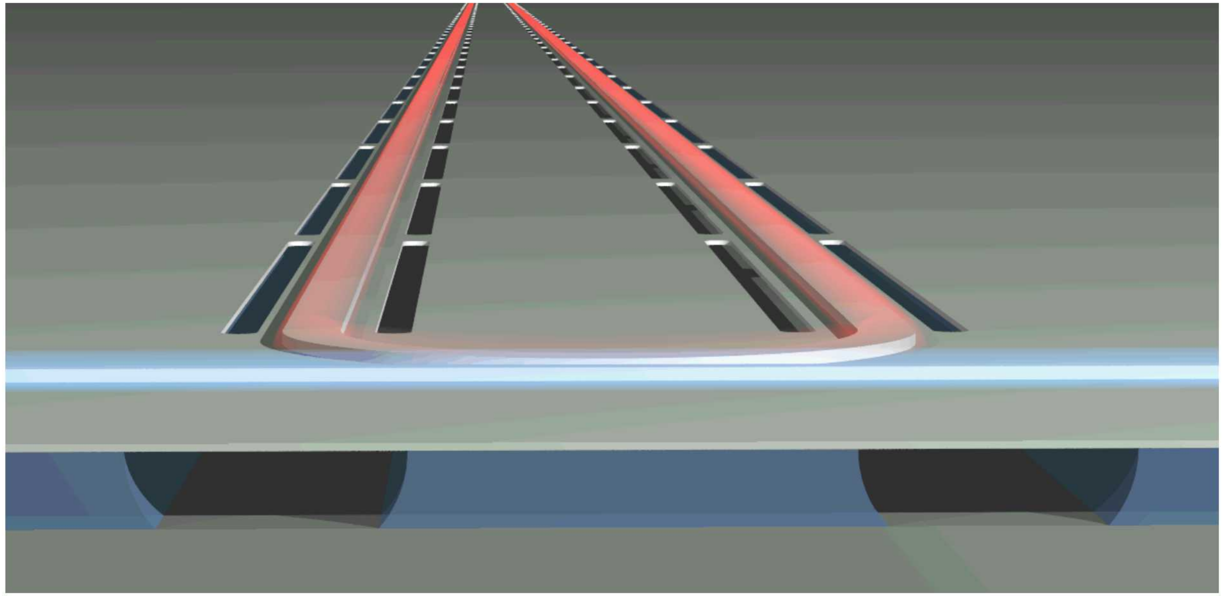
SAND2020-5323C

Unidirectional injection-locked Brillouin laser in silicon

CLEO 2020



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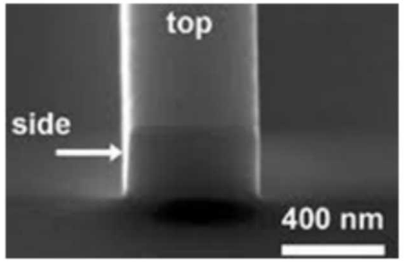
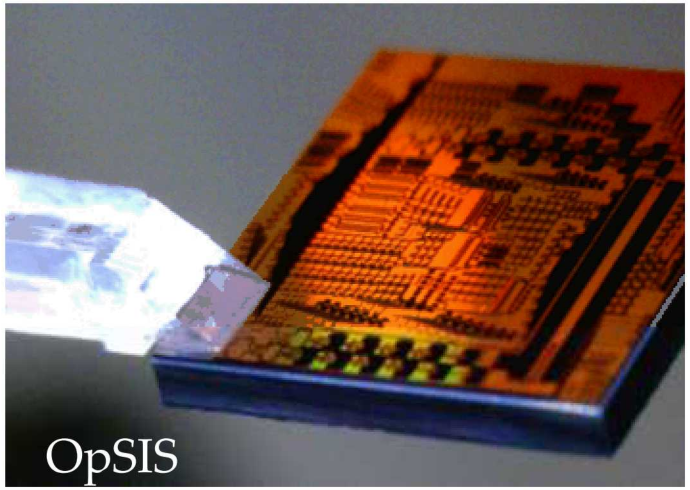
Integrated silicon photonics: power of light on a chip

Benchtop optical setup



Light can be routed in sub-wavelength optical waveguides



Photonic integrated circuit (PIC)

- **Goal:** integrate multiple optical components into complex photonic circuits
- **Advantages:** cost, scalability, performance, efficiency

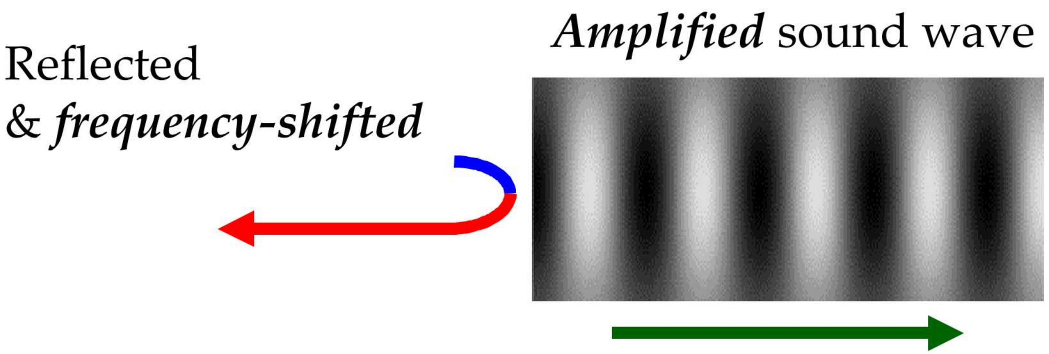
How can we develop new on-chip technologies to meet these needs?

- **Challenges:** Silicon-based lasers, amplifiers, and non-reciprocal devices

1. Engineer phase-matched nonlinearities to create **new lasers**
2. **Manipulate dynamics** to achieve a broad range of functionalities

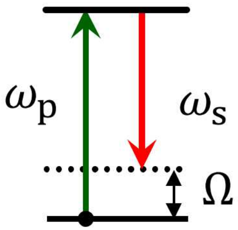
Brillouin interactions: nonlinearity mediated by sound

Brillouin processes:
- Strong optical nonlinearity
- Mediated by sound
- Arises from optical forces and photo-elasticity
- Highly tailorable
- **Net result:** stimulated optical gain



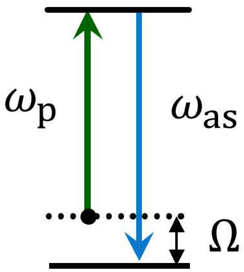
Energy conservation:

Stokes



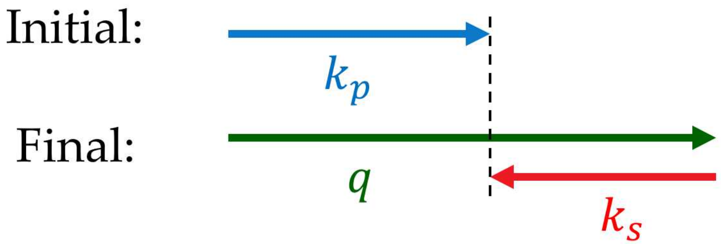
"Phonon generation"

Anti-Stokes



"Phonon annihilation"

Phase matching (momentum conservation):



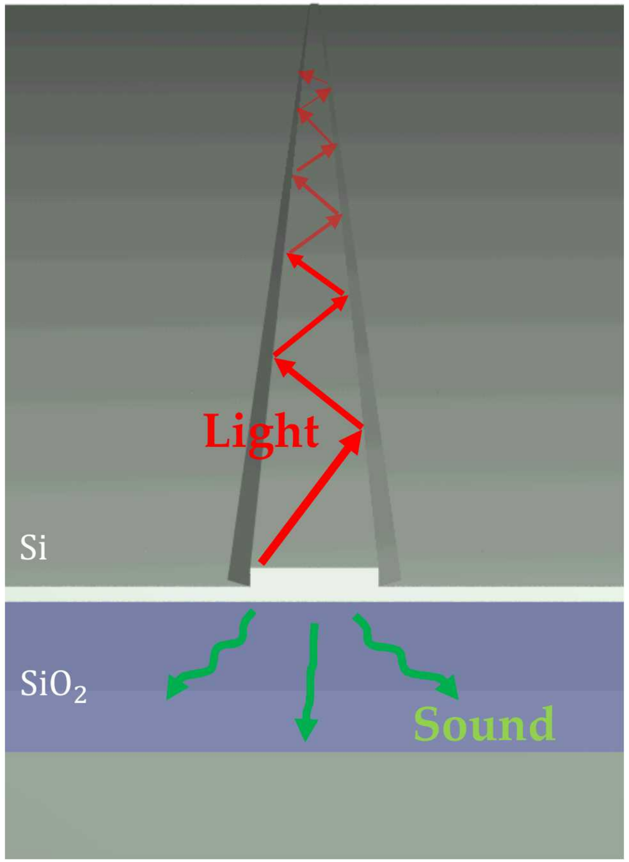
Pump $k_p = \dfrac{2\pi}{\lambda_p}$ Stokes $k_s = \dfrac{2\pi}{\lambda_s}$ Phonon $q = \dfrac{2\pi}{\lambda_a}$

