WACQT | Wallenberg Centre for Quantum Technology

Processing light with sound

in integrated photonics

https://qpl-chalmers.se/

CHALMERS
UNIVERSITY OF TECHNOLOGY

QPL
Quantum Photonics Laboratory

Asst.Prof. Raphaël Van Laer

Outline

Process light with sound?

Basic physics

Case studies

Outlook

Outline

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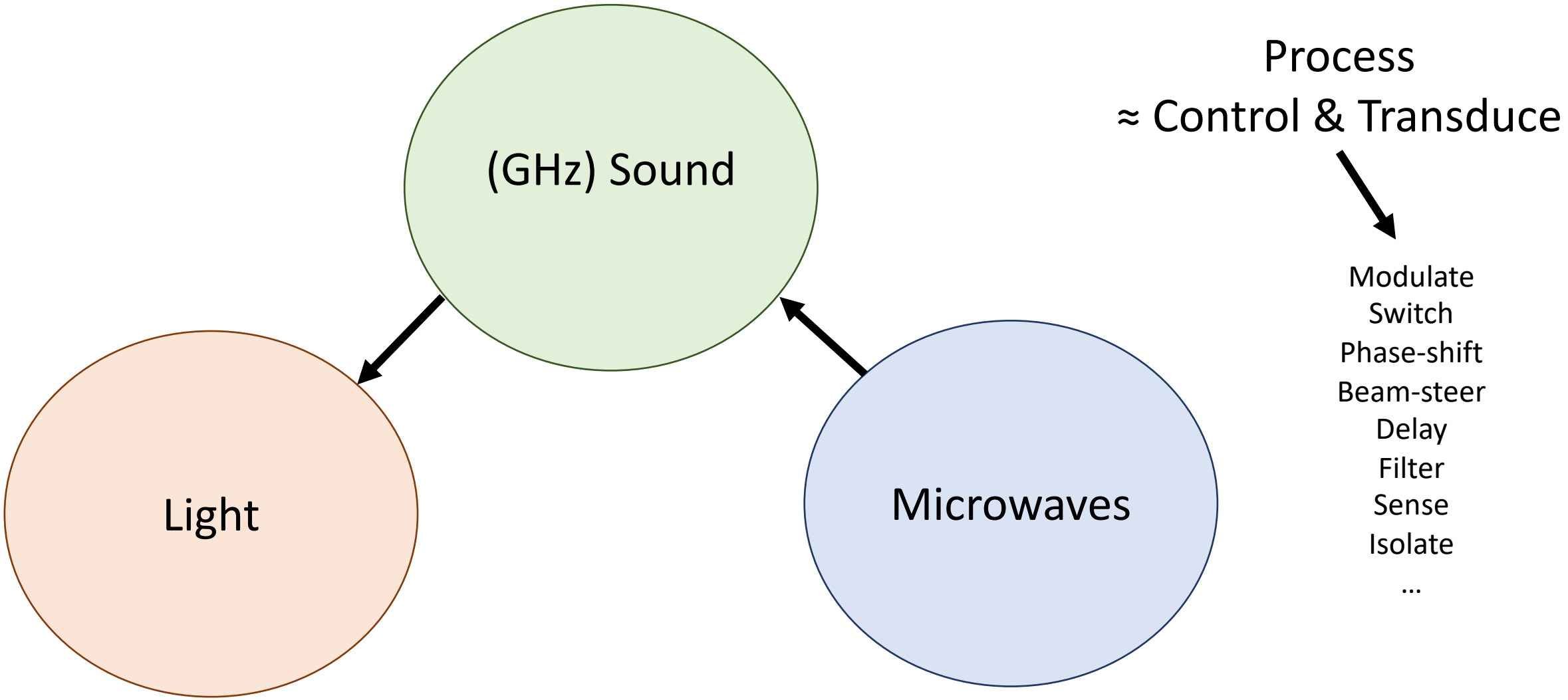
Basic physics

Case studies

Outlook

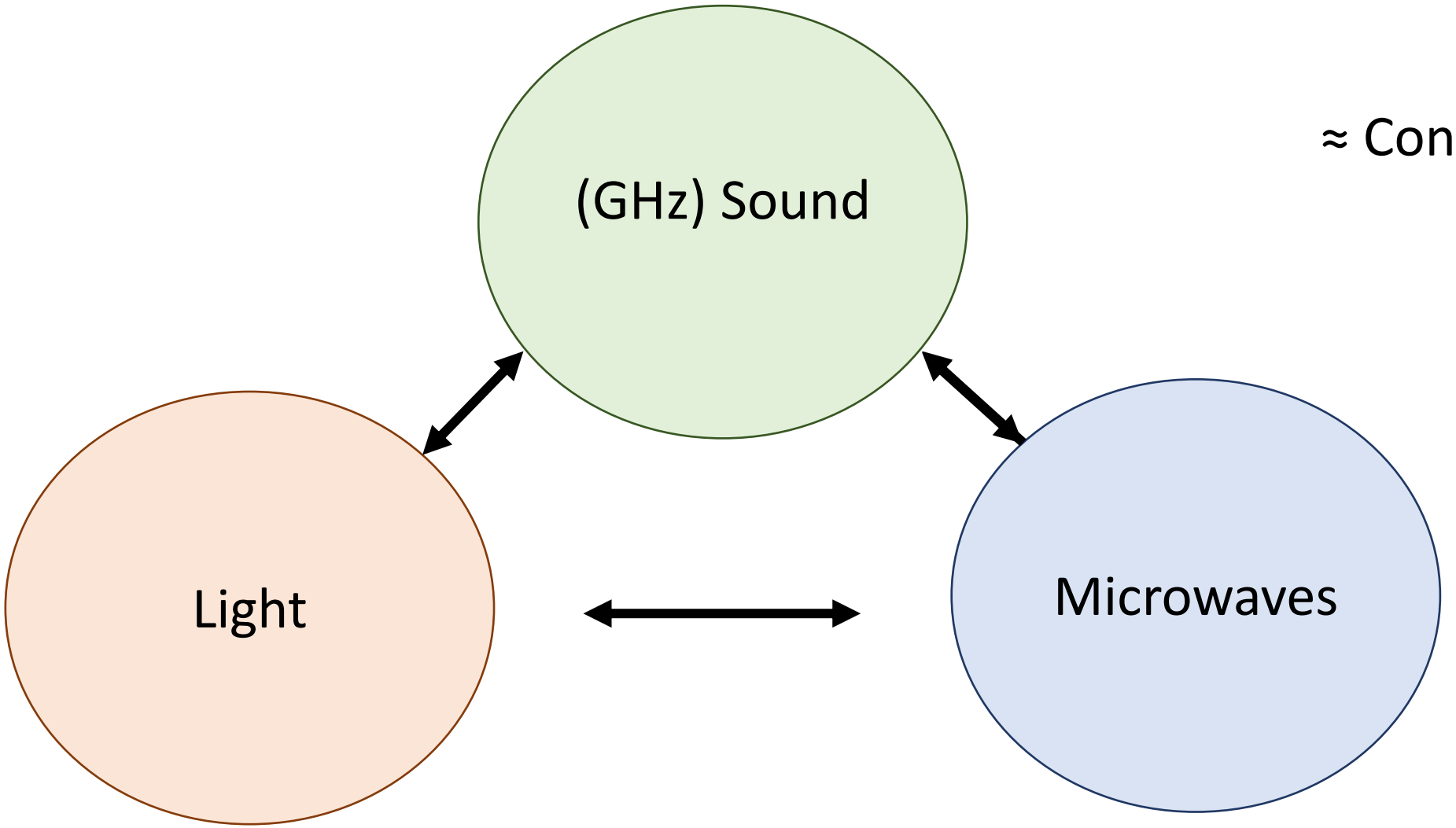
Process light with sound?



Process
≈ Control & Transduce

Modulate
Switch
Phase-shift
Beam-steer
Delay
Filter
Sense
Isolate
…

Process light with sound?



Process
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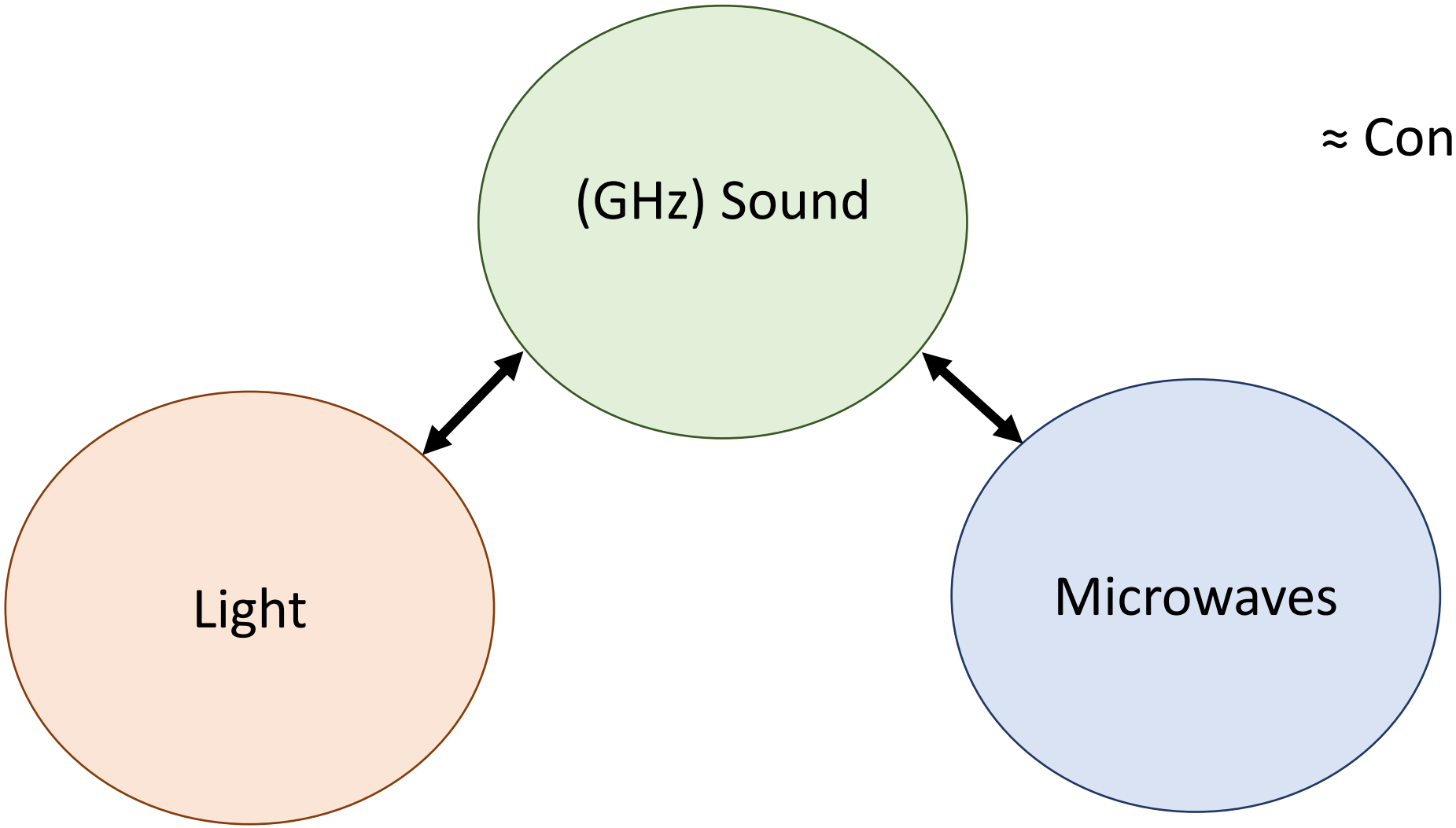
>>Broader than this tutorial

Process light with sound?



Process
≈ Control & Transduce

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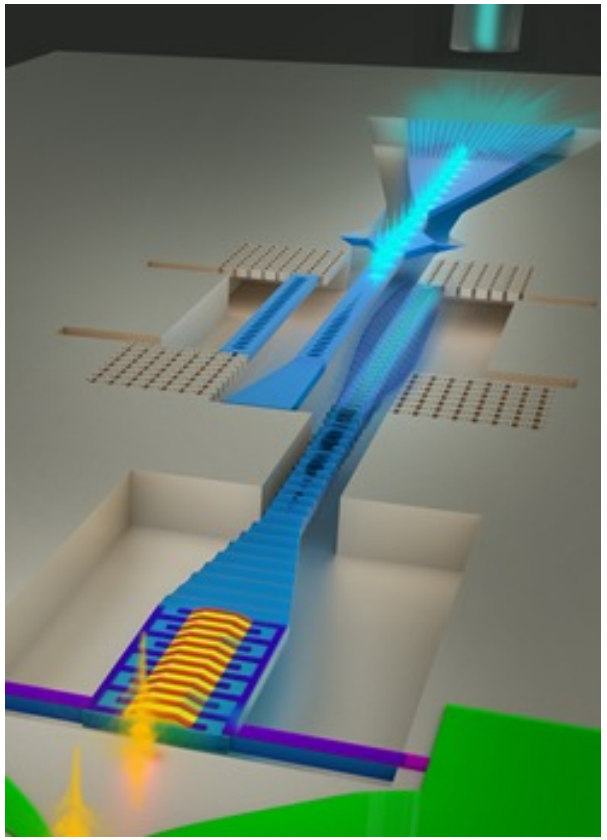
Isolate
…

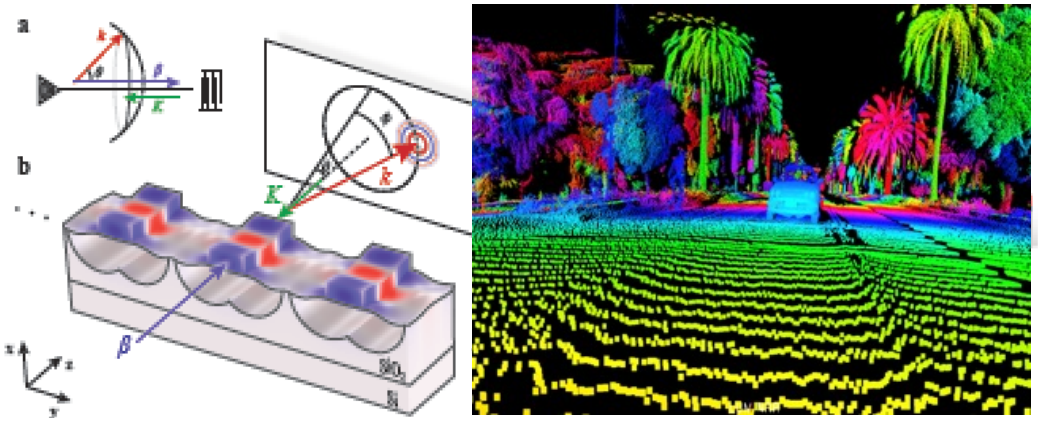
Coherently: phase & amplitude → Quantum: no measurement

Process light with sound?

Quantum transduction

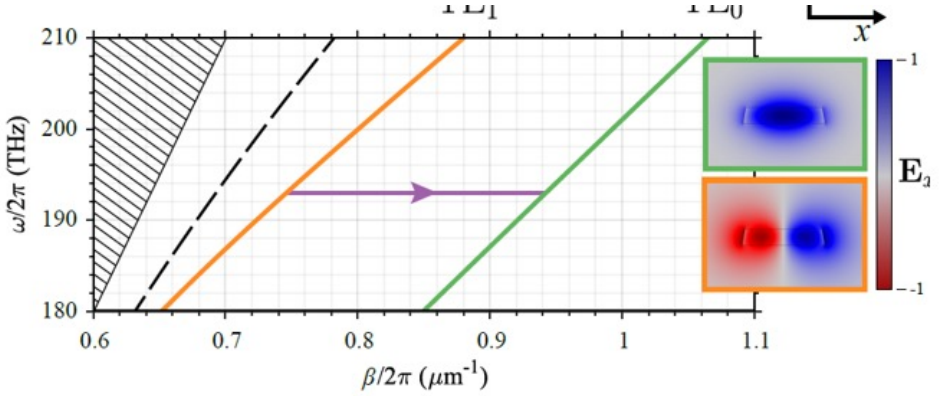


Beam-steering



Sarabalis, Van Laer et al.
Optics Express (2018)

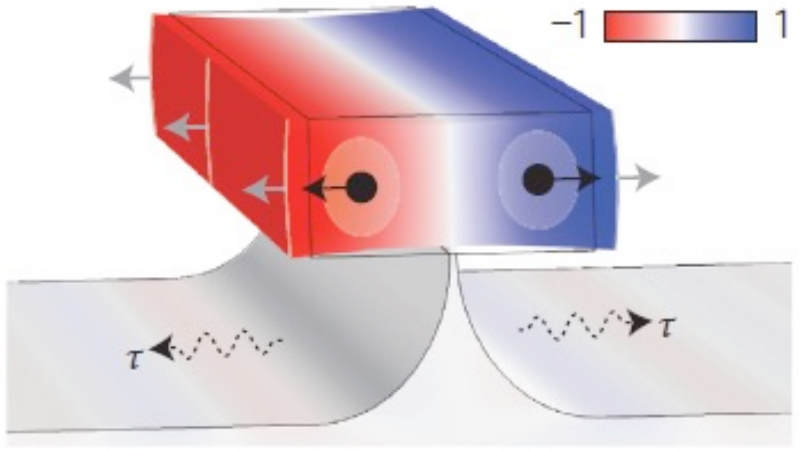
Modulation & isolation



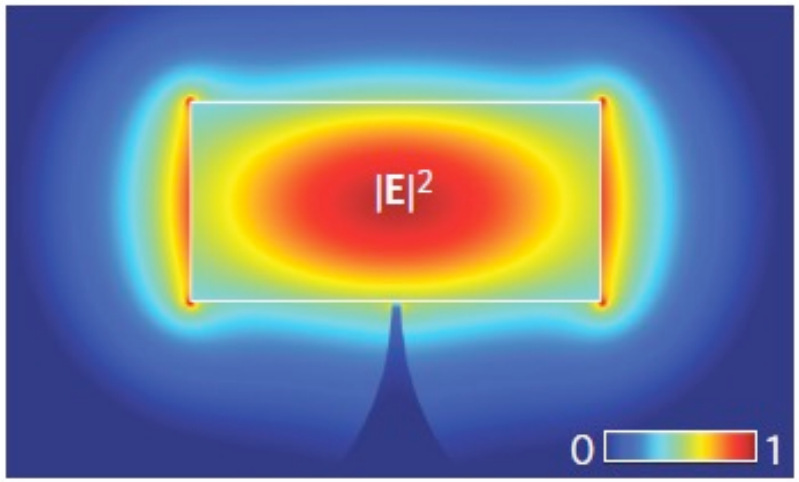
Sarabalis et al.
Optica (2021)

GHz Sound and light are a match

‘Magical’ scale convergence



10 GHz
≈1 µm



200 THz
≈1 µm

Van Laer et al.
Nature Photonics (2015)

Wavelength of 200 THz light
≈ Wavelength of GHz sound
≈1 µm

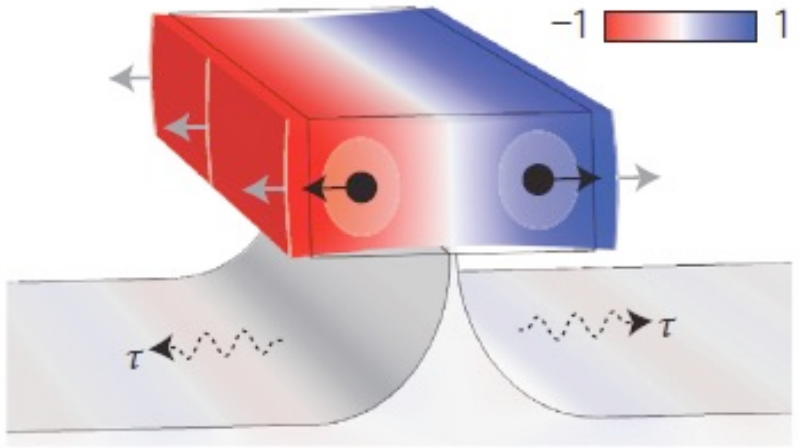
Wavelength $\lambda = \frac{v}{f}$

Speed / 10^5

Frequency / 10^5

GHz sound and light are a match

'Magical' scale convergence



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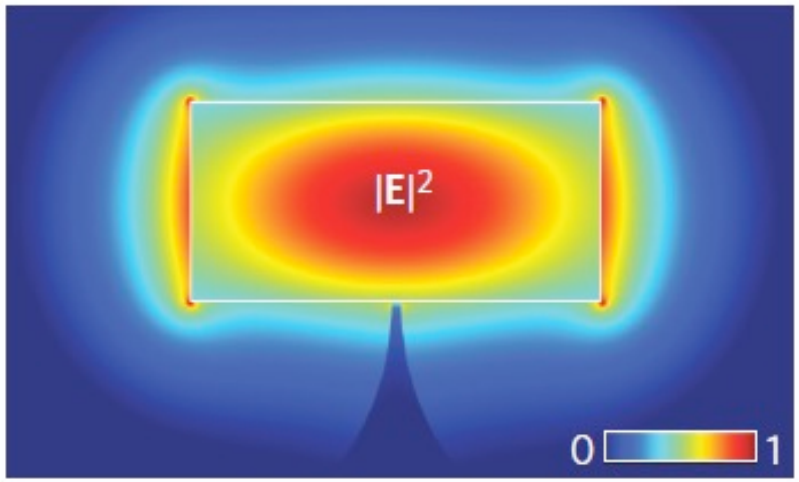


200 THz
≈1 µm

Van Laer et al.
Nature Photonics (2015)

Wavelength of 200 THz light
≈ Wavelength of GHz sound
≈1 µm

Strong, fast interactions
Low energy per (qu)bit
Dynamical gratings

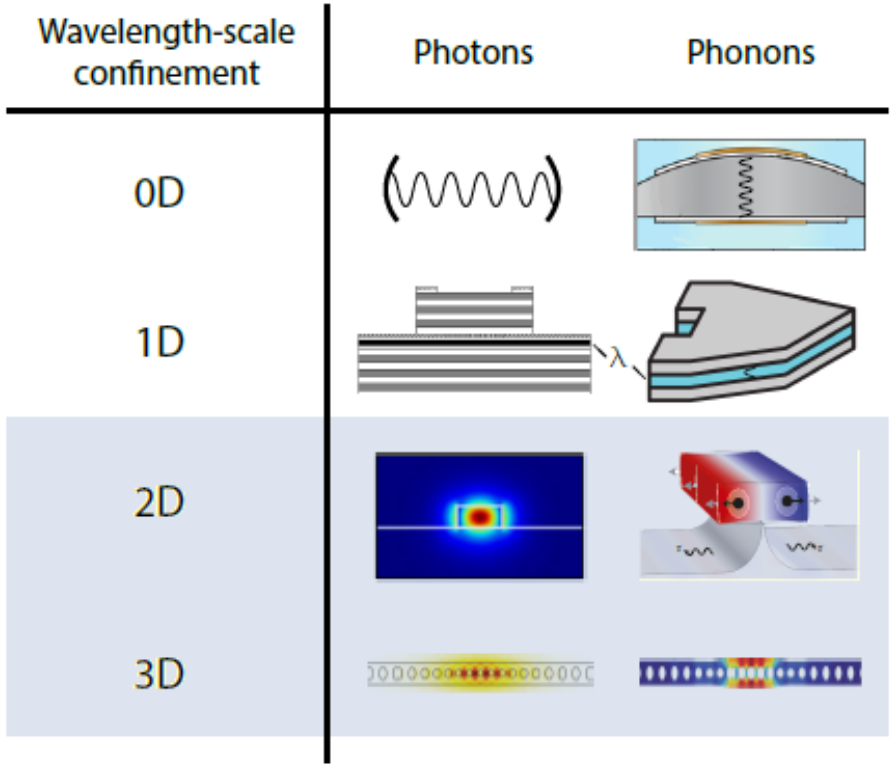
Matchin
Stiff mechanics
Disorder

Integrated photonics!

More info:
Safavi-Naeini, Van Thourhout, Baets & Van Laer. Optica 6(2) (2019)

GHz sound already widespread

Filtering, delays



Extend to integrated photonics & quantum technology

Safavi-Naeini et al. Optica (2019)

Outline

Process light with sound?

