Quantum Acousto-Optic Transducer for Superconducting Qubits

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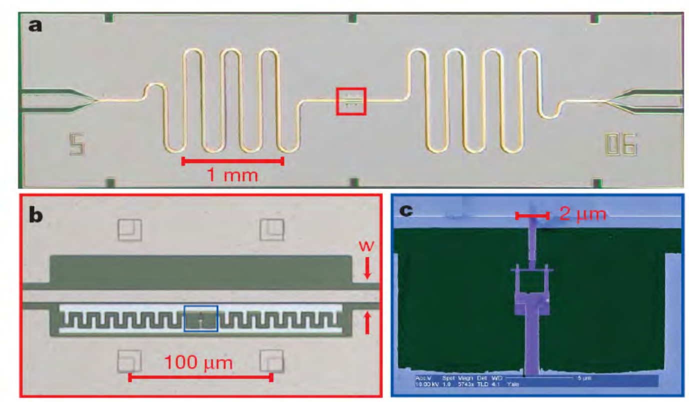
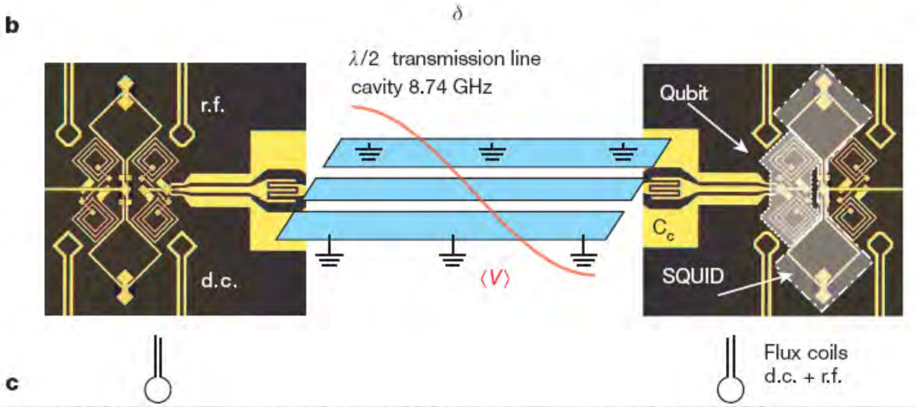
- Superconducting qubit architecture:
  circuit **Q**uantum **E**lectro-**D**ynamics
- Quantum networks and hybrid systems
- Quantum Optomechanical interface
- Circuit **Q**uantum **A**cousto-**D**ynamics
- Stimulated Brillouin Scattering
- Acousto-Optic Transducer

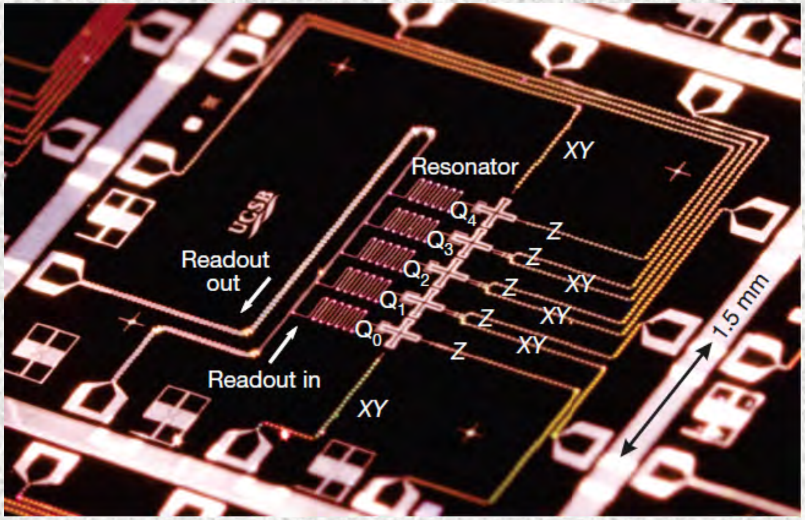
C-QED: SC qubits + MW photons



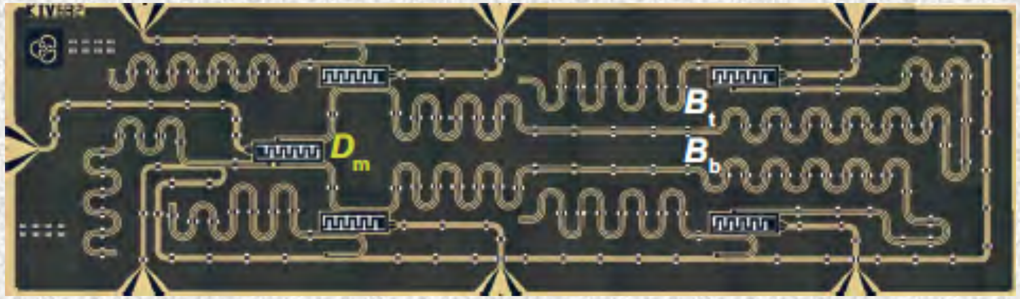
charge qubit (ETH)



phase qubit (UCSB)



5-9 X-mons (UCSB)



5 T-mons (Delft)

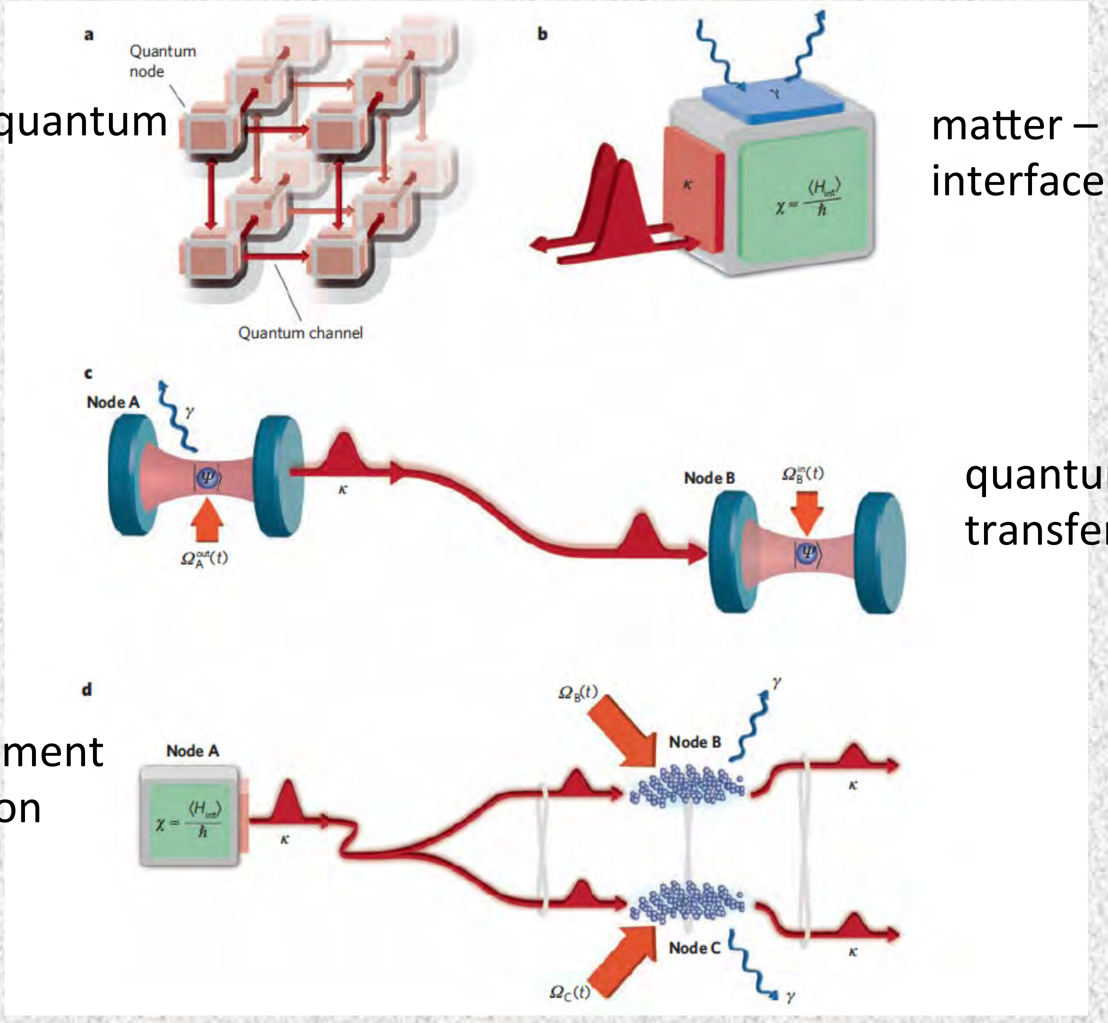
20 – 100 qubits on chip?

