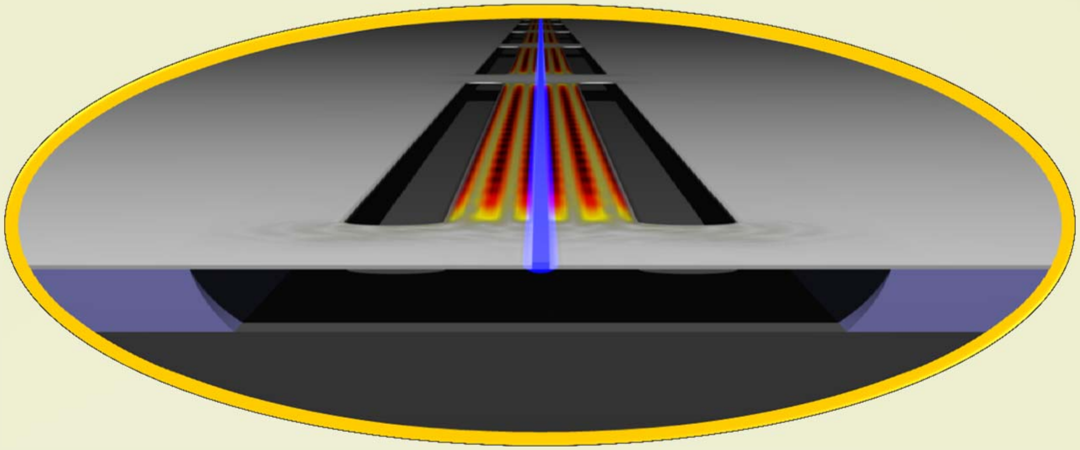
SAND2013-4696C



Coherent interference of nonlinearities in nanoscale silicon waveguides:

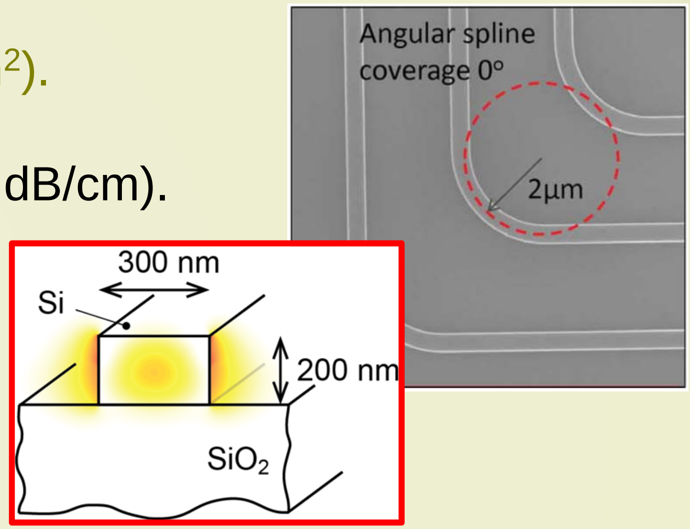
The interplay between Kerr, free-carrier dispersion, and Brillouin nonlinear responses.

Heedeuk Shin[1,2], Wenjun Qiu[3], Zheng Wang[4], Peter Rakich[1,2]

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

Silicon photonic waveguide

- Silicon waveguide (n = 3.45) on silicon dioxide substrate (n = 1.44).
- Strong field confinement (area < 1 μm^2).
- Sufficiently low propagation loss (< 1 dB/cm).
- Small bending radius (r < 3 μm).
- Nano-photonics.



Major Nonlinear Effects for use of dynamic devices

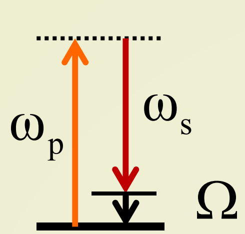
- $Re\{\chi^{(3)}\}$: Self-Phase Modulation (SPM), Cross-Phase Modulation (XPM), Four-Wave Mixing (FWM)
- $Im\{\chi^{(3)}\}$: Two-Photon Absorption (TPA), Stimulated Raman Scattering (SRS)
- TPA induced Free Carrier effect ($\chi^{(5)}$)

SBS ?

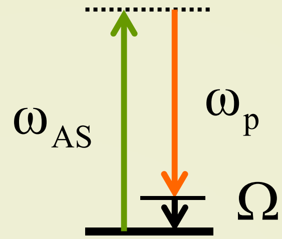
Lin, et al., Opt. Express **15**, 16604 (2007)
Leuthold, et al., Nature Photon. **4**, 535 (2010)

Stimulated Brillouin scattering (SBS)

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

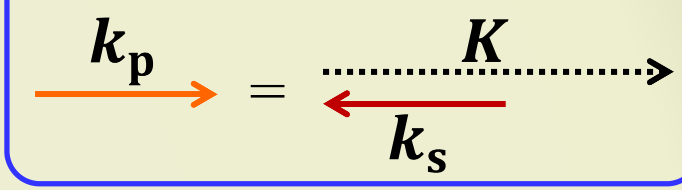


Stokes SBS



Anti-Stokes SBS

$$\boldsymbol{k}_{\mathbf{p}} = \boldsymbol{k}_{\mathbf{s}} + \boldsymbol{K}$$



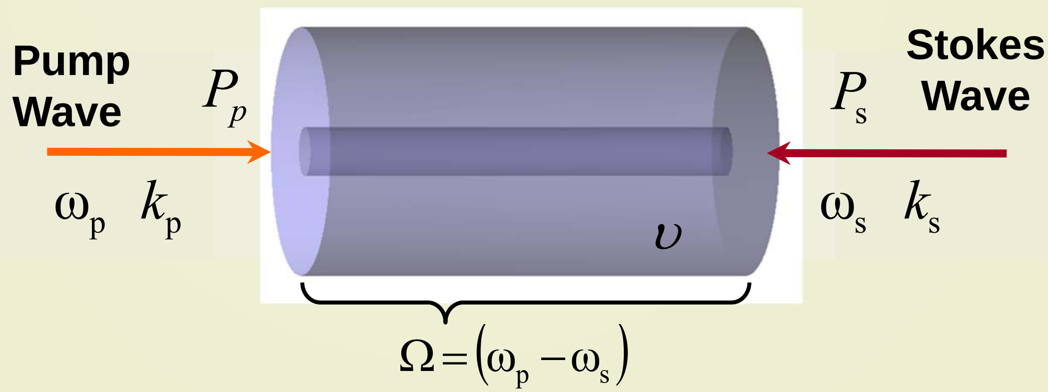
$$\Omega = 2n\omega \upsilon / c$$

Ω: Phonon angular frequency
υ: Sound velocity

n: Refractive index
ω: Optical angular frequency

R.W. Boyd, "Nonlinear optics," Chap. 9.

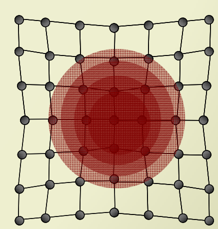
How does backward-SBS work?



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

Electrostrictive forces compress medium

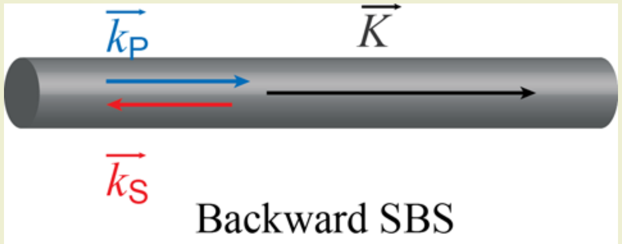
Electrostriction:



From dynamic material response.

Phase matching condition of SBS

Backward-SBS phase matching condition

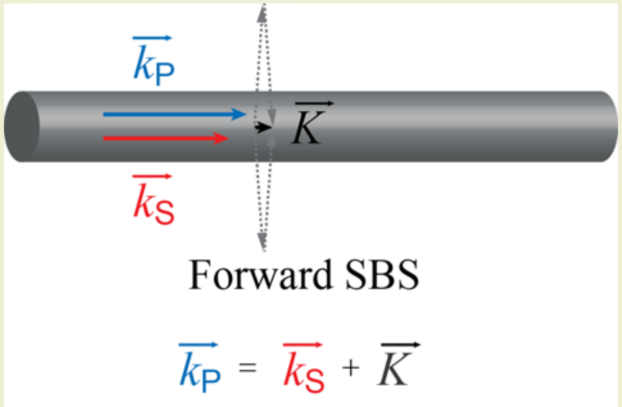


$$K = k_p - k_s \sim 2k$$

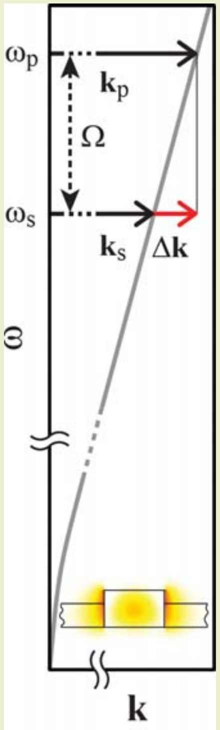
Chiao, et al., Phys. Rev. Lett. **12**, 592 (1964)

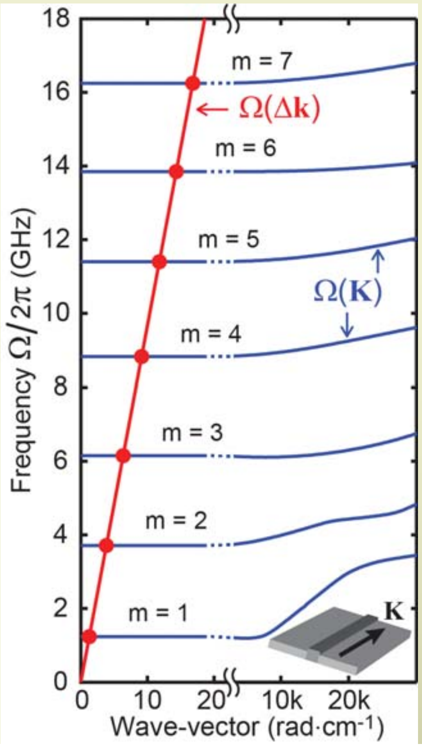
Ippen, et al., Appl. Phys. Lett. **21**, 539 (1972)

Forward-SBS phase matching condition



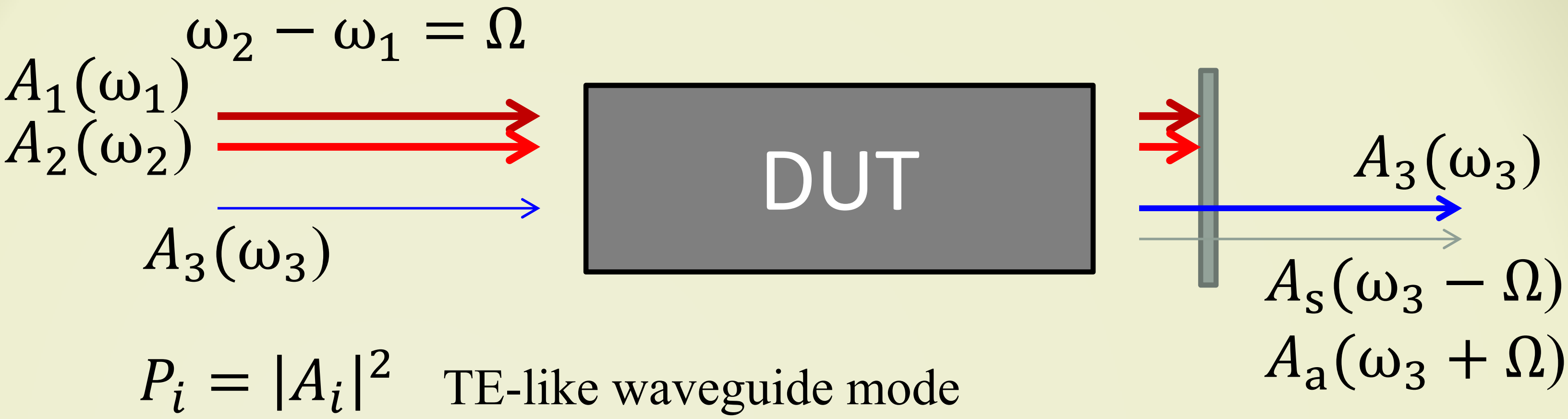
$$K = k_p - k_s \ll k$$



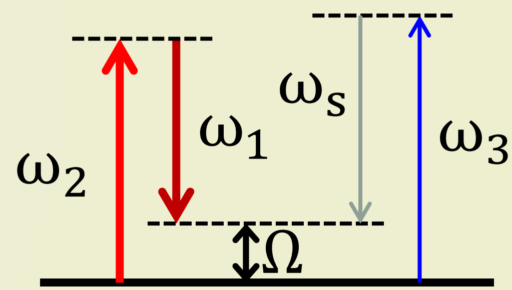


Shelby, et al., Rhys. Rev. B **31**, 5244 (1985).
Kang, et al., Nat. Phys. **5**, 276 (2009).
Wang, et al., Opt. Express **19**, 5339 (2011).

Forward SBS by two-color pump-probe



$P_i = |A_i|^2$ TE-like waveguide mode



Coupled wave equation for Stokes wave

$$\frac{dA_s}{dz} = i\left[\gamma_{SBS}^{(3)^*}(\Omega)\right] A_1^* A_2 A_3$$

- $\gamma_{SBS}^{(3)}(\Omega)$: the third order nonlinear coefficient for SBS.

$$\gamma_{SBS}^{(3)}(\Omega) = \frac{G}{2} \frac{\Omega_m/2Q}{\Omega_m - \Omega - i\,\Omega_m/2Q}, \quad \text{where } G = 2\left|\gamma_{SBS}^{(3)}(\Omega_m)\right|$$

R.W. Boyd, "Nonlinear optics," Chap. 9, Academic press

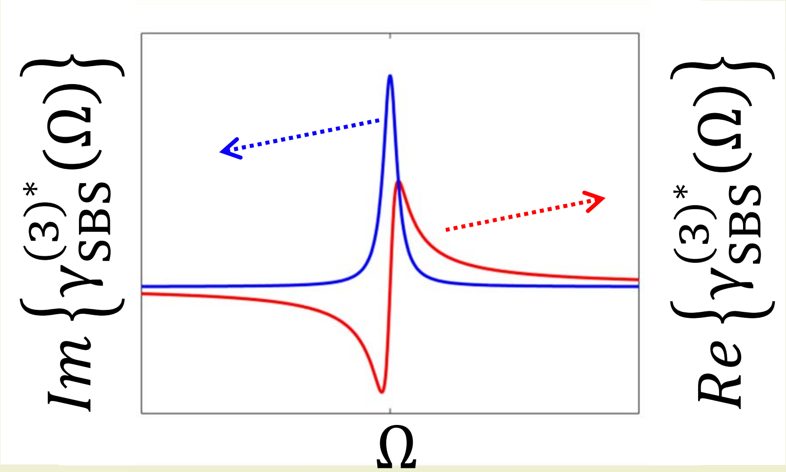
Forward SBS by two-color pump-probe

- Stokes wave amplitude

$$A_s(z) = e^{i\left[\gamma_{\mathrm{SBS}}^{(3)^*}(\Omega)\right]P_{\mathrm{p}}A_3 z}$$

$$P_{\mathrm{p}} = |A_1|^2 = |A_2|^2$$

Resonant
Brillouin Susceptibility

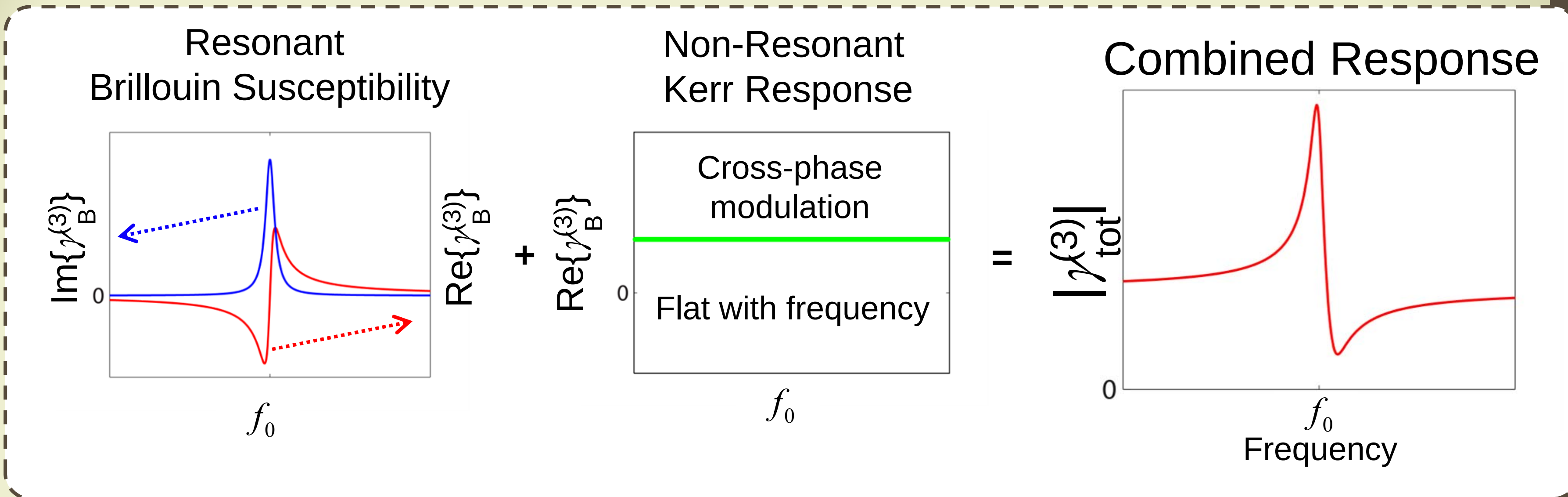


Coupled wave equation for Stokes wave with Kerr effect

$$\frac{dA_s}{dz} = i\left[\gamma_{\mathrm{SBS}}^{(3)^*}(\Omega) + 2\gamma_{\mathrm{K}}^{(3)}\right]A_1^* A_2 A_3$$

- $\gamma_{\mathrm{SBS}}^{(3)}(\Omega)$: the third order nonlinear coefficients for SBS.
- $\gamma_{\mathrm{K}}^{(3)}$: the third order nonlinear coefficients for non-degenerate FWM.

SBS nonlinear responses



$\omega_2 - \omega_1 = \Omega$

$P_i = |A_i|^2$ TE-like waveguide mode

Coupled wave equation for Stokes wave

$$\frac{dA_s}{dz} = i\left[\gamma_{\mathrm{SBS}}^{(3)^*}(\Omega) + 2\gamma_{\mathrm{K}}^{(3)} + \gamma_{\mathrm{FC}}^{(5)}(-\Omega)P_0\right]A_1^* A_2 A_3$$

- $\gamma_{\mathrm{SBS}}^{(3)}(\Omega)$: the third order nonlinear coefficients for SBS.
- $\gamma_{\mathrm{K}}^{(3)}$: the third order nonlinear coefficients for non-degenerate FWM.
- $\gamma_{\mathrm{FC}}^{(5)}(\Omega)$: the fifth order nonlinear coefficient for free carrier effects.

$$P_0 = 2(|A_1|^2 + |A_2|^2 + |A_3|^2)$$

$$g_s = C\left|\gamma_{\mathrm{SBS}}^{(3)*}(\Omega)L_{\mathrm{SBS}} + \left(2\gamma_{\mathrm{K}}^{(3)} + \gamma_{\mathrm{FC}}^{(5)}(-\Omega)P_0\right)L_{\mathrm{tot}}\right|^2 P_1P_2P_3$$

C is a constant, P_k indicates the optical power of kth field, and L_{SBS} and L_{tot} are the interaction lengths of SBS and the rest nonlinear responses, respectively.

In the absence of the Brillouin nonlinearities (e.g. for large detuning from a Brillouin resonance) the free carrier and FWM contributions to the Stokes sideband

$$g_{os} \equiv CL_{\mathrm{tot}}^2\left|2\gamma_{\mathrm{K}}^{(3)} + \gamma_{\mathrm{FC}}^{(5)}(-\Omega)P_0\right|^2 P_1P_2P_3$$

$$\frac{g_s}{g_{os}} = \left| e^{ibs} + D_m \frac{\Omega_m/2Q}{\Omega_m - \Omega - i\,\Omega_m/2Q} \right|^2$$

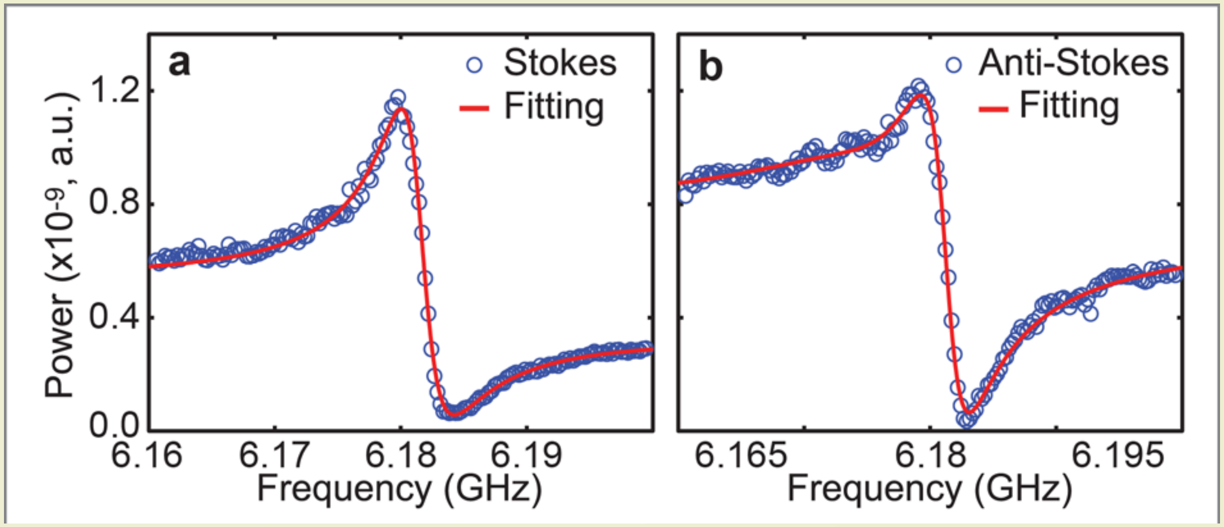
$$D_m \equiv G L_{\mathrm{SBS}} / \left(2L_{\mathrm{tot}} \left| 2\gamma_{\mathrm{K}}^{(3)} + \gamma_{\mathrm{FC}}^{(5)}(-\Omega) P_0 \right| \right)$$

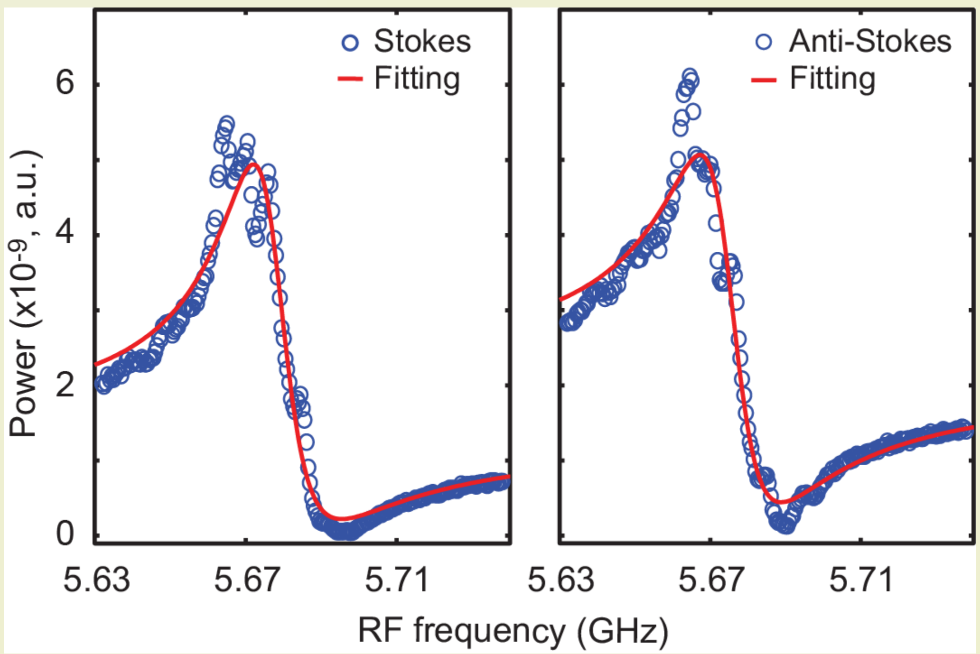
the relative strength of the Brillouin scattering effect relative to the reference nonlinear responses.

$$\left| 2\gamma_{\mathrm{K}}^{(3)} \right| \gg \left| \gamma_{\mathrm{FC}}^{(5)}(\pm\Omega) P_0 \right|$$ at high frequency (>15 GHz)

$$\eta \equiv \left| 2\gamma_{\mathrm{K}}^{(3)} + \gamma_{\mathrm{FC}}^{(5)}(\Omega_m) P_0 \right| / \left| 2\gamma_{\mathrm{K}}^{(3)} \right|$$

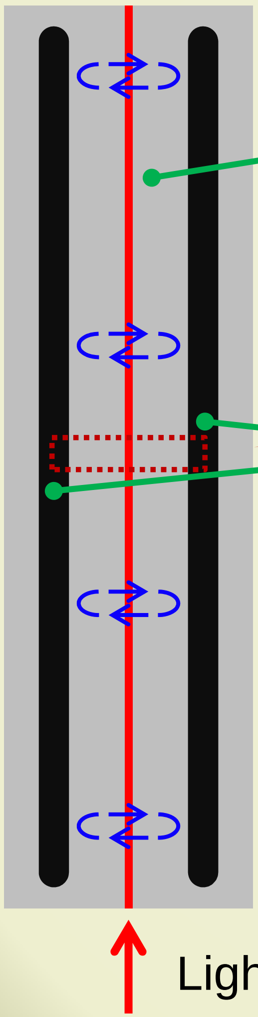
$$G = 2 D_m \eta \left| 2\gamma_{\mathrm{K}}^{(3)} \right| \frac{L_{\mathrm{tot}}}{L_{\mathrm{SBS}}}$$


a
Stokes
Fitting
b
Anti-Stokes
Fitting
Power (x10-9, a.u.)
1.2
0.8
0.4
0.0
6.16
6.17
6.18
6.19
Frequency (GHz)
6.165
6.18
6.195
Frequency (GHz)


Stokes
Fitting
Anti-Stokes
Fitting
Power (x10-9, a.u.)
6
4
2
0
5.63
5.67
5.71
5.63
5.67
5.71
RF frequency (GHz)

Brillouin Active Membrane waveguide

Brillouin Active Membrane (BAM) waveguide



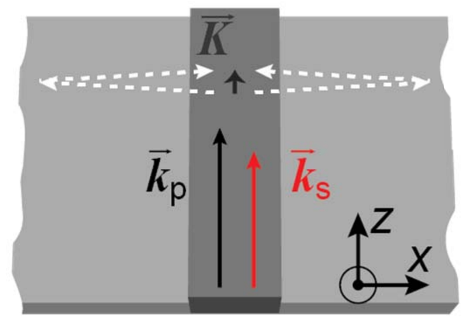
Si_3N_4 membrane acts as conduit for phonons.

Air slots

Each slot acts as a wideband phonon mirror.

Excellent phononic resonances over wide range of frequency.

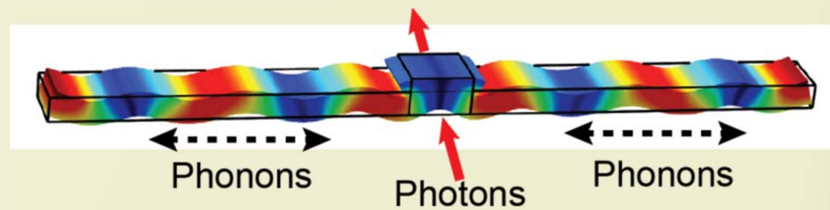
Forward SBS



Stokes forward-SBS

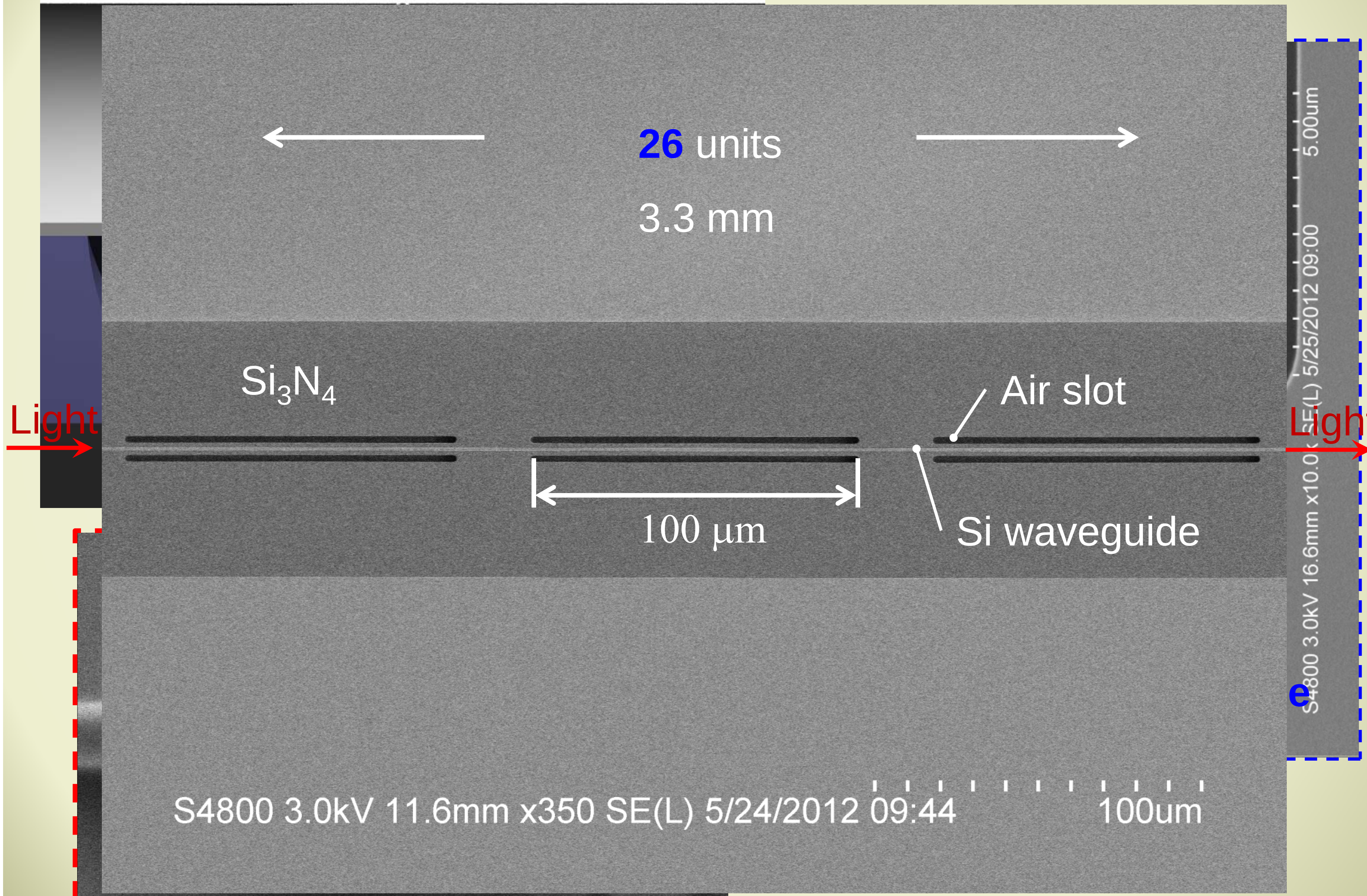
$$\vec{k}_S = \vec{k}_P - \vec{K}$$

$$|\vec{K}| << |\vec{k}|$$

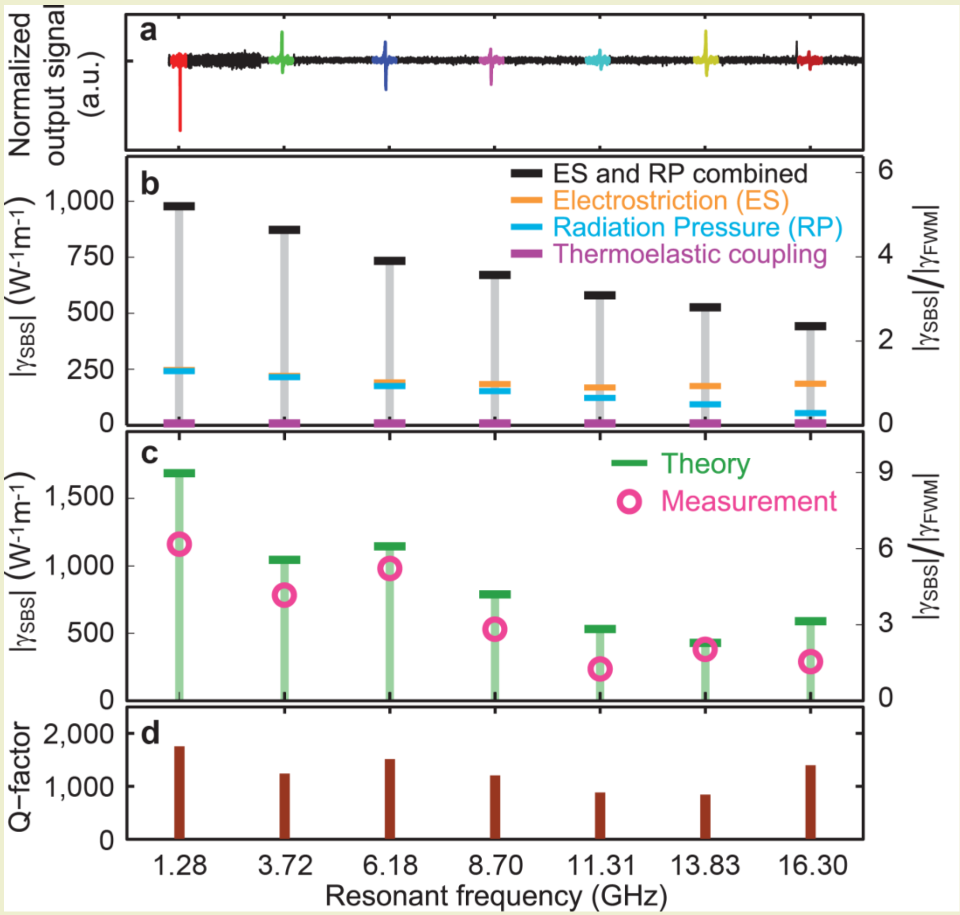


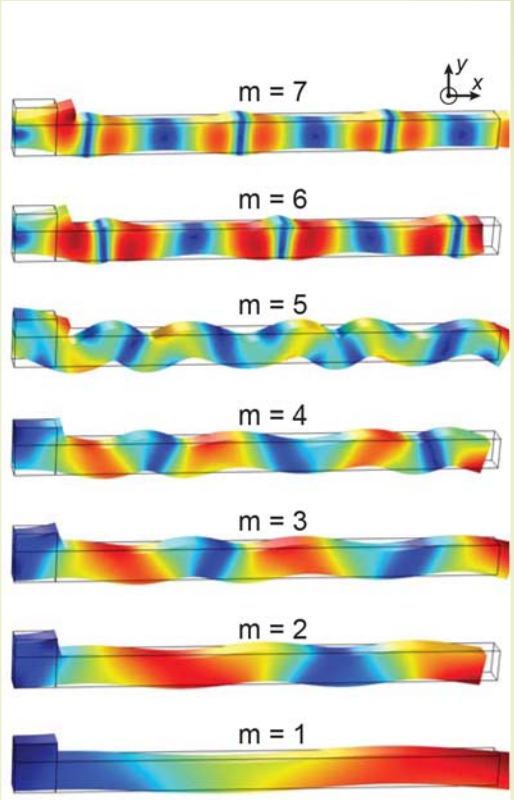
- **New physics**
- **Structure dependent resonant frequency**
- **Free control of phonon structure while optimizing photon waveguide**
- **Cascaded higher modes**

Brillouin active membrane waveguide



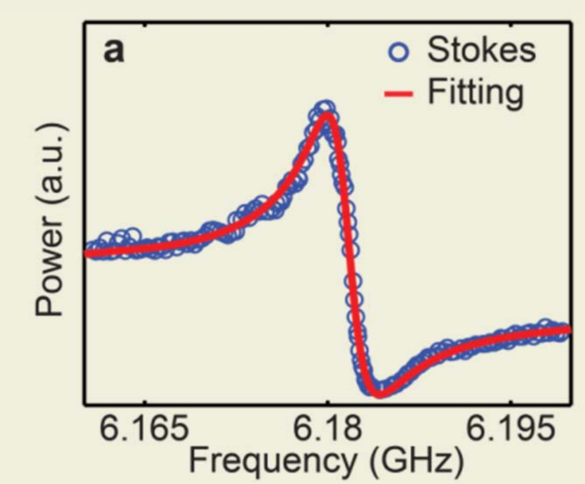
Quantitative Analysis of Brillouin Nonlinearity

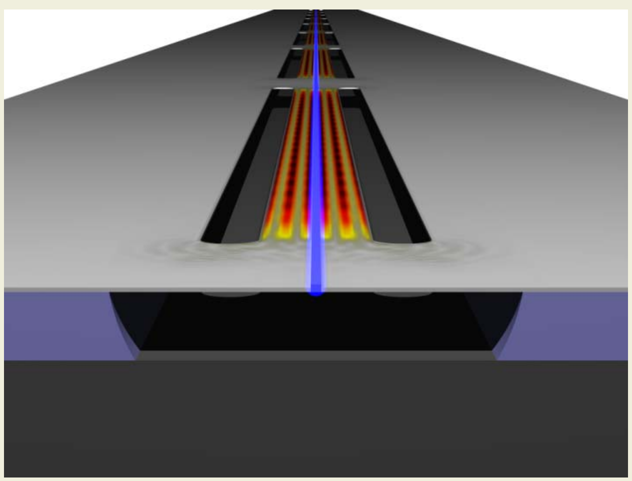




- **Efficient transduction 1-18 GHz frequencies.**
- **3,000 x stronger forward SBS than any known system.**

Conclusion





1. **First demonstration of wideband (1-18 GHz) photon-phonon interaction with high Q.**

2. **First-ever demonstration *chip-scale* Forward Stimulated Brillouin Scattering (SBS).**

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

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

   > Demonstrated tailorable nonlinear susceptibility from the coherent interference of Kerr and Brillouin nonlinearities.

3. **High f*Q product close to the intrinsic damping of Si_3N_4.**

   > f_o = 16.3 GHz and Q = 1500

Sandia National Laboratories

Acknowledgements

- Marin Soljačić
- Ryan M. Camacho
- Ihab El-Kady
- Jack Harris
- Jack Sankey
- Benjamin Zwickl
- Douglas Trotter
- Whitney Purvis Rakich

- Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Company, for the U.S. Department of Energy's National Nuclear Security Administration 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.
- SAND Report # 2013-4696 C