Basic physics

Confinement

Interactions

Case studies

Outlook

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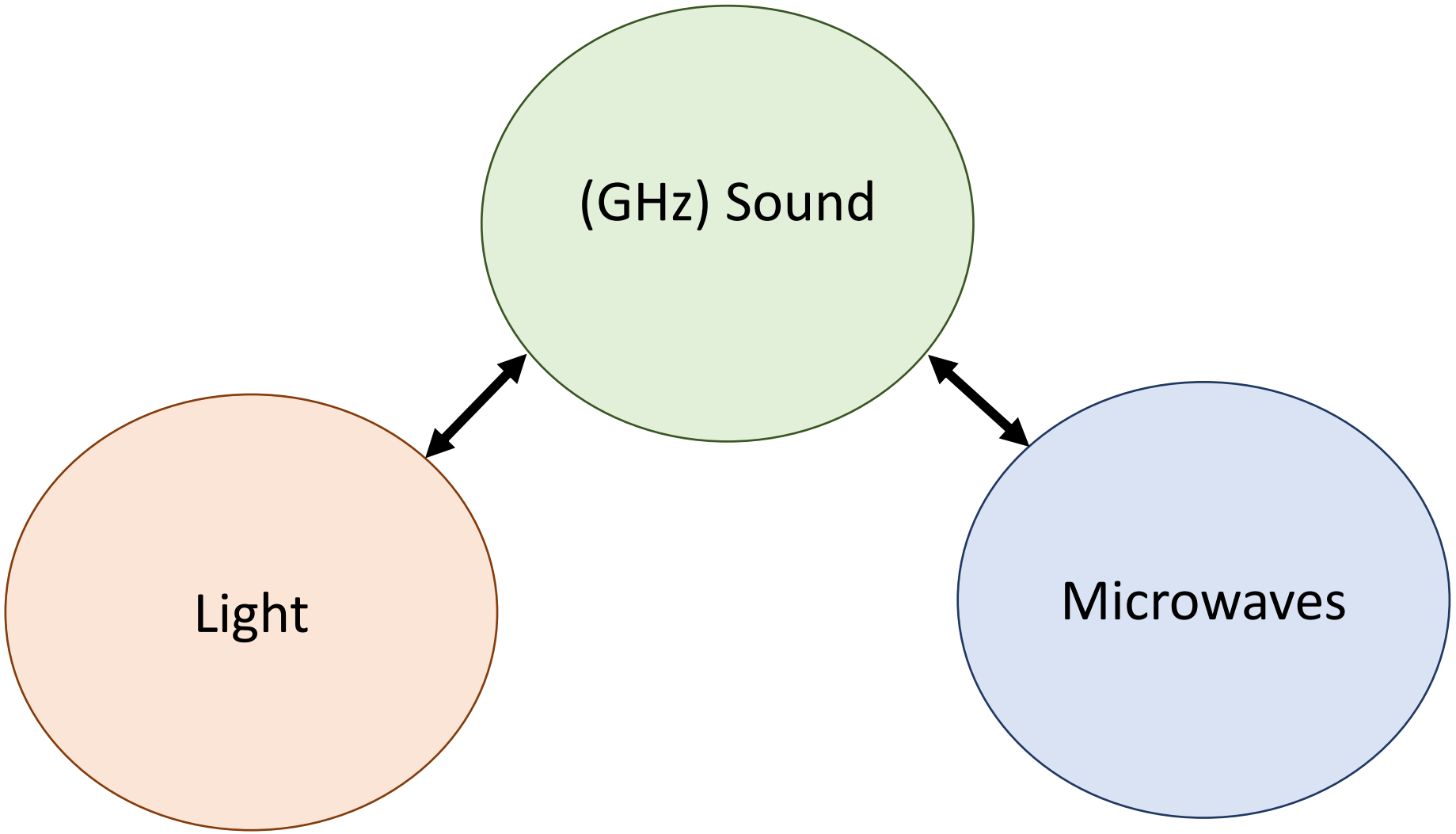
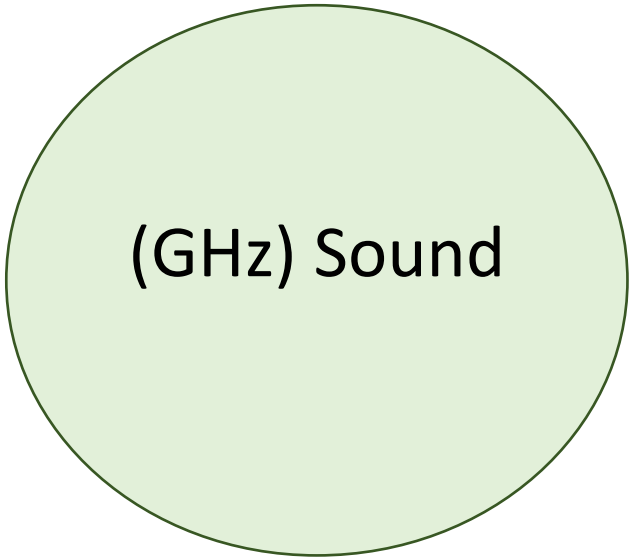
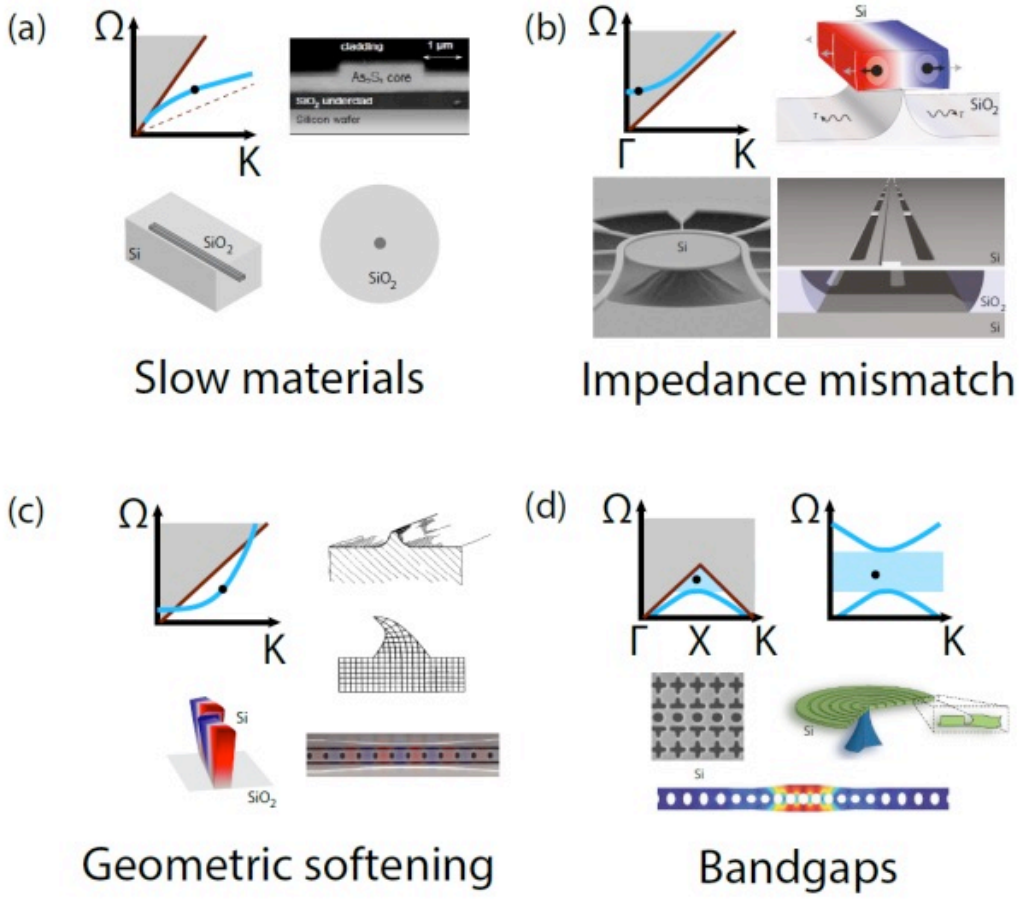


Process light with sound?

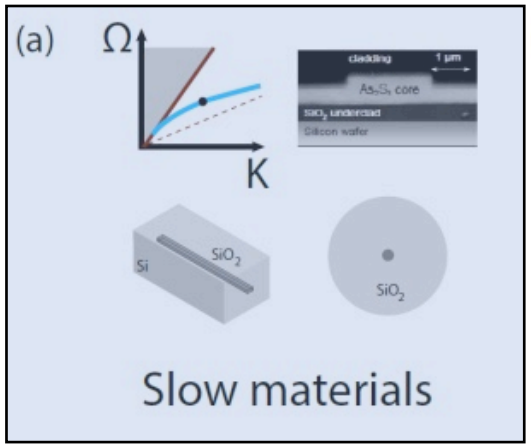


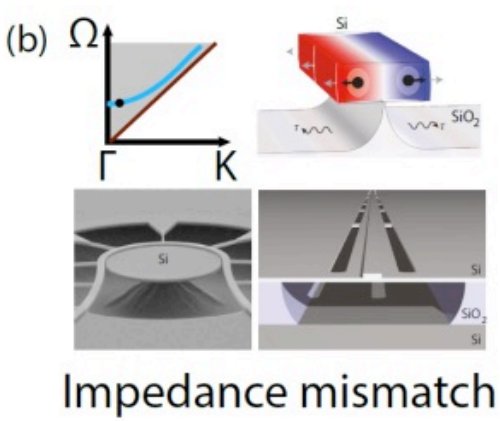
Confining GHz sound

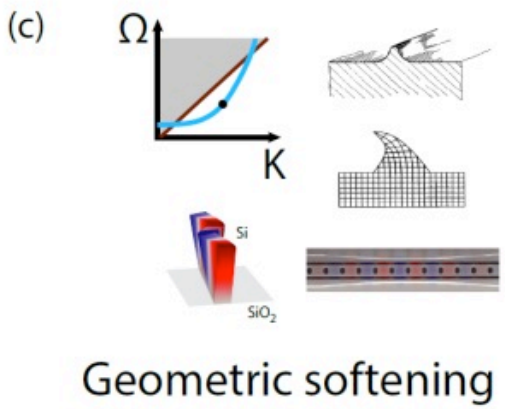


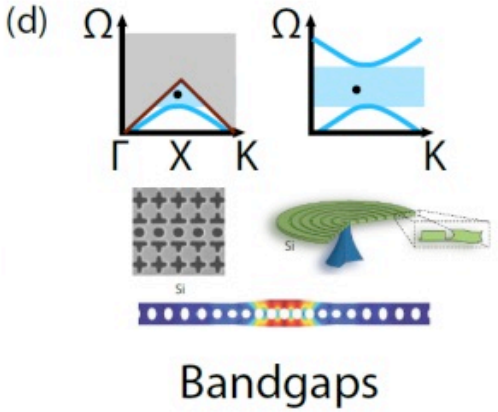
Safavi-Naeini et al. Optica (2019)

Confining GHz sound: slow materials

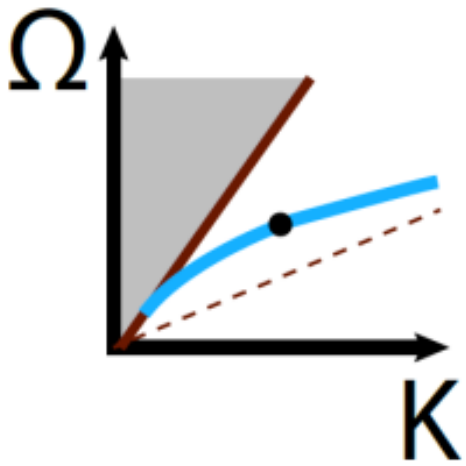








Total internal reflection

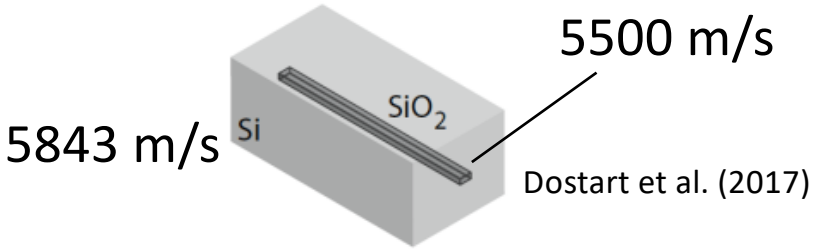


$$K(\Omega) = \Omega / v_\phi$$

Maximum slowness $1/v_\phi$

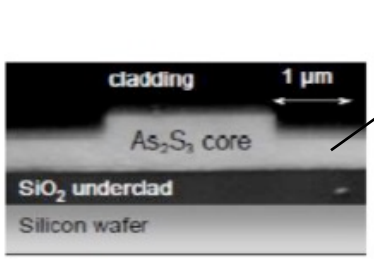
Safavi-Naeini et al. Optica (2019)

Confining GHz sound: tension with photons



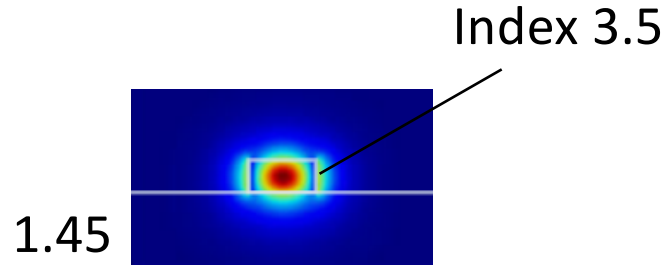
Dostart et al. (2017)

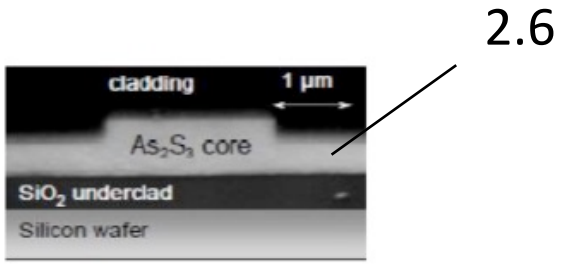
$$v_\phi = \sqrt{E/\rho}$$



Pant et al. (2011)

Phonons: soft & light materials

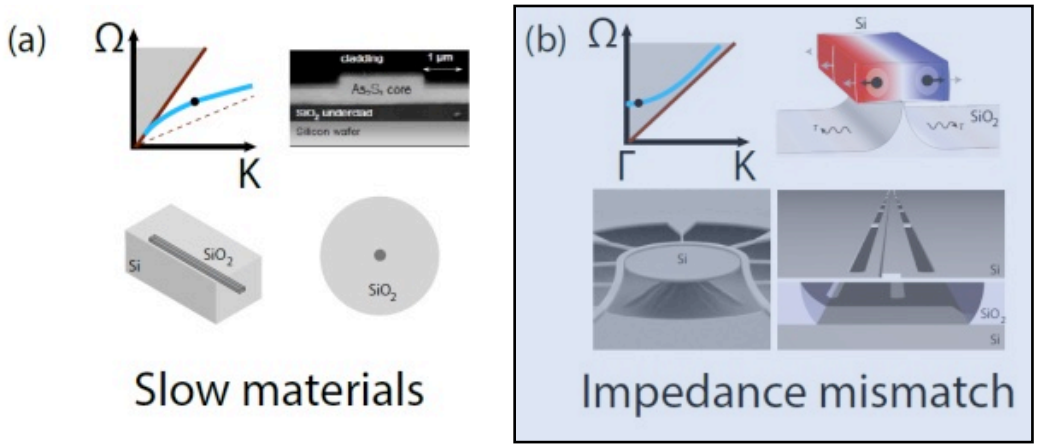


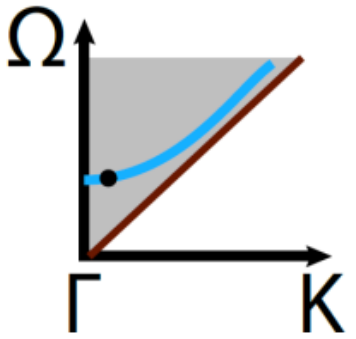


Photons: dense materials

Safavi-Naeini et al. Optica (2019)

Confining GHz sound: impedance mismatch





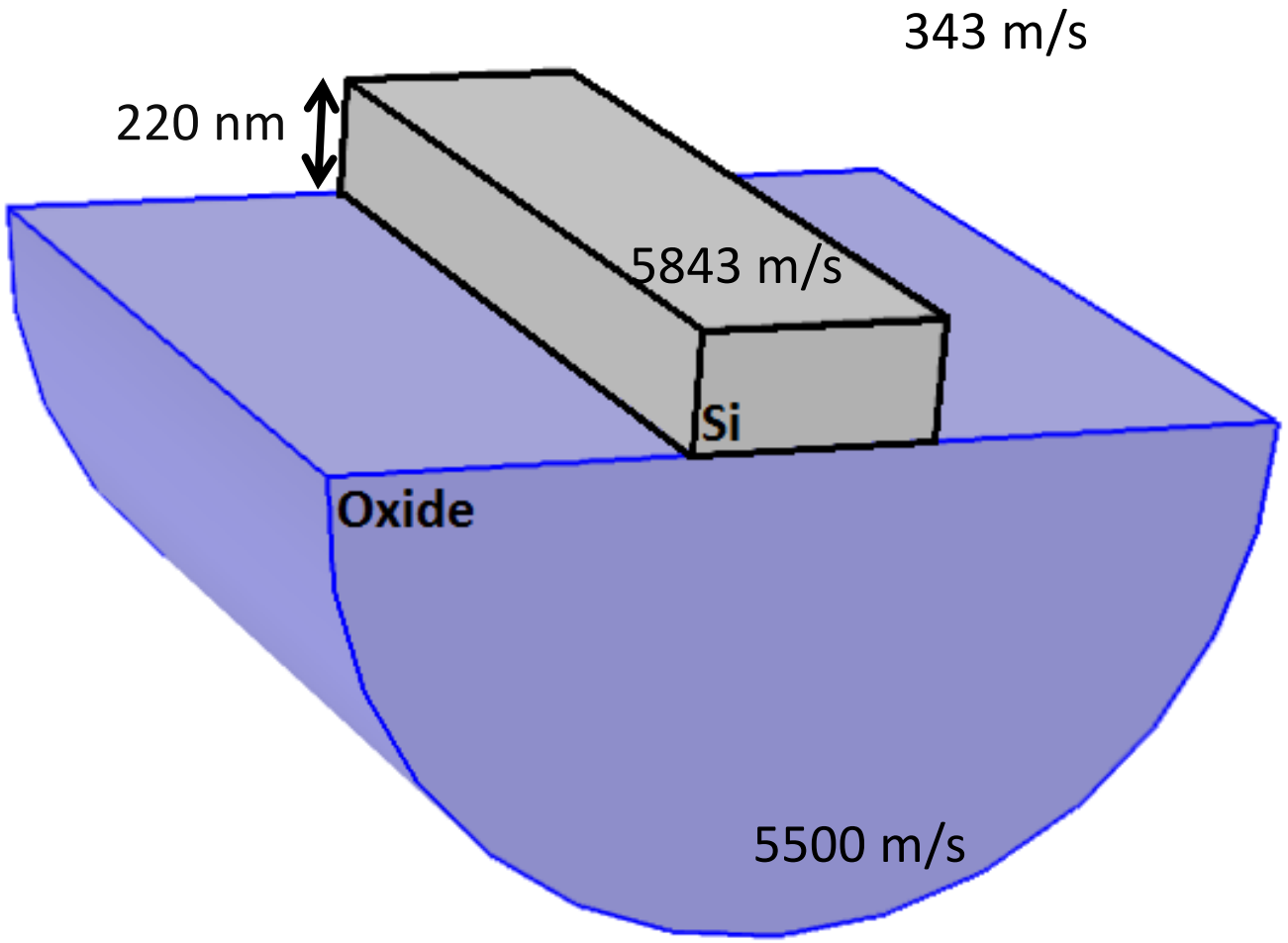
More phonons reflect when mismatch is larger

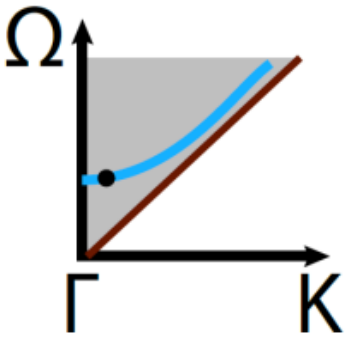
$$Z_{\mathrm{m}} = \rho v_{\phi}$$

Atmospheric air does not support phonons >500 MHz

Safavi-Naeini et al. Optica (2019)

Confining GHz sound: impedance mismatch





Safavi-Naeini et al. Optica (2019)

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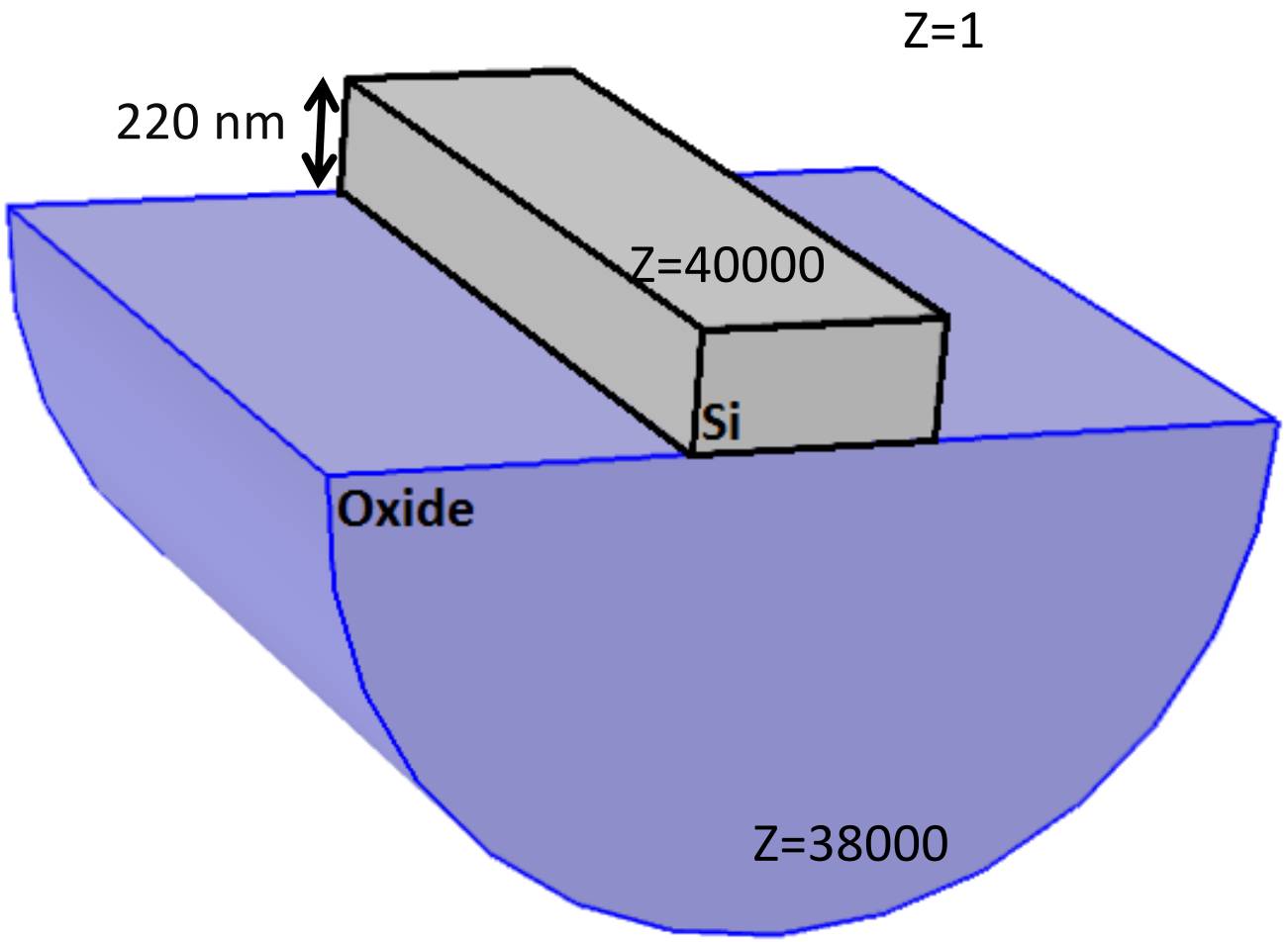

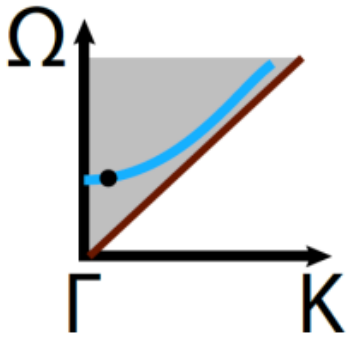

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Safavi-Naeini et al. Optica (2019)

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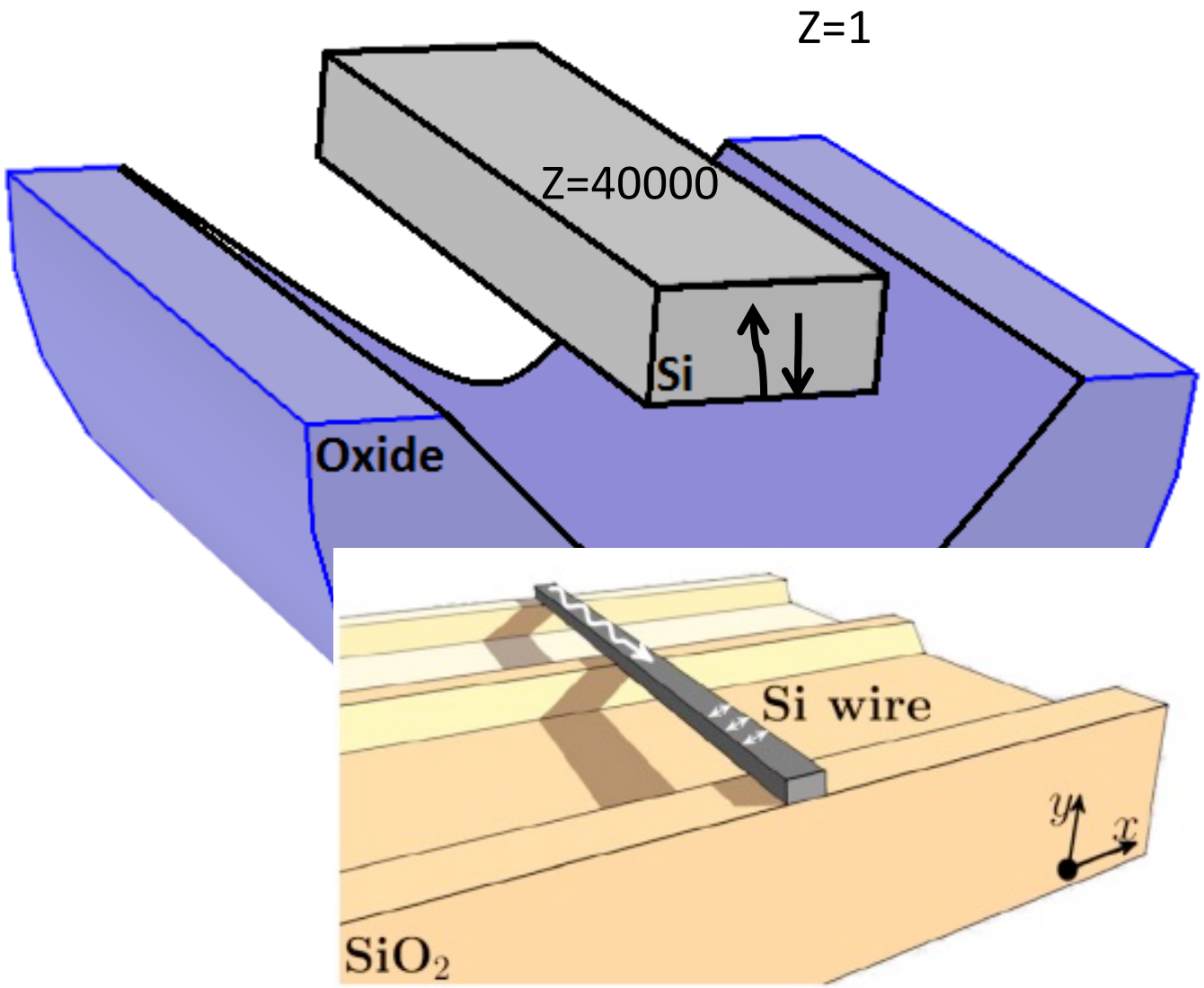
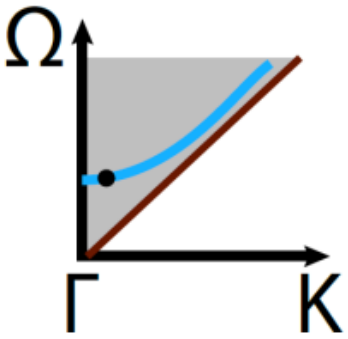


Van Laer et al. (2015)