Scaling up: quantum internet

H. J. Kimble, 2008

network of quantum processors

matter – photon interface

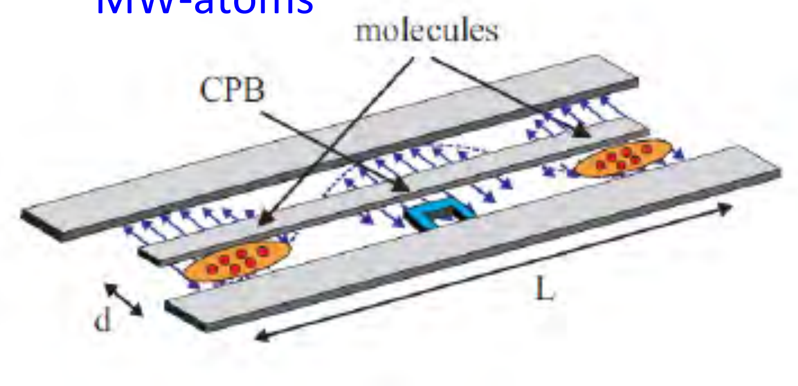


quantum state transfer

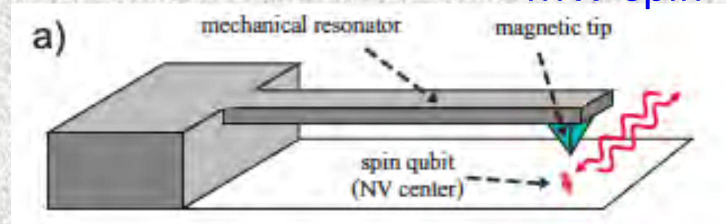
entanglement generation

Physical ideas for interfaces

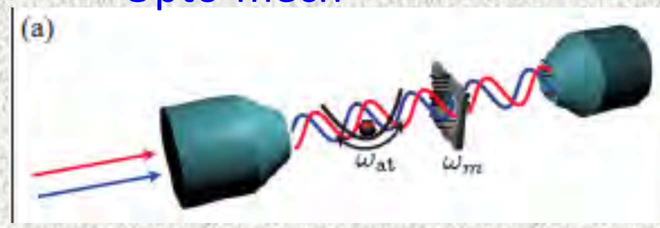
MW-atoms



MW-spin

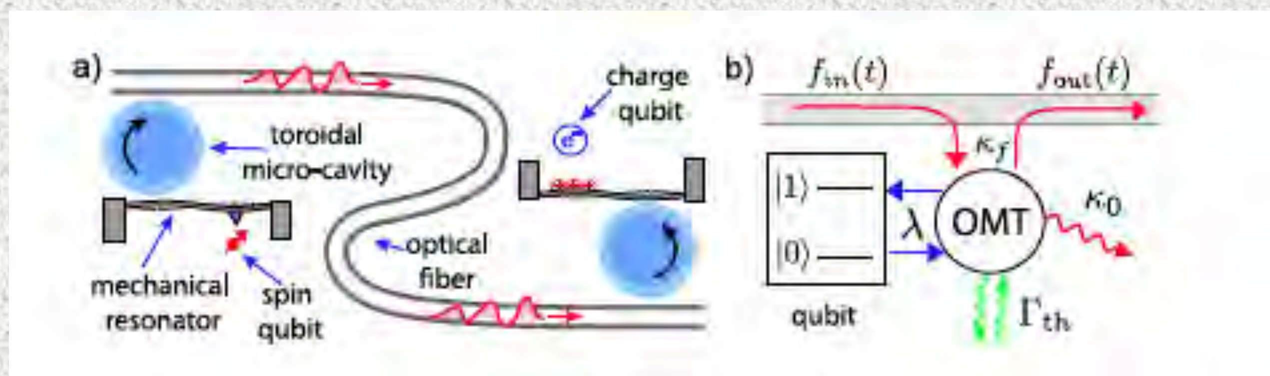


Opto-mech



Wallquist et al, Phys. Scr. **T137**, 2009
Kurizki et al, PNAS **112**, 2015

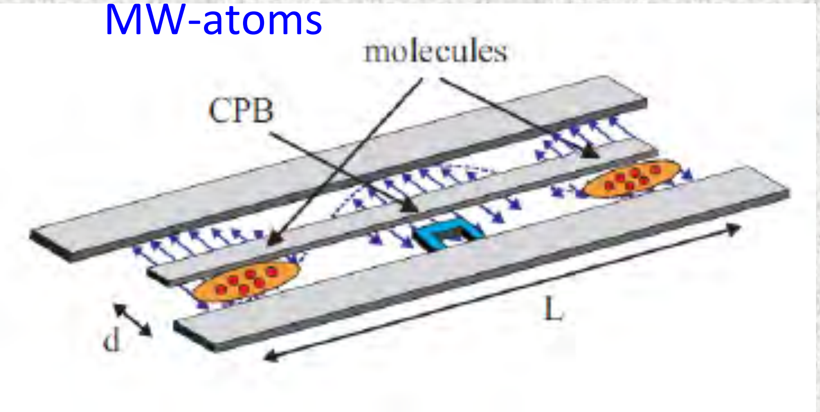
and protocols



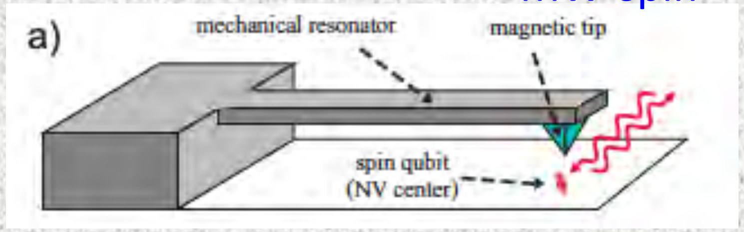
Stannigel, Rabl, Sorensen, Zoller & Lukin, PRL 2010

Physical ideas for interfaces

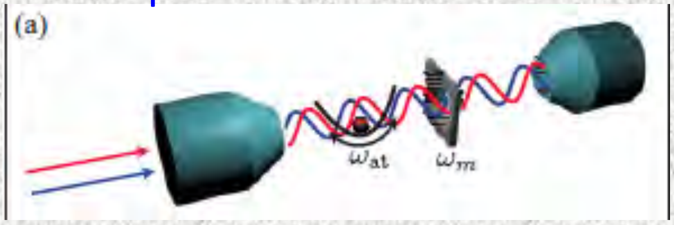
MW-atoms



MW-spin



Opto-mech

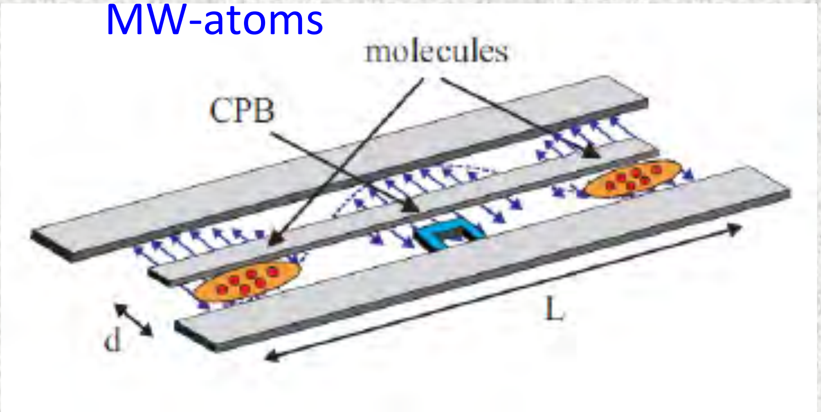


Wallquist et al, Phys. Scr. **T137**, 2009
Kurizki et al, PNAS **112**, 2015

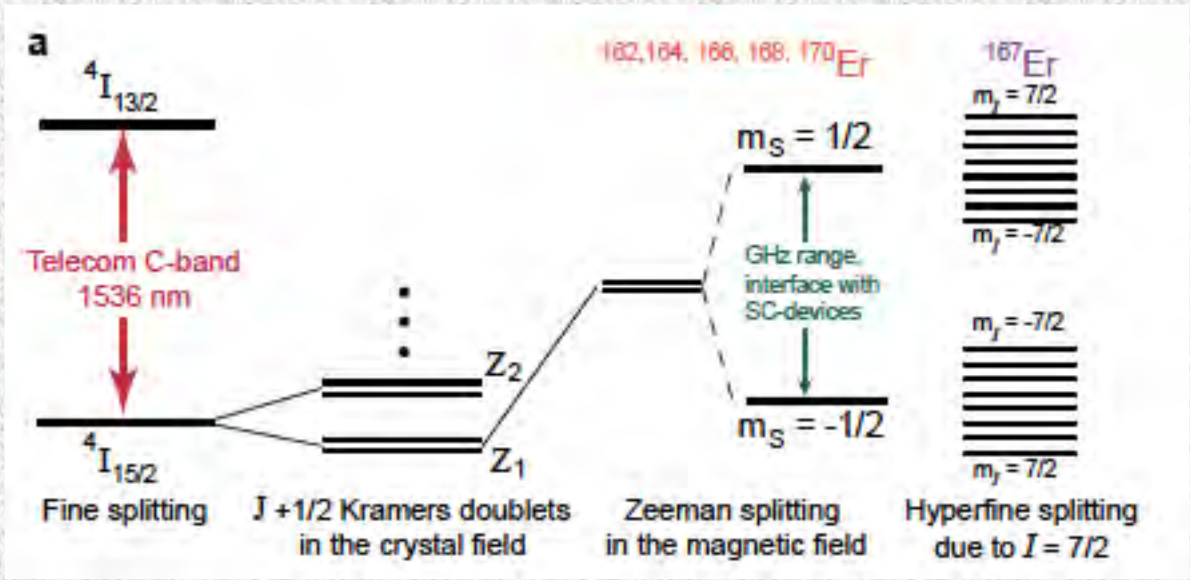
Interface challenge:

No direct coupling between MW & OPT photons is possible:
huge difference between MW and telecom frequencies
Matter (nonlinear) mediator is required

Solution I : atomic ensembles

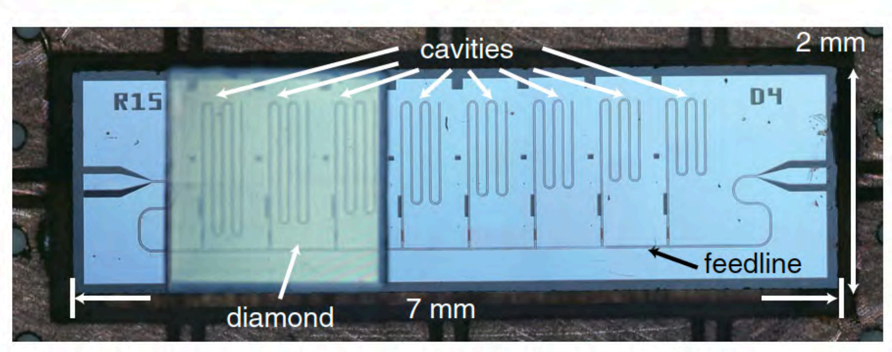


atomic energy spectra include
optical transitions & GHz transitions



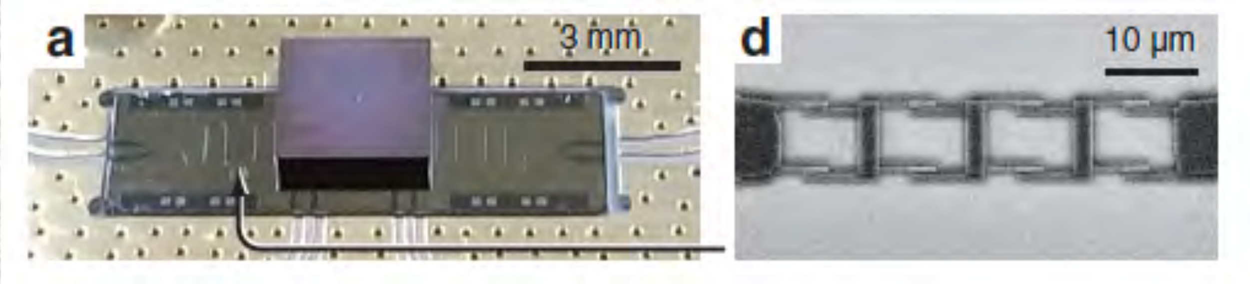
Atomic spin memory in MW cavity

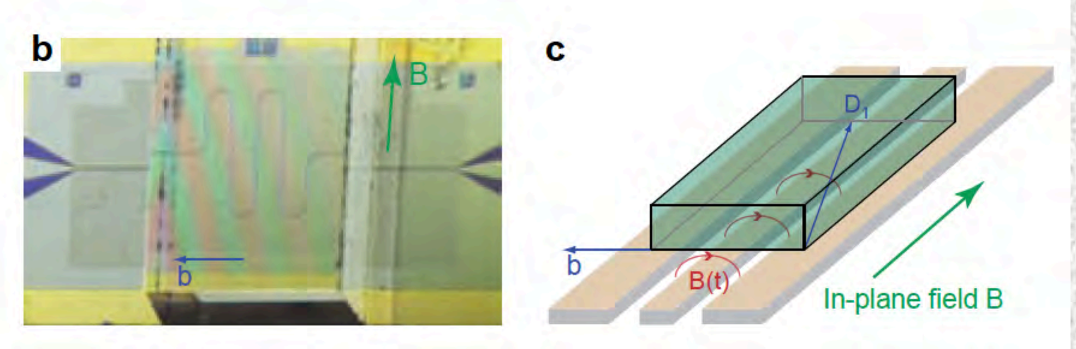
microwave photons ⇔ atomic spins



Yale: ruby, N @diamond

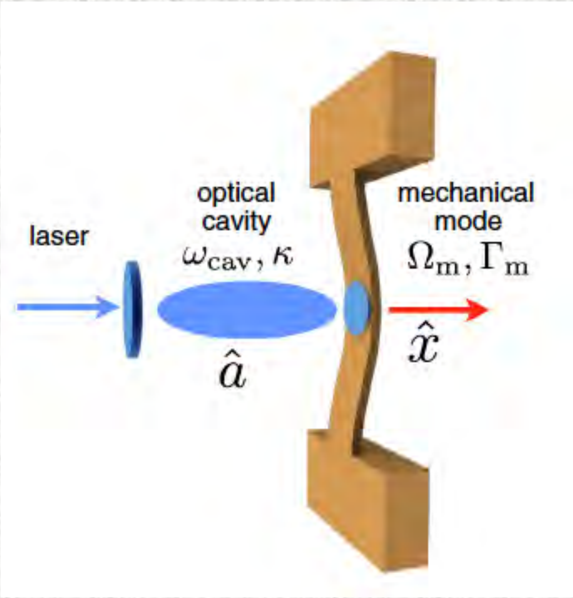
Saclay: NV @diamond



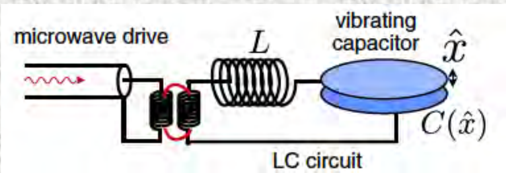


Chalmers / Karlsruhe: Er, Nd @Y_2SiO_5

Solution II : opto-mechanics



MW analog



Aspelmeyer, Kippenberg & Marquardt, RMP 2014

Opto-mechanical interaction

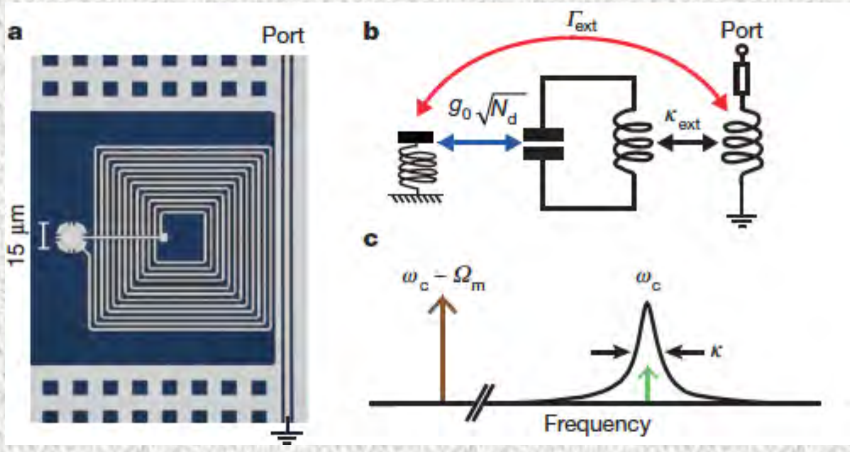
- Confined optical field in cavity exerts force on mirror, $\mathcal{F} \propto \nabla \mathcal{E} \propto \nabla E^2$
- Combination of 2 optical modes excites low frequency mechanical vibration, $\nabla \mathcal{E} \propto \exp[-i(\omega_1-\omega_2)t]$
- Oscillating mirror induces inelastic optical scattering to side bands, $\omega_2 = \omega_1 \mp \Omega$
- The process is resonantly enhanced if $\omega_1 - \omega_2 = \pm \Omega_m$

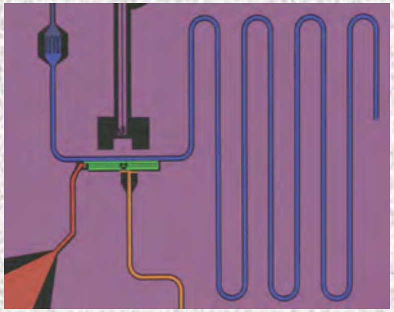
OM interaction can be used for quantum state transfer, and vacuum squeezing

