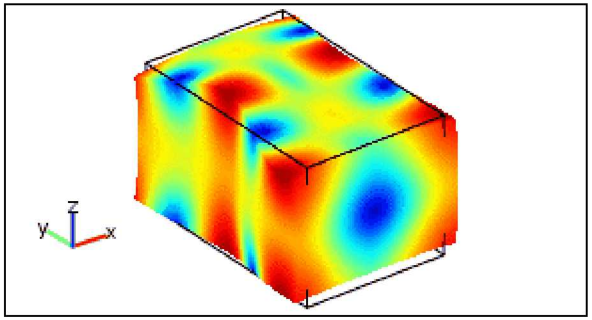
Nanoscale Backward-SBS: Tunable Phonon Emission.

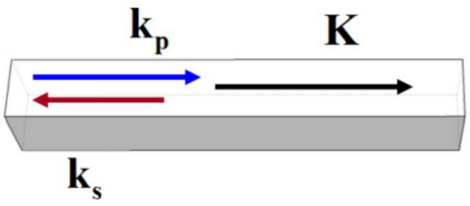


Excitation: 21.6 GHz Phonons



Excitation: 13.8 GHz Phonons

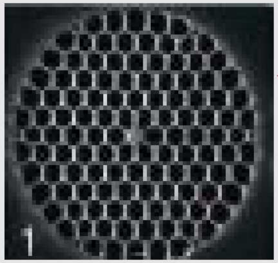




Nano-optomechanical backward-SBS:

1. Narrow-band ultra-high frequency phonons.
2. Gain is 10^4 x Larger than in Fibers.
3. SBS occurs for any optical wavelength.
4. 20% frequency tunable phonon emission.

Forward Stimulated Brillouin Scattering:

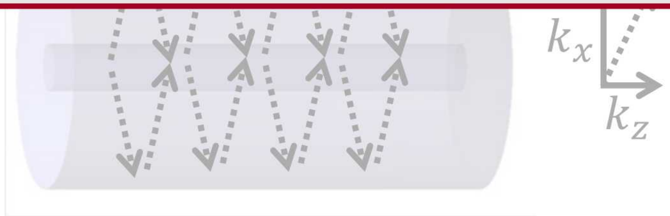


Russel

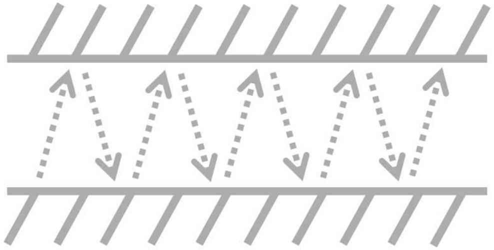
M. S. Kang, A. Nazarkin, A. Brenn, and P. S. J. Russell, *Nature Physics*, vol. 5, pp. 276-280, (2009).

G. Bahl, J. Zehnpfennig, M. Tomes, T. Carmon, Nature Communications, Vol 2, pp. 1412 (2011).

Bahl - Carmon



Reflecting boundaries:

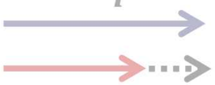


$$v_g \cdot v_p = v_a^2$$

Result:

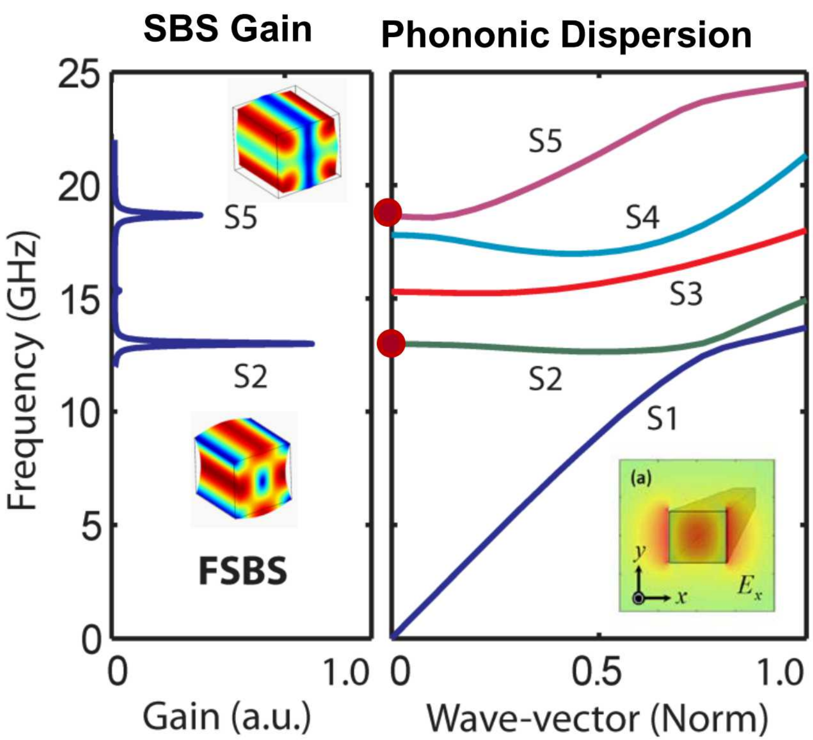
$$\begin{Bmatrix} v_p \approx 10^8\ m/s \\ v_g \approx 1\ m/s \end{Bmatrix}$$

$$\mathbf{k_p} = \mathbf{k_s} + \mathbf{K}$$



Problem: since phonon modes delocalized, forward-SBS exceedingly weak

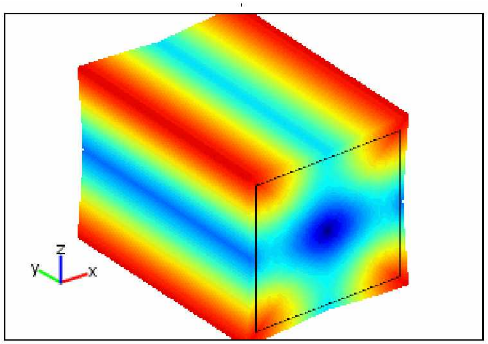
Forward-SBS: Fixed Frequency Resonances.



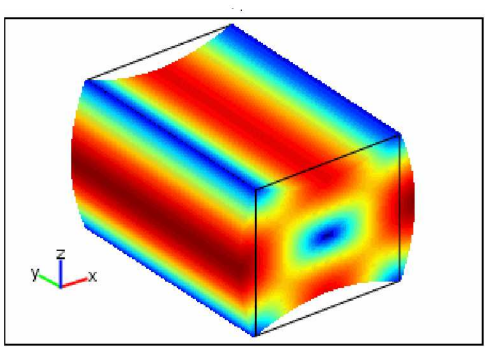
Nano-optomechanical Forward-SBS:

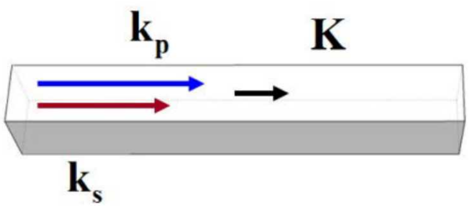
1. Stronger than backward SBS
2. Coupling mediated by slow group velocity phonons.
3. Perhaps better suited to silicon photonics: no isolator necessary

Excitation: 18.6 GHz Phonons

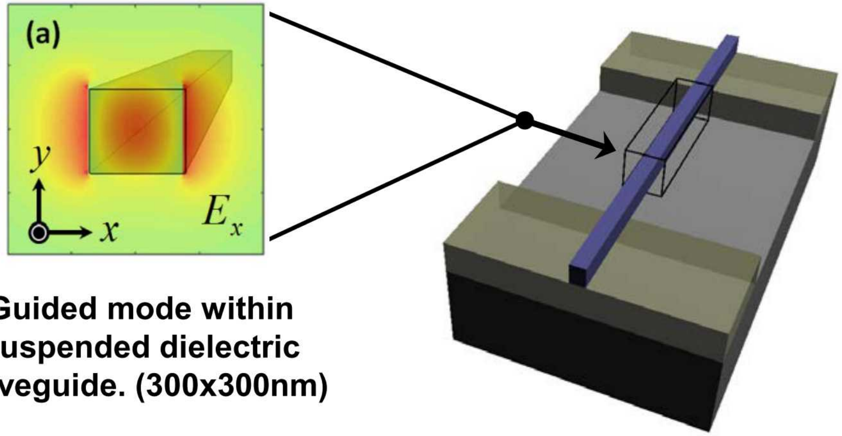


Excitation: 13.0 GHz Phonons





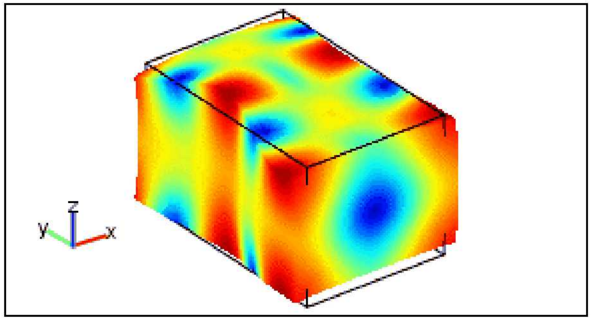
Opportunity: Integrated Brillouin Photonics



Guided mode within suspended dielectric waveguide. (300x300nm)

Suspended waveguide: L = 100 microns

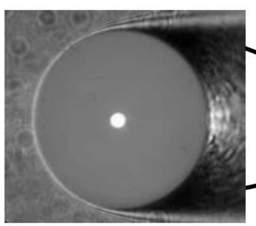
Excitation: 13.8 GHz Phonons

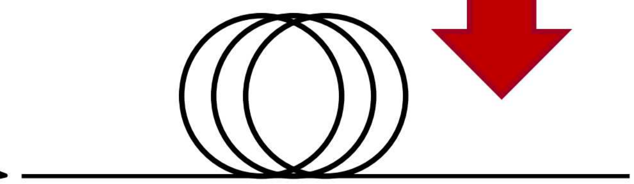


= Equivalent nonlinearity of 10-1000 meters of fiber

New Technologies:

- **Slow light & information storage**
- **Narrow-band signal amplification and lasers.**
- **Tailorable nonlinear susceptibilities.**





Fiber optic: L = 10-1000 meters

P. Rakich, C. Reinke, R. Camacho, P. Davids, and Z. Wang, "Giant Enhancement of Stimulated Brillouin Scattering in the Subwavelength Limit," *Physical Review X*, vol. 2, no. 1, pp. 1-15, Jan. 2012.

