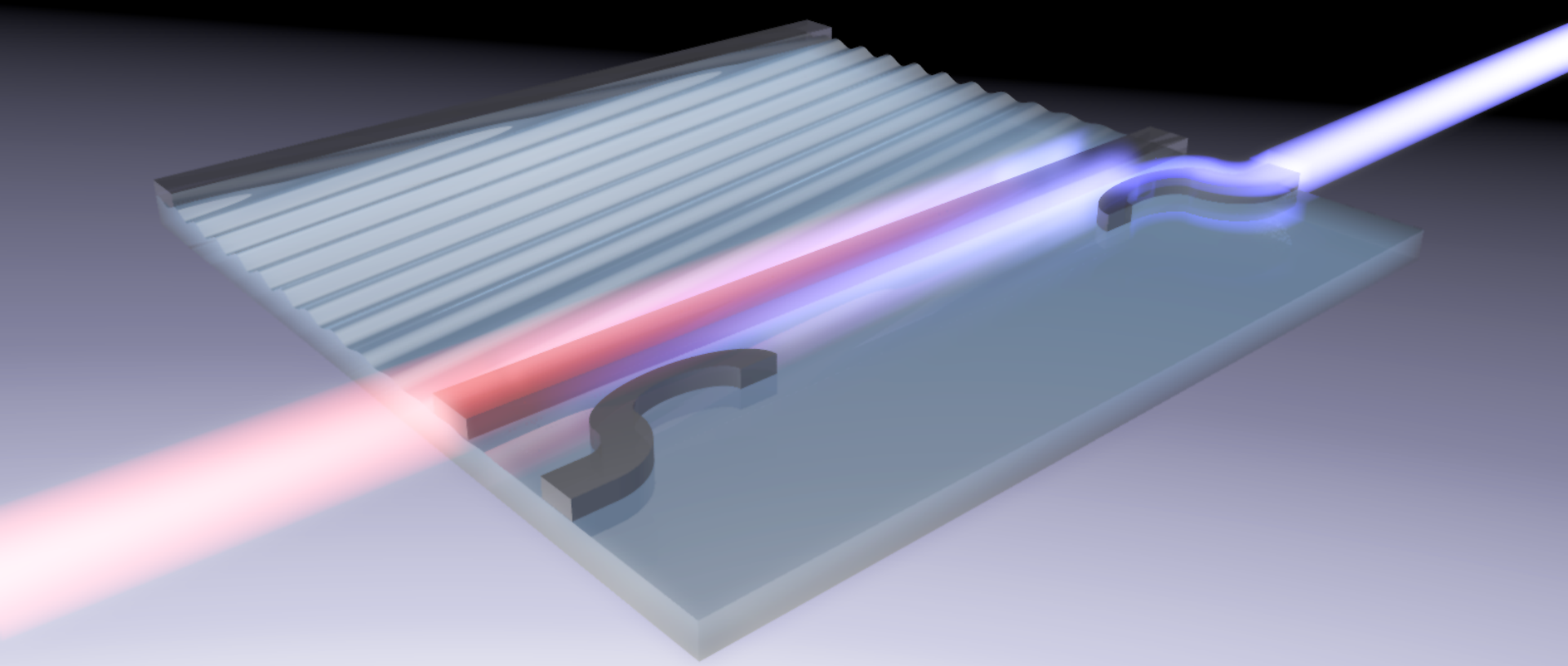
Nonreciprocal Optics with Inter-band Brillouin Scattering

Eric A. Kittlaus[1,2], Nils T. Otterstrom[2], Prashanta Kharel[2], Shai Gertler[2], and Peter T. Rakich[2]



[1] Jet Propulsion Laboratory, California Institute of Technology
[2] Department of Applied Physics, Yale University

WOMBAT 2019 - We7
Opto-Mechanical Devices II
March 27, 2018

Background

Integrated Photonics

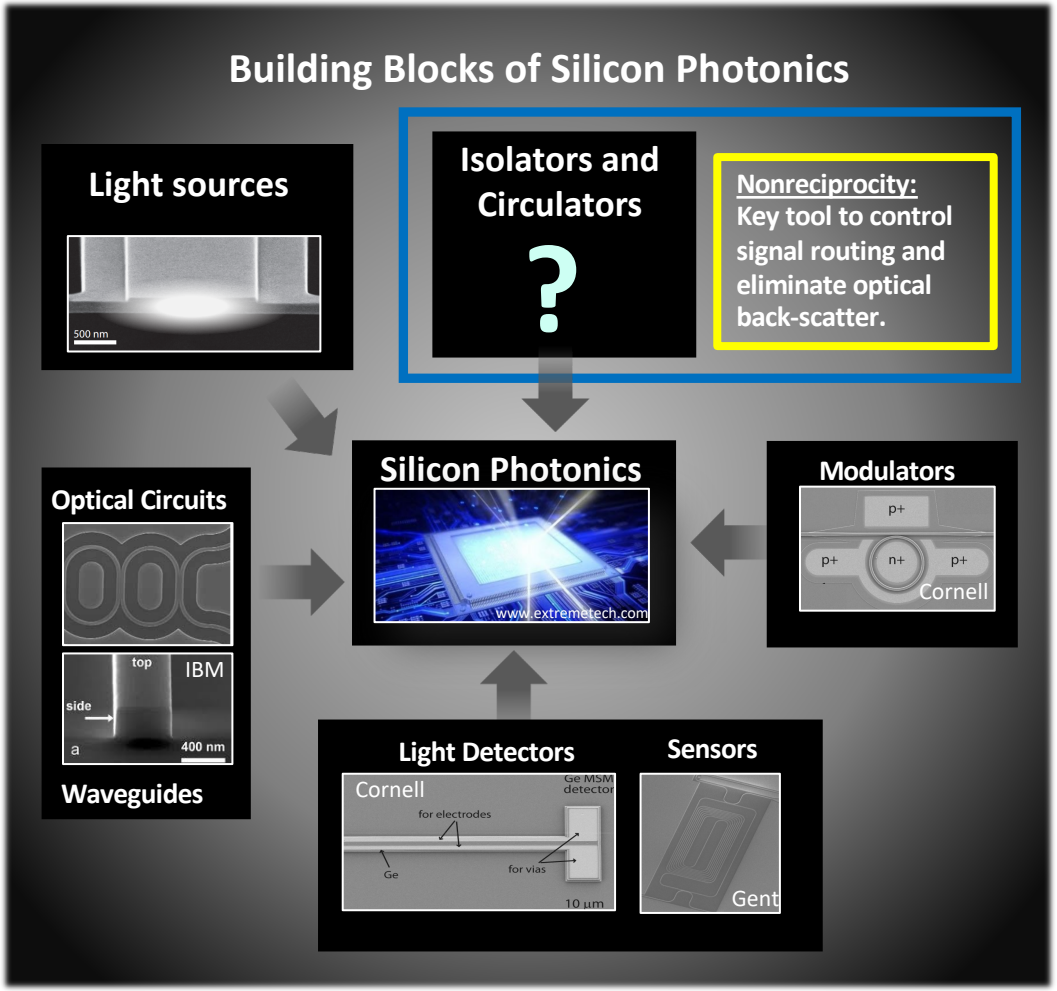
Rapidly growing field has produced integrated optical circuits, detectors, modulators, etc…

Remaining challenge: nonreciprocal devices

Creating robust isolators and circulators remains a key challenge

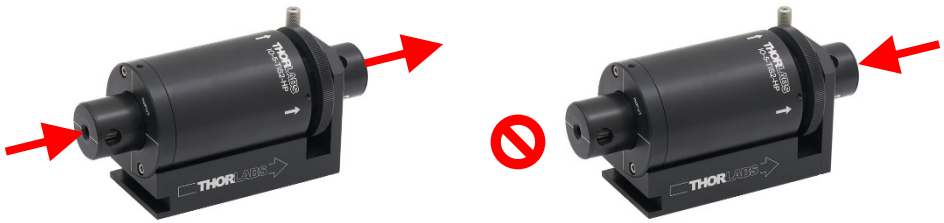
Goal

Demonstrate robust nonreciprocal operation on-chip



Nonreciprocal optics

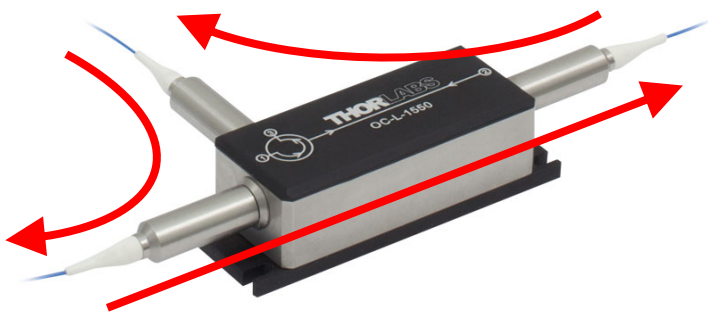
Isolator: unidirectional light transmission