Solution II : opto-mechanics

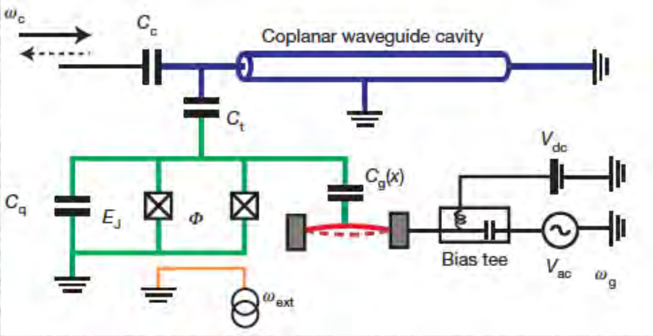
Opto-mechanical interaction in MW

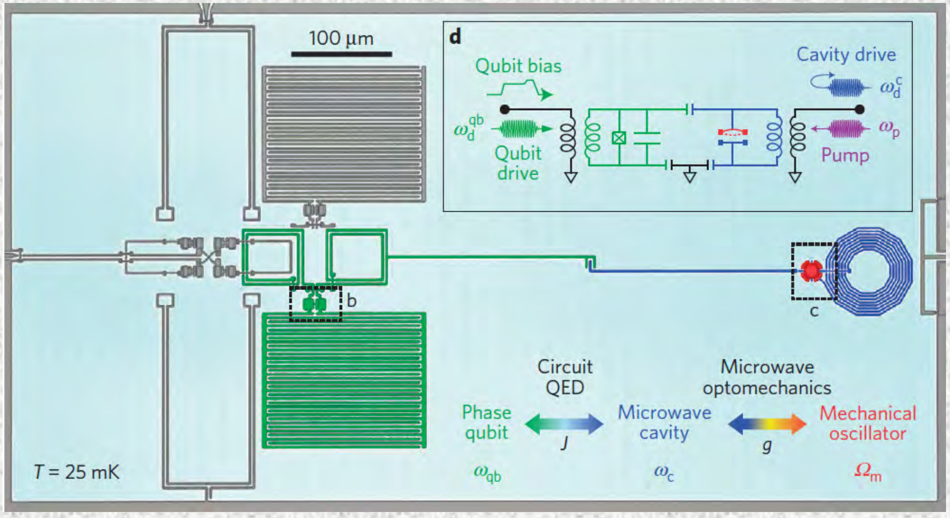
MW ⇔ MO, state transfer, NIST 2013





SC qubit ⇔ MO
Aalto 2013

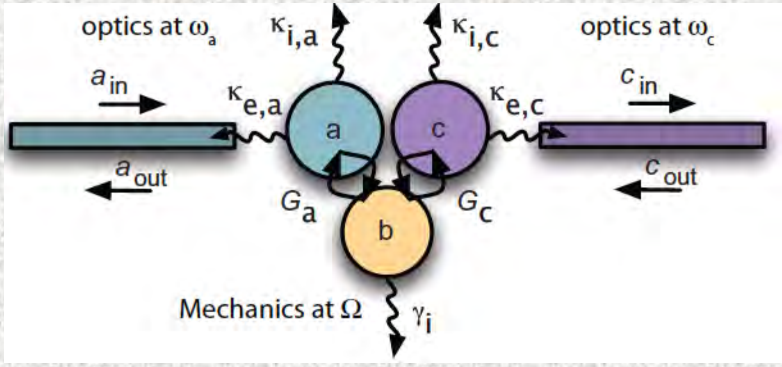




phonon/photon vacuum squeezing NIST 2015

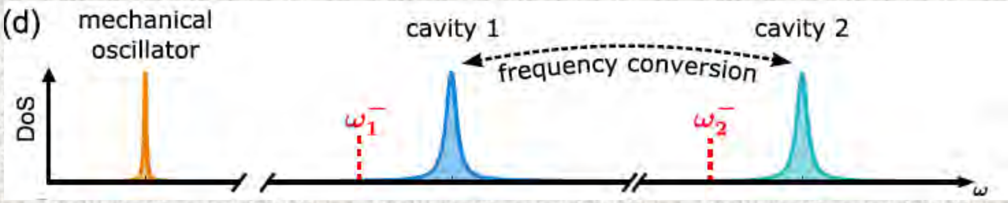
Solution II : opto-mechanics

Frequency conversion

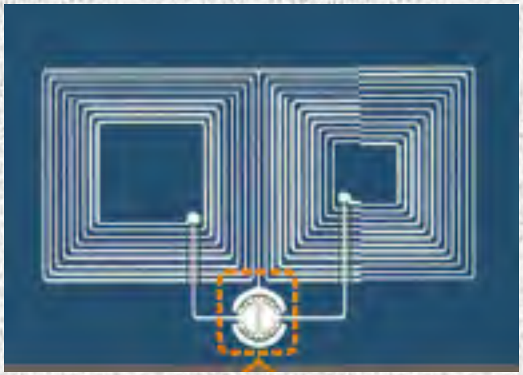


Safavi & Painter, 2011

Frequency diagram of double OM interface

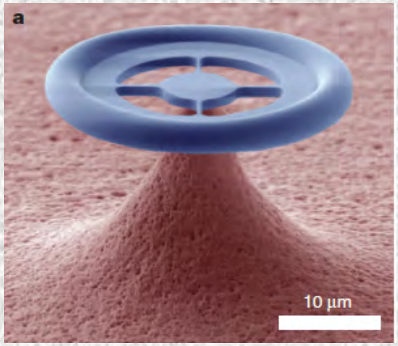


MW conversion

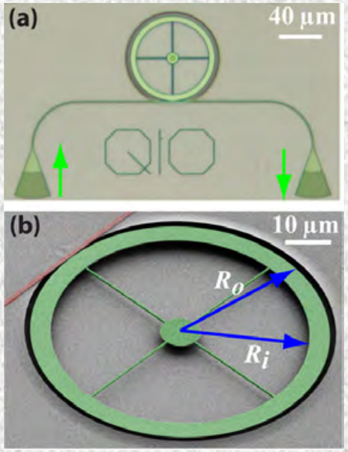


NIST 2016

Optical conversion



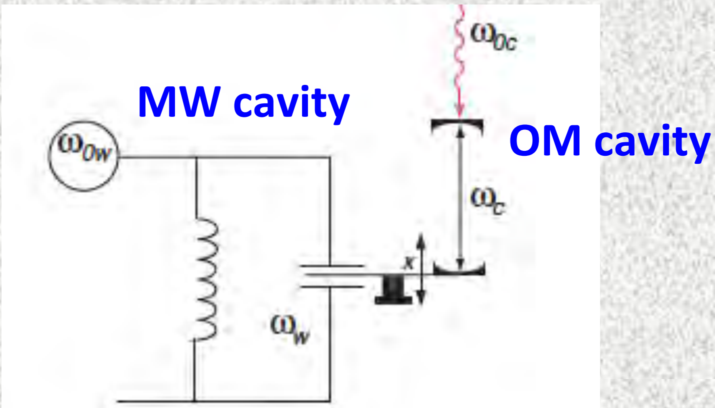
Silicon ring resonator
Kippenberg 2012



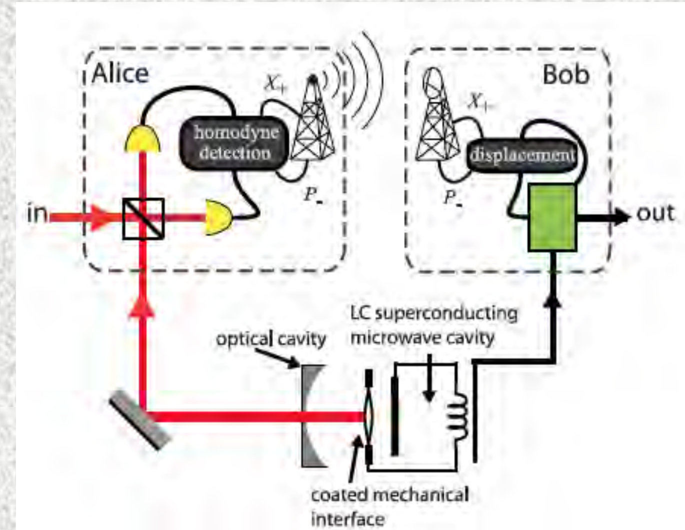
AlN weel resonator
Tang 2013

Solution II : opto-mechanics

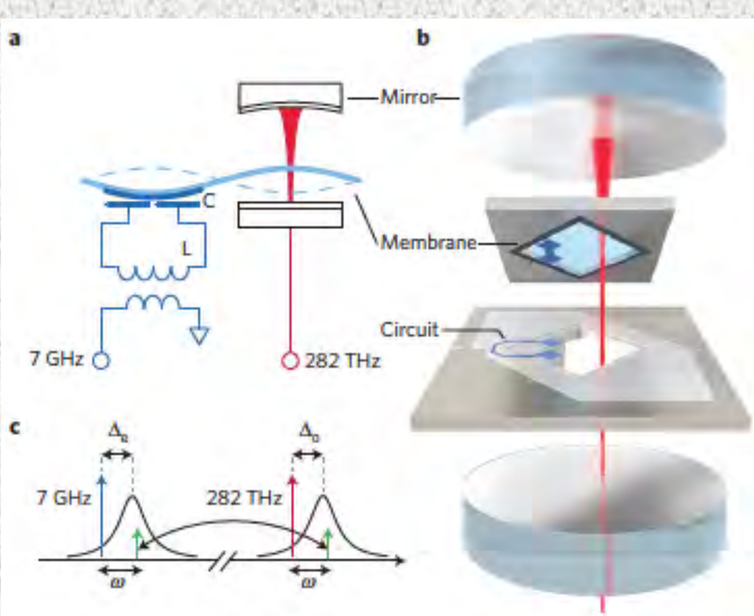
MW – Optic frequency conversion $\Omega \ll \omega$



Barzanjeh, Vitali, Tombesi & Milburn 2011



Barzanjeh, Abdi, Milburn, Tombesi & Vitali 2012



full MW-opt interface

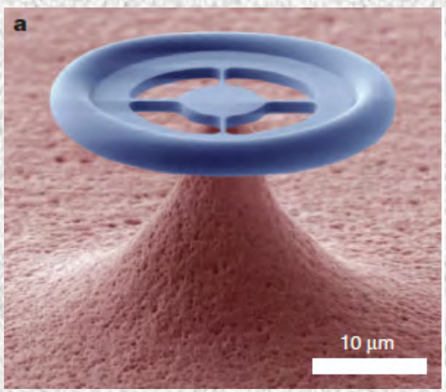
NIST 2014

Cavity Optomechanics 2014

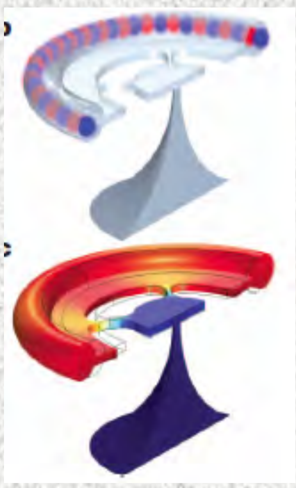
(Ed. Aspelmeyer, Kippenberg & Marquardt)

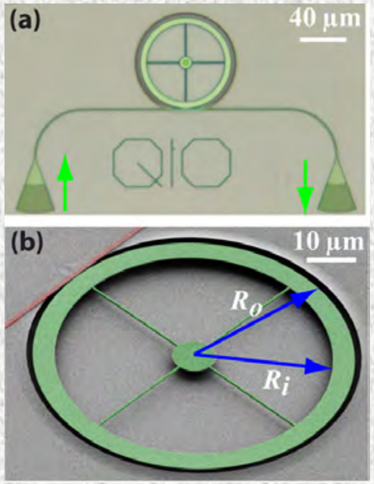
Solution III : acousto-optics

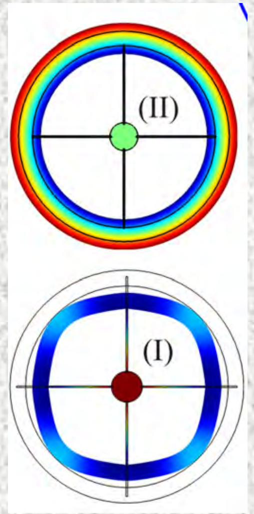
Acoustic waves in solid state integrated optics



Silicon ring resonator

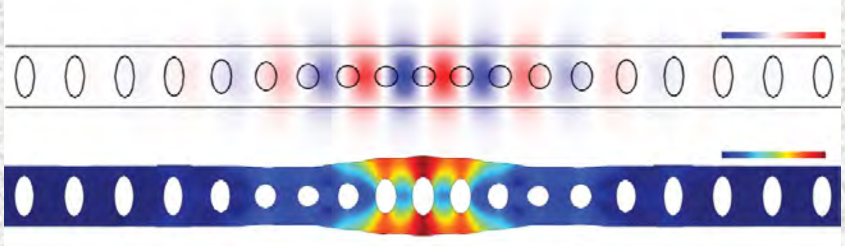






AlN weel resonator

Acousto-optic crystal



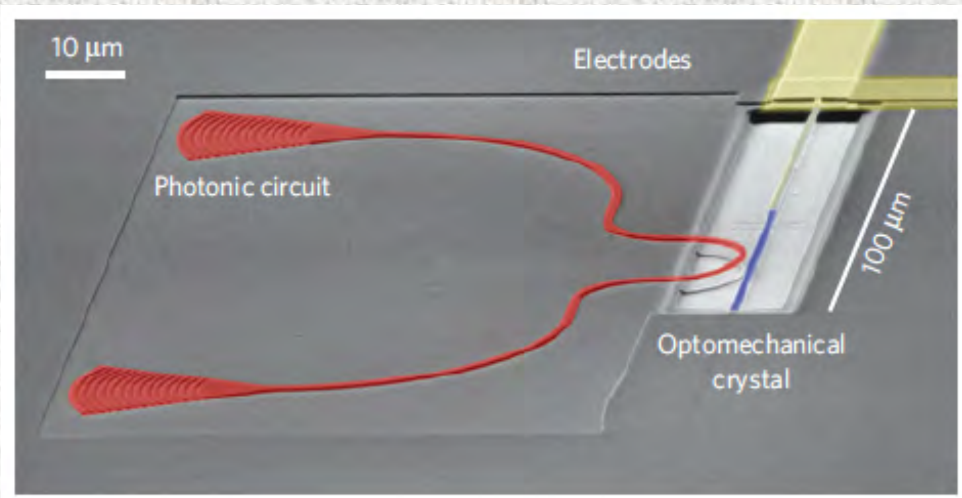
Profiles of excited optical and acoustic modes

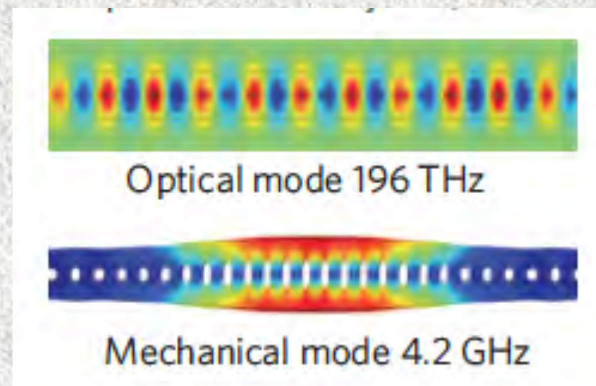
Chan, Safavi, Hill, Meenehan & Painter 2012

Solution III : acousto-optics

MW – Optic frequency conversion

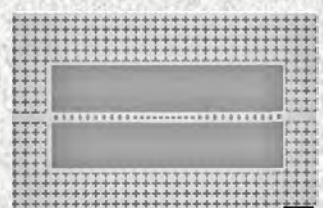
MW-opt converter piezoelectric acousto-optic crystal (AlN)

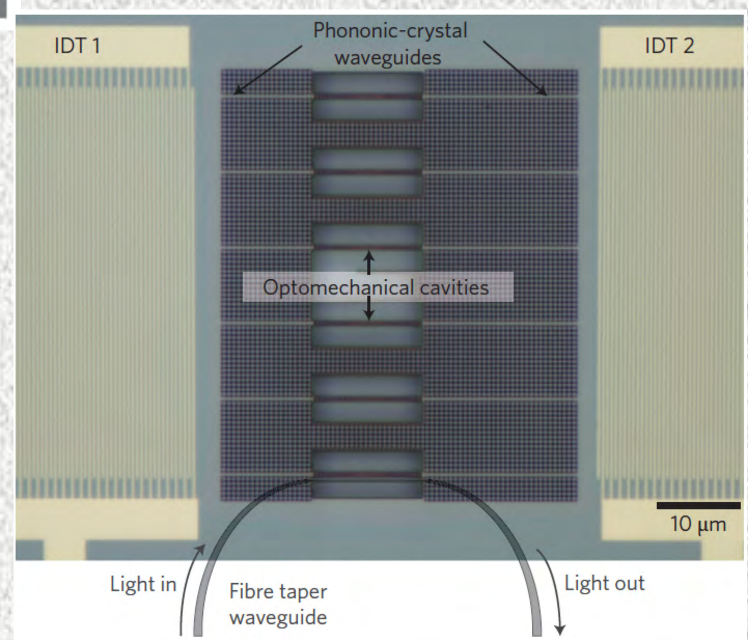




Bochmann, Vainsencher, Awschalom & Cleland, 2013

GaAs MW-SAW-opt converter
NIST Maryland 2016



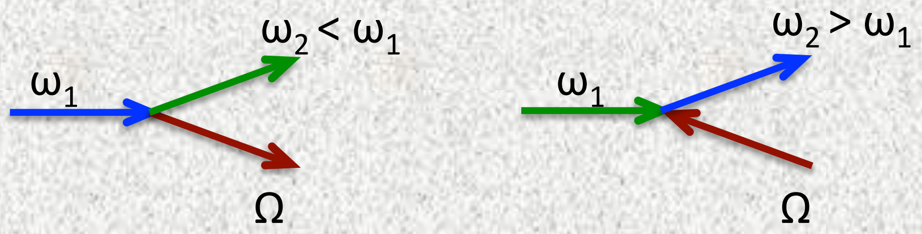


From Optomechanics to Brillouin Scattering

Brillouin Scattering: inelastic scattering of light by acoustic phonons

Classical wave picture: beatings of two optical modes propagate *in phase* with matched acoustic wave

Quantum picture:



Energy conservation $\omega_1 = \omega_2 \pm \Omega$

Momentum conservation $\mathbf{k_1} = \mathbf{k_2} \pm \mathbf{q}$

Mechanism: photo-elastic effect - variation of refraction index under elastic deformation

$$\varepsilon \rightarrow \varepsilon + \gamma \, \mathrm{div} \, \mathbf{u}$$

elasto-optic constant

Optomechanics vs Brillouin Scattering

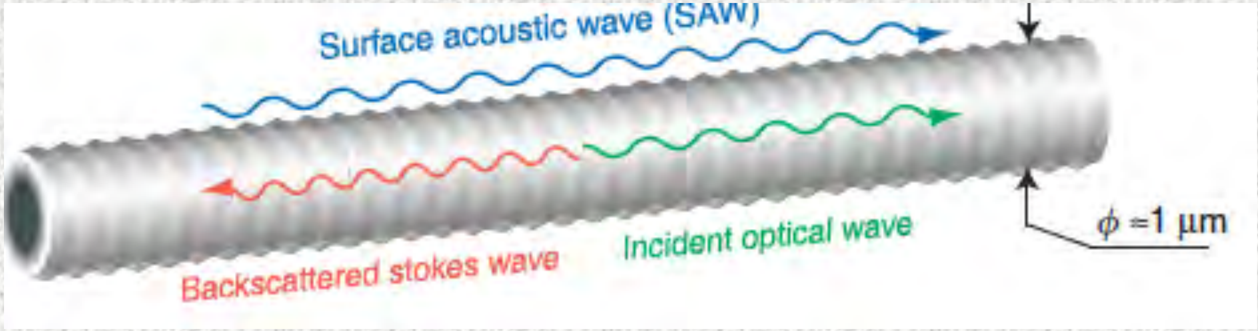
Optomechanics

- Boundary effect
- Force on boundary due to abrupt change of dielectric constant
- Shift of cavity resonant frequency due to boundary displacement
- Important: in vacuum cavities, in material wave guides with sharp edges (on scale of mechanical displacement)

Brillouin scattering

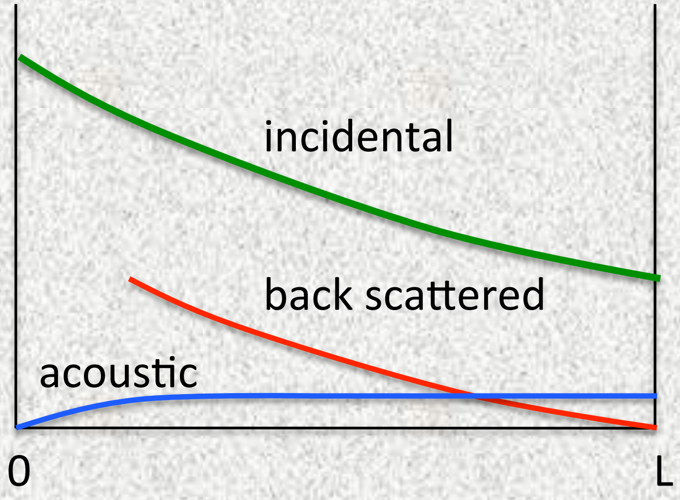
- Bulk effect
- Force on medium due sound-induced smooth variation of dielectric constant
- Shift of cavity resonant frequency due to change of speed of light
- Important: in material cavities and wave guides with smooth edges (on scale of mechanical displacement)

Stimulated Brillouin Scattering



Strong back scattering of intense light in fibers (Chiao, 1962)

Mechanism: parametric instability involving optical and acoustic modes, **incoherent** process under strong acoustic attenuation

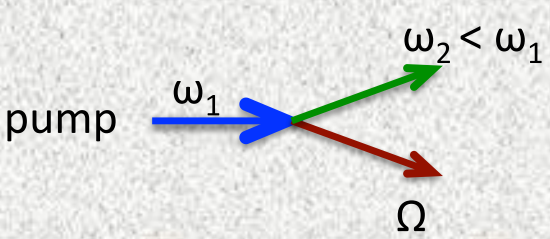


Spatial diagram
of opt mode propagation

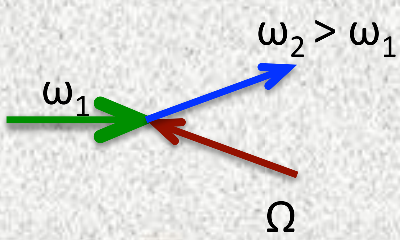
Boyd, Nonlinear optics, 2007

Stimulated Brillouin Scattering: coherent regime

- **Particular case of BS**: one strong optical mode = parametric pump enhances generic photo-elastic interaction between weak optical and acoustic modes
- In **cavity setting** effect is strongly enhanced
- At low temperature acoustic damping decreases and SBS enters **coherent regime –** coherent resonant 3-wave interaction
- SBS is a parametric effect analogous to **purely EM** parametric effects in MW and optical wave guides and cavities
- 2 regimes depending on choice of the pump



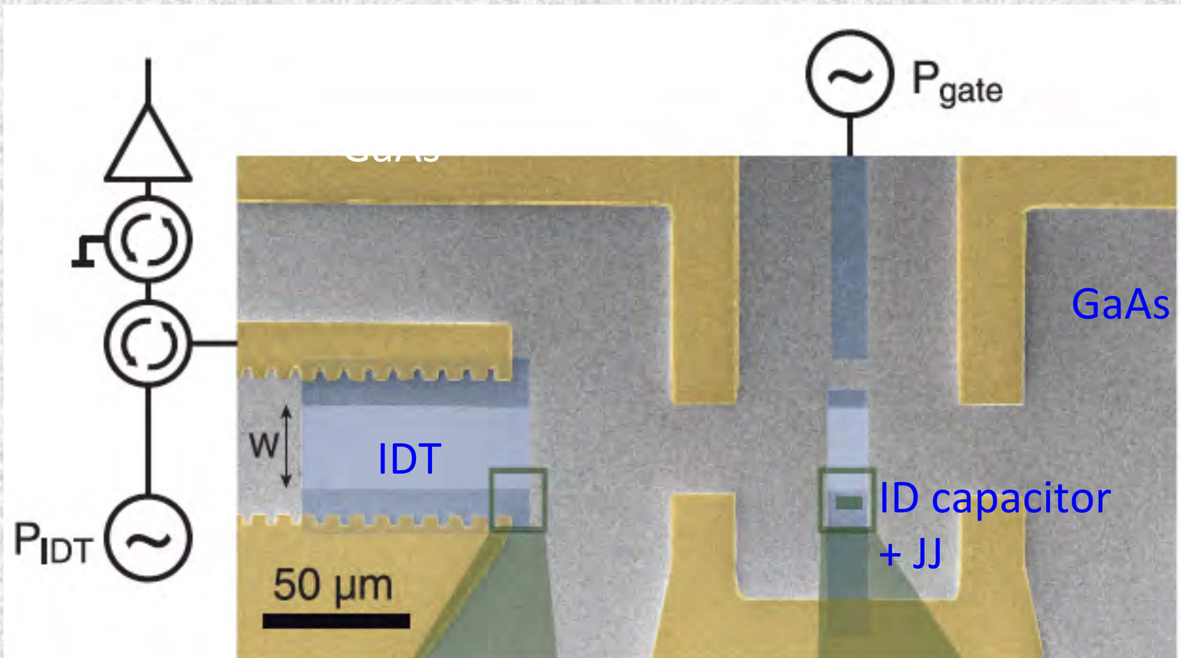
down conversion, Stokes sideband, phonon-photon entanglement



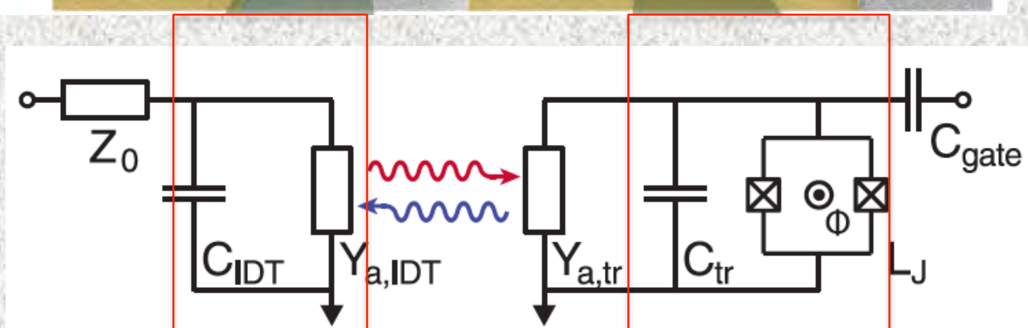
up conversion, anti-Stokes sideband, phonon-photon conversion

From c-QED to c-QAD

Chalmers experiment: strong coupling of qubit to SAW in piezoelectric

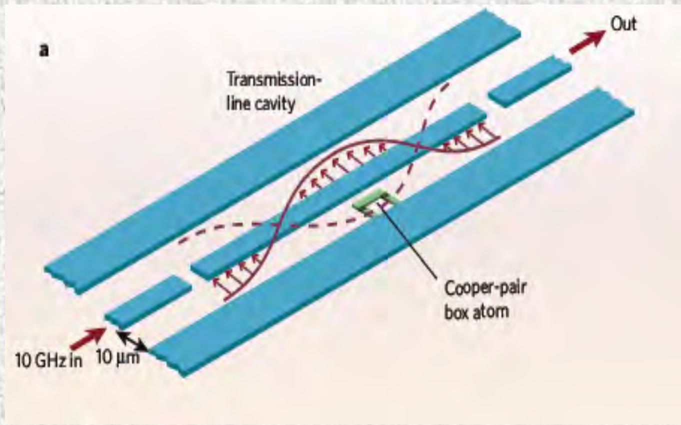


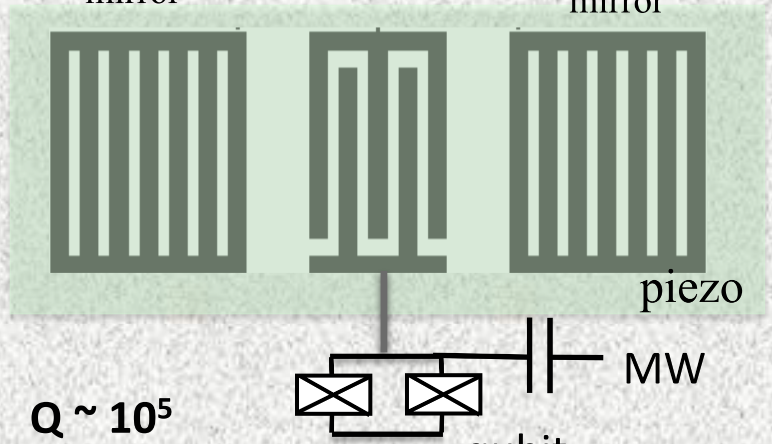
f =5 GHz
g > 30 MHz



Gustafsson, Science 2014

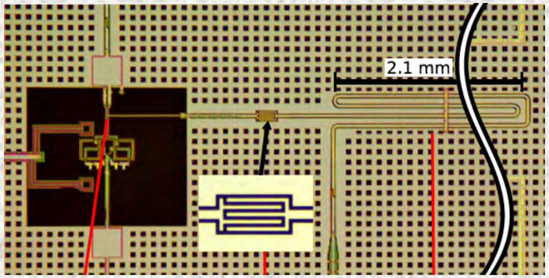
From c-QED to c-QAD



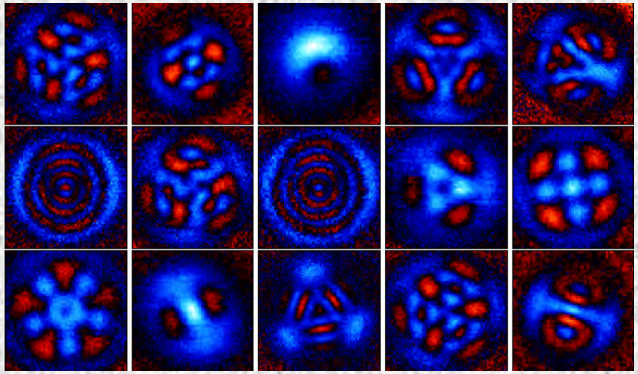


Q ~ 10^5
Leek et al, Oxford 2015

Complex phot(N)on states



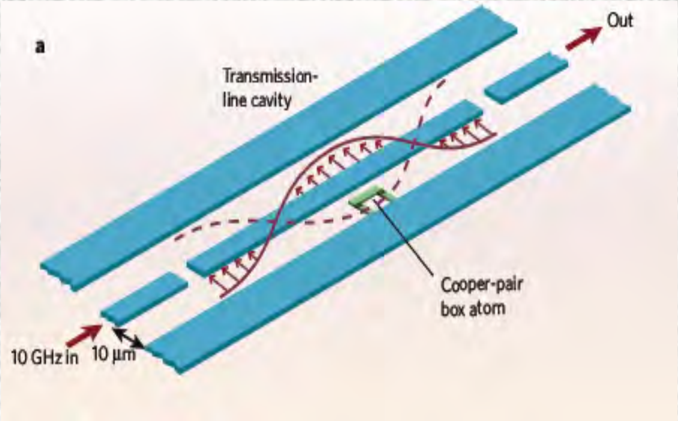
Hofheinz et al, UCSB 2008



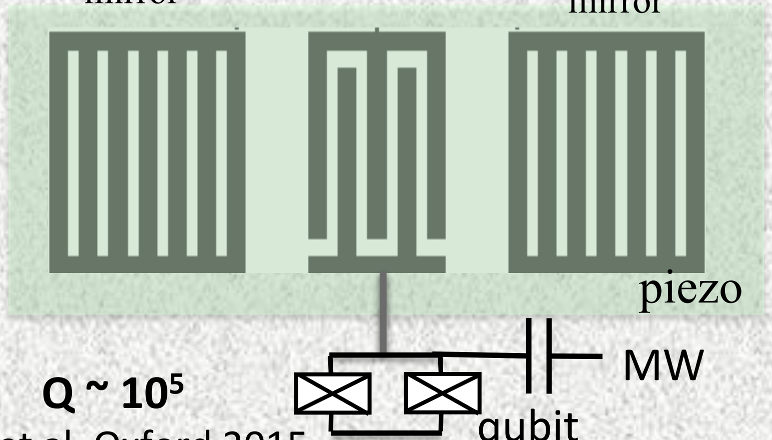
More:
Schütz, PRX 2015

From c-QED to c-QAD

MW resonator



SAW resonator

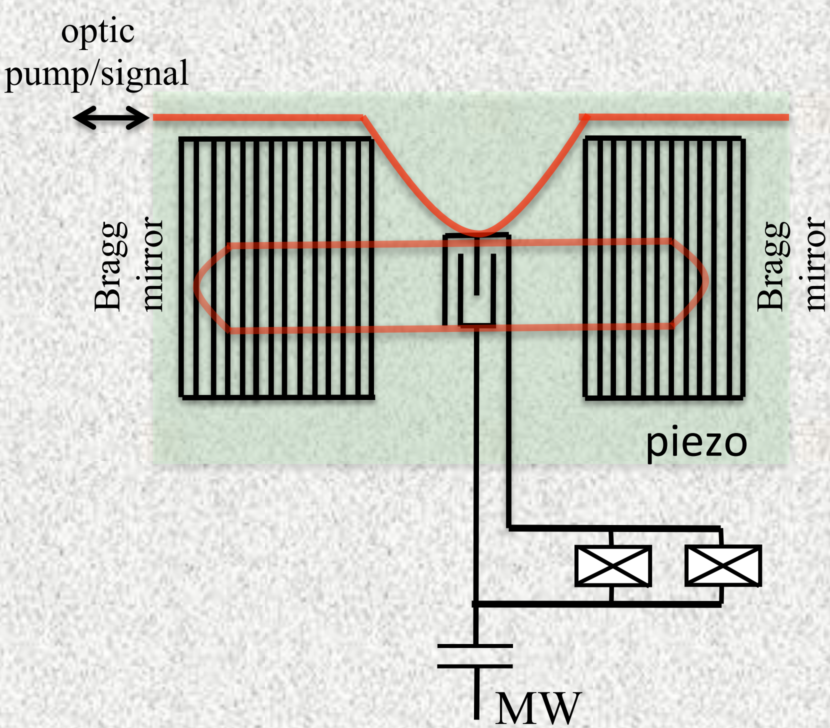


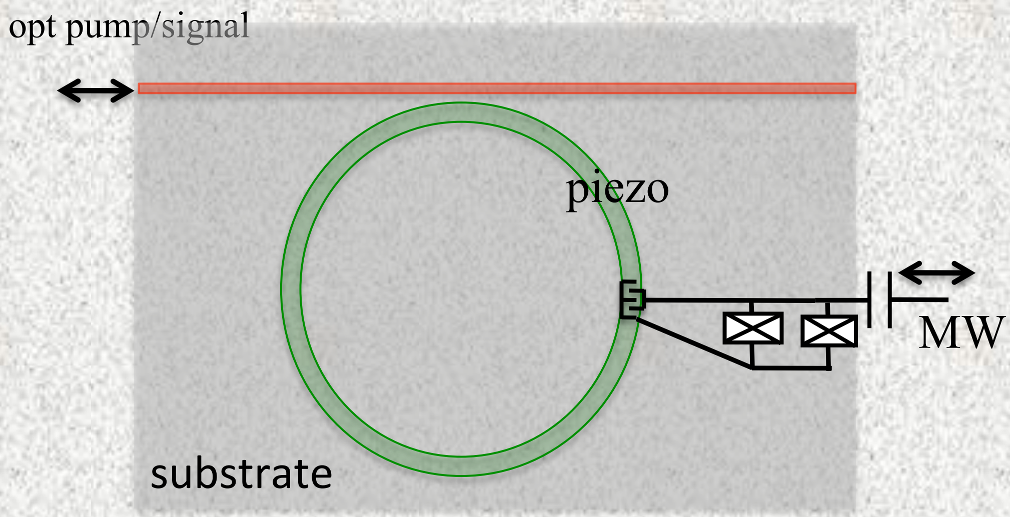
Q ~ 10^5

Leek et al, Oxford 2015

c-QAD allows coupling to optical photons

Acousto-Optic Transducer



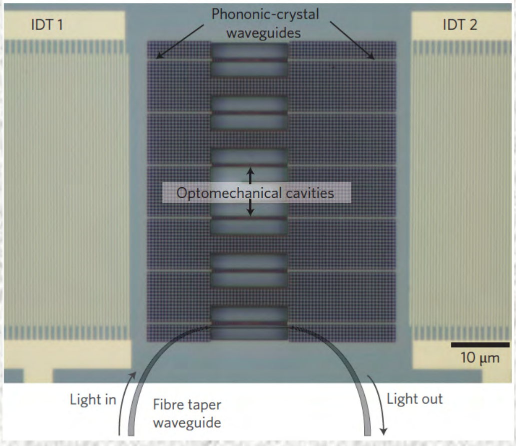


SAW ring resonator

SAW cavity

integrated with optical ring resonator (red)

Material: $LiNbO_3$, GaAs, AlN



SAW-opt crystal

SBS: classical theory

Maxwell equation $$\partial_t(\epsilon_{\alpha\beta}\dot{E}_\beta) - c^2\Delta E_\alpha = 0$$

Elasto-optic effect $$\epsilon_{\alpha\beta} \Rightarrow \epsilon_{\alpha\beta} + \gamma_{\alpha\beta\gamma\delta}\, u_{\gamma,\delta}$$

