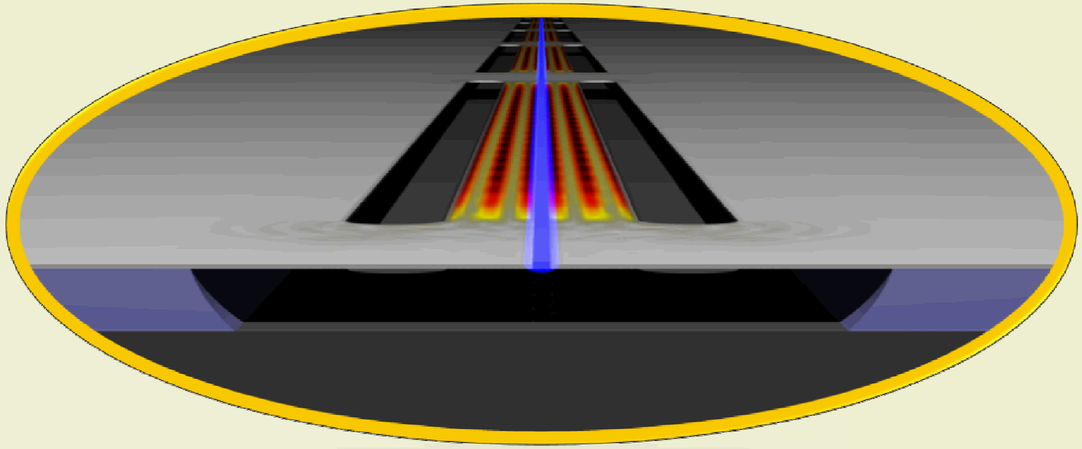
SAND2013-4838C



Stimulated Brillouin Scattering in silicon nano-photonics

Heedeuk Shin[1, 2], Wenjun Qiu[3], Robert Jarecki[2], Jonathan Cox[2]
Roy Olsson III[2], Andrew Starbuck[2], Zheng Wang[4], Peter Rakich[1]

1 Yale
2 Sandia National Laboratories
3 MIT
4 The University of Texas at Austin

What is stimulated Brillouin scattering?

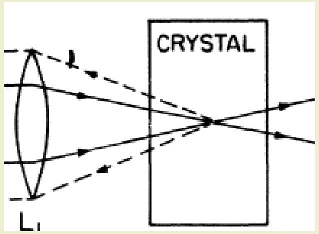
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Milestones in stimulated Brillouin scattering

Stimulated Brillouin scattering (SBS)

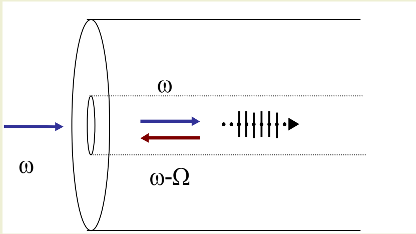
- Slow-/fast-light, long distance sensing applications, generation of GHz phonons, lasing and amplification, isolator, etc.

SBS in Bulk X-tal



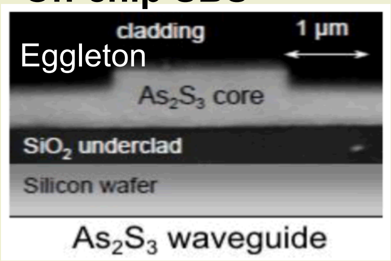
Chiao, et al., Phys. Rev. Lett. **12**, 592 (1964)

SBS in Optical Fibers

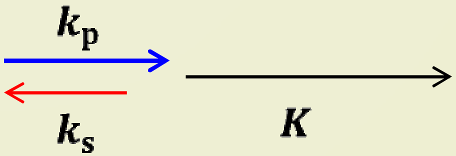


Ippen and Stolen, Appl. Phys. Lett. **21**, 539 (1972)

On-chip SBS

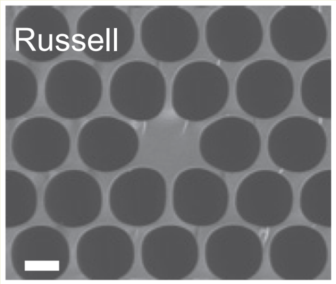


Pant, et al., Opt. Express **19**, 8285 (2011)

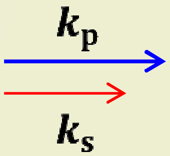


$$K = k_p - k_s \sim 2k$$

Strong forward SBS



Kang, et al., Nature Phys. **5**, 276 (2009)



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

- Structure dependent resonant frequency
- Cascaded higher modes

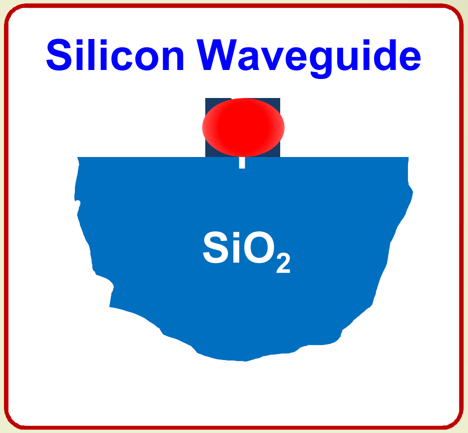
Why is SBS in silicon waveguide is important?

Why SBS in silicon waveguide?

Low cost and compatibility with CMOS technologies.

Nonlinear Effects in silicon waveguides

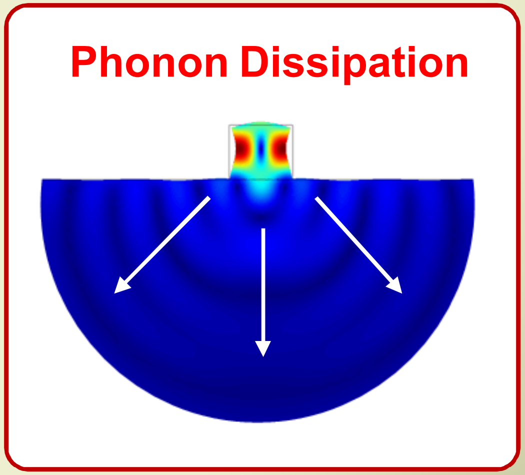
- *Re*{$\chi^{(3)}$}: Self-Phase Modulation, Cross-Phase Modulation, Four-Wave Mixing
- *Im*{$\chi^{(3)}$}: Two-Photon Absorption, Stimulated Raman Scattering
- Two-photon absorption induced Free Carrier effect ($\chi^{(5)}$)



Lin, et al., Opt. Express **15**, 16604 (2007), Leuthold, et al., Nature Photon. **4**, 535 (2010)

Why did we have hard time to observe SBS in silicon photonics?

- Strong **confinement** of both photons and phonons
- Good **overlap** between photon and phonon modes
- Strong **optical forces**

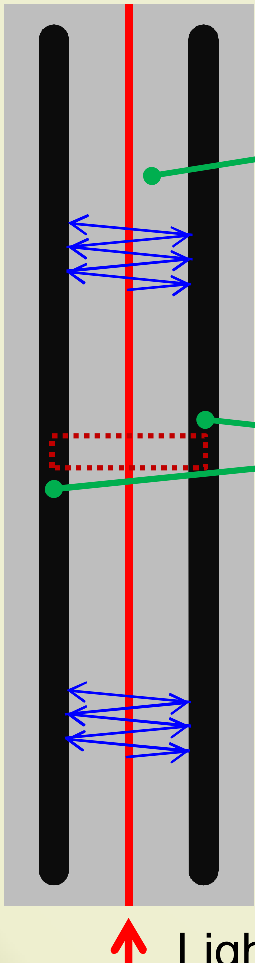


Tailorable stimulated Brillouin scattering at nanoscale silicon waveguides,
Shin, Qiu, Jarecki, Cox, Olsson III, Starbuck, Wang, Rakich
Nature Comm. 4, 1944 (2013).

How did we demonstrate SBS in silicon waveguide?

How did we demonstrate SBS in silicon?

Brillouin Active Membrane (BAM) waveguide

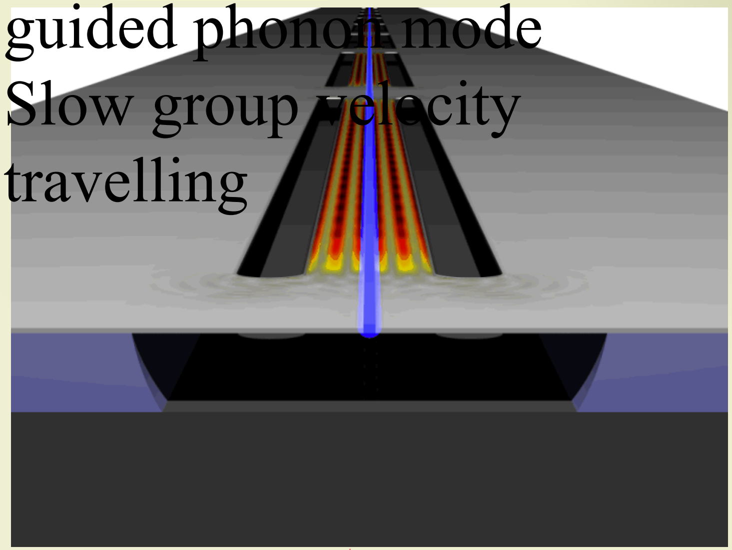


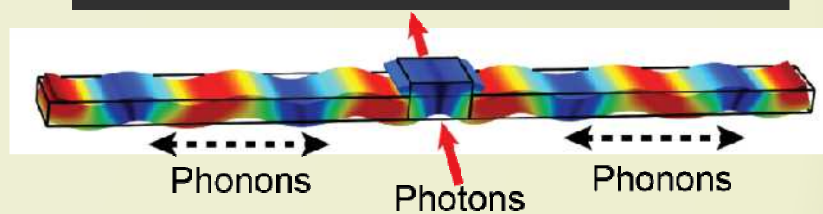
Si_3N_4 membrane acts as conduit for phonons.

Air slots

Each slot acts as a wideband phonon mirror.

Excellent phononic resonances over wide range of frequency.

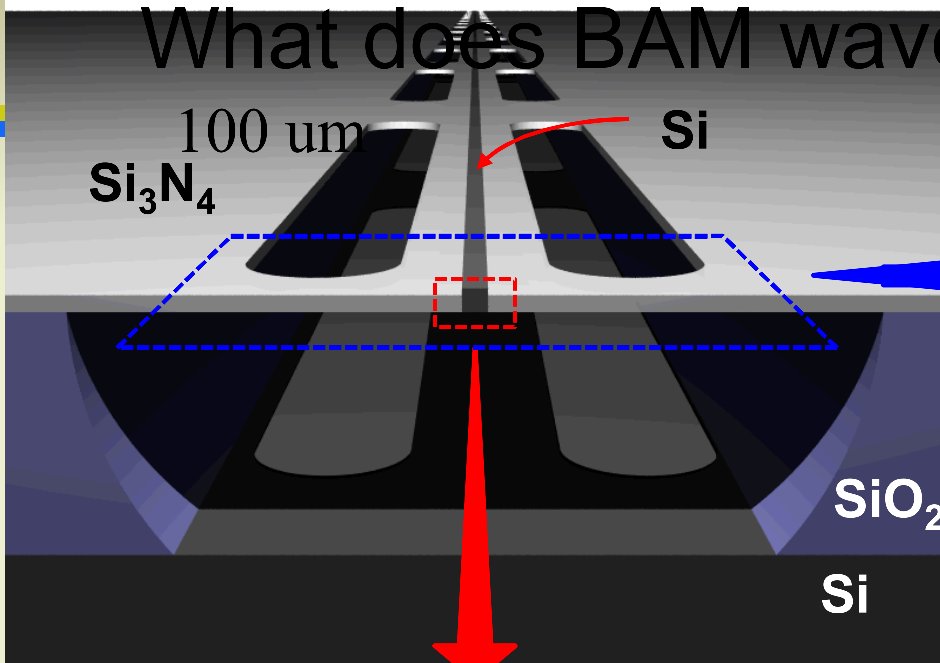


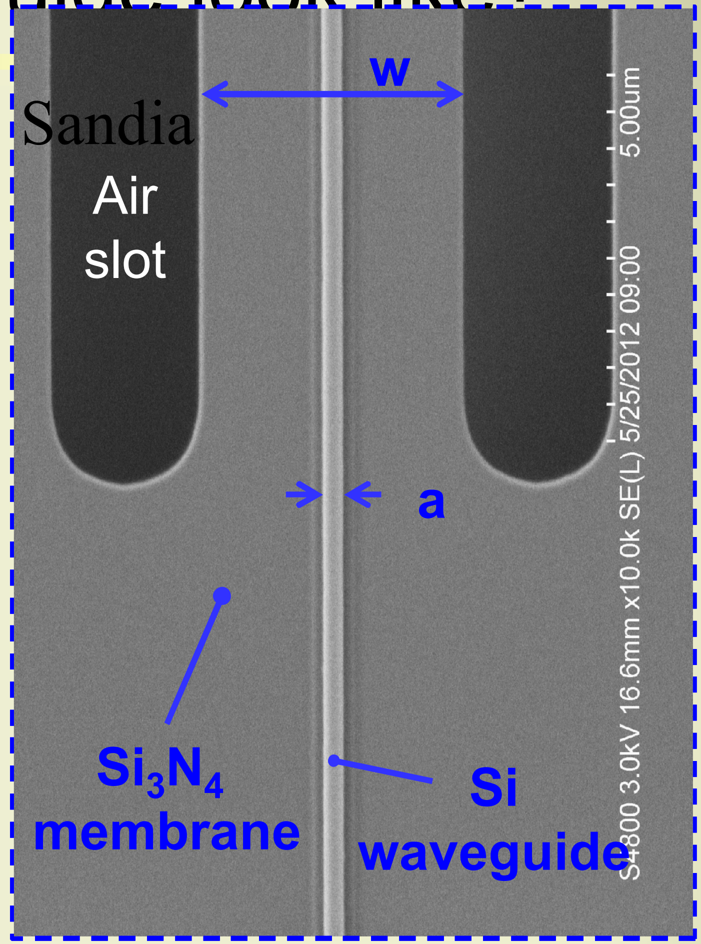


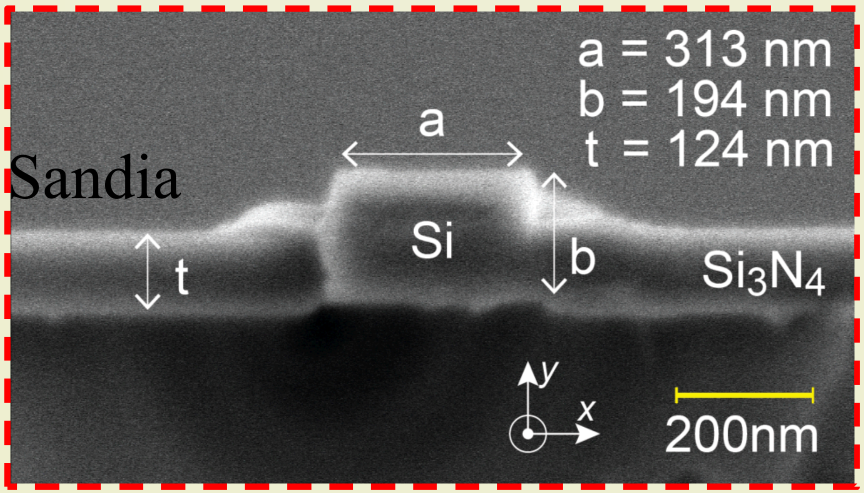
- Strong photon-phonon interaction
- Structure dependent resonant frequency
- Free control of phonon structure while optimizing photon waveguide

What does our fabricated structure look like in real?

What does BAM waveguide look like?





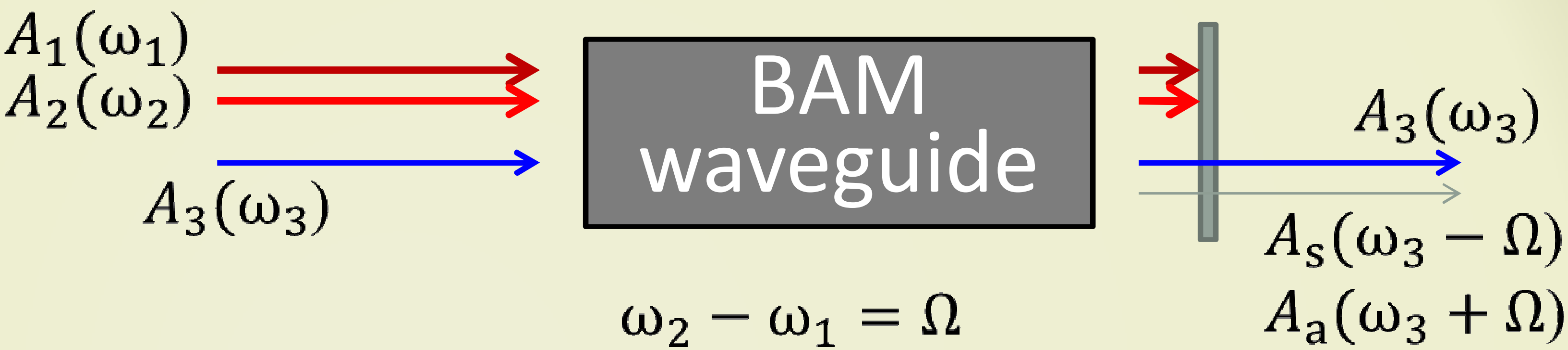


Length pitch

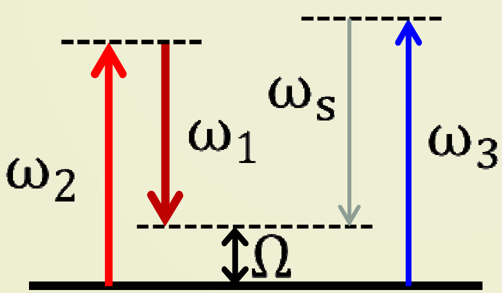
Brillouin active section

Here is our device. Then how can we measure SBS nonlinearity?

How do we measure Brillouin nonlinearity?



TE-like waveguide mode



- Two-color pump-probe technique
- Two pump fields and a probe field
- Beating between two pump fields excites phonons in silicon waveguide.
- Phonons impart a phase shift on the probe field.
- Nonlinear phase shift is detected through heterodyne interferemetry.
- SBS coherently interfere with Kerr effect and free-carrier effect.

How does this show up in our nonlinear measurement?

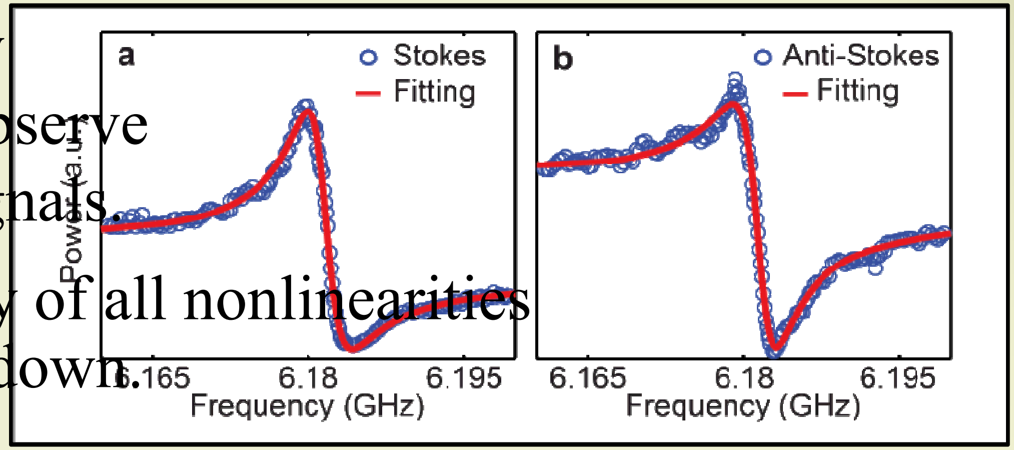
Shin, et al., Nature Comm. **4**, 1944 (2013)

What does SBS signal look like?

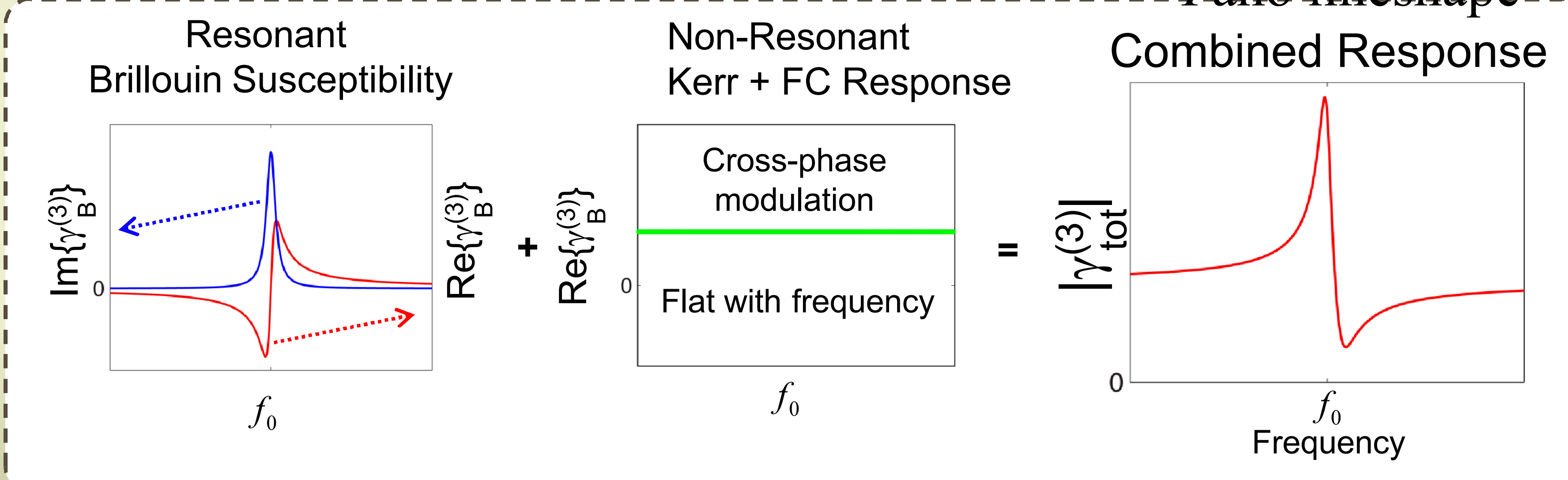
Heterodyne interfermetry allows us to separately observe stokes and anti-stokes signals.

Shows Coherent interplay of all nonlinearities

Break the nonlinearities down.



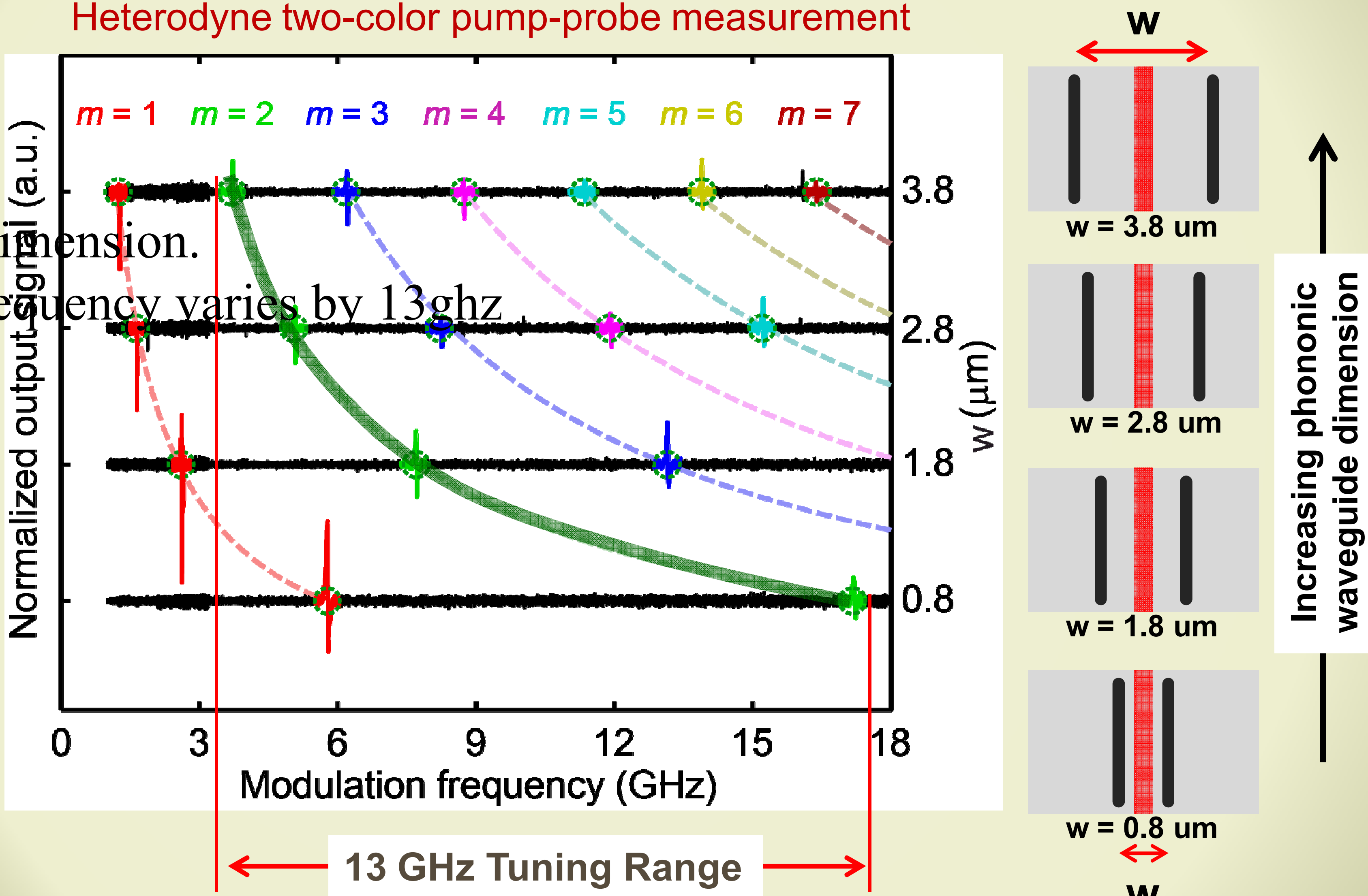
Fano lineshape



icially engineered Sharp lorentzian shape + non-resonant kerr yield fano li

Can Brillouin susceptibility be engineered?

Heterodyne two-color pump-probe measurement



e dimension.

frequency varies by 13ghz

Shin, et al., Nature Comm. 4, 1944 (2013)

What level of amplification can be

Yale

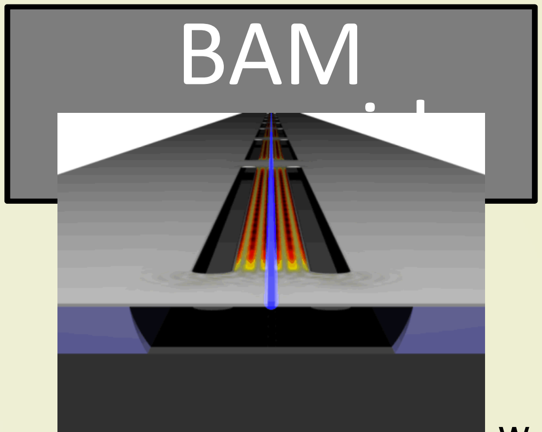
6/17/2013

CLEO 2013

How about SBS gain or depletion?

y transferpump

signal



Amplified signal

w = 0.8 mm

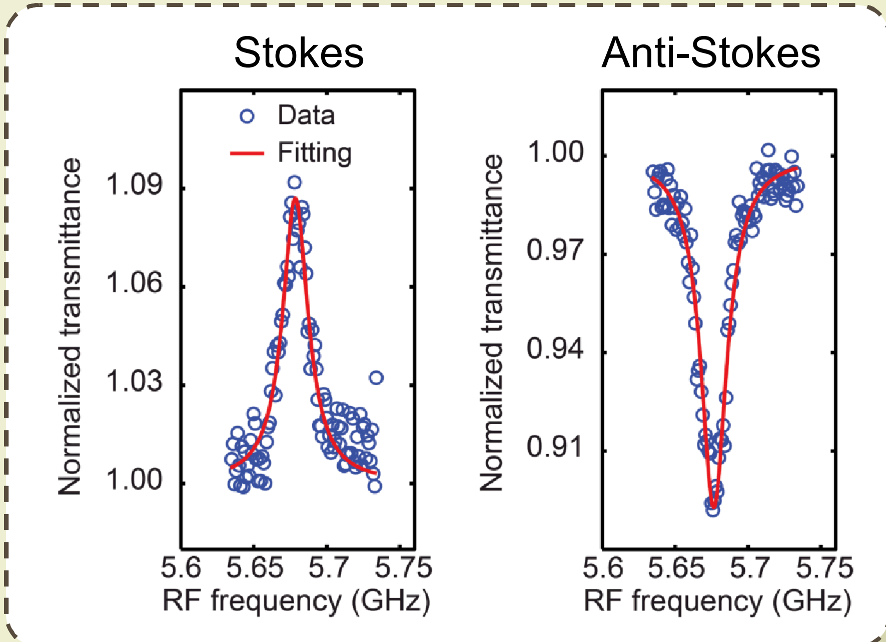
Coupling efficiency: ~ 8 dB / facet

Propagation loss: ~ 7 dB/cm

Pump power: ~ 20 mW

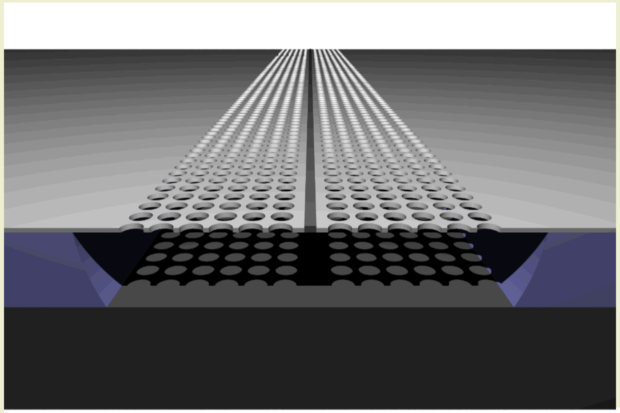
Effective length: ~ 2.1 mm

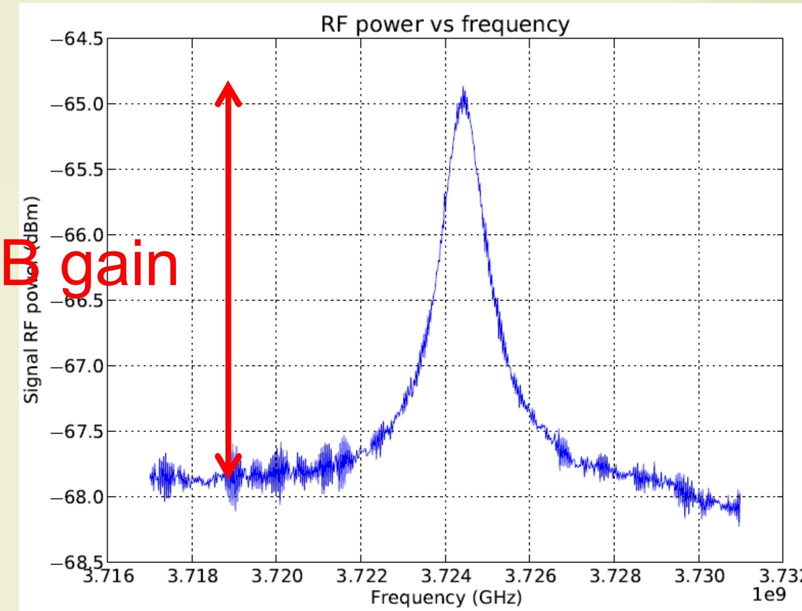
Gain coefficient: ~ 2800 $W^{-1}m^{-1}$



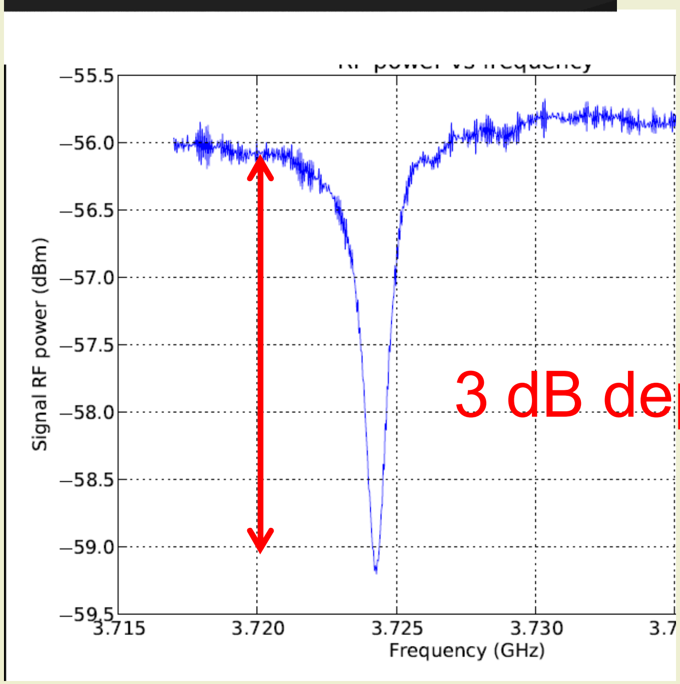
Shin, et al., Nature Comm. **4**, 1944 (2013)

Can we enhance the gain?





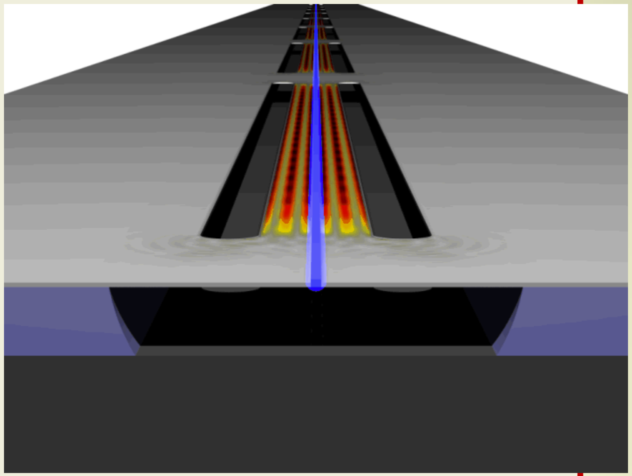
3 dB gain



3 dB depletion

Conclusion

- First-ever demonstration *chip-scale* Forward Stimulated Brillouin Scattering (SBS) in silicon waveguides.
- 1,000 times stronger SBS than any known forward SBS system.
- Tailorable nonlinear effects from 1 GHz – 24 GHz.
- Analysis of the coherent interference of Kerr, free-carrier, and SBS nonlinearities.
- Unprecedented tailorability of phononic resonances.



Tailorable stimulated Brillouin scattering at nanoscale silicon waveguides, H. Shin, etc. Nature Comm. 4, 1944 (2013).

Yale

Sandia National Laboratories

UT ECE

Peter Rakich

Heedeuk Shin

- Device Design
- Experimental Studies

Jonathan Cox

Ryan Camacho

Heedeuk Shin

Rob Jarecki

- Device Fabrication
- Experimental Studies

Zheng Wang

Marin Soljacic

Wenjun Qiu

- Multi-Physics Modeling
- Nonlinear Dynamics

- Sandia Laboratory is operated by Sandia Co., a Lockheed Martin Company, for the U.S. Department of Energy's NNSA under Contract No. DE-AC04- 94AL85000. This work was supported by the DDRE under Air Force Contract No. FA8721-05-C-000, the MesoDynamic Architectures program at **DARPA** under the direction of Dr. Jeffrey L. Rogers, and Sandia's Laboratory Directed Research and Development program under Dr. Wahid Hermina.

Thank you

- Dr. Heedeuk Shin

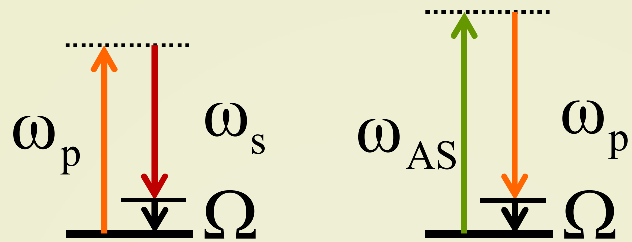
  - heedeuk.shin@gmail.com

- Prof. Peter T. Rakich

  - peter.rakich@yale.edu

Stimulated Brillouin scattering (SBS)

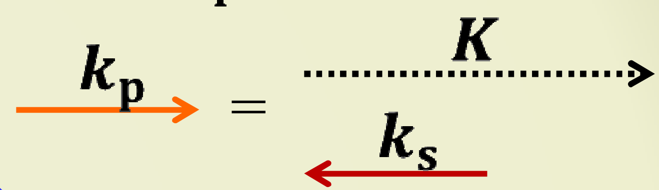
- **Scattering of light from acoustic waves.**



Stokes SBS

Anti-Stokes SBS

$$\mathbf{k}_p = \mathbf{k}_s + \mathbf{K}$$

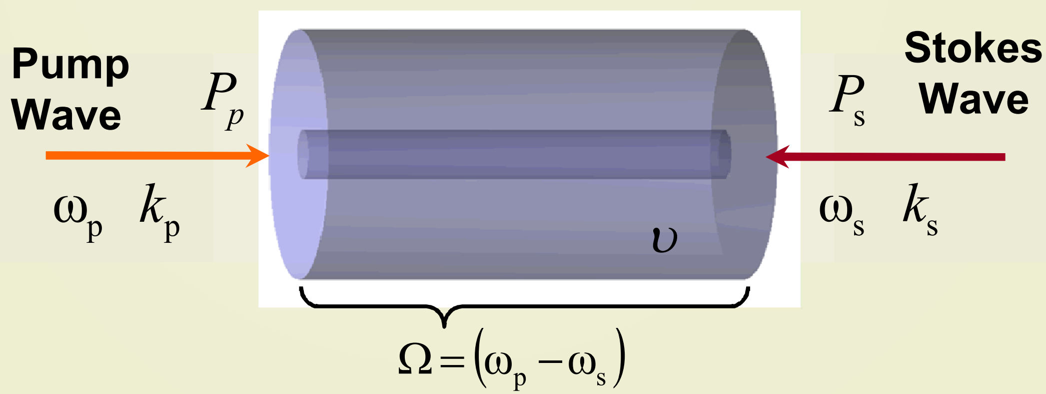


$$\Omega = 2n\omega \upsilon / c$$

Ω: Phonon angular frequency
υ: Sound velocity

n: Refractive index
ω: Optical angular frequency

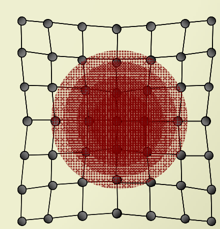
How does backward-SBS work?



- **Strong coupling requires large optical forces.**
- **Tight phonon confinement.**

Electrostrictive forces compress medium

Electrostriction:



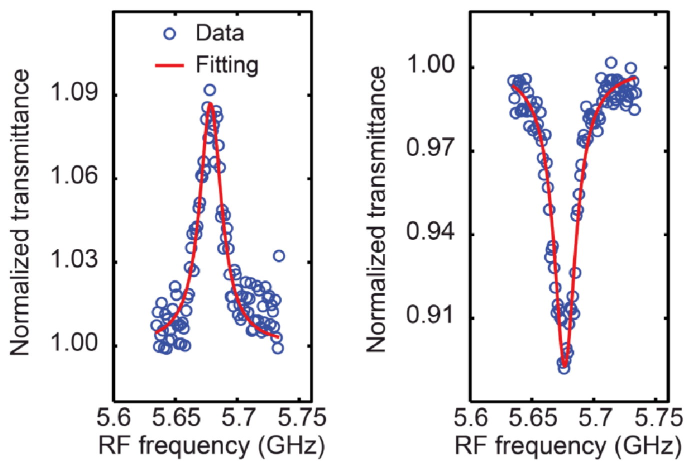
From dynamic material response.

SBS gain coefficient

$$g_B = G\frac{(\Omega_m/2Q)^2}{(\Omega_m-\Omega)^2+(\Omega_m/2Q)^2}$$

$$P_s(L,\Omega,P_p) = P_s(0,\Omega,P_p)\exp(g_B P_p L_{eff})$$

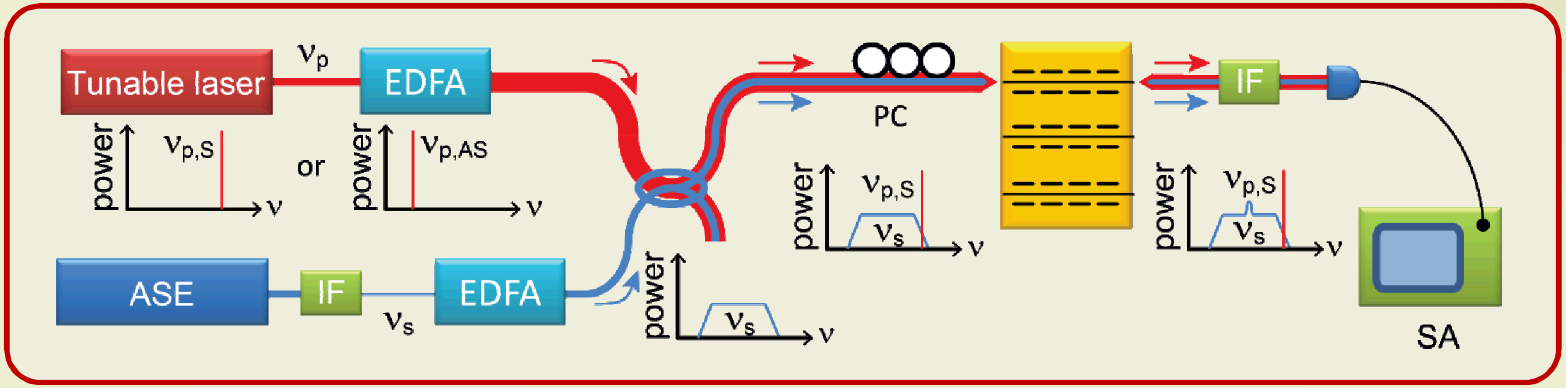
$$P_{as}(L,\Omega,P_p) = P_{as}(0,\Omega,P_p)\exp(-g_B P_p L_{eff})$$



- Extracted forward SBS gain: G = 2750 [1/m/W]
- Effective propagation length: L_{eff} = 2.1 mm
- Geometry enhanced FSBS coefficient: $g_B \sim 2.4\times10^{-10}$ [m/W]
- Phonon resonance Q-factor: $Q \sim 300$ (FWHM $\Delta\nu$ = 19 MHz)

Yale

Gain spectrum measurement



w = 0.8 mm

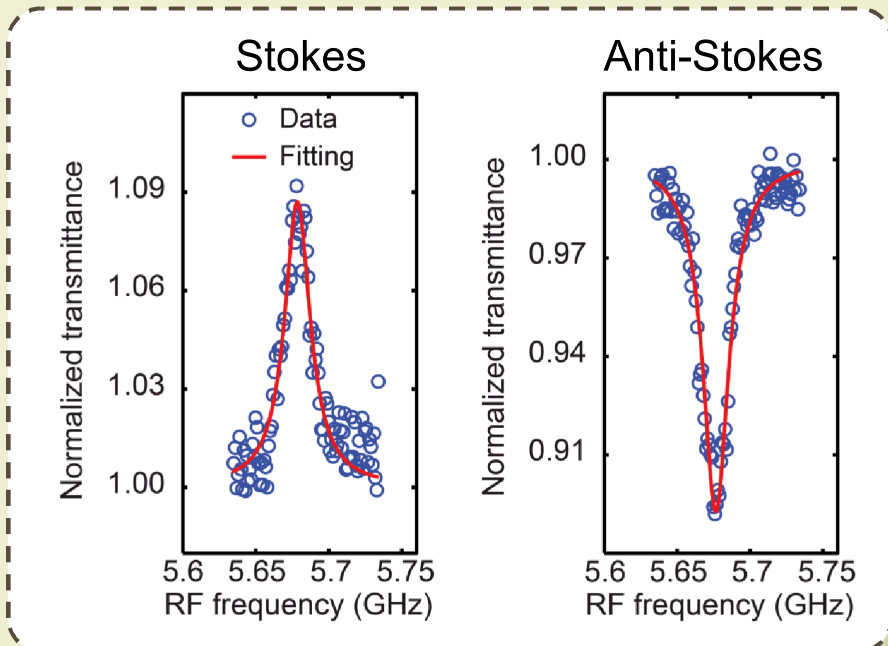
ASE : amplified spontaneous emission

IF : interference filter

EDFA : erbium doped fiber amplifier

PC : polarization controller

SA : spectrum analyzer

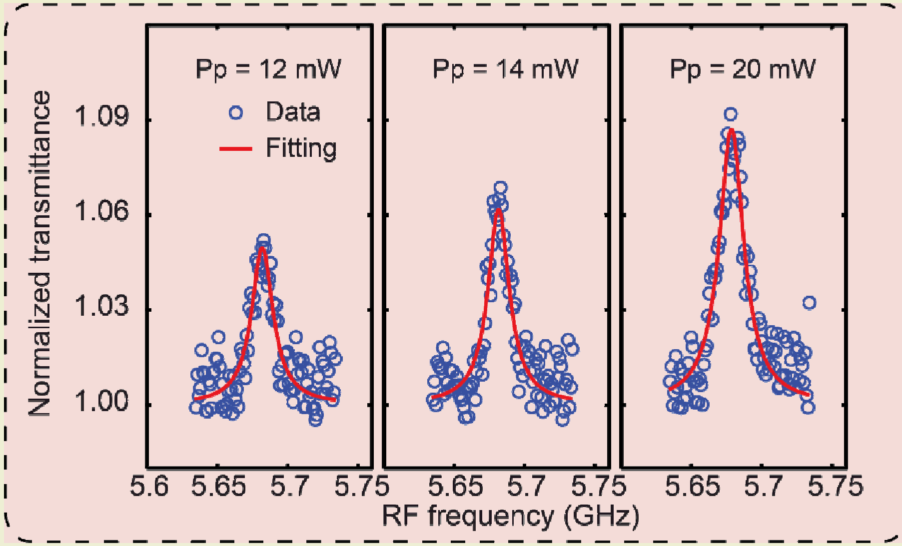


Coupling efficiency ~ 8 dB / facet

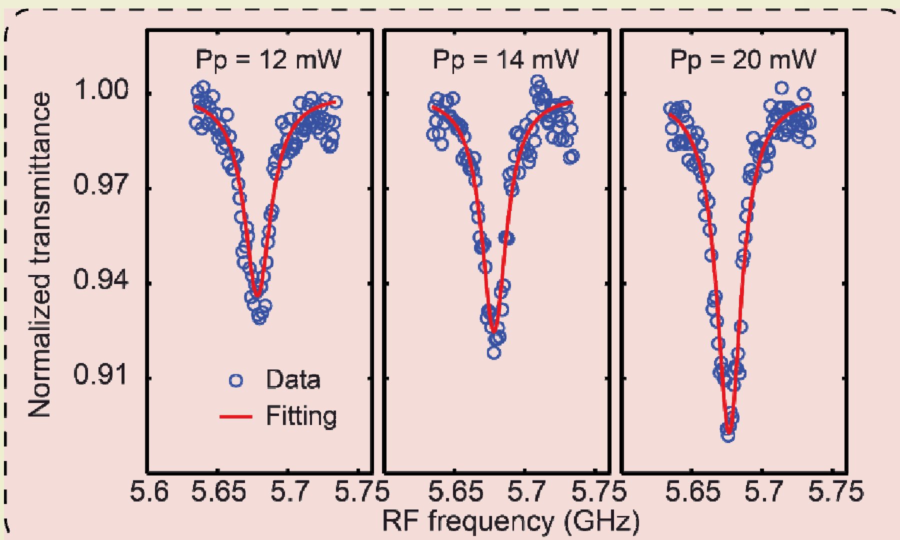
Propagation loss ~ 7 dB/cm

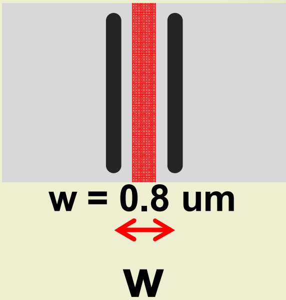
SBS gain spectrum

Stokes SBS

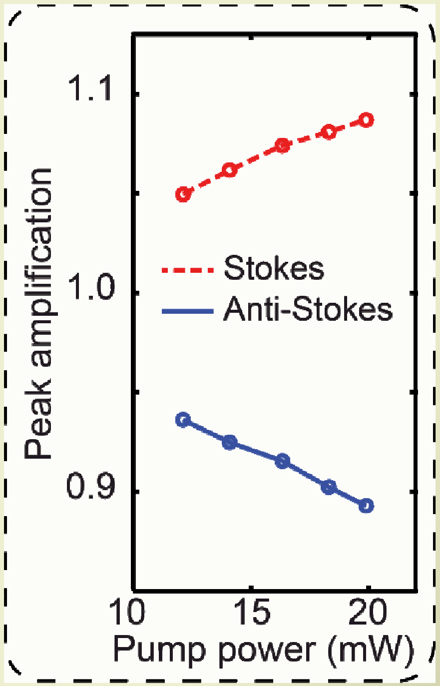


Anti-Stokes SBS

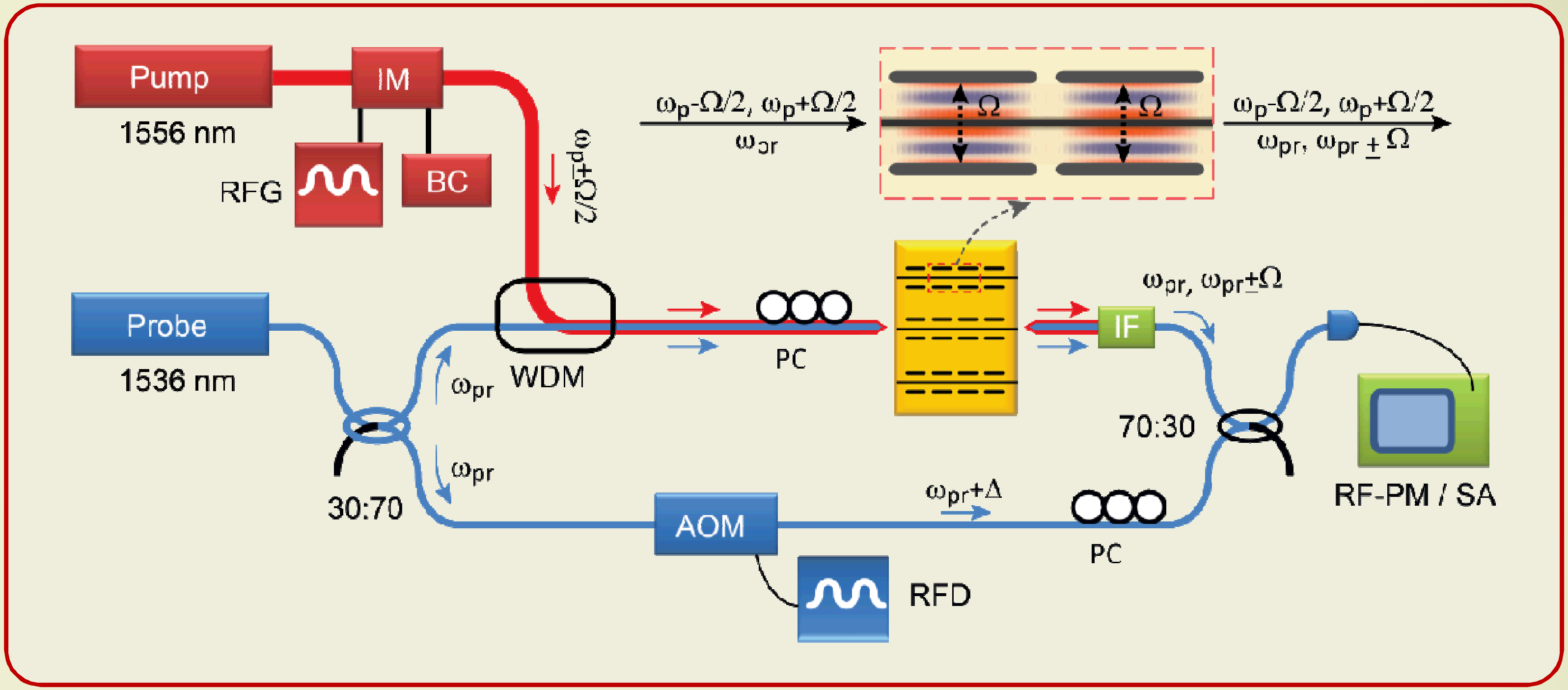




Power dependence



Heterodyne two-color pump-probe apparatus.

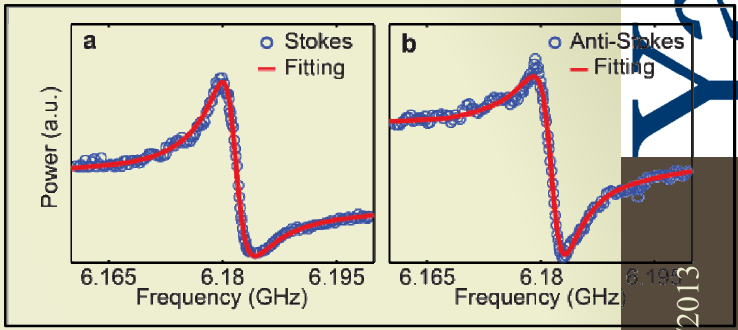


RFG :	radio frequency generator	AOM :	acousto-optic modulator
IM :	intensity modulator	RFD :	radio frequency driver
BC :	DC bias controller	IF :	interference filter
PC :	polarization controller	RF-PM :	RF power meter
WDM :	wavelength division multiplexer	SA :	spectrum analyzer

Analysis of Brillouin signal

- SBS signal

$$g_{\mathrm{SBS}} = I_{\mathrm{SBS+Kerr}}(L)/P_0$$
$$= \left| \frac{G_{\mathrm{B}}}{2} \frac{\Omega_m/2Q}{\Omega_m - \Omega - i\,\Omega_m/2Q} L_{\mathrm{SBS}} + \left(2\gamma^{(3)}_{\mathrm{FWM}} + \gamma^{(5)}_{\mathrm{FC}} P_0\right) L_{\mathrm{total}} \right|^2$$



$\gamma^{(3)}_{\mathrm{FWM}}$ Contribution from four-wave mixing

$\gamma^{(5)}_{\mathrm{FC}} P_0$ Contribution from free-carrier dispersion

Brillouin nonlinearities are quantified with relative Kerr nonlinearities.

Kerr Nonlinearity

Intrinsic Si Nonlinearity:

$$n_2 = 4.5 \times 10^{-18}\,[m^2/W]$$

NL Waveguide Coefficient:

$$\gamma_{\mathrm{K}} = 188\,[m^{-1}W^{-1}]$$

Free-carrier dispersion

Stokes

$$\gamma^{(5)}_{\mathrm{FC}} P_0 / 2\gamma^{(3)}_{\mathrm{FWM}} = 0.03$$

Anti-Stokes

$$\gamma^{(5)}_{\mathrm{FC}} P_0 / 2\gamma^{(3)}_{\mathrm{FWM}} = 0.28$$

Line-Shape Analysis:

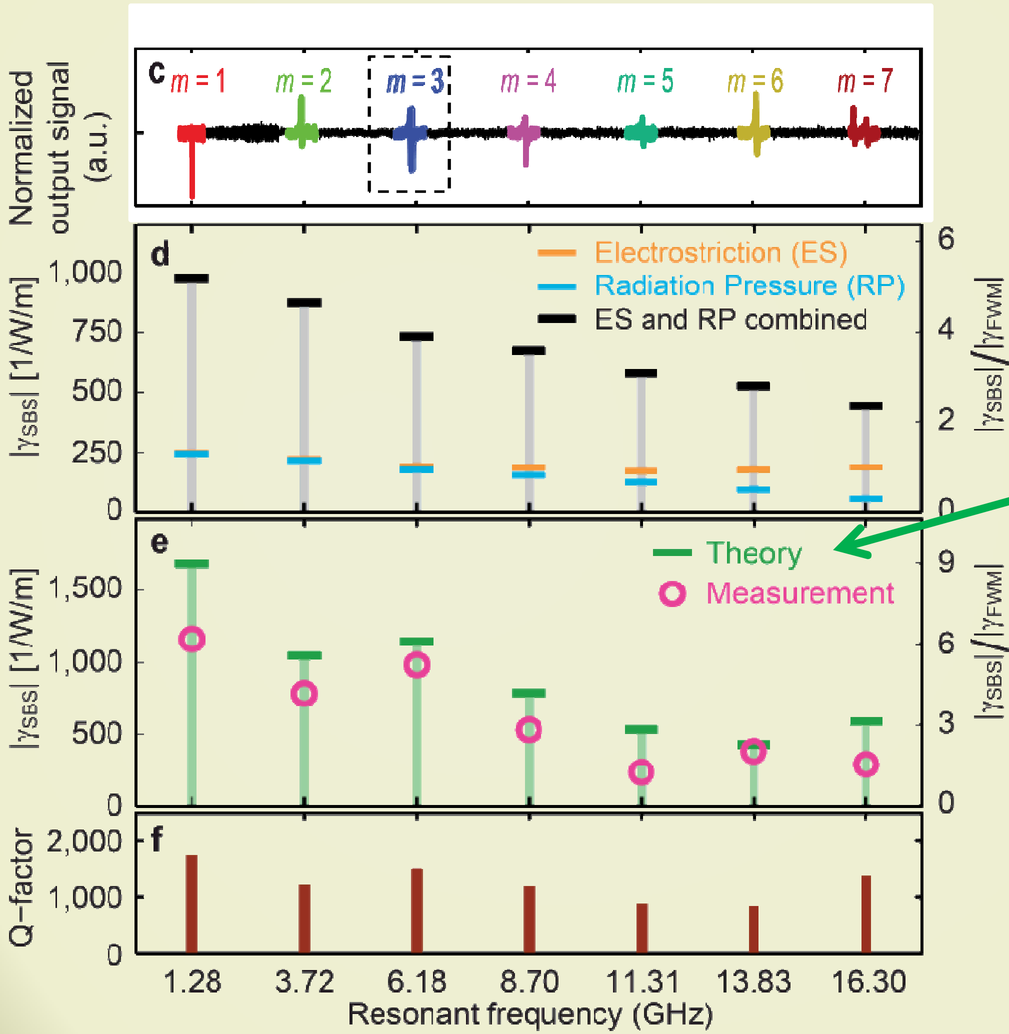
$$G_{\mathrm{B}}/\gamma_{\mathrm{K}} = 10.43$$

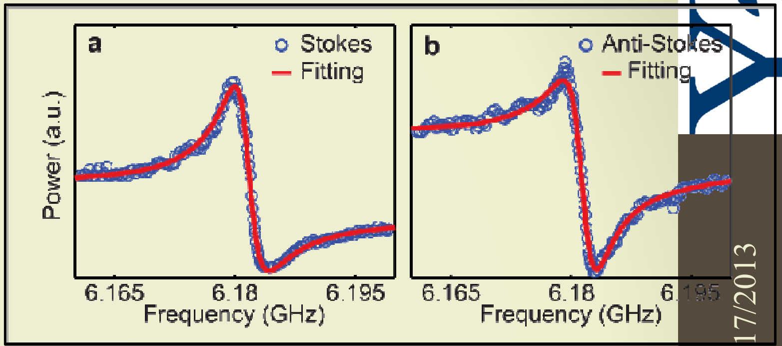
$$G_{\mathrm{B}} \simeq 1960\,[\mathrm{m}^{-1}\mathrm{W}^{-1}]$$

$$Q \simeq 1561$$

R. Dekker, *et al.*, *J. Phys. D: Appl. Phys.* **40**, R249 (2007).

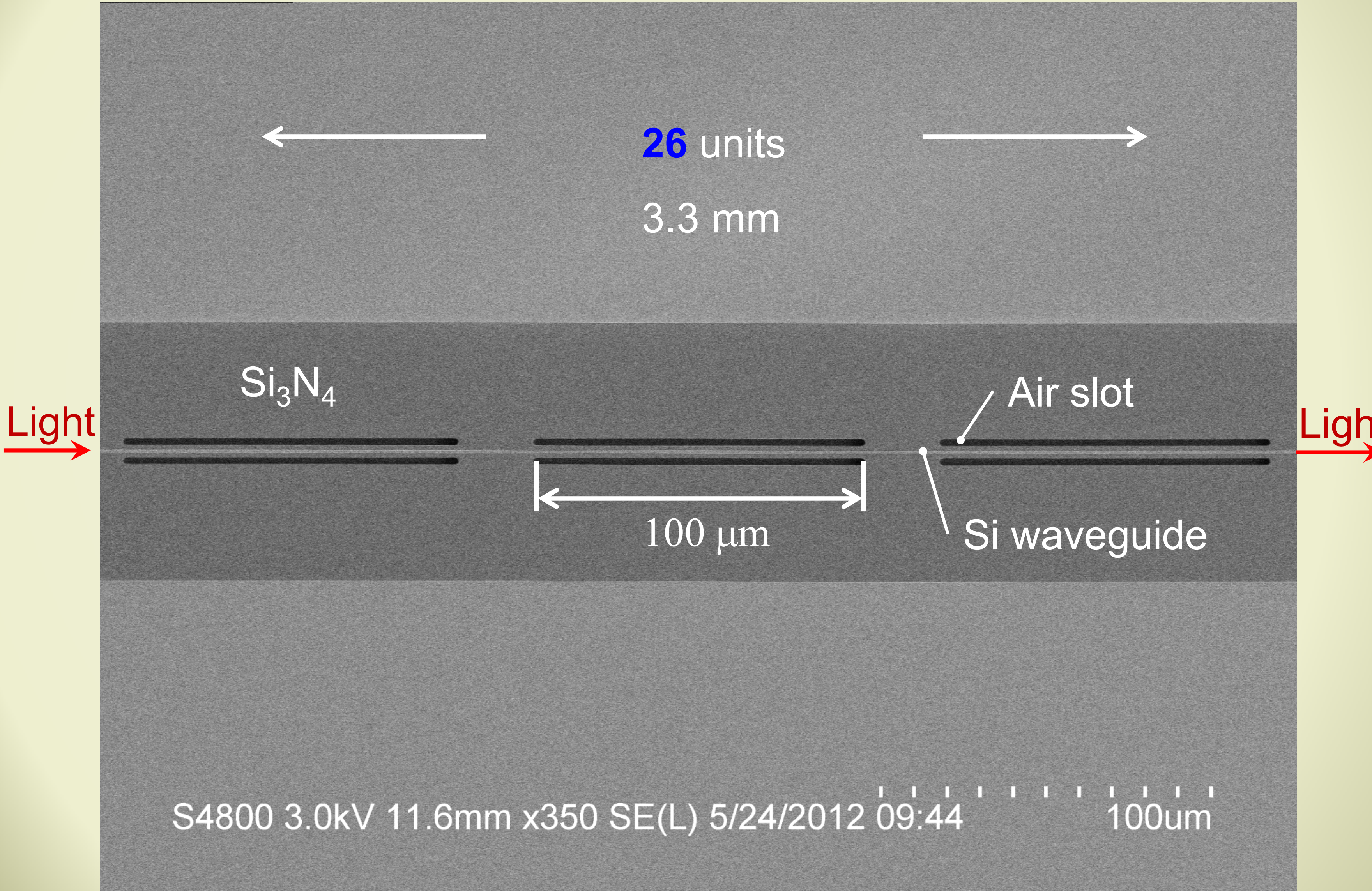
Analysis of Brillouin responses





$$\left|\gamma_{\mathrm{SBS,e}}\right| = \left|\gamma_{\mathrm{SBS,d}}\right| / 1000 \times Q$$

- **Efficient transduction 1-18 GHz frequencies.**
- **Resonances expected > 20 GHz. (limited by equipment)**
- **High f*Q product**
- **Excellent agreement between theory and experiment.**


26 units
3.3 mm
Si_3N_4
Air slot
Light
Light
100 μm
Si waveguide
S4800 3.0kV 11.6mm x350 SE(L) 5/24/2012 09:44
100um

Fabrication process