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Outline of Presentation:

1. Introduction

2. Light scattering and nonlinearity

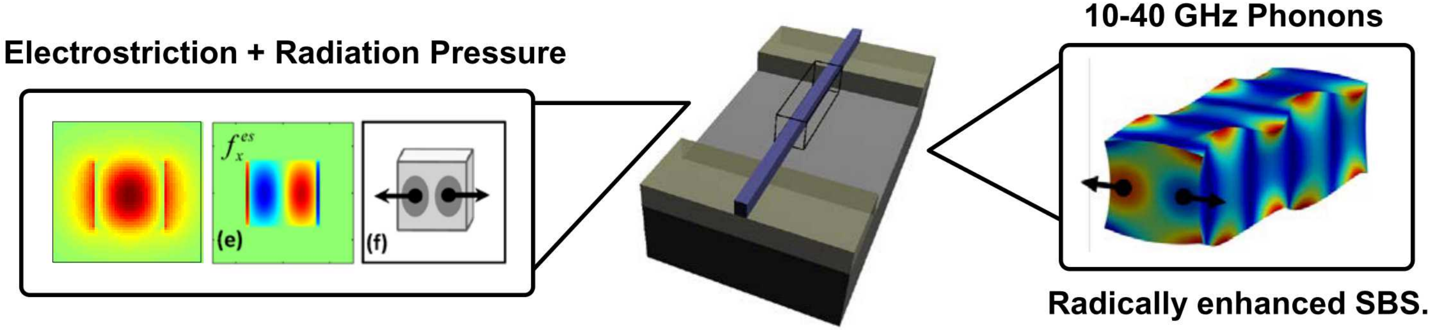
3. Optical forces at nanoscales

4. Stimulated light scattering in nanophotonics: Experiment

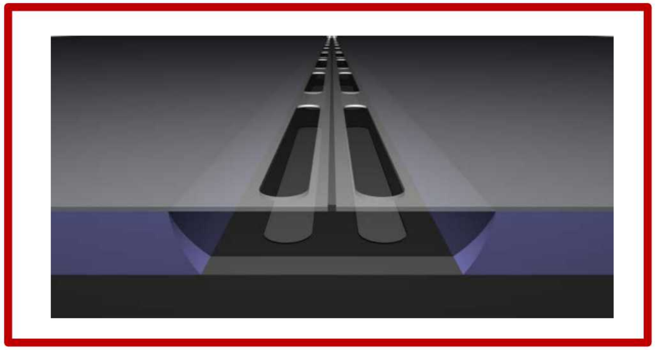
5. Novel signal processing applications

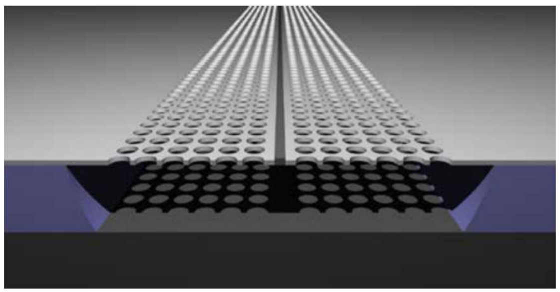
Outline of Presentation:

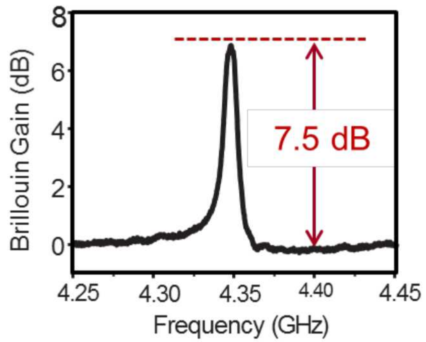
Part I: Physics of Stimulated Brillouin Scattering (SBS) at Nanoscales.



Part II: Experimental Demonstration of Forward-SBS in Silicon.

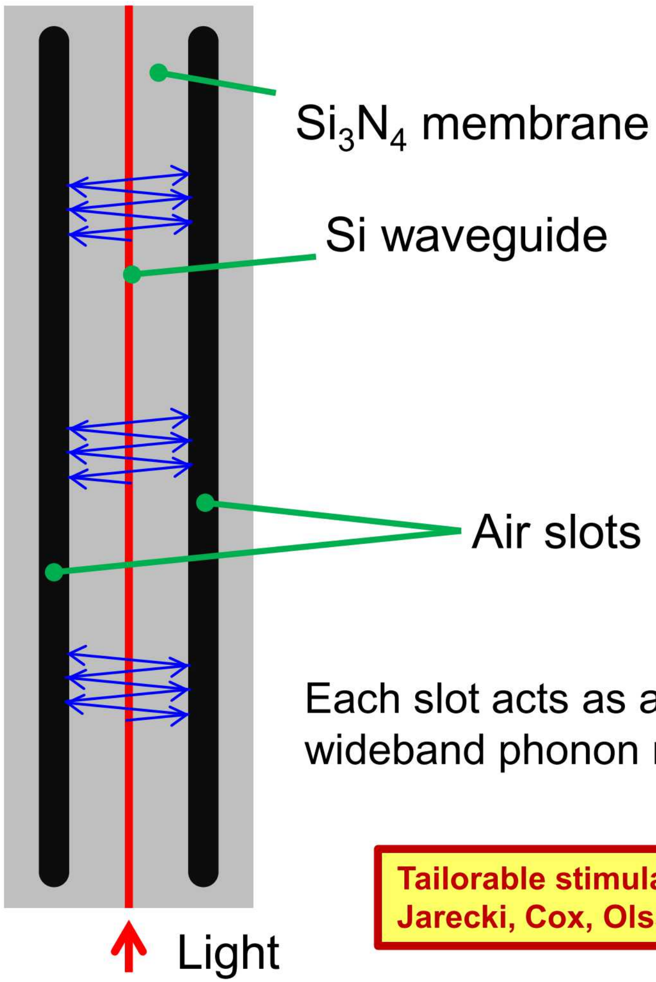




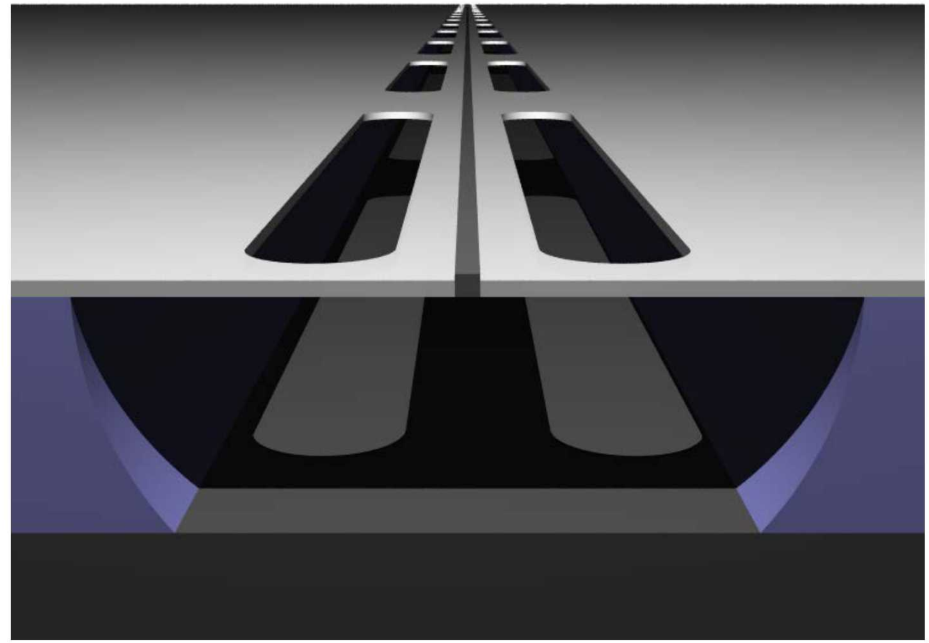


Creation of SBS in novel structure

Brillouin Active Membrane (BAM) waveguide



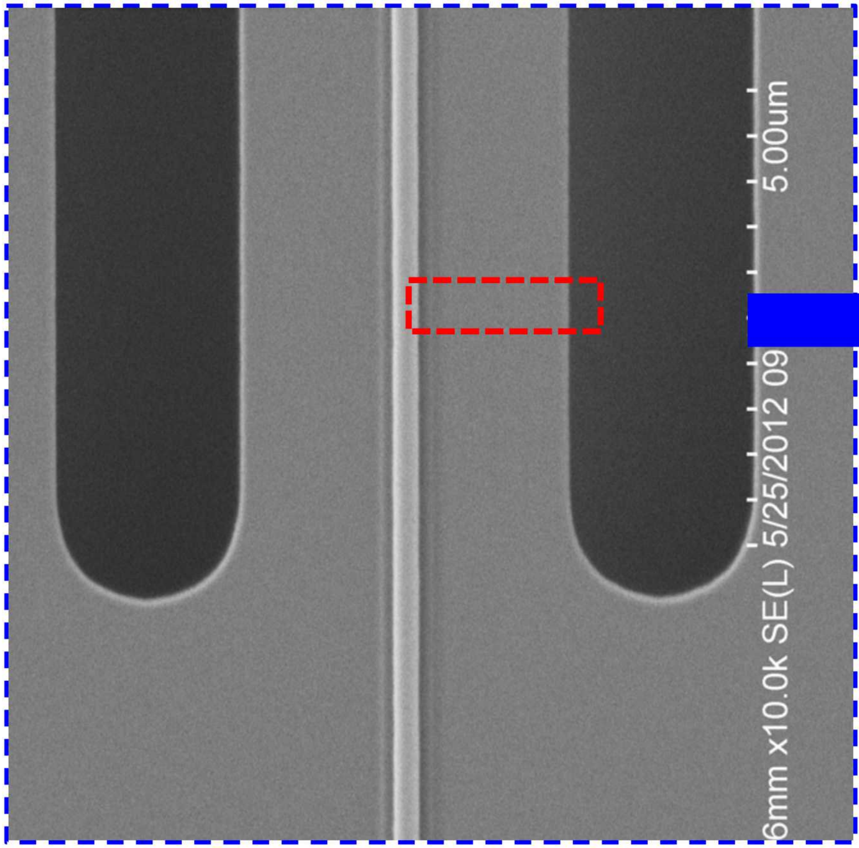
Each slot acts as a wideband phonon mirror.

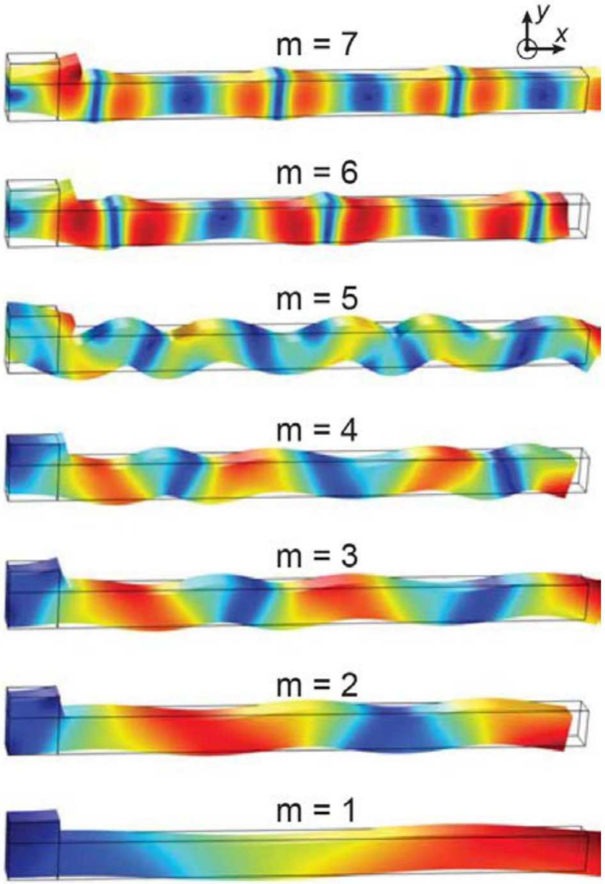


- First demonstration of SBS in silicon
- Combination of pressure & electrostriction
- Tailor nonlinear susceptibility in silicon.

Tailorable stimulated Brillouin scattering in nanoscale silicon waveguides, Shin, Qiu, Jarecki, Cox, Olsson III, Starbuck, Wang, Rakich, Nature Comm. 4, 1944 (2013).