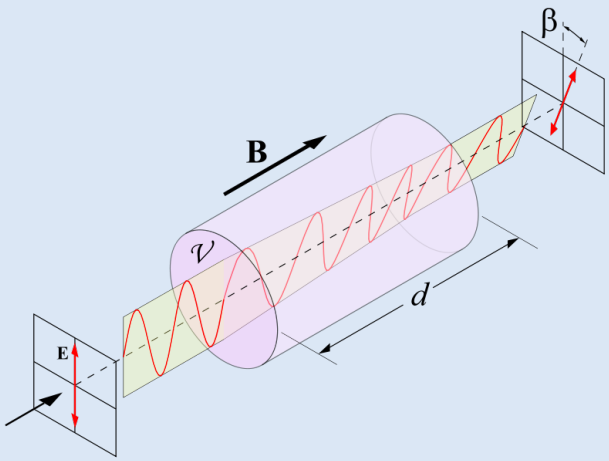
Applications of nonreciprocal light propagation:

- Protect optical components (e.g. lasers) from back-scatter
- Separate forward- and backward-propagating optical signals

Circulator: route optical signals

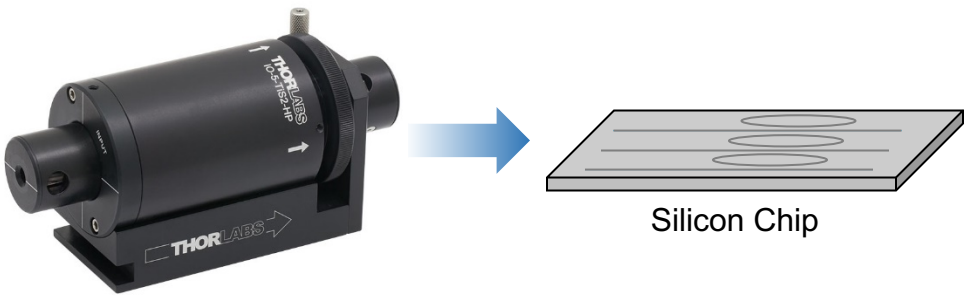


Based on magneto-optic effect

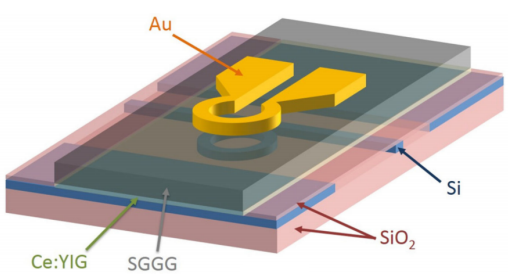


Integrated nonreciprocal optics

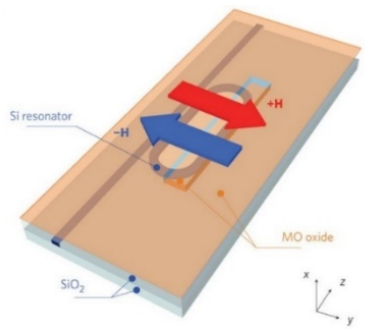
Goal: Implement nonreciprocal light propagation in integrated photonic circuits



Problem: Despite great efforts, it is difficult to adapt existing Faraday isolator technologies to integrated photonics



Huang et al., *IEEE JSTQE* **22**, 271 (2016)



Bi et al., *Nat. Photonics* **5**, 758 (2011)

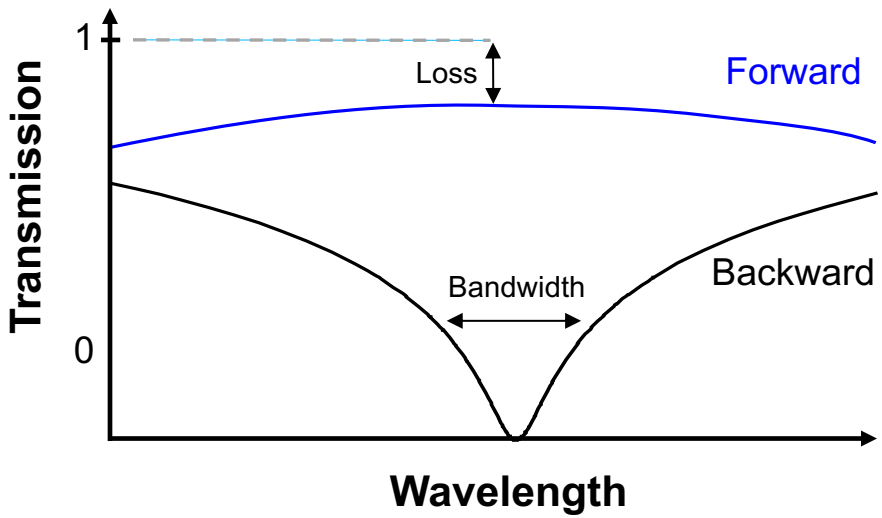
Challenges

- High insertion losses
  - Materials with strong magneto-optic response are intrinsically lossy
- Resonant structures often necessary
  - (Limits operation bandwidths to ~GHz)
- Complex fabrication
  - Challenging to integrate magneto-optic garnets with Si/SiN/InP circuits
  - Not CMOS-compatible
- Requires magnetic fields to be present

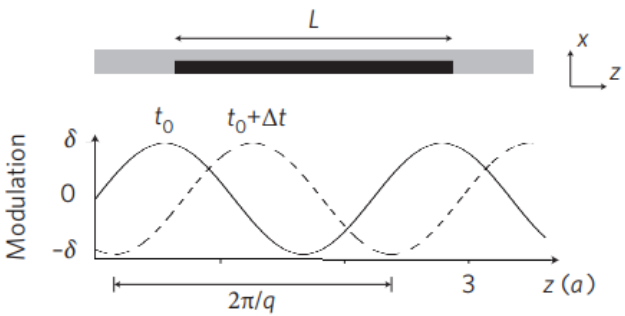
‘Wish list’ for integrated nonreciprocal optics

Ideal device

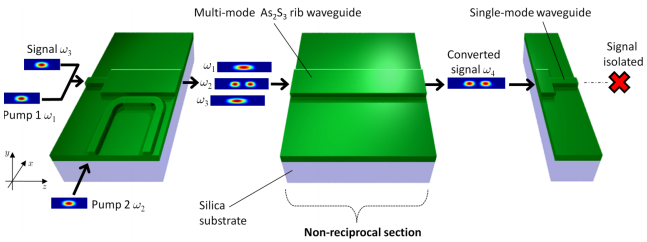
- Low insertion loss (<1 dB)
- Significant nonreciprocal contrast (>20 dB) over a large operating bandwidth (>1 nm)
- CMOS-compatible materials / no magnets



One Proposal: Time Modulation



Yu & Fan, *Nat. Photonics* **3**, 91 (2009)



Poulton et al., *Opt. Express* **20**, 19 (2009)

Theoretical proposals have shown **time-modulation of optical waveguides** as a promising path to achieve on-chip nonreciprocity

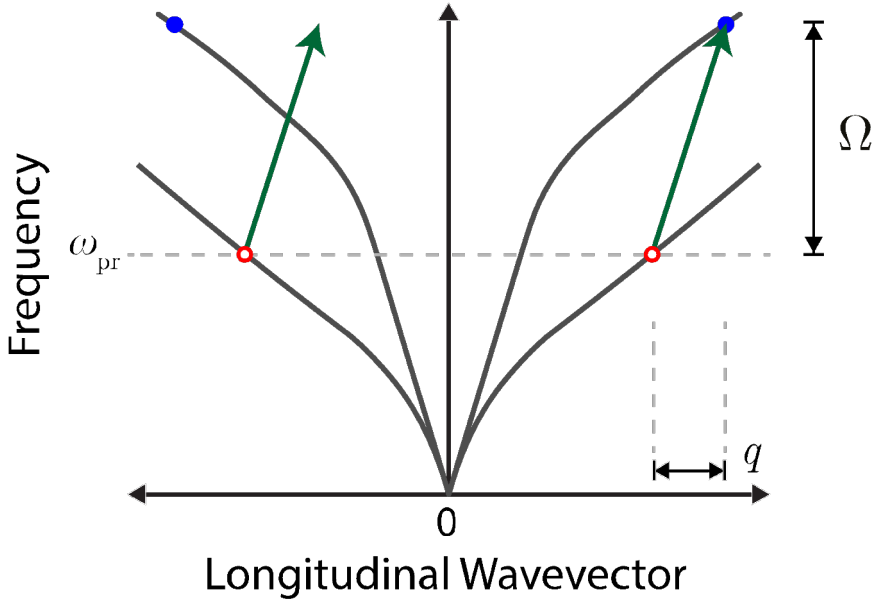
How does this work?