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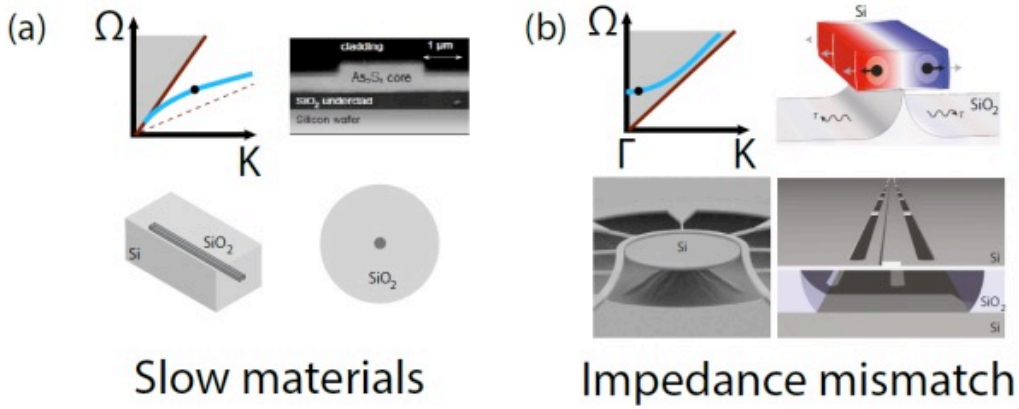
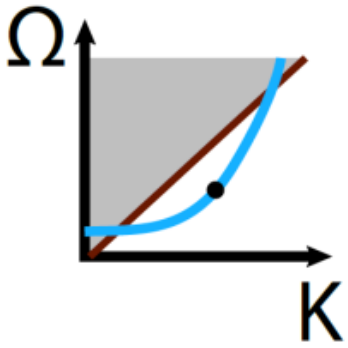
Safavi-Naeini et al. Optica (2019)

Confining GHz sound: geometric softening



Slow materials

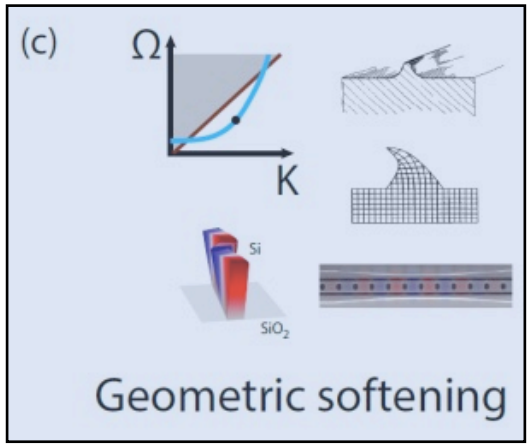
Impedance mismatch

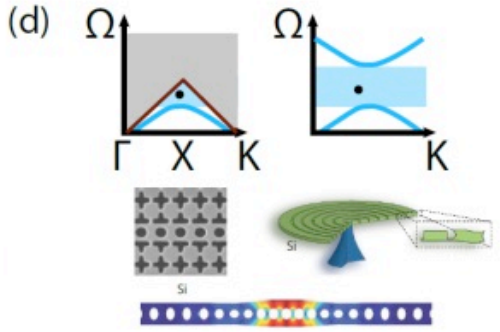


Surfaces soften structure

Rayleigh SAWs

Unique to phonons





Safavi-Naeini et al. Optica (2019)

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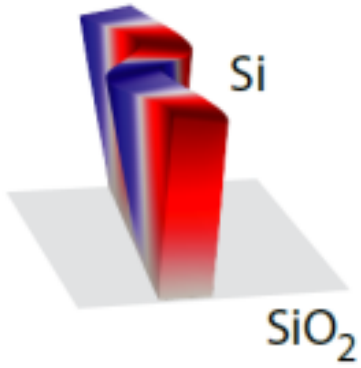
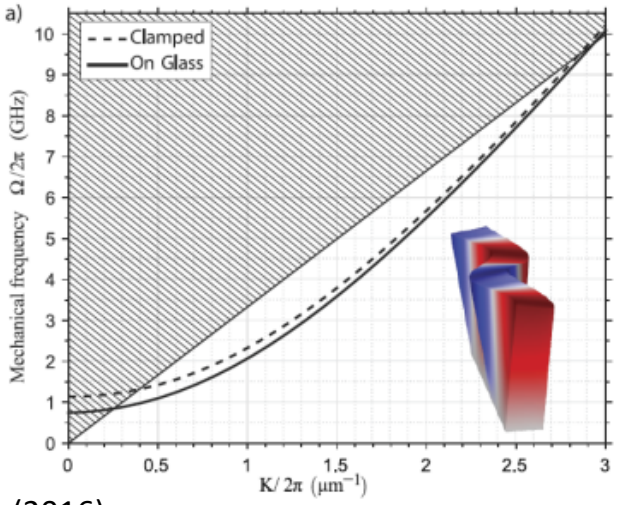
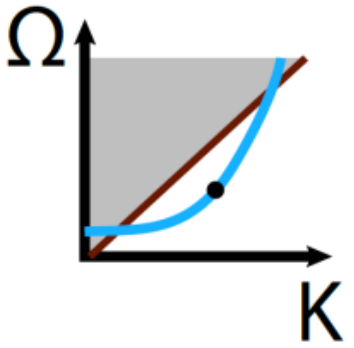




Sarabalis et al. (2016)



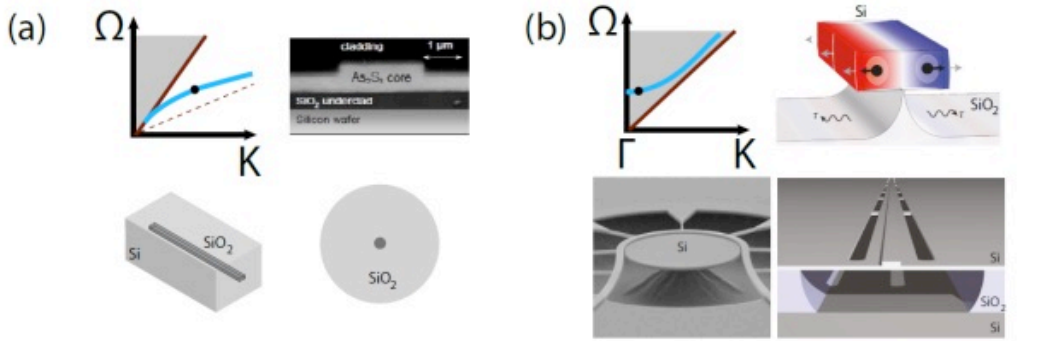
Large surface to volume ratio

$$\Omega \approx \sqrt{\frac{E}{\rho}\frac{w}{b^2}}$$

'Fins'

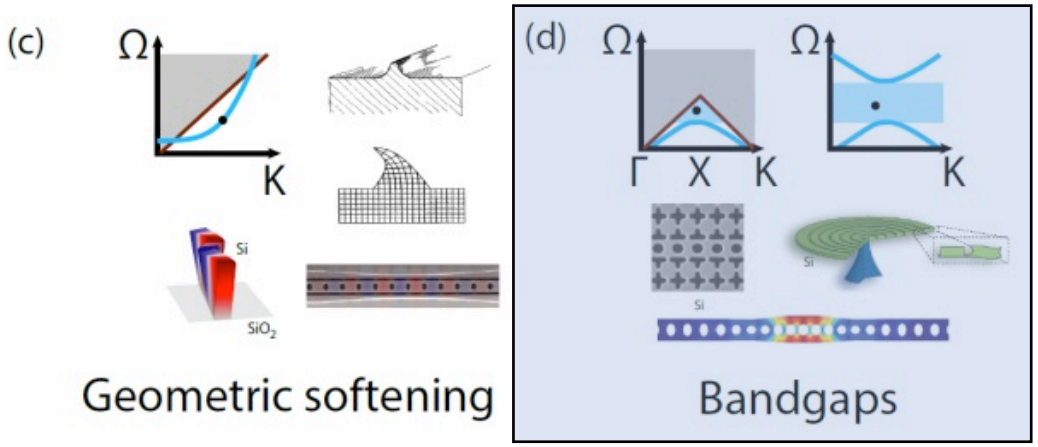
Safavi-Naeini et al. Optica (2019)

Confining GHz sound: bandgaps



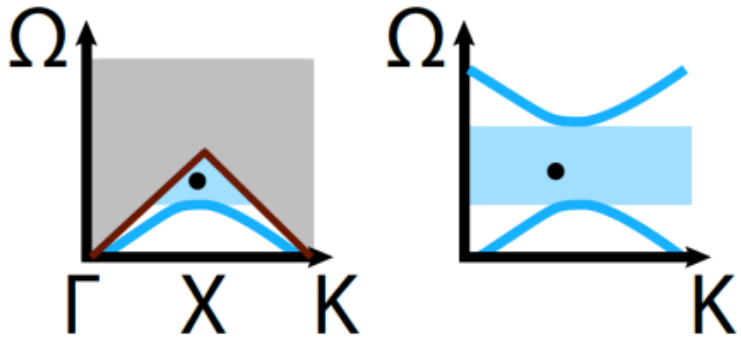
Slow materials

Impedance mismatch



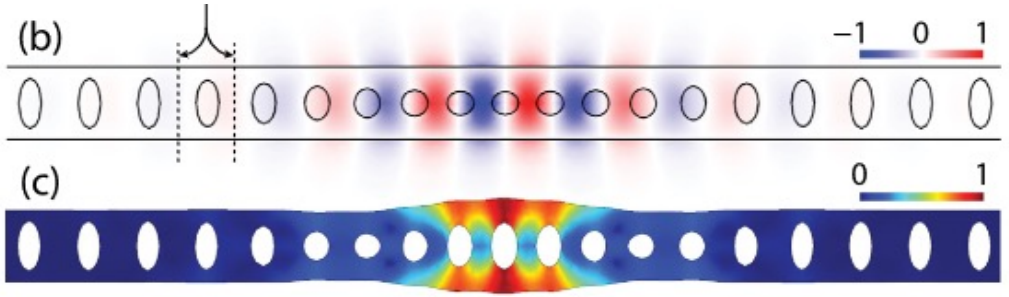
Geometric softening

Bandgaps



Make mirrors by patterning series of holes

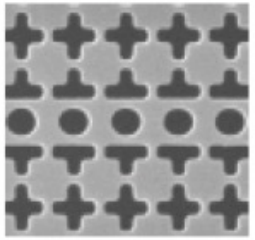
Add point- or line-defect by smooth perturbation



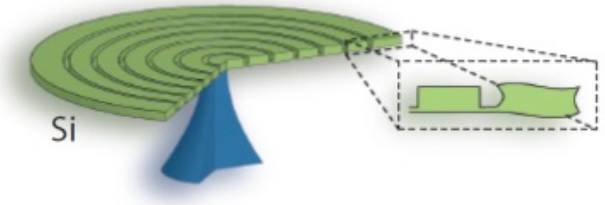
Chan et al. APL (2012)

Confining GHz sound: bandgaps

Fang et al. (2016)

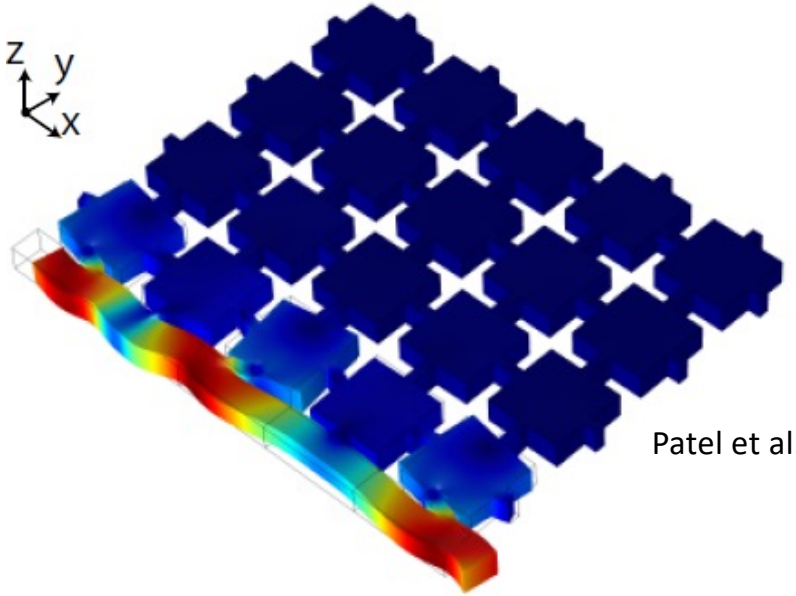


Santos et al. (2017)

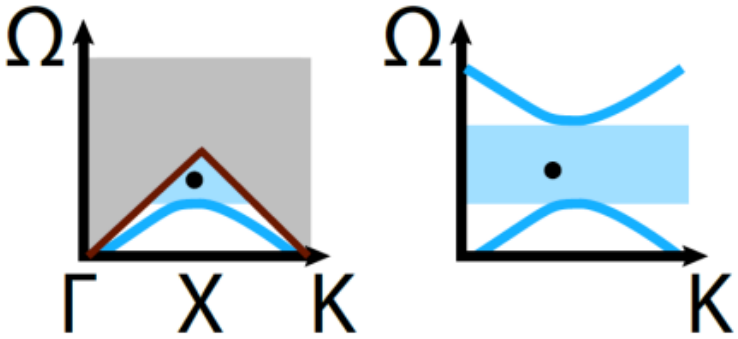


Si

Chan et al. (2012)

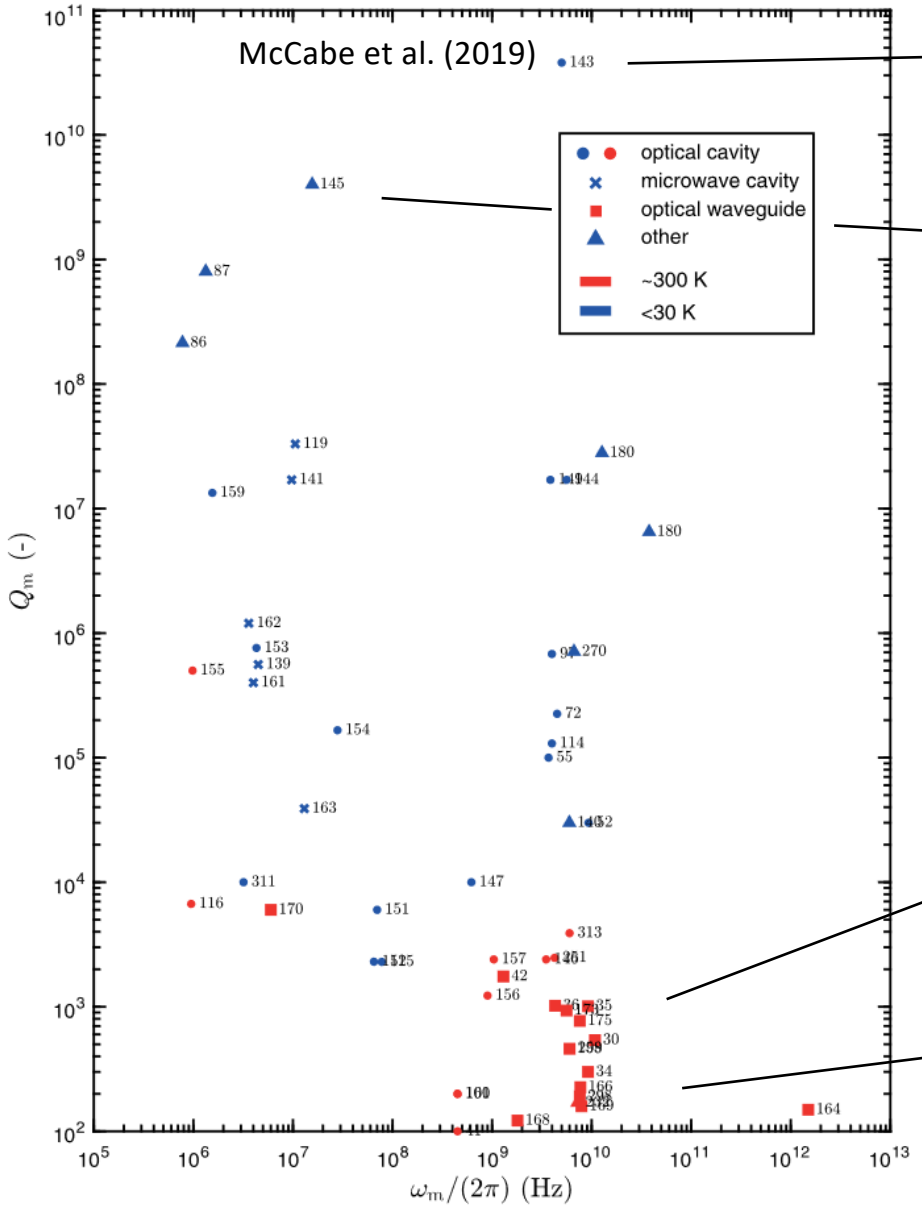


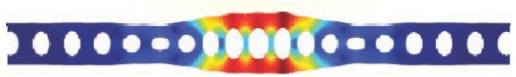
Patel et al. (2018)



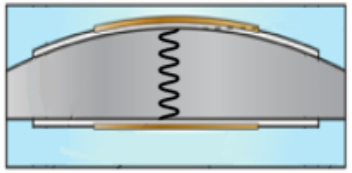
Robust to scattering!

Confining GHz sound: material limits

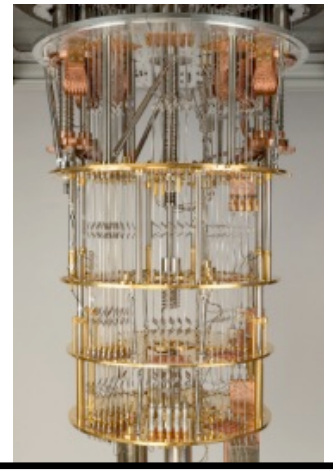


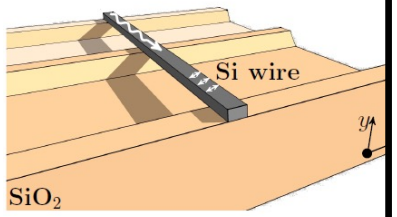


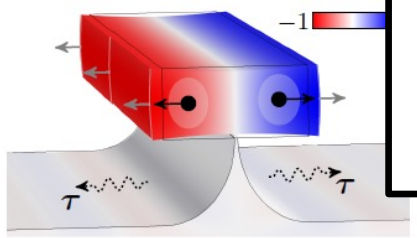
Lives for >1 second (!)



Goryachev et al. (2013)







Bulk silicon

1 GHz, room temperature

~1 cm propagation

~ 0.1 MHz linewidth

~ 10 microseconds

~1e4 quality factor

Safavi-Naeini et al. Optica (2019)

Outline

Process light with sound?

Basic physics

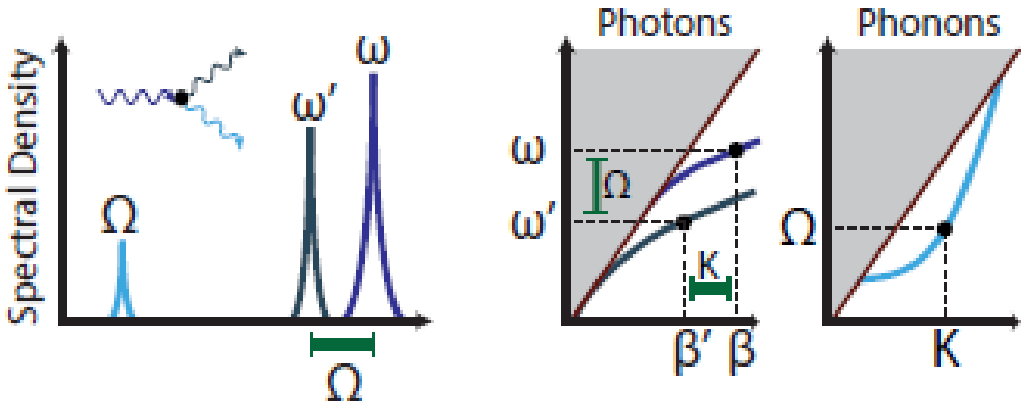
- Confinement
- **Interactions**

Case studies

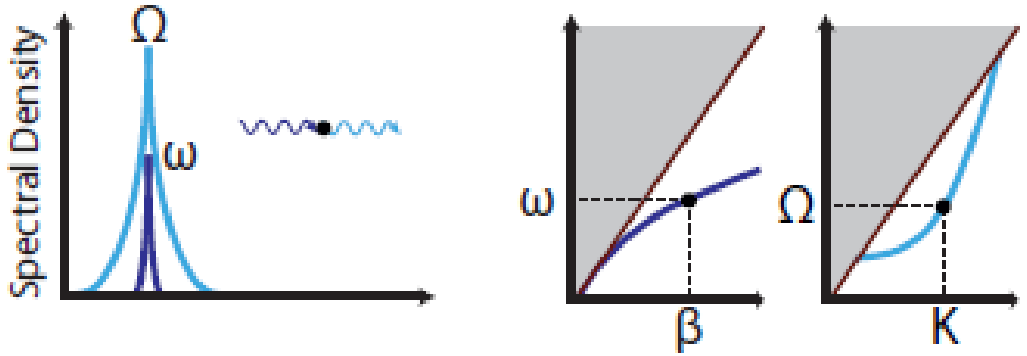
Outlook

Light-sound interaction

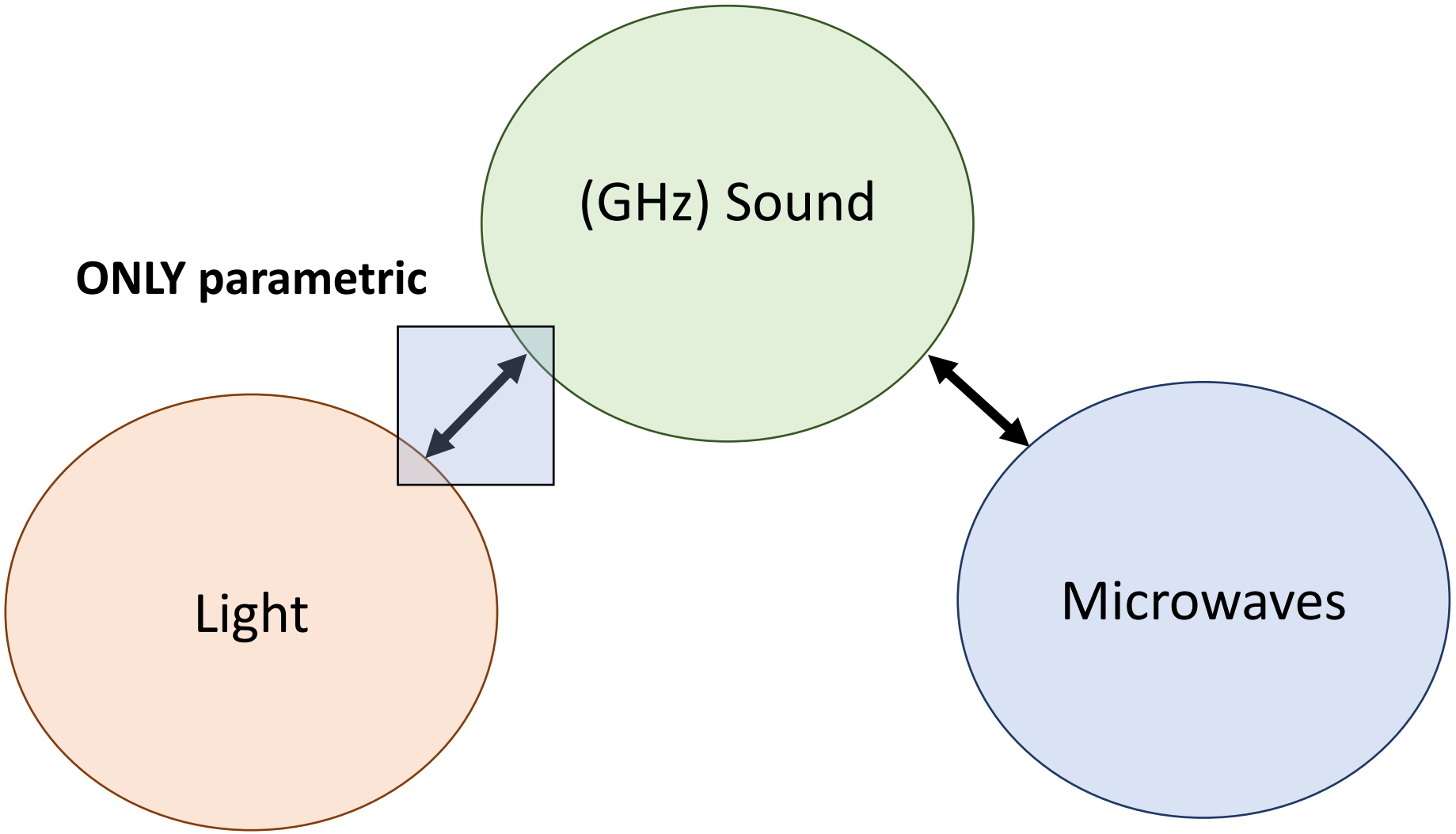
(a) Parametric coupling



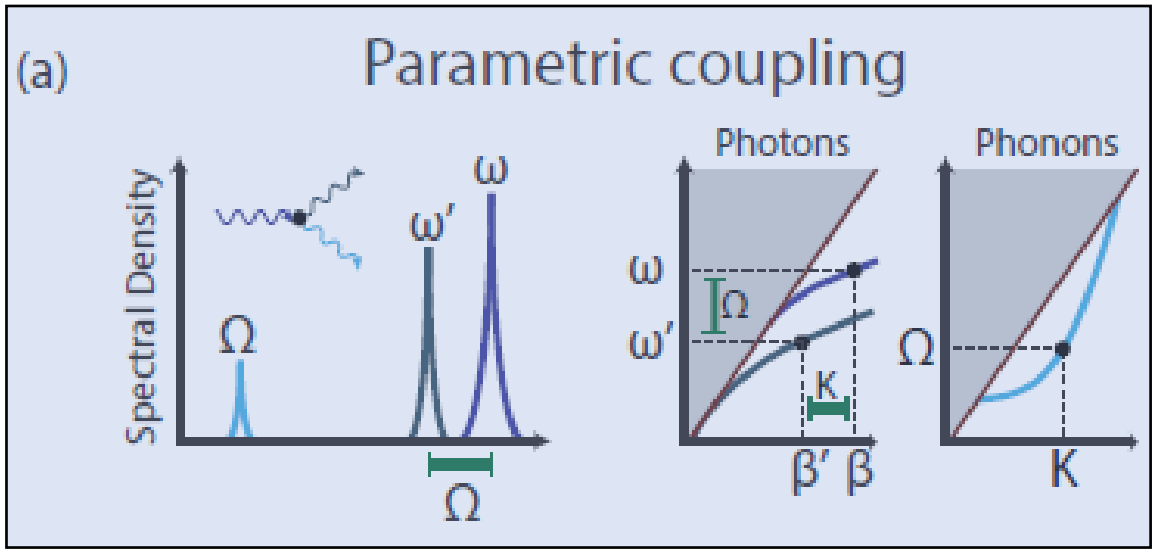
(b) Direct coupling

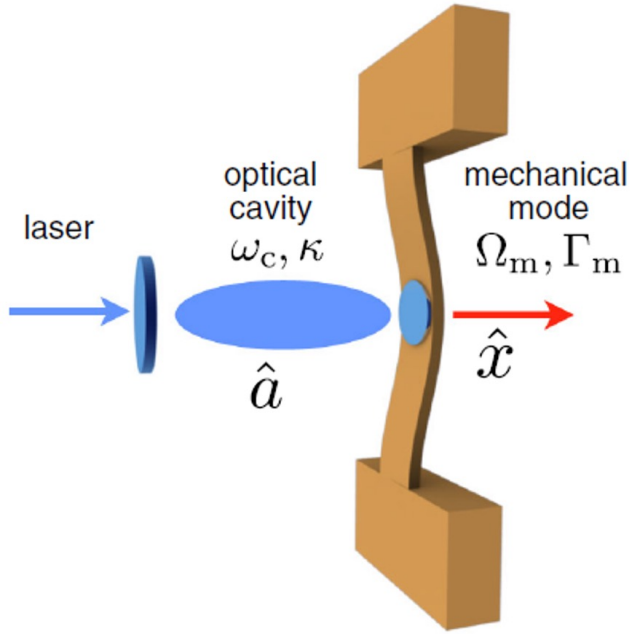


Process light with sound?



