Stimulated Brillouin scattering in silicon photonics

SAND2013-5631C

Integrated Photonics Research: IT4A

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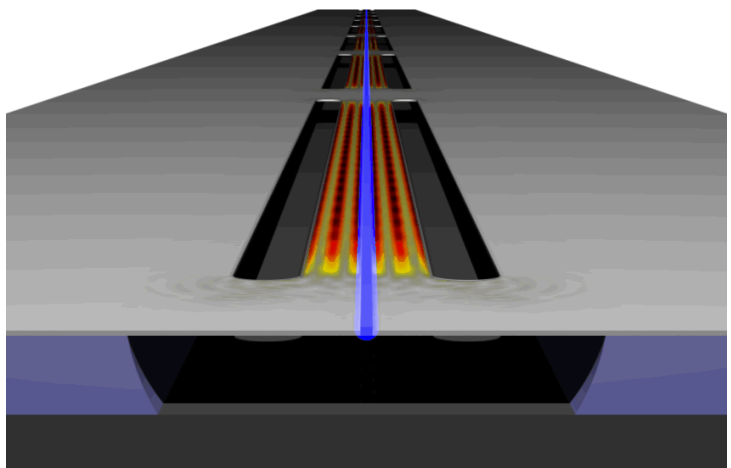
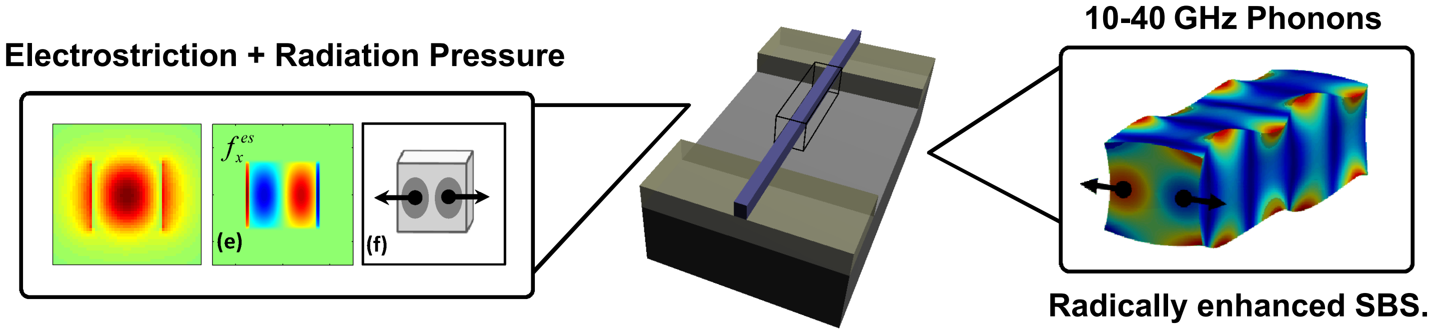
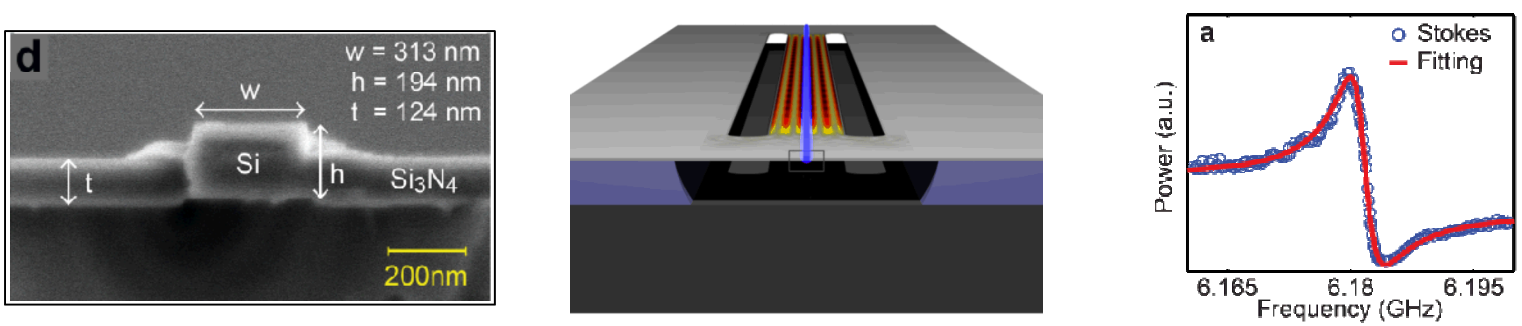


Outline of Presentation:

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



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



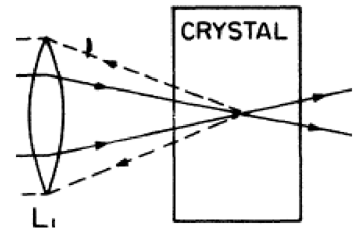
Timeline for Stimulated Brillouin Scattering:

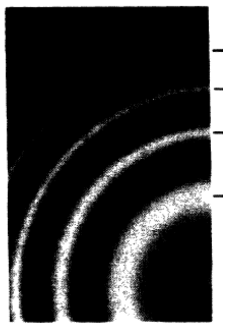
1. Bulk SBS with MASER (Chaio 1964)
2. Guided-wave SBS (Ippen, 1972)
3. Engineered SBS in fibers. (Russel 2007)

Micro ← Macro

Nano ← Micro

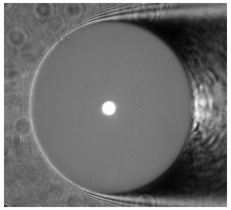
SBS in Bulk X-tal



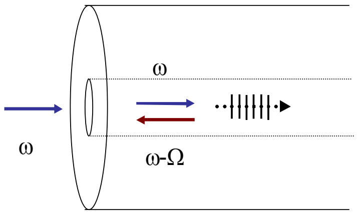


Chiao (1964)

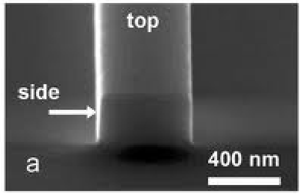
SBS in Optical Fibers



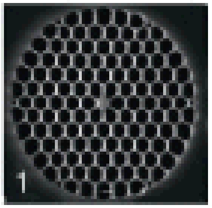
Ippen (1972)

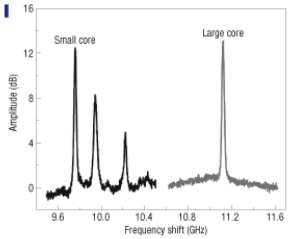


SBS in Nanophotonics?



Micro-structured Fiber



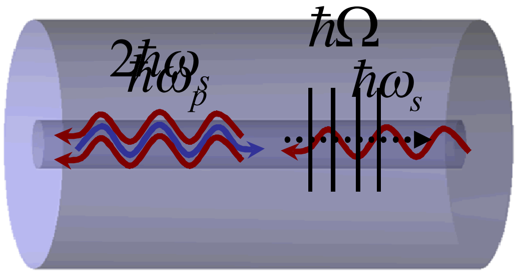


Russel (2007)

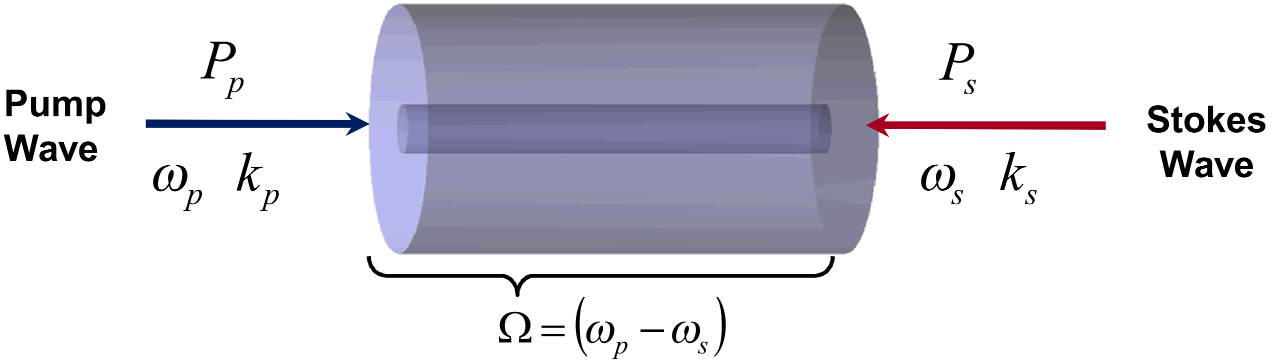
Trend: Brillouin interactions become stronger at smaller length-scales

Backward Stimulated Brillouin Scattering (SBS):

Backward-SBS

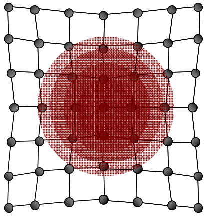


How does backward-SBS work?



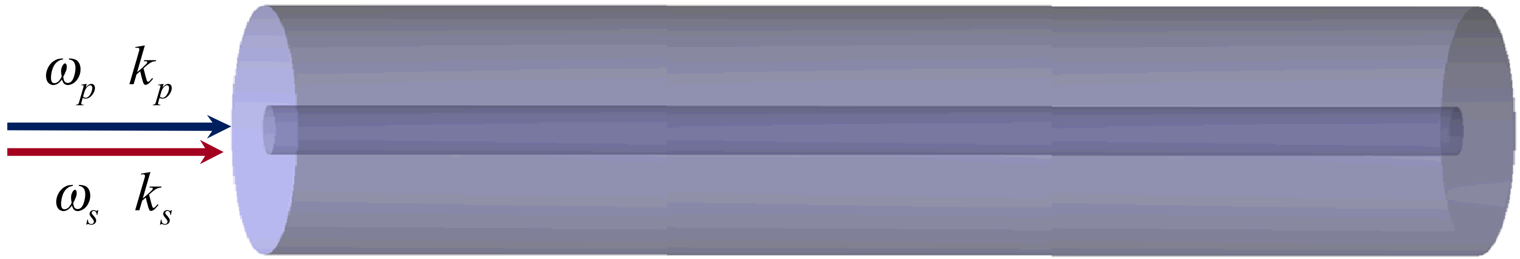
Electrostrictive forces compress medium

Electrostriction:



From dynamic material response.

Forward Stimulated Brillouin Scattering:

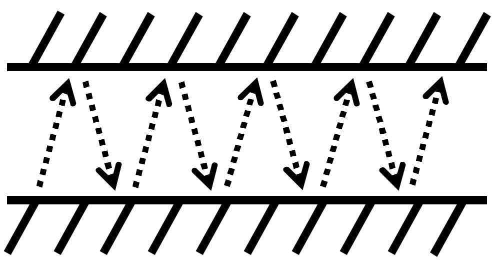


- **Fringes advance at group velocity of light!**

Q: Can the phase velocity of sound ever match the group velocity of light?

A: Yes, if the modes are highly dispersive:

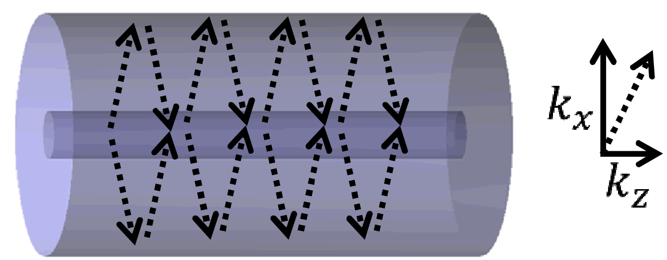
Reflecting boundaries:



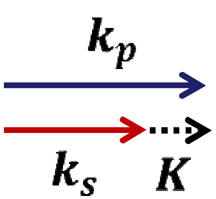
Result:

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

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



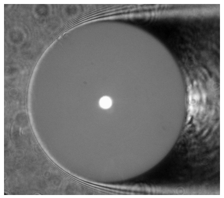
$$\mathbf{k_p} = \mathbf{k_s} + \mathbf{K}$$



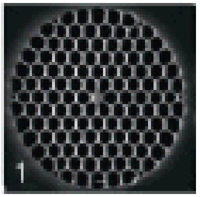
Problem: since phonon modes delocalized, forward-SBS exceedingly weak.

Various Brillouin Systems:

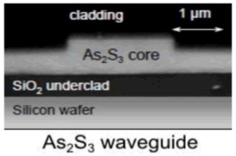
Backward-SBS Systems:



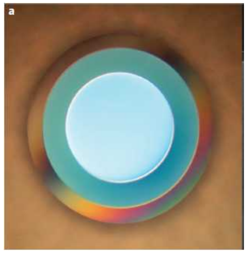
Ippen (1978)



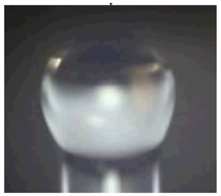
Russel Group



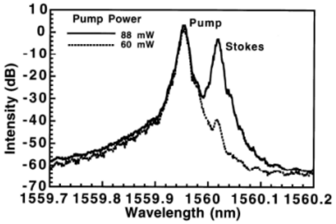
Eggleton Group



Vahala Group

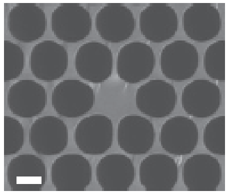


Carmon Group

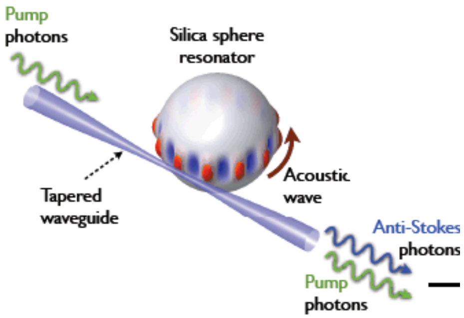


K. Abedin (2005)

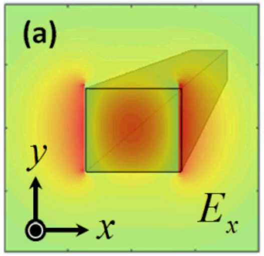
Forward-SBS Systems:



(Kang et. al Nat. Phys. 2009)



(Bahl et. al Nat. Phys. 2012)

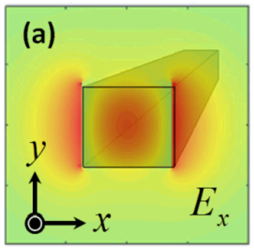


Can we engineer SBS in silicon nanophotonics?

Necessary Conditions:
1. Large optical forces.
2. Phonon confinement.