ST Modulation: one path to nonreciprocity

Nonreciprocity by indirect inter-band transitions

Spatio-temporal modulation with wavevector q and frequency Ω scatters light between distinct dispersion bands

This process is phase-matched in only one propagation direction



Condition for nonreciprocal operation:

Interaction Length

$$L \gg \frac{v_g}{\Omega}$$

Optical group velocity

Modulation Frequency

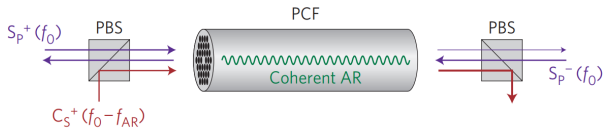
cm lengths for 10 GHz modulation!

Other critical ingredient: symmetry

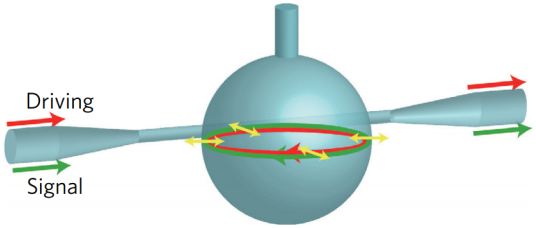
Non-magnetic nonreciprocity

Recent experimental work has explored methods to produce non-magnetic nonreciprocity.

Optomechanics



Kang et al., *Nat. Photonics* **5**, 549 (2011)

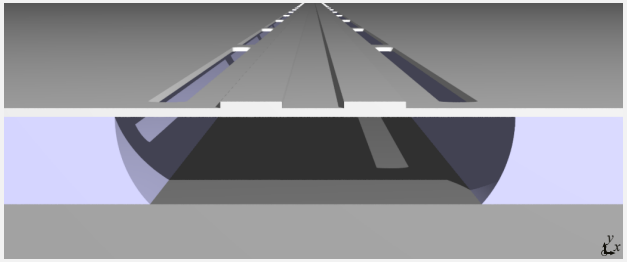


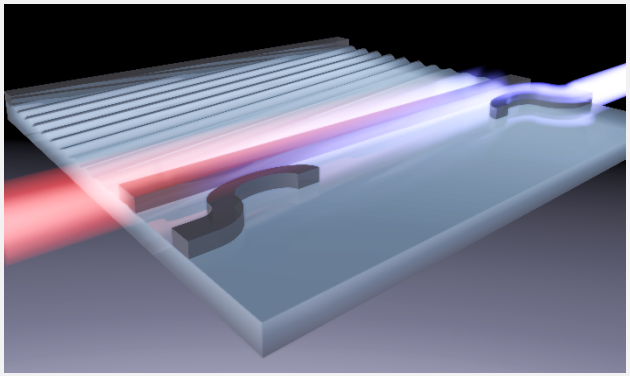
Shen et al., *Nat. Photonics* **10**, 657 (2016)

Challenge: typically very narrowband (kHz-MHz)

Non-magnetic nonreciprocity

Recent experimental work has explored methods to produce non-magnetic nonrec





One solution:
Harness acousto-optic modulation from traveling elastic waves

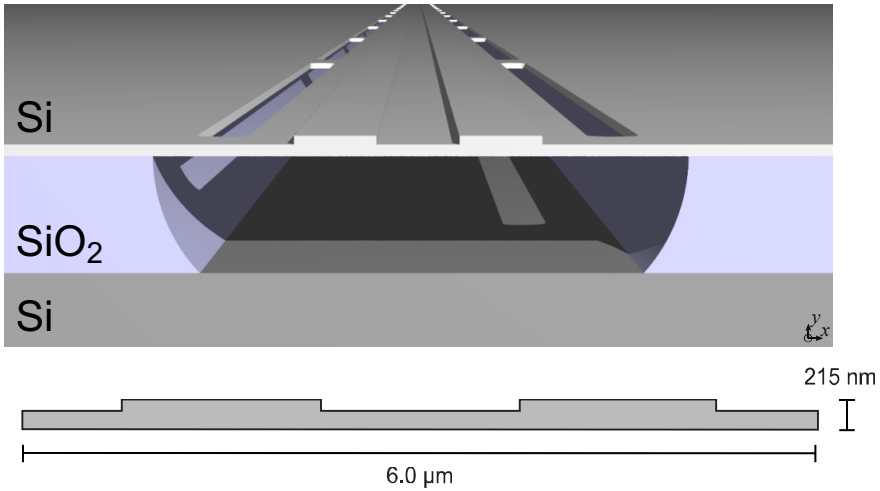
Device concept:
Silicon waveguide inter-band modulator utilizes optically driven acoustic waves to produce modulation over cm-length scales

Challenge: typically very narrowband (kHz-MHz)

Common challenge: how to induce robust spatiotemporal modulation over large interaction lengths?

Silicon waveguide inter-band modulator

Device Structure



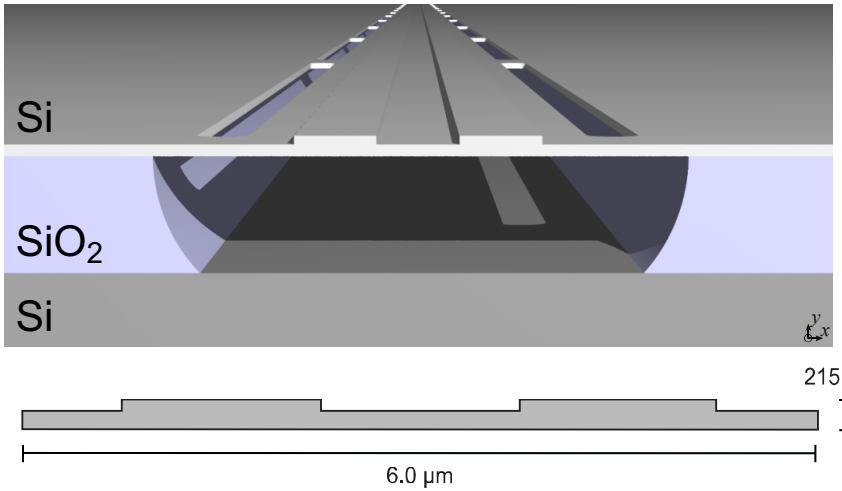
Suspended silicon optomechanical waveguide fabricated on SOI wafer

2.4 cm long device

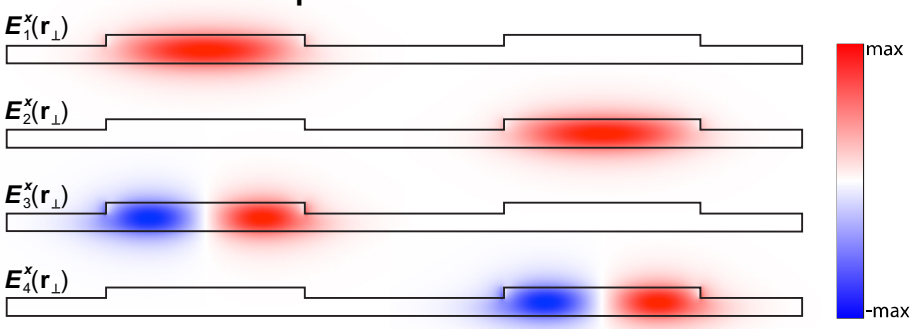
E.A. Kittlaus, N.T. Otterstrom, P. Kharel, S. Gertler, and P.T. Rakich. *Nat. Photonics.* 12, 613 (2018).