Simulation of elastic wave displacement

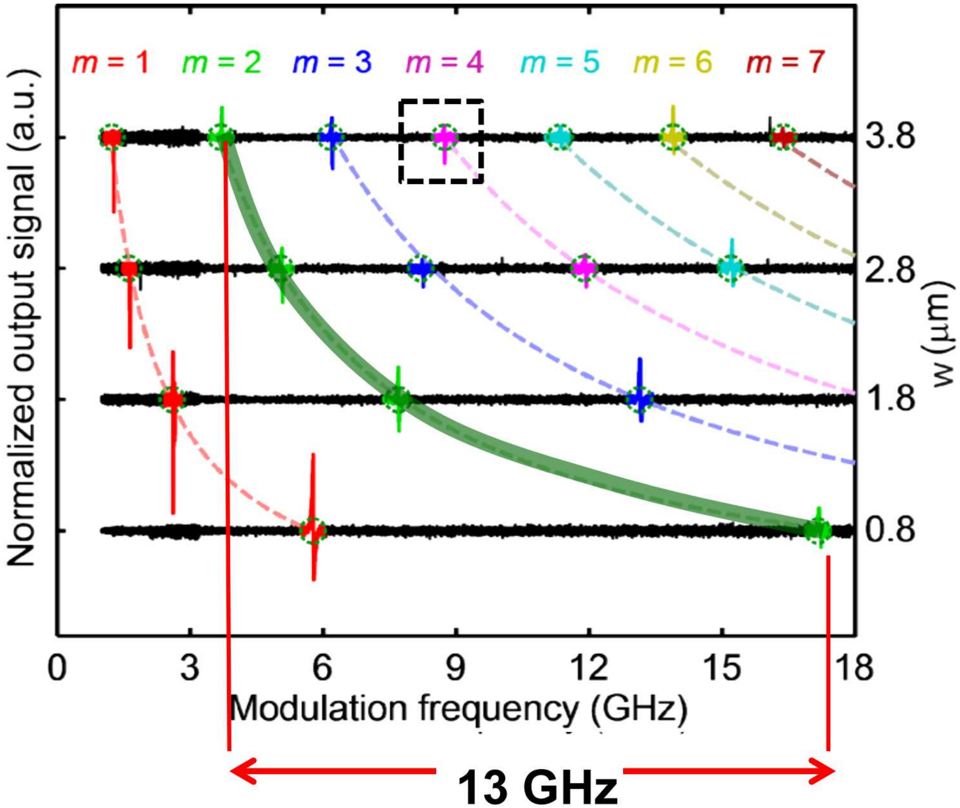


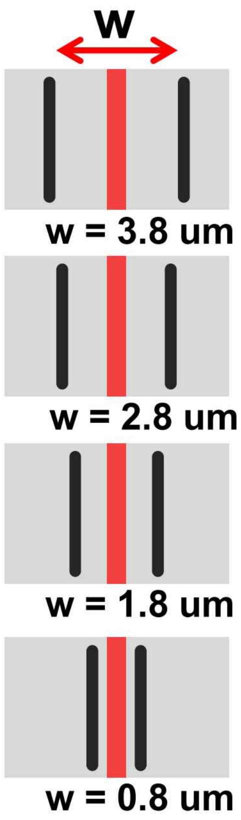


Phonons are created in the optical waveguide, but extended to the air slot edges.

This extended phononic mode enables delocalized photon-phonon interaction.

How can coupling be tailored?



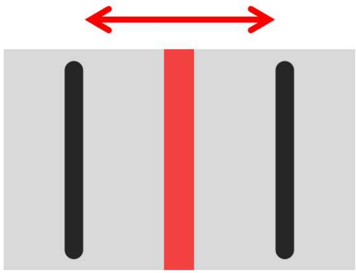


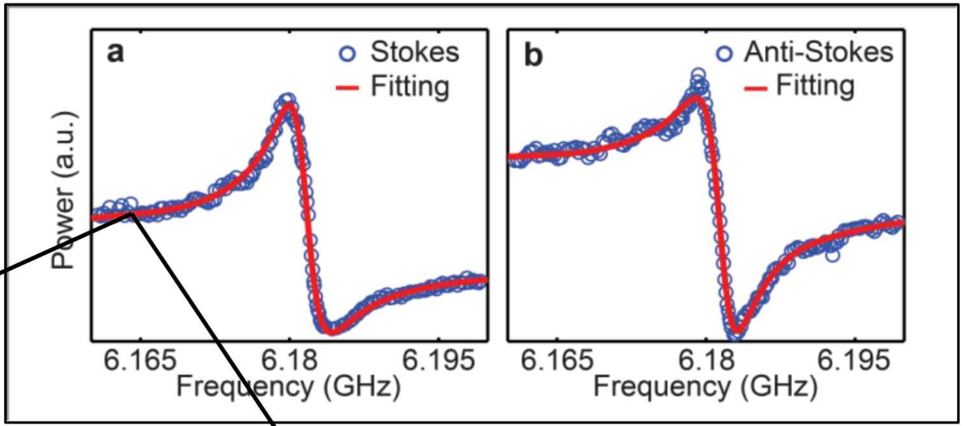
- As waveguide dimension increases, more guided modes are allowable.
- Highly tailorabile nonlinearities.

Q: How strong is photon-phonon coupling?

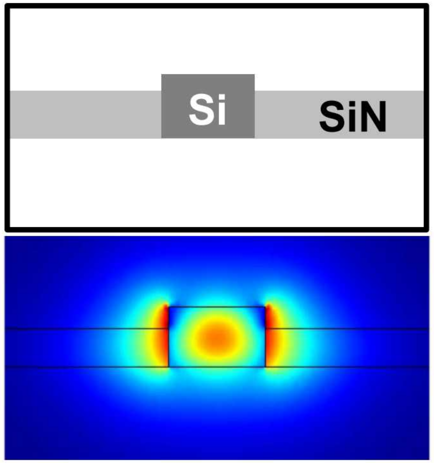
Analysis of Experimental Brillouin Signatures

$w = 3.8\ \mu m$





Si Waveguide



Kerr Nonlinearity

Intrinsic Si Nonlinearity:

$$n_2 = 4.5 \cdot 10^{-18}\ m^2/W$$

NL Waveguide Coefficient:

$$\gamma_k = 188\ W^{-1}m^{-1}$$

Brillouin nonlinearities are quantified relative Kerr nonlinearities.

Line-Shape Analysis:

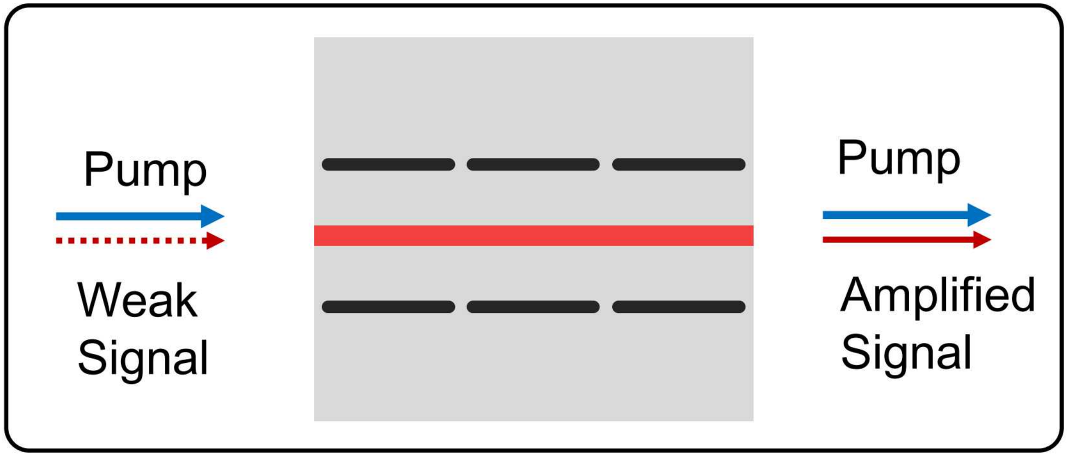
$$G_B/\gamma_k \cong 10.43$$

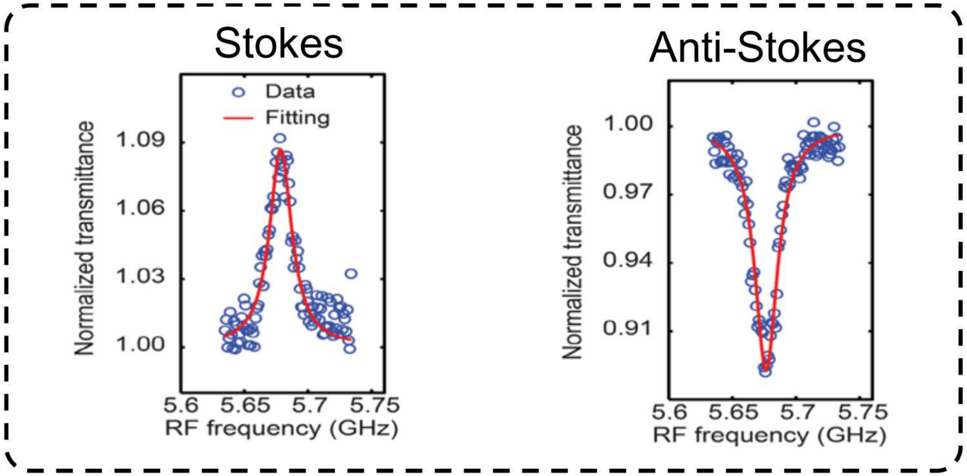
$$G_B \cong 1960\ W^{-1}m^{-1}$$

$$Q \cong 1561$$

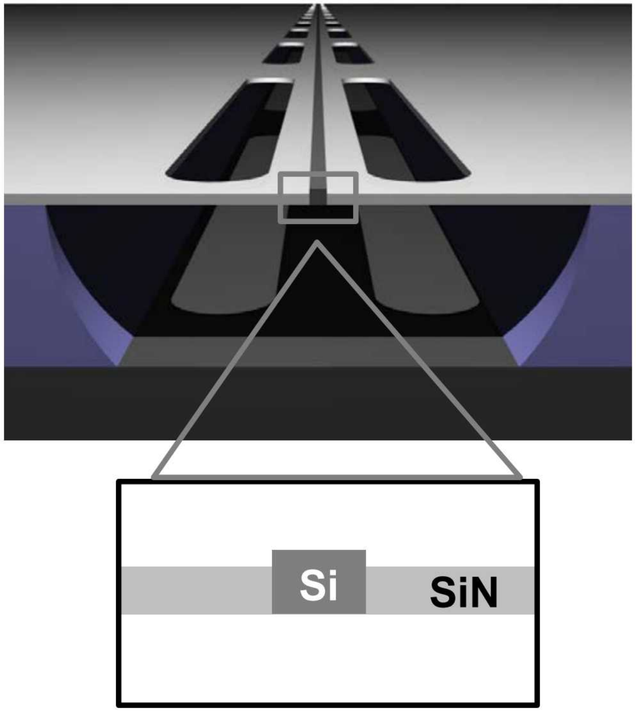
- **1000 X larger than any prior forward-SBS system.**
- **First SBS in Silicon!**

How large is the SBS amplification?





Si/SiN Waveguide



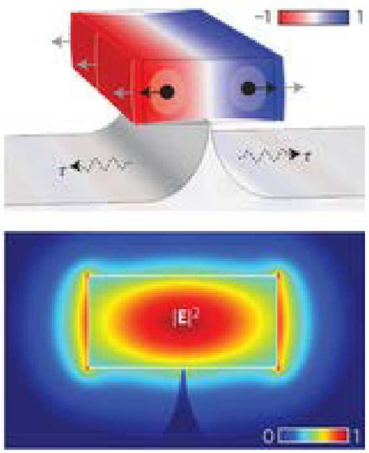
Gain coefficient: ~ 2800 $W^{-1}m^{-1}$

Losses 7dB/cm

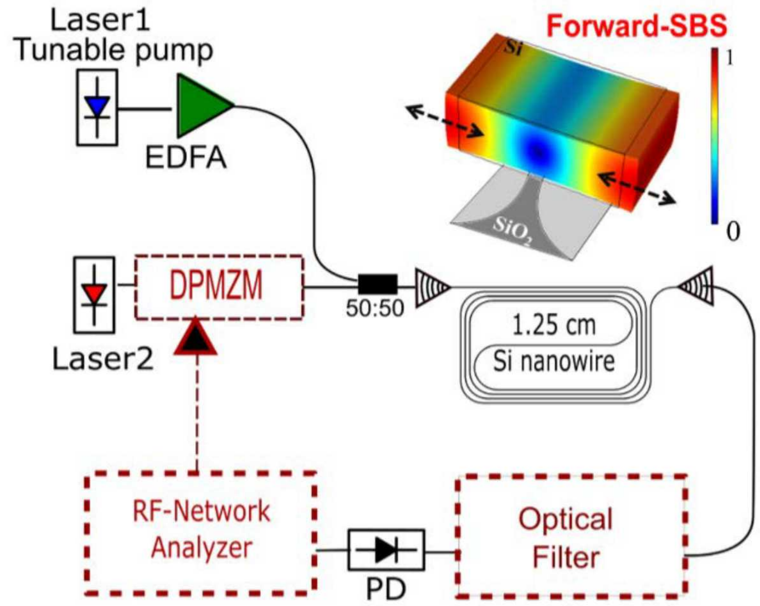
SBS Gain < 1dB; (Gain < Loss)

Q: Can we do better?

Brillouin-Active Silicon Photonics:



Van Laer, Raphaël, et al. "Interaction between light and highly confined hypersound in a silicon photonic nanowire." *Nature Photonics* 9.3 (2015): 199-203.

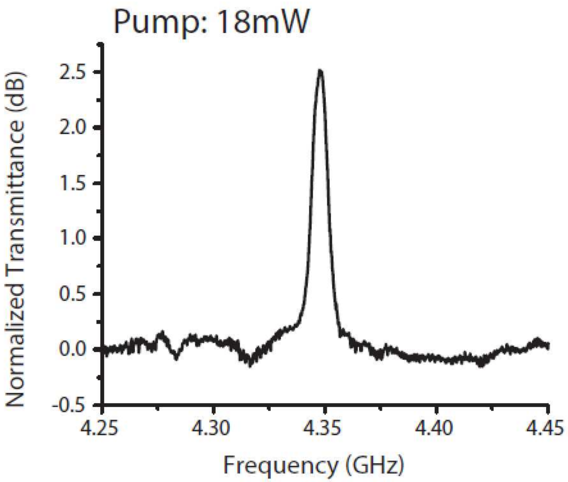


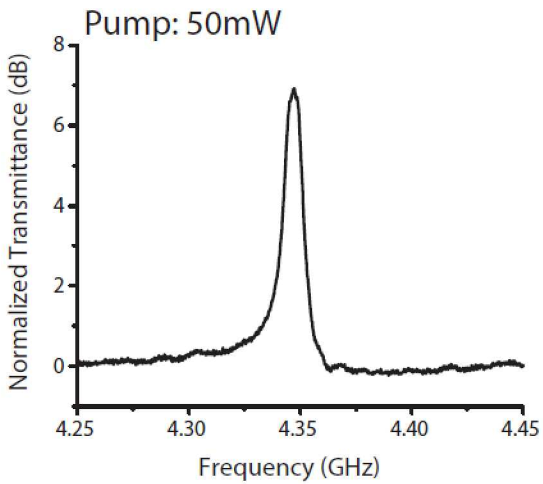
Casas-Bedoya, Alvaro, et al. "Tunable narrowband microwave photonic filter created by stimulated Brillouin scattering from a Silicon nanowire." *arXiv preprint arXiv:1506.07637* (2015).

SBS Gain 1-4 dB;

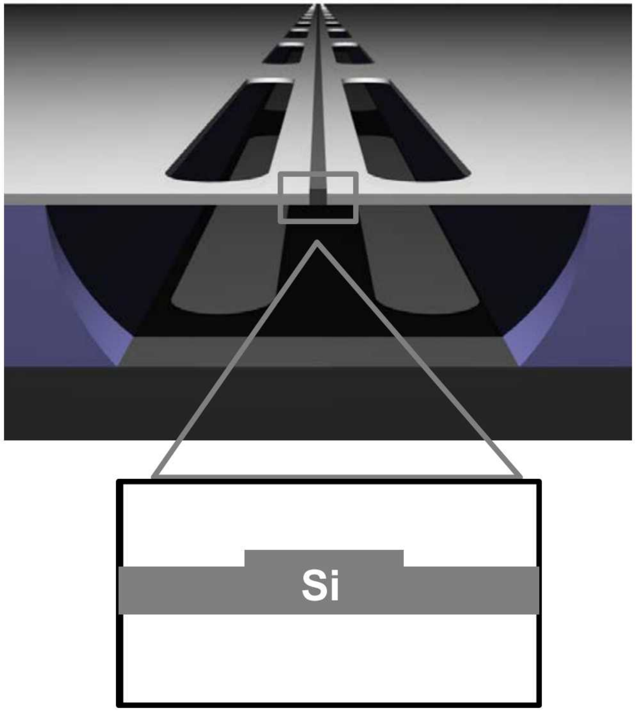
Losses High (Gain < Loss)

High Brillouin Gain Results (Unpublished)

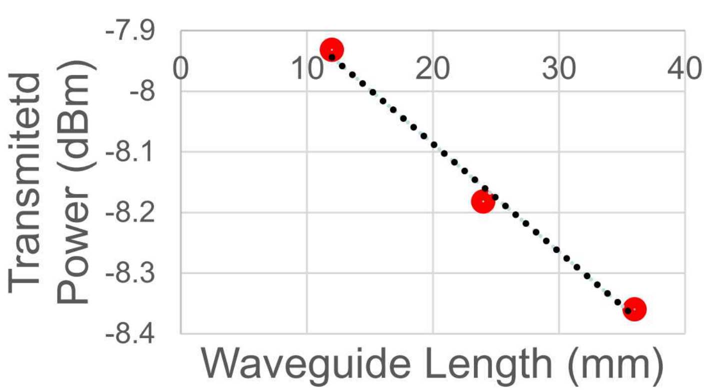




All Silicon Waveguide



Measured Waveguide Loss



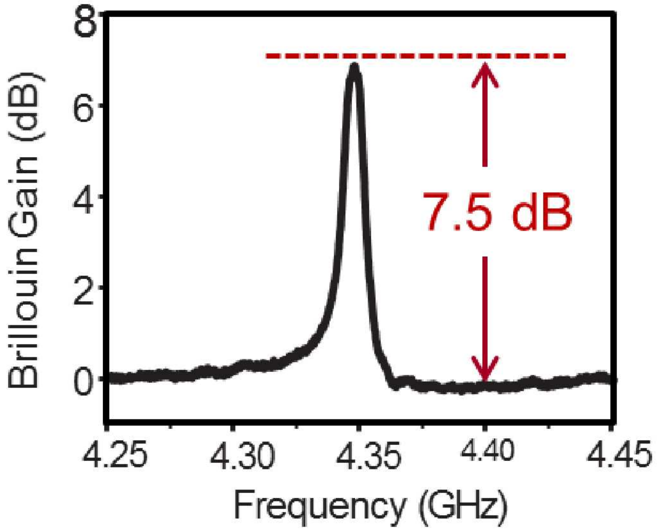
Gain coefficient: ~ 2000 $W^{-1}m^{-1}$

Losses ~0.18 dB/cm

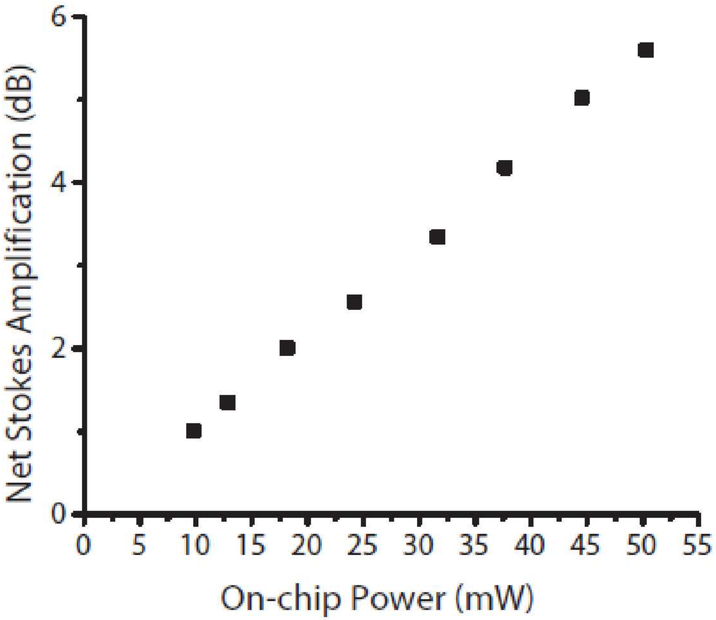
SBS Gain 7.5 dB; (Gain >> Loss)

Recent Experimental Progress: Highlights

Gain Spectrum



Net Amplification = (Gain - Nonlinear loss)



FOM	Current	Projected
$G_B PL$	~1.5	~4.5
Net Gain	6 dB	15-20 dB

- **Losses ~ 0.18 dB/cm**
- **Net amplification of 6 dB.**
- **Gain bandwidth ~ 10 MHz**

How else can we put this effect to use?

Outline of Presentation:

1. Introduction
2. Light scattering and nonlinearity
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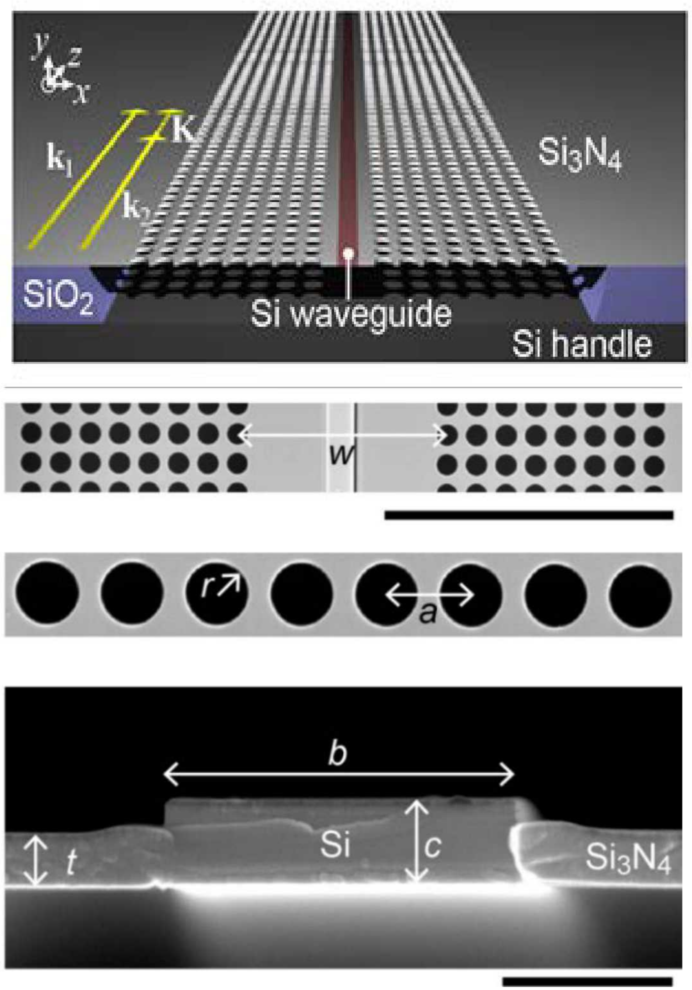
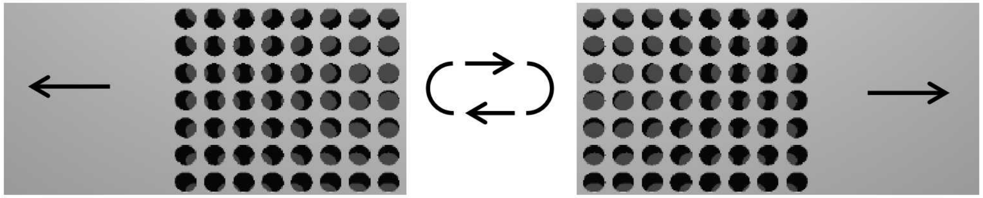
4. Stimulated light scattering in nanophotonics
5. Novel signal processing applications

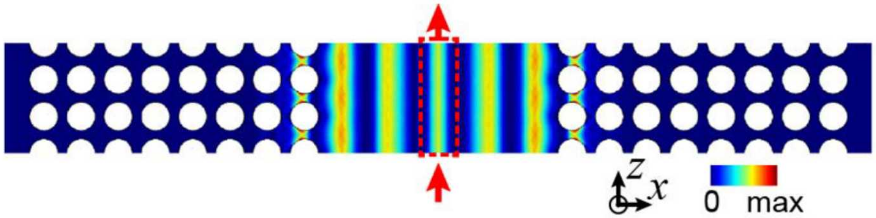
Brillouin-Active Phononic Crystal Waveguide



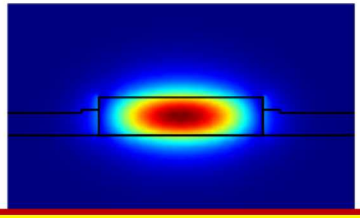
Phonons guided via Bragg Reflection.



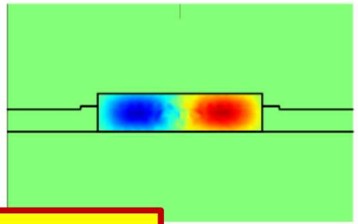
Bragg confinement of acoustic mode.



Optical mode

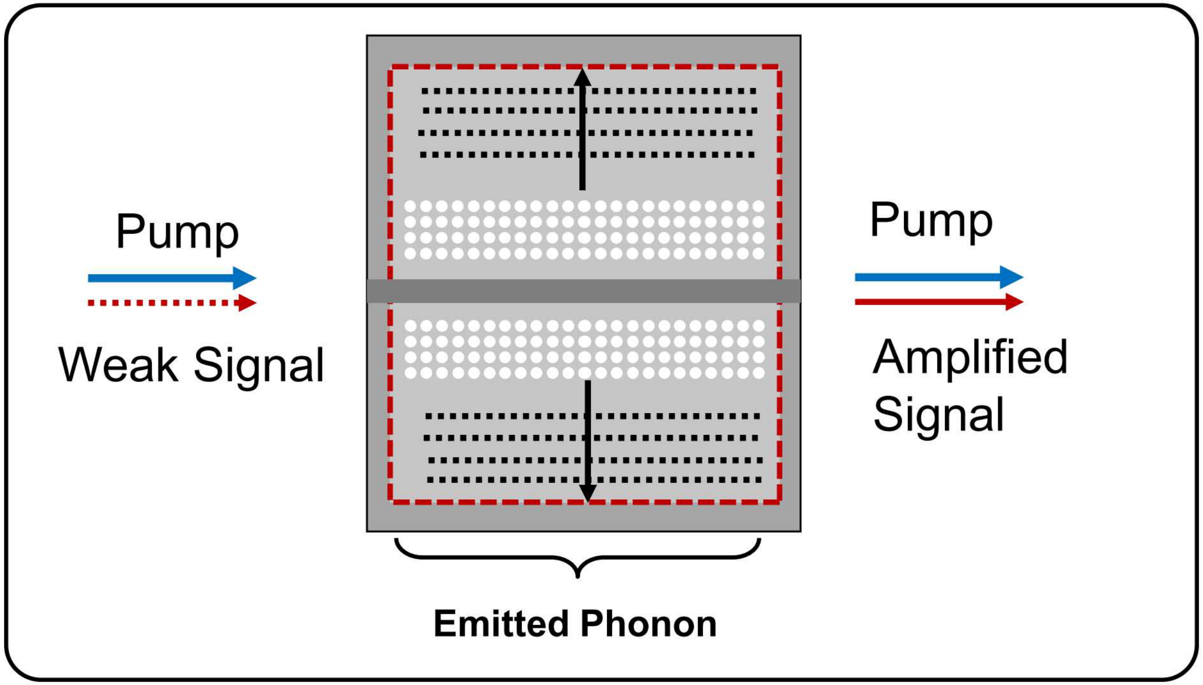


Electrostrictive forces.



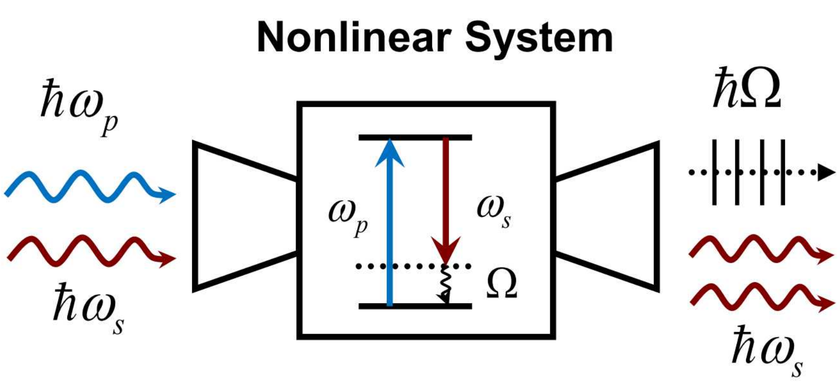
Phononic crystal offers new opportunities…

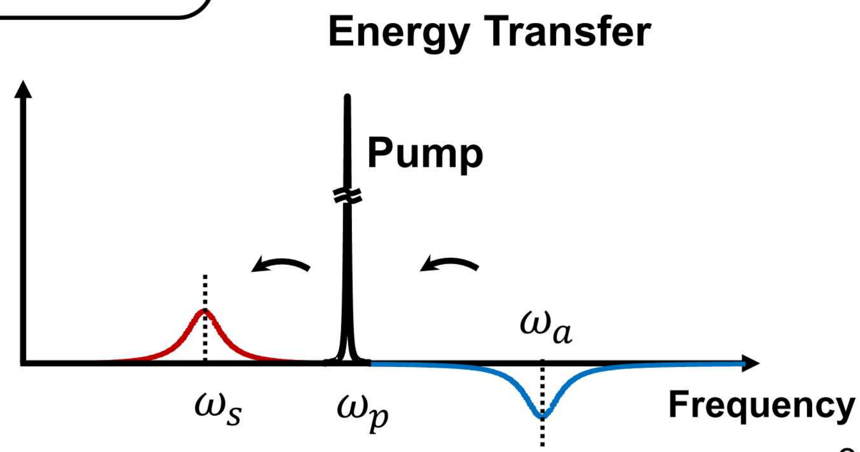
Signal Conversion and *Phonon Emission*



Result:

- **Signal amplification**
- **Optical energy transfer**
- **Phonon emission**





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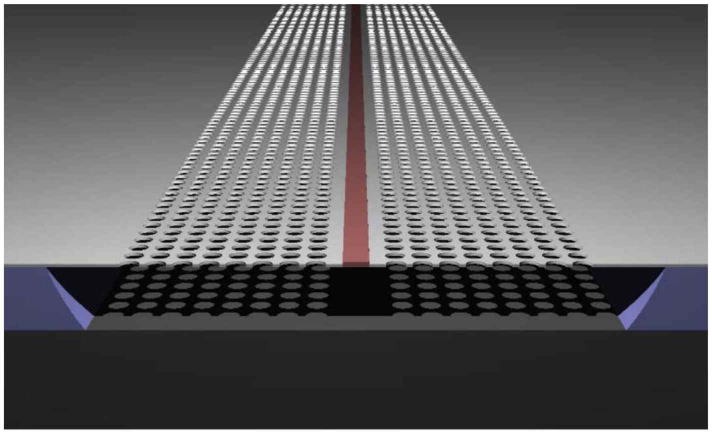
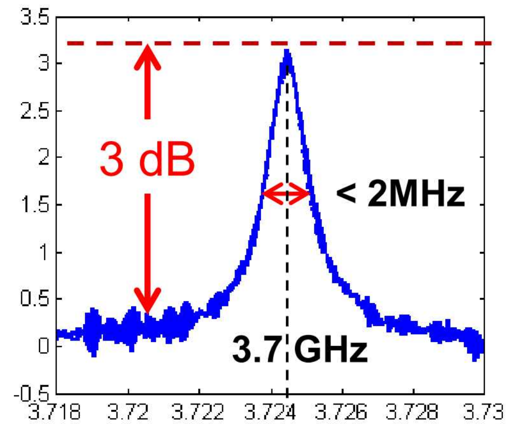
Experimental Results:

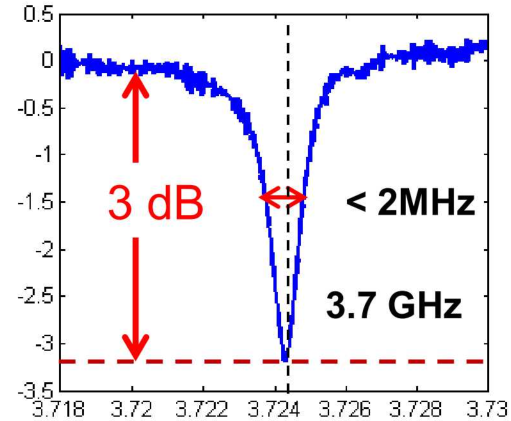
Phononic Crystal Waveguide



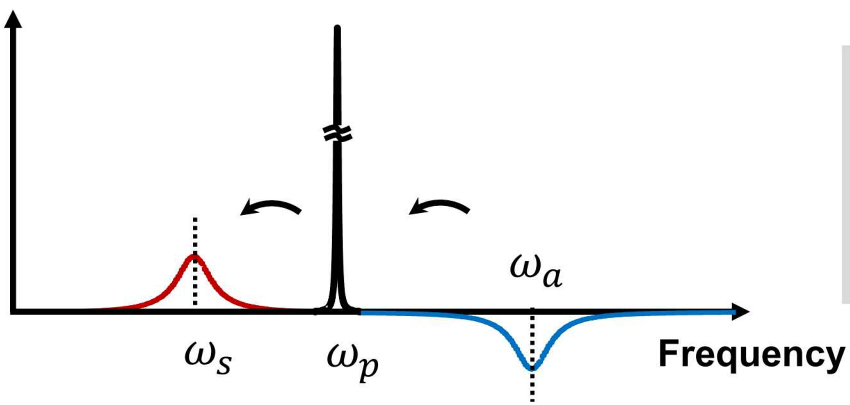
Stokes: Amplification



Anti-Stokes: Depletion



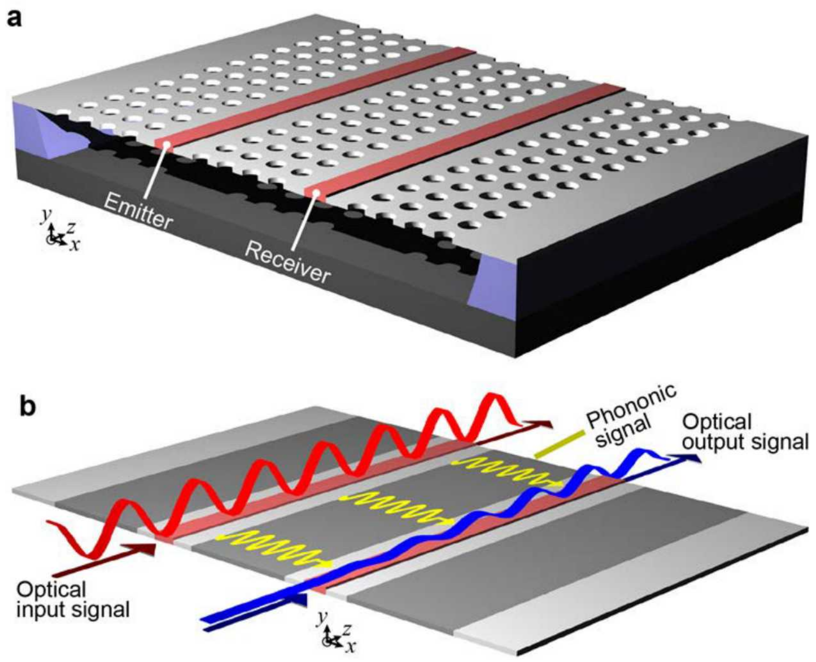
Energy Transfer



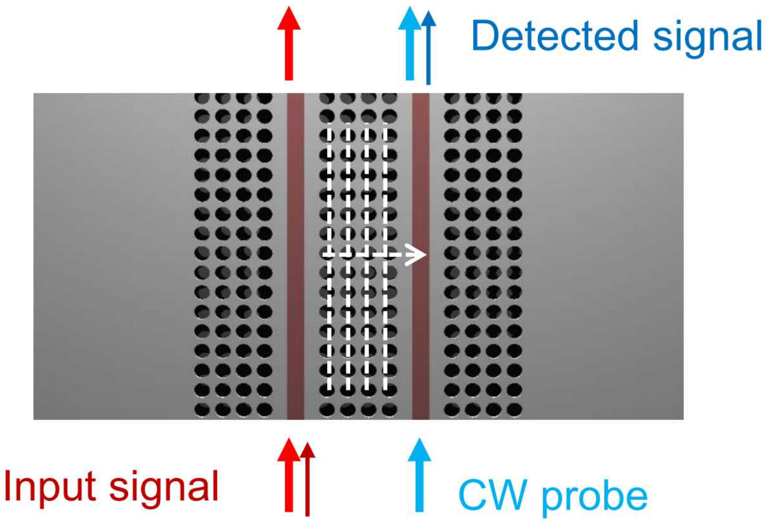
Experimental data:

- **Tailorable form of photon-phonon coupling (Brillouin interaction)**
- **Engineerable phonon emission.**

Traveling-wave phonon emit-receive functionality

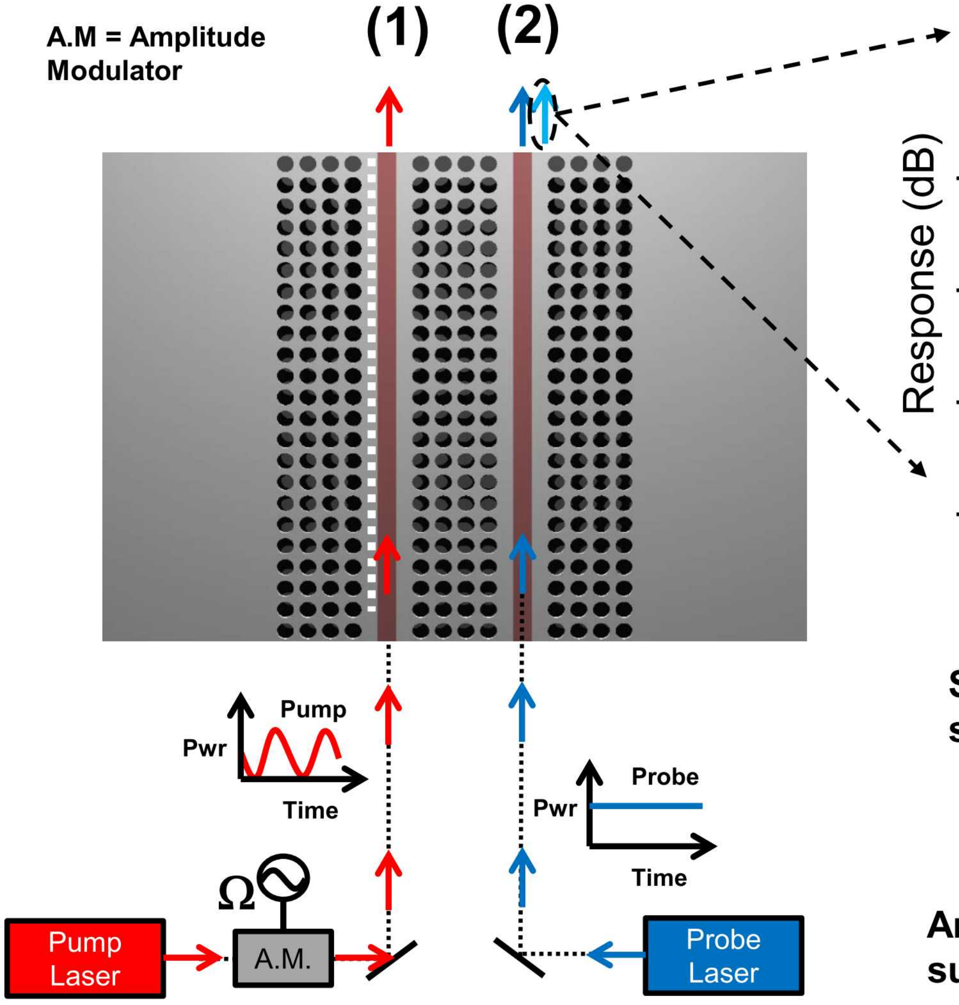


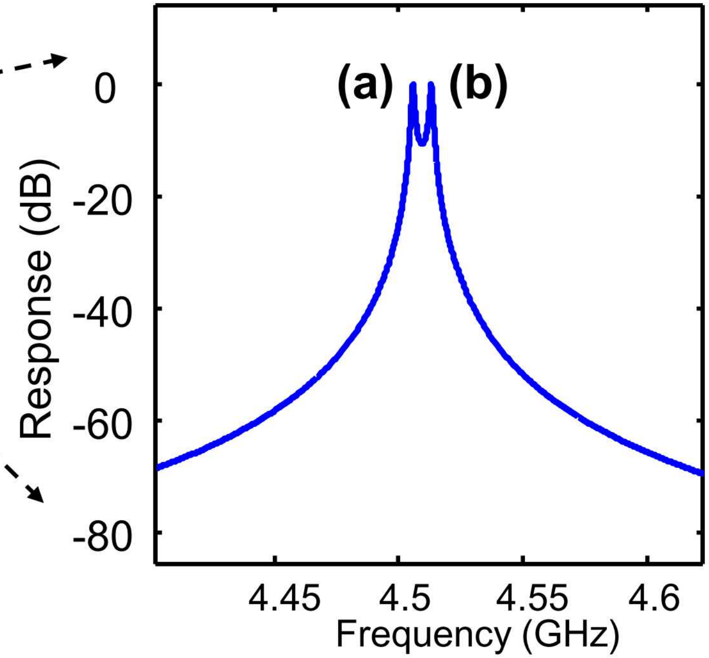
Basic Concept of Operation:



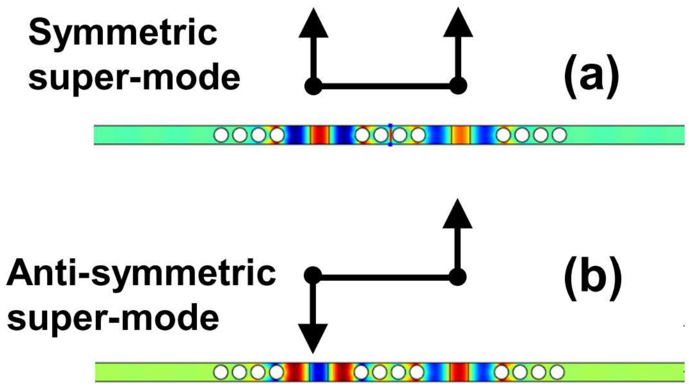
- **Optical waves are highly localized (No cross-talk)**
- **Phonon-modes are delocalized (Couples both waveguides)**
- **Hybrid interaction: nonlocal effective nonlinear response**

How does this dual-waveguide system work?





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



Brillouin-active phonon modes

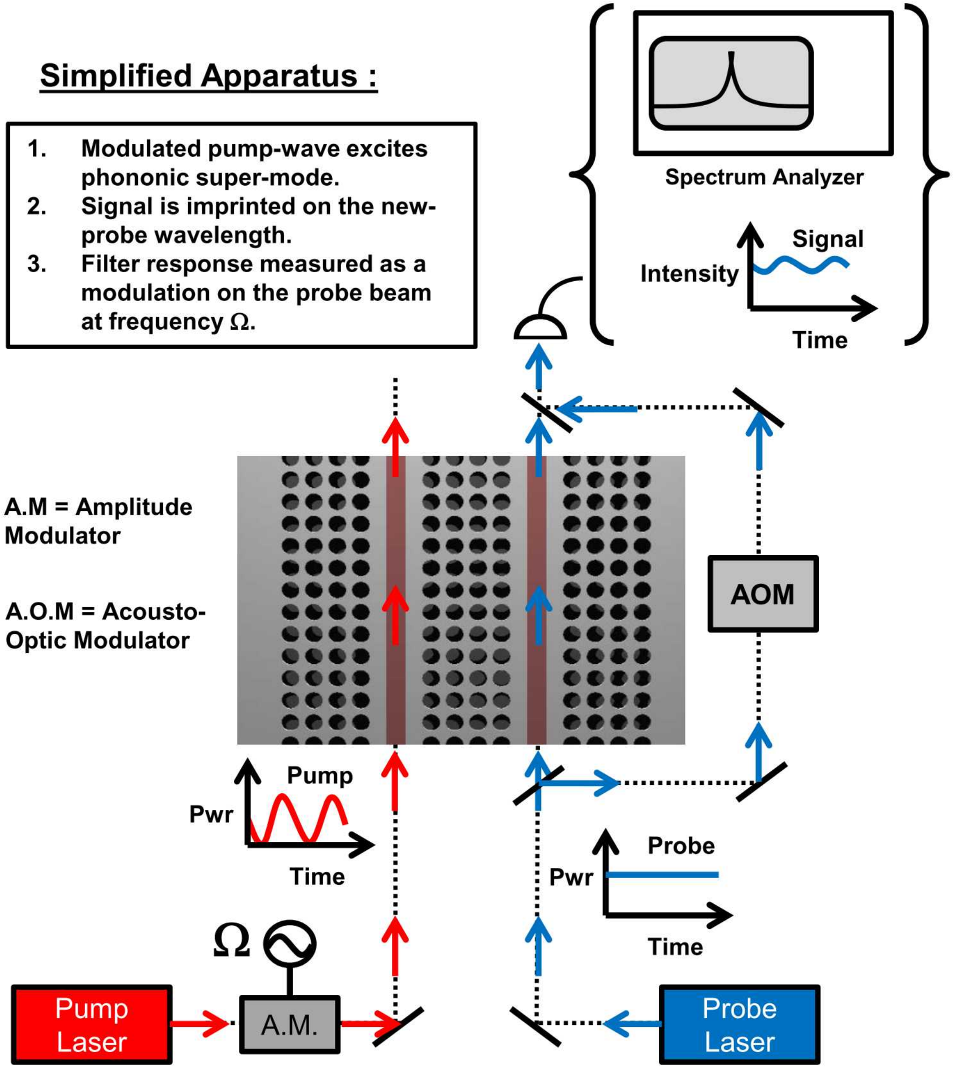
Measurement Approach and Experimental Results:

Simplified Apparatus :

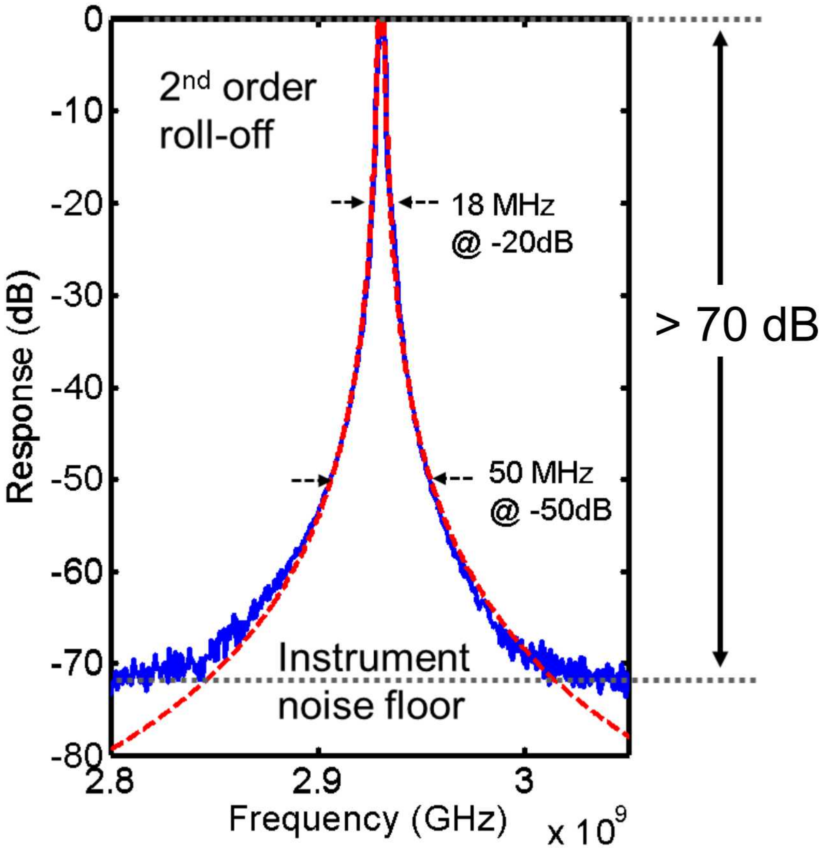
1. Modulated pump-wave excites phononic super-mode.
2. Signal is imprinted on the new-probe wavelength.
3. Filter response measured as a modulation on the probe beam at frequency Ω.

A.M = Amplitude Modulator

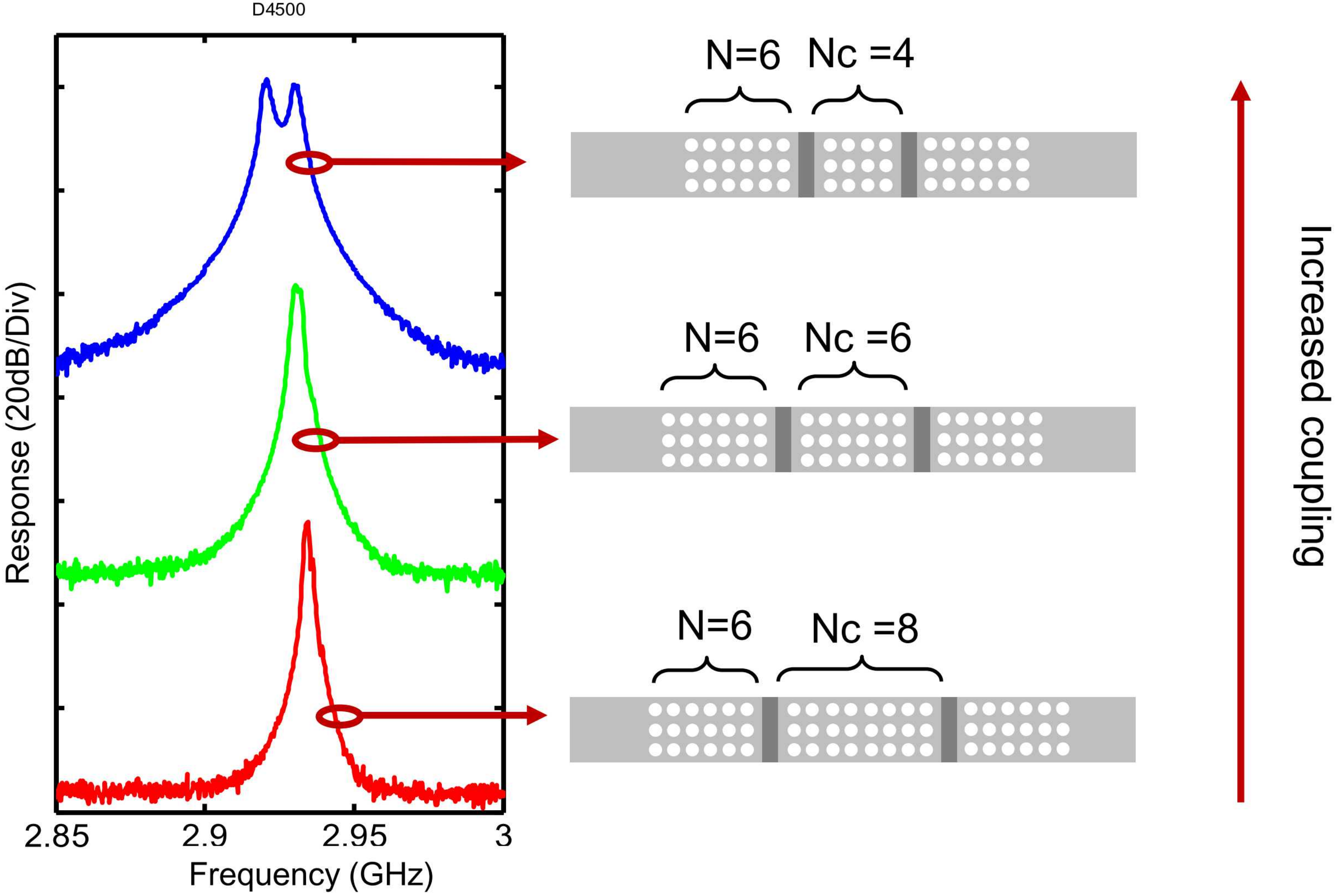
A.O.M = Acousto-Optic Modulator



- **Nonlocal energy information transfer.**
- **Information coupled by phonons. (No optical cross-talk)**



Tailor response: (variable resonant coupling)



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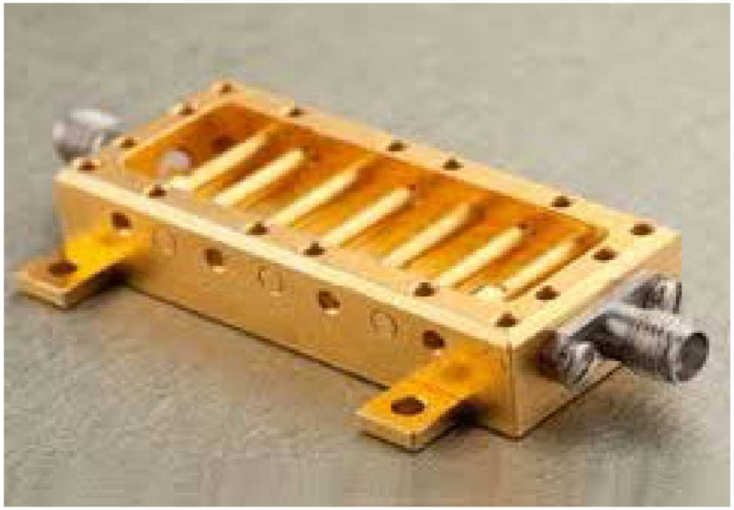
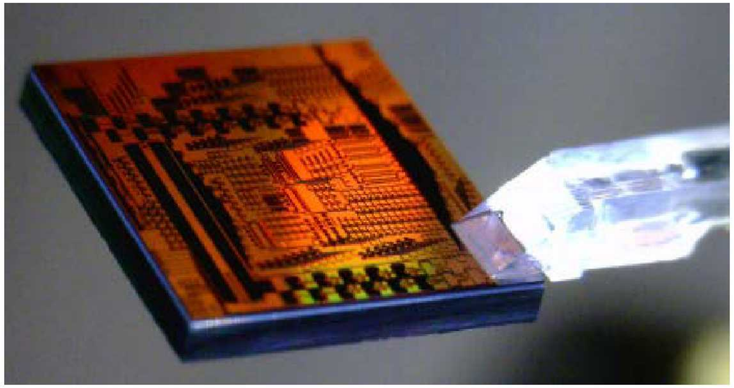
Promise of RF-Photonics: (*Gross* Simplification)

High Performance RF Components



- **Many components must be comparable in size to RF wavelength.**
- **Prevents size reduction.**

Optically Based RF-photonics



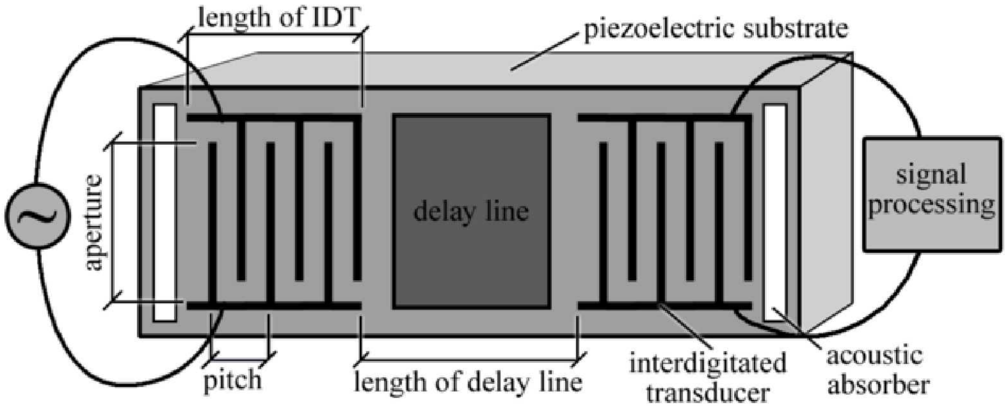
<u>Opportunity:</u>

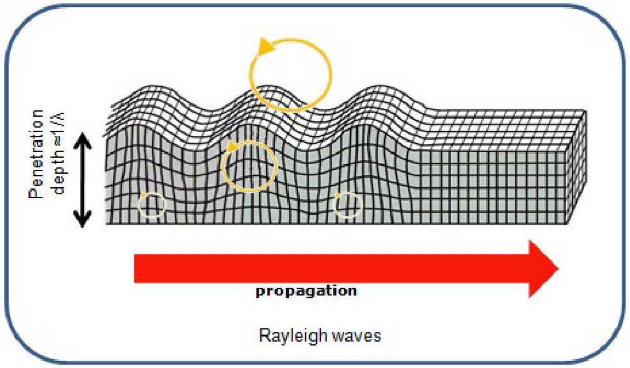
- **Encode information on guided optical waves.**
- **Integrated photonics could yield dramatic (10,000 x) size reductions.**

We can't forget "unsung hero" of signal processing → Phonons!

Why do we need acoustic waves (phonons)?

Example: Compact signal delay routinely achieved with SAW technology



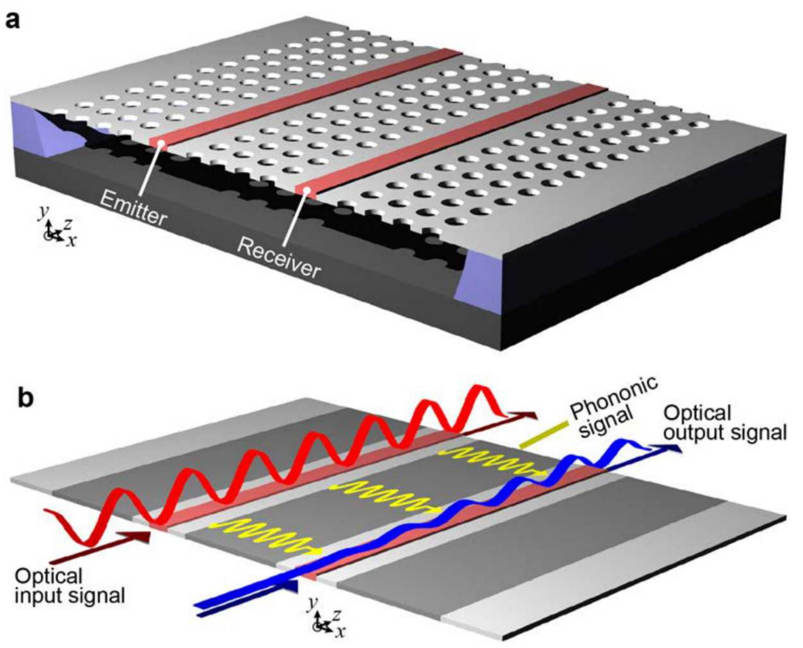


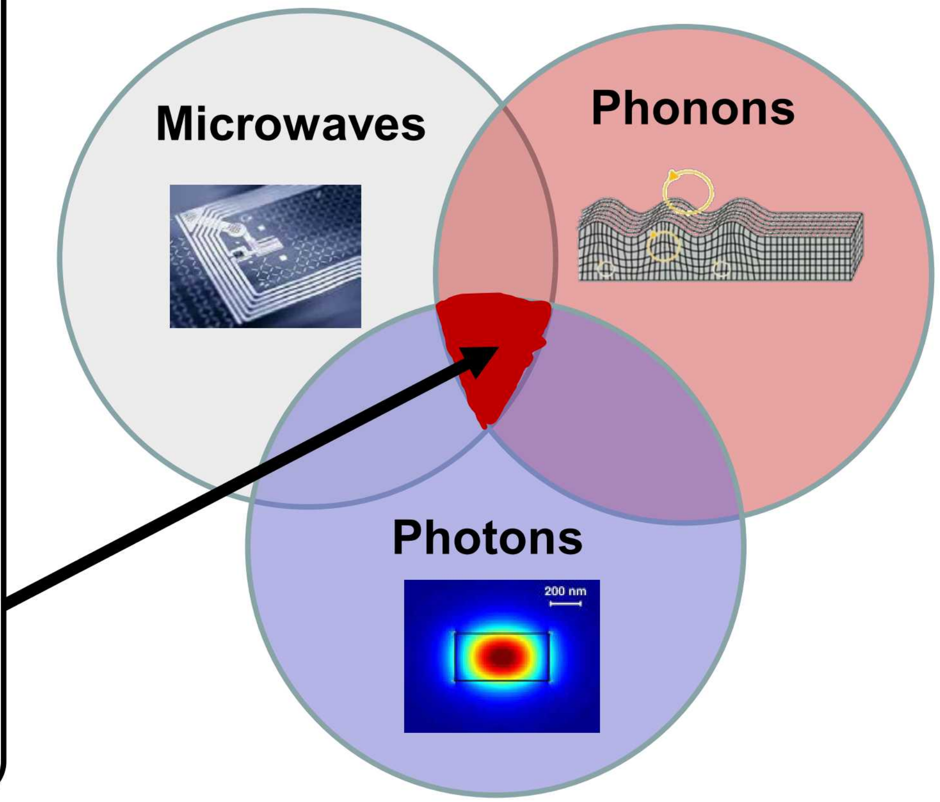
Surface acoustic wave (SAW) devices:
- **Sound ~10,000 x slower than light.**
- **Lifetimes mili-microseconds.**

Bottom line:
- **Light and sound are just different.**

Hybridization of Microwave, Photonic and Phononic signal processing

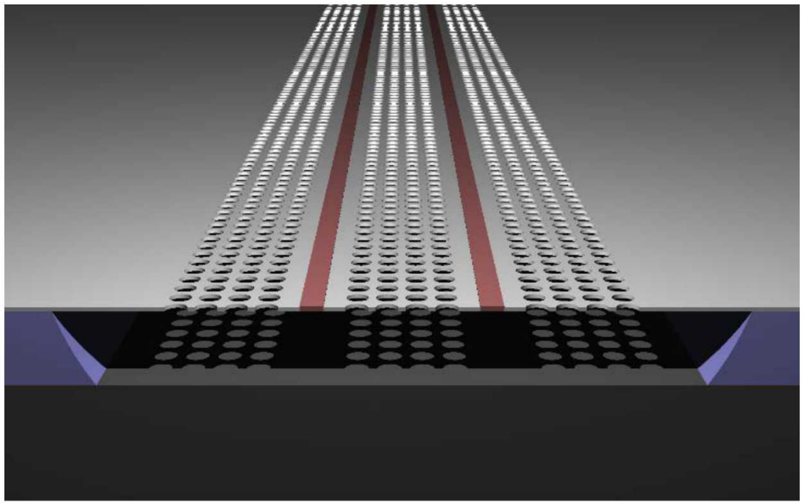
We can we marry all worlds…





Combine the merits of all three domains.

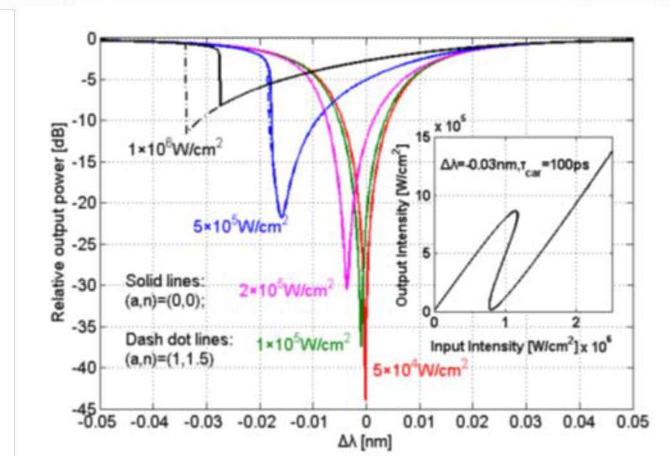
Unique (counterintuitive) properties of system:



Unique properties FSBS configuration:

- Wavelength insensitive.
- Could actually be white light!
- Tremendous 70dB dynamic range.
- Can both amplify and filter signal.
- High power (300 mW) handling

Conventional RF-photonic filtering: High-Q microcavities

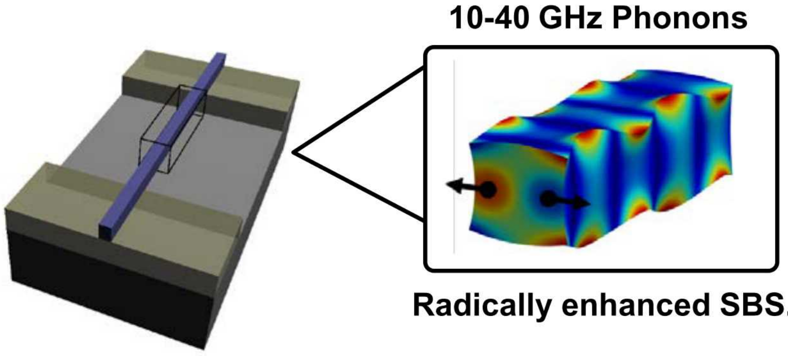


Problems:

- Shape distorted at μW powers.
- Requires narrow line lasers
- Requires frequency locking.

Summary

Theory: photon-phonon coupling.



Radically enhanced SBS.

Part I Summary:

- Radically enhanced SBS processes found.
- SBS is no longer a bulk nonlinearity.
- Boundaries alone responsible for SBS.

Part II Summary:

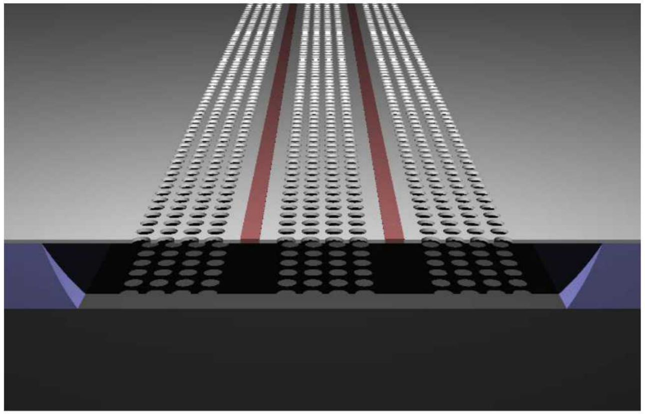
• First demonstration of SBS in silicon.

• Tailorable phonon emit-receive functionalities demonstrated.

• Presented new paradigm for high power RF-photonic filtering .

• Many applications to come.

Traveling-wave phonon emit-receive



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