Phase matching allows us to shape the dynamics

Problem #1: Brillouin interactions absent from conventional silicon waveguides

Problem: sound quickly dissipates into substrate

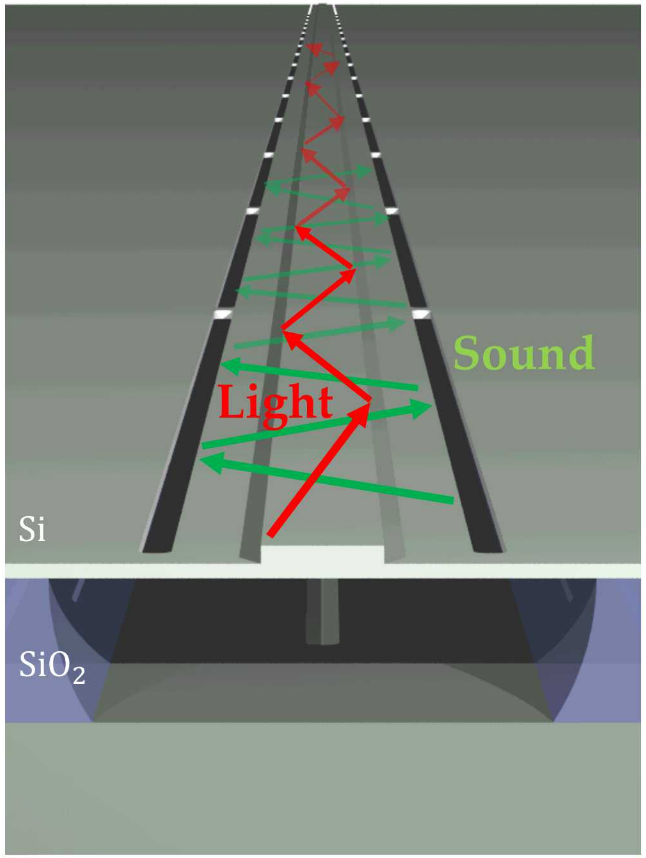
Conventional
Silicon waveguide



Optical
waveguide

Solution: create structure that confines both light and sound

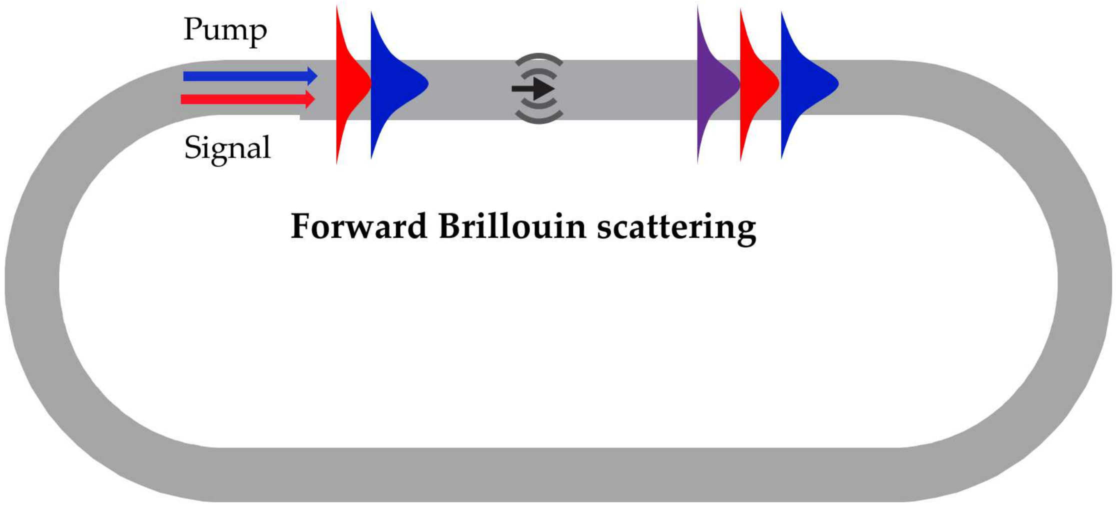
Brillouin-active
waveguide



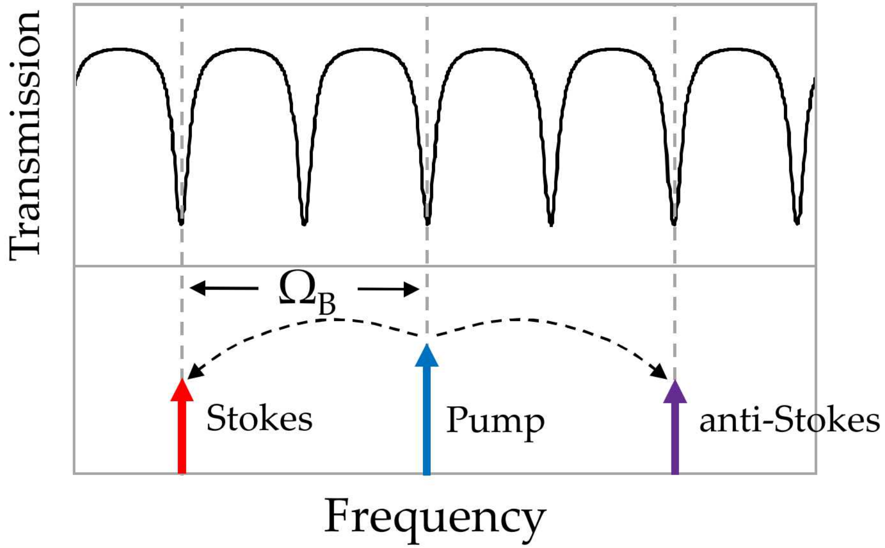
Optical + acoustic
waveguide

P.T. Rakich *et al*. ***Phys. Rev. X.*** (2012)

Problem #2: dynamics prevent amplification and lasing



Cavity spectrum



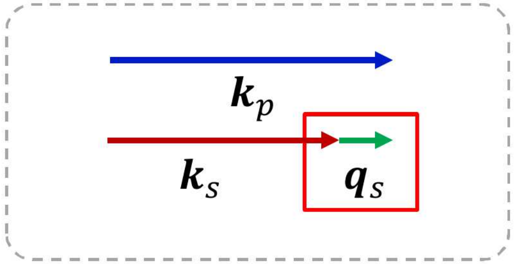
Forward Brillouin scattering:

- Pump and Stokes co-propagate
- Nontrivial dynamics prevents lasing

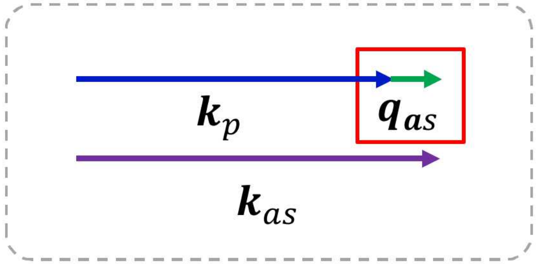
Stokes (phonon creation) and anti-Stokes (phonon annihilation) balanced
Result: no stimulated gain, no lasing!

Need to inhibit the **anti-Stokes** process:
Symmetry breaking!

Phase Matching: Stokes Process

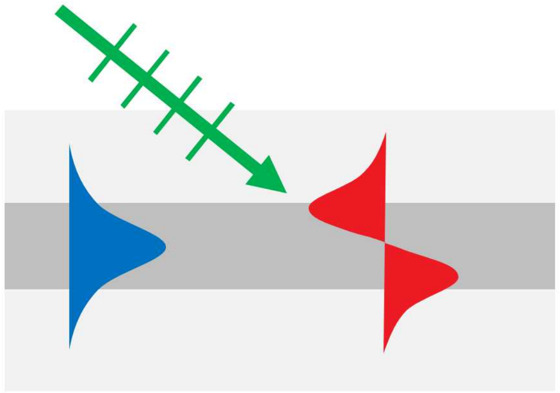


Phase Matching: Anti-Stokes

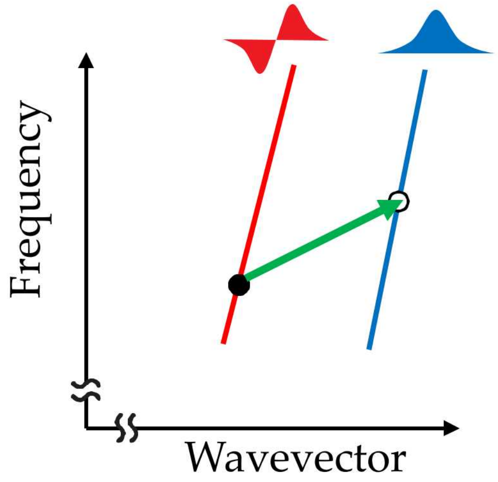


Solution: engineer inter-modal nonlinearities

Strategy: Shape dynamics by engineering inter-modal nonlinearities

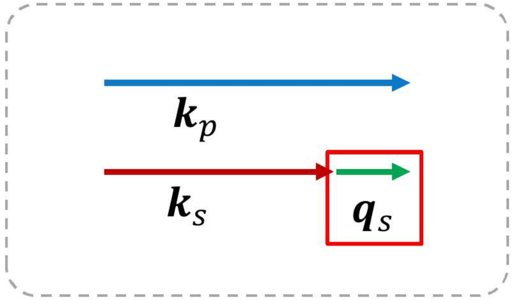


Multimode waveguide

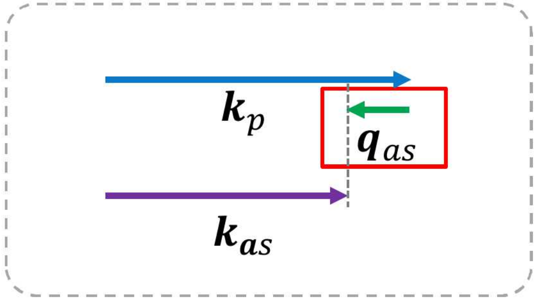


Now, Stokes and anti-Stokes processes talk to different phonons! Symmetry breaking!

Phase Matching: Stokes Process



Phase Matching: Anti-Stokes

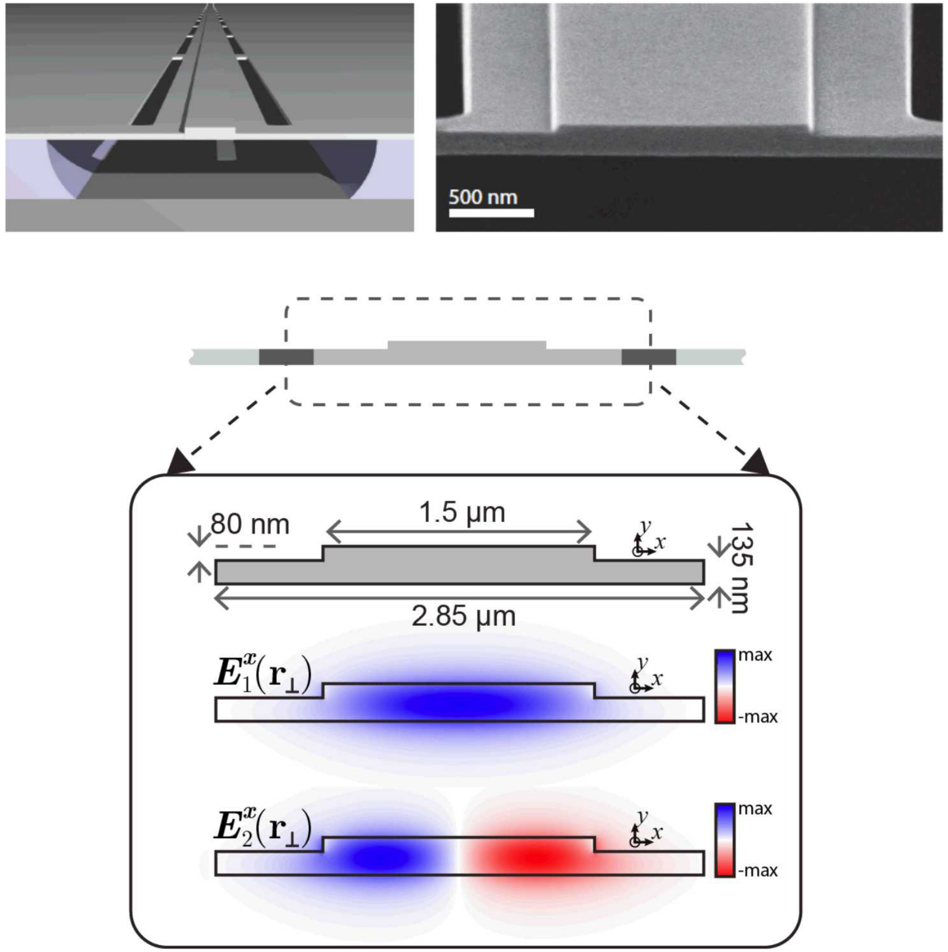


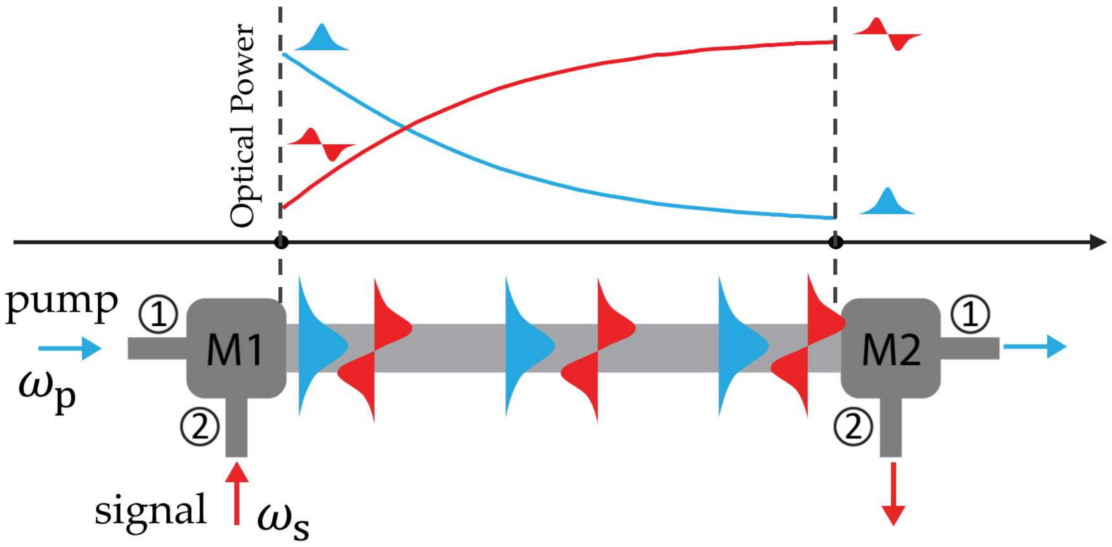
Can we do this on a silicon chip?

If so, we could make new lasers, amplifiers, and non-reciprocal devices

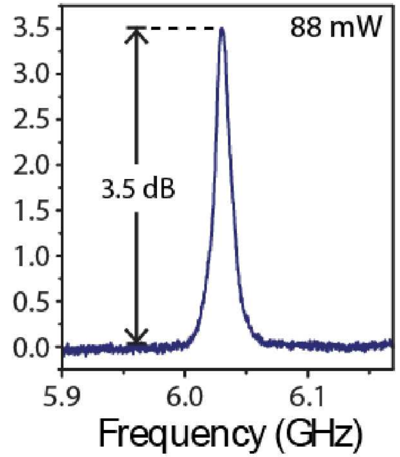
Inter-modal system: Brillouin-active waveguide

Integrated mode multiplexers couple light into two **distinct modes** of a Brillouin-active waveguide



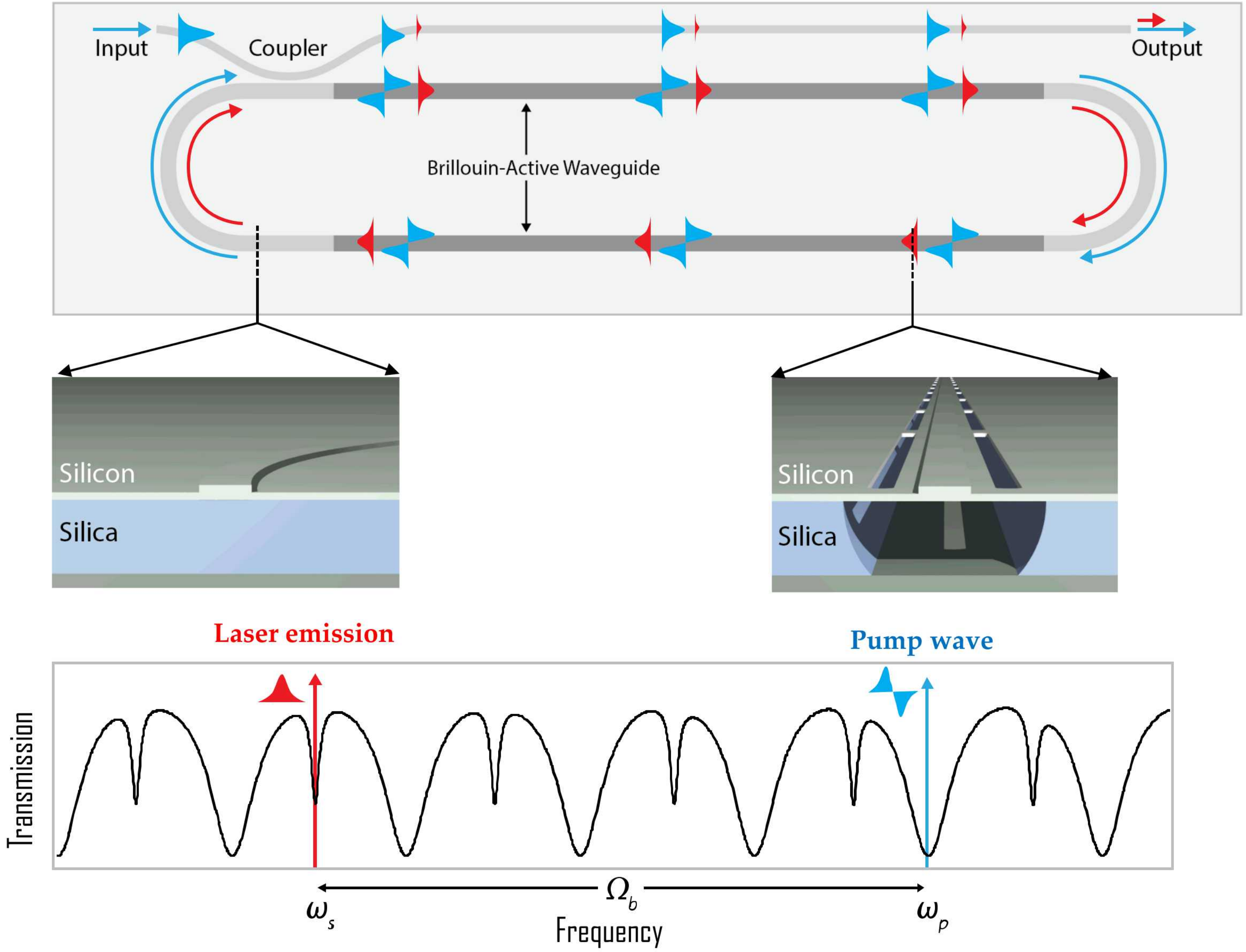


- **3.5 dB** of single-sideband gain
- **2.3 dB** of net amplification



Kittlaus, Otterstrom, Rakich. *Nature Communications* (2017).

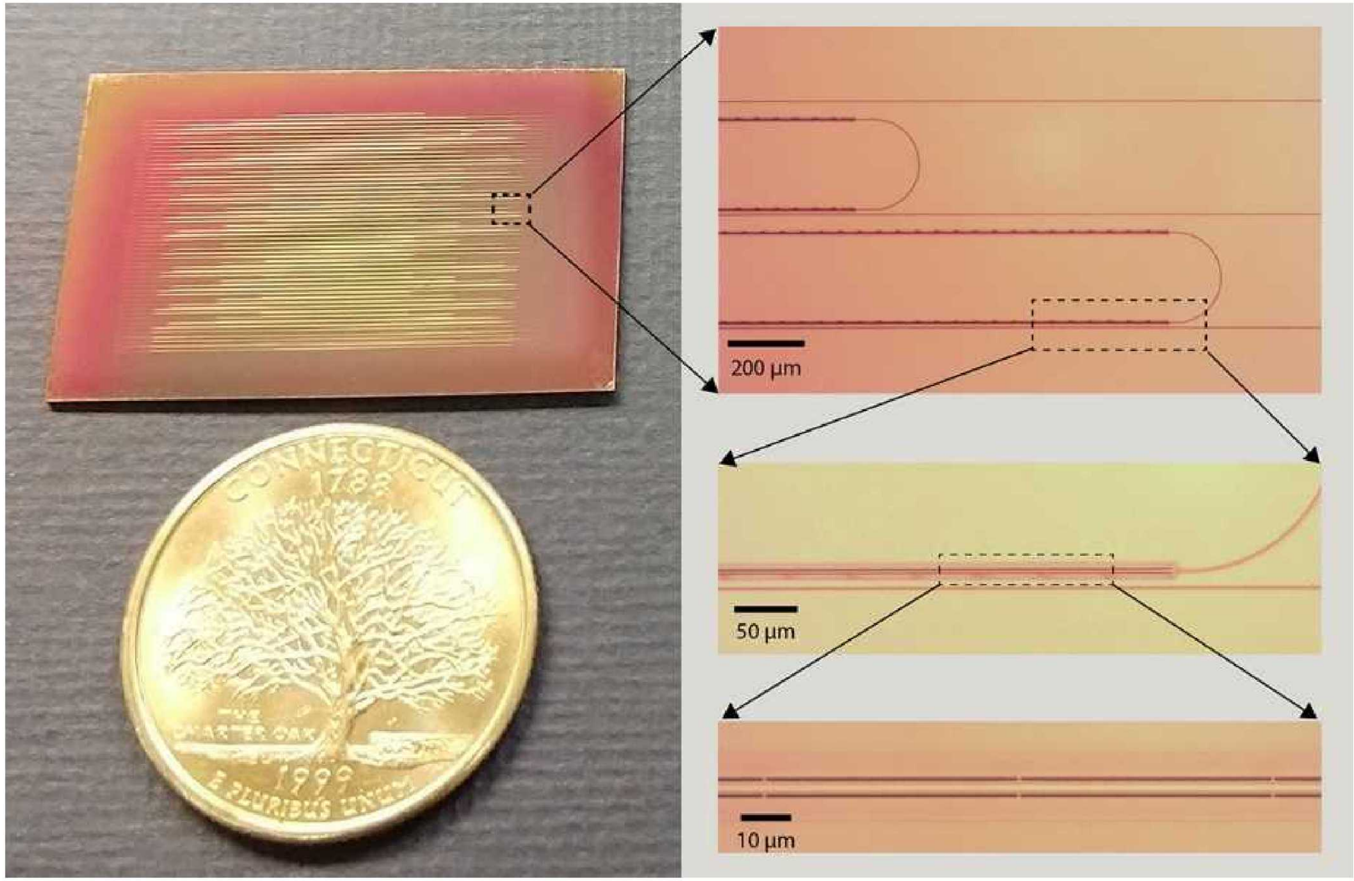
2. Silicon inter-modal Brillouin laser

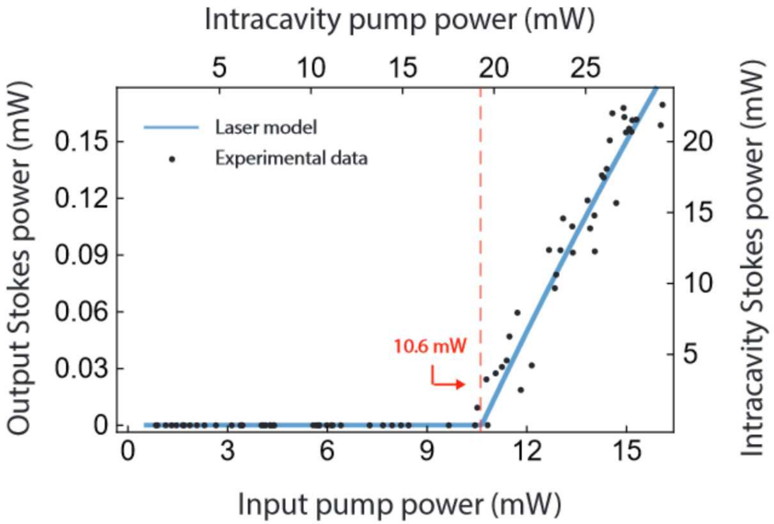


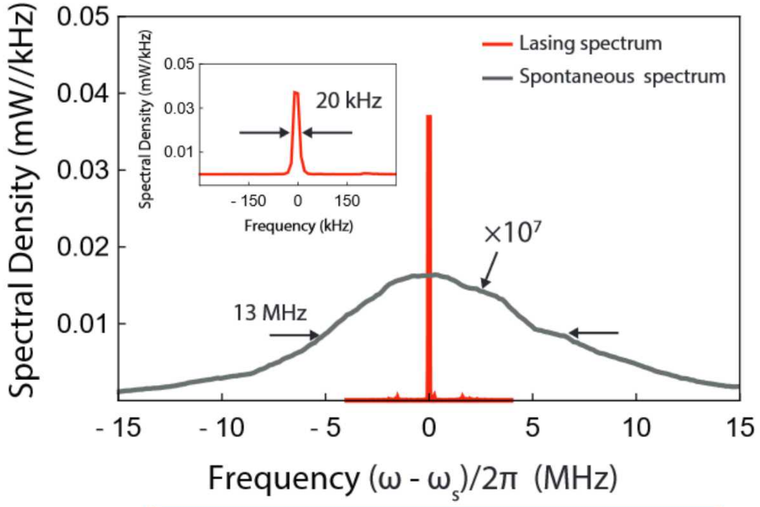
- High-Q multimode racetrack resonator
- Two distinct sets of resonances
- Brillouin-active segment suspended to support 6 GHz elastic wave
- Couple pump into antisymmetric mode satisfying the Brillouin condition
- Stokes can self-oscillate in a symmetric mode

Otterstrom, Behunin, Kittlaus, Wang, Rakich. "A silicon Brillouin laser." ***Science*** (2018).

Observation of laser oscillation







How can we harness these laser dynamics for practical on-chip technologies?

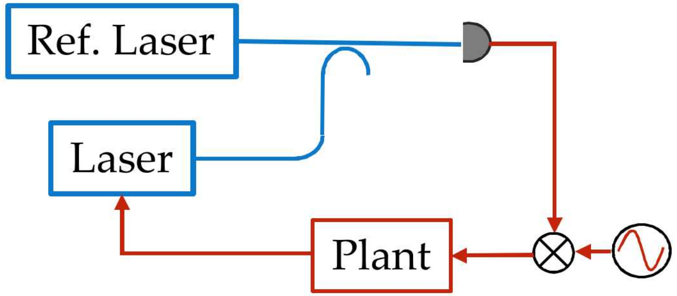
~10^3 compression factor

Otterstrom, Behunin, Kittlaus, Wang, Rakich. "A silicon Brillouin laser." *Science* (2018).

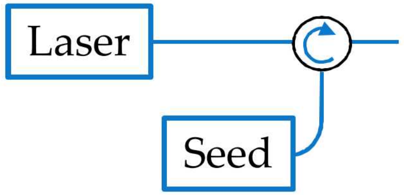
Injection locking

Goal: precisely *control* frequency/phase of a laser

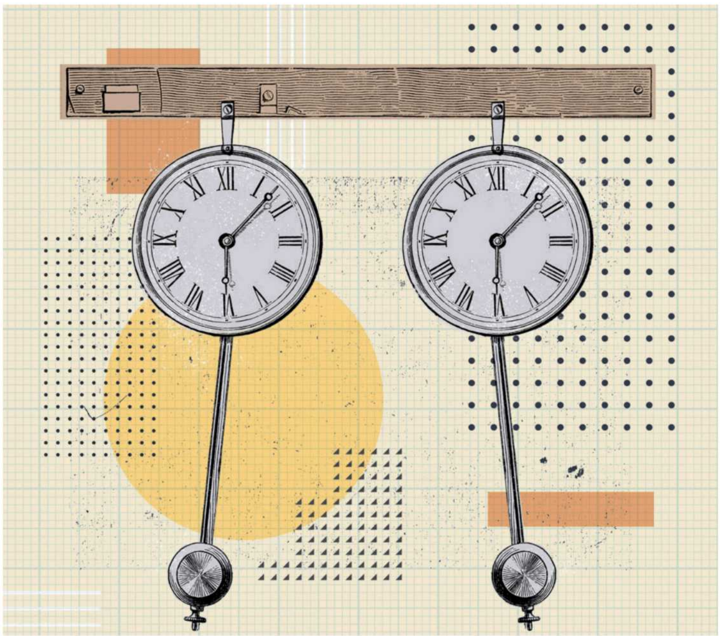
Option 1: Use active, external feedback such as an phase-locked loop



Option 2: Injection lock the laser through nonlinear synchronization



What is synchronization?



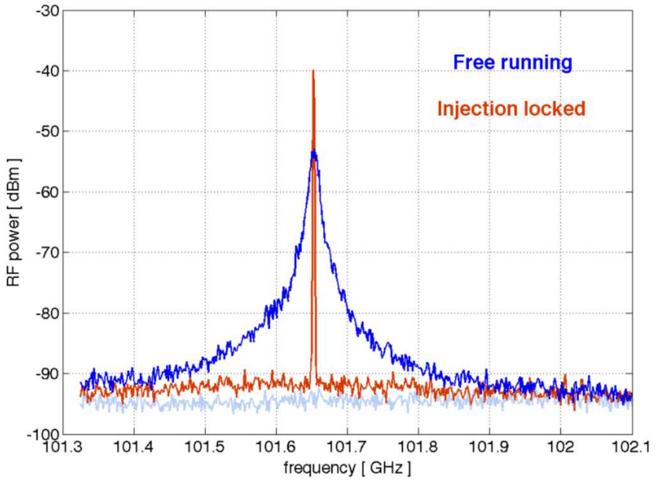
physicsworld.com/a/the-secret-of-the-synchronized-pendulums/

Synchronization requires

- Self-sustained oscillation
- Nonlinearity

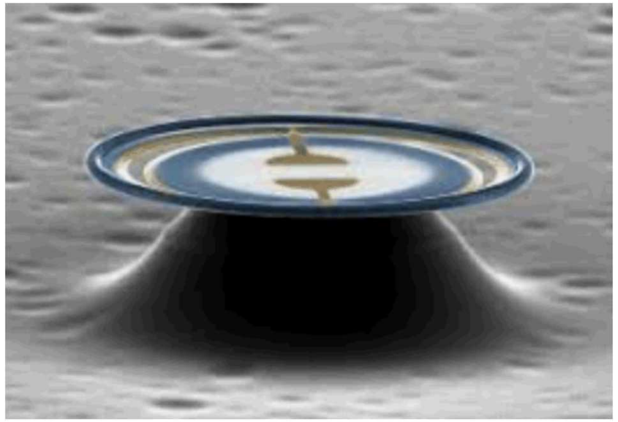
Injection locking

Semiconductor lasers



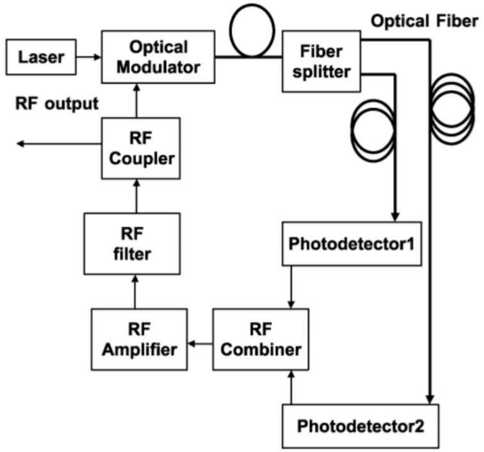
Balakier, Katarzyna, et al. *Opt. Express* (2014)

Electro-optomechanical devices



Bekker, Christiaan, et al. Optica (2017)

Opto-electronic oscillators



Zhou, Weimin, and Gregory Blasche. IEEE Trans. Microw. Theory Tech. (2005)

<u>Injection locking benefits:</u>

- Simple approach that requires no detector, complex locking electronics
- Favorable phase noise properties
- Uses: efficient, low-noise amplification, carrier recovery, microwave synthesis

Can we do this with a Brillouin laser?

Injection-locked operation of Brillouin lasers?

Conventional backward Brillouin lasers

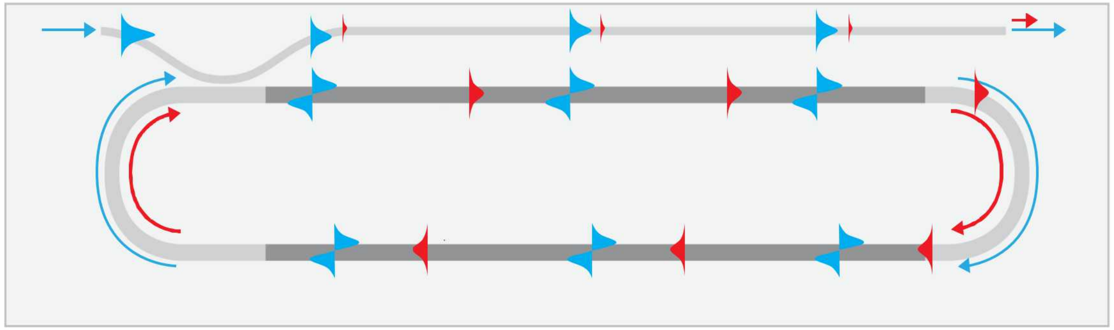
Lee et al. *Nat. Photonics* (2012)

Attractive for **low-noise properties**

However, it has not been demonstrated in conventional Brillouin lasers….

Challenges:
- Backward configuration requires circulators or isolators
- Time dynamics may not be suited to injection locking

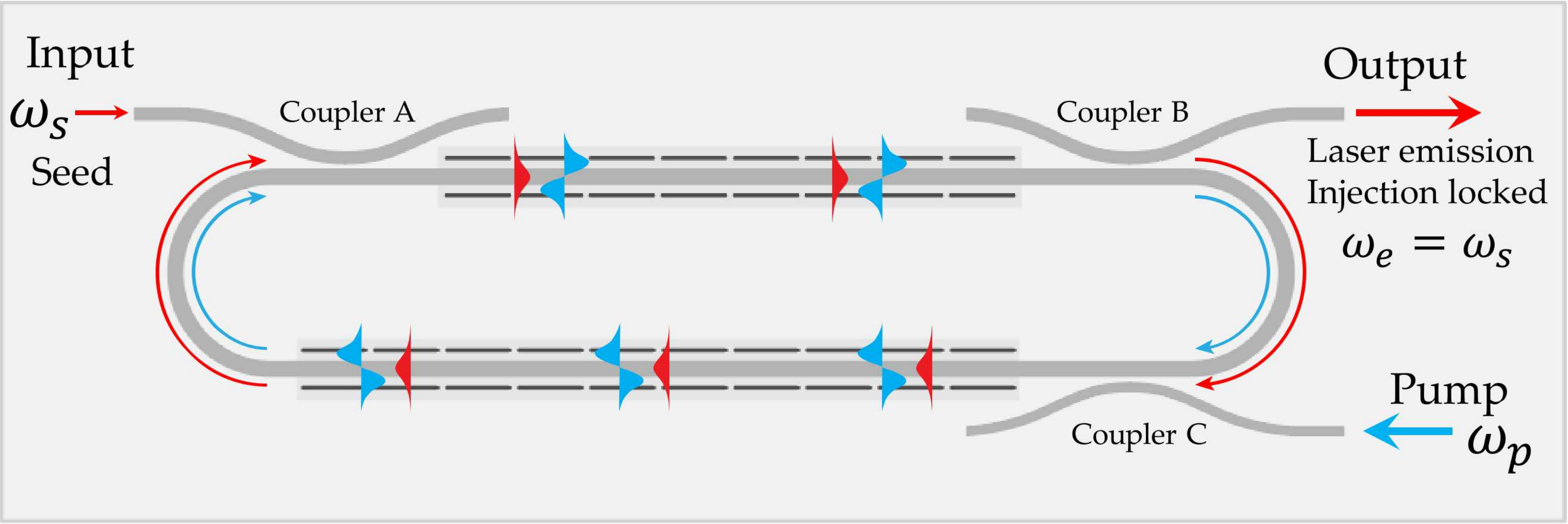
Inter-modal silicon Brillouin laser

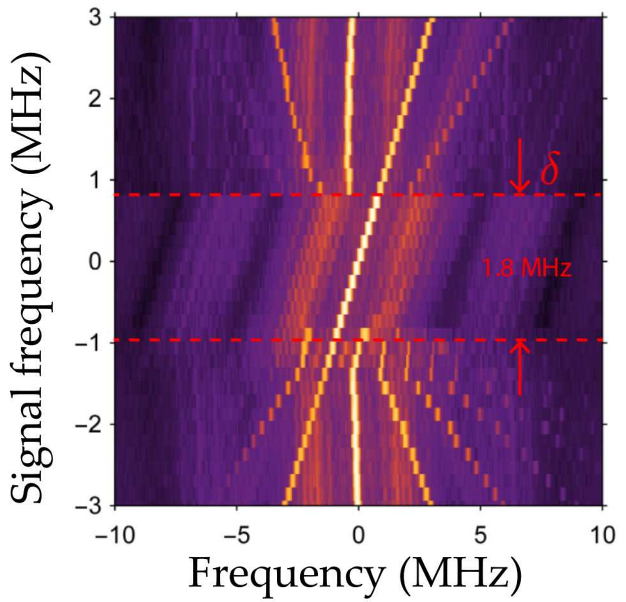


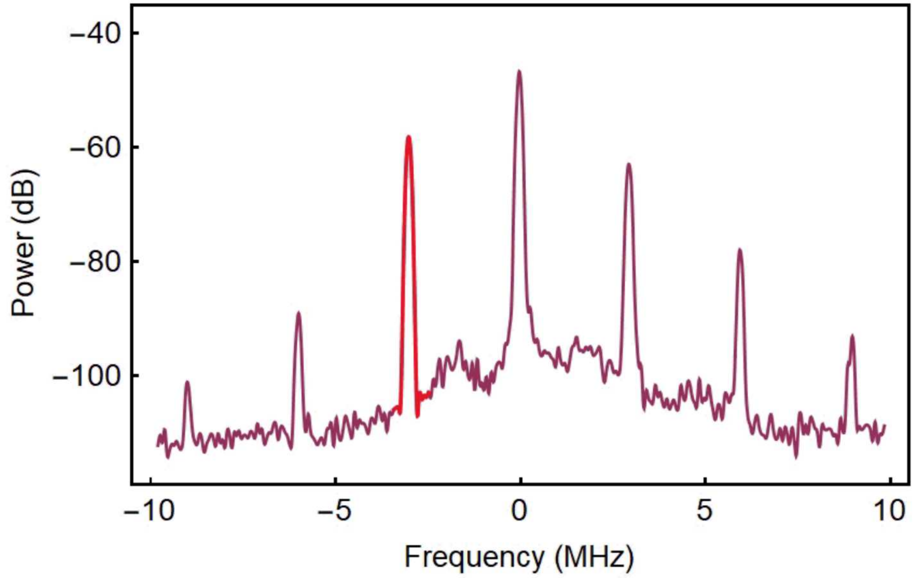
- New modal degrees of freedom
  - Independent control of pump and laser emission
  - No cascading
- Unique regime of spatio-temporal dynamics
  - Yields high degree of coherence between pump and laser emission
- Phase-matched forward gain mechanism
- CMOS-foundry compatible

Silicon Brillouin lasers ideally suited to injection locking

Injection-locked Brillouin laser (Sandia collaboration)





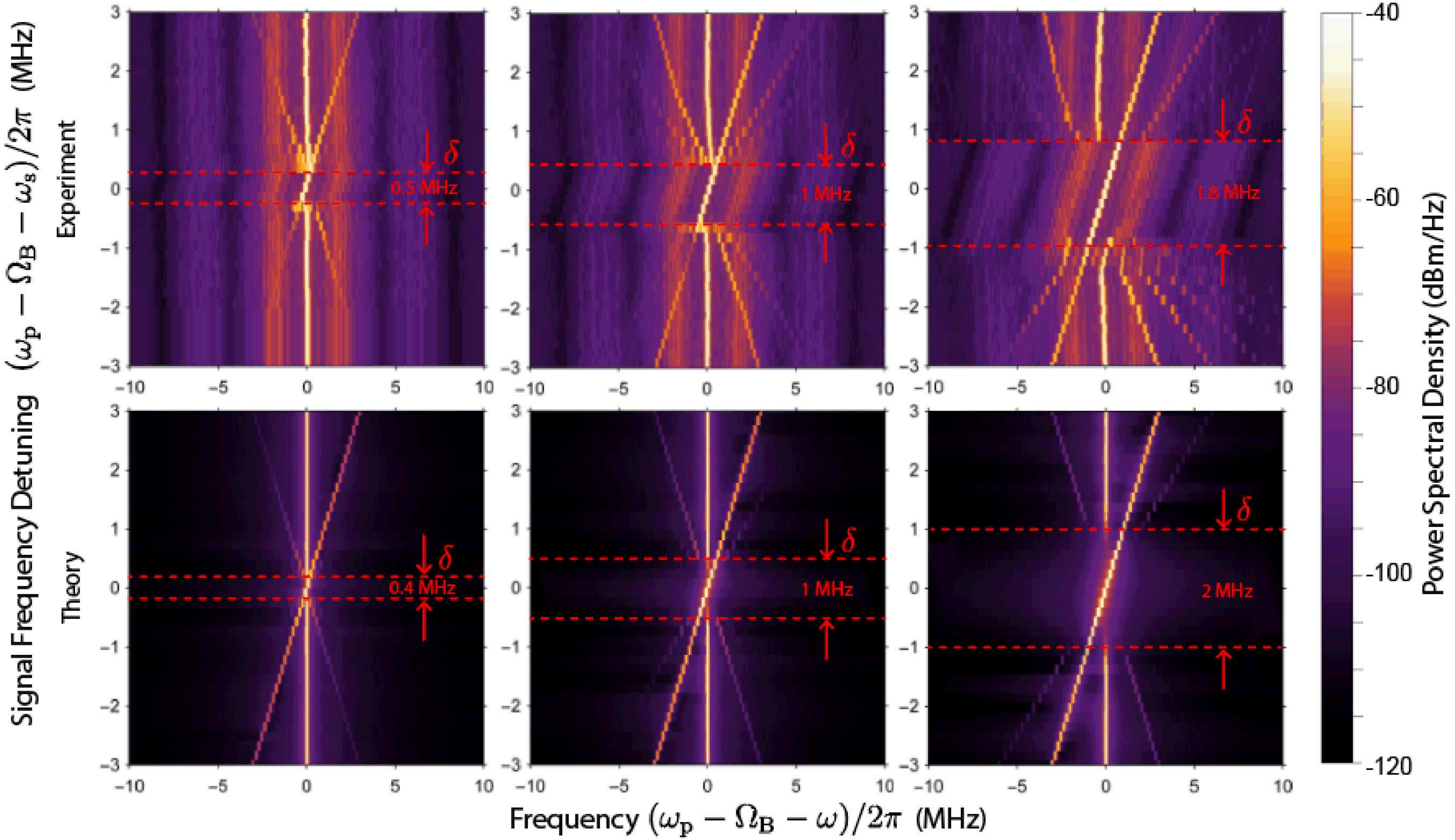


Characterizing lock range

- Inject pump wave into the antisymmetric mode that satisfies the Brillouin condition
- Once above threshold, inject a low-power seed into the symmetric spatial mode
- Sweep seed through the laser emission frequency to determine **lock range**.

What happens when we inject light in the opposite direction?

Lock range and amplification



Characterizing lock range

- Lock range expands as the seed power is increased
- Crescendo of phonon-mediated FWM outside lock range
- Stochastic simulations show good agreement

Up to 23 dB of **effective net amplification**!

What about the noise properties of the system?

Phase noise reduction properties

Driven silicon Brillouin laser dynamics:

Separate into amplitude $\delta\beta(t)$ and phase $\phi(t)$ fluctuations

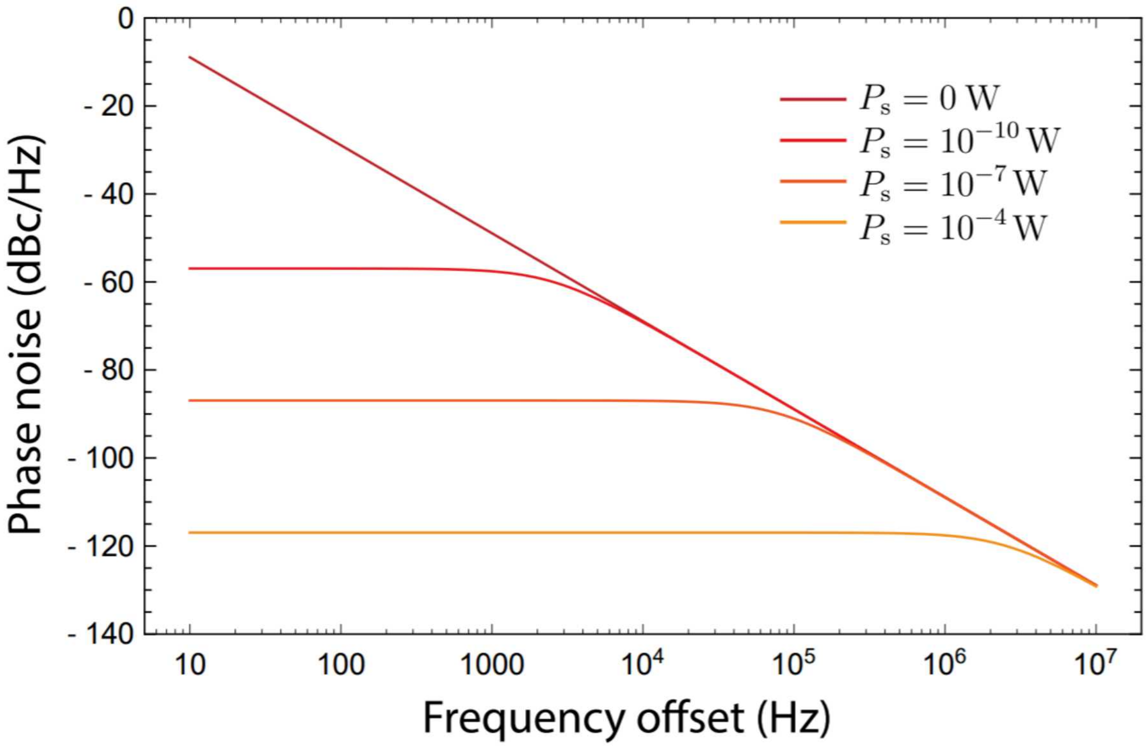
Thermal phonons

$$\mathscr{L}(f) = \frac{\Gamma(2n_{\mathrm{th}}+1)}{4\beta^2}\frac{1}{(\pi\delta)^2+(2\pi f)^2}$$

Coherent number

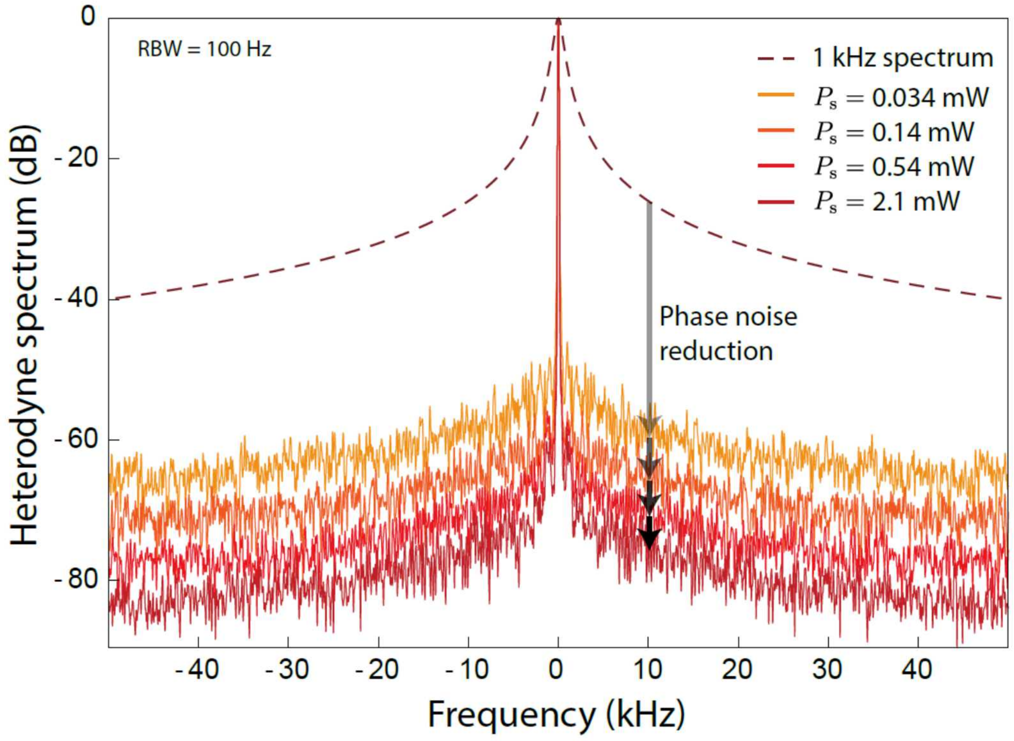
Lock range

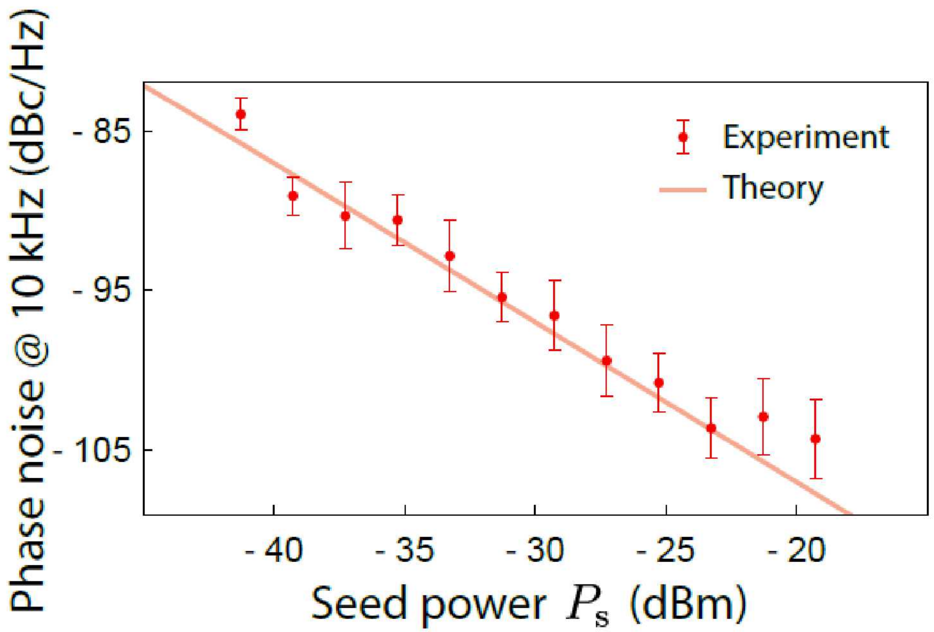
Offset freq.



Injection of a coherent seed should dramatically reduce the phase-noise beyond Schawlow-Townes limit!

Phase noise reduction properties





Thermal phonons

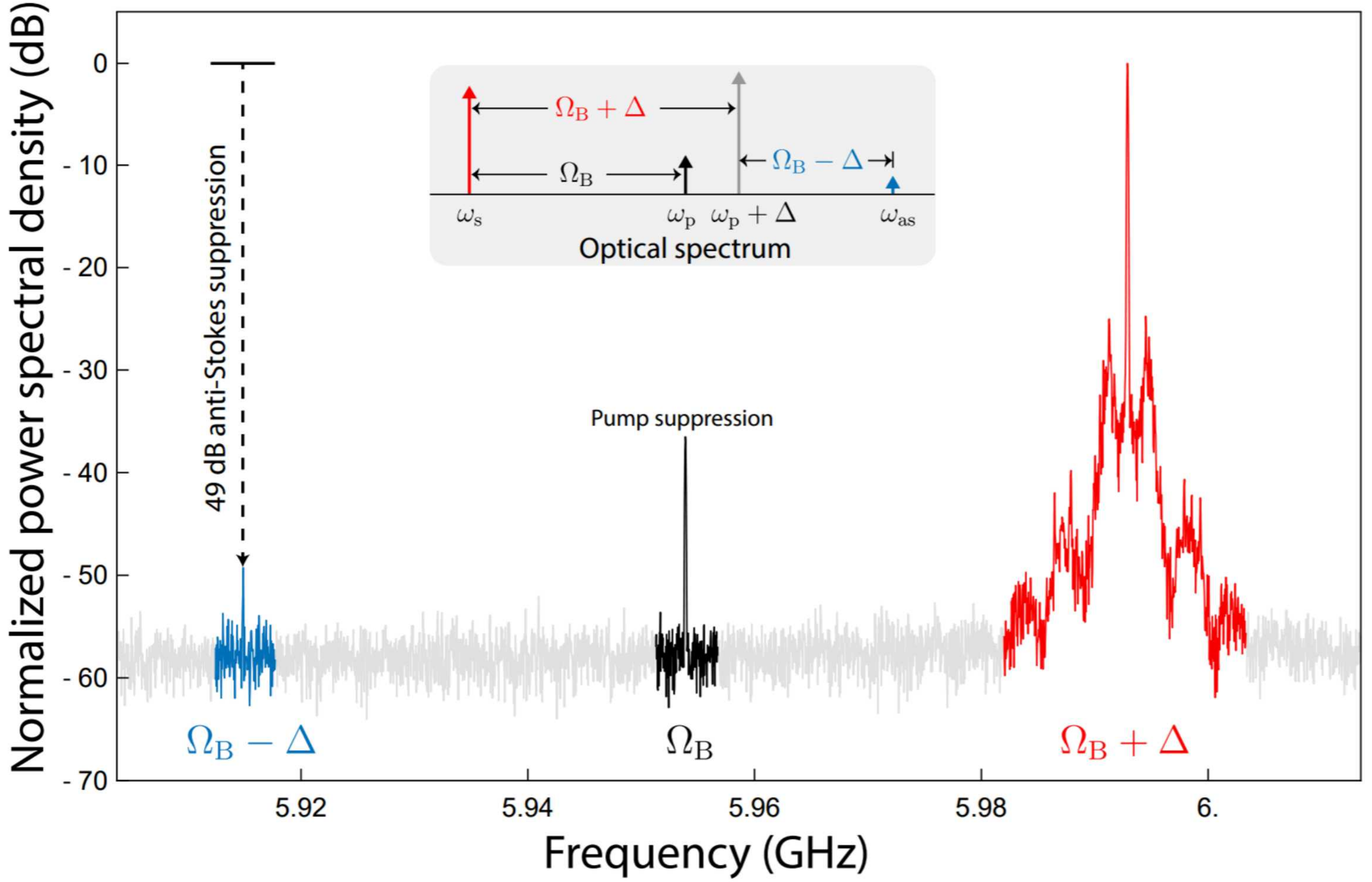
$$\mathscr{L}(f) = \frac{\Gamma(2n_{\text{th}}+1)}{4\beta^2} \frac{1}{(\pi\delta)^2 + (2\pi f)^2}$$

Coherent number Lock range Offset freq.

- ~70 dB of phase noise reduction @ 10 kHz
- <-100 dBc/Hz @10 kHz

Improve phase noise by nearly 7 orders of magnitude at low frequencies!

Single sideband characteristics and pump suppression



- 49 dB of anti-Stokes suppression
- Nearly 50 dB of pump suppression

Highly single-sideband process

- Thanks to phase-matching and mode-selective couplers

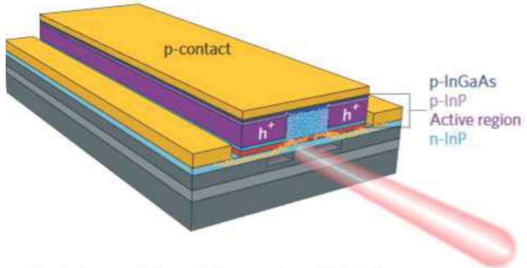
Opens the door to simple, single-sideband modulator technologies in silicon

Back-scatter immunity and non-reciprocity

Challenge: Susceptibility to feedback disrupts laser performance => need isolators

Conventional strategy: assumes laser and isolator *are distinct*.

Our new approach: Create a laser that *is itself* a non-reciprocal element



D. Liang *Nat. Photonics* (2010)

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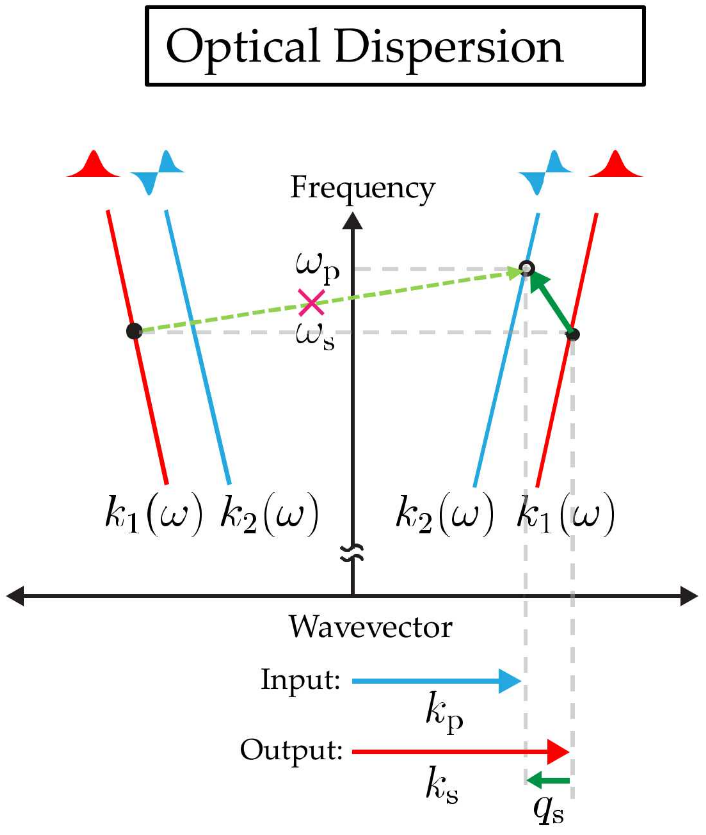
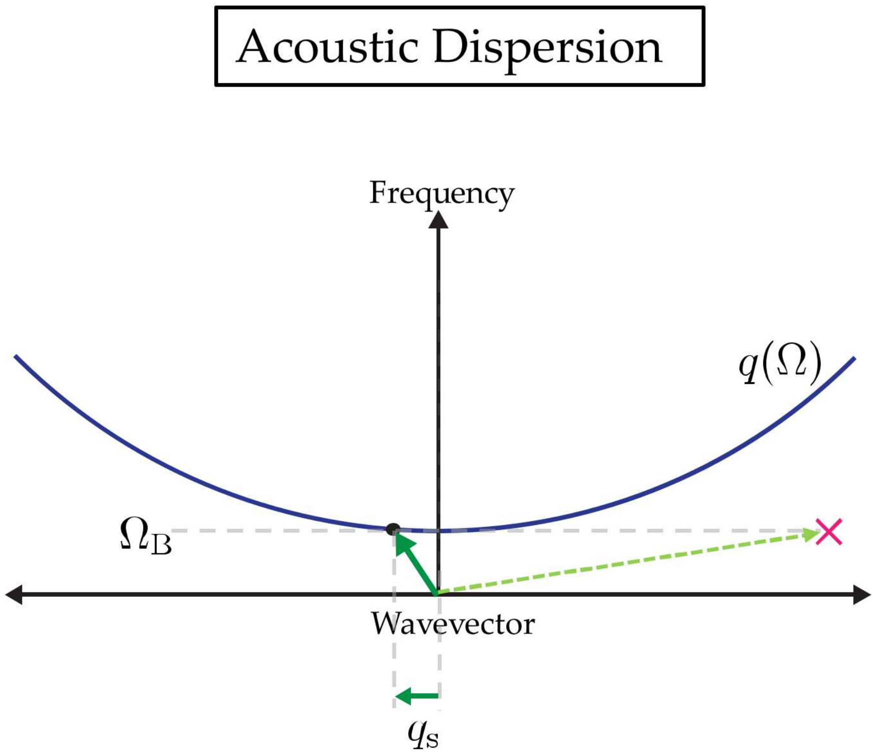
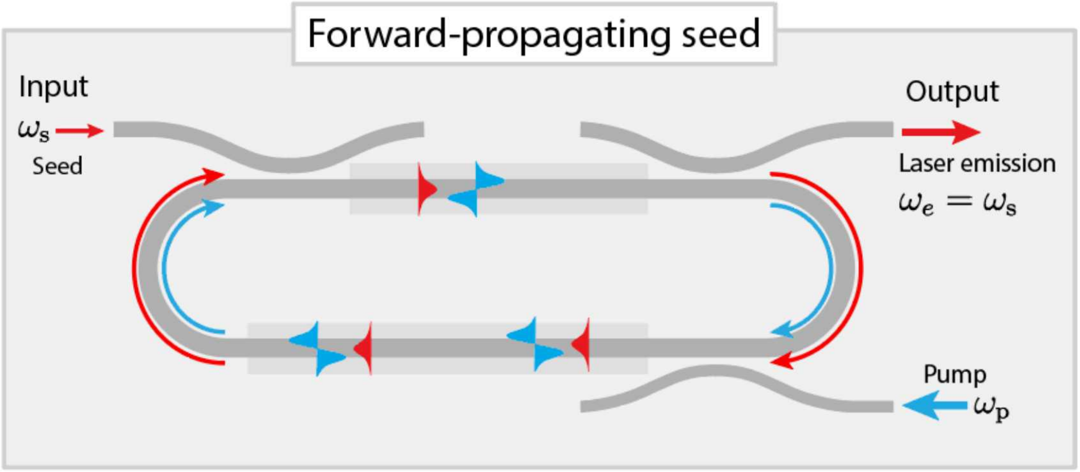
Unidirection gain mechanism

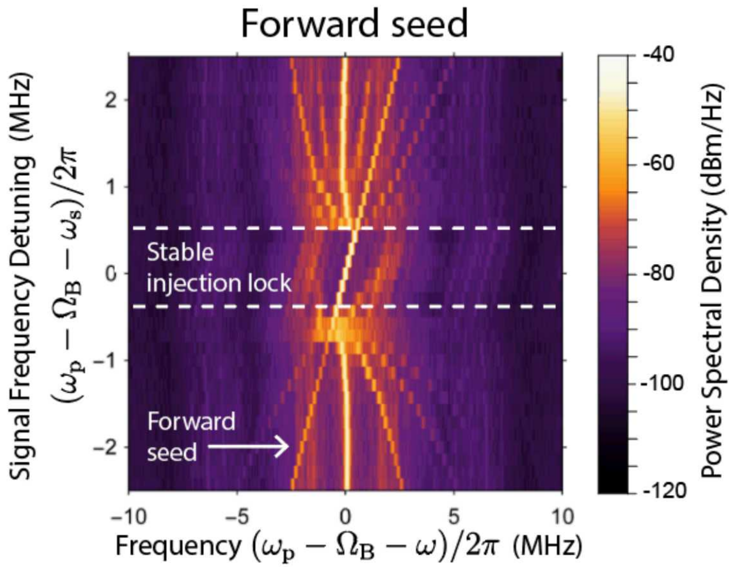


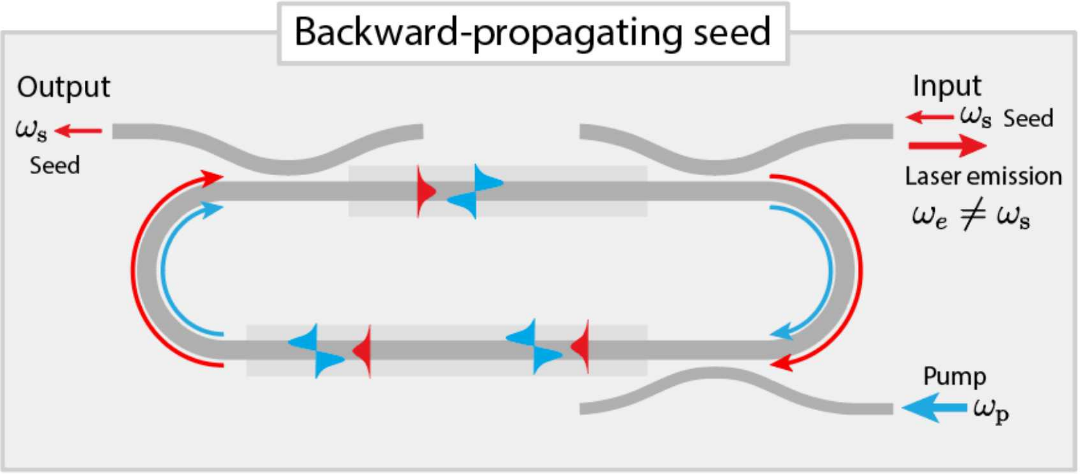


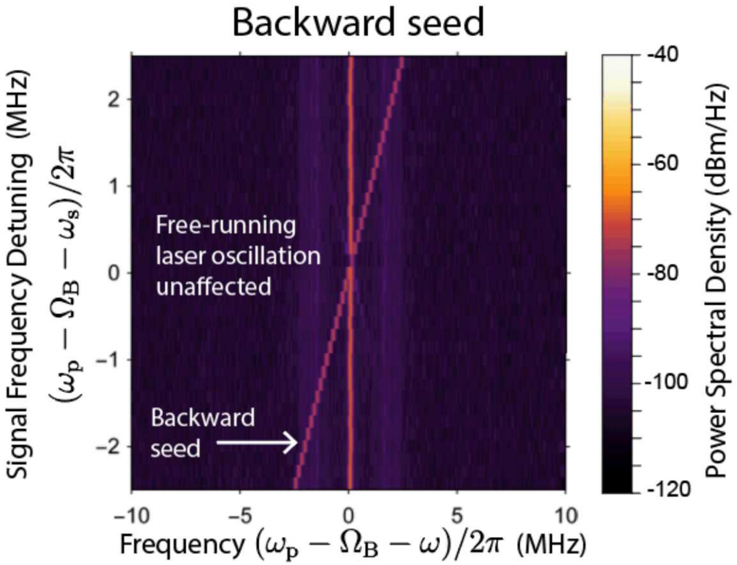
Phonon **does not phase-match** to Brillouin in the **backward** direction!=> **Unidirectional gain**

Back-scatter immunity and non-reciprocity









Nonreciprocity

- Forward propagating seed injection locks the laser
- Unwanted backward propagating interferer leaves the laser unaffected
- Nonreciprocal control and back-scatter immunity.

Conclusions

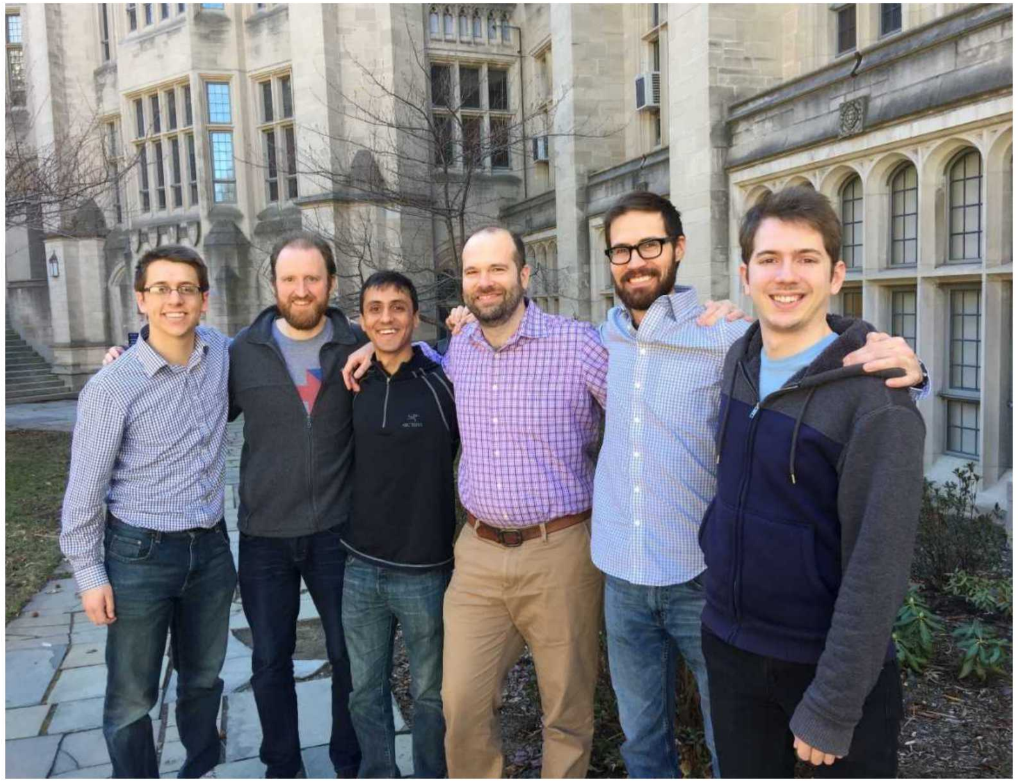
1. Engineer phase-matched nonlinearities to create a silicon Brillouin laser
2. Manipulate dynamics through injection locking to achieve a broad range of functionalities

- Record high amplification (23 dB)
- Phase noise reduction (~70 dB)
- Single-sideband amplification
- Back-scatter immunity
  - New paradigm for non-reciprocal devices in silicon
- CMOS-foundry compatible

Otterstrom, Gertler, Zhou, Kittlaus, Behunin, Gehl, Starbuck, Dallo, Pomerene, Trotter, Lentine, and Rakich. "Back-scatter immune injection-locked Brillouin laser in silicon." arXiv preprint arXiv:2001.04871 (2020)

Powerful new devices physics for silicon-based amplifiers, low-noise lasers, and non-reciprocal devices

Acknowledgements



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