Silicon waveguide inter-band modulator

Device Structure

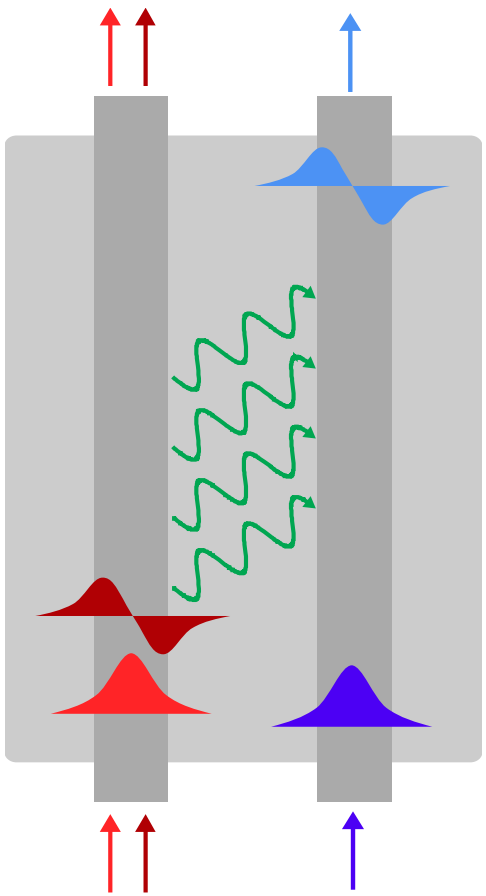


Optical Modes



Elastic Mode

Operation Scheme

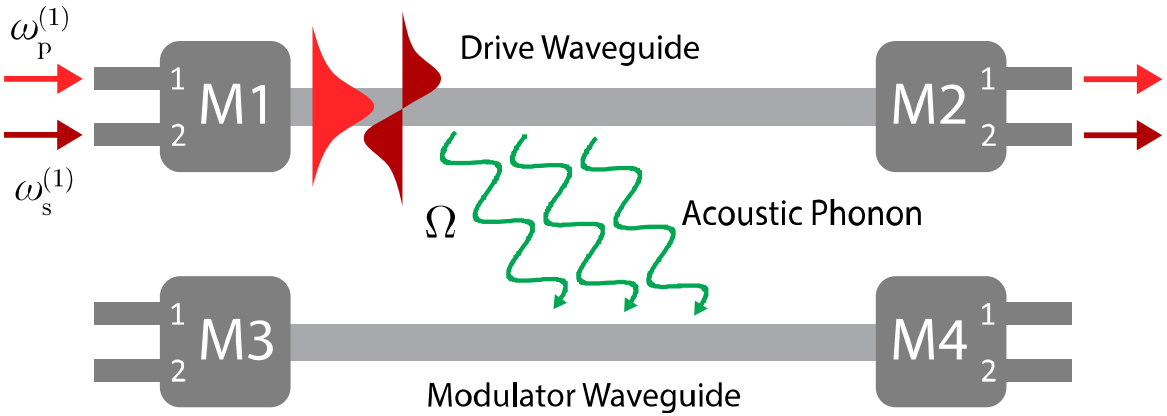


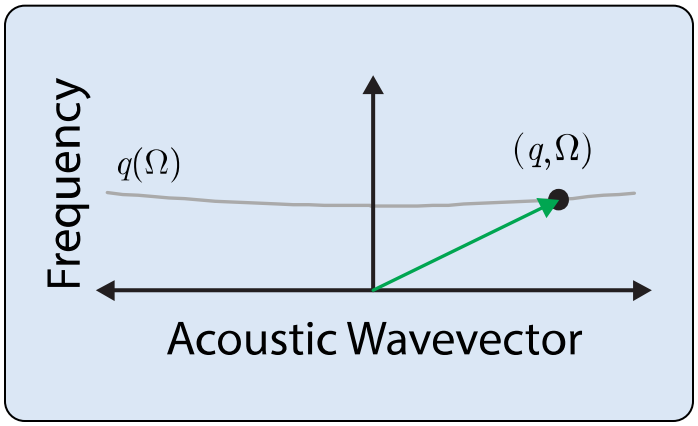
Acoustic drive created in one waveguide through optical forces

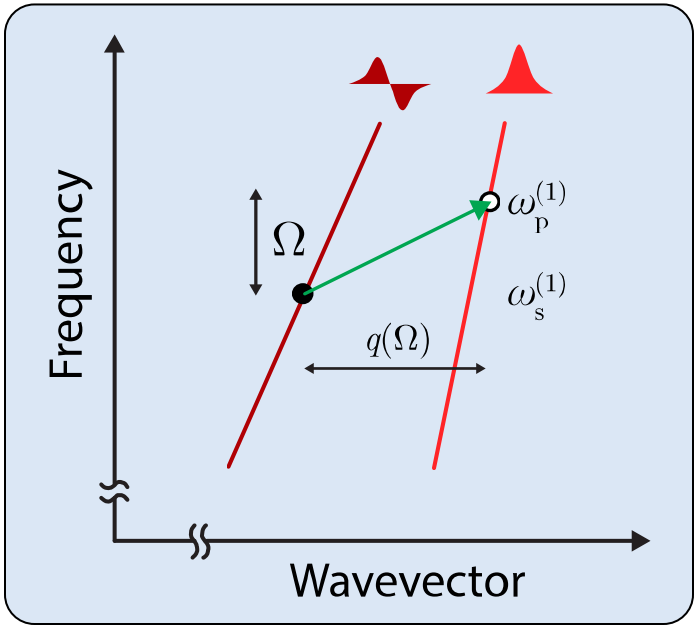
Modulates and mode-converts light in second waveguide through linear acousto-optic scattering

E.A. Kittlaus, N.T. Otterstrom, P. Kharel, S. Gertler, and P.T. Rakich. *Nat. Photonics.* 12, 613 (2018).

Silicon waveguide inter-band modulator







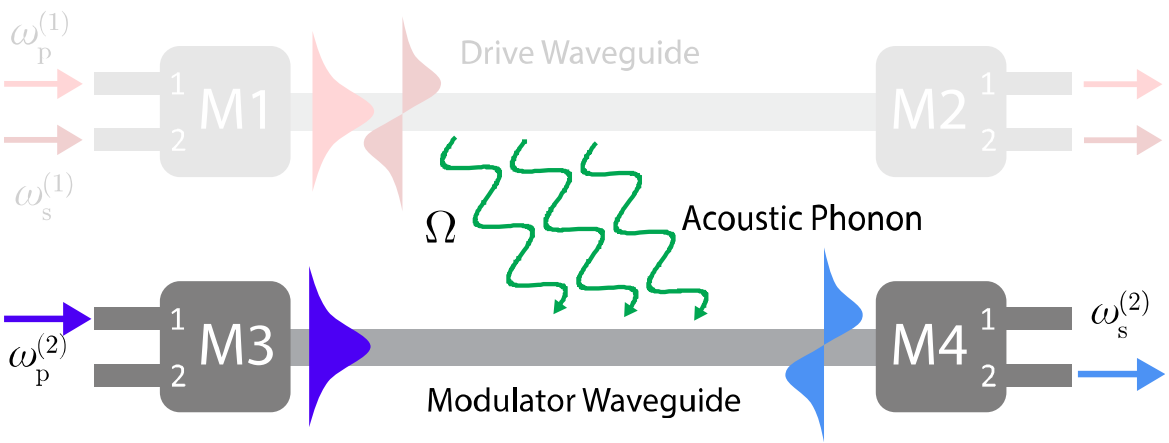
Integrated mode multiplexers couple pump waves into distinct optical modes

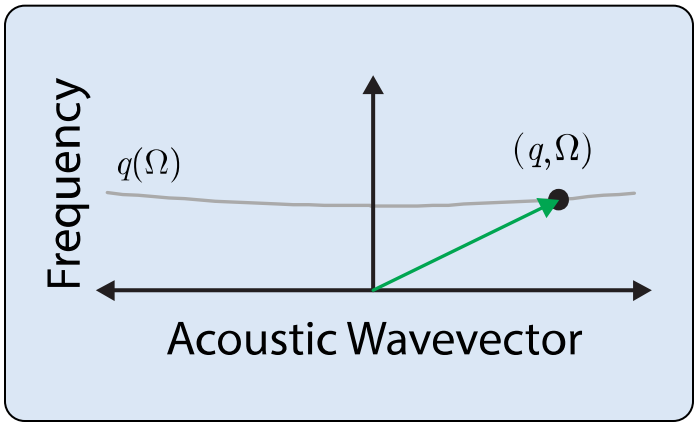
These optical waves drive a travelling acoustic phonon at difference frequency Ω through electrostriction

Wavevector of driven phonon set through optical dispersion
(phonon wavevector tunability)

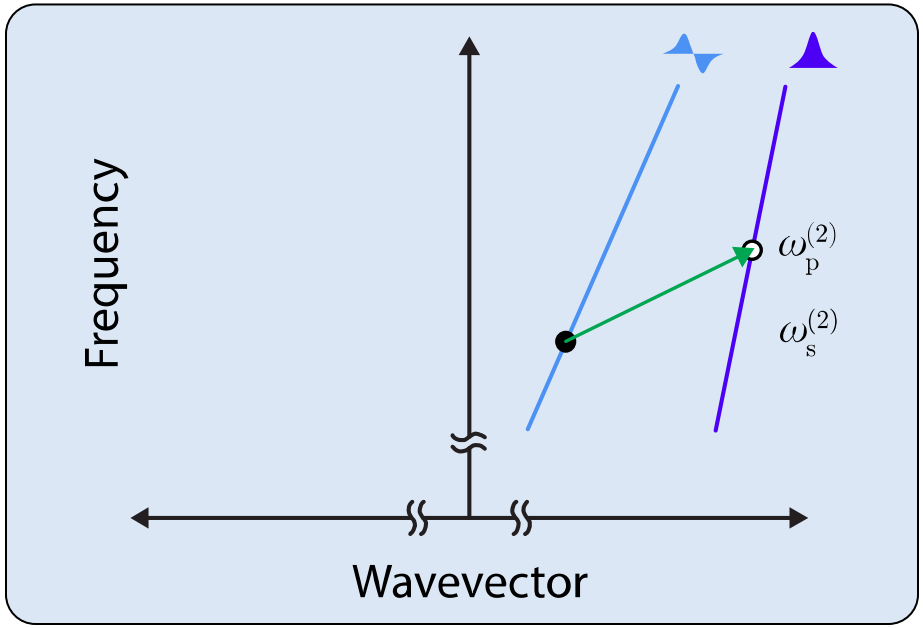
E.A. Kittlaus, N.T. Otterstrom, P. Kharel, S. Gertler, and P.T. Rakich. *Nat. Photonics.* 12, 613 (2018).