Light-sound interaction: parametric



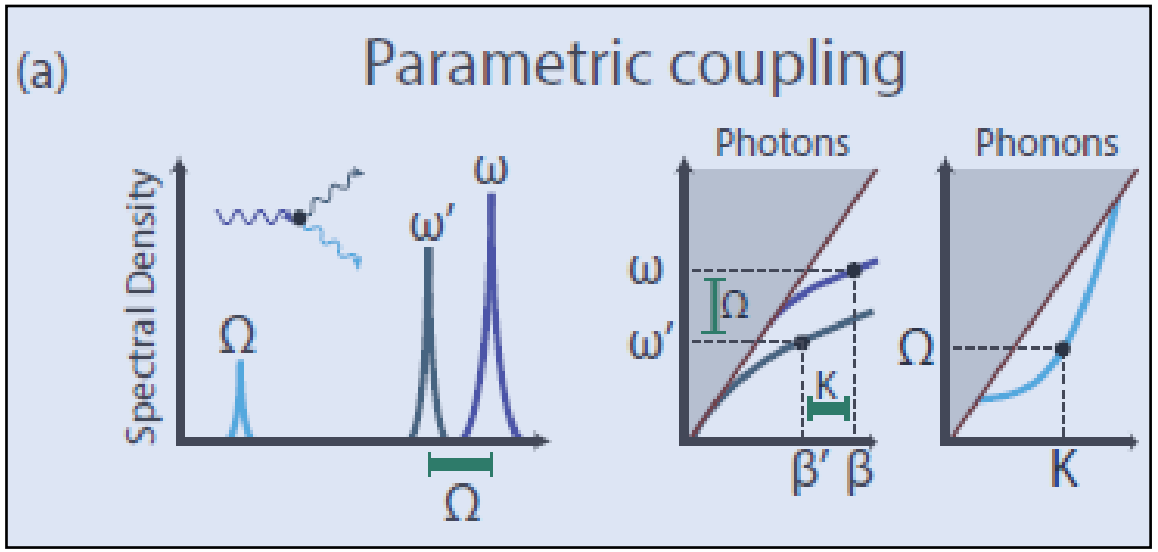


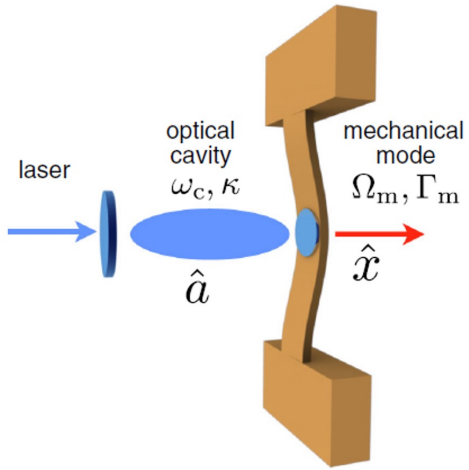
Aspelmeyer et al. (2014)

Mechanical motion changes optical cavity frequency

Safavi-Naeini et al. Optica (2019)

Light-sound interaction: parametric





Aspelmeyer et al. (2014)

$$\mathcal{H}_{\rm int} = \hbar(\partial_x \omega_o) a^\dagger a x$$

$$\mathcal{H}_{\rm int} = \hbar g_0 a^\dagger a (\delta b + \delta b^\dagger)$$

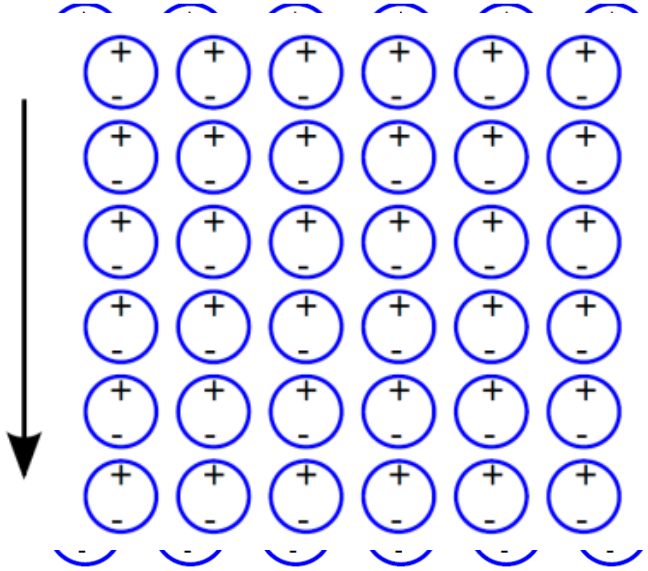
$$g_0 = (\partial_x \omega_o) x_{\rm zp}$$

Maximize interaction rate in small structures with large zero-point motion

Integrated photonics!

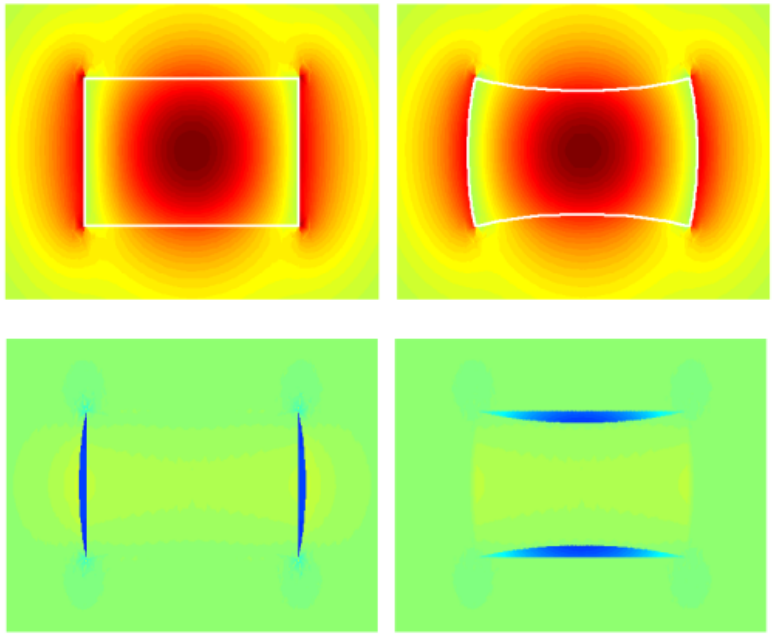
There are typically two contributions

Photo-elastic contribution

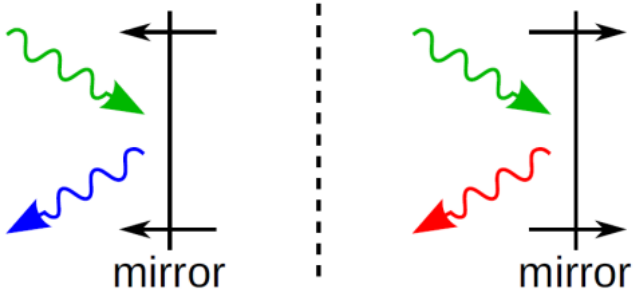


Wolff (2015)

Boundary contribution

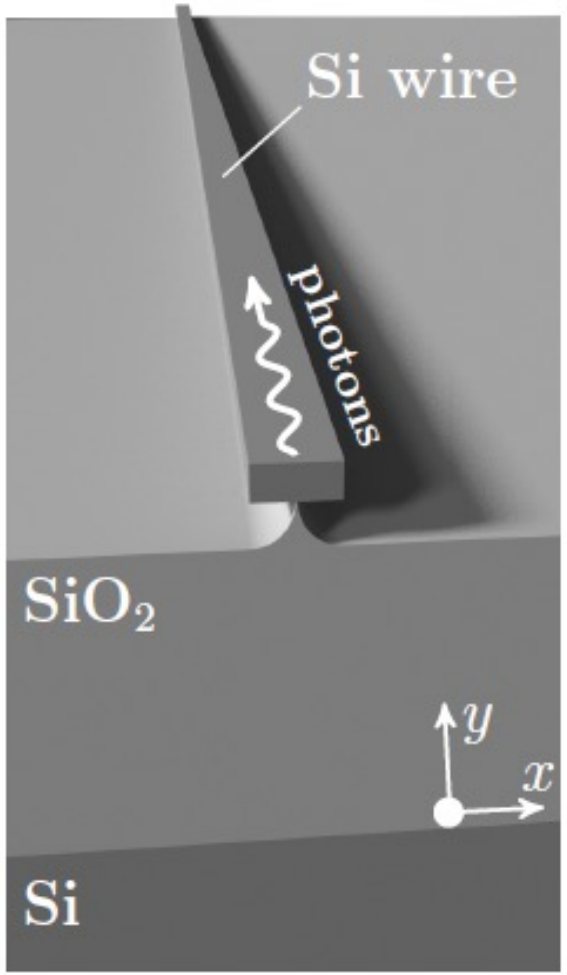


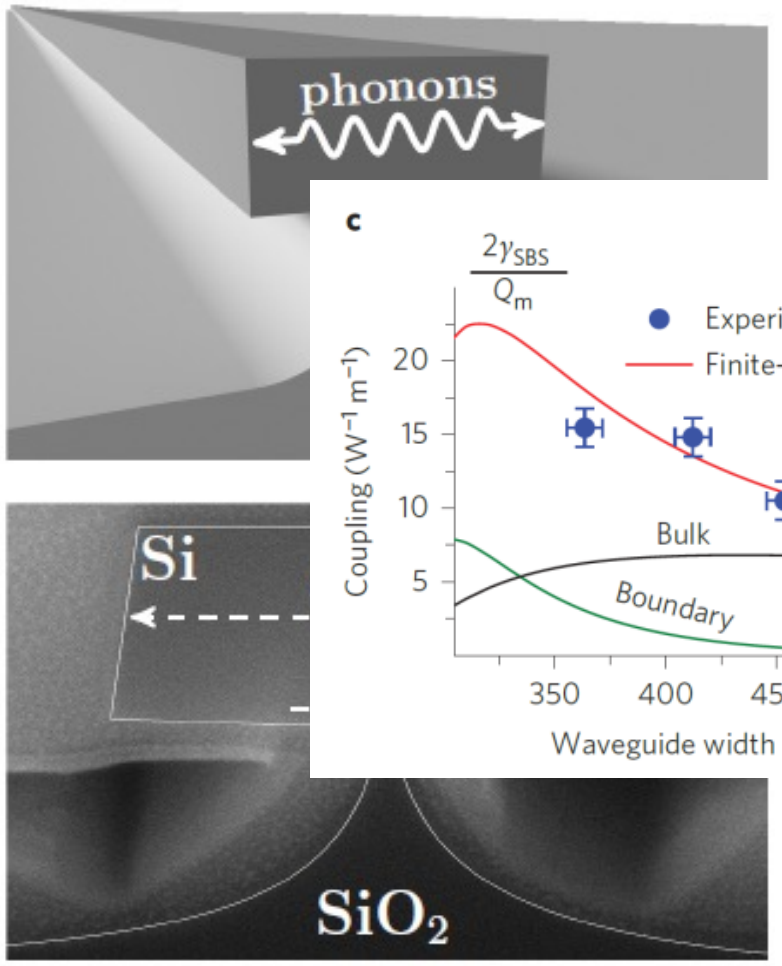
Doppler effect

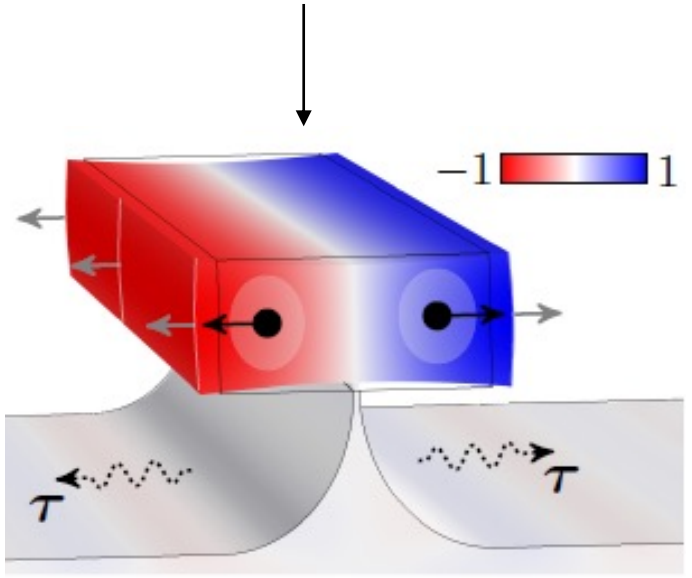


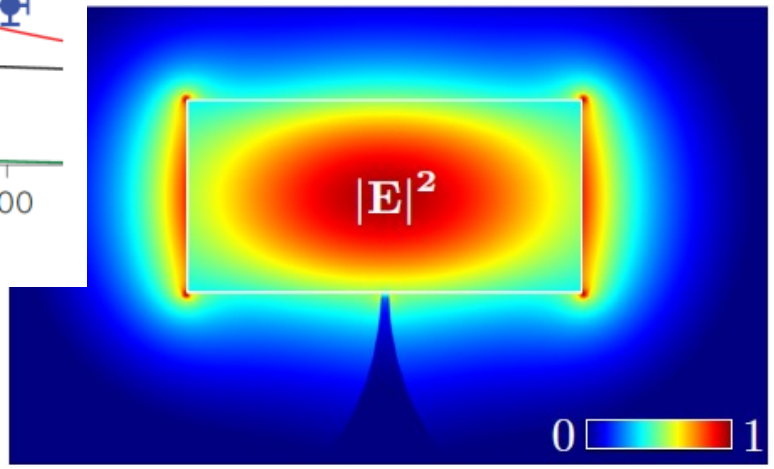
Sound changes effective refractive index

In this example the contributions add









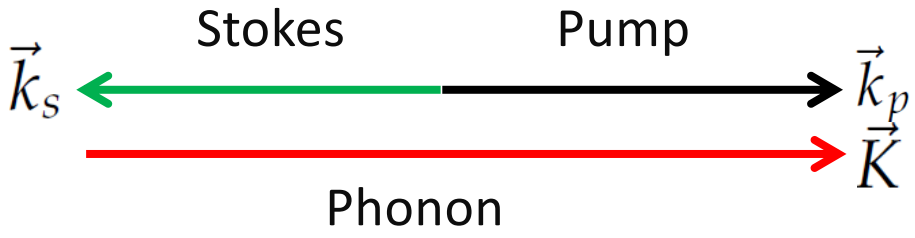
Van Laer et al. (2015)

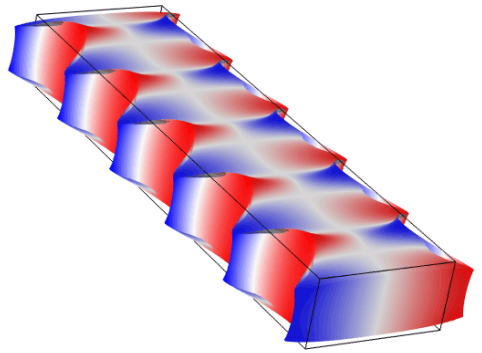
Bulk & boundary effects *add*

Momentum- and energy-conservation

Backward

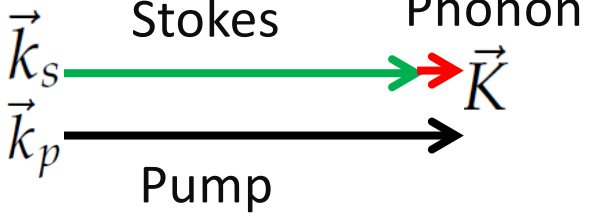
High-group-velocity phonons

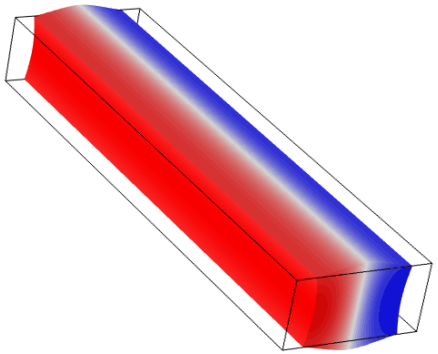




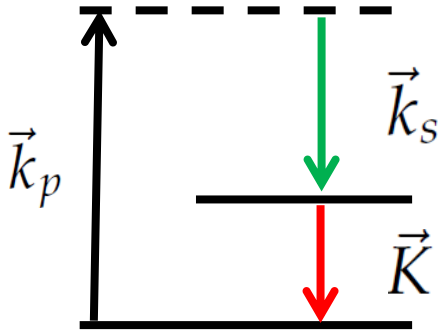
Forward

Low-group-velocity phonons





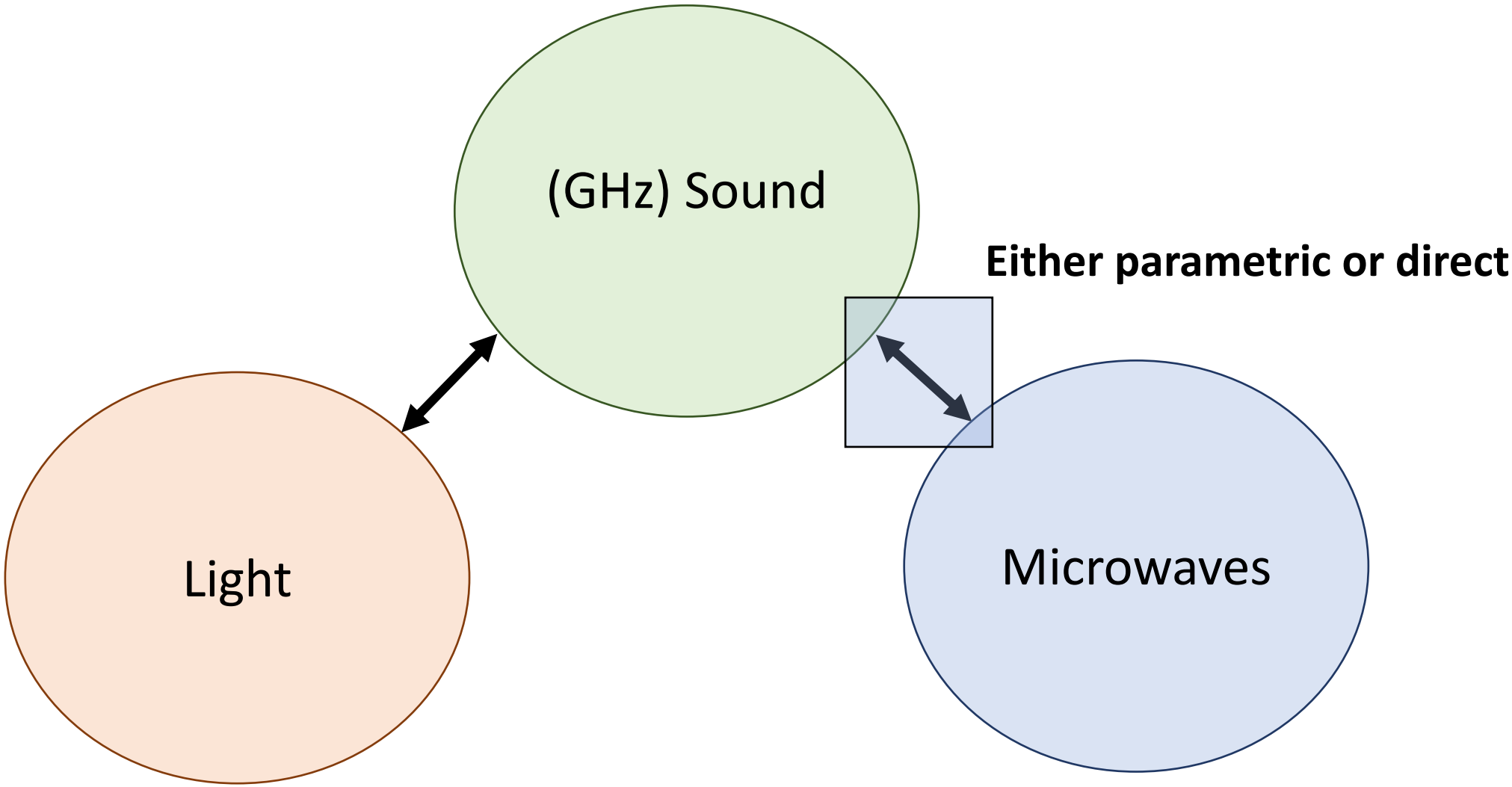
Van Laer et al. (2015)



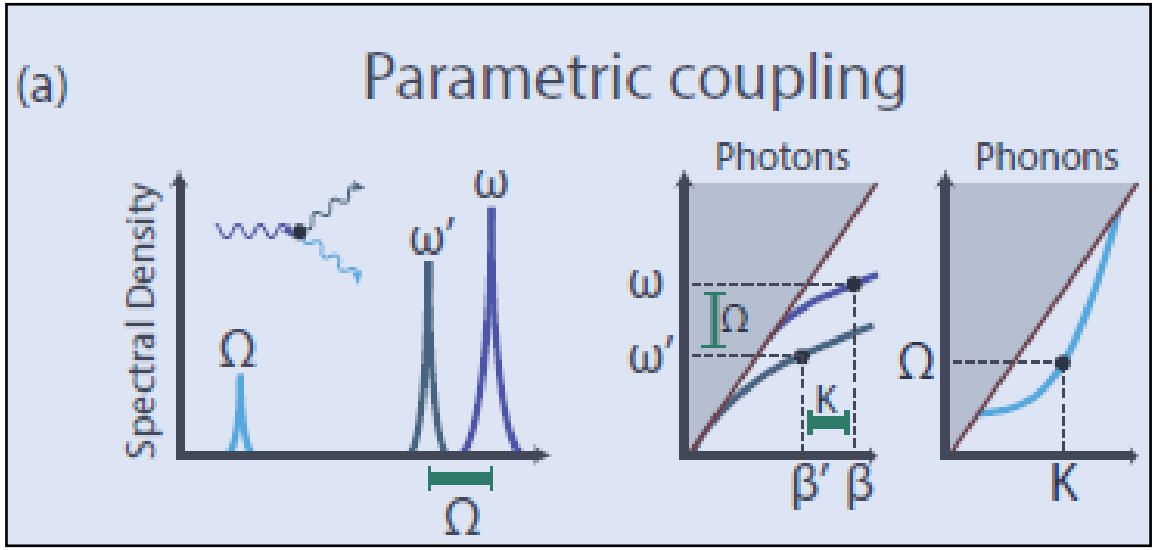
Energy and momentum conservation are necessary – but not sufficient – approximate conditions

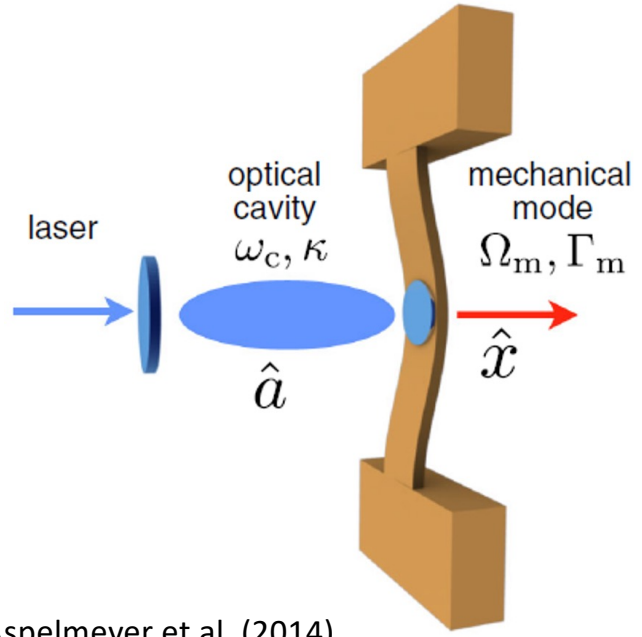
This is important in quantum hardware, isolators, beam-steering

Process light with sound?

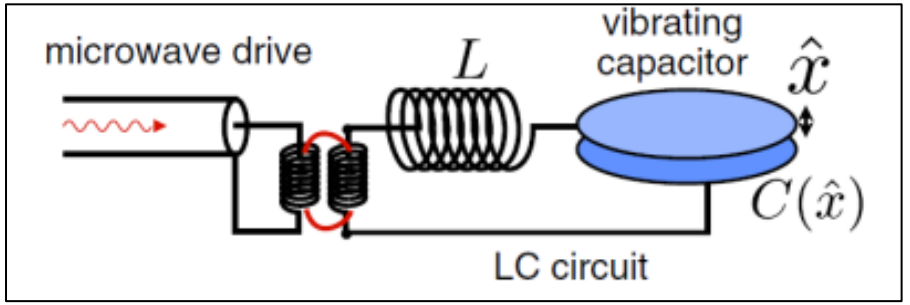


Parametric coupling to microwave photons

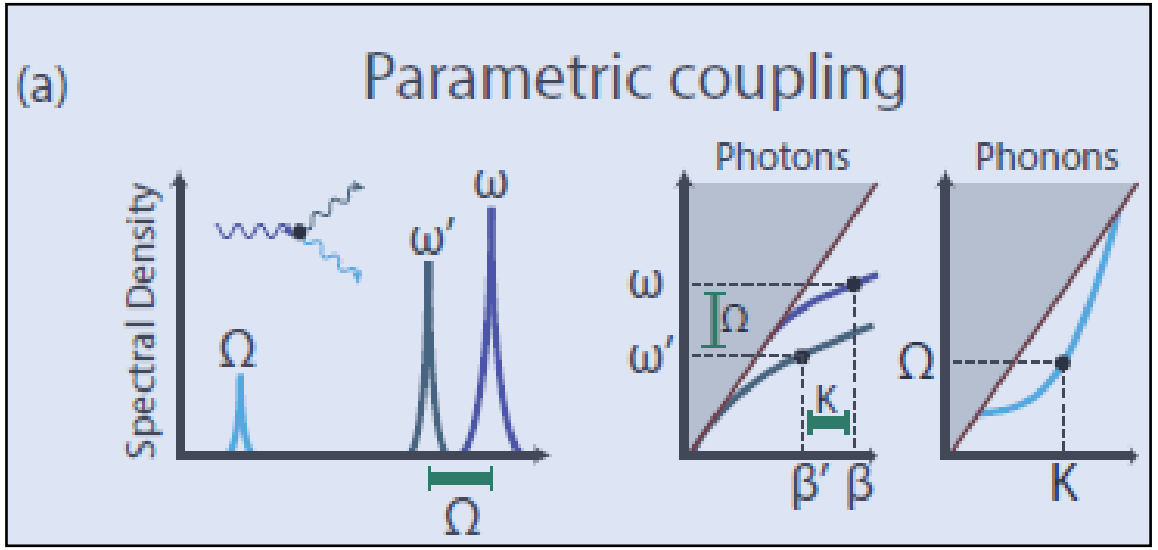


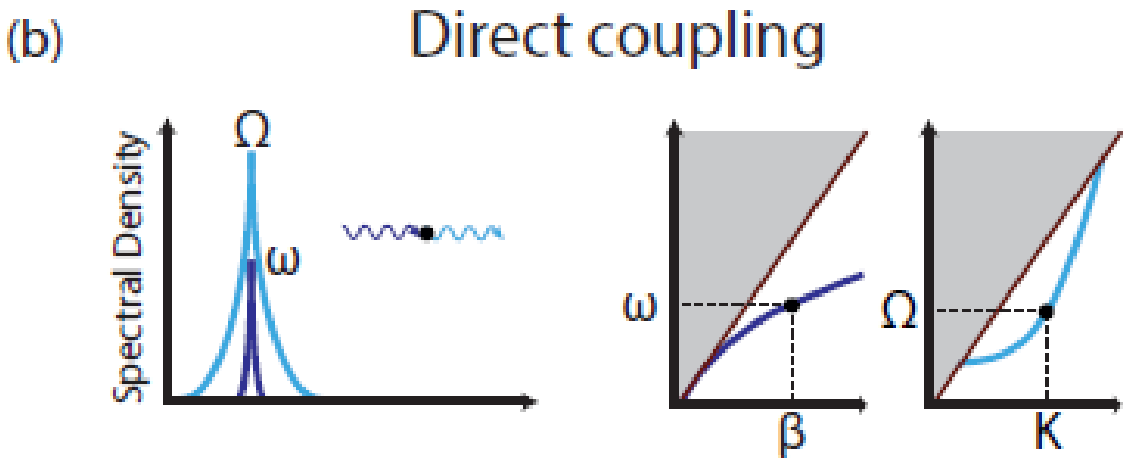


Aspelmeyer et al. (2014)

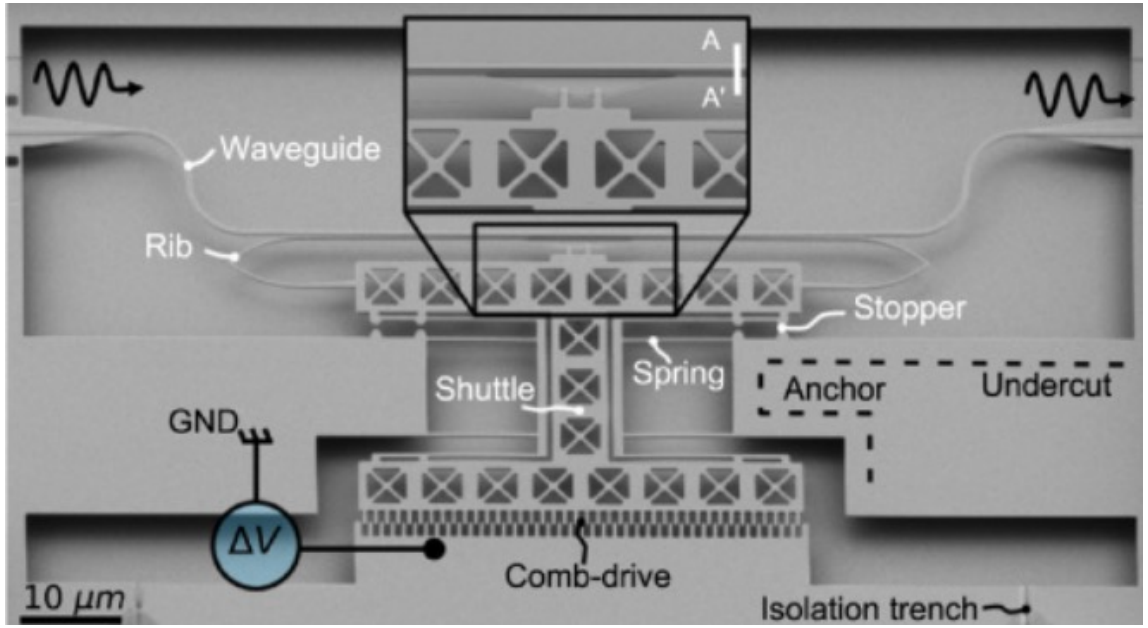


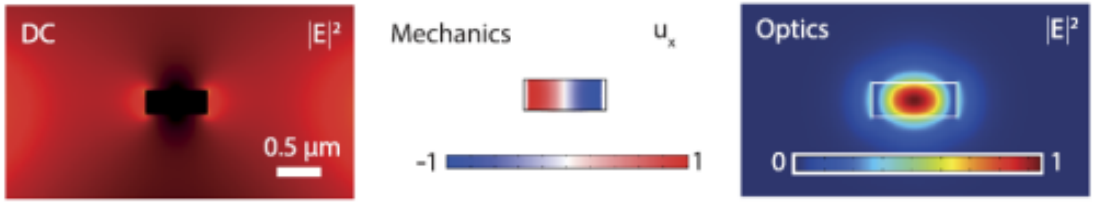
Parametric coupling to microwave photons





Edinger et al. (2021)

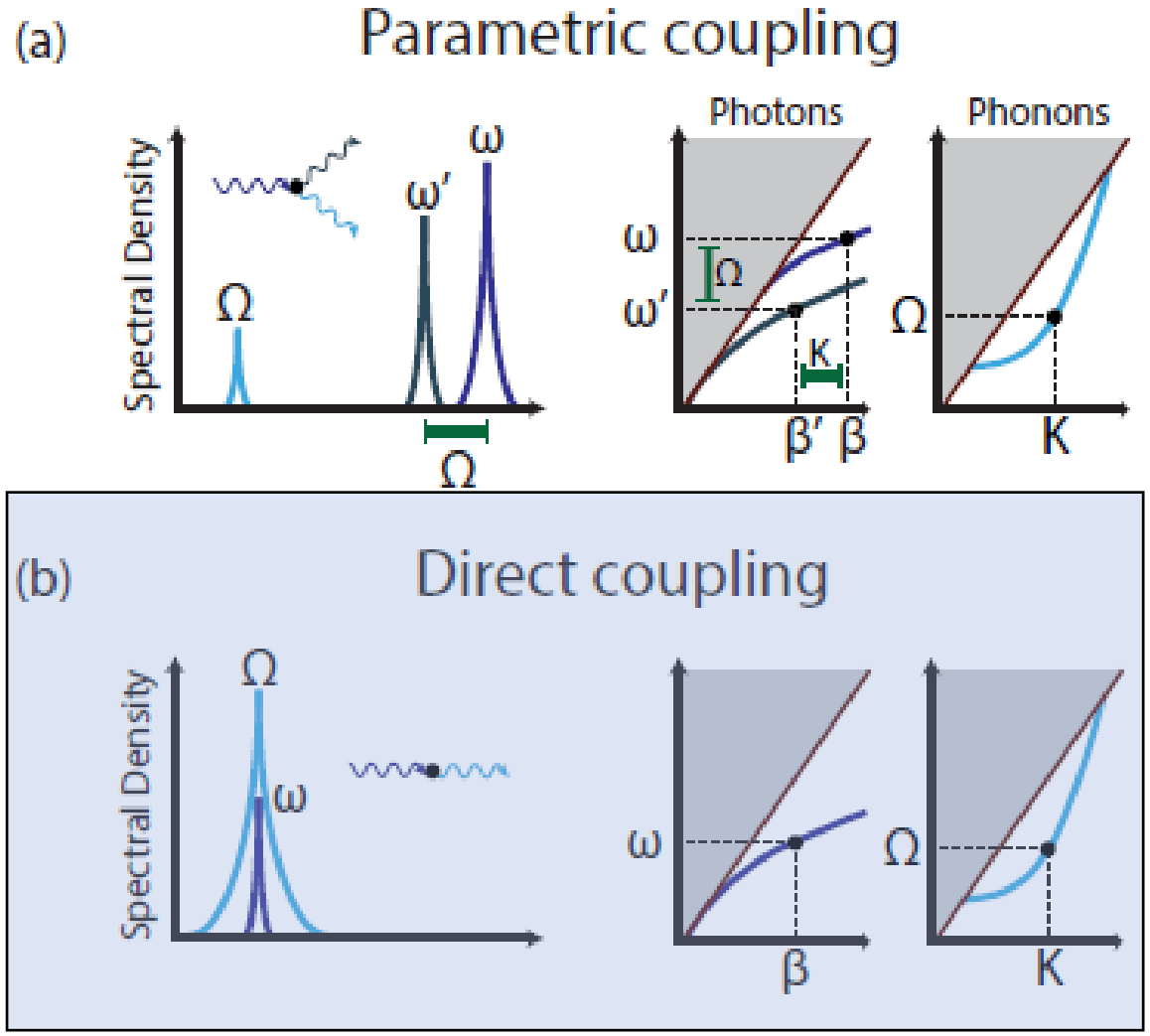




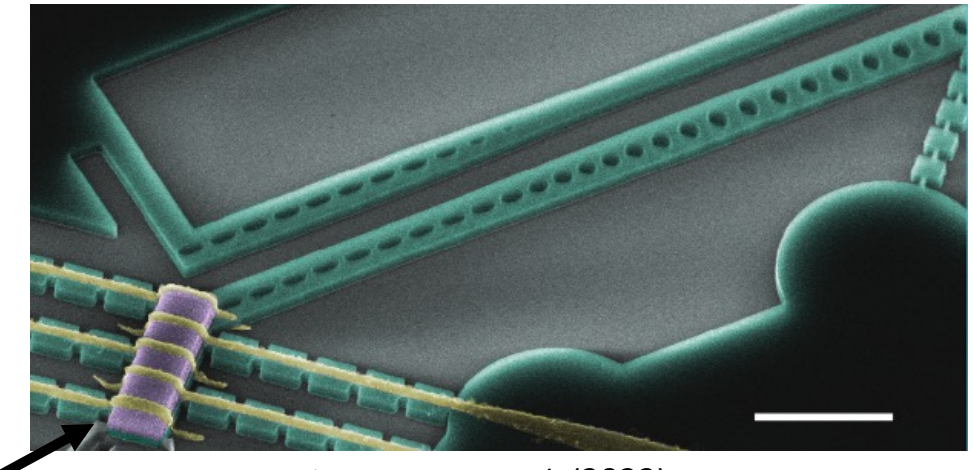
Van Laer et al. (2018)

“Capacitive” driving: both at GHz and MHz

Direct coupling to microwave photons



Piezoelectric materials



Jiang, Mayor et al. (2022)

AlN, Lithium niobate, PZT, …

Heterogeneous integration!

Micro-transfer-printing,
Wafer bonding, etc.

Outline

Process light with sound?

Basic physics

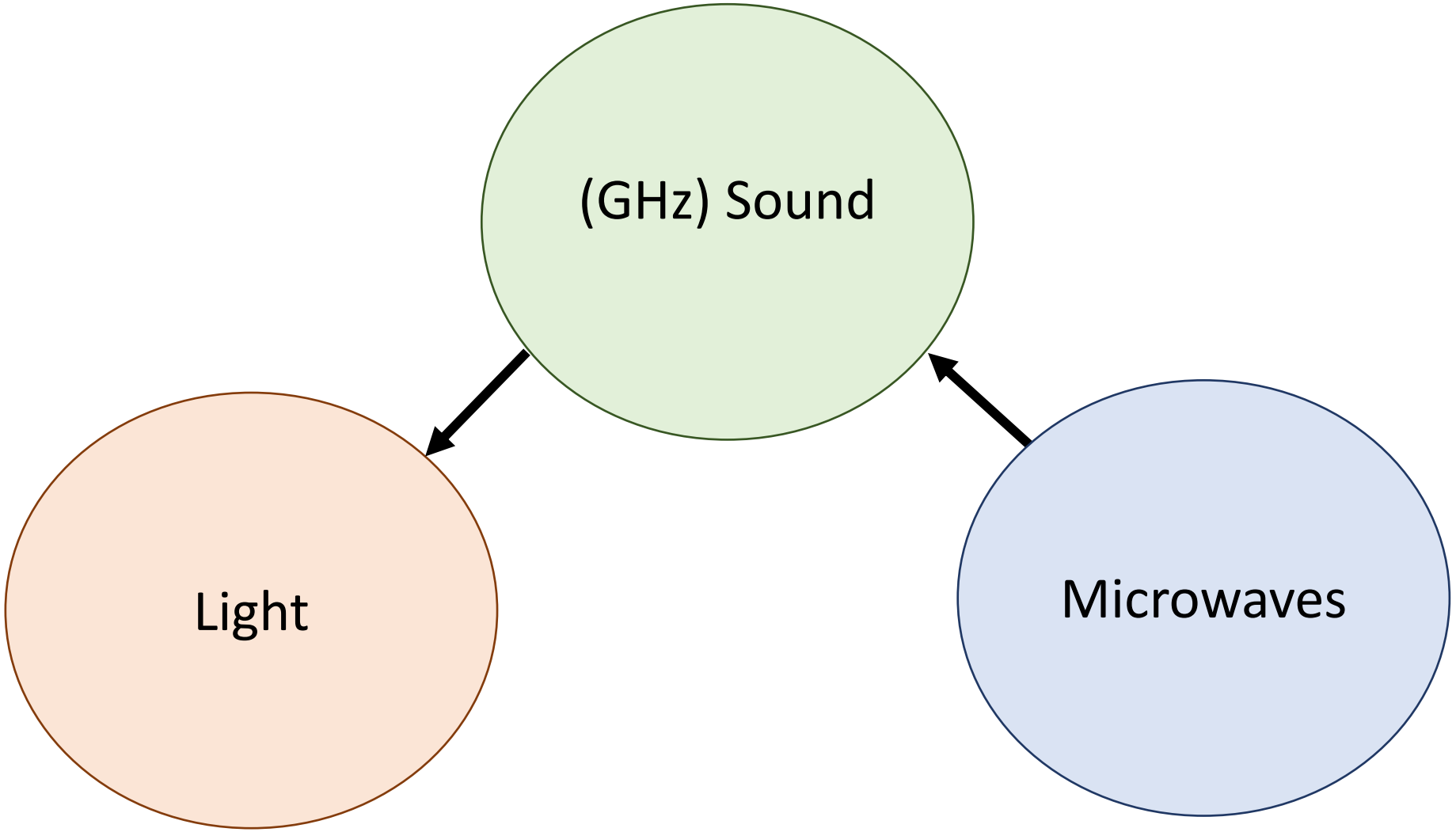
Case studies

Microwave-optics

Beam-steering

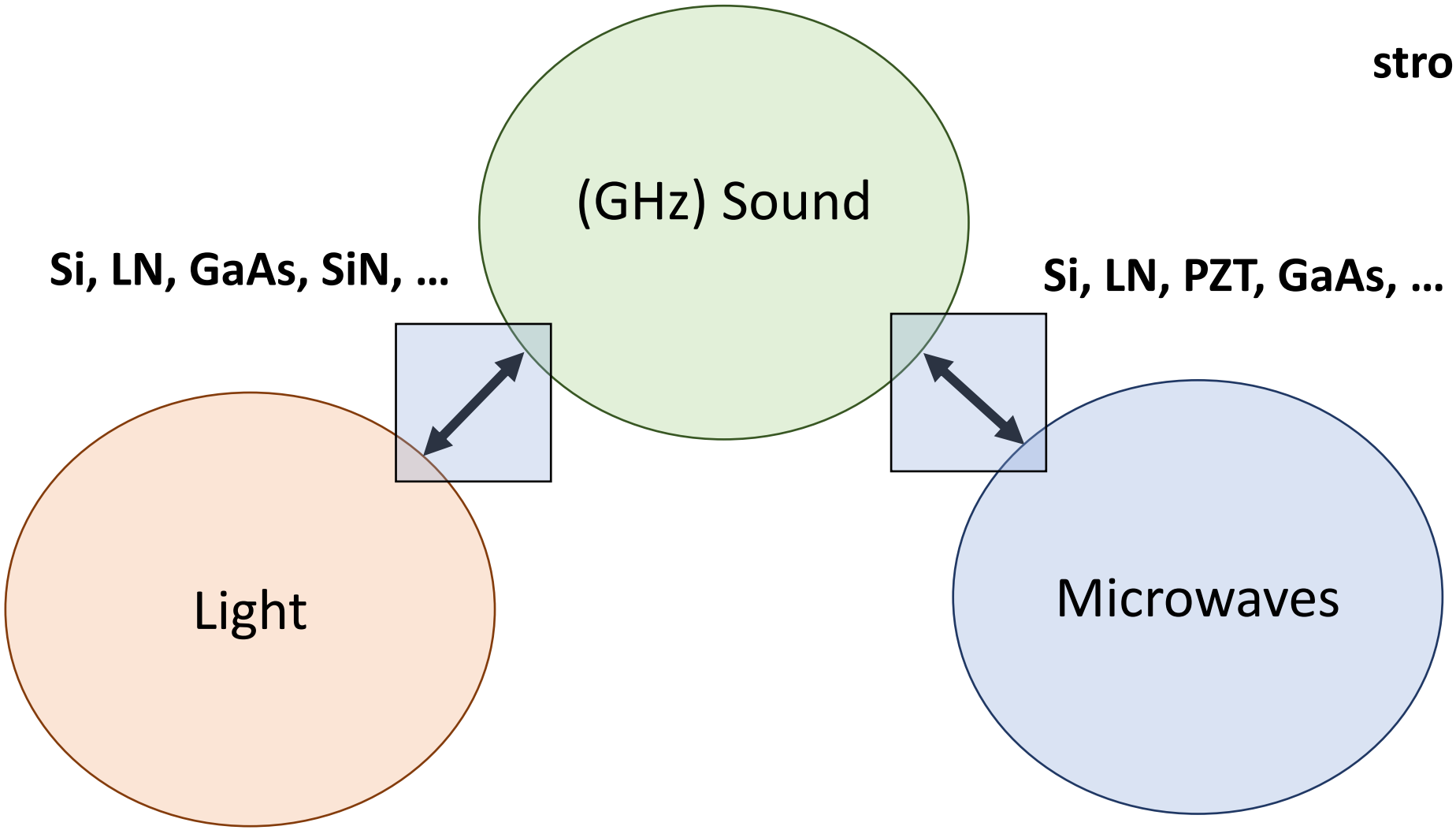
Outlook

Case study: microwave-optics transduction

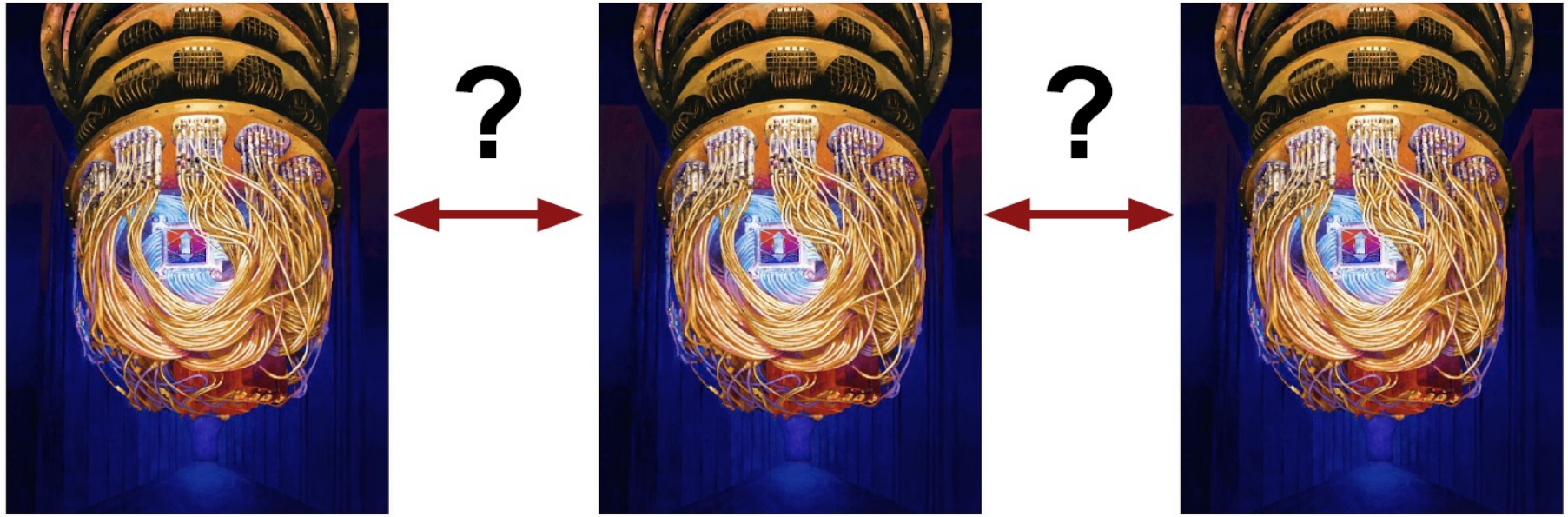


Case study: microwave-optics transduction

Desired:
strong coupling rates
low losses



Connect small quantum computers



https://ai.googleblog.com

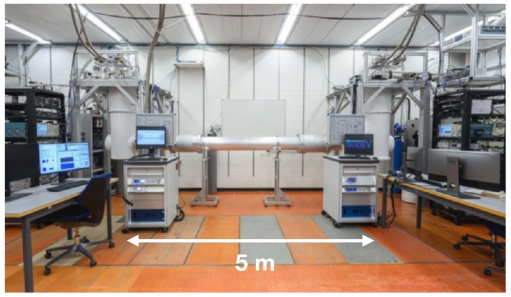


Photo: S. Storz, H. Hostettler, QuDev Lab, ETH Zurich

Microwave cable:

- 1 dB/m
- 1000 thermal photons
- coherence length < 1 mm

Telecom fiber:

- **< 0.2 dB/km**
- **1e-14 thermal photon**
- **coherence length 20 km**

Millimeter wave at 4K

- < 1 thermal photon
- lower energy cost per converted qubit
- coherence length ~ 50 m

Hybrid quantum architectures

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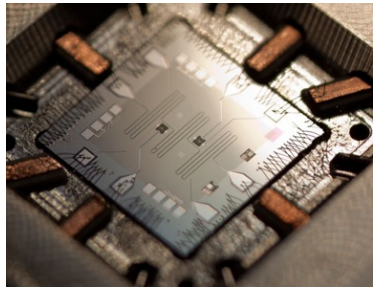
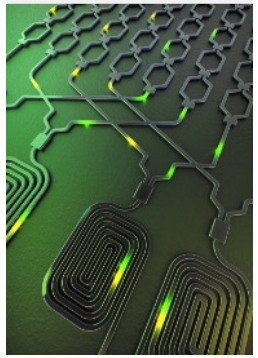
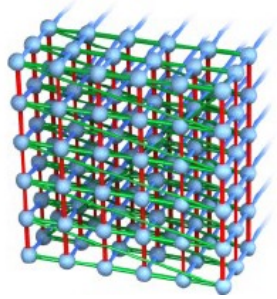
Superconducting QC

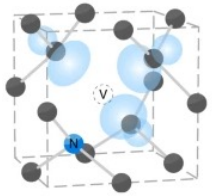


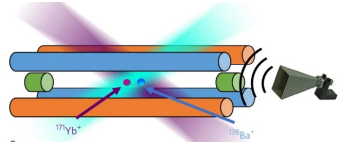
All-optical QC





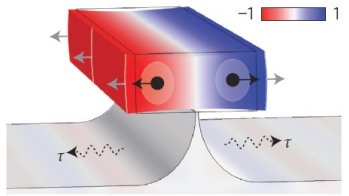
Acoustics/ions/spins/…

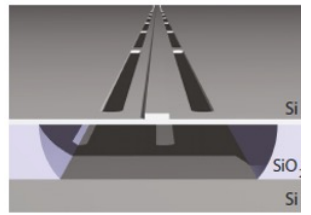




GHz phonons can drastically improve performance

Confined mechanics can **reduce energy consumption** by orders of magnitude





Classical $E_{\mathrm{bit}} = \frac{\hbar\omega_{\mathrm{m}}}{4}\left(\frac{\kappa}{g_0}\right)^2$ 1 aJ/bit $E_{\mathrm{bit}} = \frac{E_{\mathrm{mech}}}{\eta_{\mathrm{m}}}$

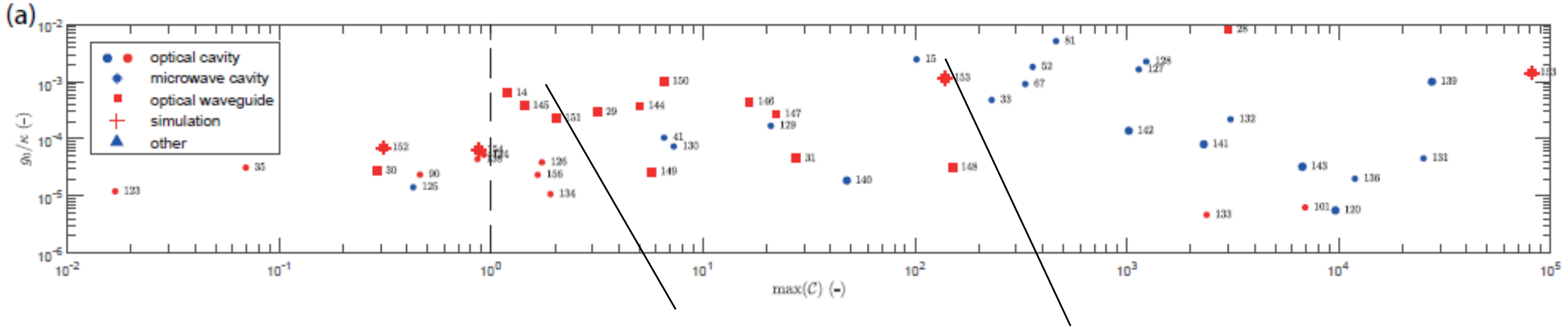
Quantum $\frac{E_{\mathrm{qbit}}}{E_{\mathrm{bit}}} \approx \frac{\omega_{\mathrm{o}}}{\omega_{\mathrm{m}}}$ 100 fJ/qubit → 100 Mqbits/s @ 10 uW

Desired:
strong coupling rates
low losses

Integrated photonics!

Safavi-Naeini et al. Optica (2019)

State of the art in energy per (qu)bit

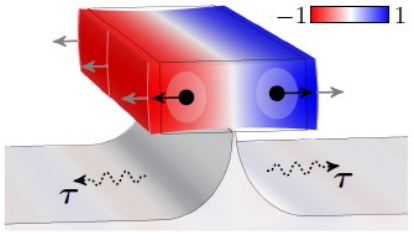


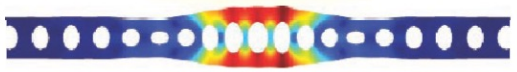
$$\frac{g_0}{\kappa}$$

Single-photon nonlinear optics

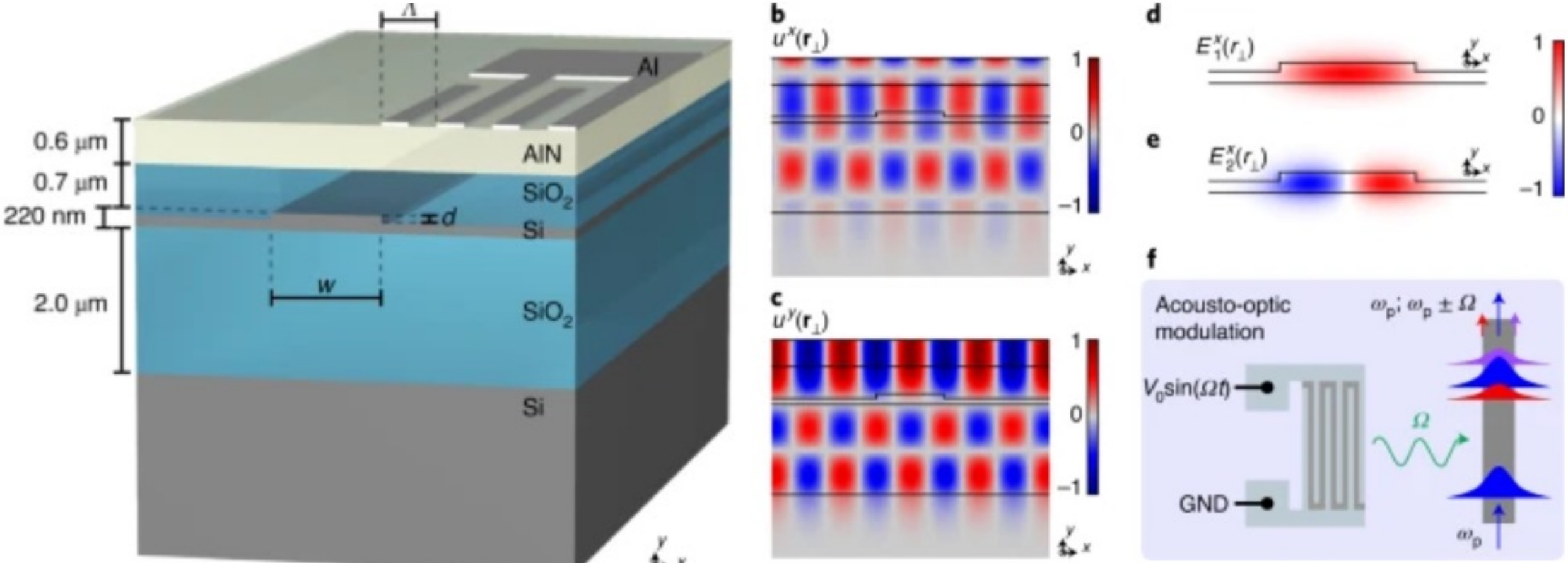
Energy-efficient electro-optic modulation

Microwave-to-optics conversion





Acousto-optic modulators in AlN-SOI



Kittlaus et al. Nature Photonics (2020)

Acousto-optic modulators in AlN-SOI

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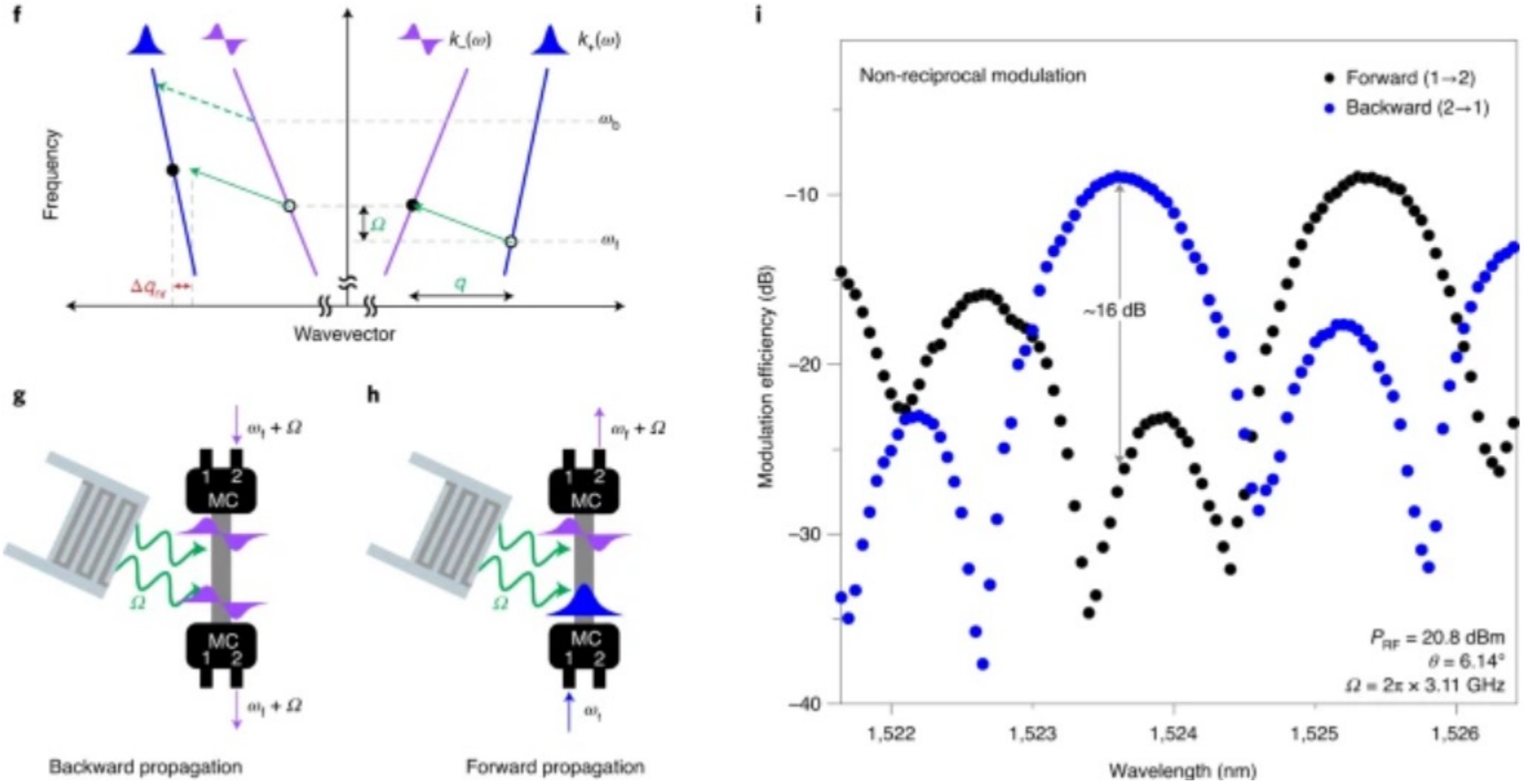
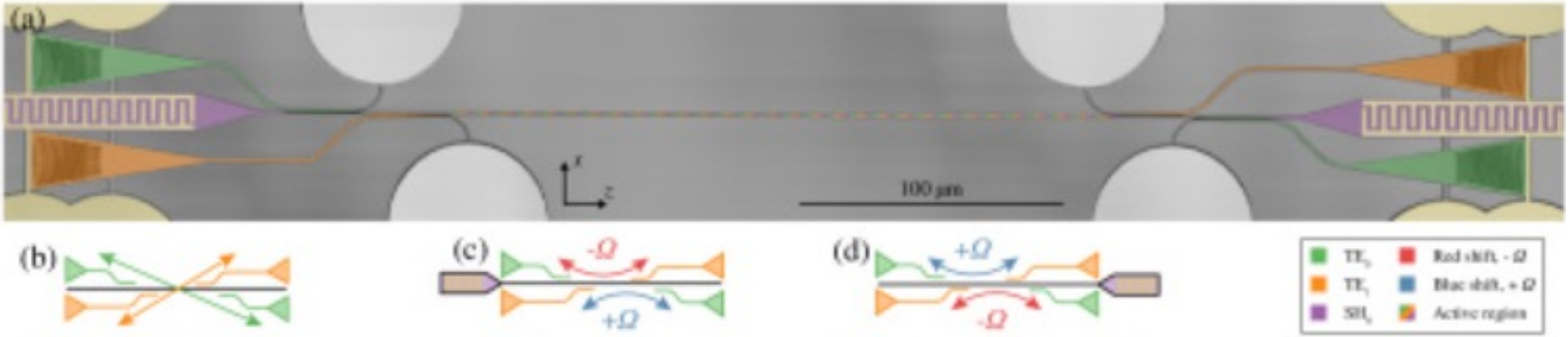
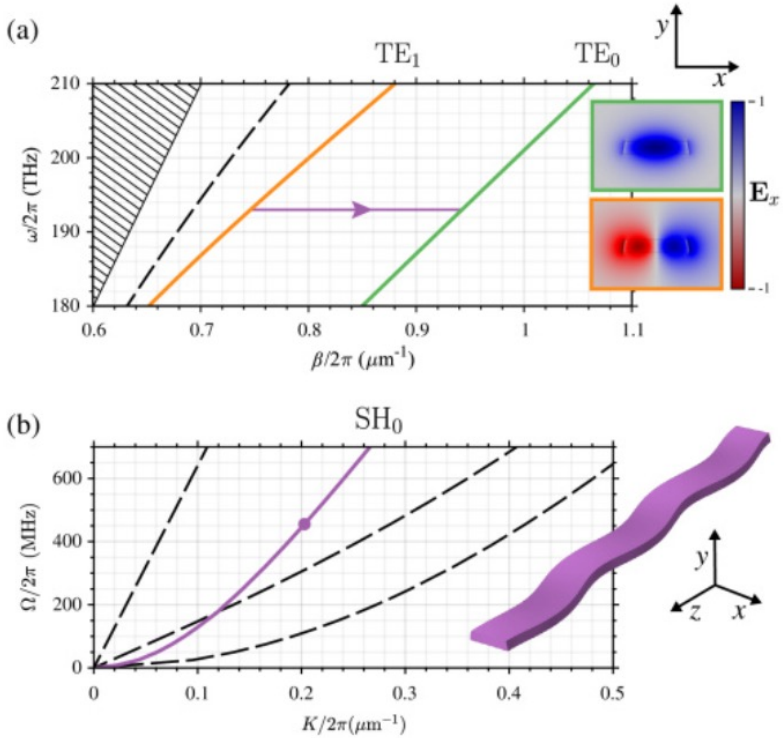


Kittlaus et al. Nature Photonics (2020)

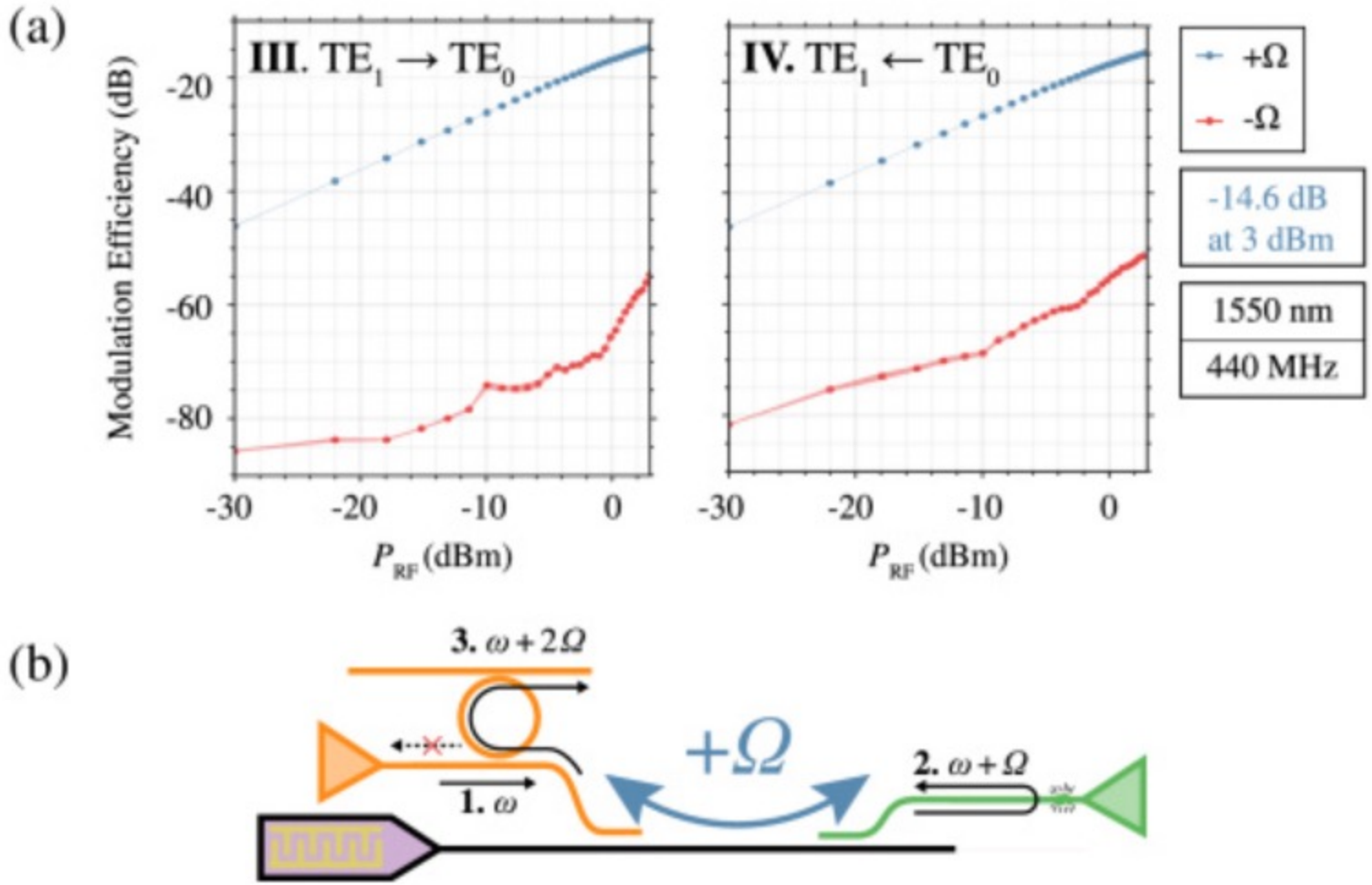
Acousto-optic modulators in LN





Sarabalis et al. Optica (2022)

Acousto-optic modulators in LN



Sarabalis et al. Optica (2022)

Steep rise towards viability

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Work	Year	λ (nm)	$\Omega/2\pi$ (MHz)	L (mm)	$P_{\pi/2}$ (mW)	γ (dB/mm)	$\lvert t_{b\mu} \rvert^2$ (dB)	$g/\sqrt{\hbar\Omega}$ ($\mathrm{mm}^{-1}\ \mathrm{W}^{-1/2}$)	$(L/\lambda)^2 P_{\pi/2}$ (MW)	η_{max} (%)
Harris [1]	1970	632.8	54	35	3.64×10^3	—	−7.5	0.057	1.1×10^4	95
Ohmachi [2]	1977	1150	245.5	4.5	550	—	−20	4.7	8.42	70
Binh [3]	1980	632.8	550	9	225	—	−25	6.54	45.5	99
Heffner [23]	1988	1523	175	25	500	—	−7.0	0.20	135	97
Hinkov [24]	1988	633	191.62	17	400	−0.1	−25	2.6	289	90
Frangen [25]	1989	1520	178	9	90	−0.05	−10	1.9	3.16	99
Hinkov [26]	1991	800	355.5	20	19.8	−0.04	−3	0.825	12.4	93
Hinkov [5]	1994	800	365	25	0.5	−0.04[b]	−3[b]	4.2	0.488	100
Duchet [6]	1995	1556	170	30	6	—	−3	0.96	2.23	100
Liu [27]	2019	1510	16,400	0.5	4.2×10^5	—	−15	0.041	46.4	2.5×10^{-4}
Kittlaus [28][c]	2020	1600	3110	0.240	4.69×10^3	—	−12	5.7	0.105	1
Kittlaus [28][c]	2020	1525.4	3110	0.960	1.48×10^3	—	−12	4.5	0.587	13.5
This work	2020	1550	440	0.25	60	−11.7	−21.9	377	1.6×10^{-3}	18

Sarabalis et al. Optica (2022)

Acousto-optic modulators in LN-SOI

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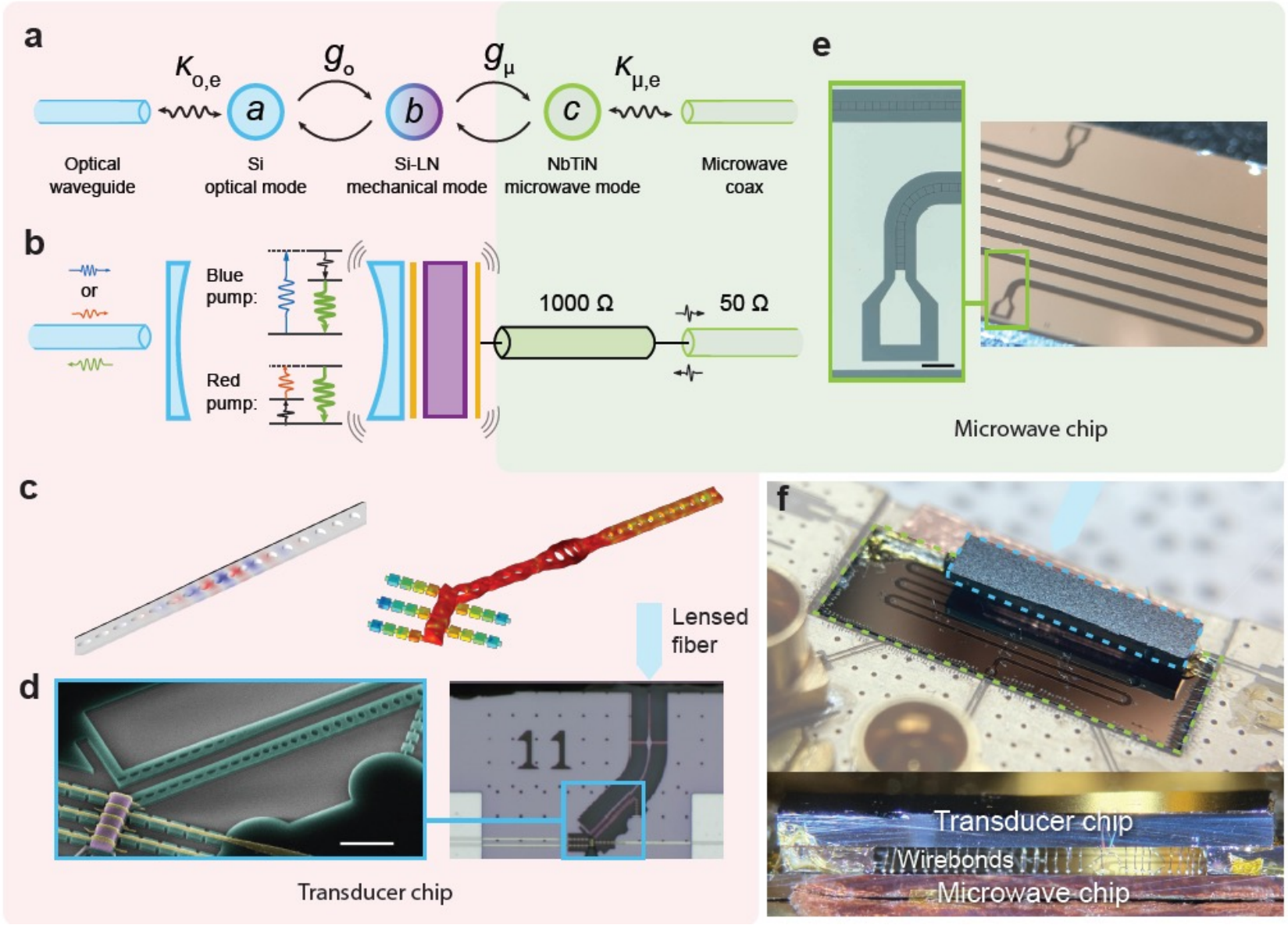
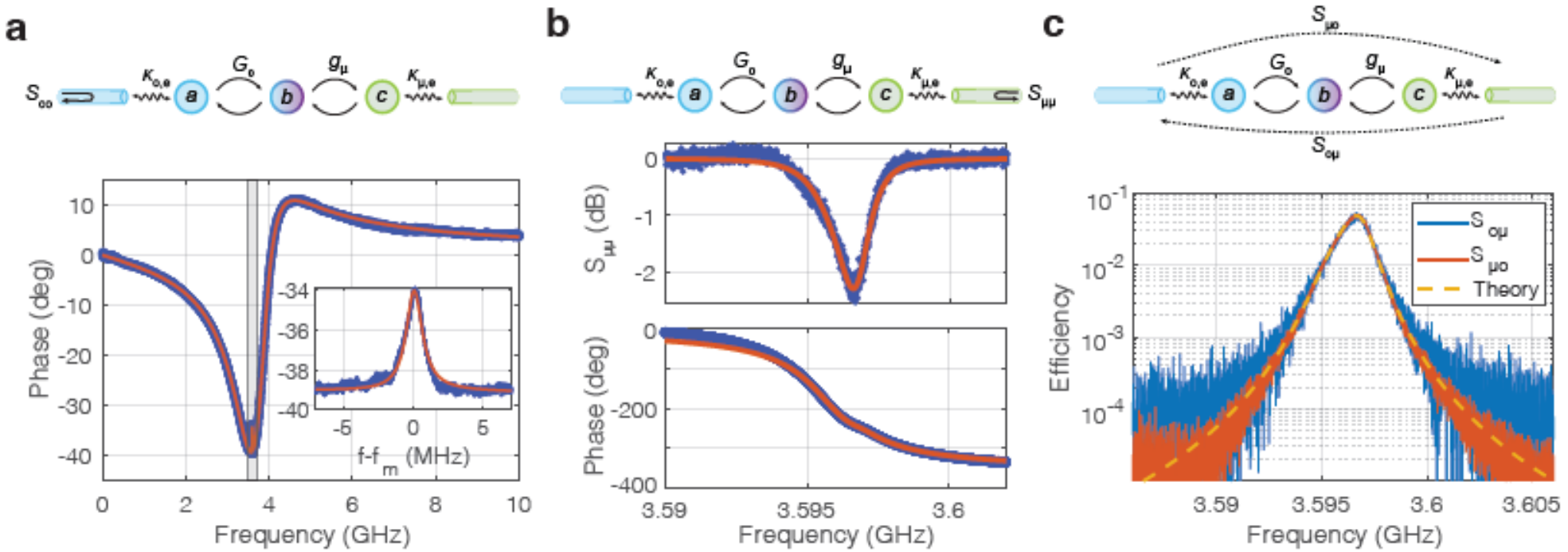
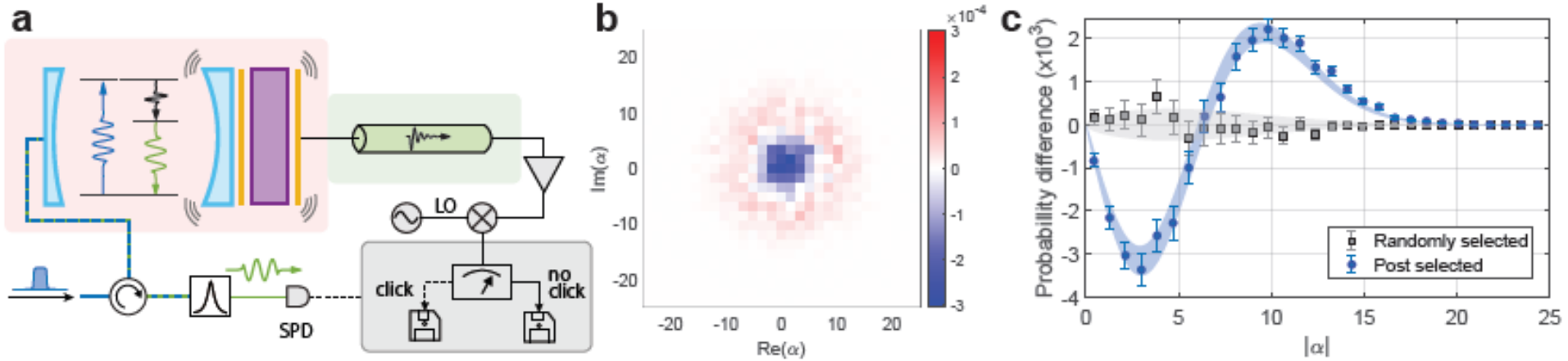


Jiang, Mayor et al. Nature Physics (2023)

Acousto-optic modulators in LN-SOI

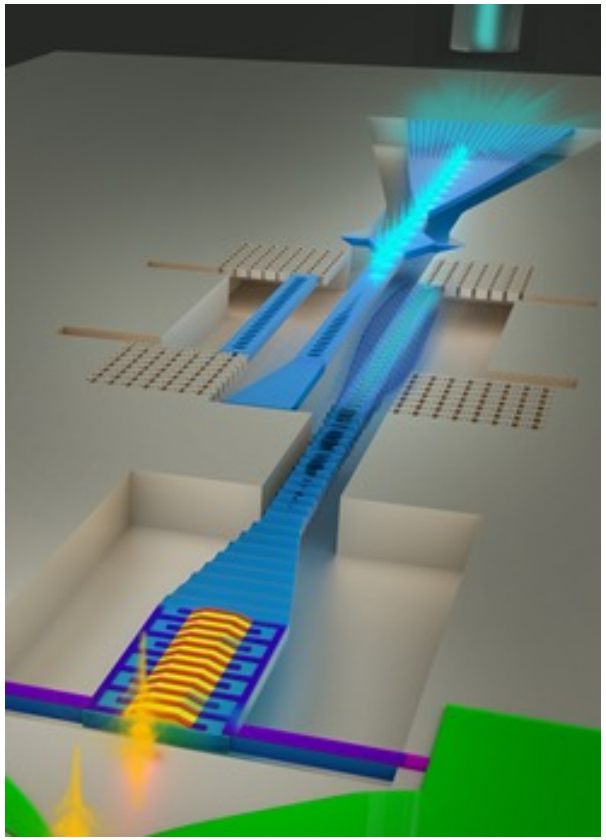
WACQT | Wallenberg Centre for Quantum Technology





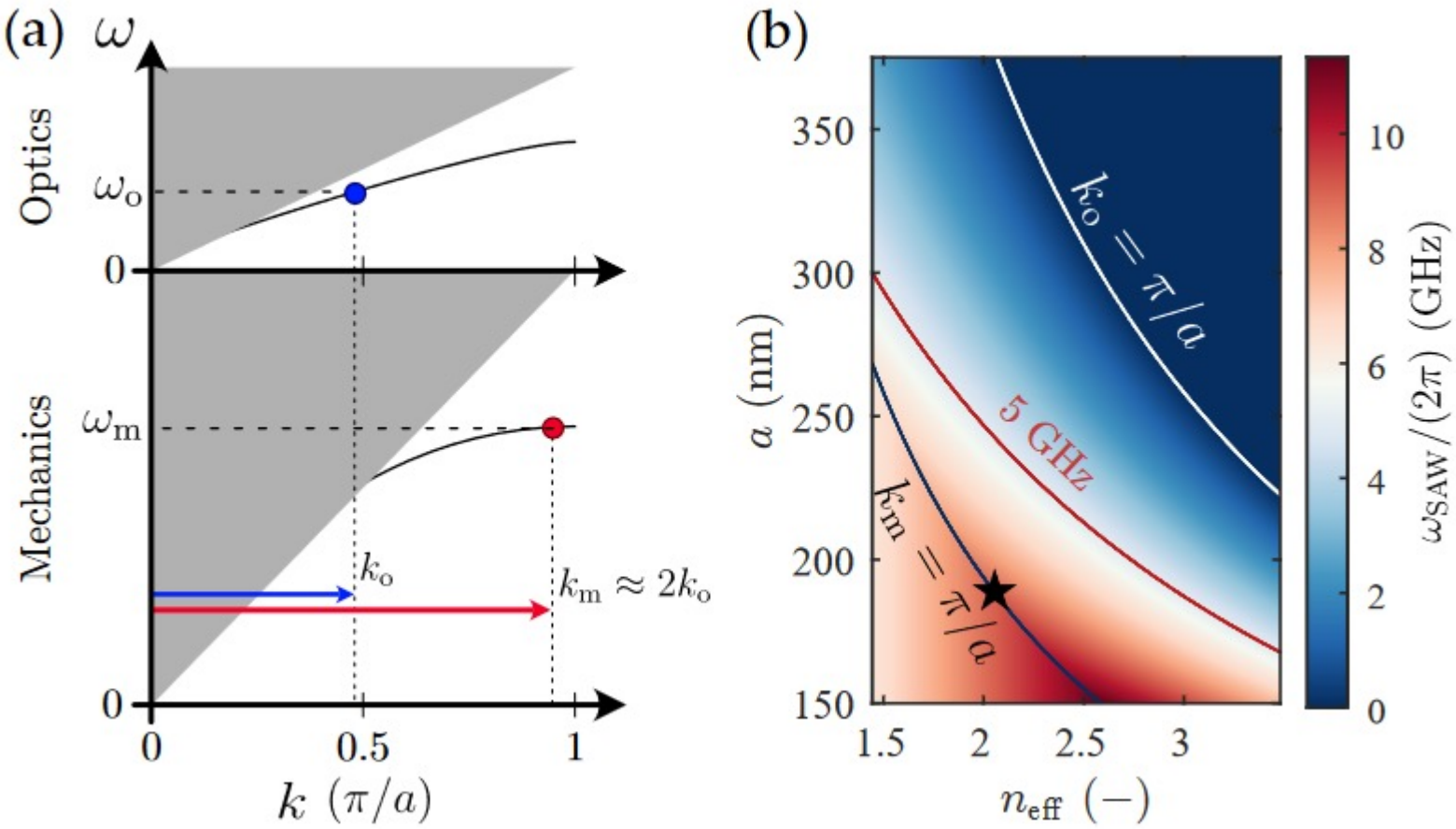
Jiang, Mayor et al. Nature Physics (2023)

Clamped optomechanical crystals in SOI



Conventional suspended

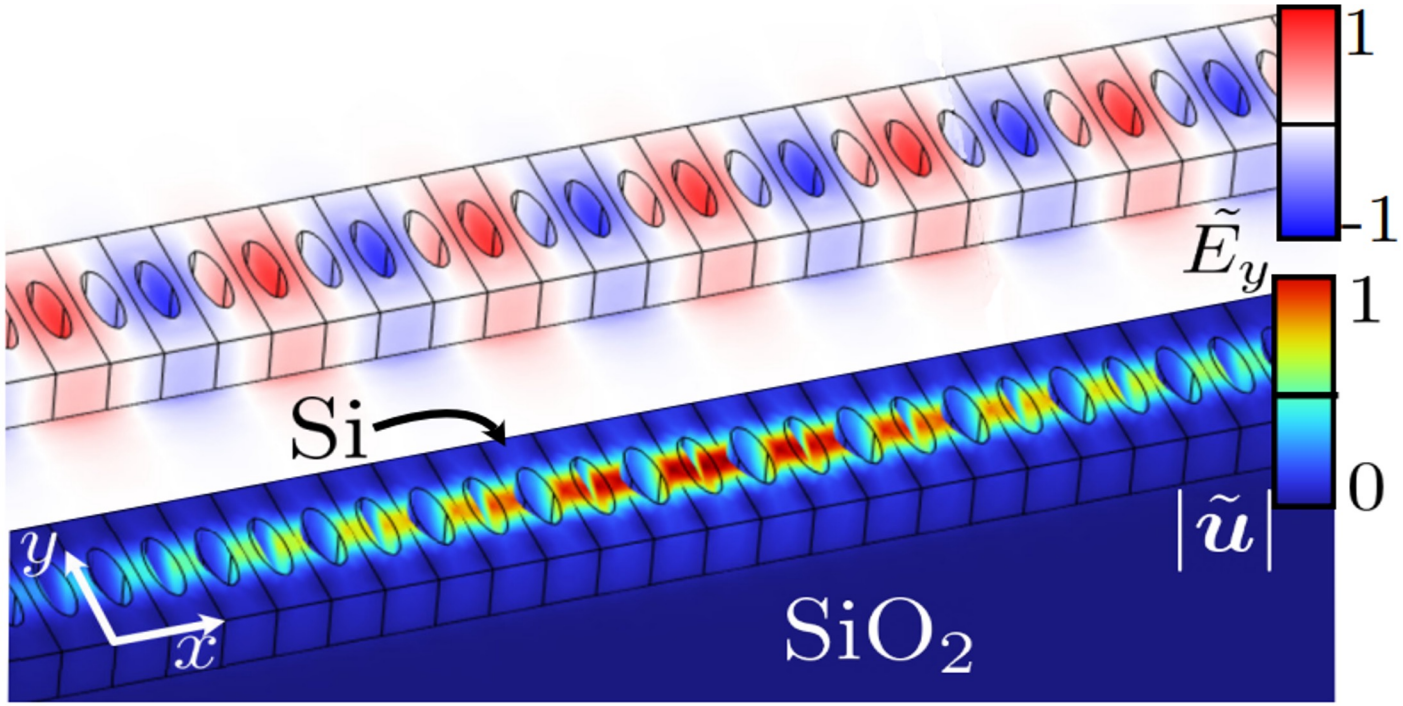
Confine GHz sound in SOI while interacting strongly with light

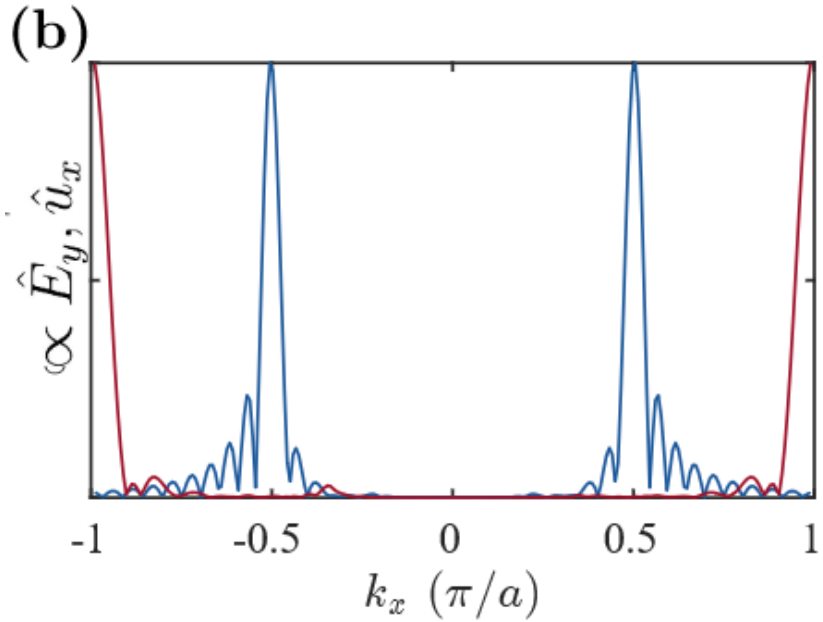


Non-suspended!

Kolvik, Burger et al. Optica (2023)

Clamped optomechanical crystals in SOI



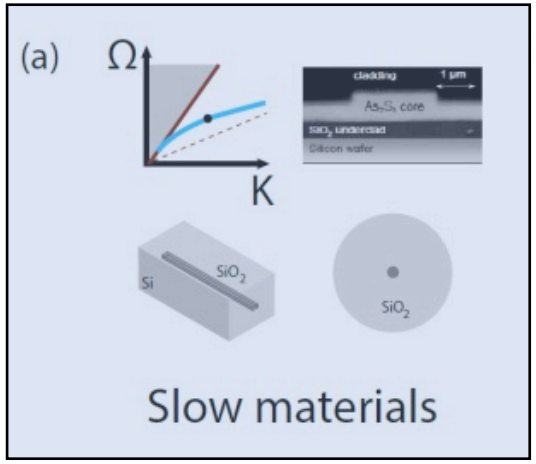


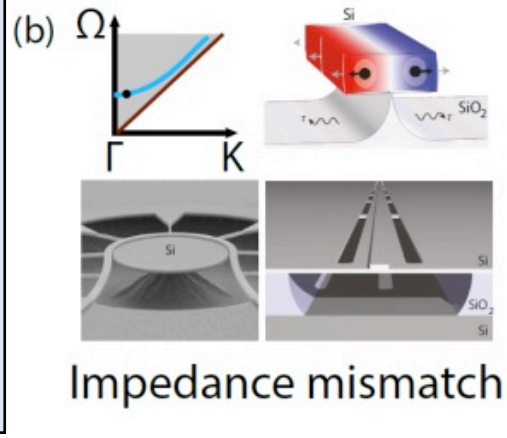
Counter-propagating optomechanical interactions as strong as in suspended structures

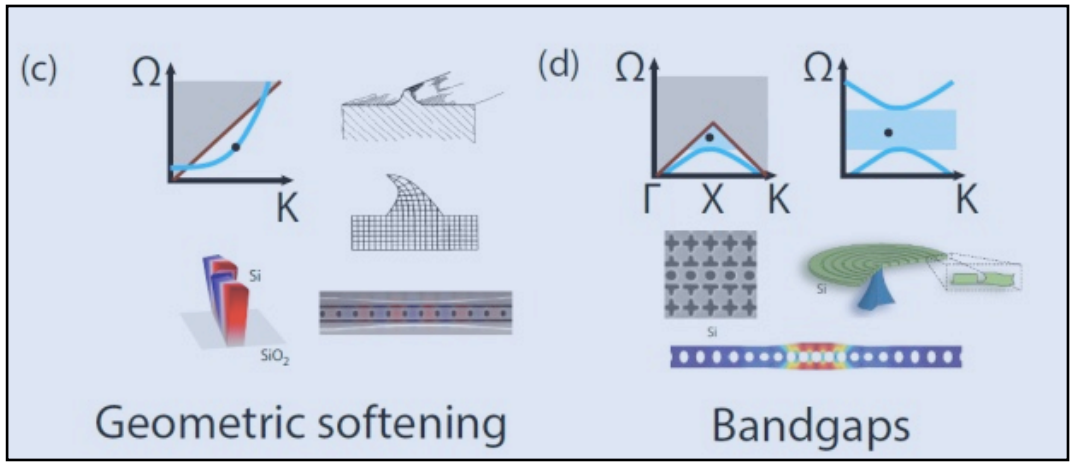
Kolvik, Burger et al. Optica (2023)

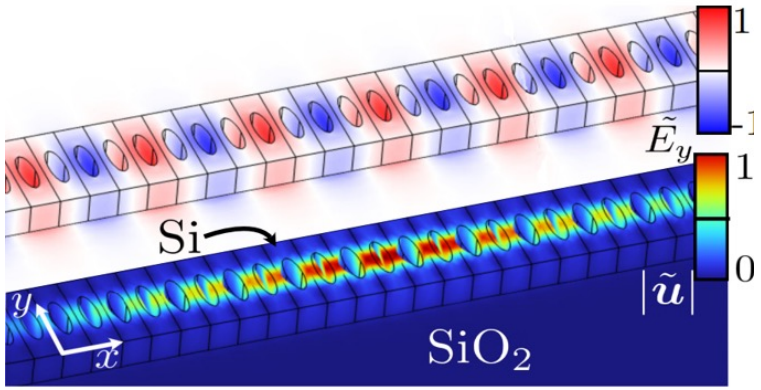
Clamped optomechanical crystals in SOI

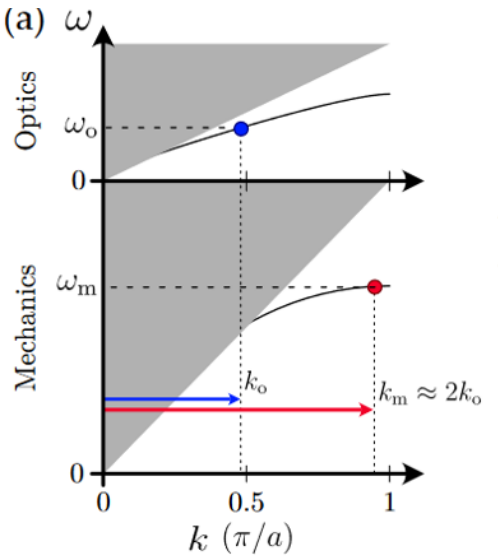
WACQT | Wallenberg Centre for Quantum Technology



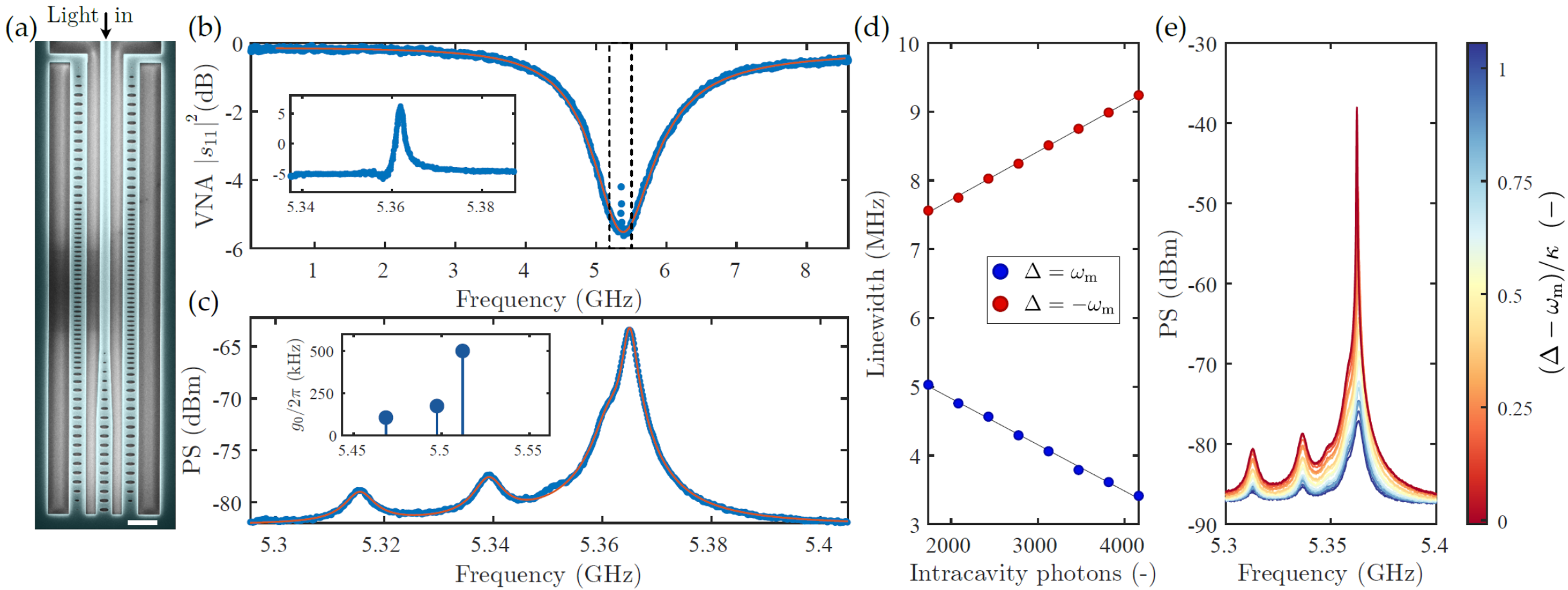








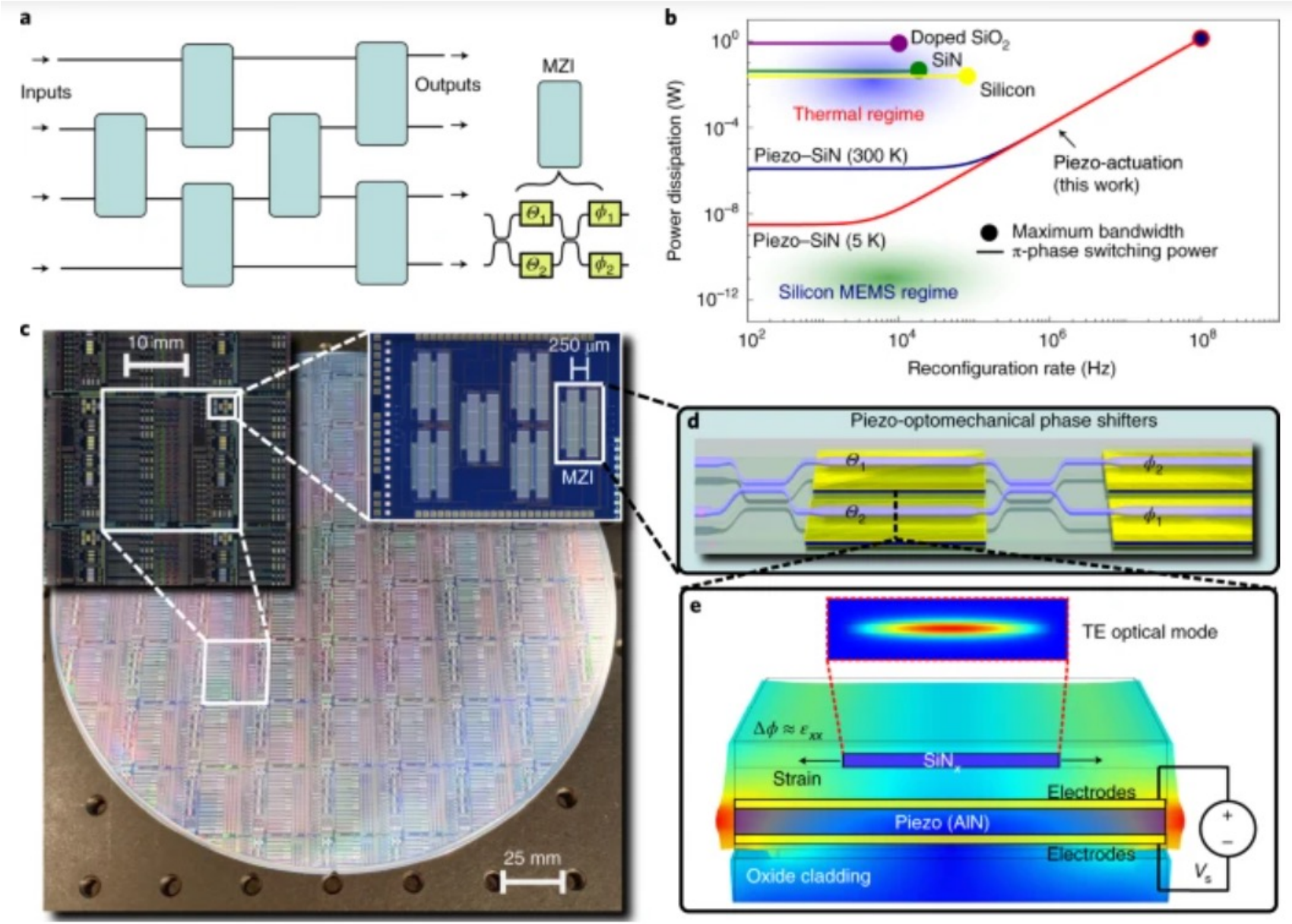
Clamped optomechanical crystals in SOI



Reduced fabrication complexity
Improved thermal anchoring(?)

Kolvik, Burger et al. Optica (2023)

Piezo phase shifters in AlN-SiN



No static power
>100 MHz

Programmable photonics

Dong et al. Nature Photonics (2021)

Outline

Process light with sound?

Basic physics

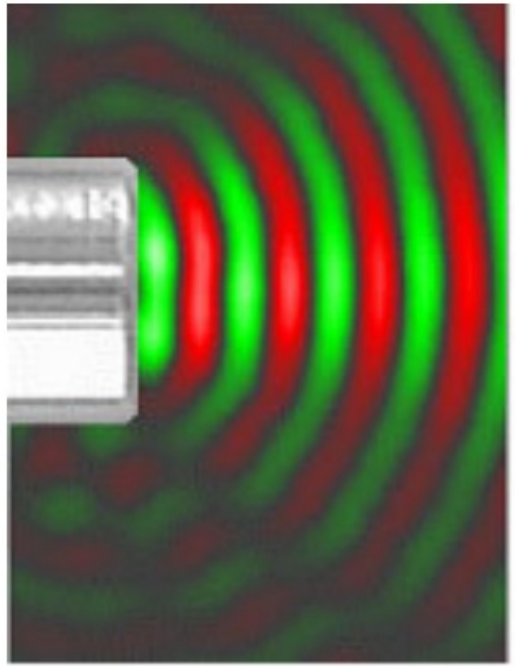
Case studies

- Microwave-optics
- **Beam-steering**

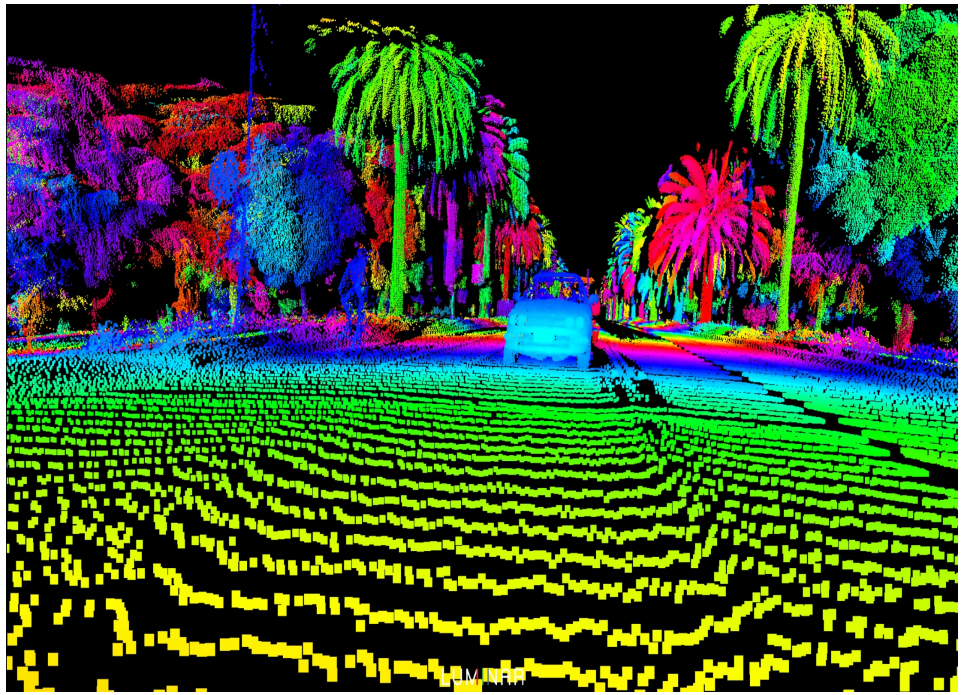
Outlook

Beam-steering with sound

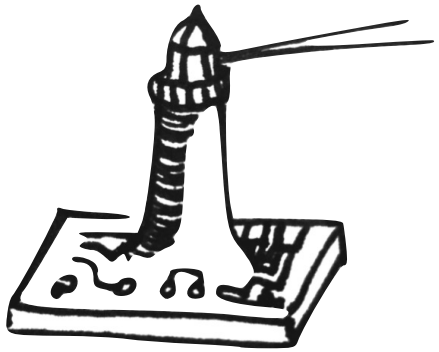
Free-space communication



Doppler vibrometry

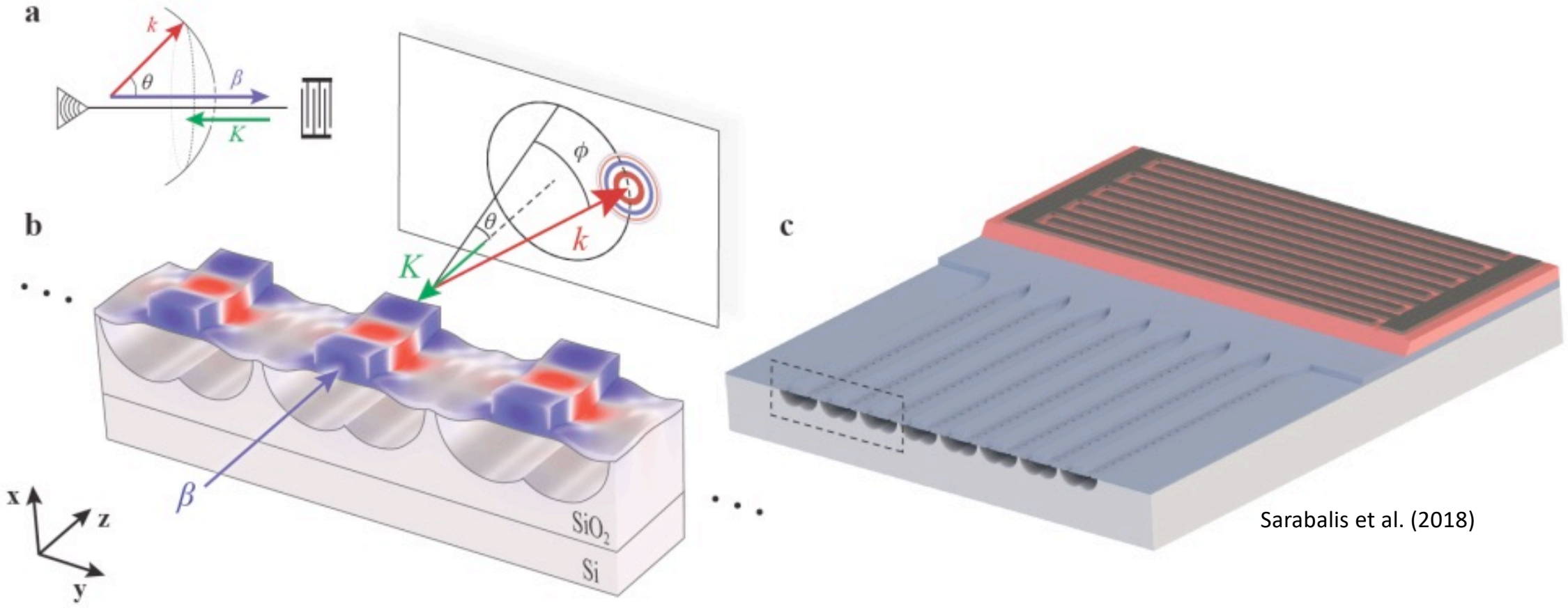


Lidar



“Coupling to continuum”

Beam-steering with sound

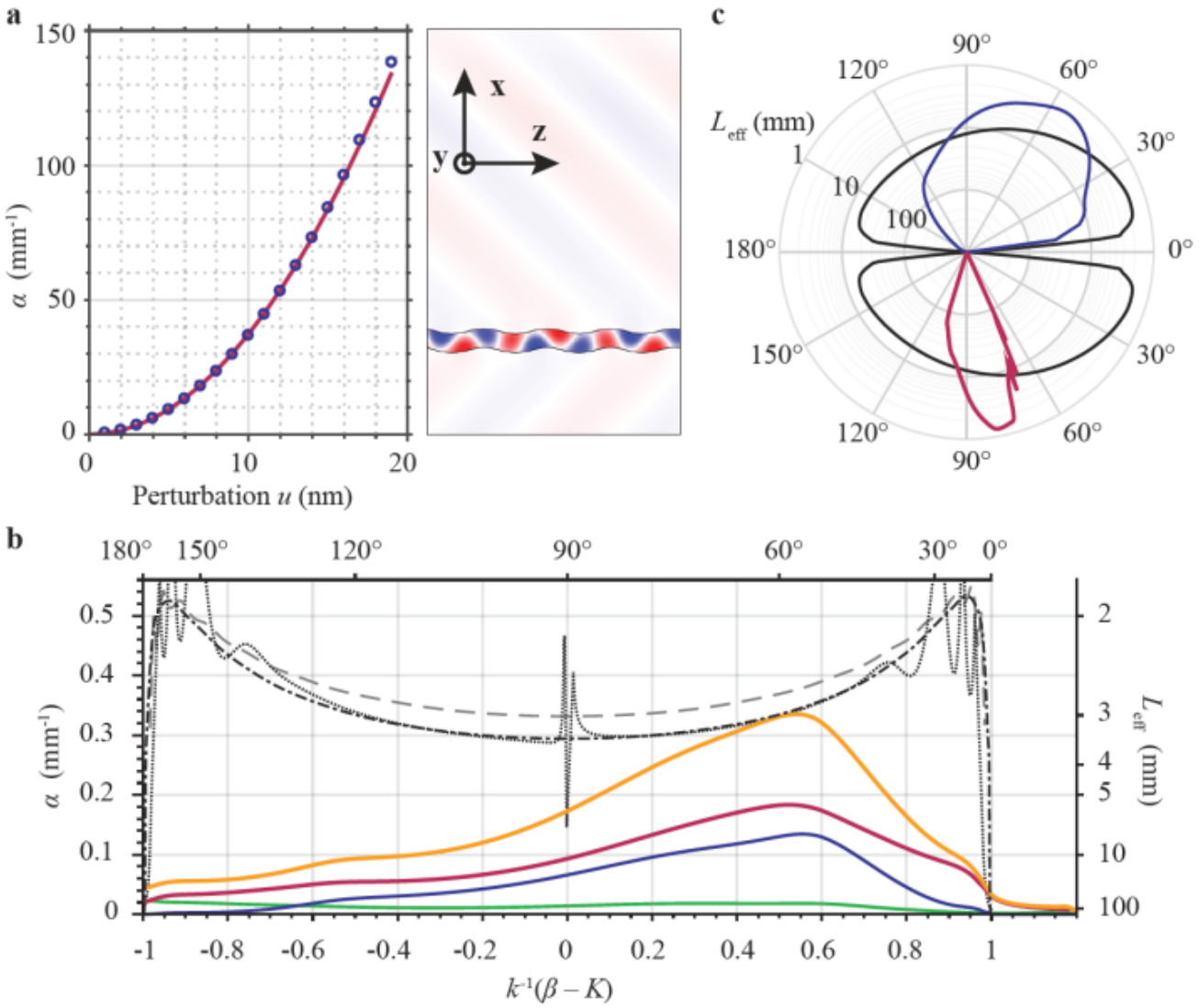


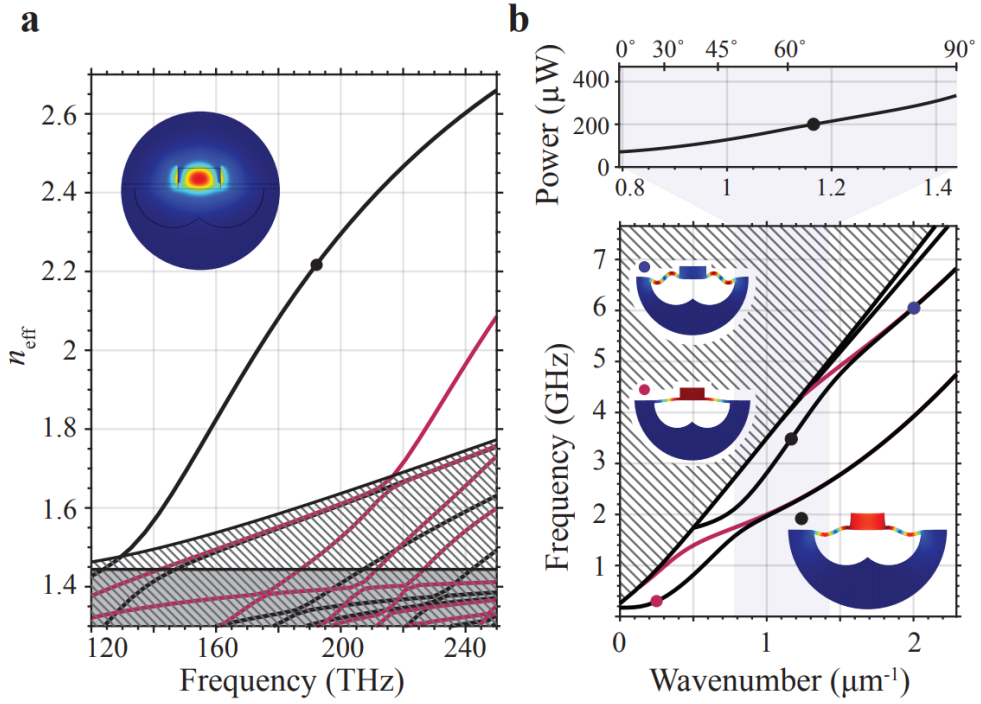
Sarabalis et al. (2018)

Optomechanical antennas

No need for
tunable lasers
rotating gimbals

Beam-steering with sound

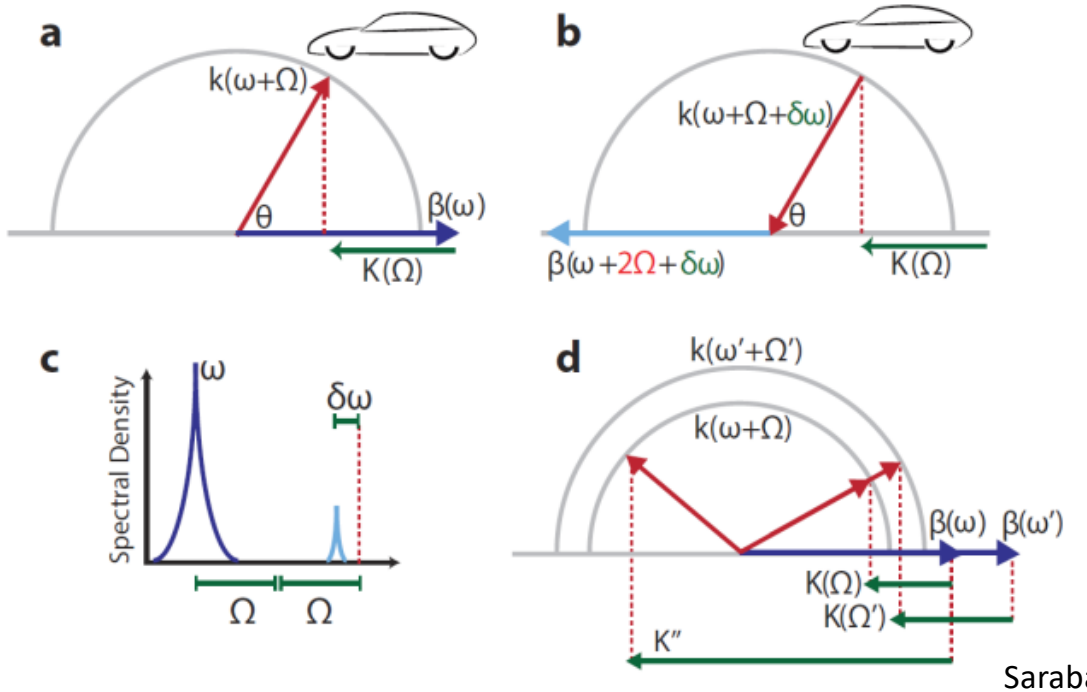




Sarabalis et al. (2018)

A milliwatt of mechanical power to scatter out the optical photons

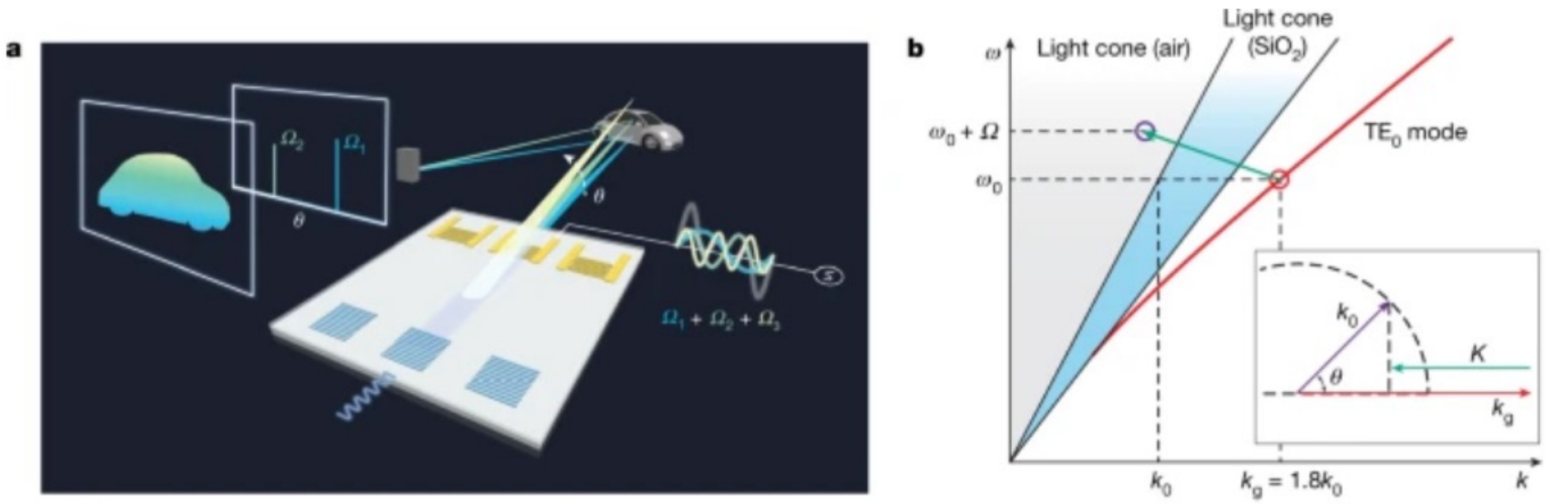
The system distinguishes sending and receiving

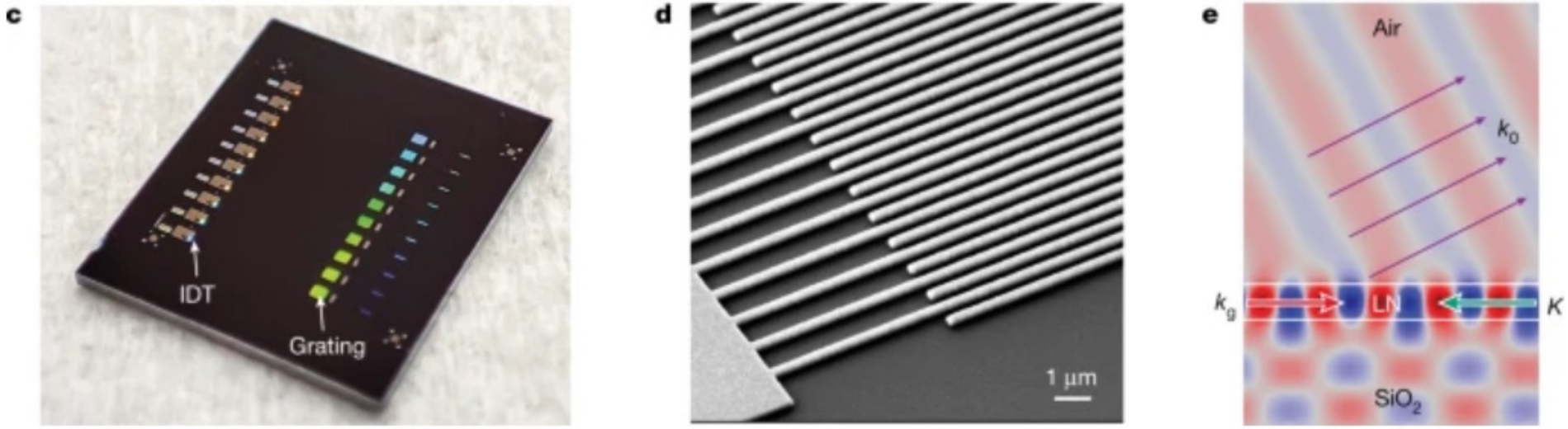


Sarabalis et al. (2018)

The beam-steering system
is nonreciprocal

Rapid progress on such systems

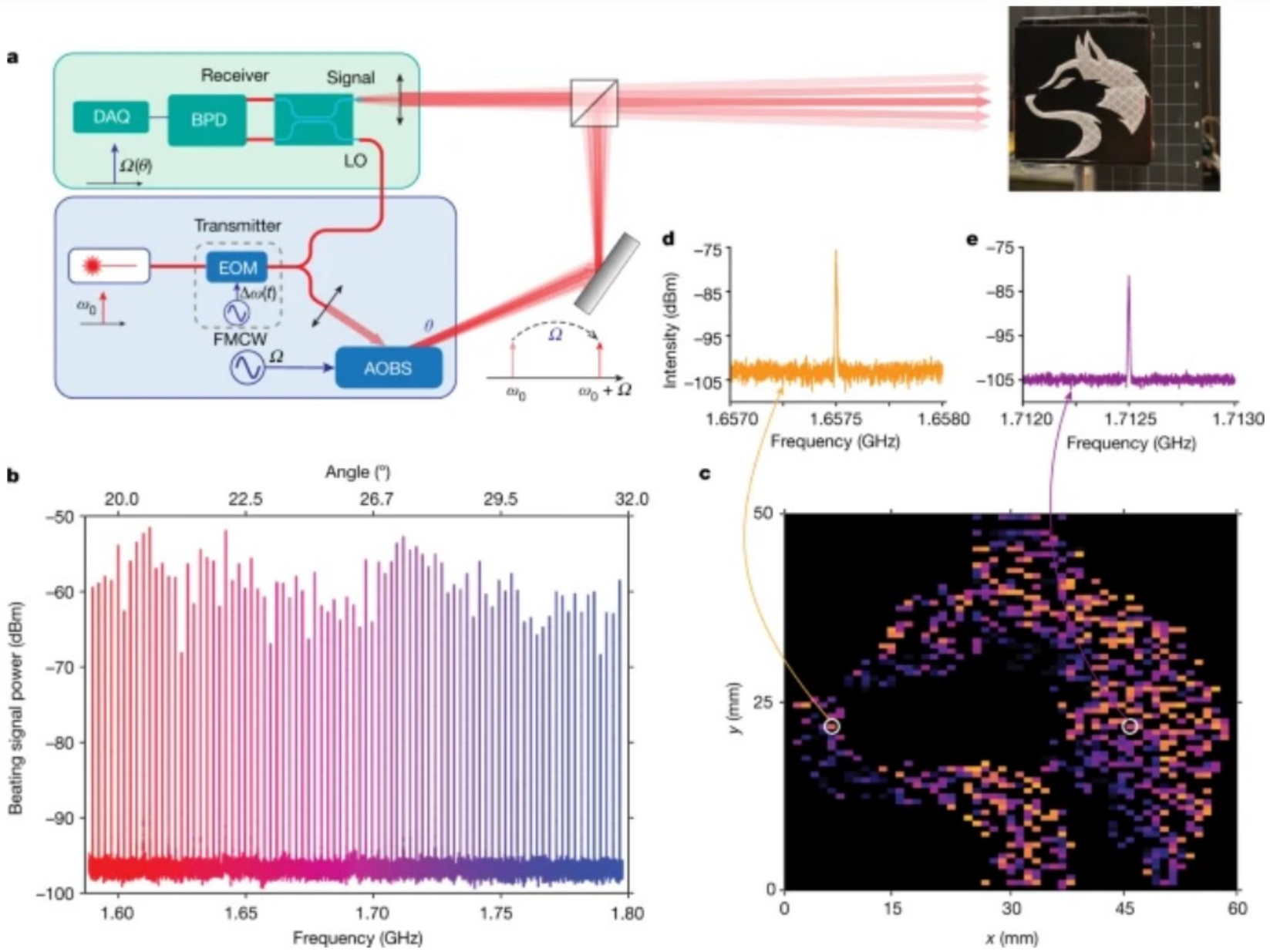




Non-suspended LNOI

Li et al. Nature (2023)

Outlook: processing light with sound

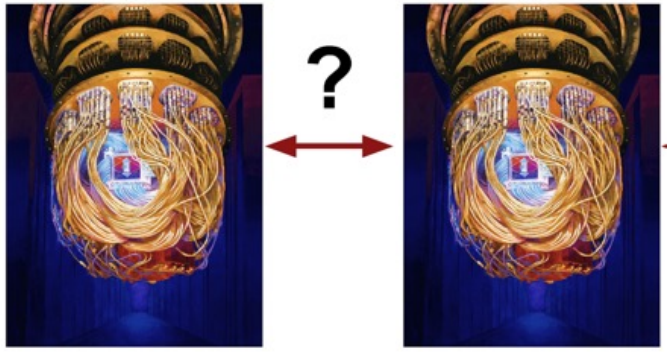


Frequency-angular resolving

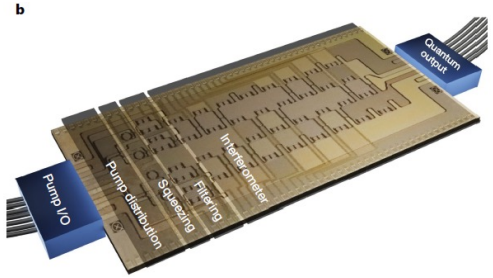
Li et al. Nature (2023)

Outlook

Quantum computing - superconducting

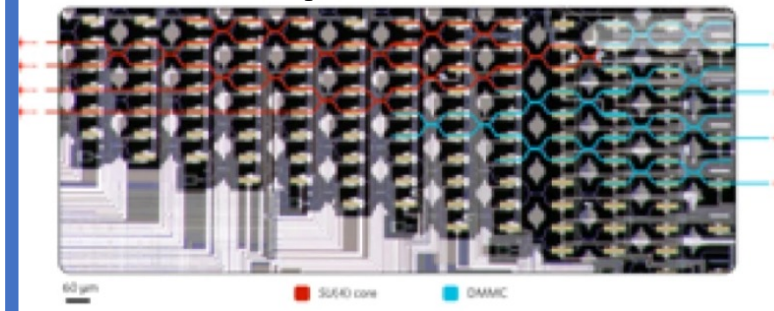


Quantum computing - all-optical

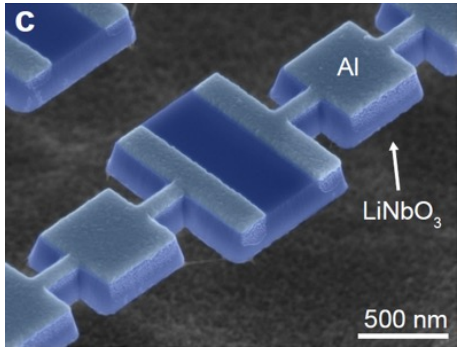


PsiQuantum

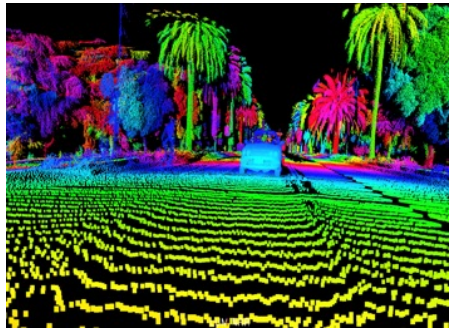
Programmable photonics



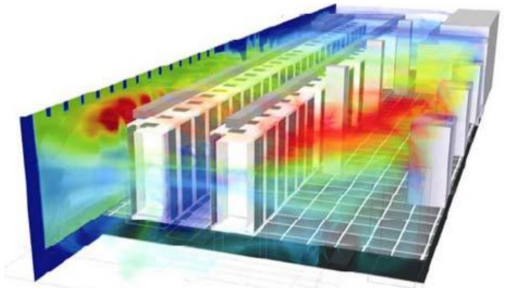
Acousto-optics is viable



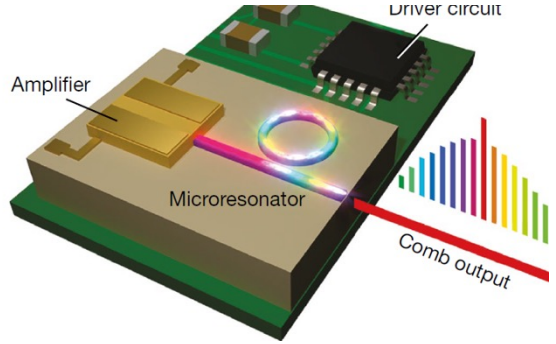
Quantum acoustics in silicon



LIDAR



Datacenters



Frequency combs

Questions?

https://qpl-chalmers.se/

CHALMERS
UNIVERSITY OF TECHNOLOGY

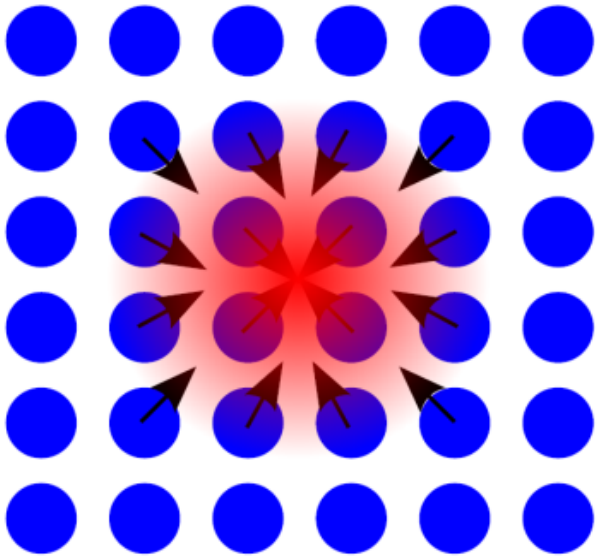
QPL
Quantum Photonics Laboratory

Vacancies for PhDs, postdocs:

raphael.van.laer@chalmers.se

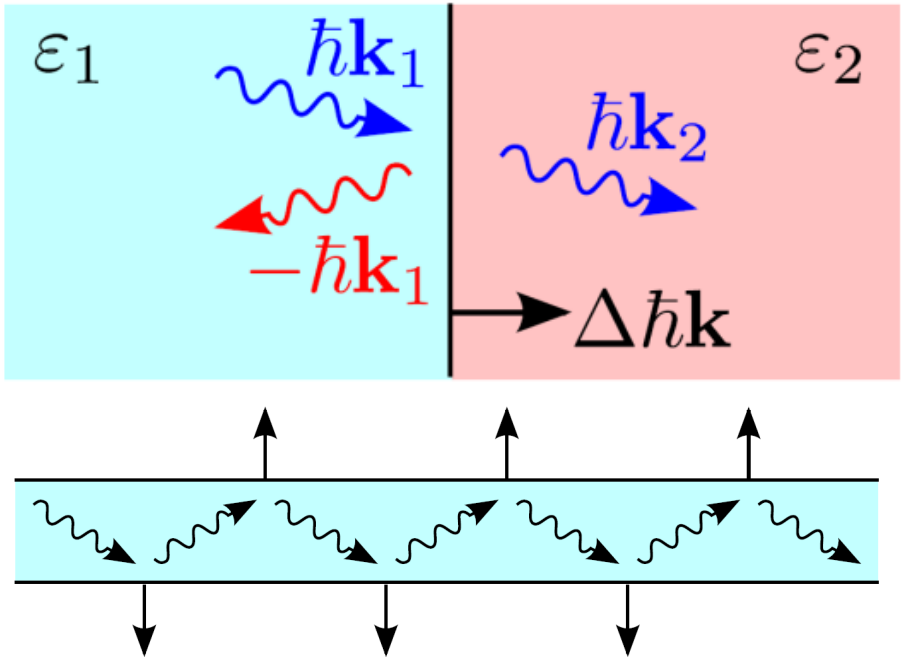
Optical forces as reverse-scattering

Photo-elastic contribution
Electrostriction



Wolff (2015)

Boundary contribution
Radiation pressure



“Gradient forces”
Scattering picture: no ambiguity about photon momentum