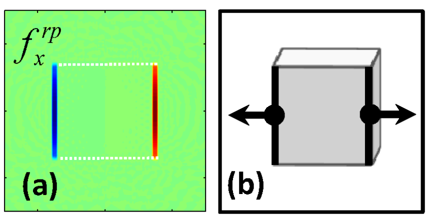
Optical Forces at Nano-scales

Silicon Waveguide.

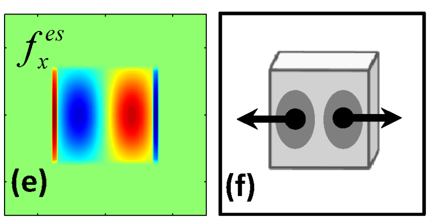


300nm x 300nm

Radiation Pressure



Electrostrictive Forces

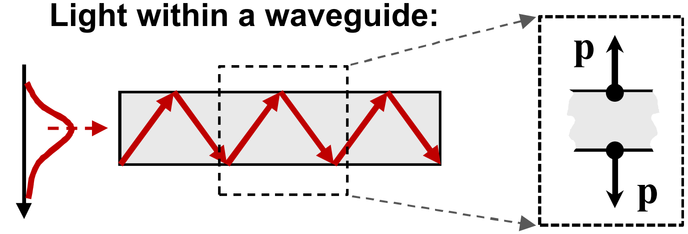


Both: Radically enhanced at nanoscales.

Radiation Pressure.

Radiation Pressure: Scattering from boundaries.

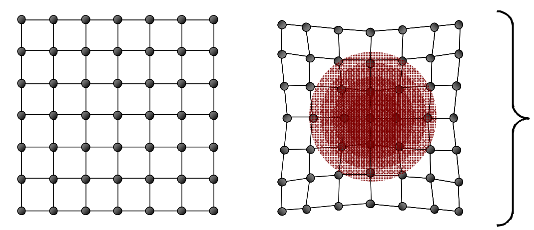
Light within a waveguide:



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?**

What Governs Strength of Electrostrictive Force?

<u>**Dependence on material properties:**</u>

$$\left\{ \begin{array}{ll} \varepsilon_{kl} & \text{(Dielectric Tensor)} \\ p_{jkmn} & \text{(Elasto-optic Tensor)} \end{array} \right\}$$

Electrostrictive Stress in Cubic Crystal (Si):

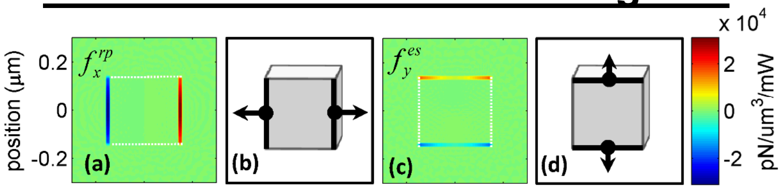
$$\sigma_{kl}^{es} = -\frac{1}{2}\varepsilon_o \cdot n^4 \cdot p_{ijkl} \cdot E_i E_j$$

Force Density: $\mathscr{F}_j = -\partial_i \sigma_{ij}$

Important Properties of Stress/Force
1. Increases as n^4.
2. Proportional to p_{ijkl} .
3. Sign & magnitude depends on p_{ijkl}

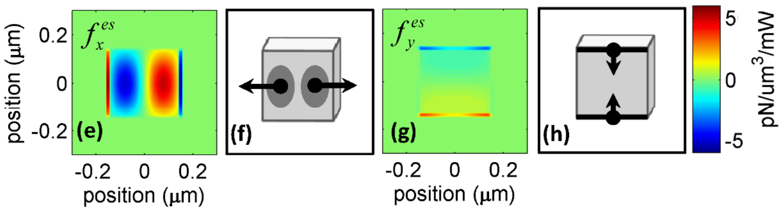
Example: Silicon waveguide.

<u>**Radiation Pressure: Si waveguide**</u>



1. Force localized to boundary.
2. Directed outward.

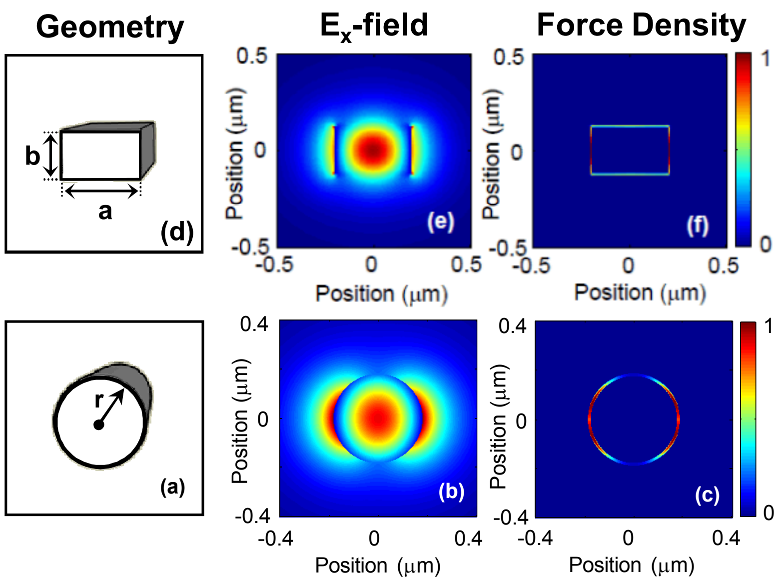
<u>**Electrostriction: Si waveguide**</u>



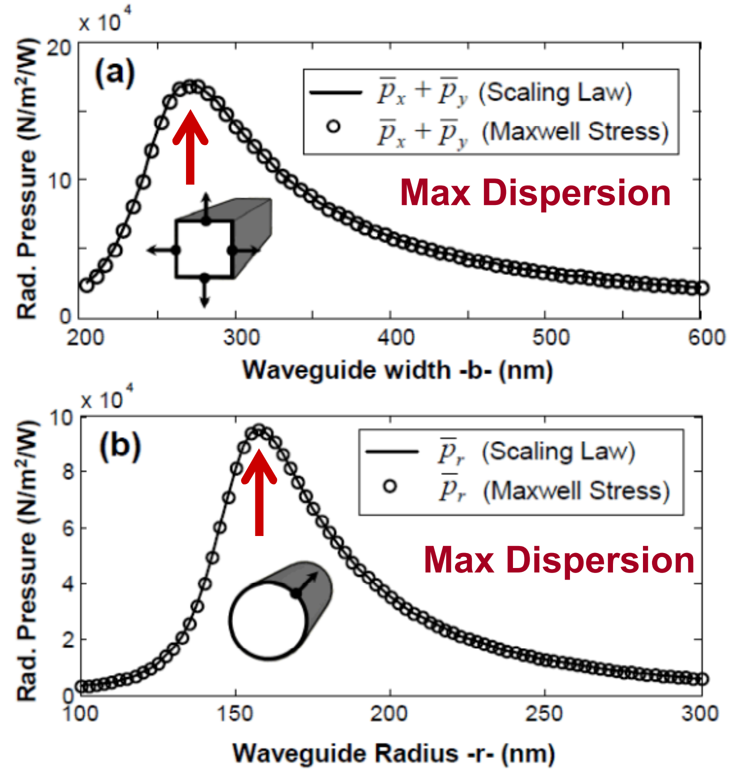
1. Force distributed within volume.
2. Directed outward or inward.

[1] P. T. Rakich, P. Davids, and Z. Wang, "Tailoring Optical Forces in Waveguides Through Radiation Pressure and Electrostriction," Opt. Express 18, 14439-14453 (2010)

Key to Radiation Pressure: Dispersion.



Comparison of Maxwell Stress & Scaling Law



TIR Guidance

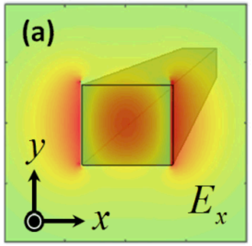
Radiation Pressure:

$$\overline{p}^{rp} = \frac{P_{opt}}{c \cdot A} \cdot (n_g - n_p)$$

Relation Holds for *Any Dielectric Waveguide* and *Any Guided Mode*!

[1] P. T. Rakich, Z. Wang, and P. Davids "Scaling of Optical Forces in Dielectric Waveguides: Rigorous Connection Between Dispersion and Radiation Pressure," *Optics Letters*.

Nanoscales: Coherent Combination of Forces:



Silicon Waveguide.

TE-Like Mode

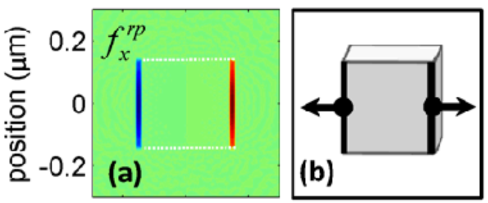
300nm x 300nm

How Large are Forces?

Material	Pressure (Pwr = 100mW)
Si	~5 x10^4 N/m^2

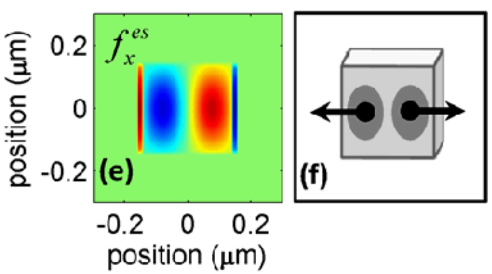
5 People standing on manhole cover

Radiation Pressure



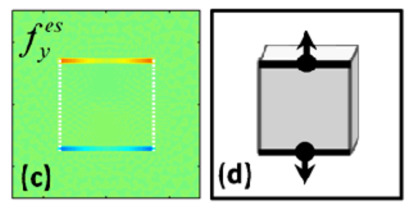
Electrostriction

+



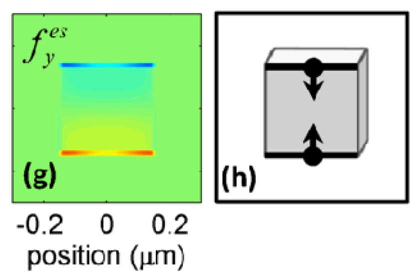
Forces Enhanced

Radiation Pressure



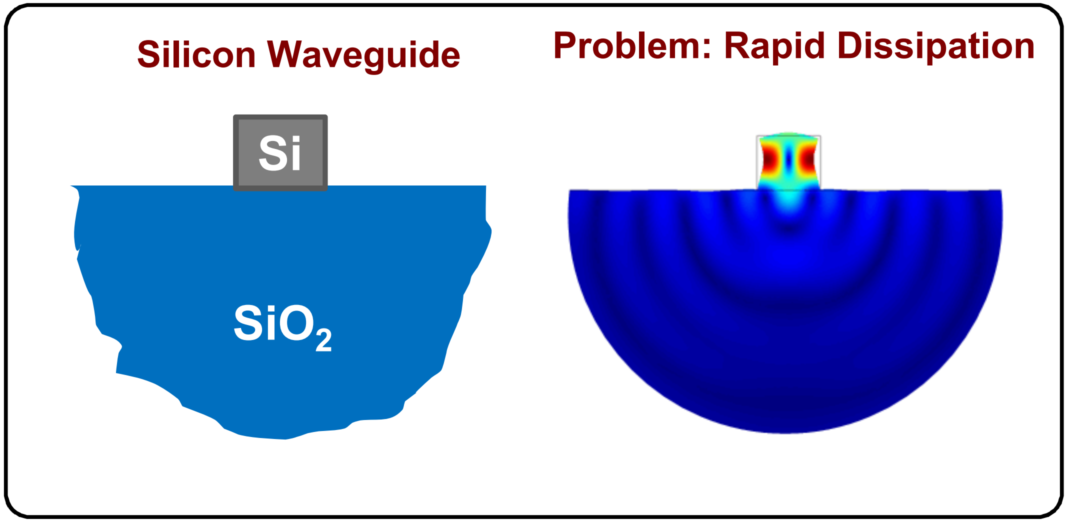
Electrostriction

+

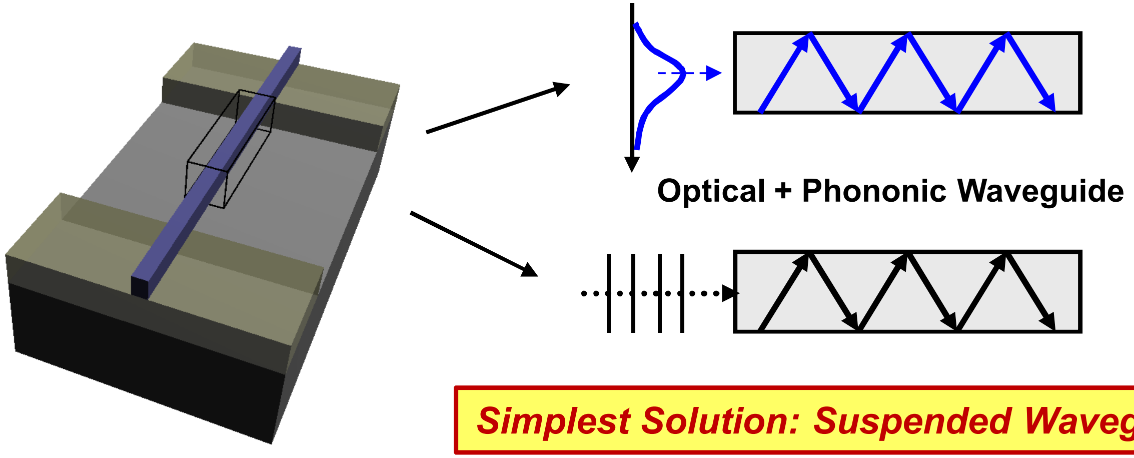


Forces Cancel

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



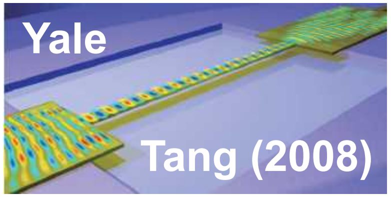
A: Requires control of the phonon modes.

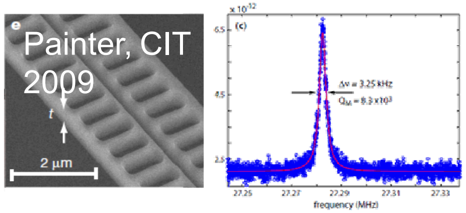


Simplest Solution: Suspended Waveguide

Revised Paradigm for SBS at Nanoscales:

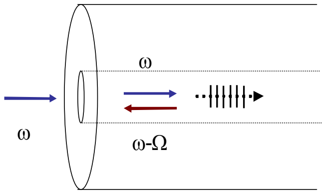
Optomechanics



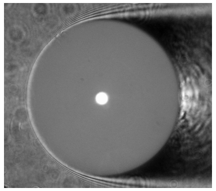


Nanoscales:
Radiation pressure mediated photon-phonon coupling.