Silicon waveguide inter-band modulator





Light injected in the **forward** direction is mode-converted and frequency shifted if phase-matching is satisfied



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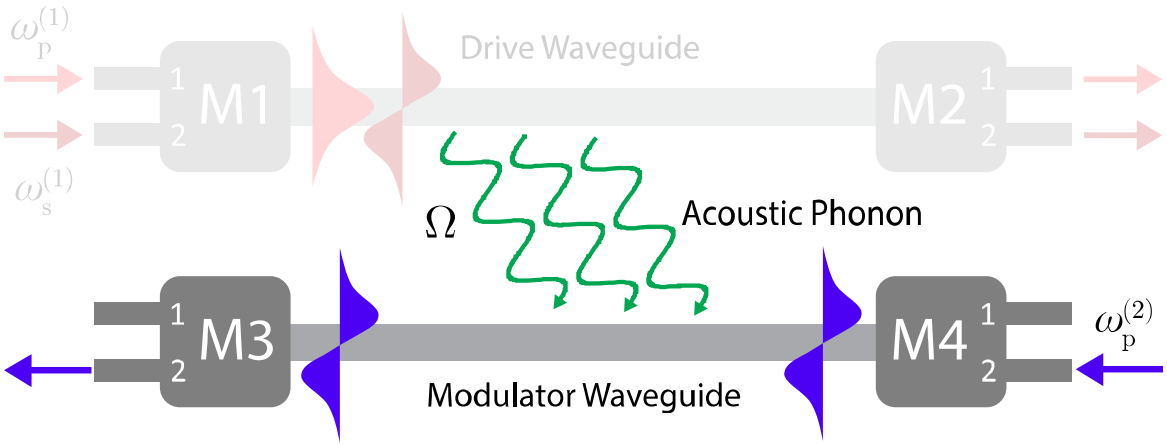
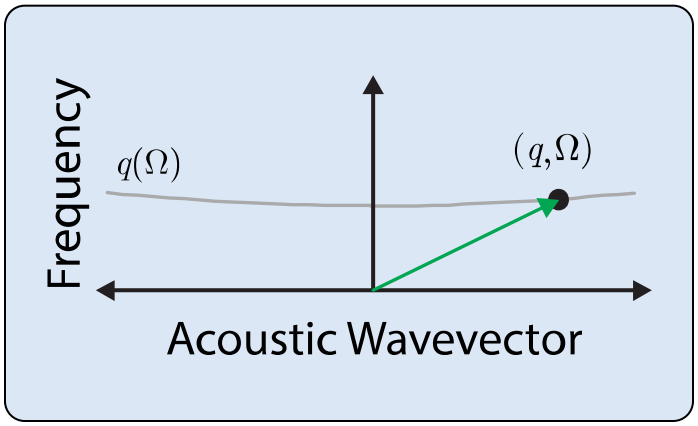
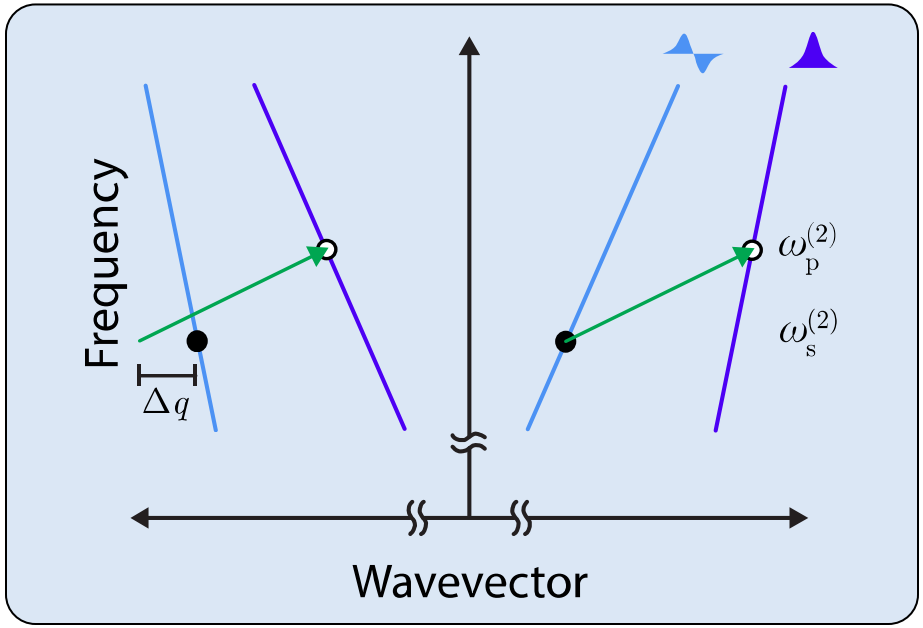
Silicon waveguide inter-band modulator





Light injected in the **backward** direction is not phase-matched to an inter-band transition, so it passes through the device unaffected



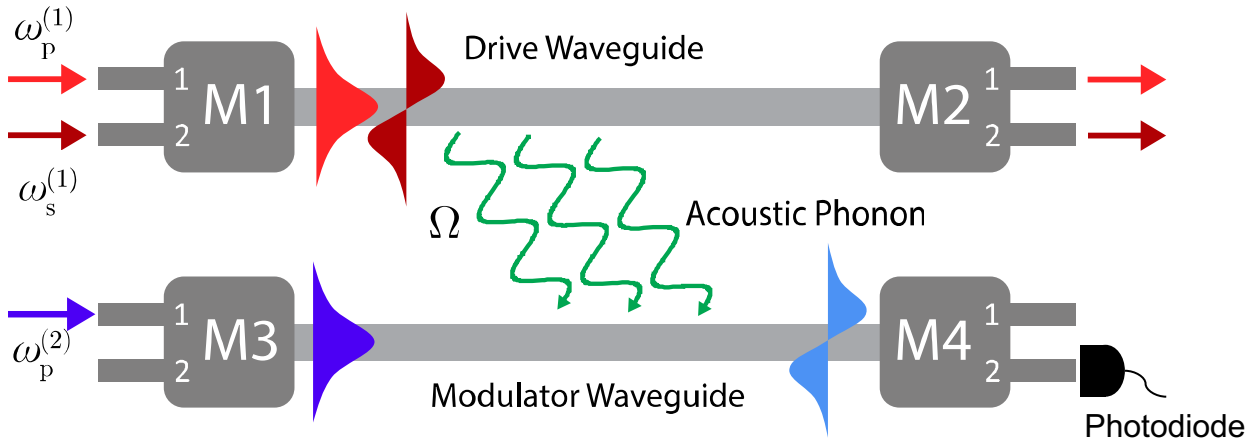
Result: travelling elastic wave breaks symmetry between forward- and backward-propagating optical waves

E.A. Kittlaus, N.T. Otterstrom, P. Kharel, S. Gertler, and P.T. Rakich. *Nat. Photonics.* 12, 613 (2018).

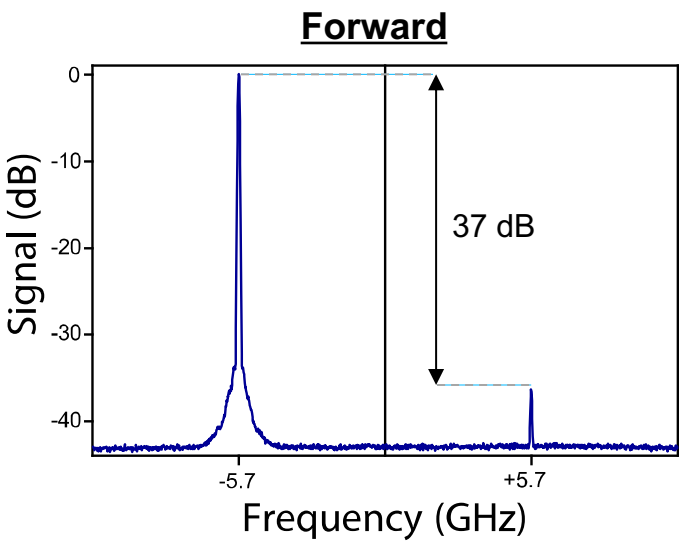
Single-sideband Modulation

Measurement Scheme:

$$\Omega = 2\pi \times 5.7\ \text{GHz}$$
$$\lambda_p^{(1)} = 1550.0\ \text{nm}$$
$$\lambda_p^{(2)} = 1545.5\ \text{nm}$$



Output Optical Spectrum:



Light is single-sideband frequency-shifted by $-\Omega$ with 37 dB suppression of unwanted components

Analogous to acousto-optic modulator

Modulation efficiency ~1%

E.A. Kittlaus, N.T. Otterstrom, P. Kharel, S. Gertler, and P.T. Rakich. *Nat. Photonics.* 12, 613 (2018).

