SAND2011-3703C

Fundamental Limits of Force and Transductions in Nano-Optomechanics.

Phononics 2011

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Outline of Presentation:

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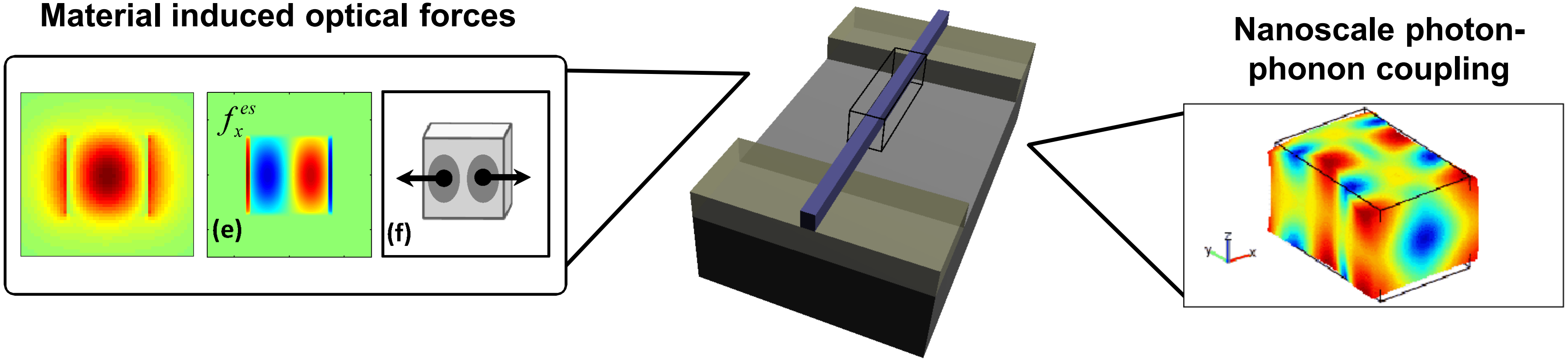
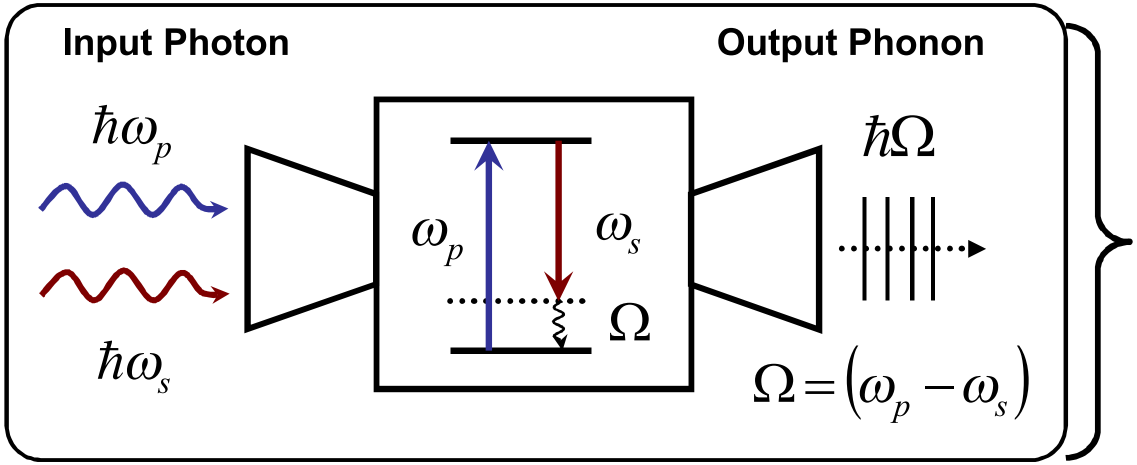
1. Overview of photon-phonon coupling at micro- and nanoscales.
2. Examine origins of optical forces within nanoscale materials and geometries.
3. Explore scaling of stimulated photon-phonon coupling via new framework.



Result: Giant Enhancement of Stimulated Brillouin Scattering at Nanoscales

How Does Stimulated Brillouin Scattering Work?

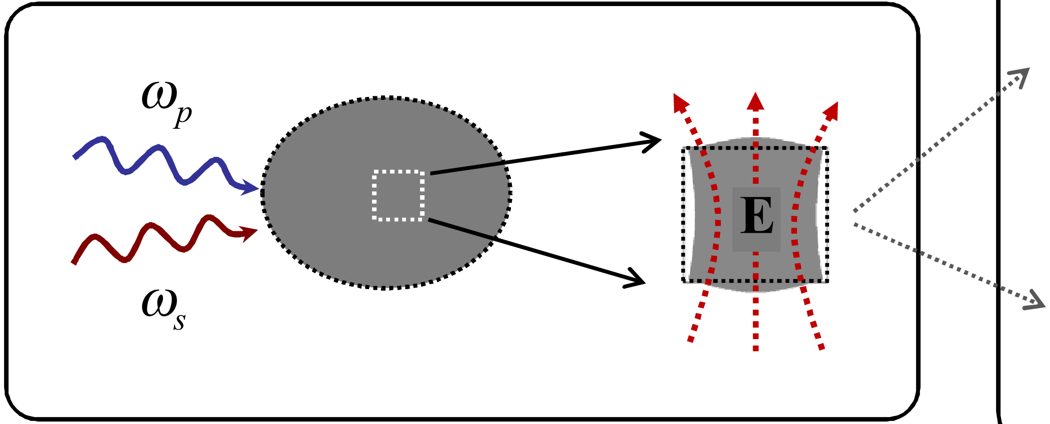
Physics of stimulated phonon generation:



Stimulated Brillouin Scattering (SBS)

- Yields coherent phonon generation.
- Mediated by optical forces.

Micro-scale origins of parametric process:



Interference yields intensity "Beat Note".

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

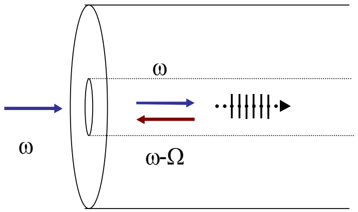
Optical Force: Proportional to Intensity.

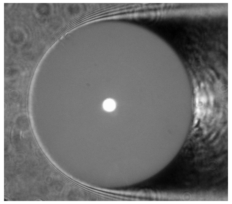
$$F(t) \approx \alpha \cdot \sqrt{P_p \cdot P_s} \cdot \cos(\Omega \cdot t)$$

Time Varying Forces Transduce Phonon.

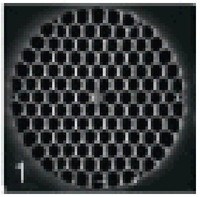
Guided-Wave Stimulated Brillouin Scattering:

Microscale Guided-Wave Stimulated Brillouin Scattering :

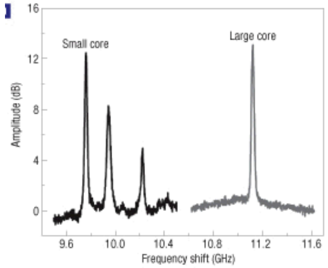




Ippen (1978)

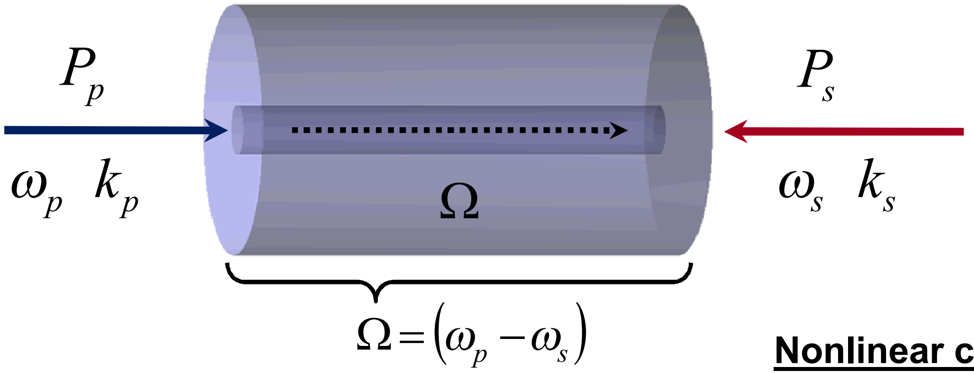


Russel



Lineage:
Nonlinear optics
Spectroscopy

How microscale stimulated Brillouin scattering works:



Pump Wave

Stokes Wave

$$\Omega=\left(\omega_p-\omega_s\right)$$

- Wave interference & forces induce guided elastic wave.
- Photon-phonon coupling mediated by electrostriction.

Nonlinear conversion:

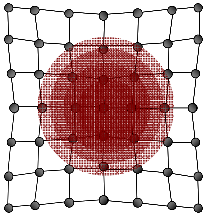
$$dP_s/dz = G_B \cdot P_p P_s$$

↑

SBS gain

SBS: Mediated by electrostriction.

Electrostriction:

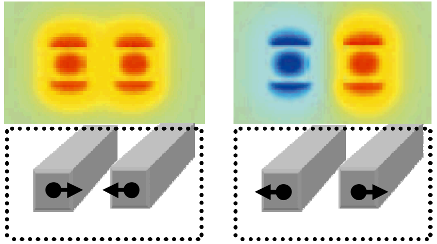


From dynamic material response.

Nanoscales: light-matter interactions change in a fundamental way….

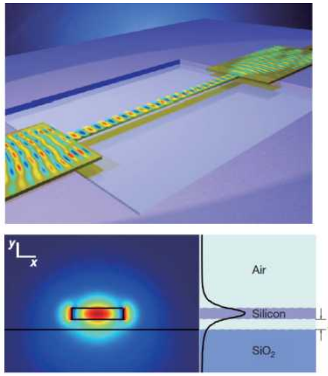
Enhanced Radiation Pressure at Micro and Nanoscales

Symmetric **Asymmetric**



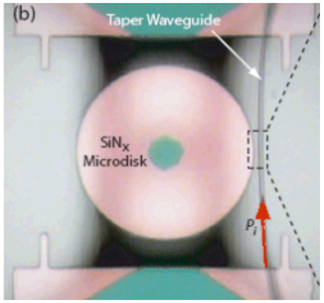
Attractive force **Repulsive force**

Povinelli, et. al. Opt. Lett. 30,3042 (2005).

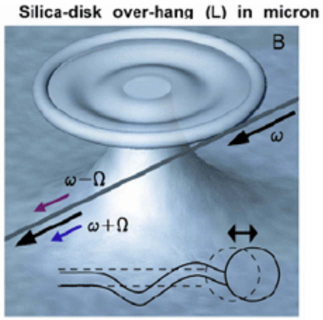


Mo Li *et al.* Nature 1, 480–484 (2008).

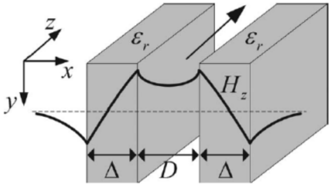
Optical microdisk



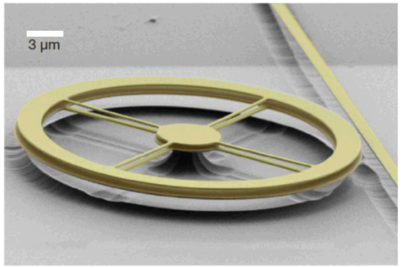
Eichenfield, M. *et al.* Nat. Photon. 1, 416–422 (2007).



T. Carmon, H. Rokhsari, L. Yang, T. Kippenberg, and K. Vahala, Phys. Rev. Lett. 94, 223902 (2005).

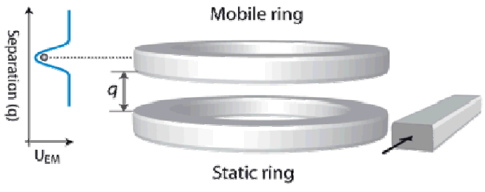


A. Mizrahi & L. Schächter Opt. Lett. 32, (2007), p.692-694

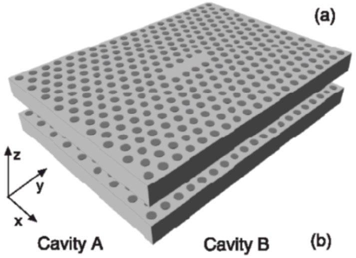


G. S. Wiederhecker, L. Chen *et al* Nature 462 2009, p.633

Dual microring geometry:



Rakich, Popovic *et al.* Nat. Photon. 1, 685-669 (2007).

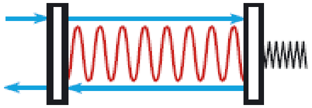


Notomi, M. and Taniyama, H. Phys. Rev. Lett. 94, p23903 (2006)

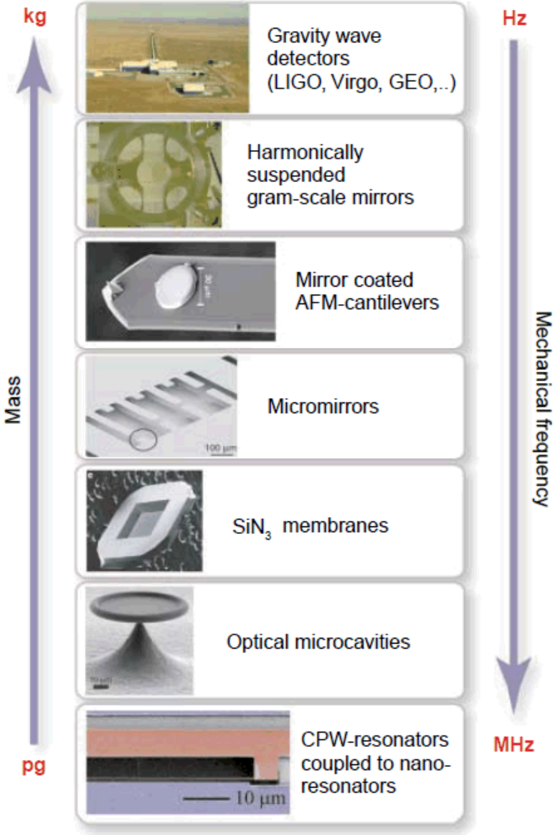
- **Most of studies have focused on forces between discrete bodies.**
- **We will see that optical forces within bodies become very important to consider as well…**

Nano Optomechanics: Stimulated Scattering

Cavity Optomechanics

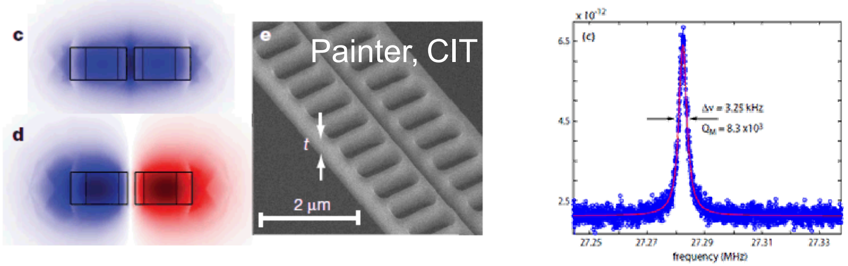


Walther 1983



Kippenberg, Vahala, Science 2008

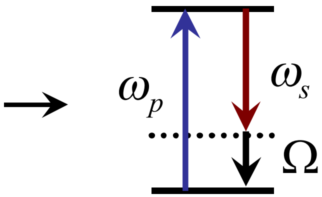
Optomechanical Parametric Oscillation



Radiation Pressure

Eichenfield, *et. al.* Nature, 459, 550 (2009).

Radiation pressure mediates photon-phonon coupling.



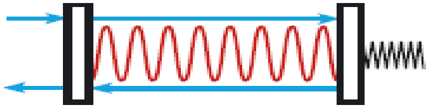
←**Optical photons**

←**Acoustic Phonon**

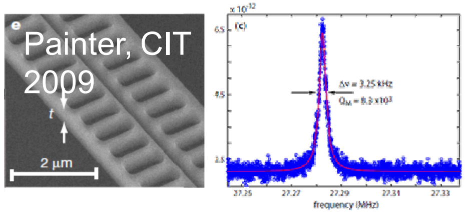
- **Formally equivalent to Brillouin process.**
- **<u>A key distinction</u>: mediated by radiation pressure.**

Traveling-wave SBS at nanoscales:

Cavity Optomechanics



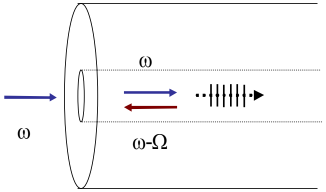
Walther 1983

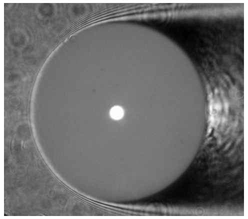


Painter (2009)

Nanoscales:
Radiation pressure Mediated Stimulated Brillouin processes

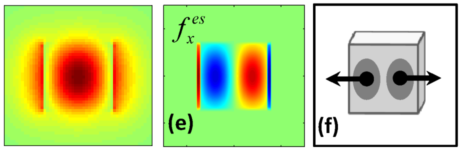
Microscales:
Electrostrictively Mediated Stimulated Brillouin processes

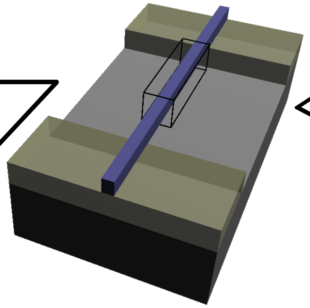




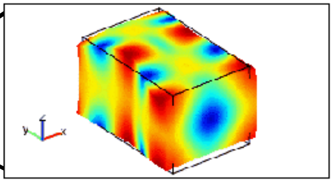
Result: Giant Enhancement of Stimulated Brillouin Scattering at Nanoscales

Electrostriction + Radiation Pressure





10-40 GHz Phonons

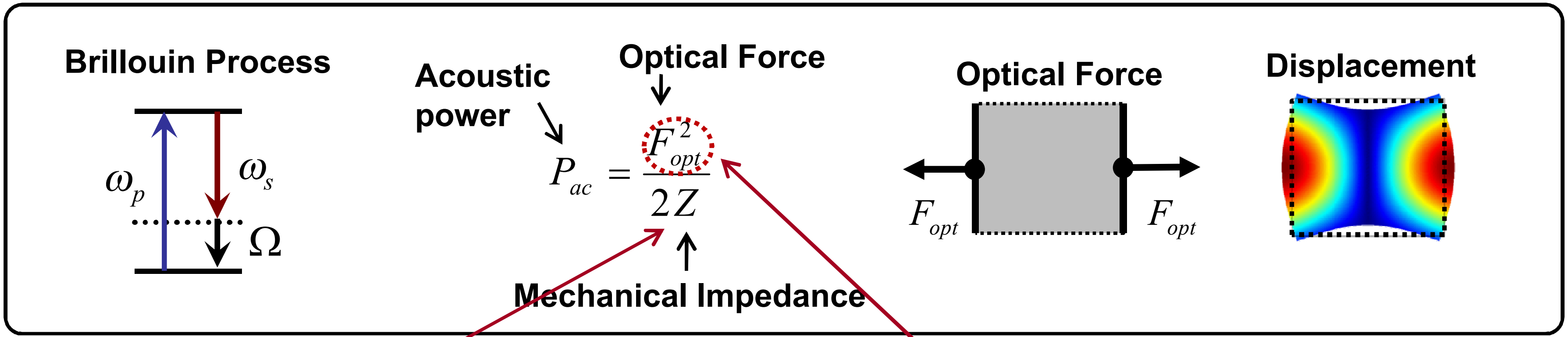


Radically enhanced SBS.

Electrostriction & Radiation Pressure mediate SBS

How to Formulate SBS Gain in Nanoscale Systems?

For a time-harmonic force, $F(t) = F_{opt} \cdot \cos(\Omega \cdot t)$, produced by modal beating:



$$P_{ac} = \frac{F_{opt}^2}{2Z}$$

“Mechanical Transduciton in Periodic Media,” R. Camacho, (Paper 0130), Next.

“Analysis of Forces in Nanophotonic Waveguides,” C. Reinke. (Paper 0170), 2:40-3:00 PM

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

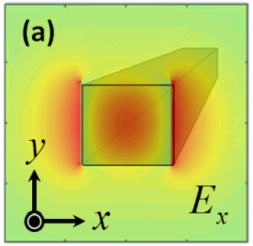
SBS gain

Exact solution: $G_B = \left(\frac{\omega_s}{\Omega}\right) \cdot \frac{1}{P_s P_p} \frac{F_{opt}^2}{Z} \alpha$ ← **Geometric scale-factor**

Strong photon-phonon coupling requires: (1) large optical force, (2) small mechanical impedance.

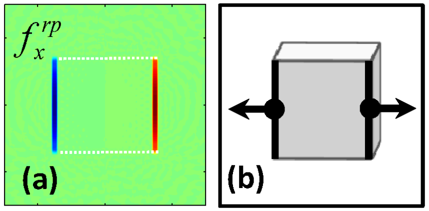
Optical Forces at Nano-scales

Silicon Waveguide.

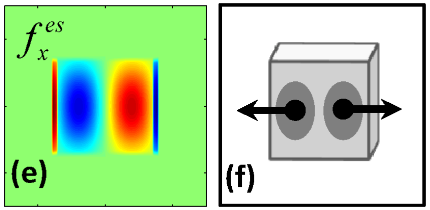


300nm x 300nm

Radiation Pressure



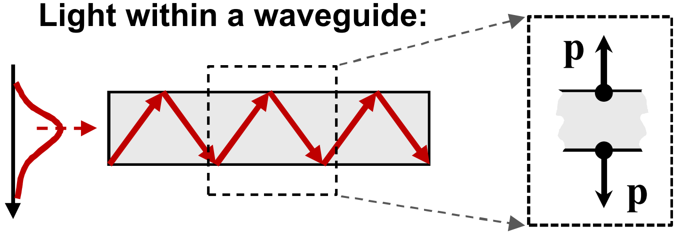
Electrostrictive Forces



Radiation Pressure.

Radiation Pressure: Scattering from boundaries.

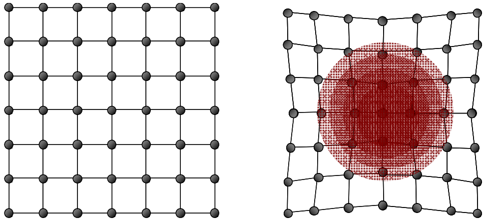
Light within a waveguide:



Entirely depends on geometry.

Electrostrictive Forces

Electrostriction: dynamic response of media to light.

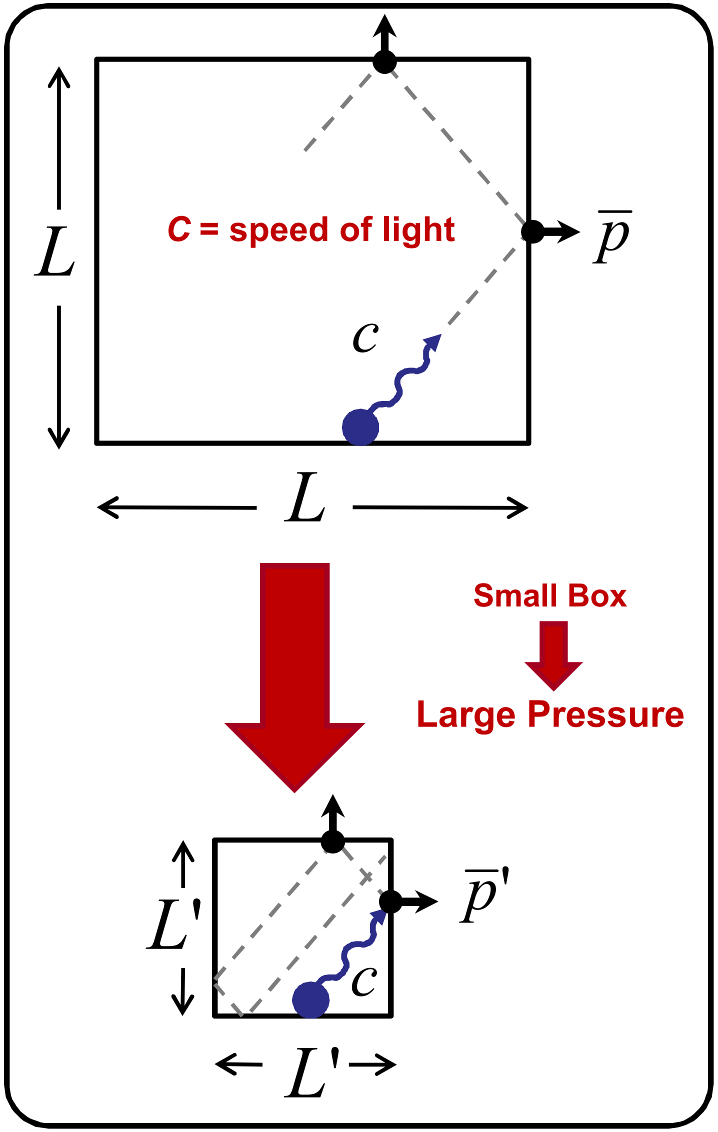


Depends primarily on material properties.

Both: Radically enhanced at nanoscales.

How to understand origin and enhancement?

Why is Radiation Pressure Enhanced at Nano-scales?



Equation of State for an Ideal Photon Gas:

Pressure → $\boxed{\bar{p}V = \frac{1}{3} \cdot N \cdot \hbar\omega}$ ← **Photon Energy**

Volume

# of photons

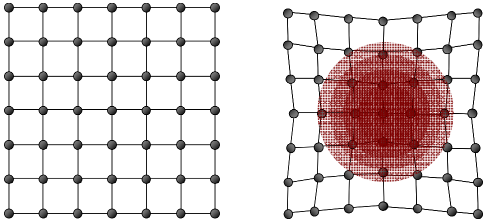
Pressure Per Photon:

$$\boxed{\bar{p} = \frac{1}{3} \cdot \frac{\hbar\omega}{V} = \frac{1}{3} \cdot \frac{\hbar\omega}{L^3}}$$

For L/L’ = 1000, p’/p = 1,000,000,000.

Each photon packs more punch at nanoscales!

Optical Forces Within Dielectric Media



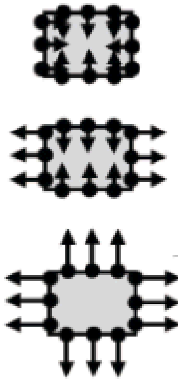
$$S = \alpha \cdot E_i + \beta \cdot E_i E_j$$

Strain

Piezo Coeff.

Electrostrictive Coeff.

Electrostriction = Material induced optical forces.
- All dielectrics exhibit electrostriction (not piezo electricity).
- Sign and magnitude are tailorable by choice of material



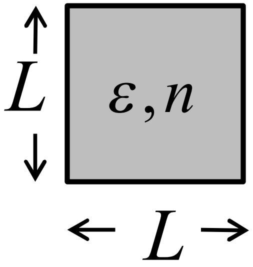
Germanium

Silicon

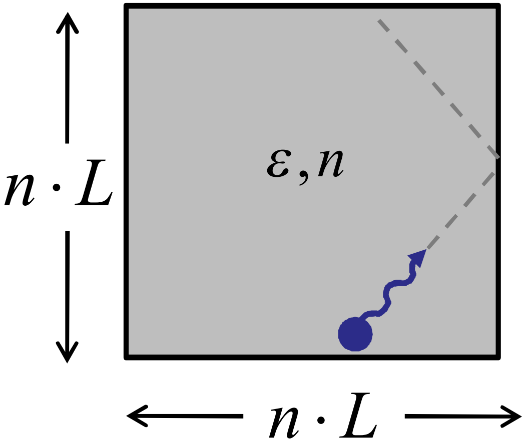
GaAs

What's going on?

Box: Real Space



Box: Photon's Perspective



From Photon's Perspective:

- Space is now quite different.

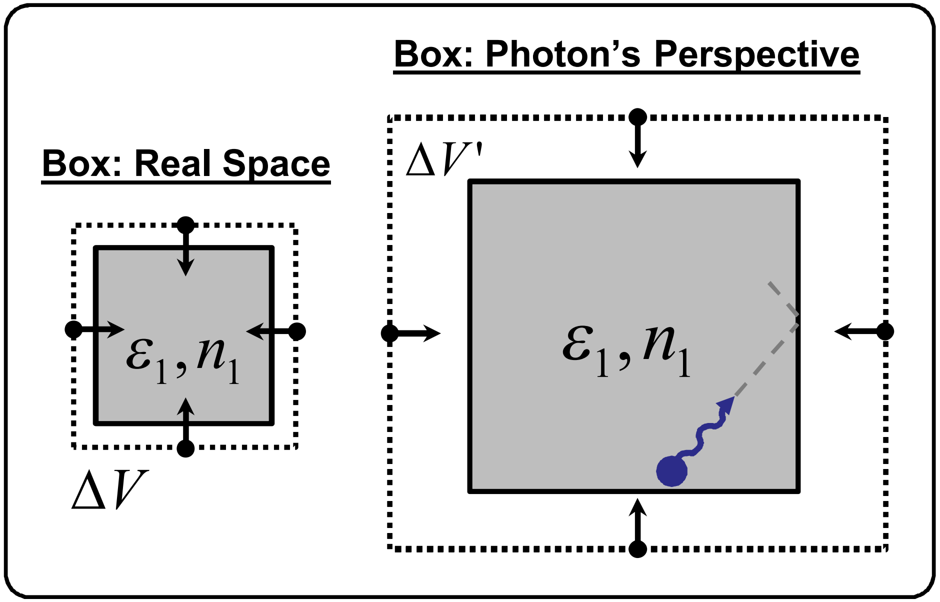
$$\boxed{V \Rightarrow V \cdot n^3}$$

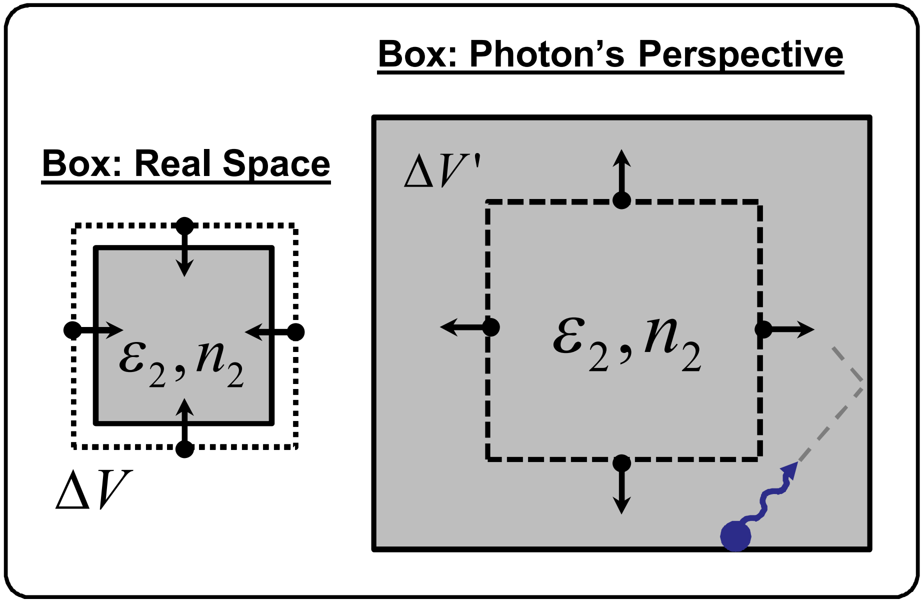
Box seems much bigger.

Oddities don't end here…

Electrostriction: Material Induced Forces

Since $\partial n/\partial V \neq 0$, distortion of the box is perceived quite differently by a photon:





Photon gas within a dielectric:

$$\boxed{\Delta V' \Rightarrow n^3 \Delta V + 3n^2 V \cdot \left(\frac{\partial n}{\partial V}\right) \cdot \Delta V}$$

Correction due to dynamic response

Photon gas within a dielectric:

$$\boxed{\bar{p} = \frac{1}{3} \cdot \frac{N \cdot \hbar\omega}{V} \left[1 + \frac{3}{n} \frac{\partial n}{\partial V}\right]}$$

Electrostriction

Alternative: Electrostrictive Stress & Force.

Dependence on material properties:

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

Electrostrictive Stress in Cubic Crystal (Si):

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

Force Density:

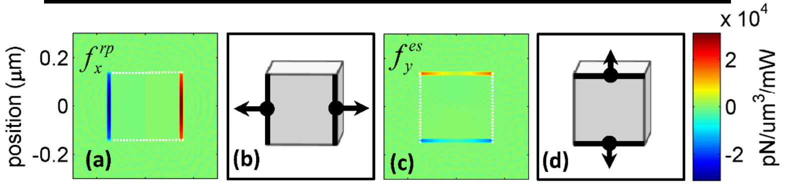
$$\mathscr{F}_j = -\partial_i \sigma_{ij}$$

Important Properties of Stress/Force

1. Increases as n^4.
2. Proportional to p_{ijkl} .
3. Sign & magnitude depends on p_{ijkl}

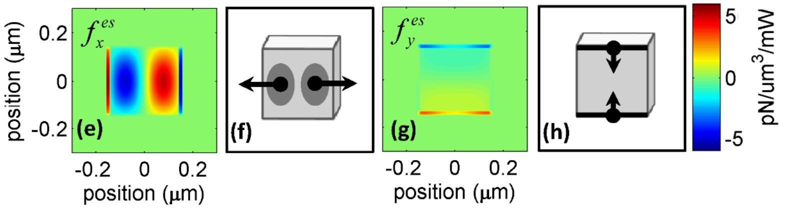
Example: Silicon waveguide.

Radiation Pressure: Si waveguide



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

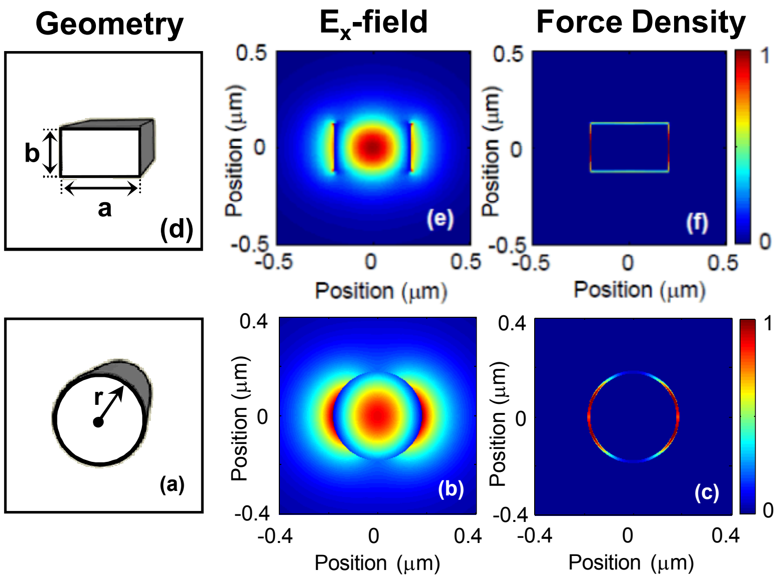
Electrostriction: Si waveguide



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)

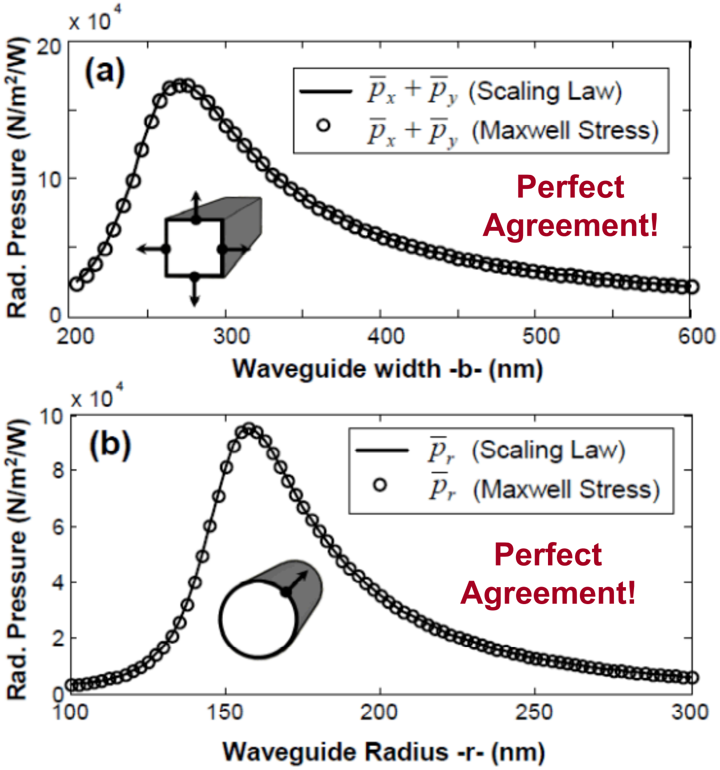
Key to Radiation Pressure: Dispersion.



Radiation Pressure:

$$\overline{p}^{rp} = \frac{P_{opt}}{c\cdot A}\cdot(n_g - n_p) \le \frac{P_{opt}}{c\cdot A}\cdot(2\Delta n)$$

Comparison of Maxwell Stress & Scaling Law

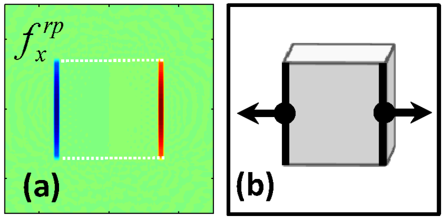


Relation Holds for *Any Dielectric Waveguide* and *Any Guided Mode*!

[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: The Neglected Optical Force Dominates!

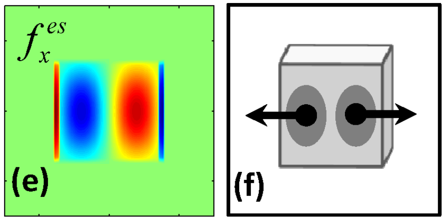
Radiation Pressure



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

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

Electrostrictive forces



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?

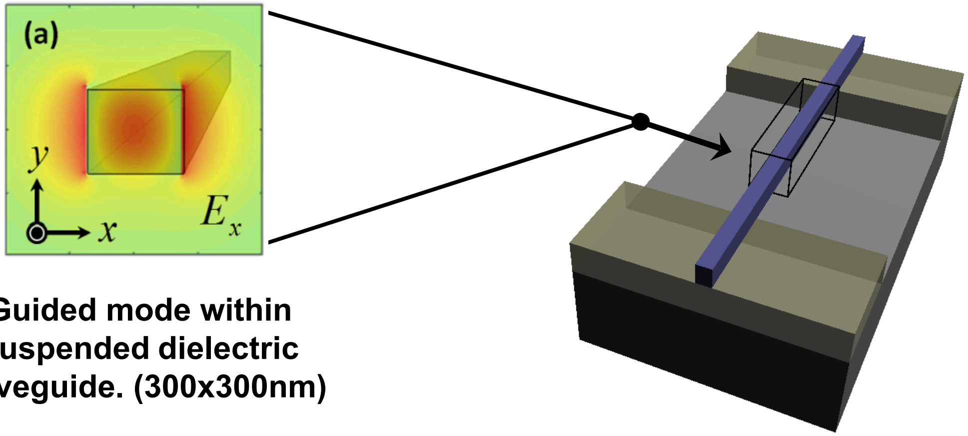
Material	Pressure (Pwr = 100mW)
Si	~5 x10^4 N/m^2
Ge	~10^6 N/m^2

5-50 People standing on manhole cover

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

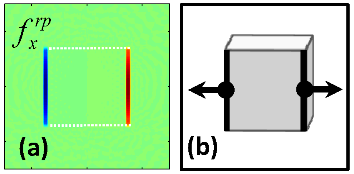
Stresses Approach Material Yield Strength

Next: Examine photon-phonon coupling.

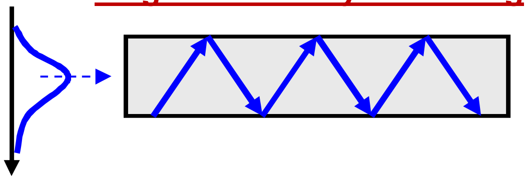


Guided mode within suspended dielectric waveguide. (300x300nm)

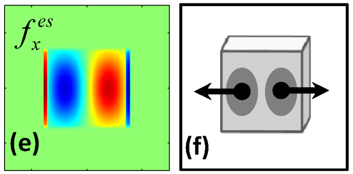
Radiation Pressure



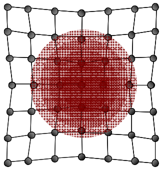
Origin: Boundary Scattering



Electrostrictive forces



Origin: Dynamic Material Response



Akin to piezoelectricity

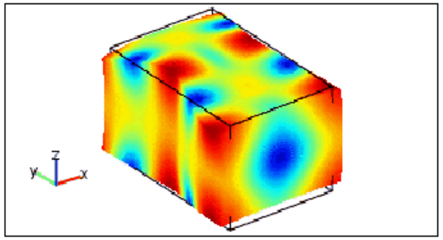
$$\boxed{S = \alpha \cdot E_i + \beta \cdot E_i E_j}$$

Strain

Piezo Coeff.

Electrostrictive Coeff.

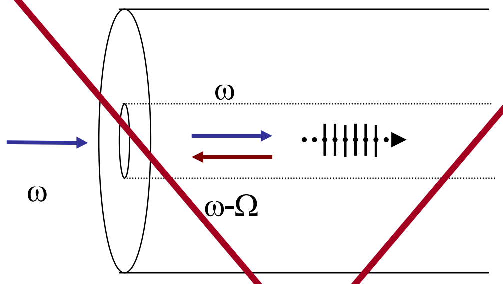
Generalized theory of photon-phonon coupling:



Reveals powerful new photon-phonon coupling processes at nanoscales.

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.~~
- ~~Simplified elastic-wave mode.~~

Not valid at nanoscales.

Unified Treatment of SBS: Valid at any Length-Scale

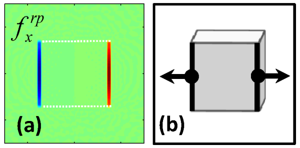
Canonical relation for SBS gain:

$$\boxed{dP_s/dz = G_B \cdot P_p P_s.}$$

SBS gain

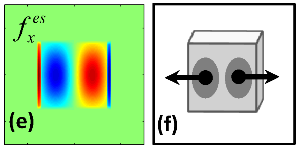
$$\boxed{G_B(\Omega) = \frac{1}{\delta z}\frac{\omega_s}{\Omega}\cdot\frac{1}{P_p\cdot P_s}\int_{\delta V}\langle\, \mathbf{f}_\Omega(\mathbf{r},t)\cdot \dot{\mathbf{u}}(\mathbf{r},t)\,\rangle\cdot dV,}$$

Radiation Pressure:



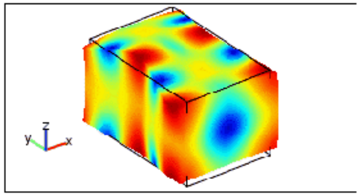
+

Electrostriction:



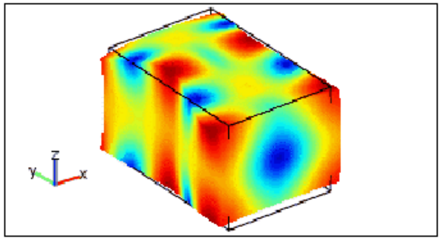
Time harmonic force

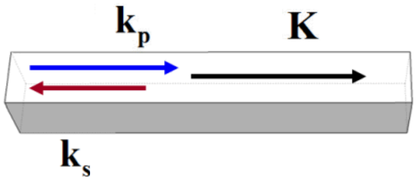
Velocity distribution

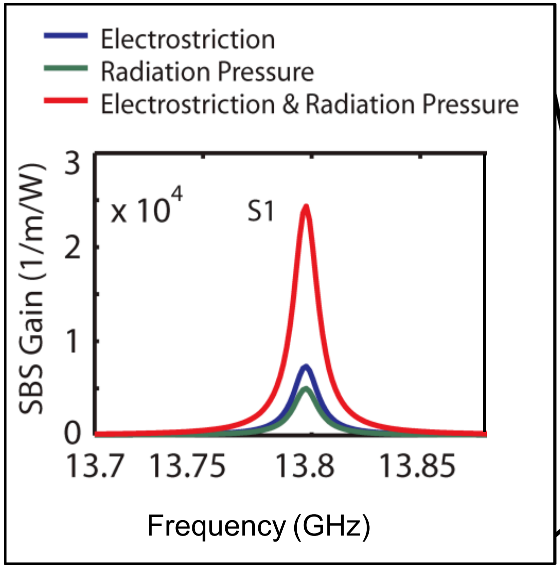


SBS Radically Enanced at Nanoscales:

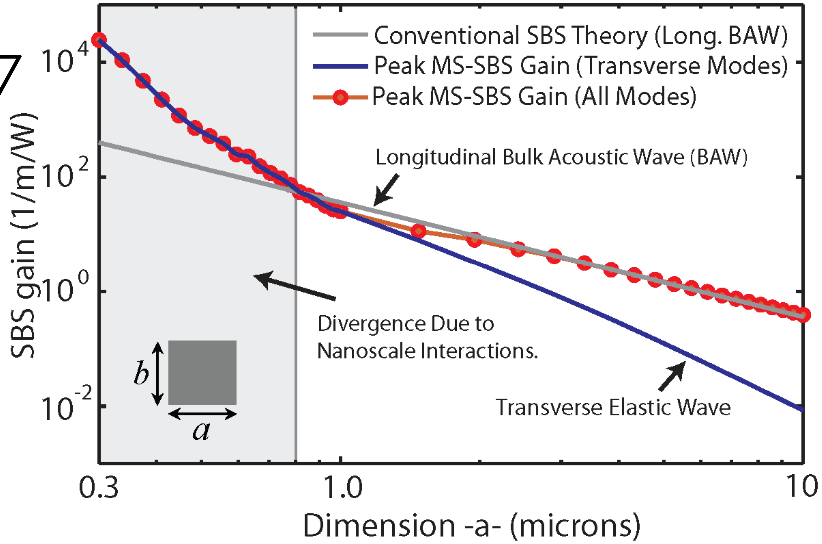
Nanoscale Stimulated Brillouin Scattering (SBS)

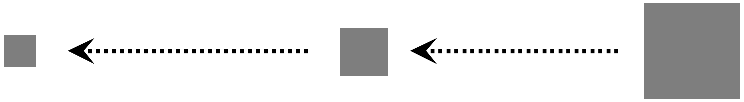






Photon-phonon coupling vs dimension.





Conventional Treatment of SBS.

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

Conventional theory:

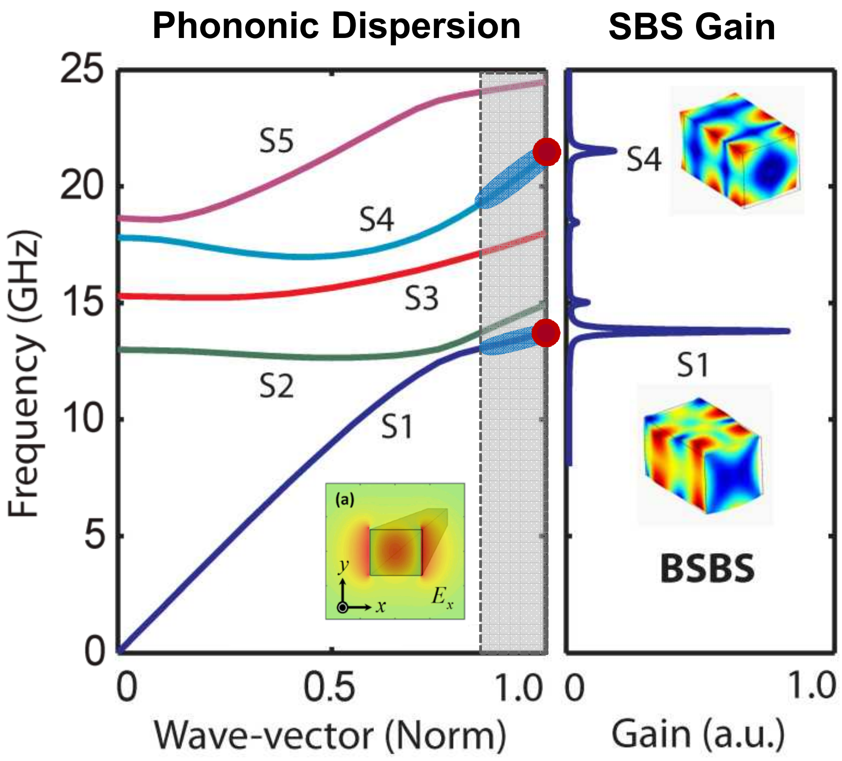
1. **Silicon material properties used.**
2. **Perfect agreement from 2-10 microns.**

Nanoscale SBS:

1. **For dimensions < 800nm, conventional SBS theory breaks down.**
2. **Rigorous model reveals 100x enhanced SBS at small dimensions.**

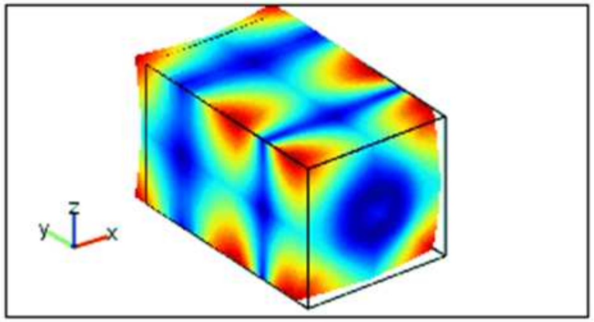
Coherent combination of electrostriction and radiation pressure produce further enhancement.

Nanoscale Backward-SBS: Tunable Phonon Emission.

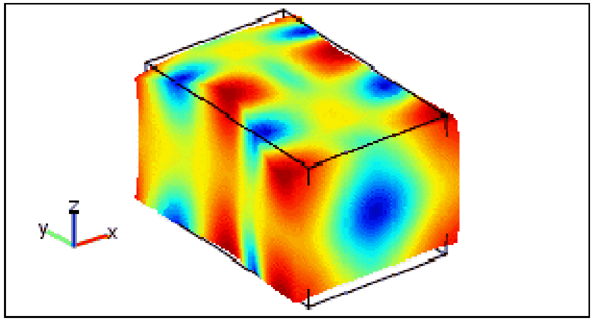


Nano-optomechanical backward-SBS:

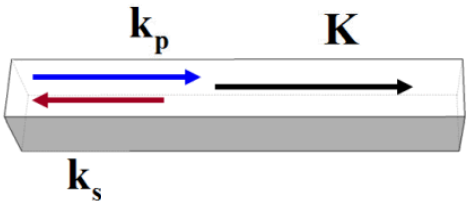
1. **Gain is 10^6 x Larger than in Fibers.**
2. **20% frequency tunable phonon emission.**



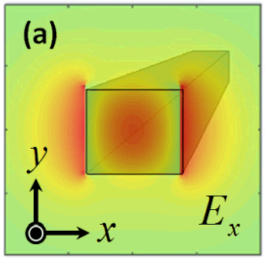
Excitation: 21.6 GHz Phonons



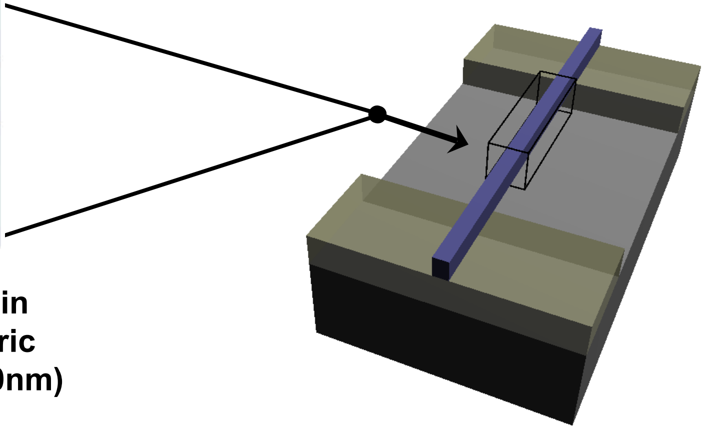
Excitation: 13.8 GHz Phonons



How Strong is SBS:

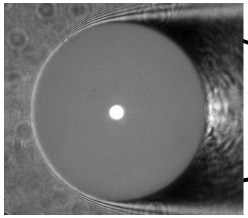


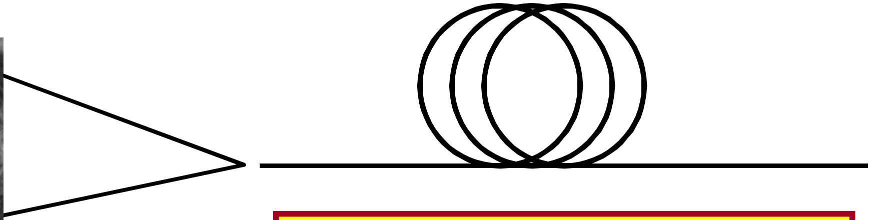
Guided mode within suspended dielectric waveguide. (300x300nm)



Suspended waveguide: L = 100 microns

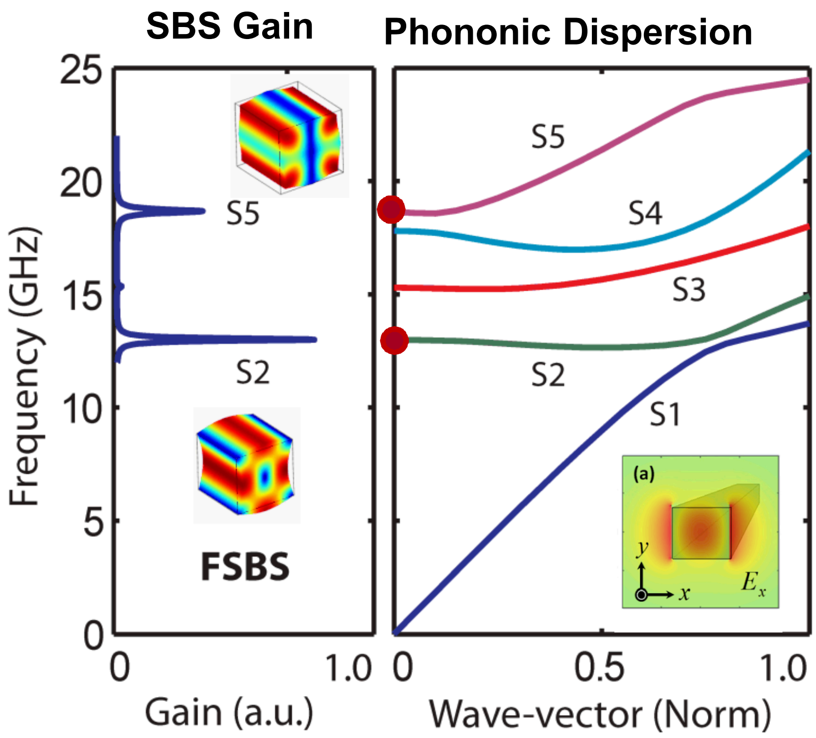
= SBS nonlinearity of 10-100 meters of fiber





Fiber optic: L = 10-100 meters

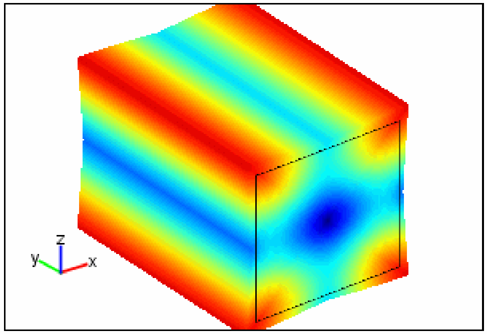
Forward-SBS: Fixed Frequency Resonances.



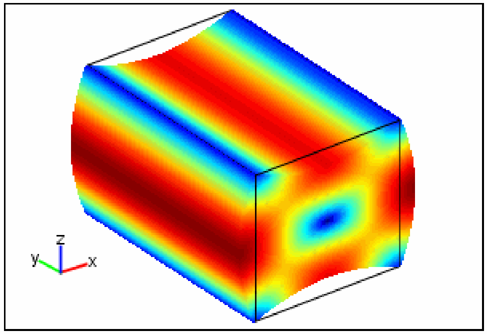
Nano-optomechanical Forward-SBS:

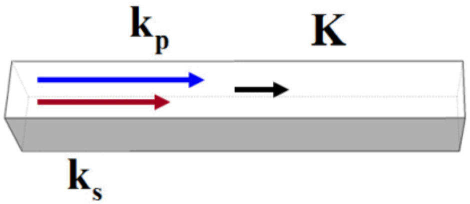
1. **Generally forbidden in guided wave-systems.**
2. **Ultra-low threshold parametric oscillation possible.**

Excitation: 18.6 GHz Phonons



Excitation: 13.0 GHz Phonons



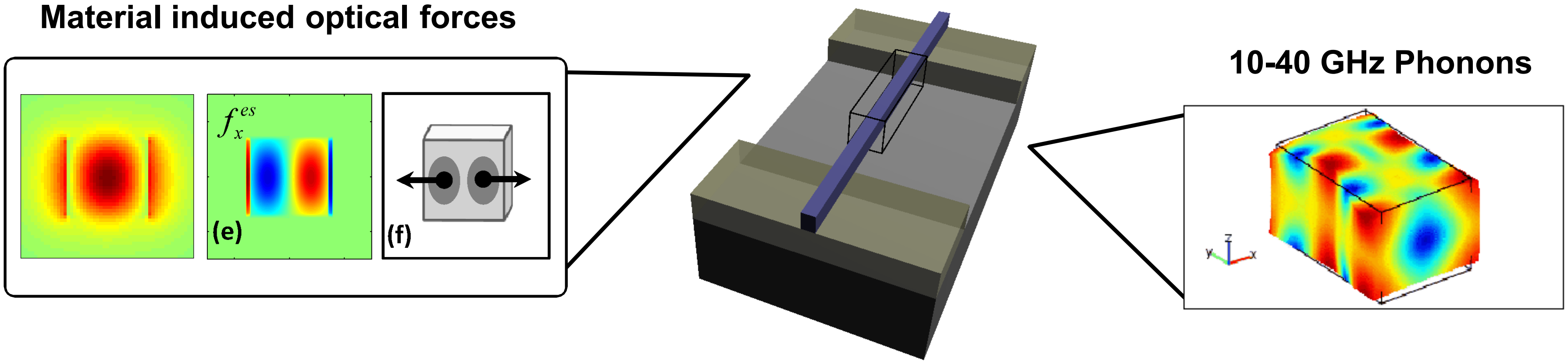


Conclusions:

Developed unified treatment of SBS at nanoscales:

1. Valid at any lengthscale (micro- to nano-scales).
2. Radically enhanced SBS processes found
   - ➔ Resulting from electrostriction & radiation pressure.
3. Forward SBS: Excitation of ultra-high frequency modes.
4. Backward SBS 1E6 x stronger than in fiber.
5. Important step towards highly tailorable chip-scale SBS.

"Giant Enhancement of Stimulated Brillouin Scattering at Nanoscales," P. Rakich, C. Reinke, R. Camacho, P. Davids, Z. Wang, (submission to PRL).



Material induced optical forces

10-40 GHz Phonons

Acknowledgments:

Special thanks:

Ihab El-kady, Troy Olsson, Milos Popovic

Funding Agencies:

DARPA—MTO (PMs: Mike Haney, Scott Rodgers, Jeff Rogers).

DOE—Laboratory Directed Research and Development funding.

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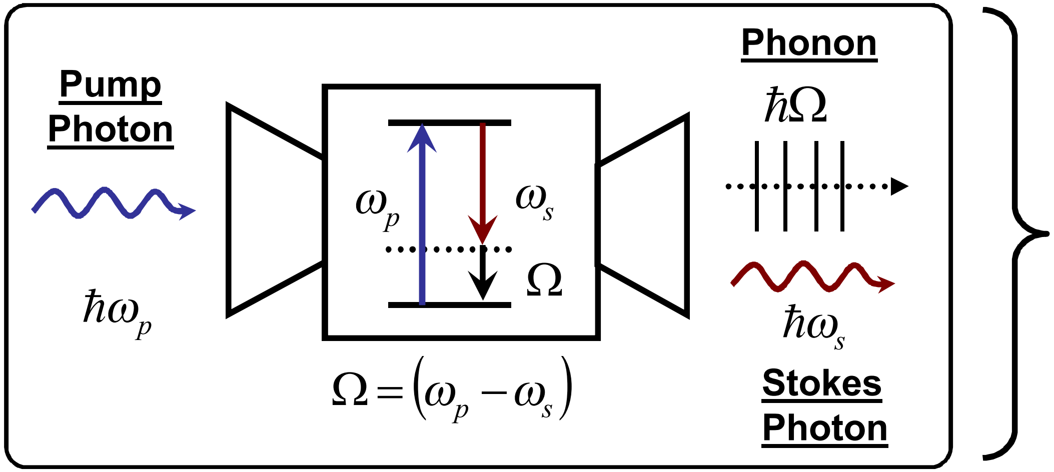
This work was supported in part by the office of the Director of Defense Research and Engineering under Air Force contract FA8721-05-C-0002.

Backup Slides Follow:

What is a Brillouin Process?

Brillouin Scattering Energy Level Diagram:



Pump Photon

$\hbar\omega_p$

ω_p ω_s Ω

$$\Omega = (\omega_p - \omega_s)$$

Phonon

$\hbar\Omega$

$\hbar\omega_s$

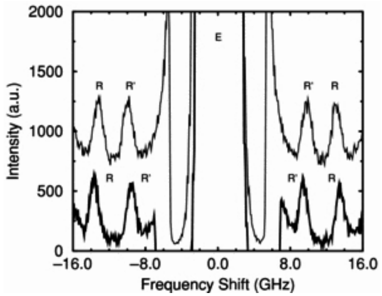
Stokes Photon

Brillouin Scattering:

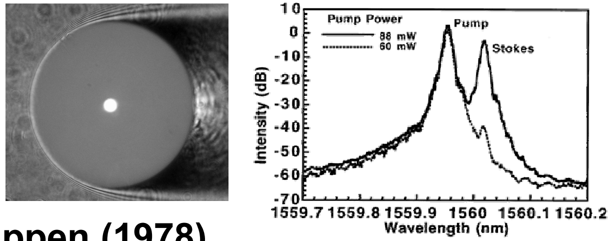
3^{rd} order Parametric process by which photons couple to acoustic phonons.

Bulk Media — Micro-Scales — Nano-Scales →

BLS in Bulk Media

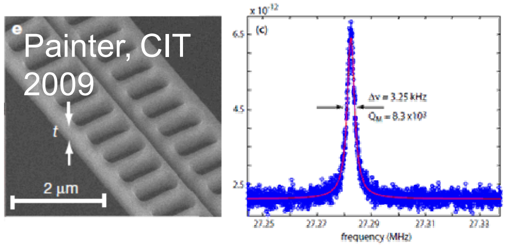


SBS bulk media and optical fibers



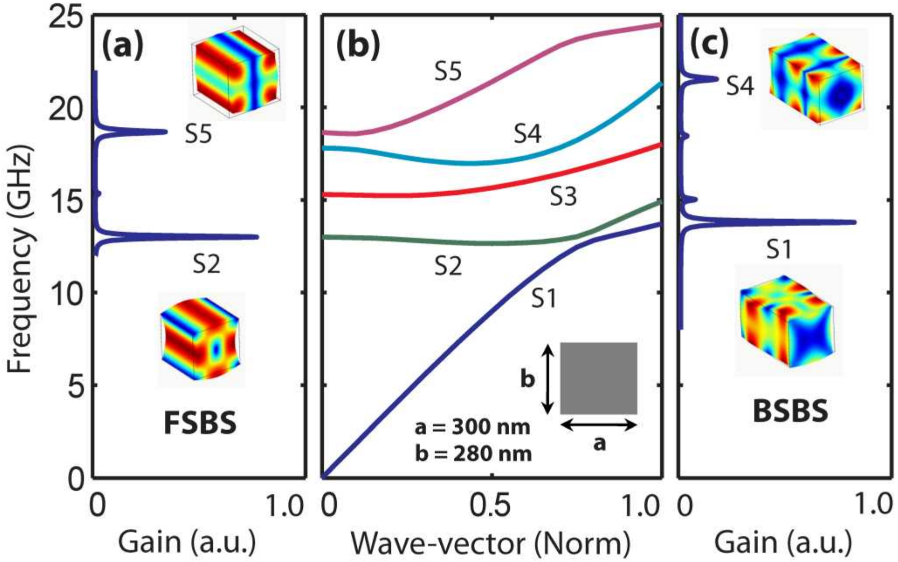
Ippen (1978)

Nano-scale SBS and BLS



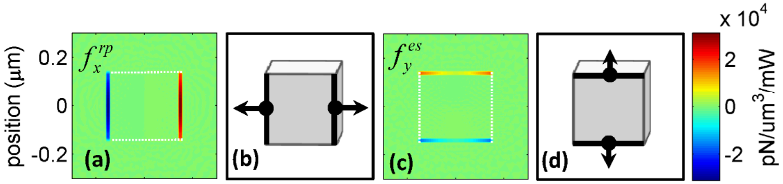
Painter (2009)

Contributions of Different Forces at Nanoscales:

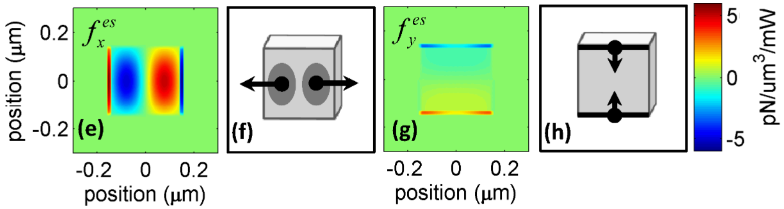


SBS Gain **Phononic Dispersion** **SBS Gain**

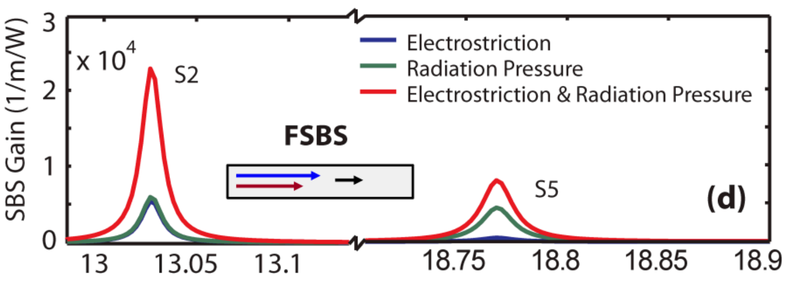
Radiation Pressure:



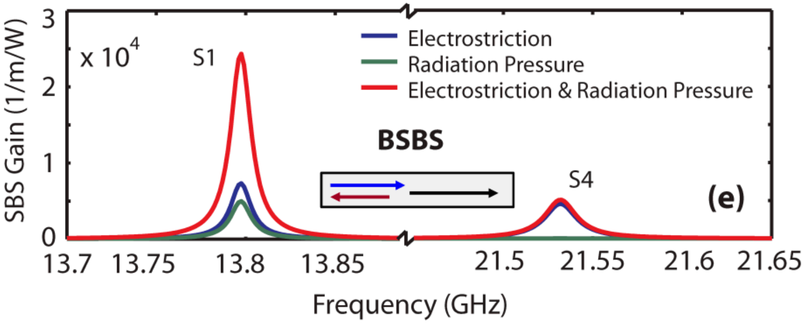
Electrostriction:



Forward SBS (FSBS):

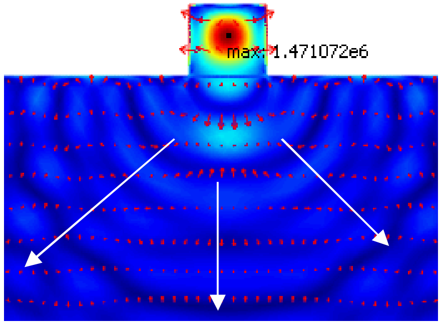


Backward SBS (BSBS):



SBS in Silicon Photonics?

Transduced Waves:

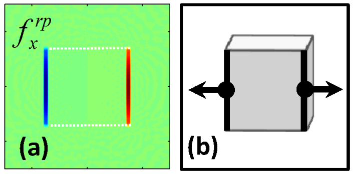


Canonical Treatment of SBS is not valid for Si waveguides!

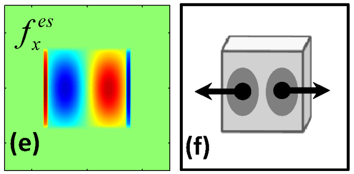
What's Different?

- **Elastic Wave Leakage:**
  - **➔Makes SBS extremely weak.**
- **Must treat combination of:**
  1. **Radiation Pressure**
  2. **Electrostriction**

Radiation Pressure



Electrostrictive forces

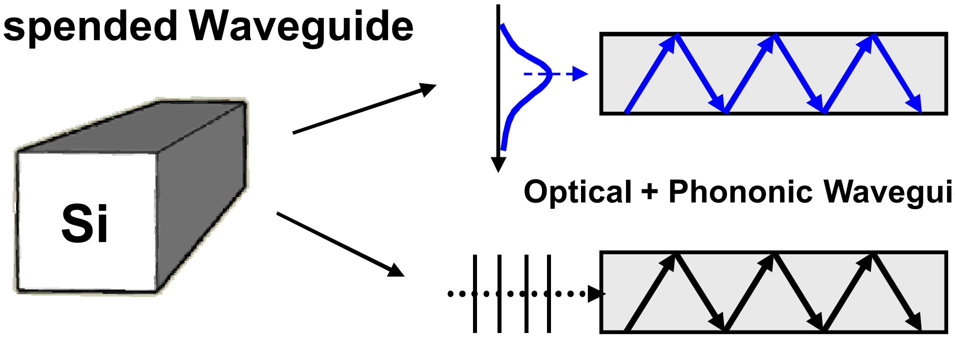


Simplest Way to Control Photons and Phonons for Enhanced SBS:

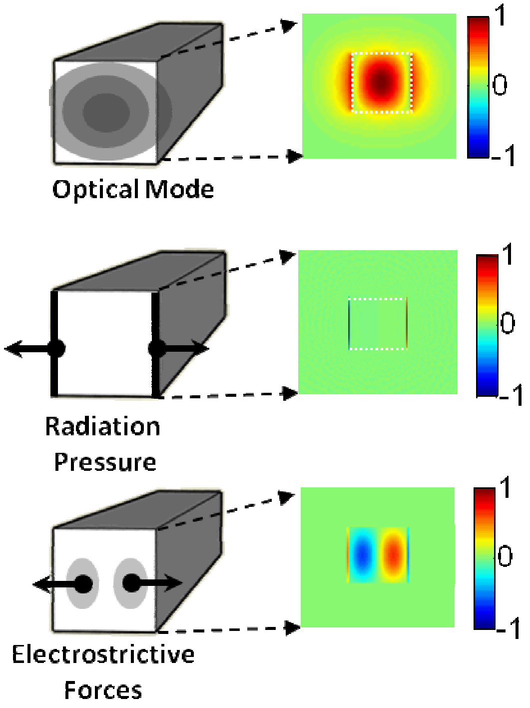
Nano-wire Supports:

- **Guided *Optical Wave***
- **Guided *Elastic Wave***

Suspended Waveguide



Nanoscales: The Neglected Optical Force Dominates!



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

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

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 man-hole cover

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

Stresses Approach Material Yield Strength

Significance of LDRD: Big Picture & Impact.

<u>LDRD: Goals</u>

1. Advance science of nanoscale optical forces & transduction.
2. Explore technological impact & potential benefits to DOE mission.

<u>Physical Optics & Optomechanics:</u>

1. Origins of nanoscale optical forces.
    a. Effect of geometry and material.
    b. Effective medium properties.
2. Radically new stimulated phonon emission mechanisms at nanoscales.

<u>Heat Transport & Ultrafast Science:</u>

1. Stimulated Mach-wave emission enables:
    a. Phononic pump probe experiments
    b. Phonon transport & lifetimes.
    c. Phonon dispersion & bandgaps meas.
    d. Mechanical properties of media.

<u>Theory & Modeling:</u>

1. Multi-scale models of photon-phonon coupling (micro- and nano-scales).
2. Powerful new formalisms for optical forces.
3. Novel scaling laws for optical forces with nanoscale geometry and material

<u>Novel Devices & Applications:</u>

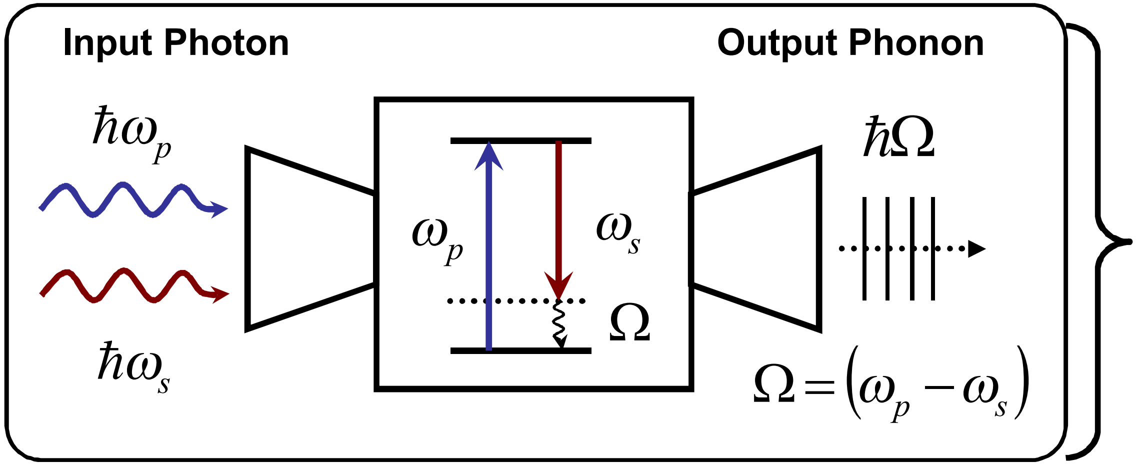
1. Ultra-broadband chip-scale delays.
2. Pulsed phonon lasers & frequency combs.
3. Tunable ultrahigh frequency oscillators.
4. Sensors and microphones.
5. Phonon amplifiers and modulators.
6. Ultra-broadband acousto-optics… etc.

<u>Fabrication & Metrology:</u>

1. Unique and general experimental platform for study of optical forces & photon-phonon coupling.
2. First-in-class methods for ultrafast pump probe studies of phononic effective media.
3. First-in-class Brillouin scattering measurements.

How are Phonons (acoustic waves) Generated by Light?

Physics of stimulated phonon generation:

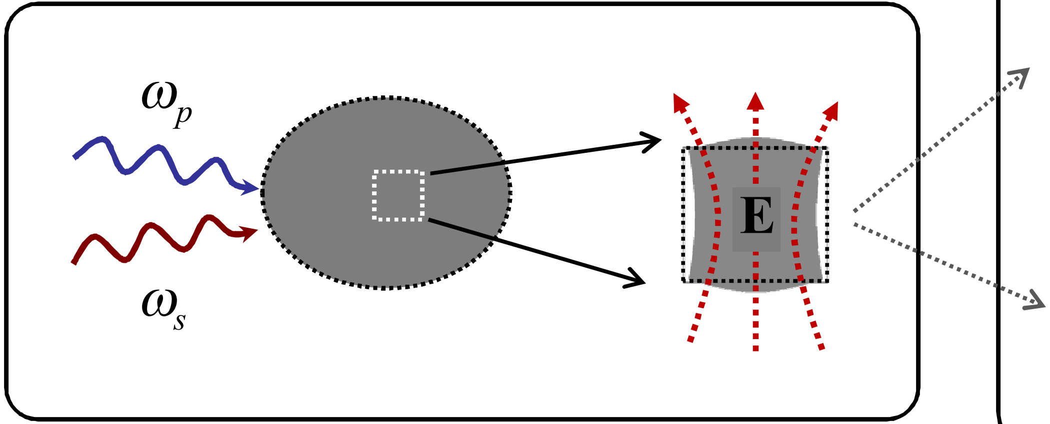


$$\Omega = \left(\omega_p - \omega_s\right)$$

<u>Stimulated Brillouin Scattering (SBS)</u>

Describes all optomechanical photon-phonon coupling processes (including cavity optomechanics).

Micro-scale origins of parametric process:



Interference yields intensity “Beat Note”.

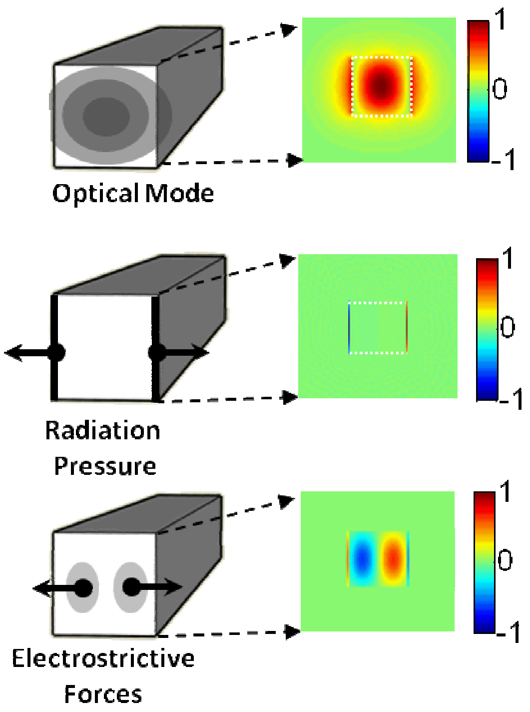
$$|E(t)|^2 = 2E_pE_s \cdot \cos(\Omega \cdot t) + C$$

Optical Force: Proportional to Intensity.

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

Time Varying Forces Transduce Phonon.

Optical Forces at Nano-scales



Forces produced by two Effects:

1. Radiation Pressure

2. Electrostriction

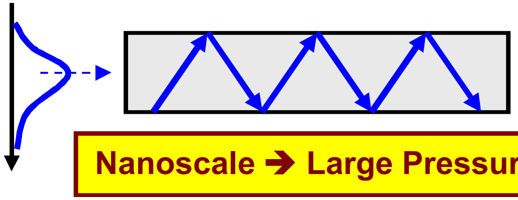
Both Scale to large values with nanometer-scale optical confinement (e.g. 10^4 N/m^2)

Radiation Pressure Generally VERY Small: Not Any More.

Photon momentum

$$p = \hbar k$$

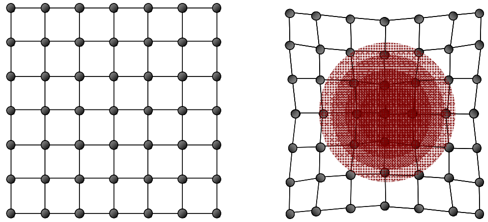
Radiation Pressure



Nanoscale → Large Pressure

Pressure increases to 10^4 N/m^2 in nanoscale waveguides.

Electrostrictive forces → Material induced forces



Akin to piezoelectricity

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

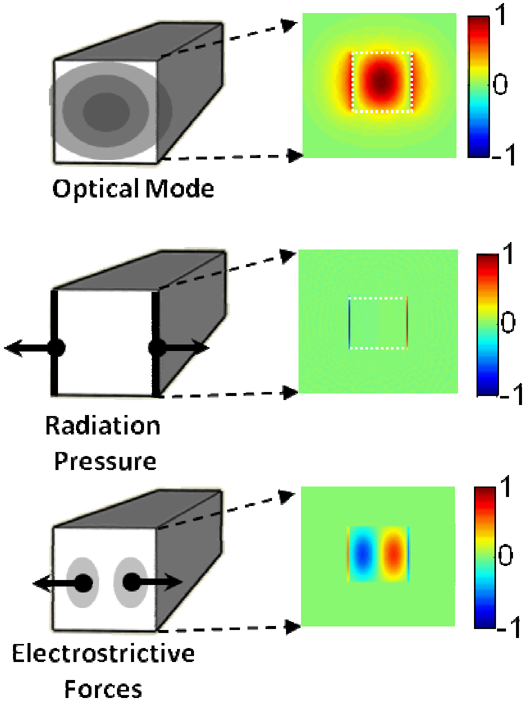
Strain

Piezo Coeff.

Electrostrictive Coeff.

Electrostriction = Material induced optical forces.
- **All dielectrics exhibit electrostriction (not piezo electricity).**
- **Sign and magnitude are tailorable by choice of material.**
- ***We are the first to treat electrostriction in nano-scale systems.***

Nanoscales: The Neglected Optical Force Dominates!



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

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 man-hole cover

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

Stresses Approach Material Yield Strength

Historical Introduction to Optical Forces:

The concept of light induced motion has a very rich history:

- **Timeline for Radiation Pressure:**

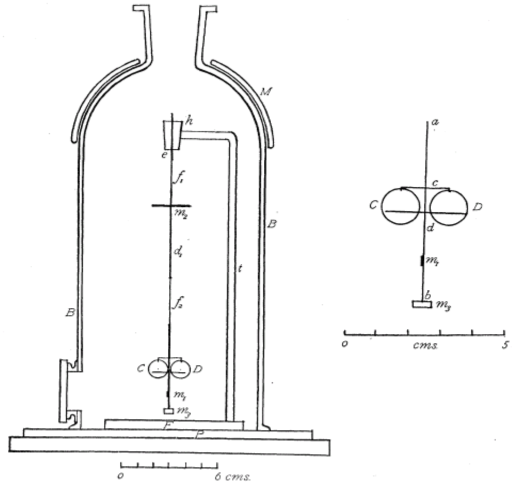
  (1619) Kepler: Speculated solar repulsion.

  (1873) Maxwell: Theoretical basis for pressure.

  (1901) Lebedew, Nichols: Experimental evidence.

- **Optical Forces:** ***Very difficult to observe.***
  (60 Watt lamp → Force ≈ 400nN)

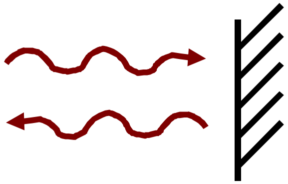
- **First observation: Thermal lamp & torsion balance**



Lebedev, P. (1901).

Photon momentum:

$$|p| = \hbar k$$



Imparted momentum:

$$|\Delta p| = 2\hbar \cdot k$$

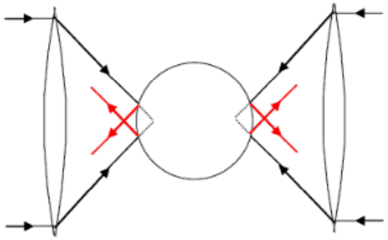
Radiation Pressure: Produced by photon recoil.

1. Nichols, E. F. & Hull, G. F. *Phys. Rev.* 13, 307–320 (1901).
2. Maxwell, J. C. *A Treatise on Electricity and Magnetism* (1873).
3. Lebedev, P. *Ann. Phys. (Leipz.)* 6, 433–458 (1901).

More Recent Work Involving Optical Forces:

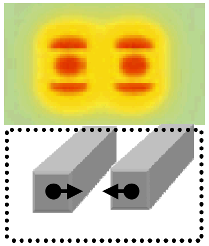
- (1970s) Optical tweezers: Trapping small of particles (Power = 50 mW, Force ≈ 50 pN)
- (1970s) Coherent phonon generation in fiber.
- (1980s) Free-space Interferometers: Optical Bistability (Power = 100 mW, Force ≈ 650 pN)
- (1990s) Laser Trapping and Cooling: Atoms
- (2000s) Nano-scale actuation with light and optically driven parametric oscillation.

Optical Tweezers:



Ashkin 1970

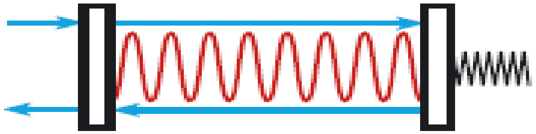
Symmetric



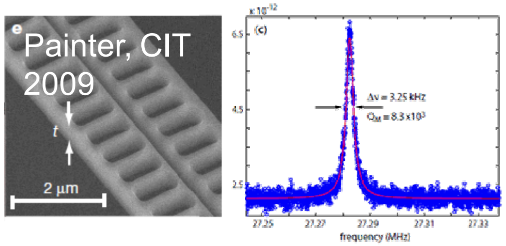
Optical force

Povinelli, (2005).

Cavity Optomechanics



Walther 1983

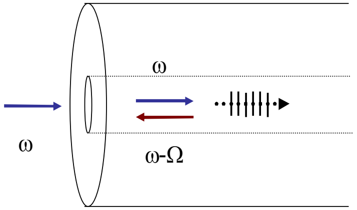


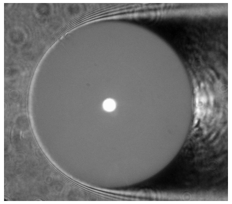
Painter (2009)

High fidelity "tuning-fork"

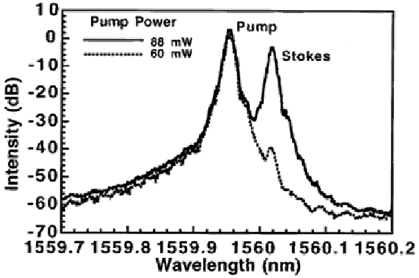
Broadband phonon emitter

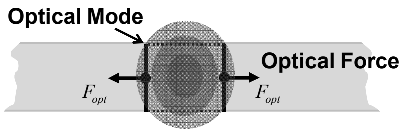
Stimulated Brillouin Scattering

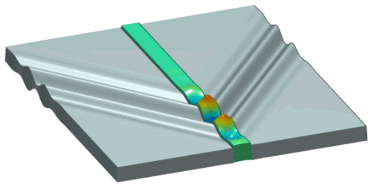




Ippen (1978)

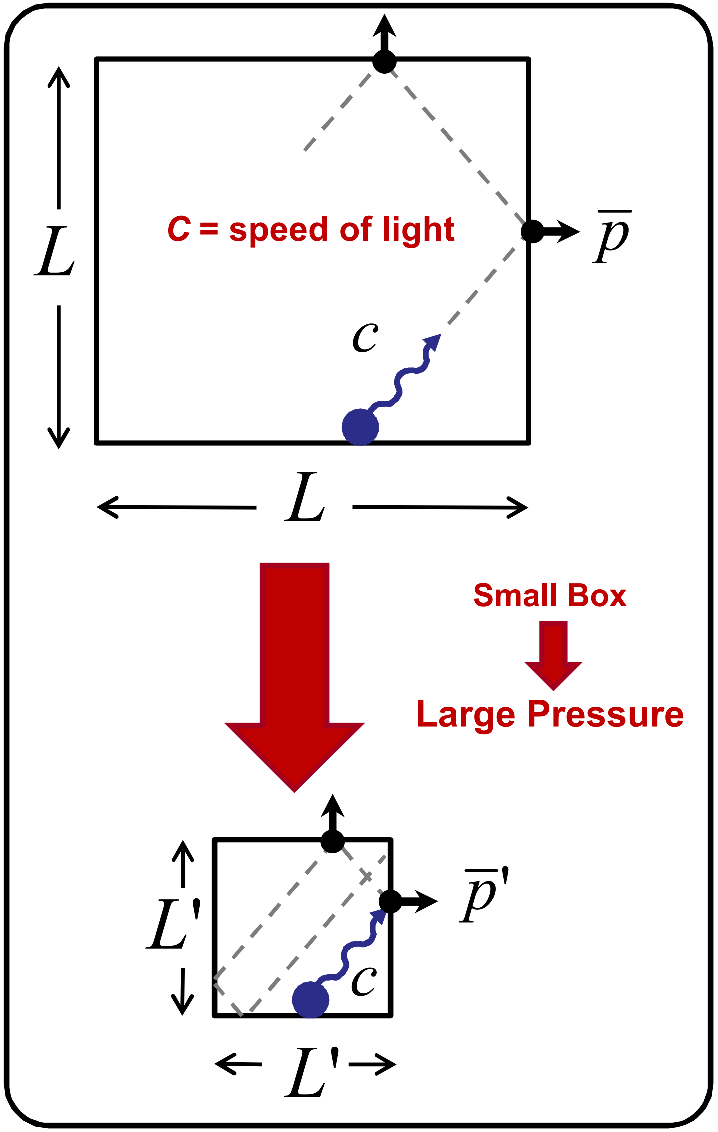






Sandia (2011)

Radiation Pressure at Nano-scales



Atomic Gas:

Volume Energy

$$\boxed{\bar{p}V = N\cdot \overbrace{k_B T}^{\text{Energy}}}$$

\# of atoms

pressure

Photon Gas:

Photon Energy

$$\boxed{\bar{p}V = \frac{1}{3}\cdot N\cdot \overbrace{\hbar\omega}^{\text{Photon Energy}}}$$

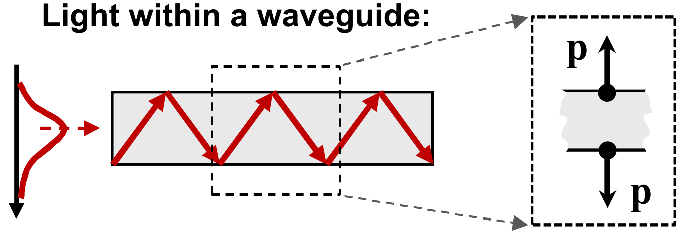
\# of photons

Pressure Per Photon:

$$\boxed{\bar{p} = \frac{1}{3}\cdot\frac{\hbar\omega}{V} = \frac{1}{3}\cdot\frac{\hbar\omega}{L^3}}$$

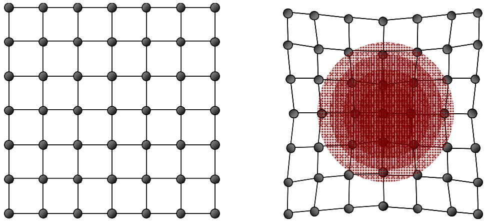
For L/L’ = 1000, p’/p = 1,000,000,000.

Light within a waveguide:



Same Idea holds within a waveguide.

Optical Forces Within Dielectric Media



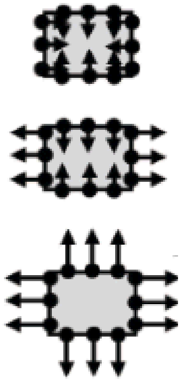
$$S = \alpha \cdot E_i + \beta \cdot E_i E_j$$

Strain

Piezo Coeff.

Electrostrictive Coeff.

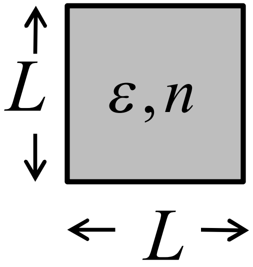
Electrostriction = Material induced optical forces.
- **All dielectrics exhibit electrostriction (not piezo electricity).**
- **Sign and magnitude are tailorable by choice of material**



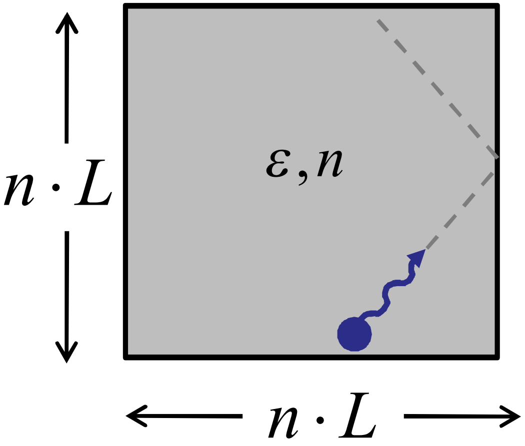
Electrostriciton: possible force distributions.

What's going on?

Box: Real Space



Box: Photon's Perspective



From Photon's Perspective:

- **Space is now quite different.**

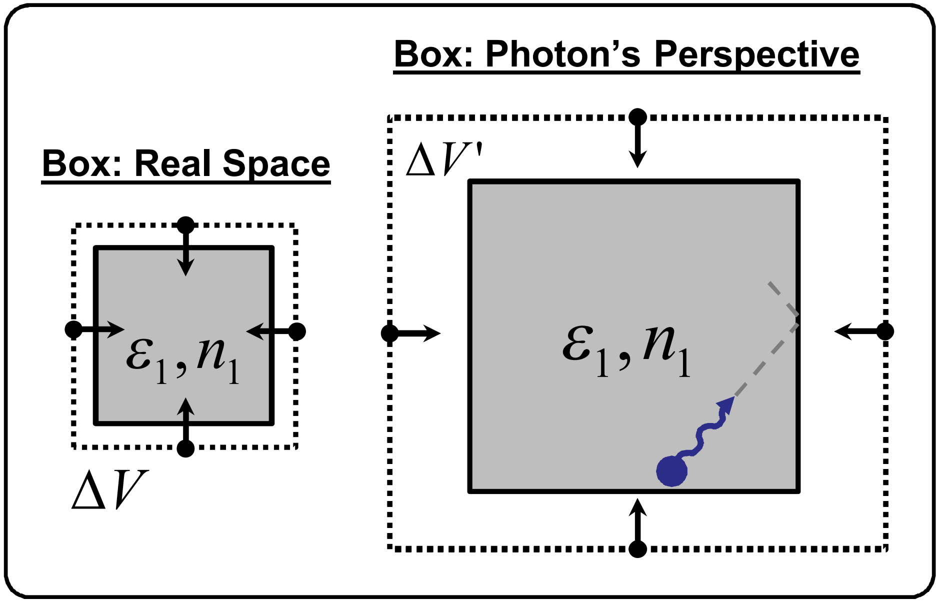
$$\boxed{V \Rightarrow V \cdot n^3}$$

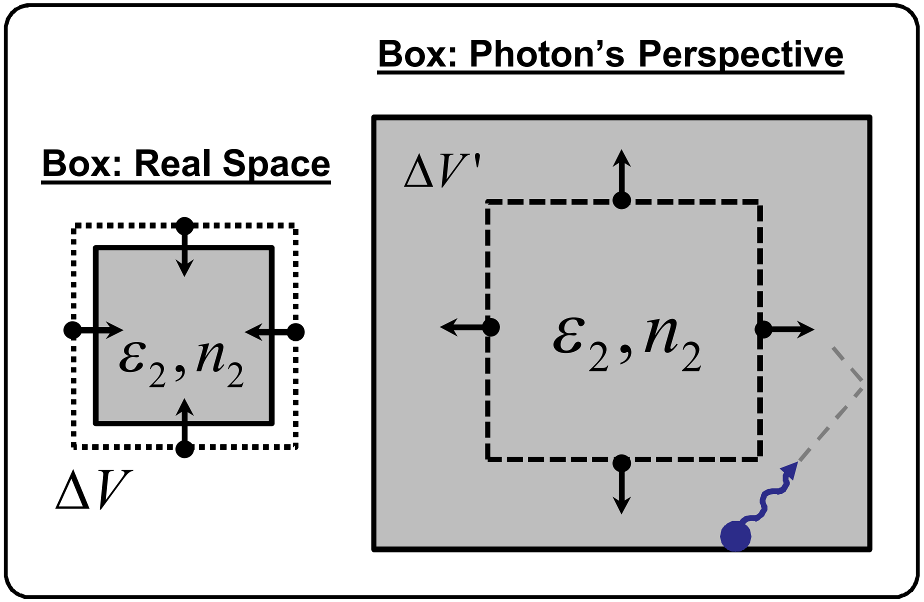
Box seems much bigger.

Oddities don't end here…

Electrostriction: Material Induced Forces

Since $\partial n/\partial V \neq 0$, distortion of the box is perceived quite differently by a photon:





Photon gas within a dielectric:

$$\Delta V' \Rightarrow n^3 \Delta V + 3n^2 V \cdot \left(\boxed{\frac{\partial n}{\partial V}} \right) \cdot \Delta V$$

Correction due to dynamic response

Photon gas within a dielectric:

$$\bar{p} = \frac{1}{3} \cdot \frac{N \cdot \hbar\omega}{V} \left[1 + \frac{3}{n} \boxed{\frac{\partial n}{\partial V}} \right]$$

Electrostriction