Microscales:
Electrostrictively mediated photon-phonon coupling.

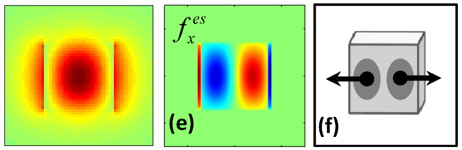


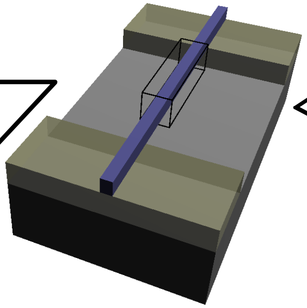
Fiber-SBS



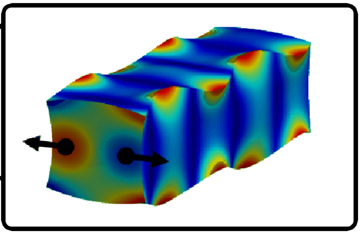
Result: Giant Enhancement of Stimulated Brillouin Scattering at Nanoscales

Electrostriction + Radiation Pressure





10-40 GHz Phonons

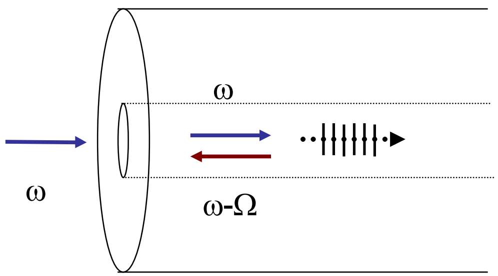


Radically enhanced SBS.

- **No longer bulk material nonlinearity.**
- **Challenges 40-yr SBS paradigm.**
- **Geometry introduces new nonlinearities.**

Yale How to Formulate SBS Gain in Nanoscale Systems?

Microscale SBS Theory:



$$g_B = \frac{2\pi n^7 p_{12}^2}{c\lambda_p^2 \rho v_a \Delta v_B}$$

- Neglects radiation pressure.
- Neglects boundary induced polarization currents

Not valid at nanoscales.

Full Vectorial Treatment: Valid at any Length-Scale

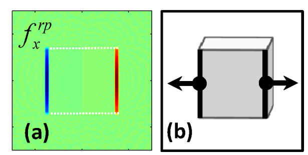
Canonical relation for SBS gain:

$$dP_s/dz = G_B \cdot P_p P_s.$$

SBS gain

$$G_B(\Omega) = \frac{1}{\delta z}\frac{\omega_s}{\Omega}\cdot\frac{1}{P_p \cdot P_s}\int_{\delta V}\langle\, \mathbf{f}_\Omega(\mathbf{r},t)\cdot \dot{\mathbf{u}}(\mathbf{r},t)\,\rangle \cdot dV,$$

Radiation Pressure:



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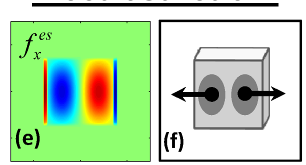
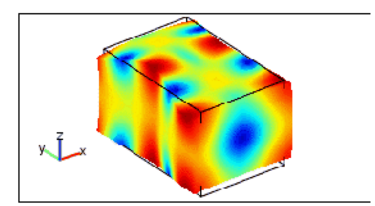
Electrostriction:



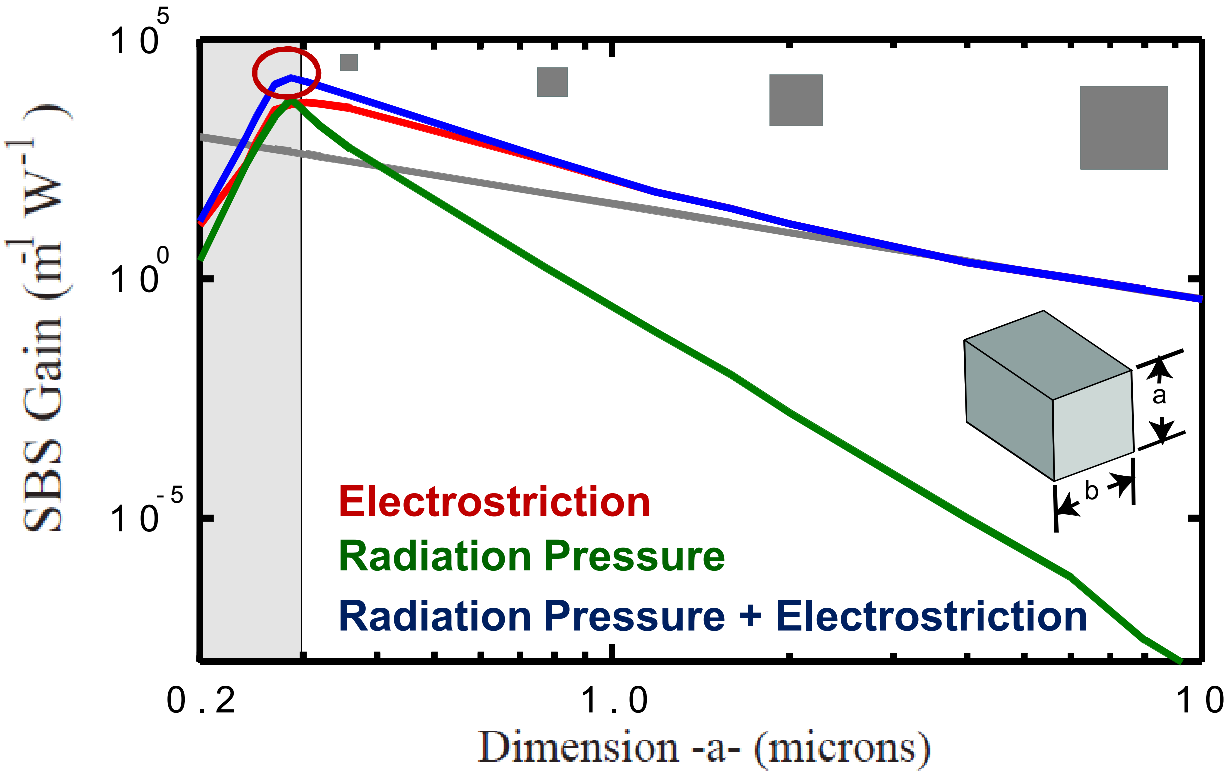
Time harmonic force

Velocity distribution



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.

The Scaling of Backwards SBS at Nanoscales:

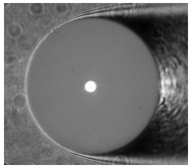


Conventional Treatment of SBS.

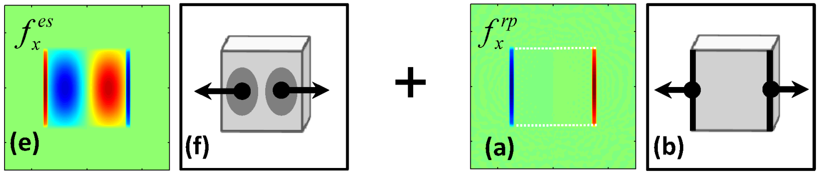
$$g_B = \frac{2\pi n^7 p_{12}^2}{c\lambda_p^2 \rho v_a \Delta\nu_B}$$

Conventional theory:

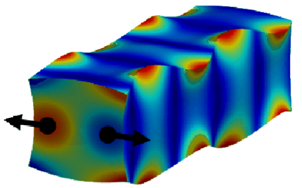
1. **Silicon material properties used.**
2. **Perfect agreement from 2-10 microns.**



Electrostrictive forces **Radiation Pressure**

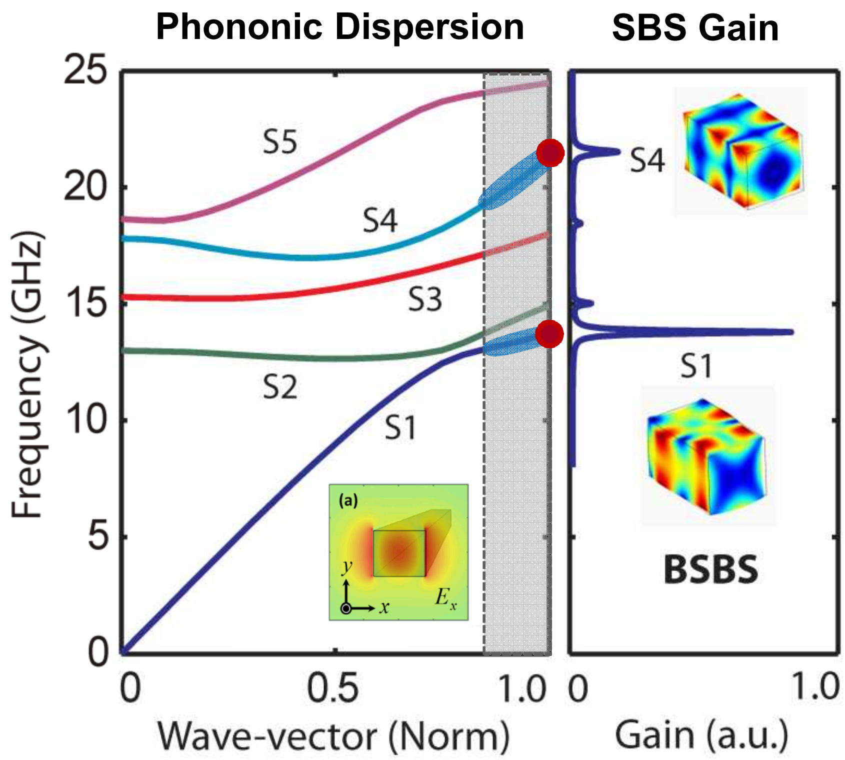


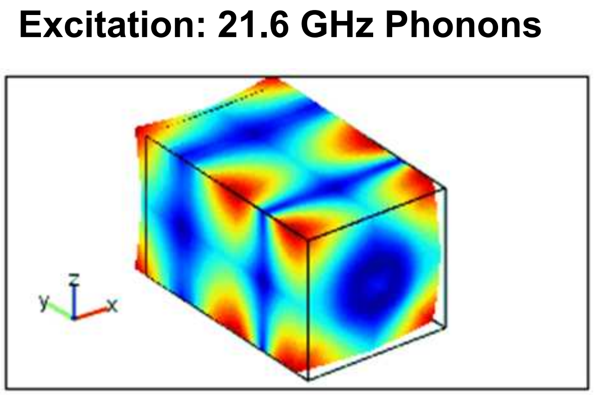
Giant Stimulated Brillouin Scattering (SBS)

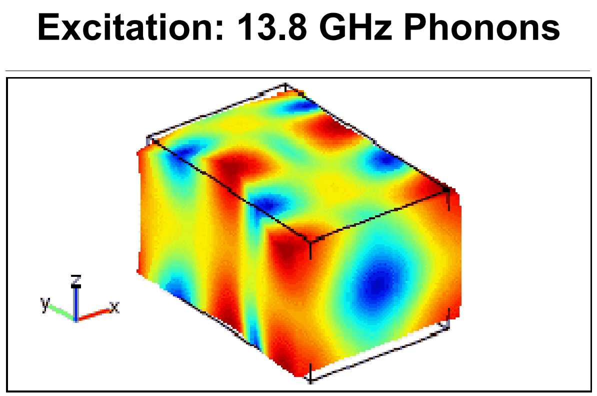


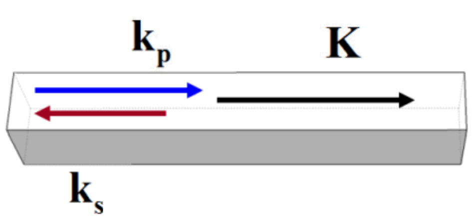
100x larger than predicted by scalar theories

Nanoscale Backward-SBS: Tunable Phonon Emission.





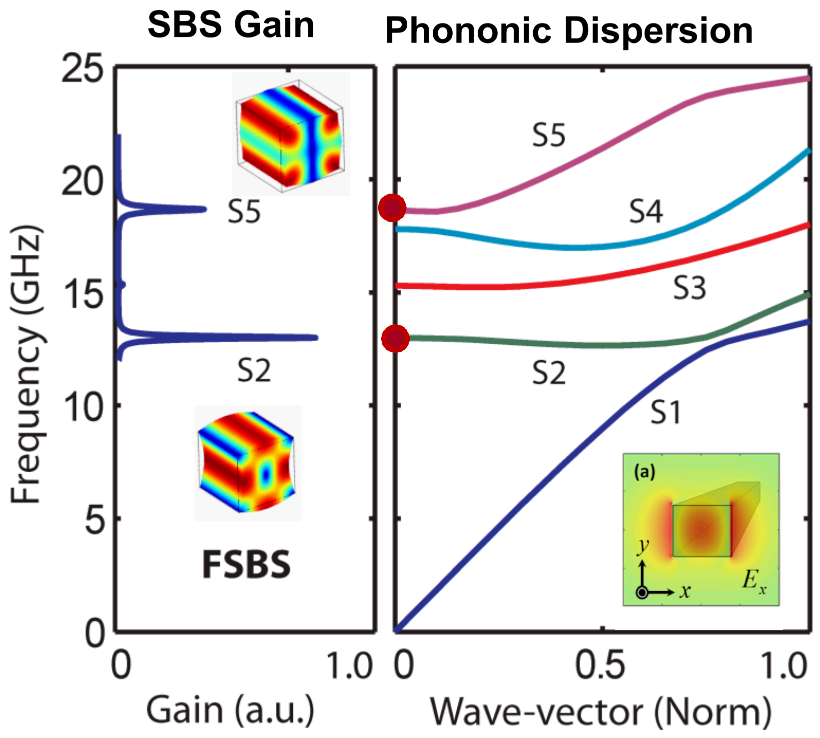


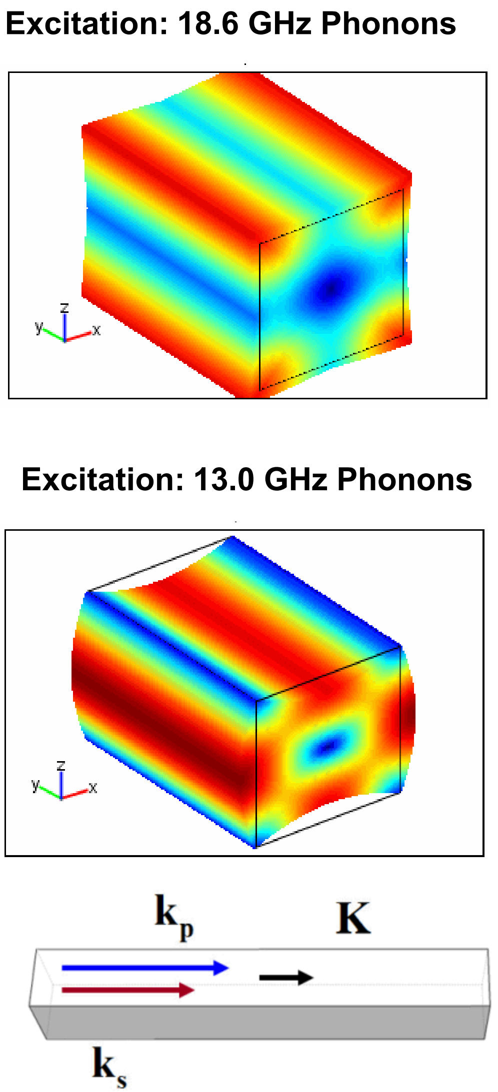


<u>Nano-optomechanical backward-SBS:</u>

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-SBS: Fixed Frequency Resonances.

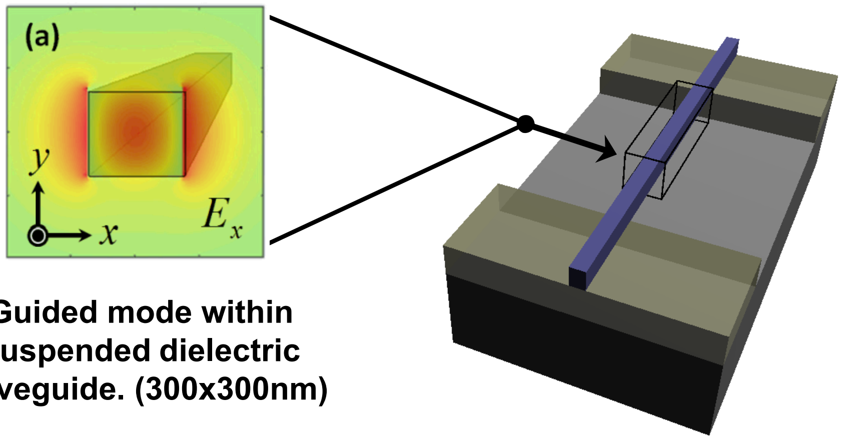




Nano-optomechanical Forward-SBS:

1. Generally forbidden in guided wave-systems.
2. Negligible anchoring losses ➔ intrinsic Mech. Q.
3. Ultra-low threshold parametric oscillation possible.

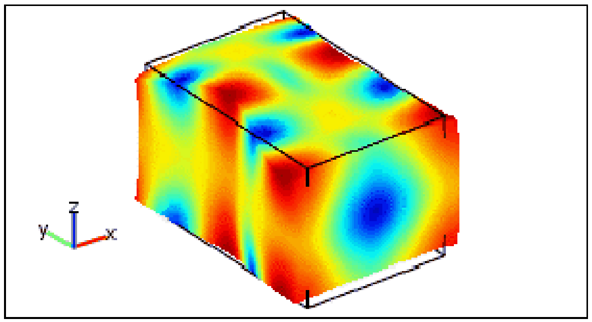
Narrow-Band High-frequency RF Oscillators:



Guided mode within suspended dielectric waveguide. (300x300nm)

Suspended waveguide: L = 100 microns

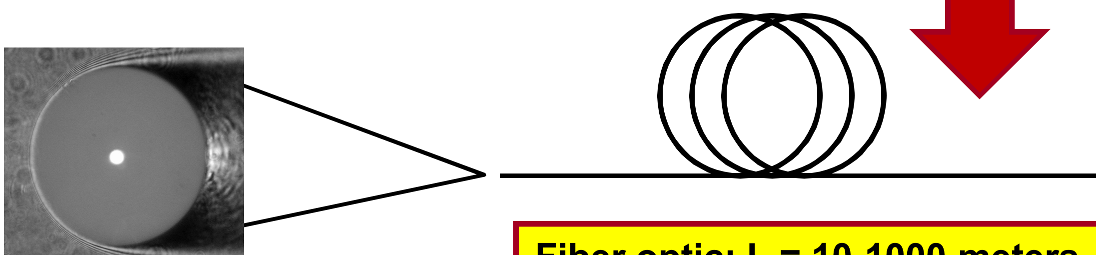
Excitation: 13.8 GHz Phonons



= 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.

Future Directions for SBS in Silicon Photonics:

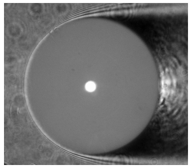
Slow and Fast Light via Backward Stimulated Brillouin Scattering

[1] K. Y. Song, K. S. Abedin, K. Hotate, M. González Herráez, and L. Thévenaz, "Highly efficient Brillouin slow and fast light using As2Se3 chalcogenide fiber," *Optics Express*, vol. 14, no. 13, pp. 5860-5865, 2006.

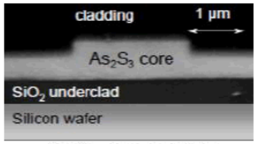
[2] Y. Okawachi et al., "Tunable all-optical delays via Brillouin slow light in an optical fiber," *Physical review letters*, vol. 94, no. 15, p. 153902, 2005.

[3] Ravi Pant, Adam Byrnes, Christopher G. Poulton, Enbang Li, Duk-Yong Choi, Steve Madden, Barry Luther-Davies, and Benjamin J. Eggleton, "Photonic-chip-based tunable slow and fast light via stimulated Brillouin scattering," Opt. Lett. 37, 969-971 (2012)

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



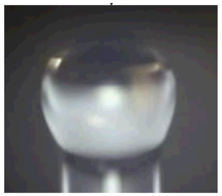
Eggleton



As_2S_3 waveguide

Narrow Band SBS Lasers

[1] 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.

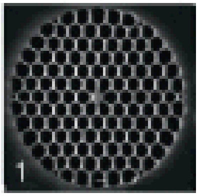


Carmon

RF Signal Processing and Acousto-Optics via Forward-SBS

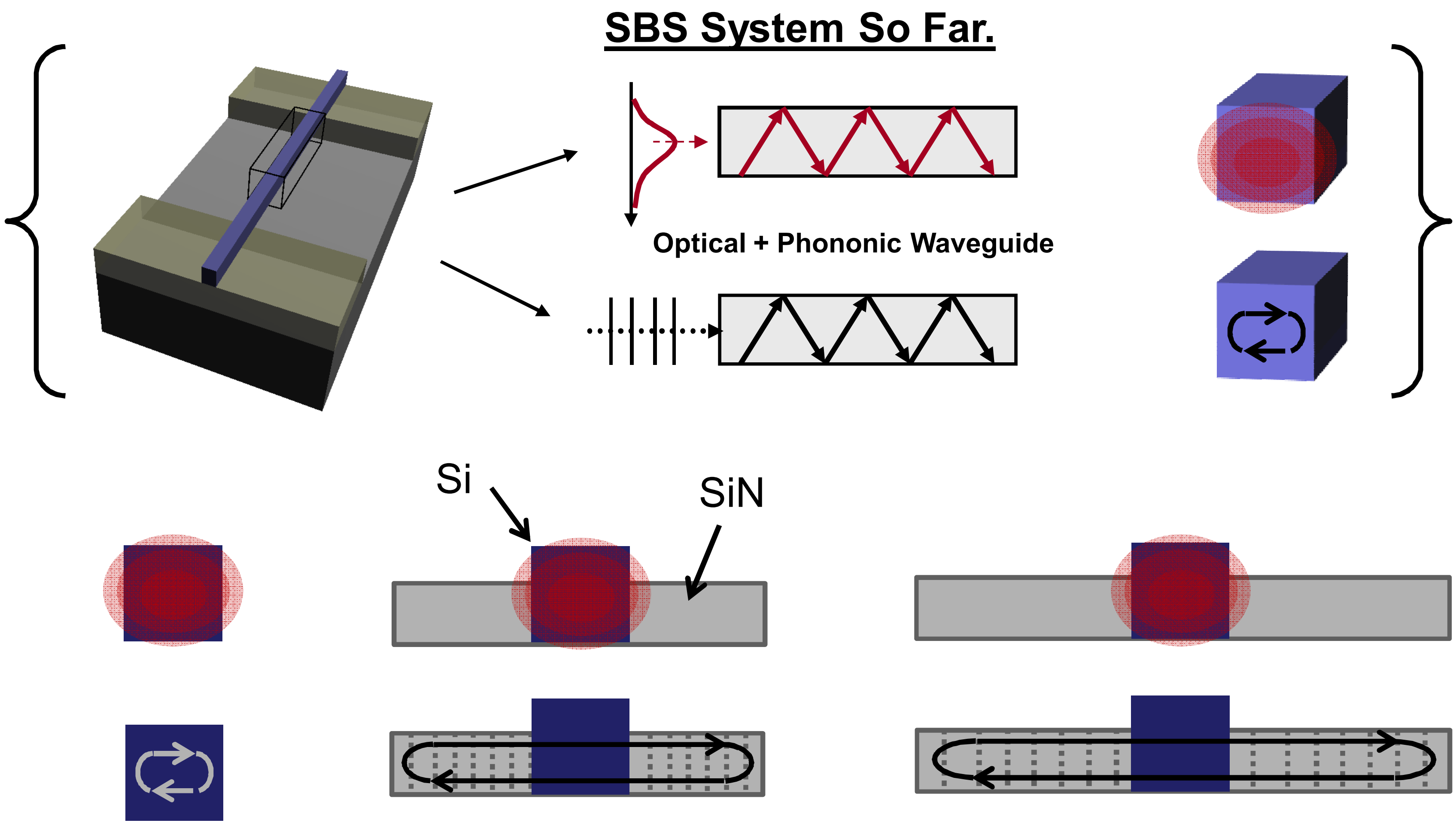
[1] M. S. Kang, A. Nazarkin, A. Brenn, and P. S. J. Russell, "Tightly trapped acoustic phonons in photonic crystal fibres as highly nonlinear artificial Raman oscillators," *Nature Physics*, vol. 5, no. 4, pp. 276-280, Mar. 2009.

[2] M. S. Kang, a. Butsch, and P. S. J. Russell, "Reconfigurable light-driven opto-acoustic isolators in photonic crystal fibre," Nature Photonics, no. August, pp. 1-5, Aug. 2011.



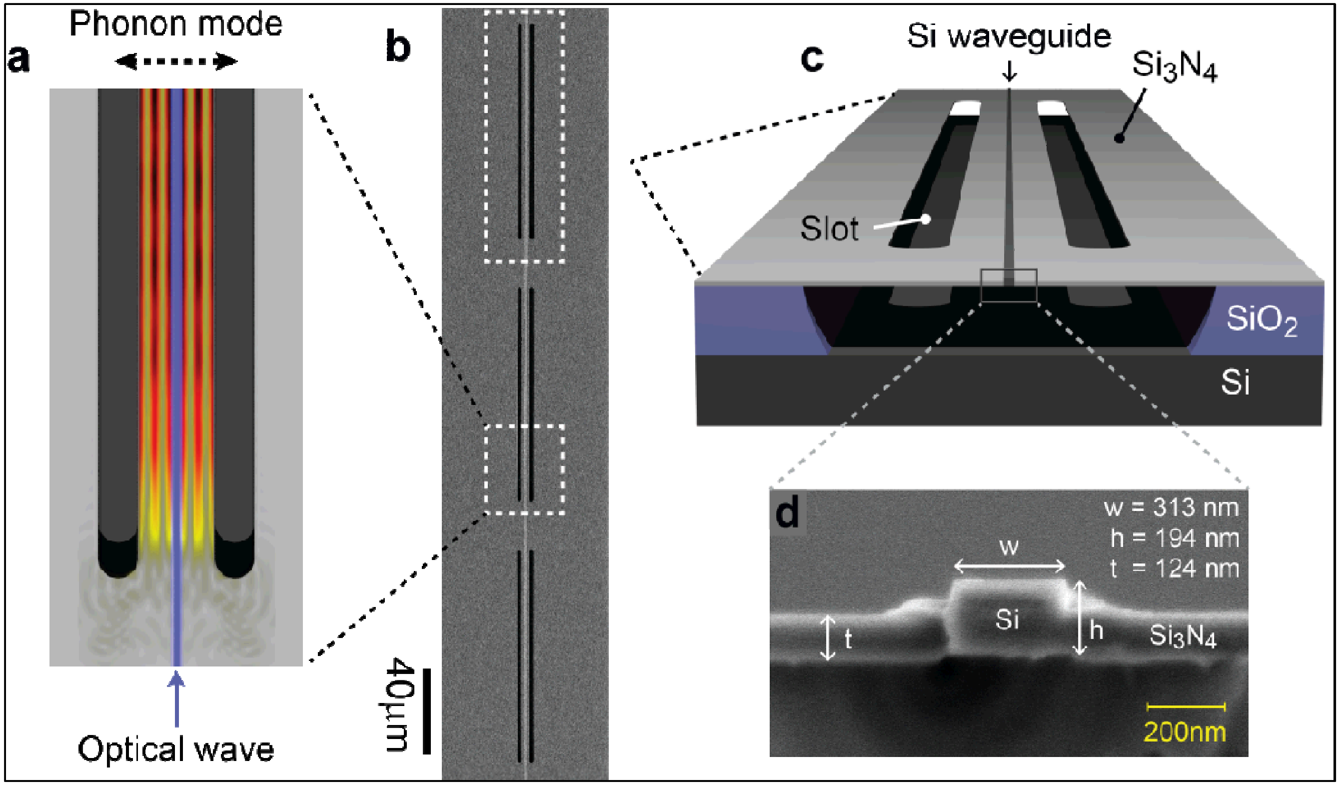
Russel

Part II: Experimental Demonstration of SBS



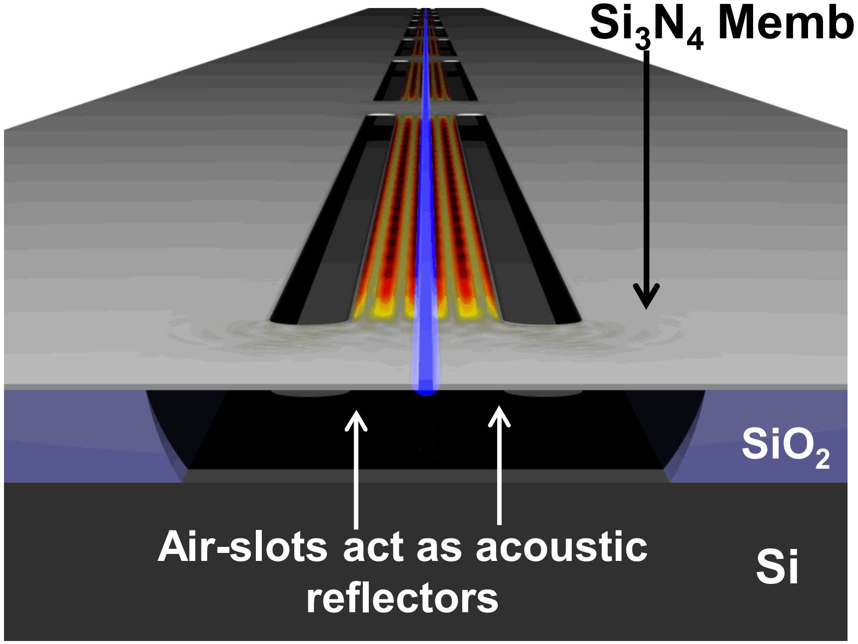
Experimental system: Can tailor phononic guidance independent of optical forces.

Fabricated Brillouin Active Waveguides.

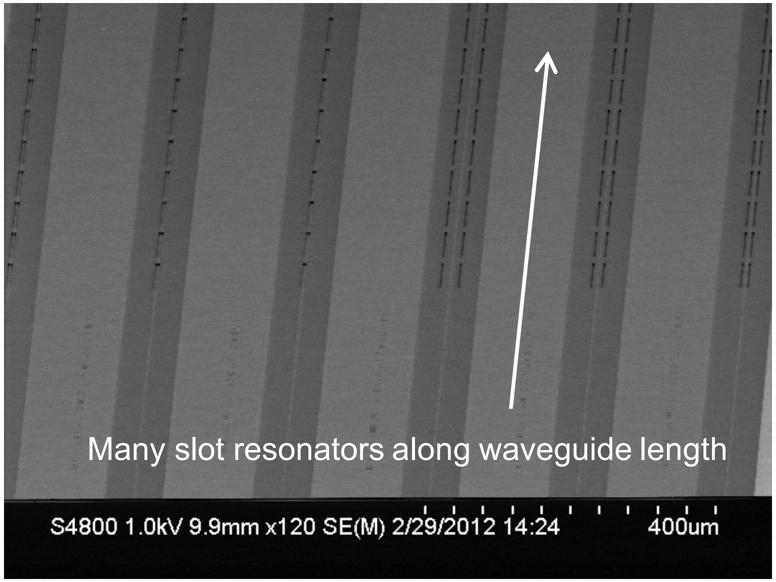


- 5mm-long devices realized with a concatenation of 26 Brillouin active waveguide segments.
- Nonlinear response coherently adds to yield tremendous aggregate Brillouin gain.

Brillouin Active Silicon Waveguides:



SEM of fabricated waveguides

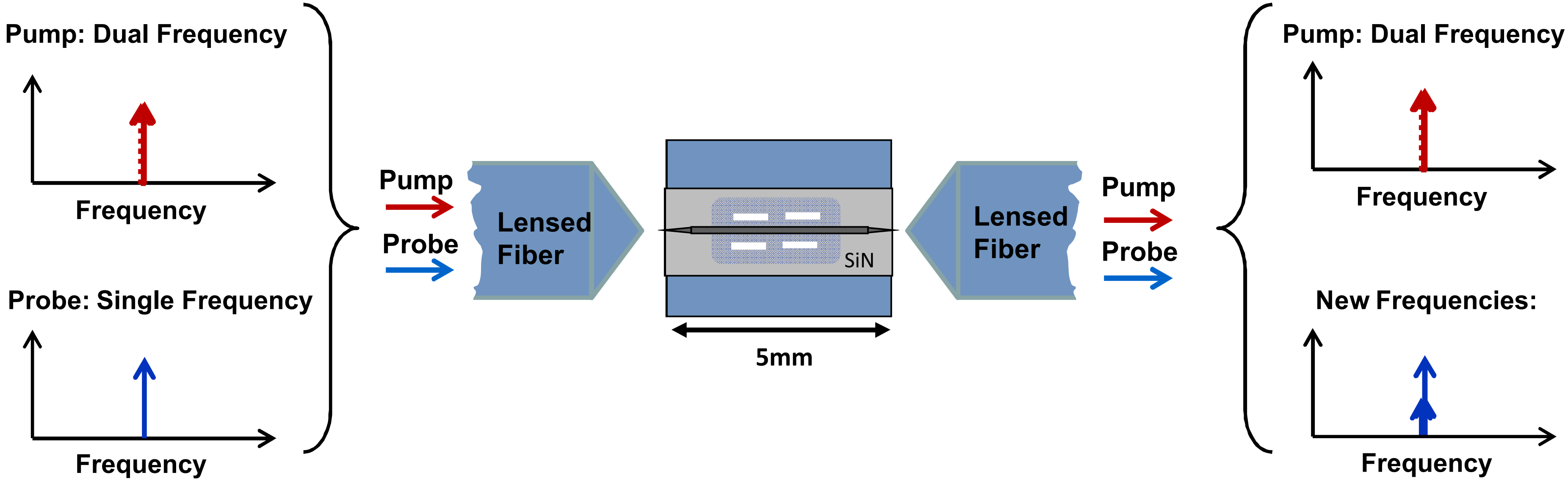


- Light guided via total internal reflection.
- 5mm-long devices realized with a concatenation of 26 Brillouin active waveguide segments.

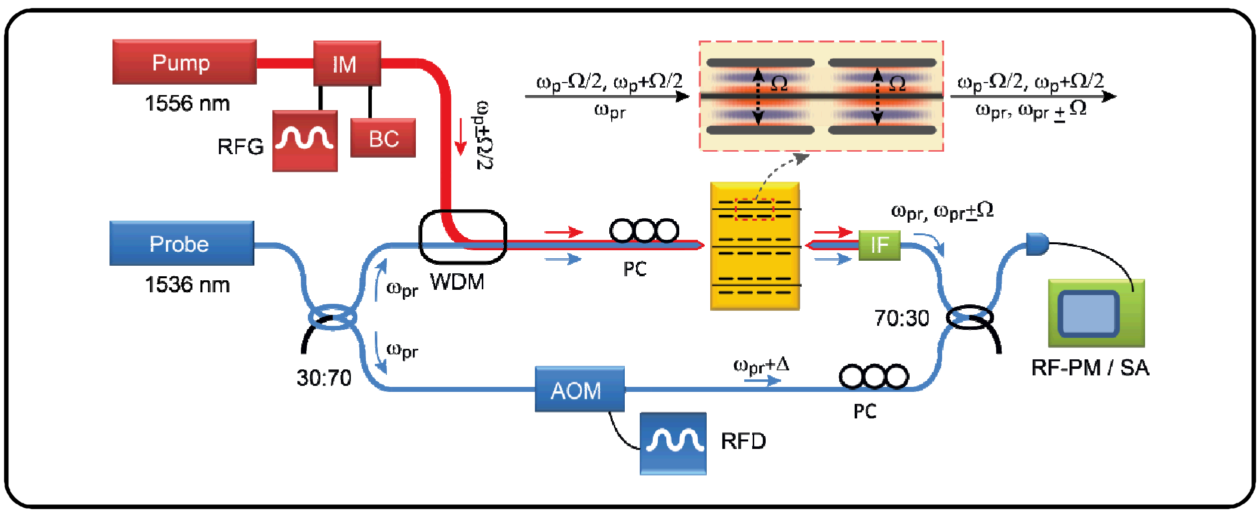
- Before we present any data, we should say a few things about:

1. The measurement apparatus.
2. Coherent addition of nonlinearities.

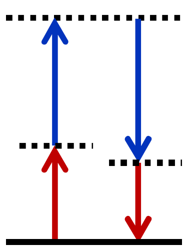
SBS Measurements:



Heterodyne cross-phase modulation apparatus.



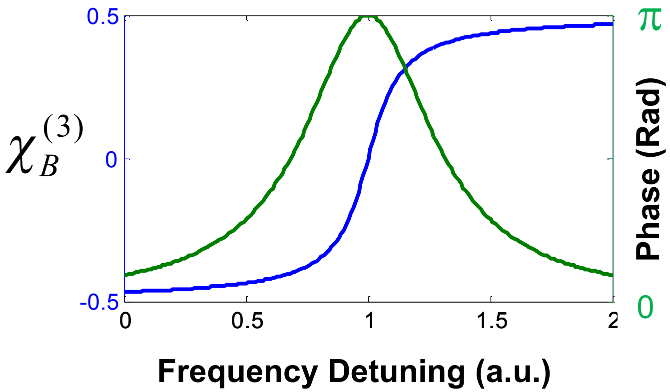
Measurement of nonlinear susceptibility



Four-Wave Mixing Transition

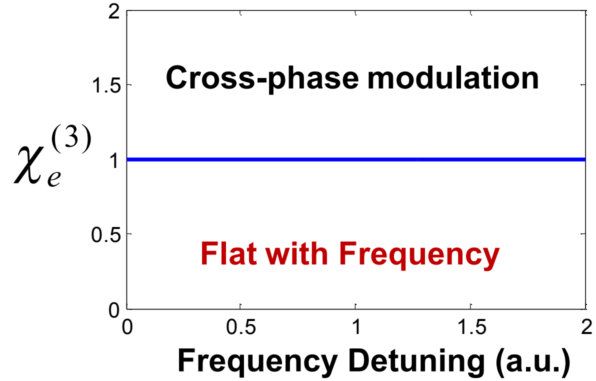
Total Nonlinear Susceptibility:

Resonant Brillouin Susceptibility

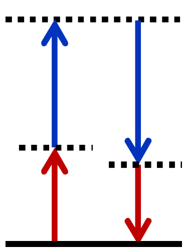


+

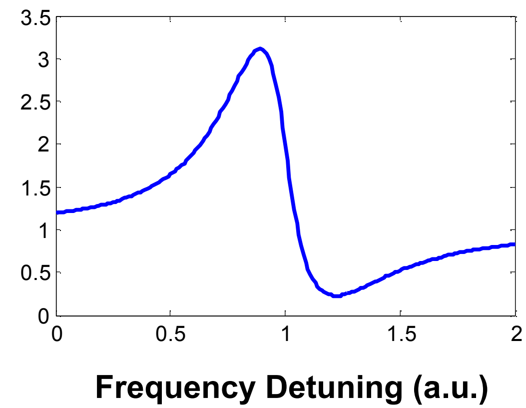
Non-Resonant Electronic Response



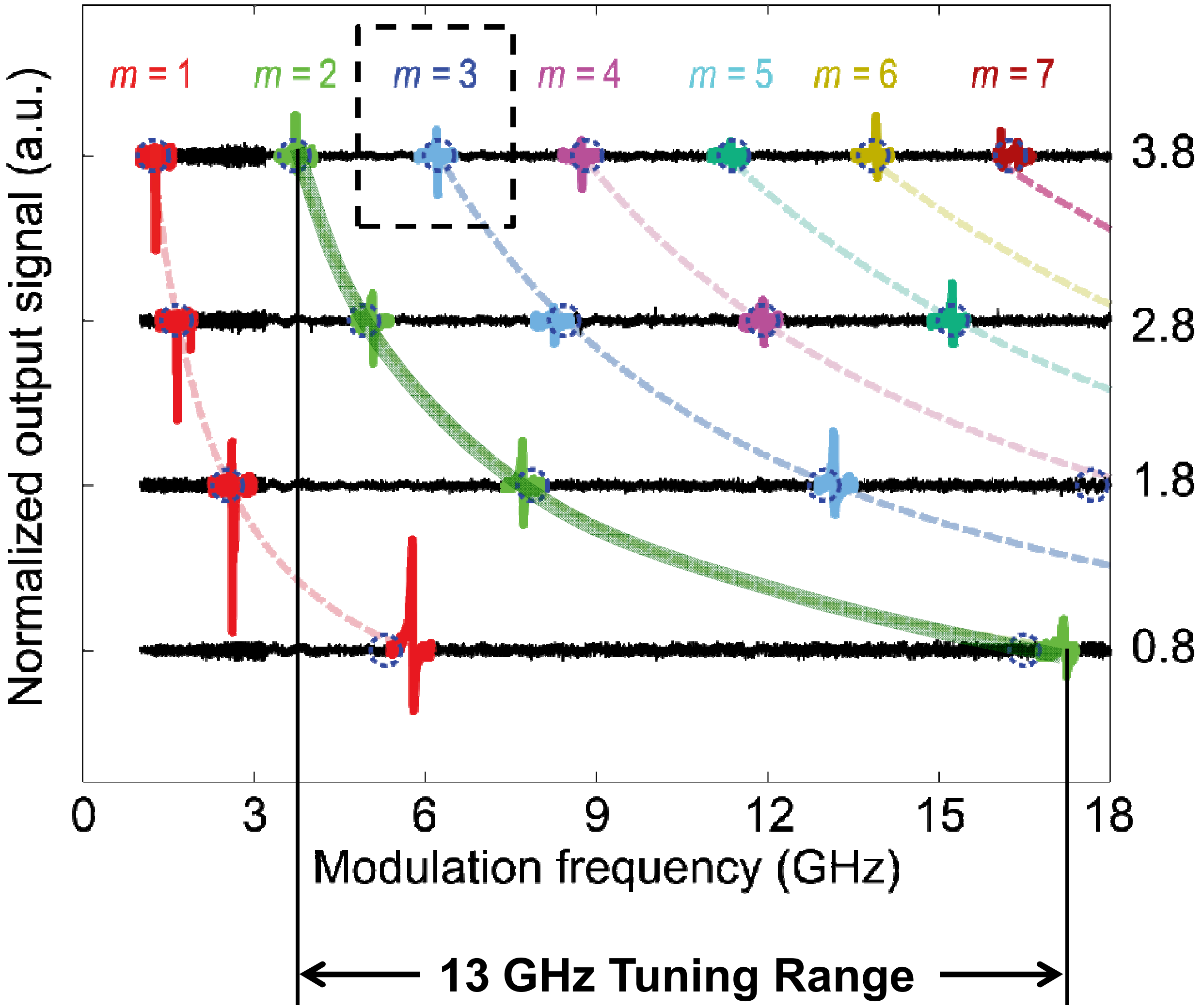
FWM Transition

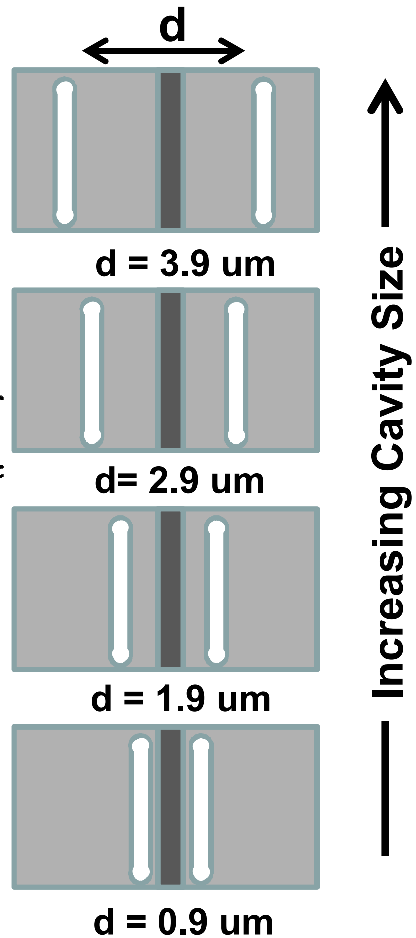


Combined Response

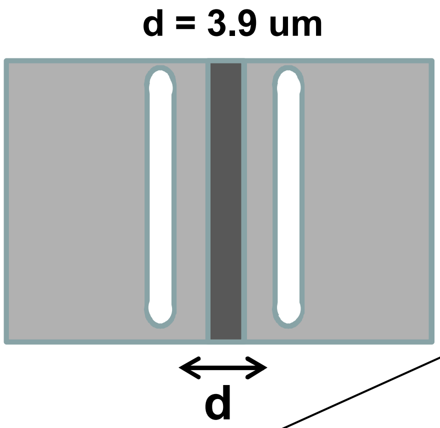


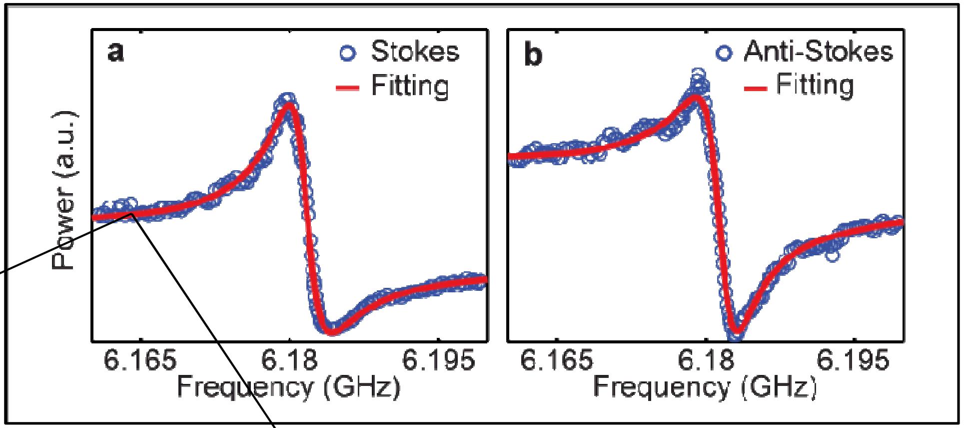
Mapping of Brillouin-Active Phonon Modes



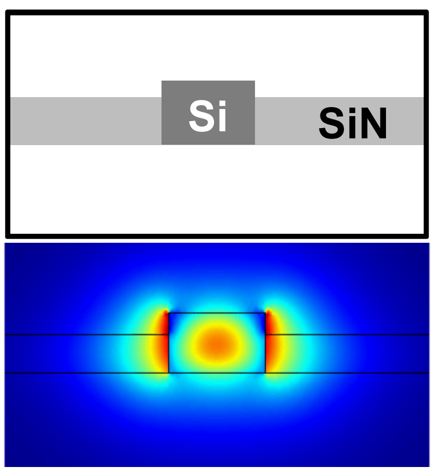


Analysis of Experimental Brillouin Signatures





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:

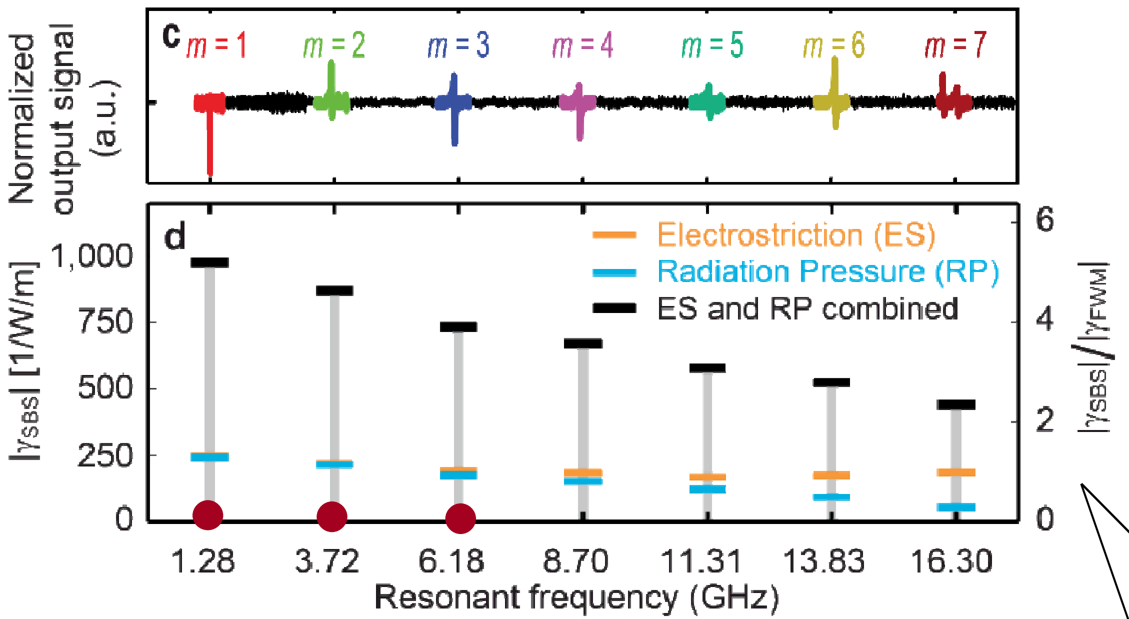
$$G_B/\gamma_k \cong 10.43$$

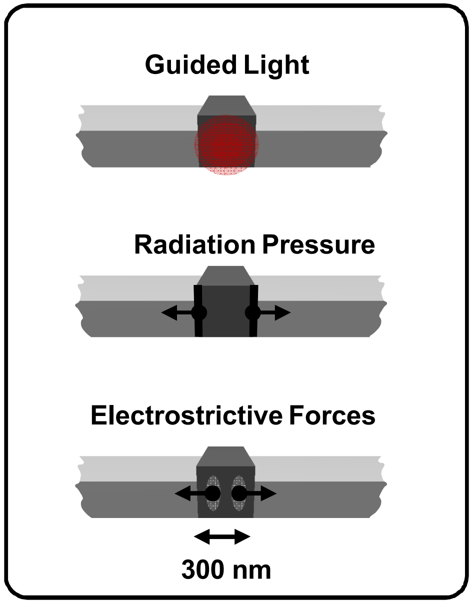
$$G_B \cong 1960\, W^{-1} m^{-1}$$

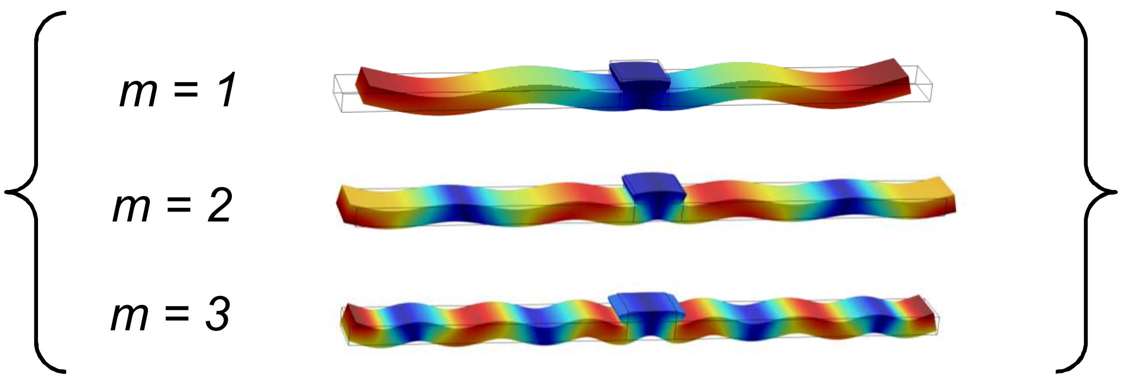
$$Q \cong 1561$$

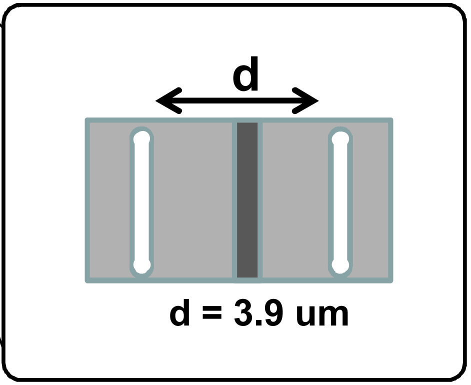
- **1000 X larger than any prior forward-SBS system.**
- **First SBS in Silicon!**

Numerical Model of Photon-Phonon Coupling

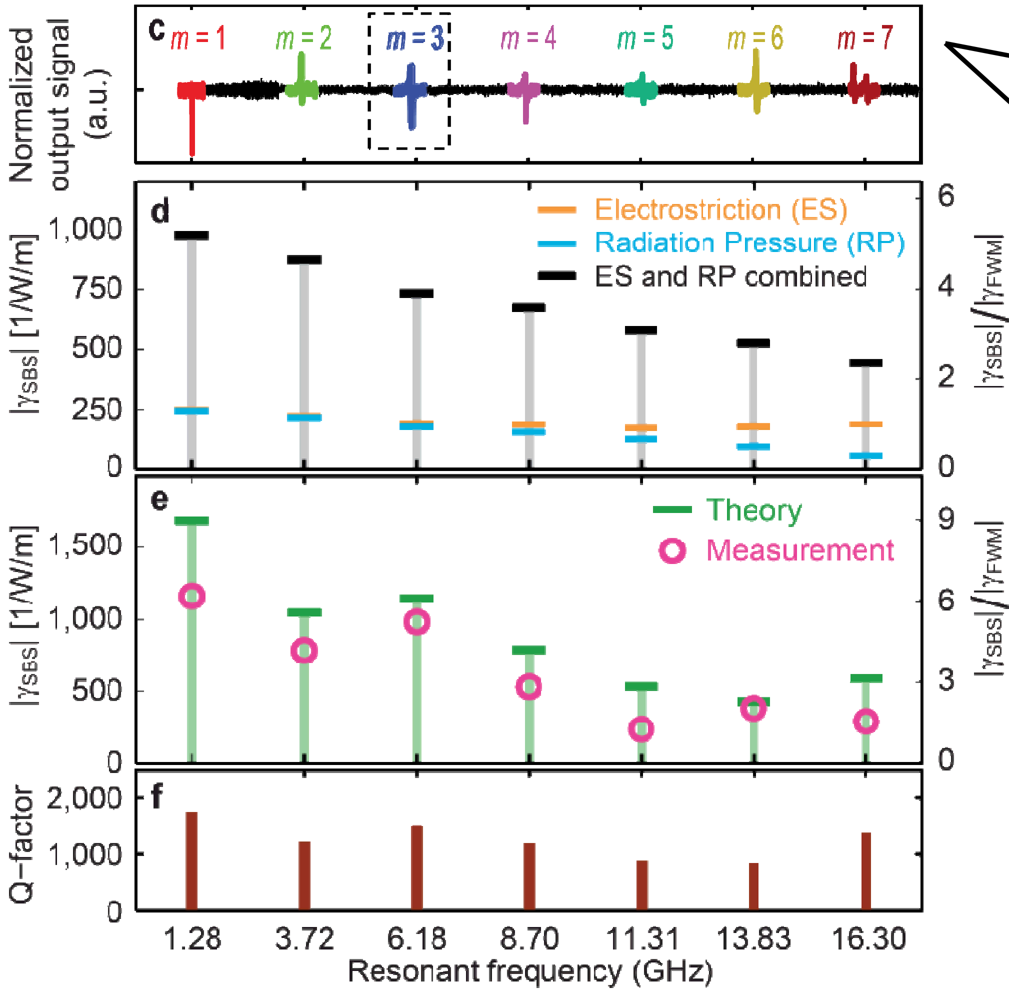


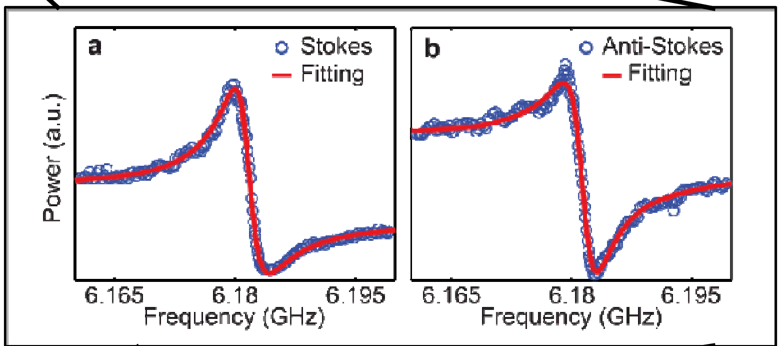






Quantitative Analysis of Brillouin Nonlinearity

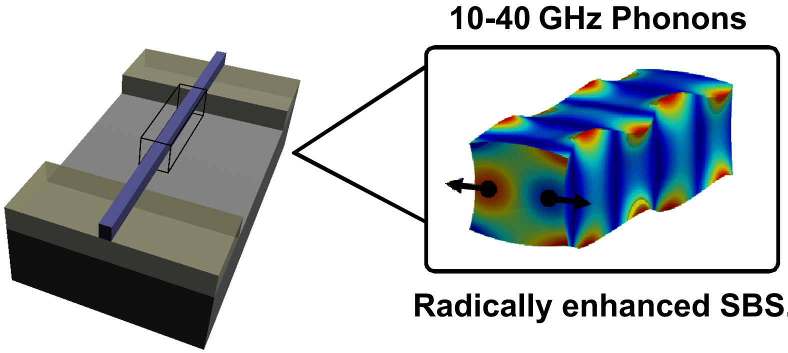




- Efficient transduction 1-18 GHz frequencies.
- Brillouin resonances observed at higher (24 GHz) frequencies
- Electrostriction and Radiation pressure are clearly playing important role.

Summary & Conclusion

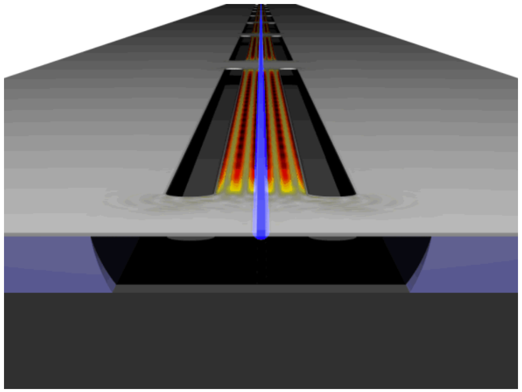
Theory: photon-phonon coupling.



Part I Summary:

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

Experiment: Forward-SBS in Silicon



Part II Summary:

- First demonstration of SBS in silicon.
- Exhibits 3000x stronger forward-SBS nonlinearity than any prior system.
- Many applications to come.

Our Team:

Yale	Sandia National Laboratories	UT ECE
<u>Peter Rakich</u> Heedeuk Shin	Jonathan Cox Ryan Camacho Troy Olsson Rob Jarecki	<u>Zheng Wang</u> Wenjun Qiu (MIT)

Acknowledgments:

Funding Agencies:

DARPA—MTO (PM: Jeff Rogers).

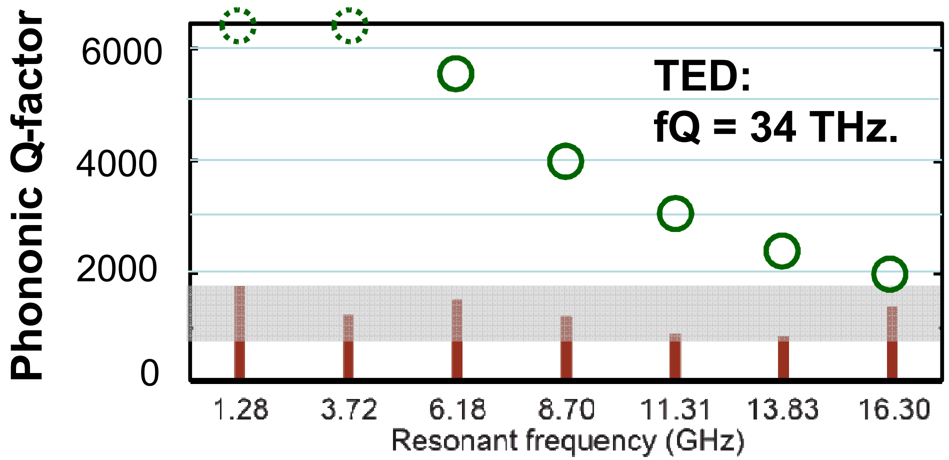
DOE—Laboratory Directed Research and Development funding.

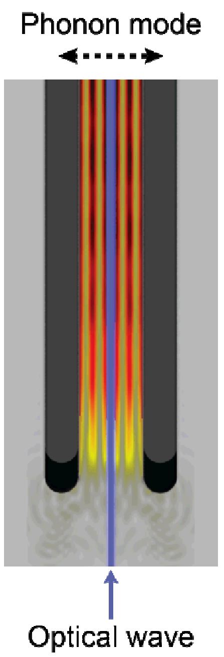
Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. This work was supported in part by the office of the Director of Defense Research and Engineering under Air Force contract FA8721-05-C-0002.

Challenge 1: Enhancement of Parametric Gain

Q: How to obtain ultimate efficiency and noise performance?

A: Enhance parametric gain further.





- Mean Q-factor ~1500
- Some improvement before thermoelastic damping limit
- Possible culprits: Anchoring losses, roughness.

D. Wilson, C. Regal, S. Papp, and H. Kimble, "Cavity optomechanics with stoichiometric SiN films," ***Physical review letters*****, vol. 103, no. 20, p. 207204, 2009.**

Summary of Recent Accomplishments:

1. First demonstration of wideband (1-18 GHz) stimulated Mach-wave phonon emission.
2. First-ever demonstration *chip-scale* Forward Stimulated Brillouin Scattering (SBS).

   > First demonstration of SBS in silicon.

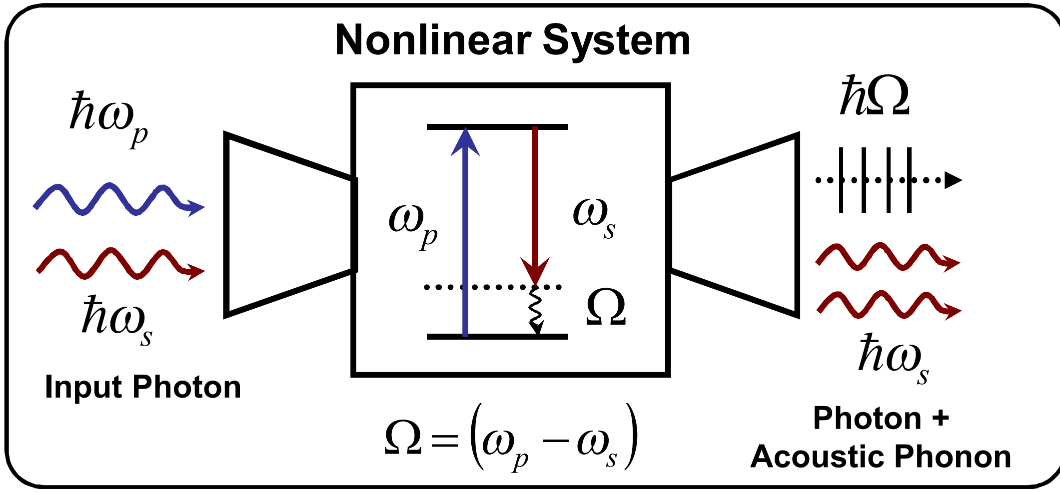
   > 3,000 x stronger SBS than any known system.

   > Demonstrated tailorable phonon emission from 1GHz-18GHz.

   > Demonstrated tailorable nonlinear susceptibility from the coherent interference of Kerr and Brillouin nonlinearities.
3. Demonstrated device physics for tailorable bandwidth phononic crystal Mach-wave emitter.

How Does Stimulated Brillouin Scattering Work?

Physics of Brillouin Scattering:

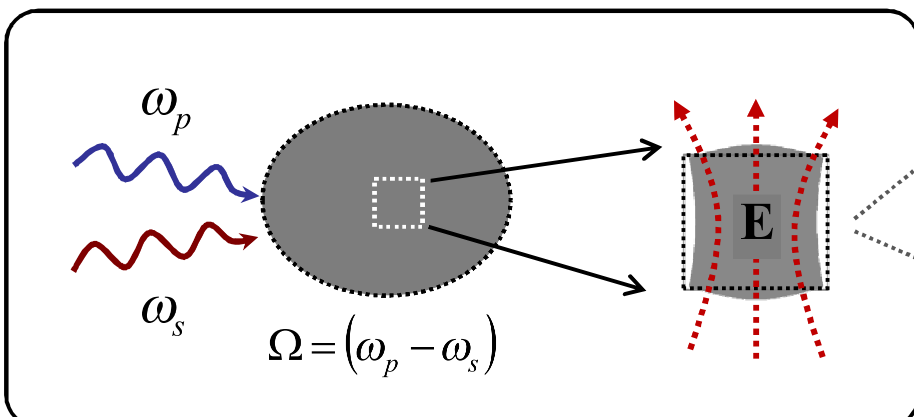


Brillouin Process:

- Coupling between *acoustic* phonons and photons.

- At the heart of all optomechanical interactions.

Micro-scale origins of parametric process:



Interference yields intensity "Beat Note".

$$|E(t)|^2 = 2E_pE_s \cdot \cos(\Omega \cdot t) + C$$

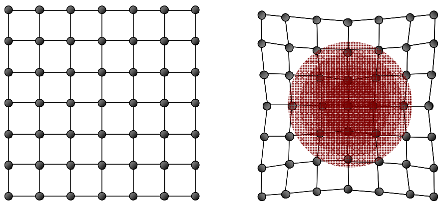
Optical Force: Proportional to Intensity.

$$F(t) \approx \alpha \cdot \sqrt{P_p \cdot P_s} \cdot \cos(\Omega \cdot t)$$

Time Varying Forces Excite Phonons.

Optical Forces Within Dielectric Media

Origin of electrostrictive forces: dynamic material response.



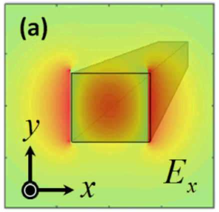
$$S = \alpha \cdot E_i + \beta \cdot E_i E_j$$

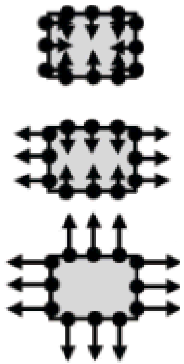
Strain (S) — Piezo Coeff. (α) — Electrostrictive Coeff. (β)

Electrostriction = Material induced optical forces.

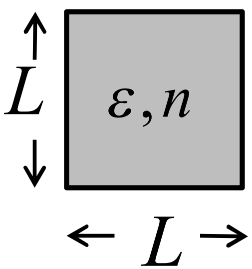
- All dielectrics exhibit electrostriction (not piezo electricity).
- Sign and magnitude are tailorable by choice of material

Medium properties dictate force dist.

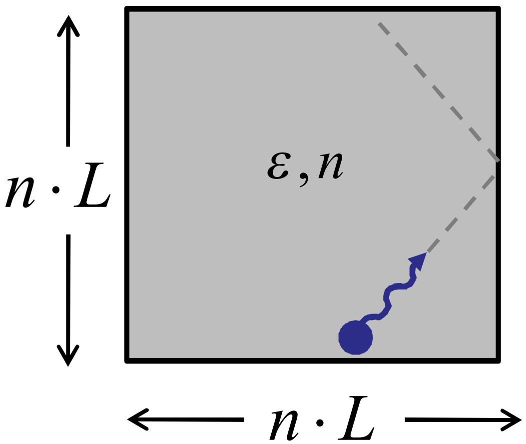




Box: Real Space



Box: Photon's Perspective



From Photon's Perspective:

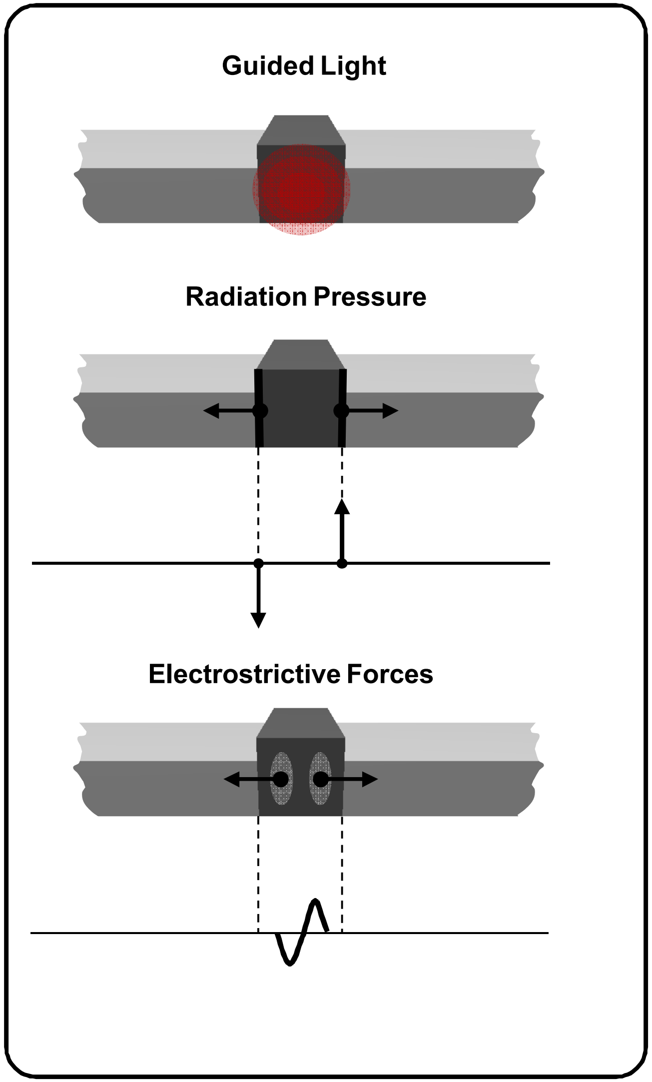
- Space is now quite different.

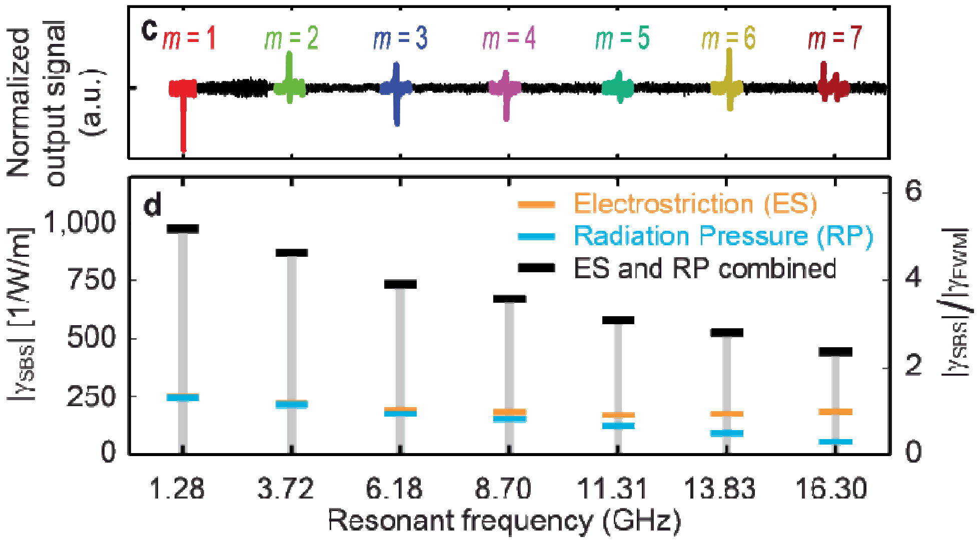
$$V \Rightarrow V' = V \cdot n^3$$

Box seems much bigger.

Oddities don't end here…

Origins of Wide-Bandwidth Coupling:



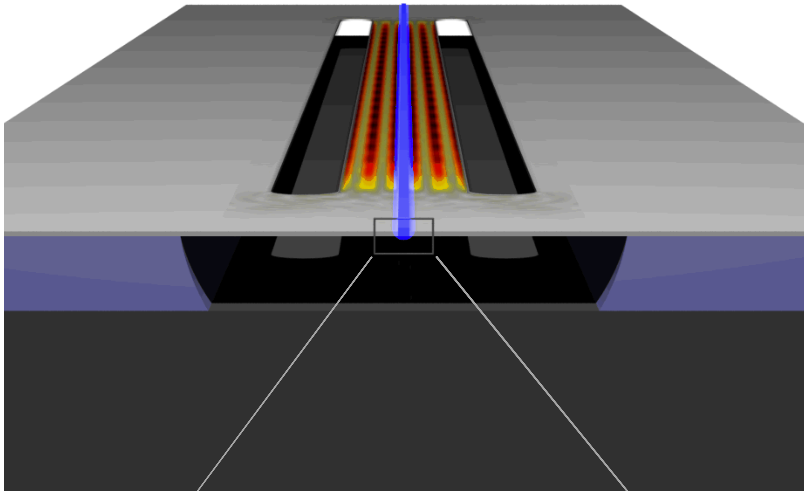


- <3dB variation in total gain from 1-18 GHz.
- Transductive bandwidth of RP is ~10 GHz.
- Transductive bandwidth of ES > 18 GHz.

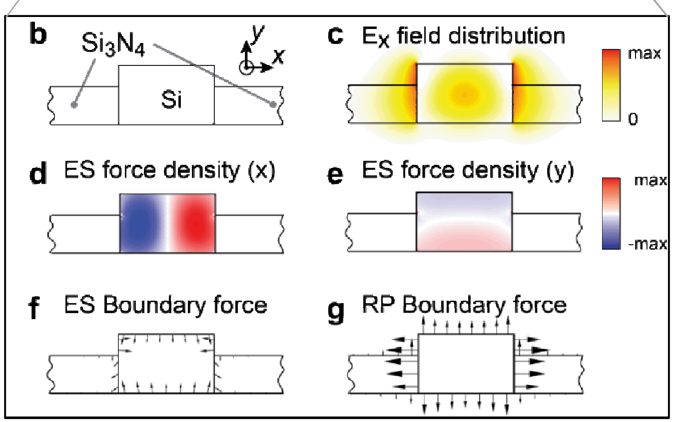
<u>Q: What is responsible for large bandwidth?</u>

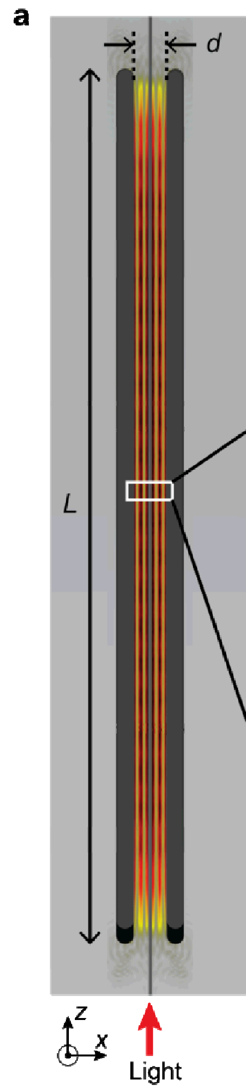
A: The higher spatial fundamental frequency associated with electrostriction more efficiently excite waves to higher bandwidths.

Engineerable Brillouin-Active Phonon Modes.



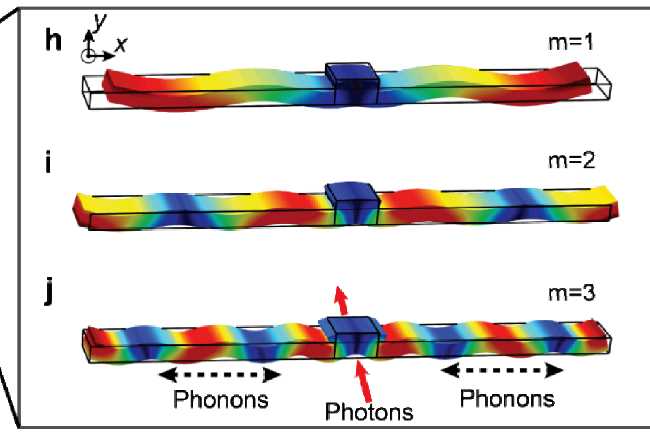
Mode and Optical Forces





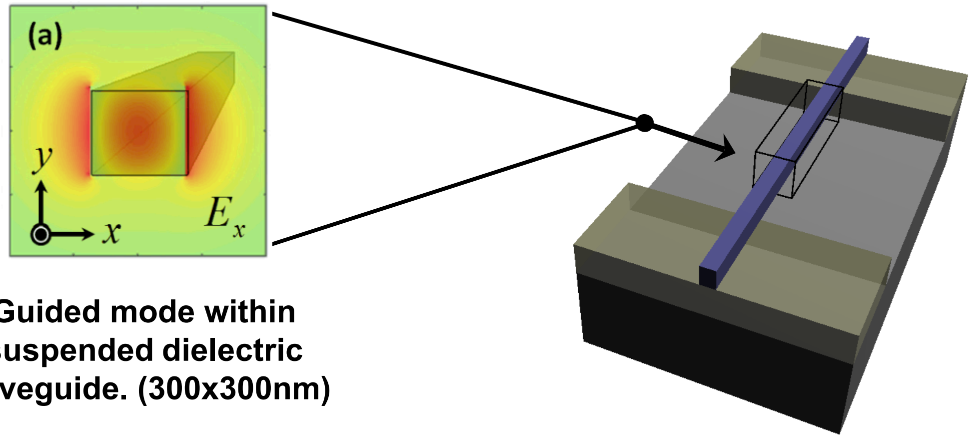
L = 100 microns
d = 3.8 microns

Brillouin Active Phonon Modes



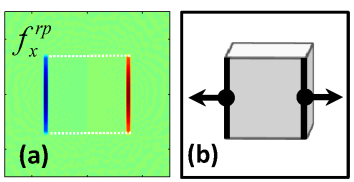
- Tailorable Brillouin mode spectrum
- Supports 1-100 GHz phononmodes.
- Phononic modes and optical forces independently controlled.

Next: Examine photon-phonon coupling.

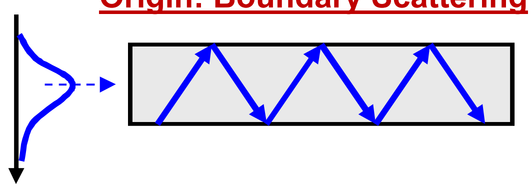


Guided mode within suspended dielectric waveguide. (300x300nm)

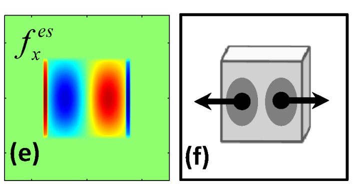
Radiation Pressure



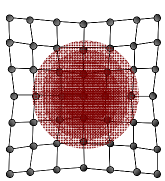
Origin: Boundary Scattering



Electrostrictive forces



Origin: Dynamic Material Response



Akin to piezoelectricity

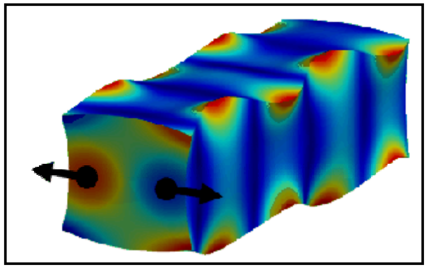
$$S = \alpha \cdot E_i + \beta \cdot E_i E_j$$

Strain

Piezo Coeff.

Electrostrictive Coeff.

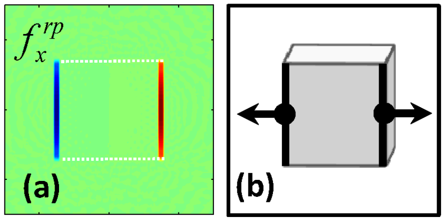
photon-phonon coupling:



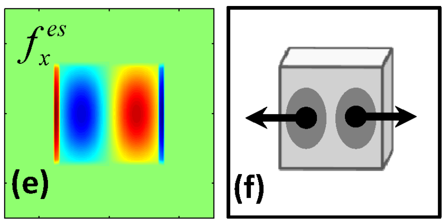
Efficient ultra-high frequency phonon emission.

Nanoscales: Electrostriction Has a Large Effect!

Radiation Pressure



Electrostrictive forces



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

Simp

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	~5 x10[4] N/m[2]
Ge	~10[6] N/m[2]

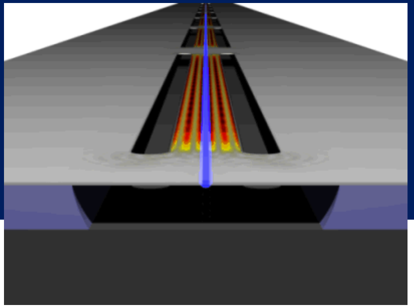
5-50 People standing on manhole cover

Material	Pressure (Pwr = 1kW)
Si	~5 x10[8] N/m[2]
Ge	~10[10] N/m[2]

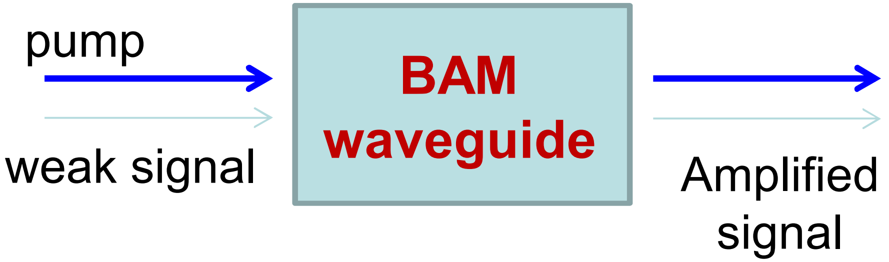
Stresses Approach Material Yield Strength

Yale

How large is the SBS gain?



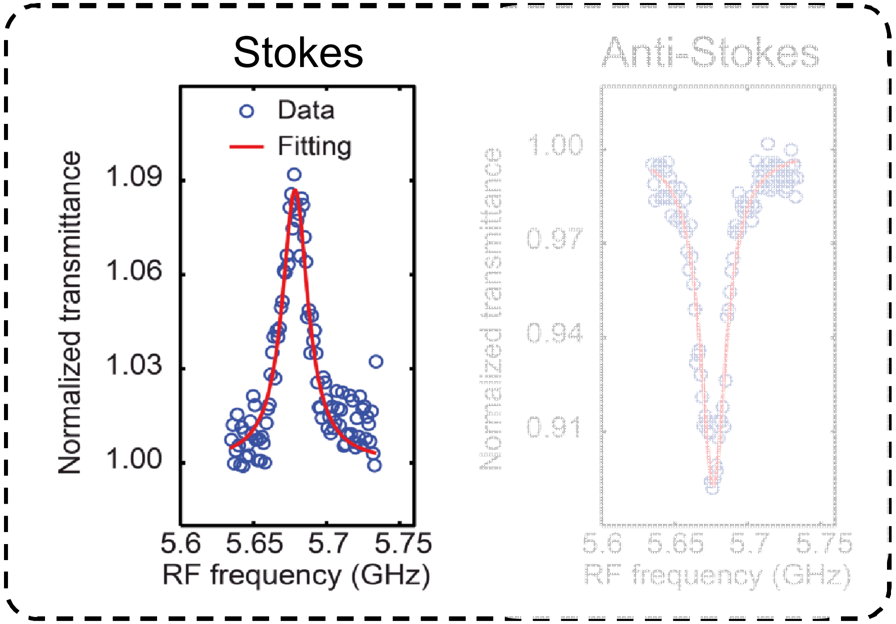
How do we quantify the SBS gain?



- Injection of strong pump beam + weak signal
- Amplified signal

What do these gain measurements tell us?

- 10 % amplification/depletion for Stokes/anti-Stokes fields
- Consistent with our previous heterodyne measurements
- Large gain coefficient, but overall gain is modest.



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

What limits gain?

- Gain limited by power handling & linear loss in waveguide

Can we improve overall Brillouin gain?

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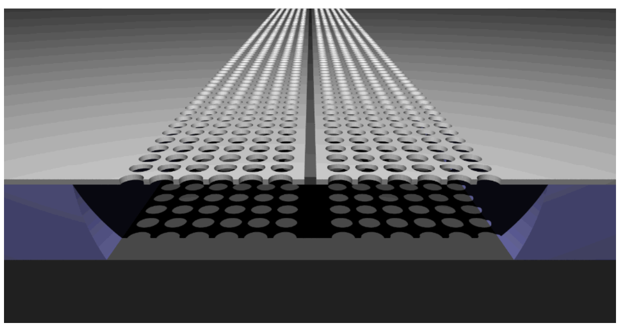
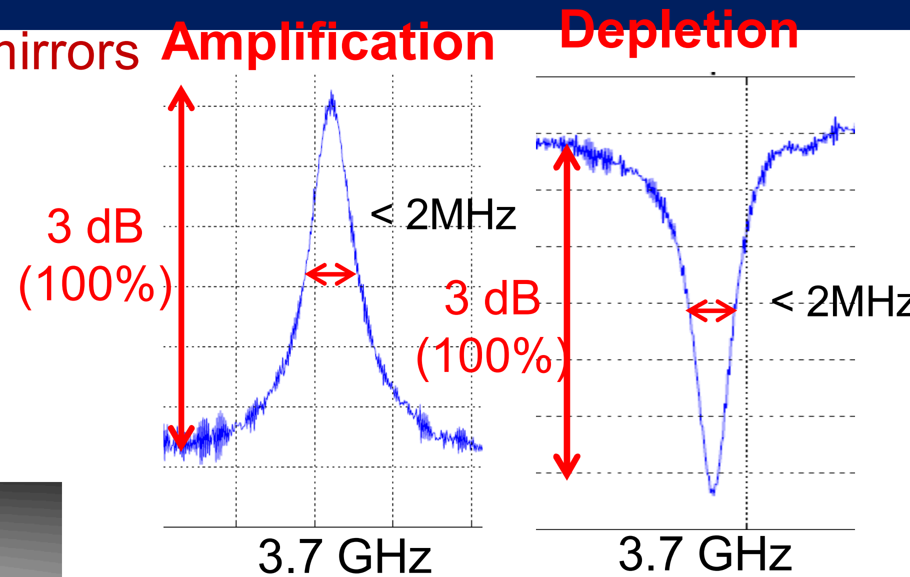
Yes, we can enhance the SBS gain.

BAM waveguide with phononic mirrors

- Same concept (hybrid photon-phonon waveguide)
- Phonon guided through Bragg reflection
- Wider silicon waveguide (1 um)





Results

- Higher power handling
- Lower propagation loss
- Longer effective interaction length
- Better photon-phonon coupling at low frequency

- 10 times enhancement than previous result
- We believe there is opportunity to enhance performance further.
- Expecting many applications

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