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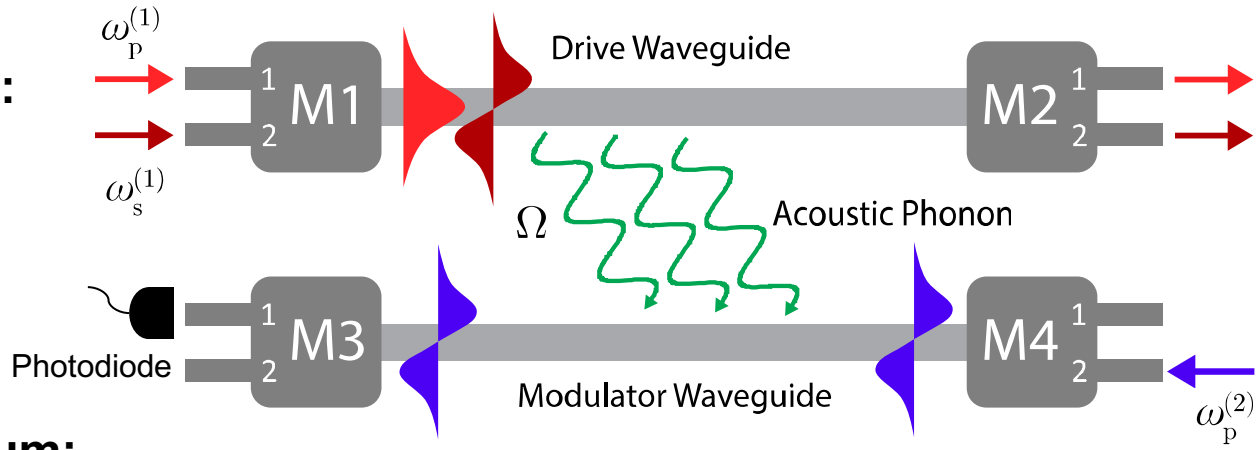

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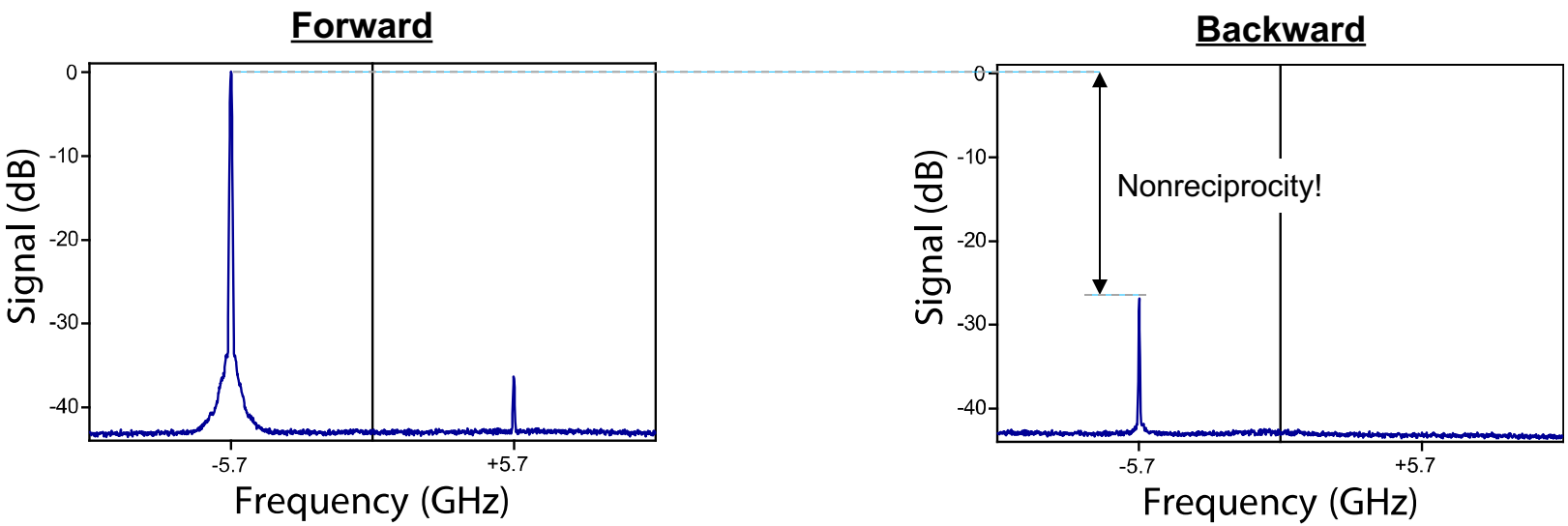

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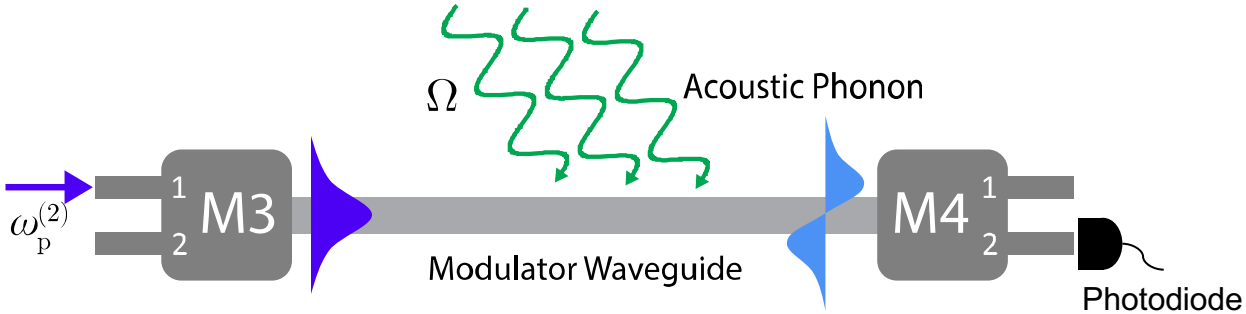
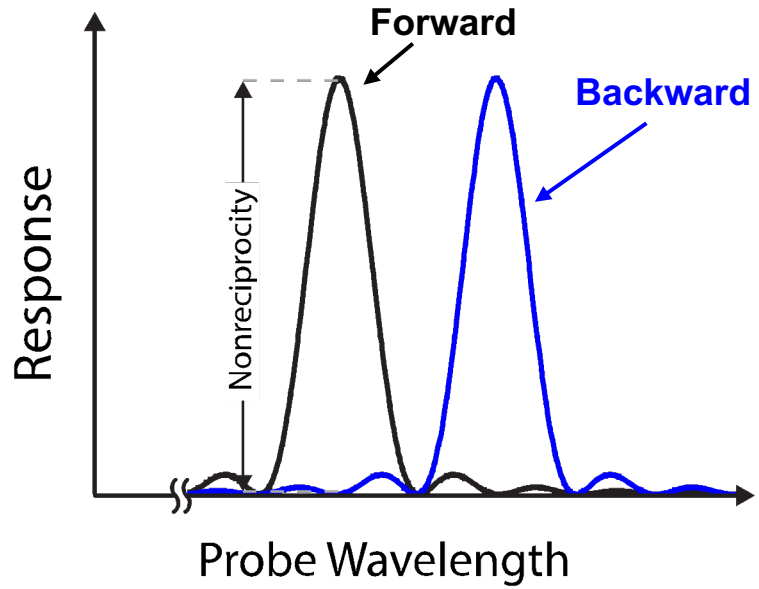
Nonreciprocal response

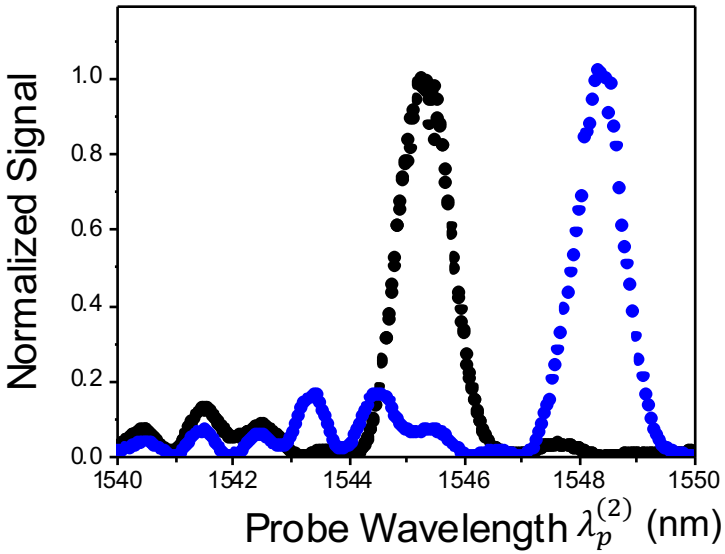


$\Omega = 2\pi \times 5.7$ GHz
$\lambda_p^{(1)} = 1550.0$ nm
$\lambda_p^{(2)} =$ variable