* $$\partial_t(\epsilon_{\alpha\beta}\dot{E}_\beta) - c^2\Delta E_\alpha + \gamma_{\alpha\beta\gamma\delta}\,\partial_t(\dot{E}_\beta\, u_{\gamma,\delta}) = 0$$

photo-elastic

Interaction energy $$U_{int} = \frac{1}{8\pi}\gamma_{\alpha\beta\gamma\delta}\, E_\alpha E_\beta\, u_{\gamma,\delta}$$

Acoustic equation

piezoelectric

* $$\rho\ddot{u}_\gamma - c_{\alpha\beta\gamma\delta}u_{\alpha,\beta\delta} + \frac{1}{8\pi}\gamma_{\alpha\beta\gamma\delta}\,(E_\alpha E_\beta)_{,\delta} - e_{\alpha\beta\gamma}\varphi_{,\alpha\beta} = 0$$

photo-elastic $$-\epsilon_{\alpha\beta}\varphi_{,\alpha\beta} + 4\pi e_{\alpha\beta\gamma}u_{\beta,\gamma\alpha} = 0$$

Kroll 1965, Shen & Blombergen 1965

Cavity mode representation

A(x,t) – fast variable; **u**(x,t), φ(x,t) – slow variables

Opt eigen functions

$$A_\alpha(r,t) = (1/\sqrt{L}) \sum_{k,n} A_n(k,t) e^{ikx} \psi_\alpha^n(r_\perp, k),$$

$$u_\alpha(r,t) = (1/\sqrt{L}) \sum_{q,m} u_m(q,t) e^{iqx} \phi_\alpha^m(r_\perp, q),$$

Ac eigen functions

Interaction energy

$$\mathcal{L}_{\text{int}} = \frac{1}{8\pi c^2} \sum_{\substack{nn'm \\ kk'q}} \mathcal{M}_{nn'm}^{kk'q} \dot{A}_n(k) \dot{A}_{n'}(k') u_m(q)$$

Interaction matrix element

$$\mathcal{M}_{nn'm}^{kk'q} = \gamma_{\alpha\beta\gamma\delta} \int \frac{dV}{\sqrt{L^3}} \psi_\alpha^n(r_\perp, k) \psi_\beta^{n'}(r_\perp, k') \times e^{i(k+k')x} \left(\phi_\gamma^m(r_\perp, q) e^{iqx}\right)_{,\delta}.$$

Resonant triad

$$\mathcal{L}_{\text{int}} \sim A_n(k) A_{n'}^*(k') u_m(q) + A_n^*(k) A_{n'}(k') u_m^*(q)$$

Quantum Hamiltonian

After choosing pump mode and quantizing weak modes, *a* – optic, *b* - acoustic

up-conversion $$\mathcal{H}_{\rm SBS} = -\hbar\sqrt{N}_p(g_0 e^{-i\omega_p t}\, a^\dagger b + g_0^* e^{i\omega_p t}\, a b^\dagger)$$

down-conversion $$\mathcal{H}_{\rm SBS} = -\hbar\sqrt{N}_p(g_0 e^{-i\omega_p t}\, a^\dagger b^\dagger + g_0^* e^{-i\omega_p t}\, a b)$$

pump photon #

vacuum coupling rate $$g_0 = \mathcal{M}\sqrt{\frac{\hbar\omega_p\omega_s\Omega}{32\epsilon^2\rho s^2}}$$

$$\mathcal{M} \sim \gamma/\sqrt{V}$$ cavity volume

photoelastic coeff

VS, PRA 2016

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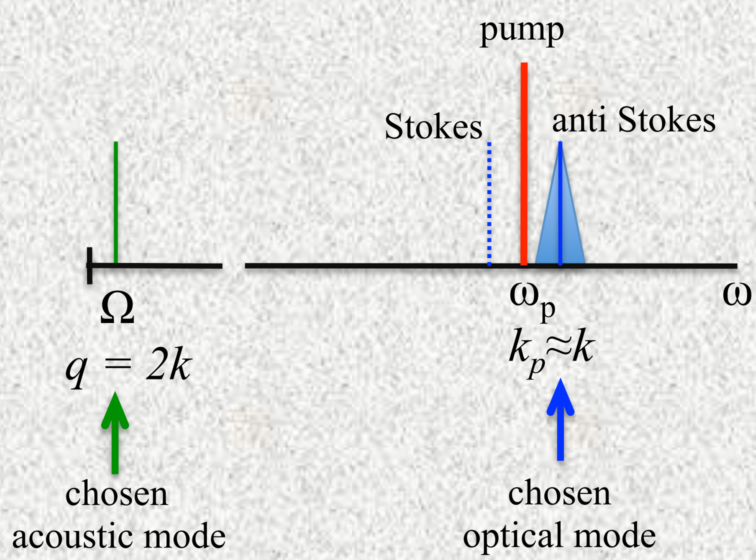
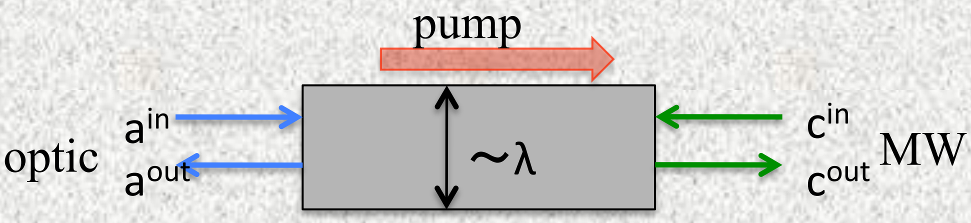


Suppressing vacuum fluctuation amplification

VS, PRA 2016

Acousto-optic transducer: quantum theory



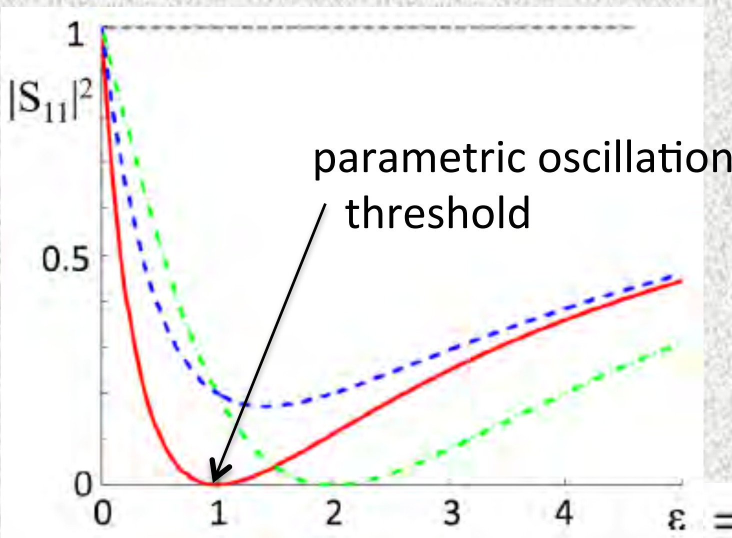
c ⇔ b linear coupling via IDT

Langevin equations

$$i\dot{a} + (\delta\omega + i\kappa)a + g_0\sqrt{N_p}\,b = \sqrt{2\kappa_0}\,a_{\text{in}},$$
$$i\dot{b} + (\delta\Omega + i\Gamma)b + g_0^*\sqrt{N_p}\,a = \sqrt{2\Gamma_0}\,c_{\text{in}}$$

Optic reflection coefficient

$$S_{11} = 1 - 2i\kappa_0(\delta\Omega + i\Gamma)/D$$
$$D = (\delta\omega + i\kappa)(\delta\Omega + i\Gamma) - |g_0|^2 N_p$$



$$\varepsilon = |g_0|^2 N_p/\kappa_0\Gamma_0$$

Full conversion in absence of internal losses;

$$|S_{11}|^2 + |S_{12}|^2 = 1$$

Optimal pump strength @ δω, δΩ = 0

$$1 = |g_0|^2 N_p/\kappa_0\Gamma_0$$

Acousto-optic transducer: numbers

	LiNbO	GaAs	AlN
n	2,2	3,5	2
p	0,17	0,14-0,16	0,02
$\gamma = pn^4$	3,9	21-23	0,32
g_0 MHz/√V[μ^3]	1,7	5,9-9,6	0,06

$Q_{ac} \sim 10^4$; $\kappa < 2\Omega$ - resolved side band $\Longrightarrow$ $Q_{opt} > 2 \times 10^4$

Condition for optimum conversion

$Q_{opt} \sim 10^5$ $\Longrightarrow$ **$N_p \sim 10^4 / \mu^3$** (LiNbO)

Heating from pump

Internal optical losses ~ 0,1 κ_0 ~ 1 GHz $\Longrightarrow$ **$P_{diss} \sim 1\ \mu W/\mu^3$**

Resonance at pump frequency $\Longrightarrow$ **$P_{pump} \sim 10\ \mu W$**

Conclusions

- Piezoelectric SAW resonators have potential for providing alternative to MW resonators for superconducting qubits
- Advantage of SAW resonators is a possibility of coupling to optical photons
- Physics of coupling is fundamental elasto-optic interaction – dominant optical nonlinearity
- Stimulated Brillouin Scattering provides parametric mechanism for acousto-optic frequency conversion (alternatively amplification and phonon-photon entanglement)
- Proposed transducer employs SBS in integrated acousto-optical cavity, which is able to provide complete reversible phonon-photon conversion at feasible pumping power
- Challenges: high quality SAW resonators, small acoustic volumes
- State-of-the-art integrated acousto-optic devices are suitable for transducer implementation