Expected Transmission



Experimental Response



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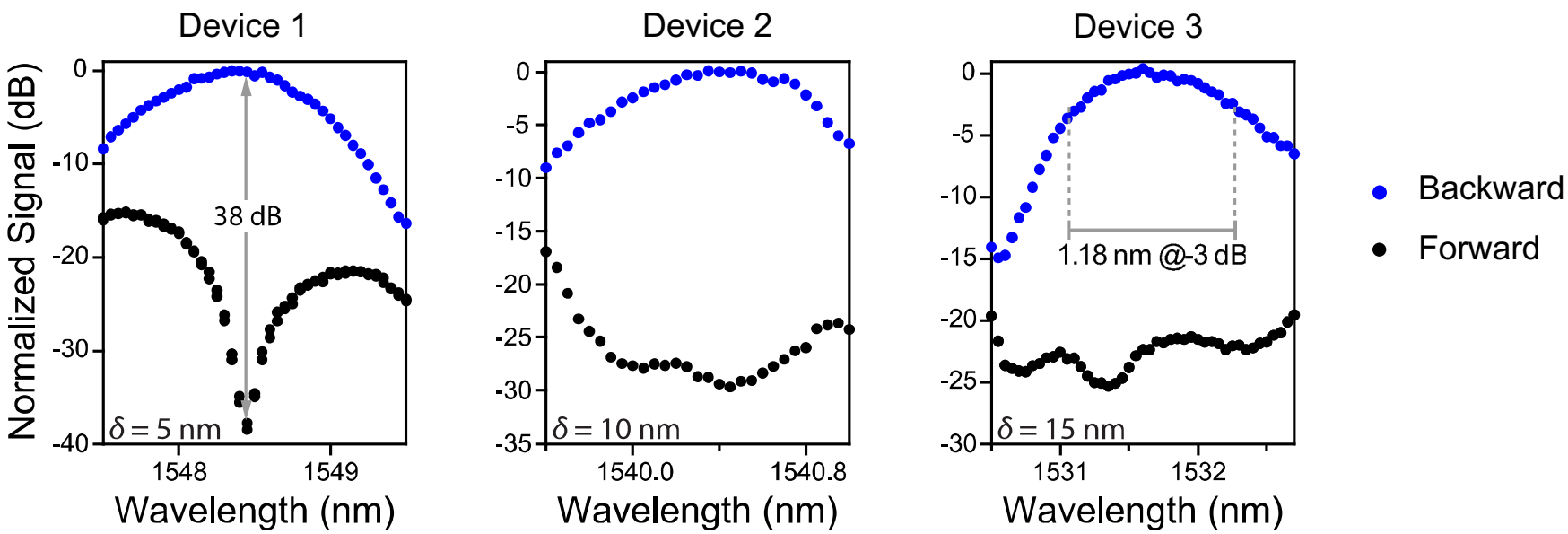
Nonreciprocal response

Characteristic broadband modulation with significant nonreciprocal contrast

$\lambda_p^{(1)} = 1550.0\ \mathrm{nm}$



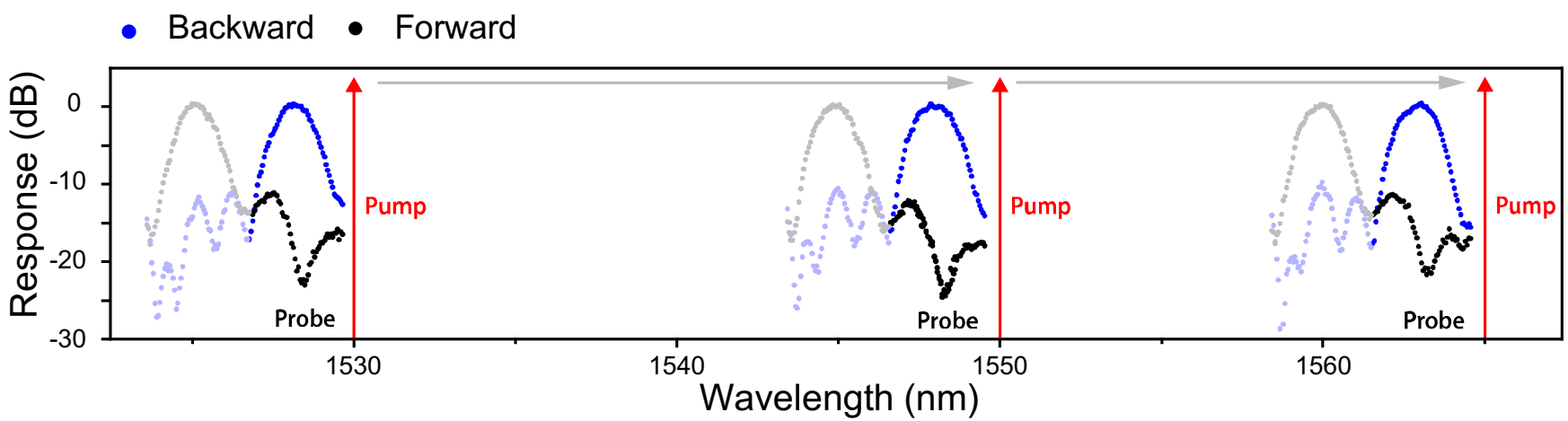
Demonstrated nonreciprocal operation over ~nm bandwidths!

E.A. Kittlaus, N.T. Otterstrom, P. Kharel, S. Gertler, and P.T. Rakich. *Nat. Photonics.* 12, 613 (2018).

Optical wavelength tuning

- Driven phonon wavevector is directly related to optical pump wavelength
- Phonon wavevector determines modulator operation wavelength

Result: operation wavelength directly tunable through optical pump tuning



Demonstrated nonreciprocal operation across the entire c-band in a single device

E.A. Kittlaus, N.T. Otterstrom, P. Kharel, S. Gertler, and P.T. Rakich. *Nat. Photonics.* 12, 613 (2018).

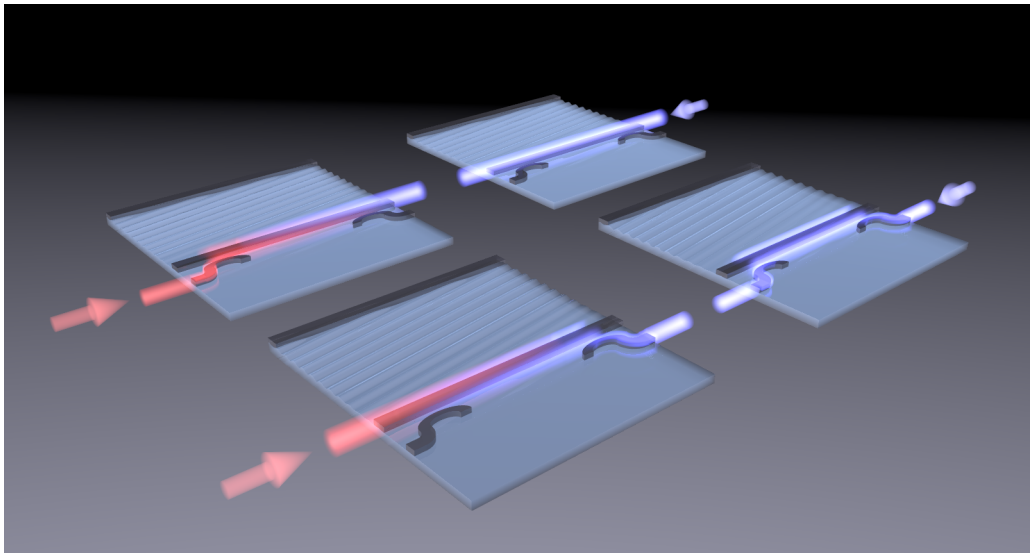
Summary

Summary

- Demonstrated broadband and low-loss nonreciprocal acousto-optic light scattering in a traveling-wave geometry

Takeaways

- Phonons can be a very useful tool for creating spatiotemporal modulation!
- With further work, broadband waveguide-integrated, acousto-optic isolators should be possible



E.A. Kittlaus, N.T. Otterstrom, P. Kharel, S. Gertler, and P.T. Rakich, "Nonreciprocal Inter-band Brillouin Modulation." *Nat. Photonics* 12, 613 (2018).

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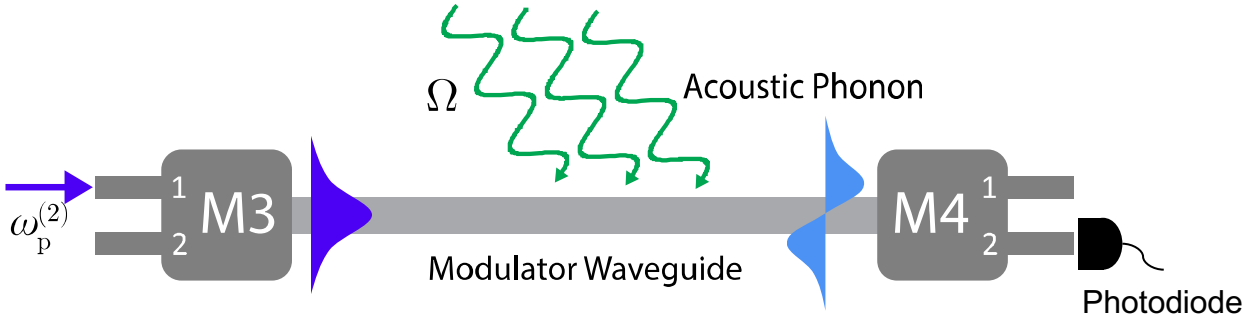
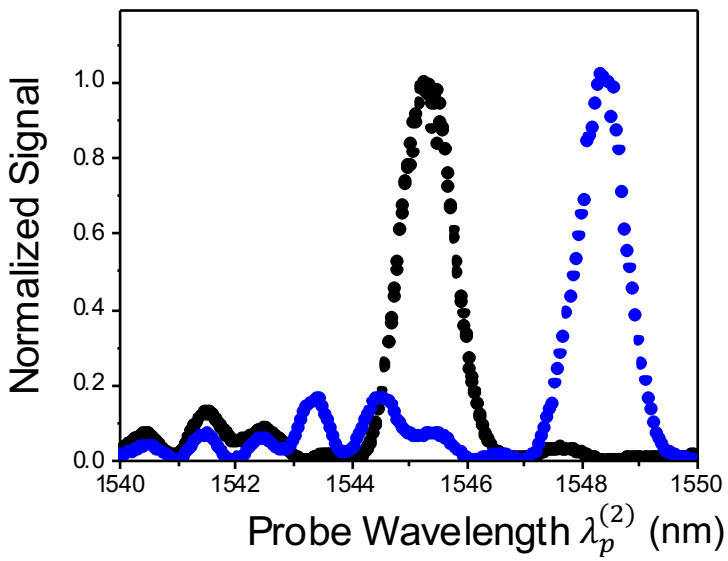
END

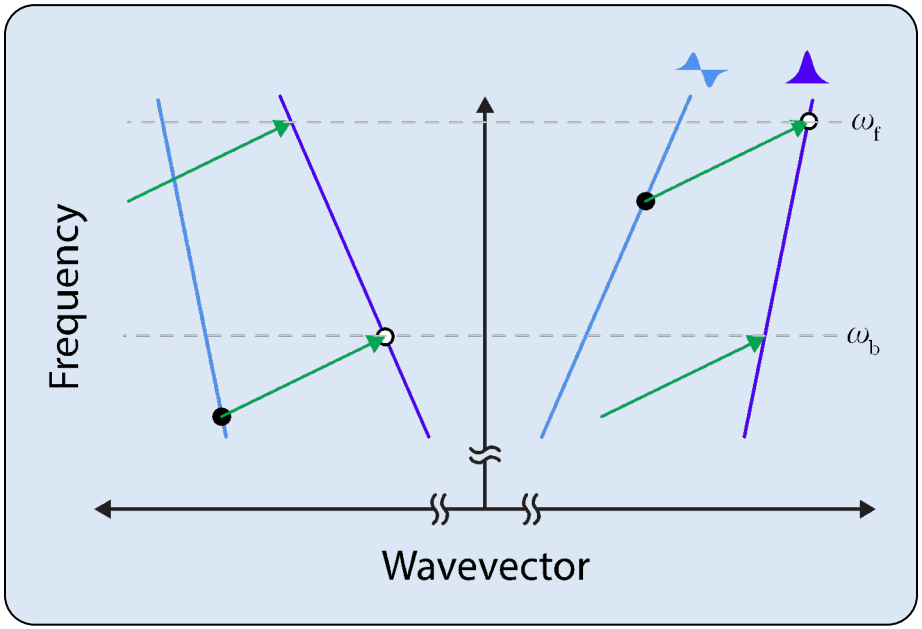
Nonreciprocal Response

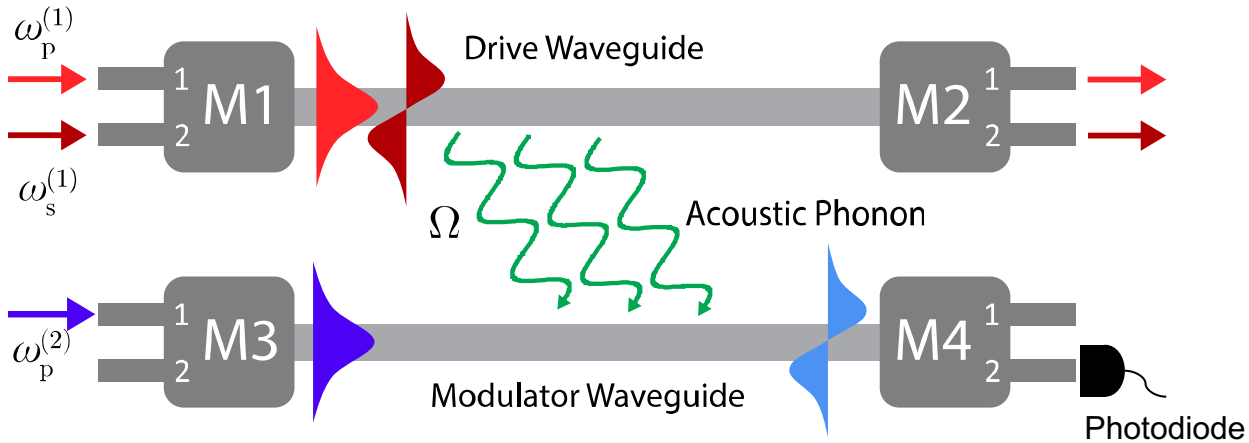
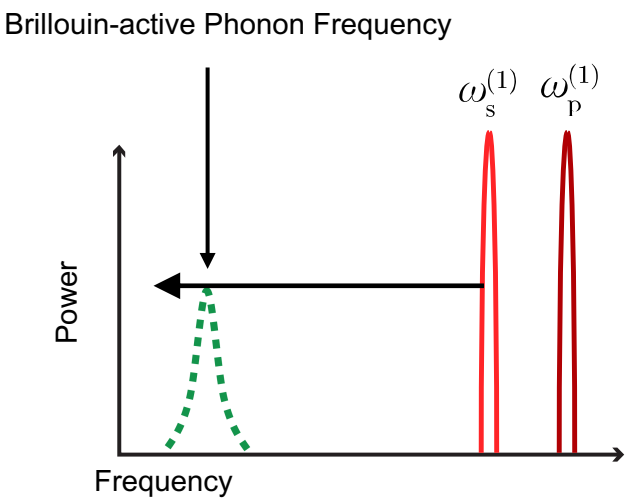
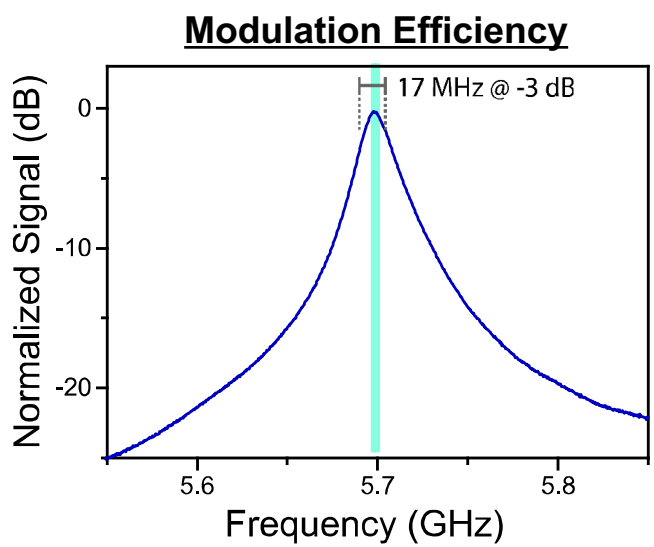
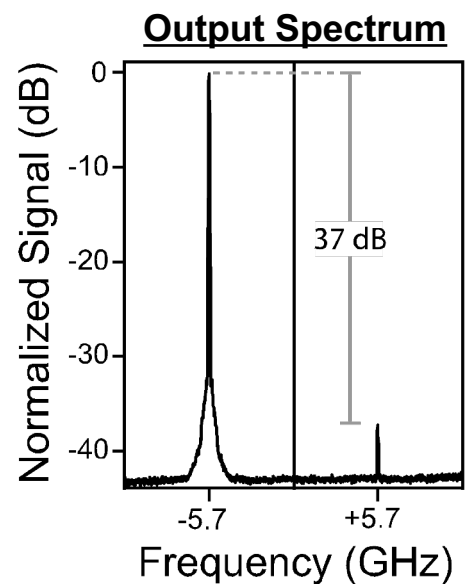


$$\Omega = 5.7\ \text{GHz}$$
$$\lambda_p^{(1)} = 1550.0\ \text{nm}$$
$$\lambda_p^{(2)} = \text{variable}$$

Experimental Response





Phonon Spectroscopy

Measurement Scheme: