WP1: Photon conversion at vastly different wavelengths

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EPFL – Institute of Physics

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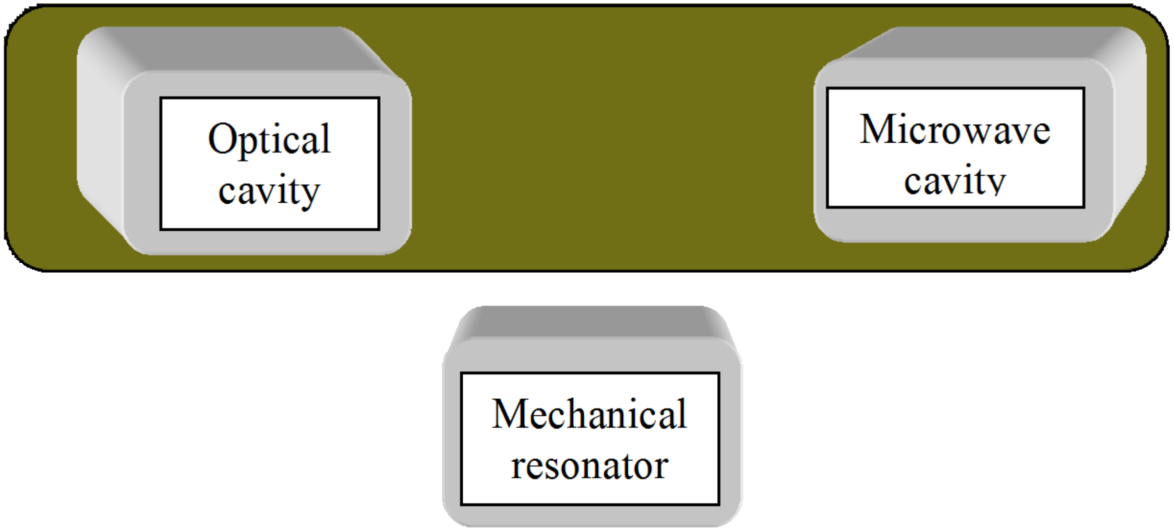
Overview



Tasks:

- 1.1. Realization of a direct coherent microwave-to-optical link
- 1.2 Development of large gain-bandwidth product microwave amplifiers with minimal added noise

Outline

1. Progress on realization of coherent microwave-to-optical link

1. Microwave amplification in the reversed dissipation regime of cavity optomechanics

2. Nonreciprocal microwave optomechanical circuit

3. Wideband Josephson parametric amplifiers

Outline

1. **Progress on realization of coherent microwave-to-optical link**

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Coupling of microwave and optical fields

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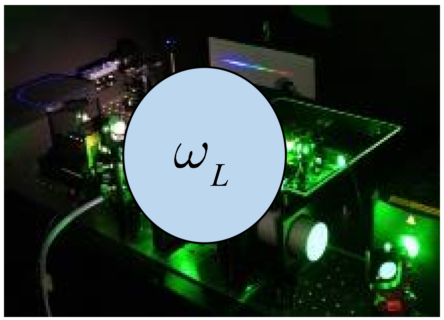
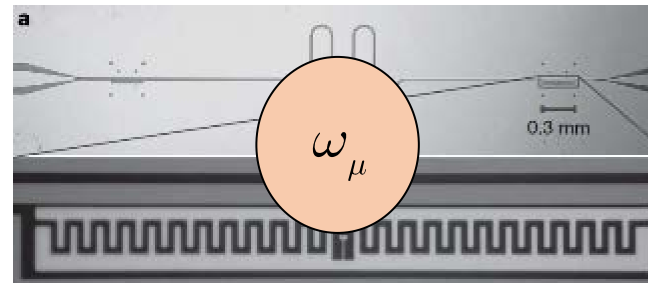
Ω_c

Optical fields



Microwave fields



Environment

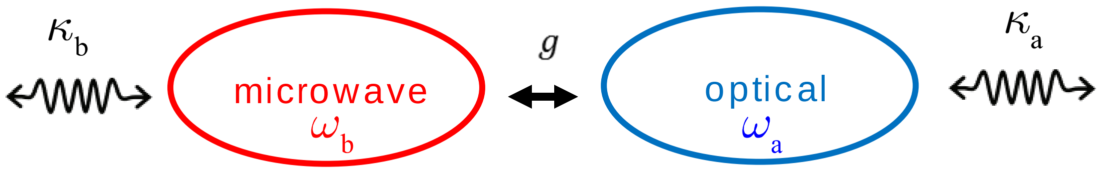
$\hbar\omega_L \gg k_B T_{\text{env}}, k_B T_{\text{room}}$

Environment

$k_B T_{\text{room}} \gg \hbar\omega_\mu \gg k_B T_{\text{env}}$

How can this coupling be achieved?

Direct electro-optic coupling approach



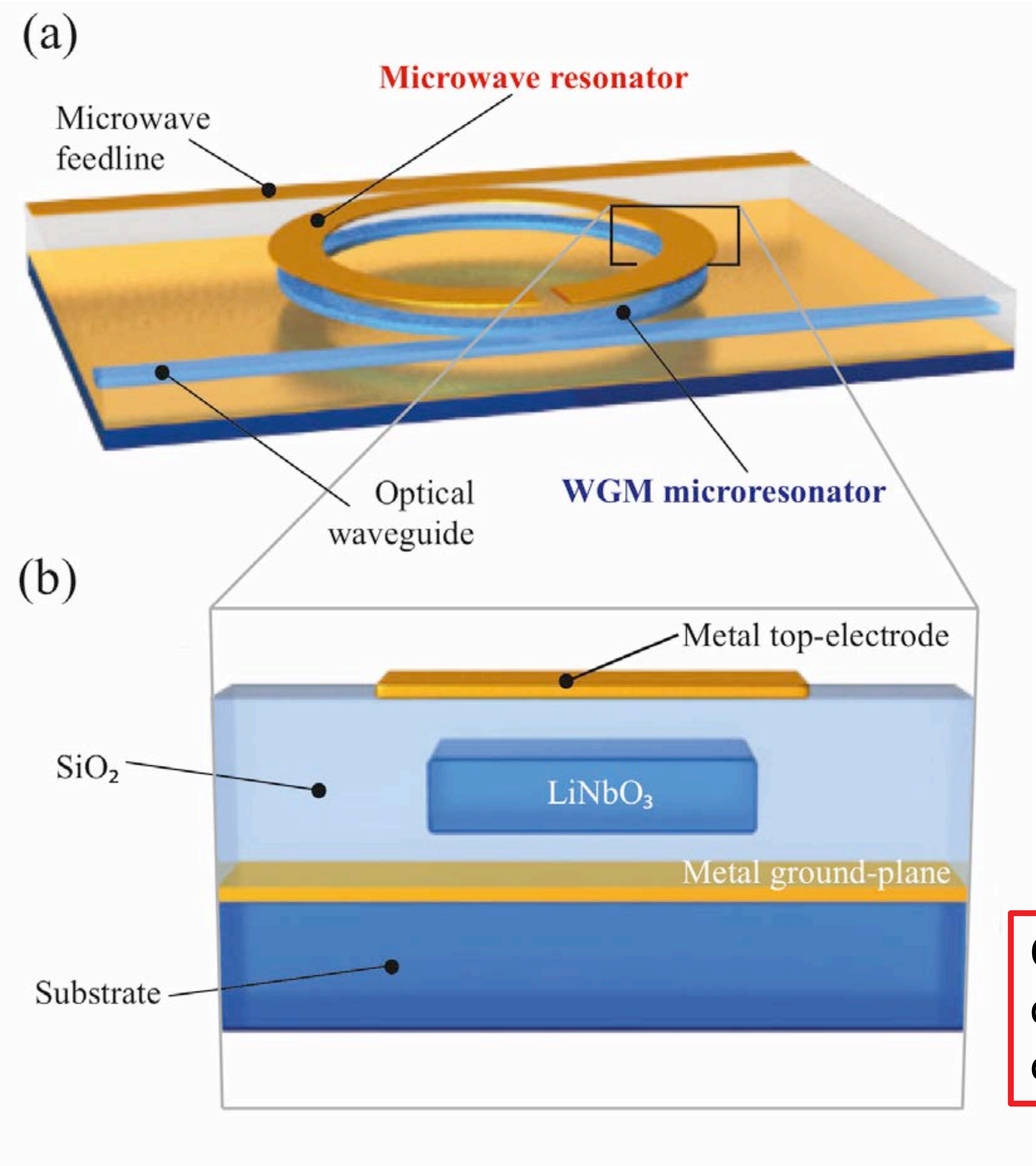
Pockels effect: change in the refractive index is linearly proportional to the electric field.

$$\frac{\delta\omega_a}{\omega_a} \approx \frac{\int_{\mathcal{V}} \mathbf{E}_a^* \varepsilon_0 \delta\varepsilon(\mathbf{r}) \mathbf{E}_a d\mathcal{V}}{\int_{\mathcal{V}} \varepsilon_0 \varepsilon(\mathbf{r}) \mathbf{E}_a^* \cdot \mathbf{E}_a d\mathcal{V}}$$

$$\hat{H} = \hbar\omega_b \hat{b}^\dagger \hat{b} + \hbar\omega_a \hat{a}^\dagger \hat{a} - \hbar g_0 \left(\hat{b} + \hat{b}^\dagger\right) \hat{a}^\dagger \hat{a}$$

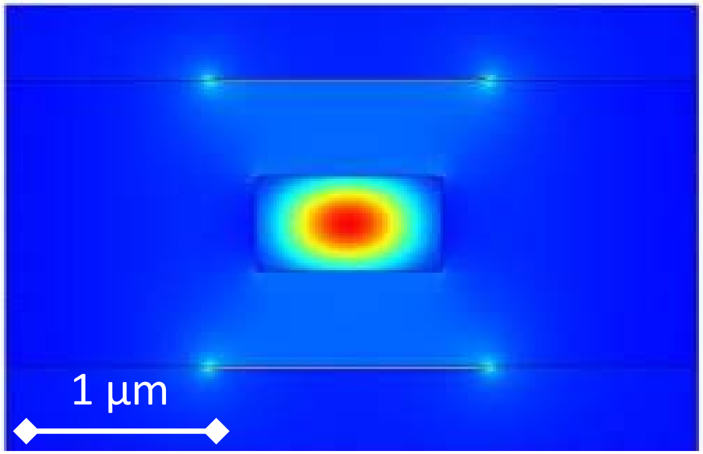
M. Tsang, PRA 81,063837 (2010) and PRA 84, 043845 (2011)
C. Javerzac-Galy et al., PRA 94, 053815 (2016)

Circuit and FEM simulation results



Using realistic system parameters, large values of single-photon coupling strength were simulated.

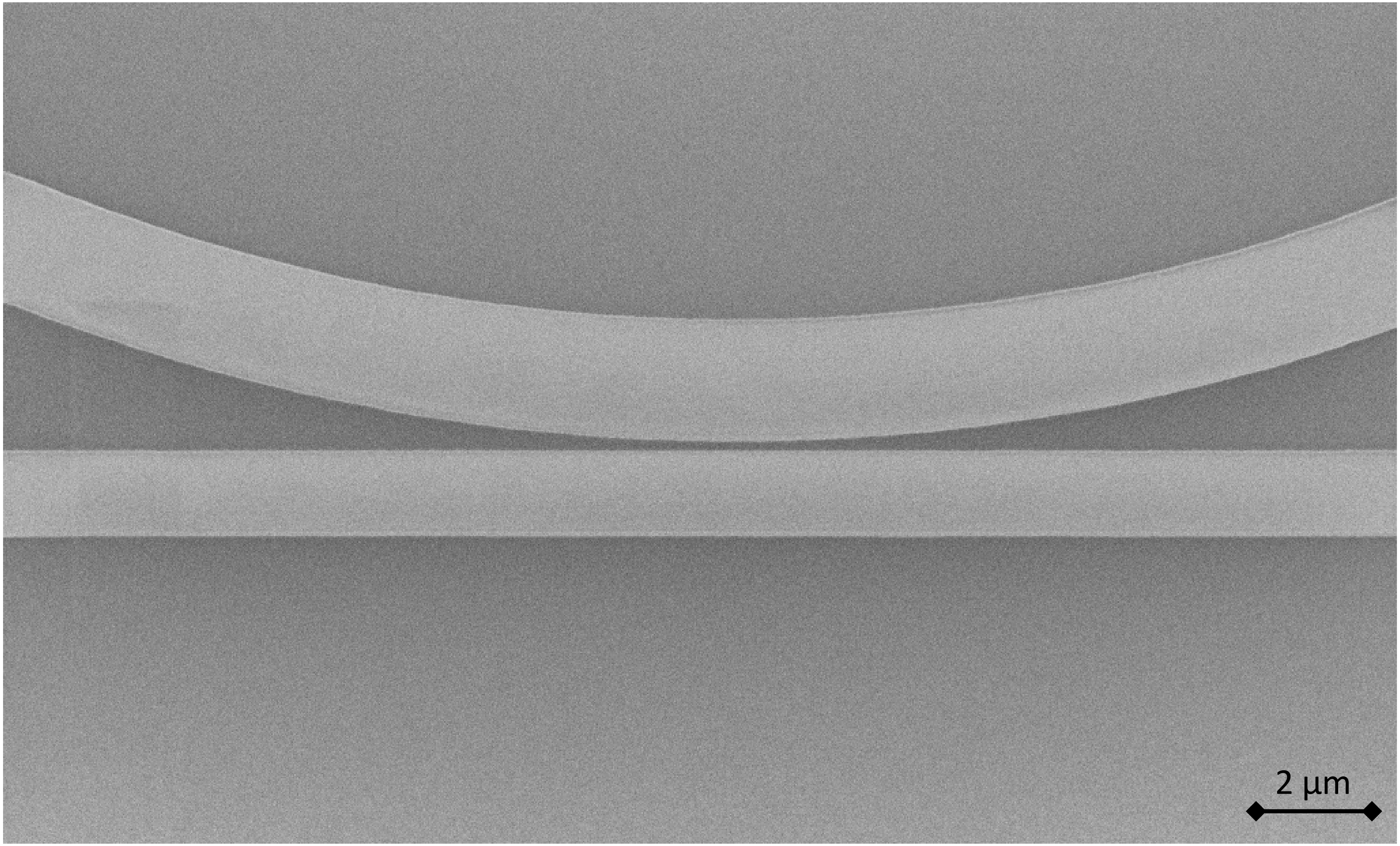
$$g_0 \sim 2\pi \cdot 50 \text{ kHz}$$



Optimal conversion (unity cooperativity) can be reached with less than a milliwatt of input power (on-chip).

C. Javerzac-Galy et al., PRA 94, 053815 (2016)

LNOI WGM resonators



Fabrication flow

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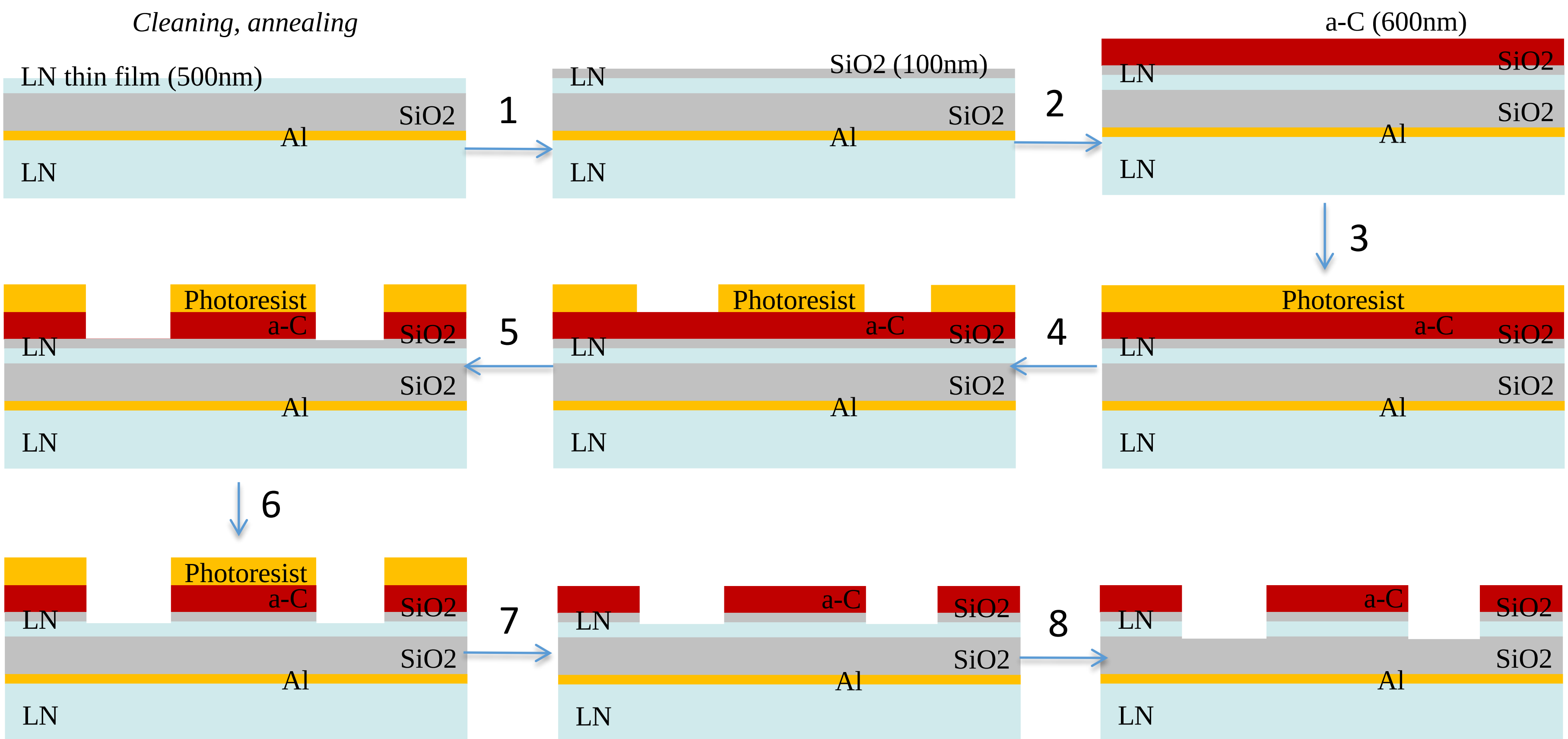
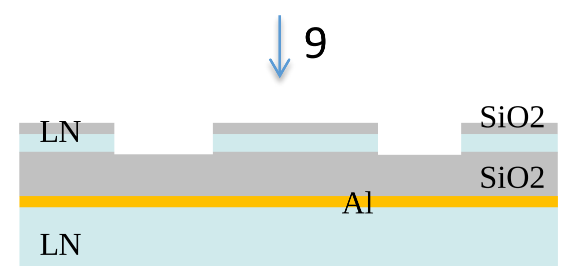
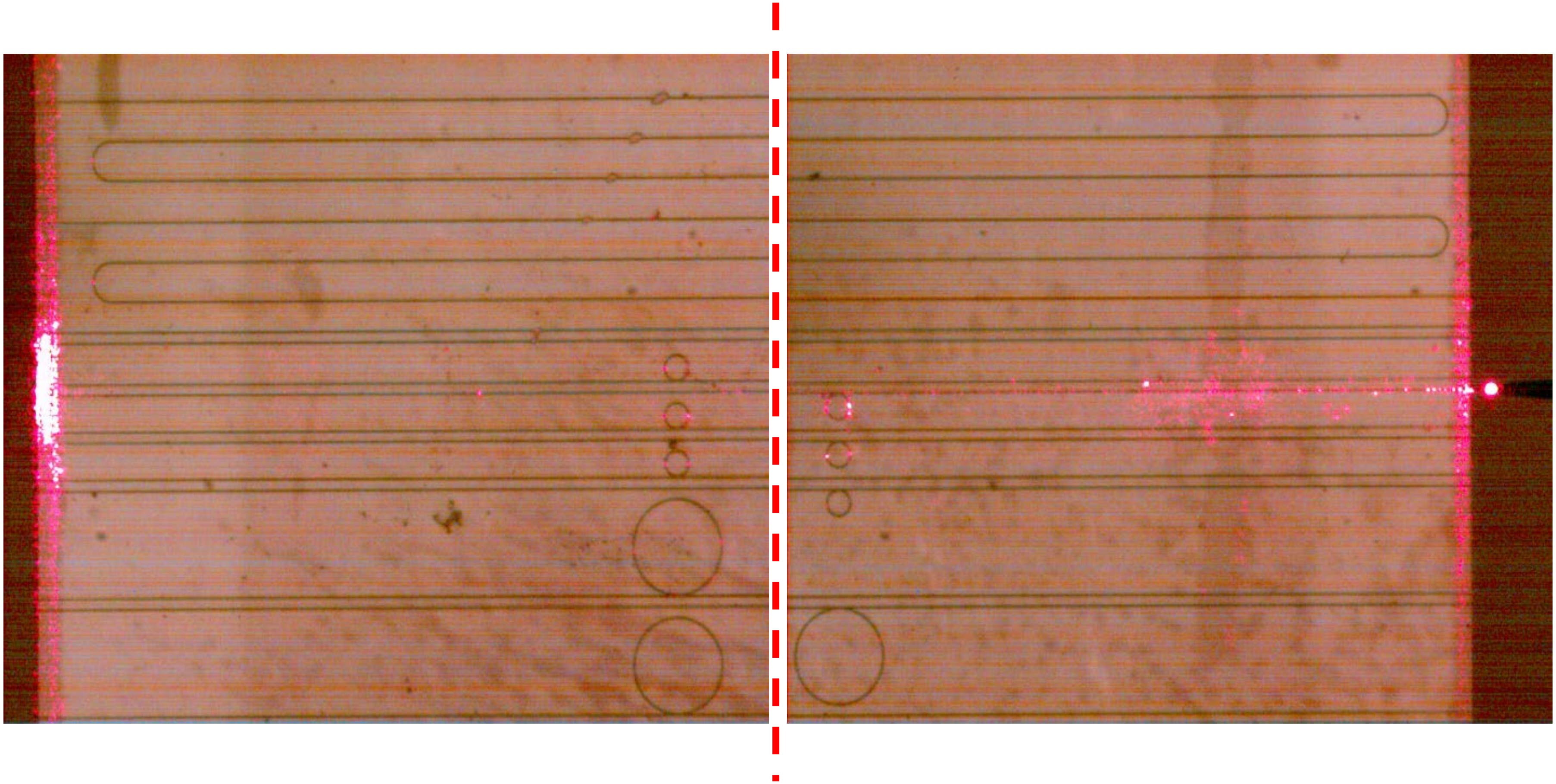




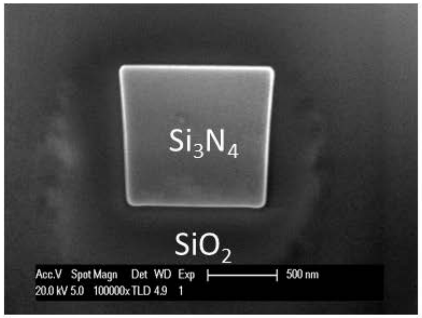
1, 2: SiO$_2$ and amorphous carbon mask deposition
3, 4: ebeam lithography
5, 6, 8: a-C, SiO2 and LN etching
7, 9: PR removal and a-C stripping

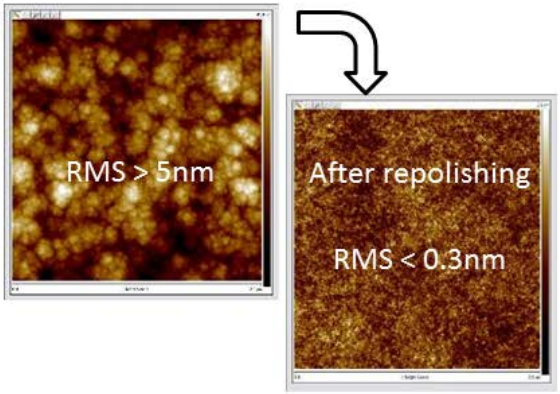
Test results

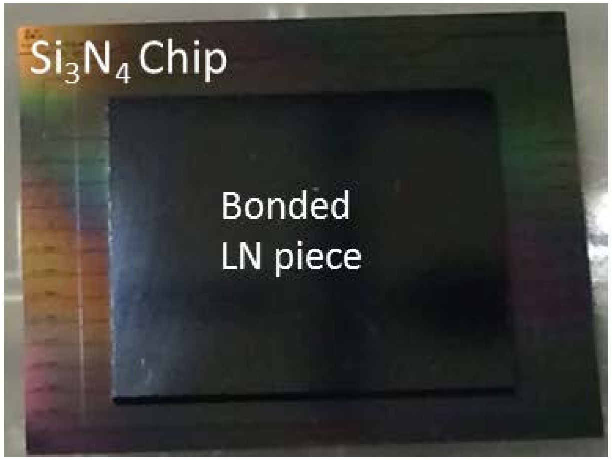


- Some part of the input light goes into waveguides (can be seen from scattering on the waveguide), however there is significant scattering into cladding layer
- No clear output coupling from the WG

LN on silicon nitride hybrid platform







L. Chang et al., Optics Letters 42, 803 (2017)

LN on silicon nitride hybrid platform

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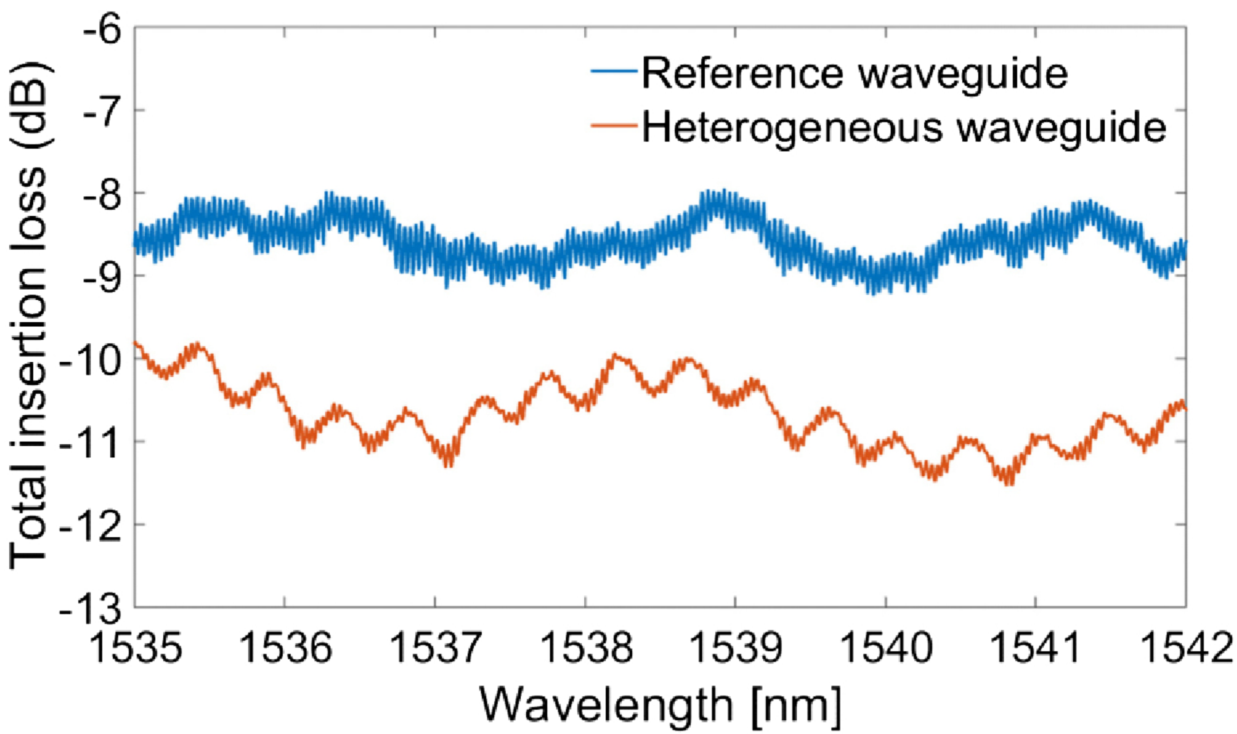
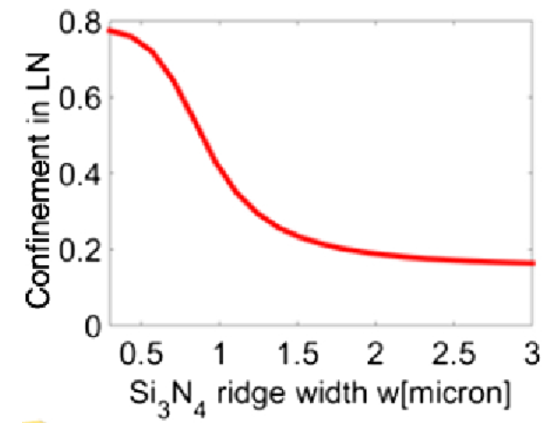
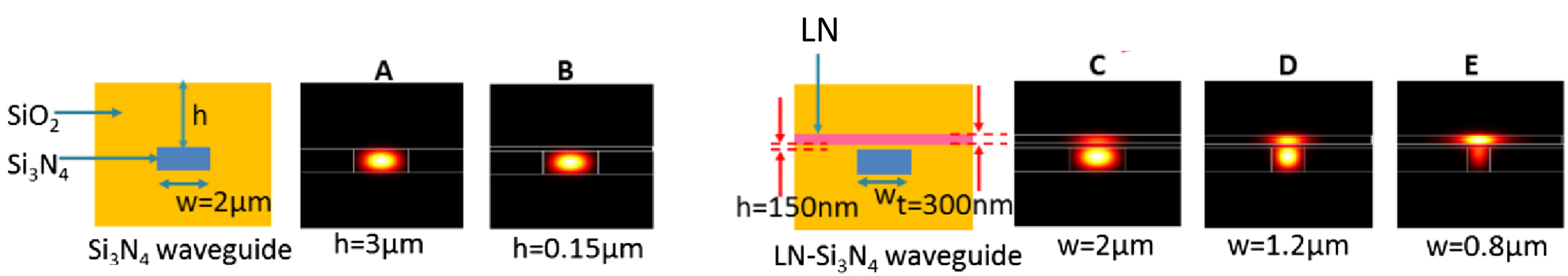


- 1 cm long waveguides
- TE light is coupled through Si_3N_4 waveguides





New platform for integrated non-linear optical circuits

L. Chang et al., Optics Letters 42, 803 (2017)

Outline

1. Progress on realization of coherent microwave-to-optical link

1. **Microwave amplification in the reversed dissipation regime of cavity optomechanics**

2. Nonreciprocal microwave optomechanical circuit

3. Wideband Josephson parametric amplifiers

The reversed dissipation regime

Optomechanical interactions

$$\Delta = -\Omega_m$$

$$H_{int} \approx -\hbar g_0 \sqrt{n_{cav}} \left(\delta \hat{a}^\dagger \hat{b} + \delta \hat{a} \hat{b}^\dagger \right)$$

Coherent exchange of quanta, cooling

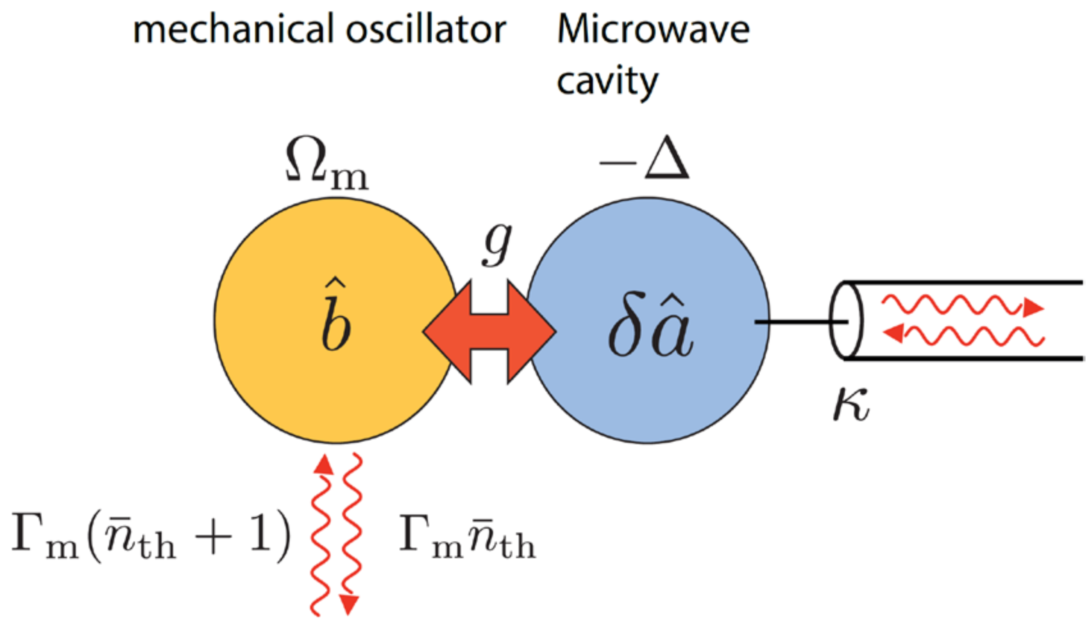
Electromagnetic mode damps mechanical oscillator on red sideband

$$\Delta = +\Omega_m$$

$$H_{int} \approx -\hbar g_0 \sqrt{n_{cav}} \left(\delta \hat{a}^\dagger \hat{b}^\dagger + \delta \hat{a} \hat{b} \right)$$

Amplification and two mode squeezing

Electromagnetic mode amplifies mechanical oscillator on blue sideband



Conventional dissipation hierarchy: $\kappa \gg \Gamma_m$

$\Gamma_{\text{eff}} \longrightarrow \kappa_{\text{eff}}$

Reversed dissipation hierarchy : $\kappa \ll \Gamma_m$

Change in the *mechanical* damping rate, becomes change in the *optical* decay rate.

Nunnenkamp, Sudhir, Feofanov, Roulet, Kippenberg, PRL 113, 023604 (2014)

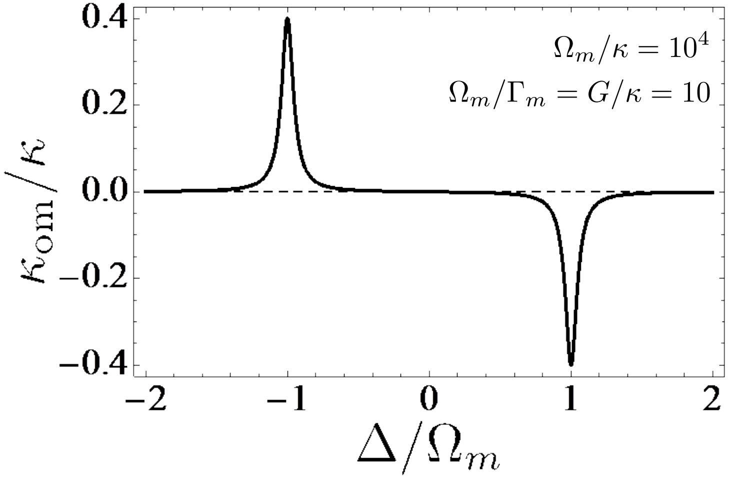
The reversed dissipation regime

Reversed dissipation hierarchy : $\kappa \ll \Gamma_m$

Mechanics *amplifies* electromagnetic mode on blue sideband

$$\Gamma_{\text{eff}} \longrightarrow \kappa_{\text{eff}}$$

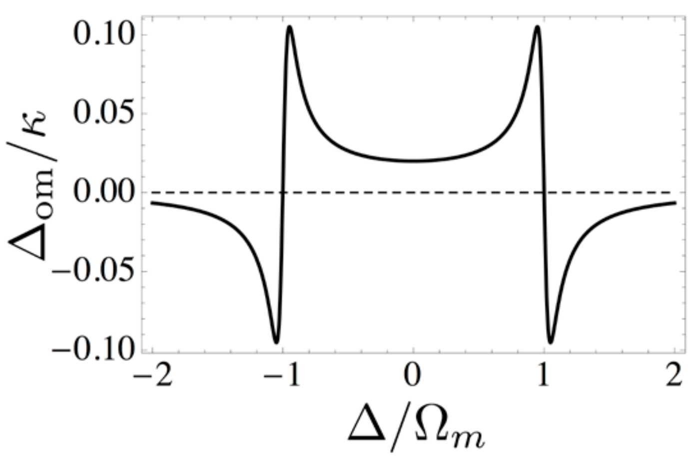
Change in the *mechanical* damping rate, becomes change in the *optical* decay rate.



Change in the electromagnetic decay rate (mechanical damping)

$$\kappa_{\text{om}} = \frac{\Gamma_{\text{eff}} g_0{}^2 n_p}{(\Gamma_{\text{eff}}/2)^2 + (\Delta + \Omega_m)^2} - \frac{\Gamma_{\text{eff}} g_0{}^2 n_p}{(\Gamma_{\text{eff}}/2)^2 + (\Delta - \Omega_m)^2}$$

Change in the electromagnetic resonance freq.



$$\Delta\omega_{\text{om}} = \frac{\Gamma_{\text{eff}} g_0{}^2 n_p (\Delta - \Omega_m)}{(\Gamma_{\text{eff}}/2)^2 + (\Delta + \Omega_m)^2} - \frac{\Gamma_{\text{eff}} g_0{}^2 n_p (\Delta + \Omega_m)}{(\Gamma_{\text{eff}}/2)^2 + (\Delta - \Omega_m)^2}$$

Modified cavity response

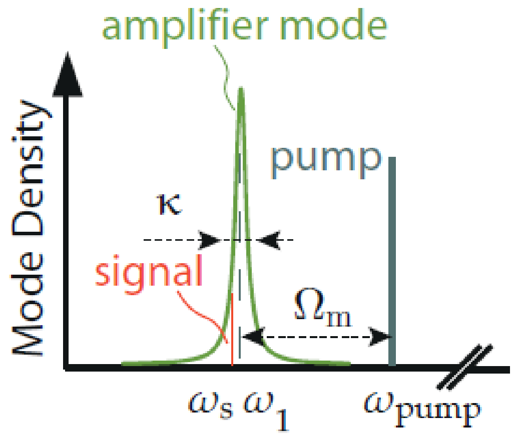
$$\boxed{S_{11}(\omega) = 1 - \frac{\kappa_{\text{ex}}}{(\kappa_0 + \kappa_{\text{ex}} + \kappa_{\text{om}})/2 + i(\omega_c + \Delta\omega_{\text{om}} - \omega)}}$$

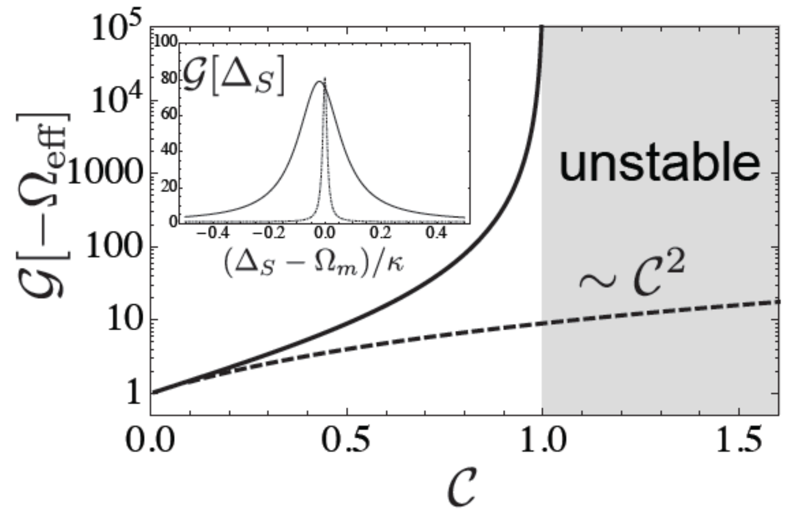
Nunnenkamp, Sudhir, Feofanov, Roulet, Kippenberg, PRL 113, 023604 (2014)

Amplification in the reversed dissipation regime

Amplification scheme

$$\Gamma_m \gg \kappa$$





$$\hat{a}_{out} = A(\omega)\hat{a}_{in} + \underbrace{B(\omega)}_{|B|\ll|A|}\hat{a}^\dagger_{in} + C(\omega)\hat{b}_{in} + \underbrace{D(\omega)}_{|C|\ll|D|}\hat{b}^\dagger_{in}$$

The system operates as a **phase preserving parametric amplifier**

Gain of the amplifier

$$\mathcal{G}(\Delta_s) = \left|\frac{D(\omega)}{A(\omega)}\right|^2 = \left|\frac{4\mathcal{C}\,\kappa}{\kappa_{\text{eff}}/2 - i(\Delta_s + \Delta_{\text{eff}})}\right|^2$$

$$\mathcal{G}(0) = \left|\frac{1+\mathcal{C}}{1-\mathcal{C}}\right|^2$$

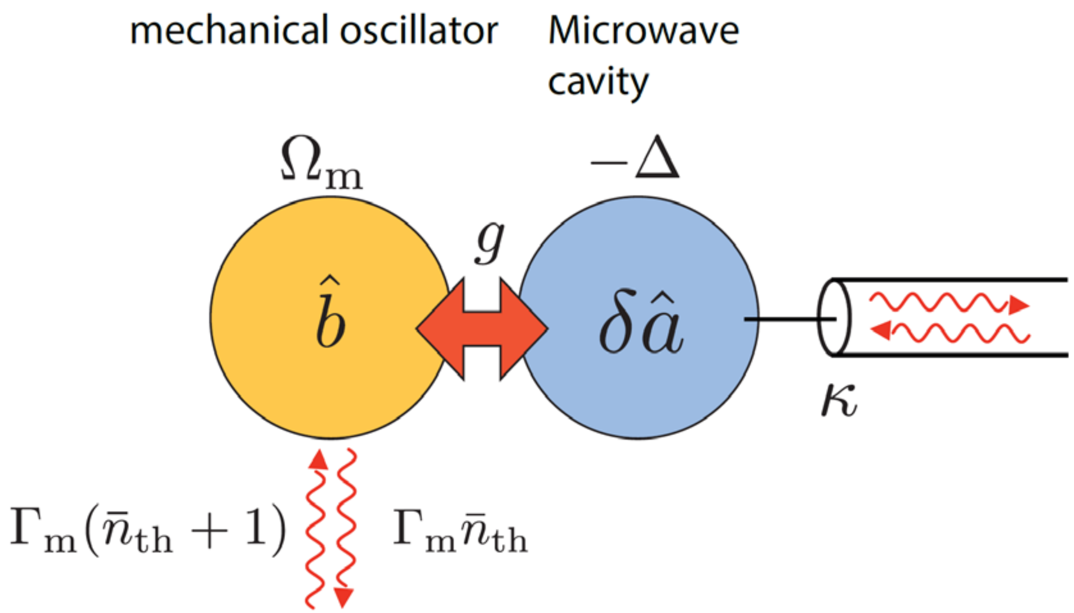
Noise added by the amplifier

$$\mathcal{N} = \left(n_{\text{eff}} + \frac{1}{2}\right) \approx \frac{4\mathcal{C}\left(n_{\text{eff}} + \frac{1}{2}\right)}{(\mathcal{C}+1)^2} \xrightarrow{n_{\text{eff}}} \frac{1}{2}$$

Providing a dissipative but cold mechanical oscillator therefore realizes a **quantum limited phase preserving amplifier** based on a mechanical oscillator

Nunnenkamp, Sudhir, Feofanov, Roulet, Kippenberg, PRL 113, 023604 (2014)
C. M. Caves, PRD 26, 1817 (1982).

Two-mode implementation of the reversed dissipation regime



Nunnenkamp, Sudhir, Feofanov, Roulet, Kippenberg, PRL 113, 023604 (2014)

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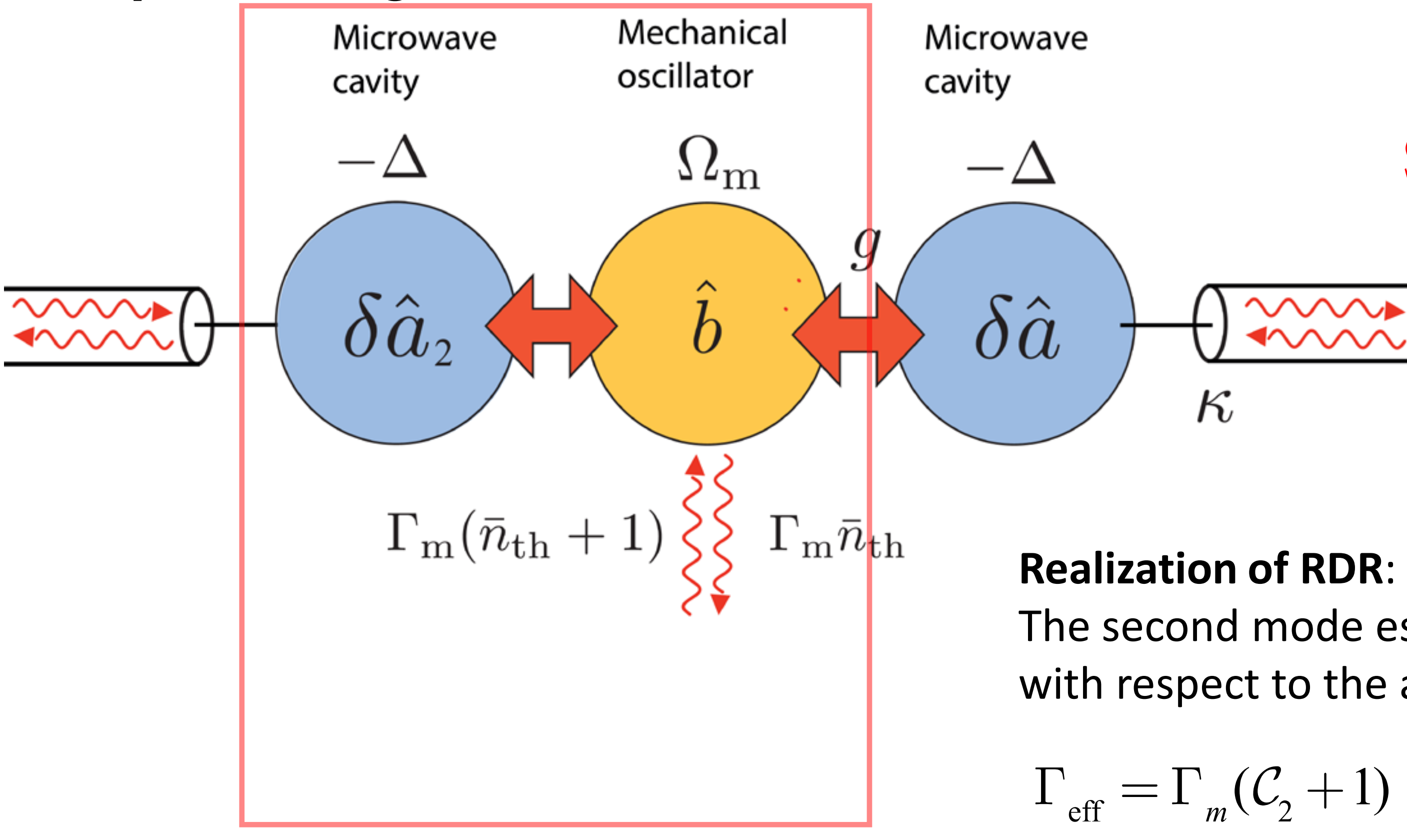


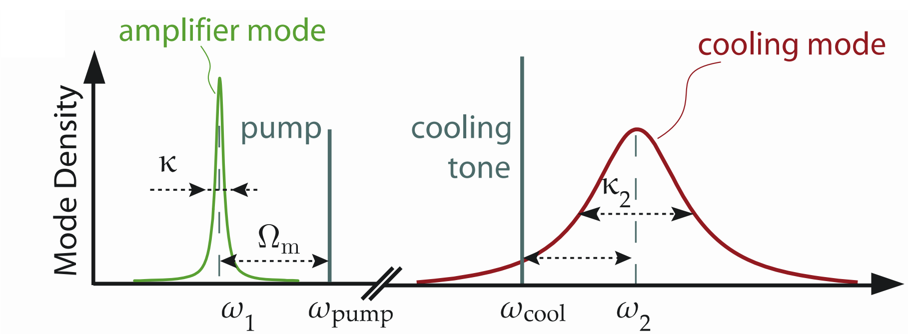
$$\Omega_m \gg \kappa_2 \gg \kappa$$

Realization of RDR:
The second mode establishes the RDR with respect to the amplifier mode:

$$\Gamma_{eff} = \Gamma_m(\mathcal{C}_2 + 1)$$

$$\Gamma_{eff} \rightarrow \kappa_2 / 2 \gg \kappa$$

$$\text{for } \mathcal{C}_2 = \frac{4G_2^2}{\kappa_2 \Gamma_m} \gg 1$$

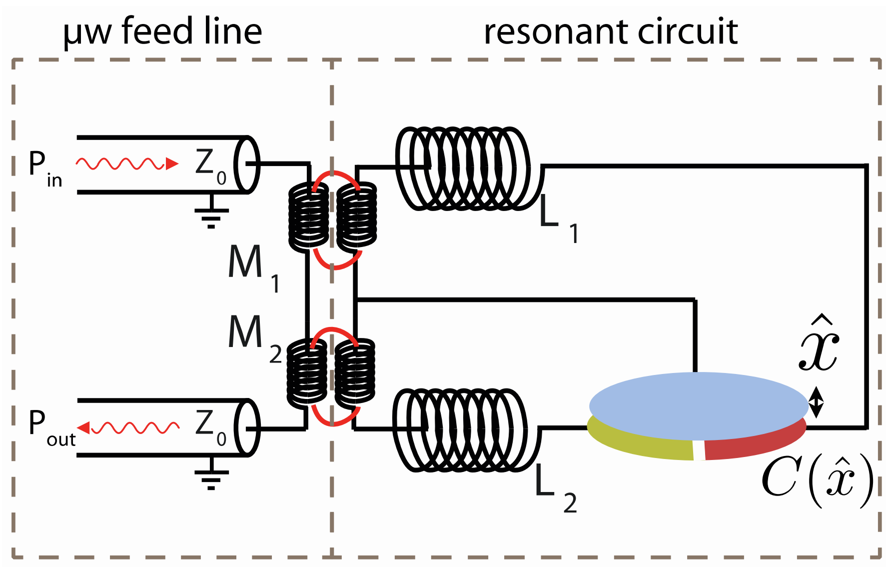


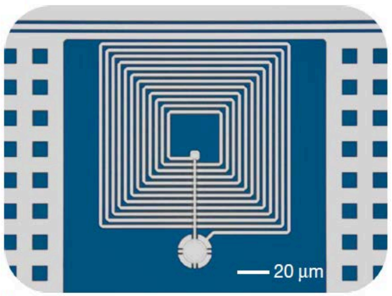
Nunnenkamp, Sudhir, Feofanov, Roulet, Kippenberg, PRL 113, 023604 (2014)

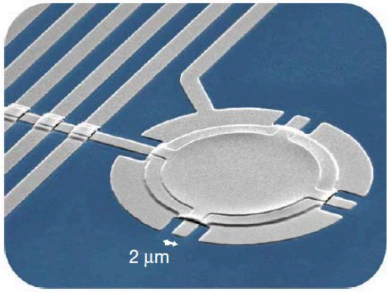
Two-mode implementation of the reversed dissipation regime

Required parameters are feasible with superconducting microwave circuits

	$\omega_c / 2\pi$	$\kappa / 2\pi$	$\Omega_m / 2\pi$	$\Gamma_m / 2\pi$	$g_0 / 2\pi$	$P_{in}(= P_{2,in})$
Proposed	7.5 GHz	10 kHz	1 MHz	50 Hz	100 Hz	0.3 nW
Teufel et al[1]	7.5 GHz	170 kHz	10 MHz	30 Hz	230 Hz	100 nW



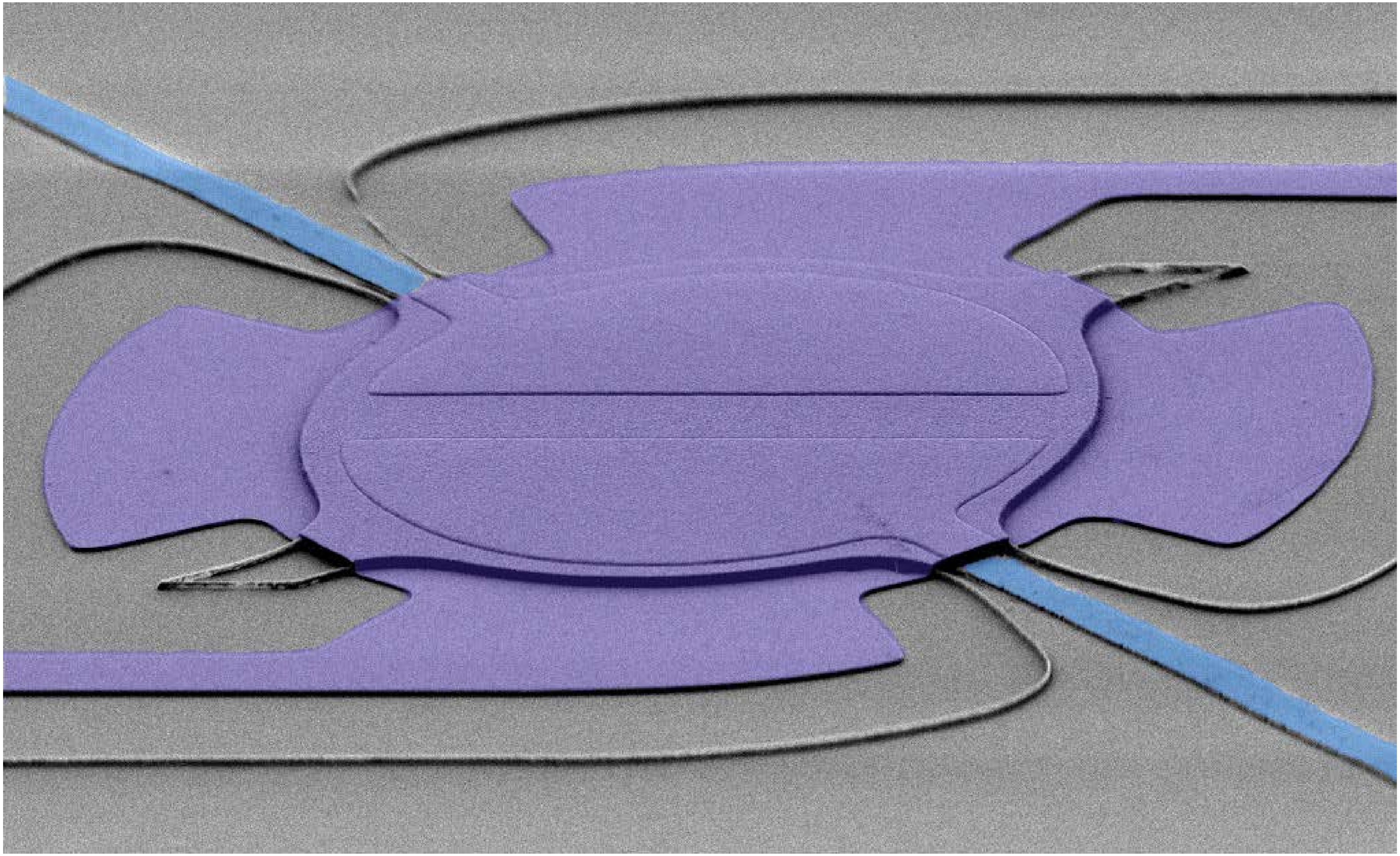




A particular challenge: to fabricate an optomechanical system with multiple EM modes coupled to a mechanical element and with precisely engineered parameters (e.g. very dissimilar coupling rates)

Nunnenkamp, Sudhir, Feofanov, Roulet, Kippenberg, PRL 113, 023604 (2014)
J. D. Teufel et al. Nature 471, 7337 (2011)

Circuit design and fabrication



Process flow – dual-mode circuits

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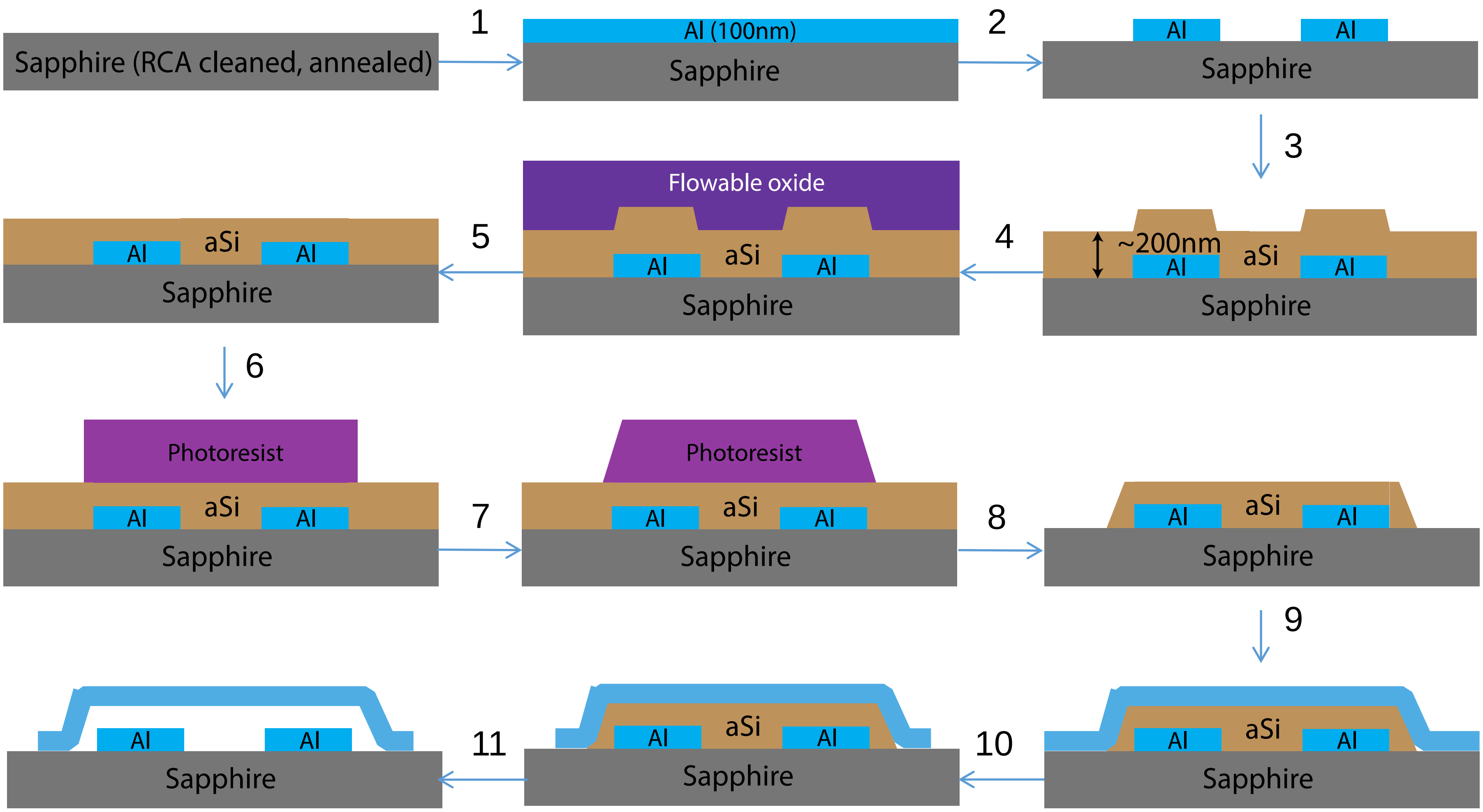
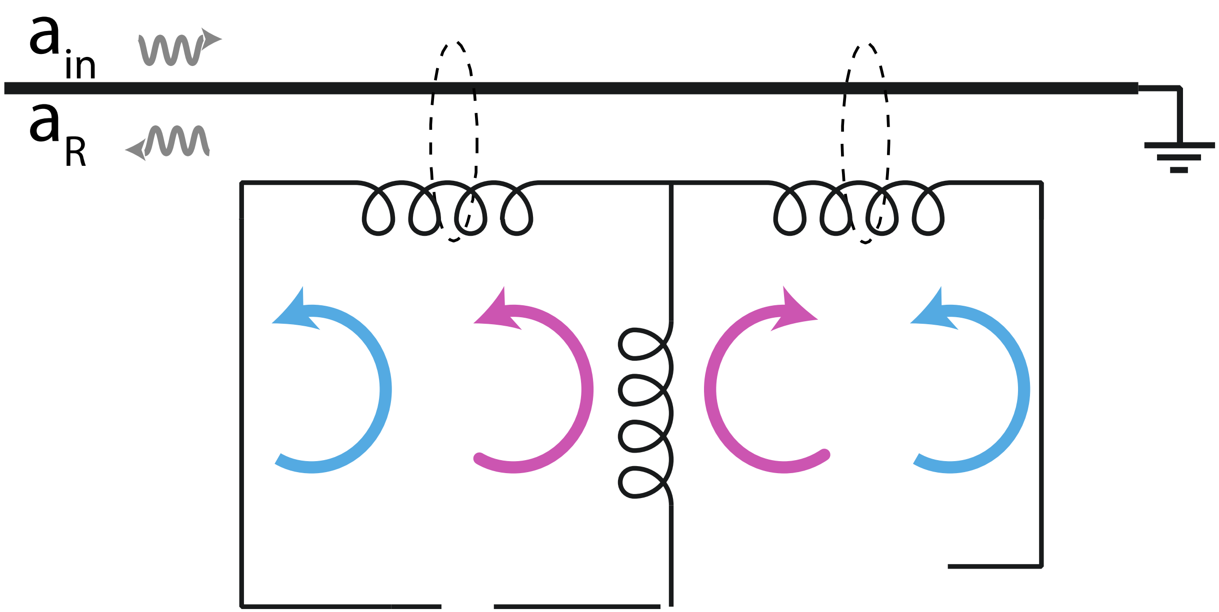
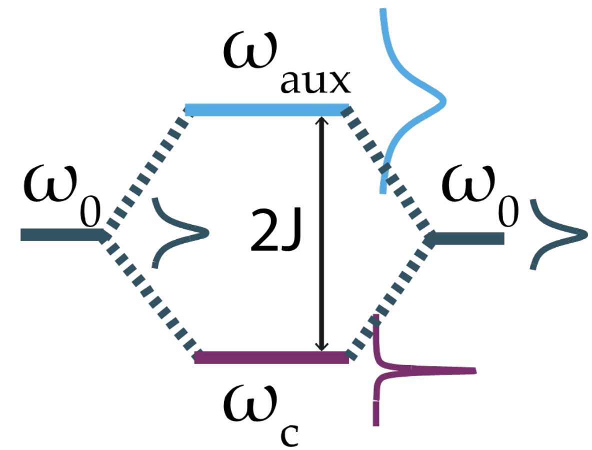


1, 3, 9:	**metal and sacrificial layer (Si) deposition**
2, 8, 10:	**metal and Si etch**
4, 5:	**planarization of Si layer (for split-plate drums)**
6, 7:	**lithography to open Si layer (with reflow)**
11:	**releasing the drum capacitor (XeF_2)**

K. Cicak et al., APL 96, 093502 (2010)

New approach – hybrid modes





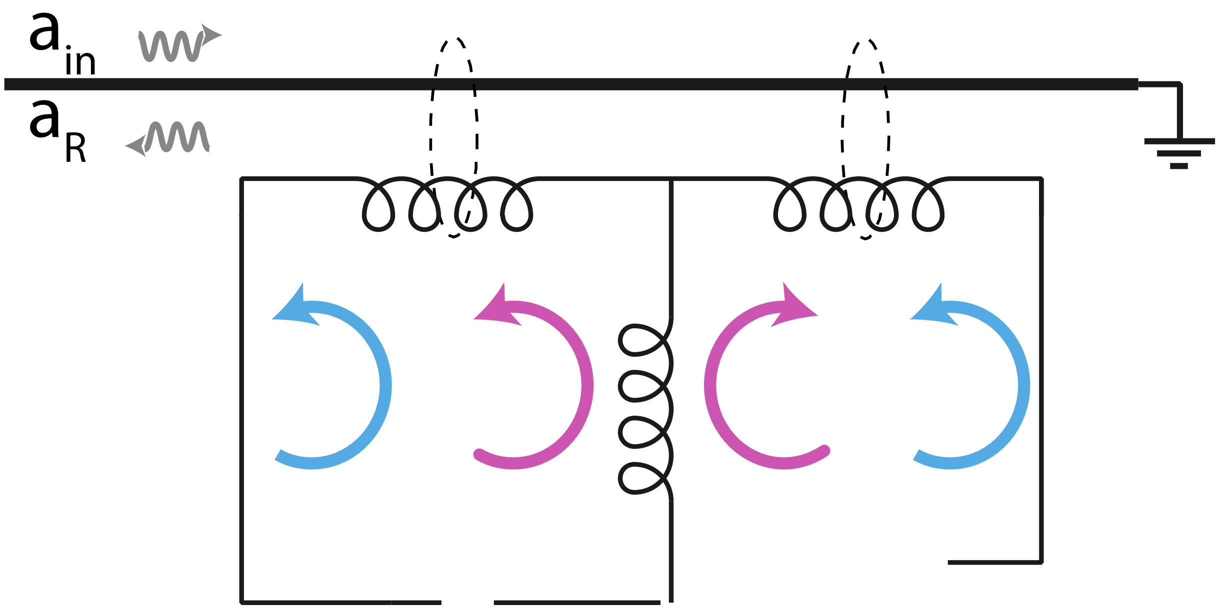
$$\hat{a}_{s,a} = \sqrt{2}^{-1}(\hat{a}_1 \pm \hat{a}_2)$$

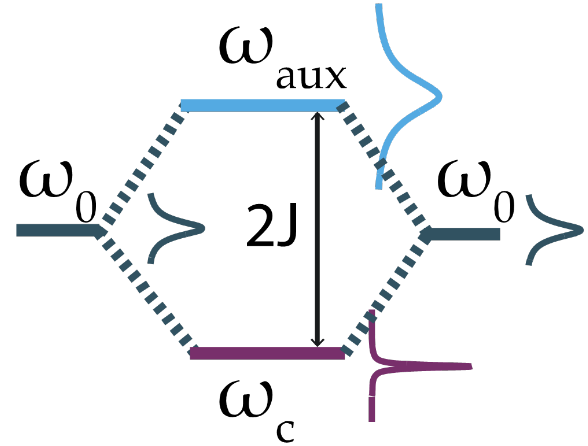
$$\hat{H}_{int} = \hbar J(\hat{a}_1^\dagger \hat{a}_2 + \hat{a}_2^\dagger \hat{a}_1) + \hbar g_0 \hat{a}_1^\dagger \hat{a}_1 (\hat{b} + \hat{b}^\dagger)$$

$$\hat{H}_{int} = \hbar J(\hat{a}_s^\dagger \hat{a}_s - \hat{a}_a^\dagger \hat{a}_a) + \hbar \frac{g_0}{2}(\hat{a}_a^\dagger \hat{a}_a + \hat{a}_s^\dagger \hat{a}_s)(\hat{b} + \hat{b}^\dagger)$$

L. D. Tóth et al., arXiv:1602.05180, accepted to Nature Physics

New approach – hybrid modes





$$\hat{a}_{s,a} = \sqrt{2}^{-1}(\hat{a}_1 \pm \hat{a}_2)$$

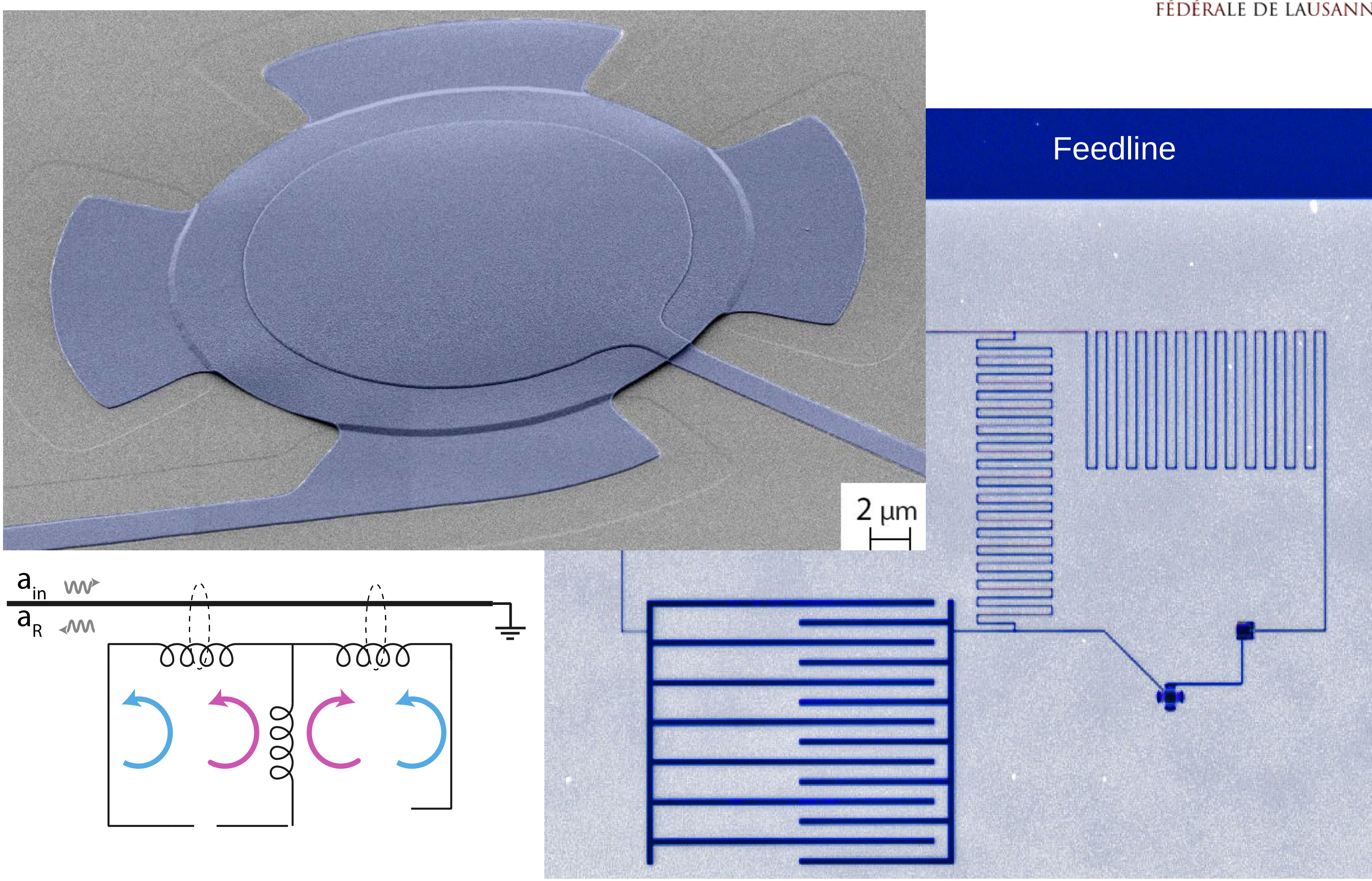
$$\hat{\mathcal{H}} = \hbar\omega_0\left(\hat{a}_1^\dagger\hat{a}_1 + \hat{a}_2^\dagger\hat{a}_2\right) + \hbar\sum_k \omega_k \hat{c}_k^\dagger\hat{c}_k + \hbar J\left(\hat{a}_1^\dagger\hat{a}_2 + \mathrm{H.c.}\right) + \hbar\sum_k\left(g_k^{(1)}\hat{a}_1\hat{c}_k^\dagger + \mathrm{H.c.}\right) + \hbar\sum_k\left(g_k^{(2)}\hat{a}_2\hat{c}_k^\dagger + \mathrm{H.c.}\right)$$

$$\hat{\mathcal{H}} = \hbar\omega_0\hat{a}_s^\dagger\hat{a}_s + \hbar(\omega_0 - J)\hat{a}_a^\dagger\hat{a}_a + \hbar\sum_k \omega_k\hat{c}_k^\dagger\hat{c}_k + \hbar\sum_k\left(\frac{g_k^{(1)} + g_k^{(2)}}{\sqrt{2}}\hat{a}_s\hat{c}_k^\dagger + \mathrm{H.c.}\right) + \hbar\sum_k\left(\frac{g_k^{(1)} - g_k^{(2)}}{\sqrt{2}}\hat{a}_a\hat{c}_k^\dagger + \mathrm{H.c.}\right)$$

Bright and dark modes due to interference

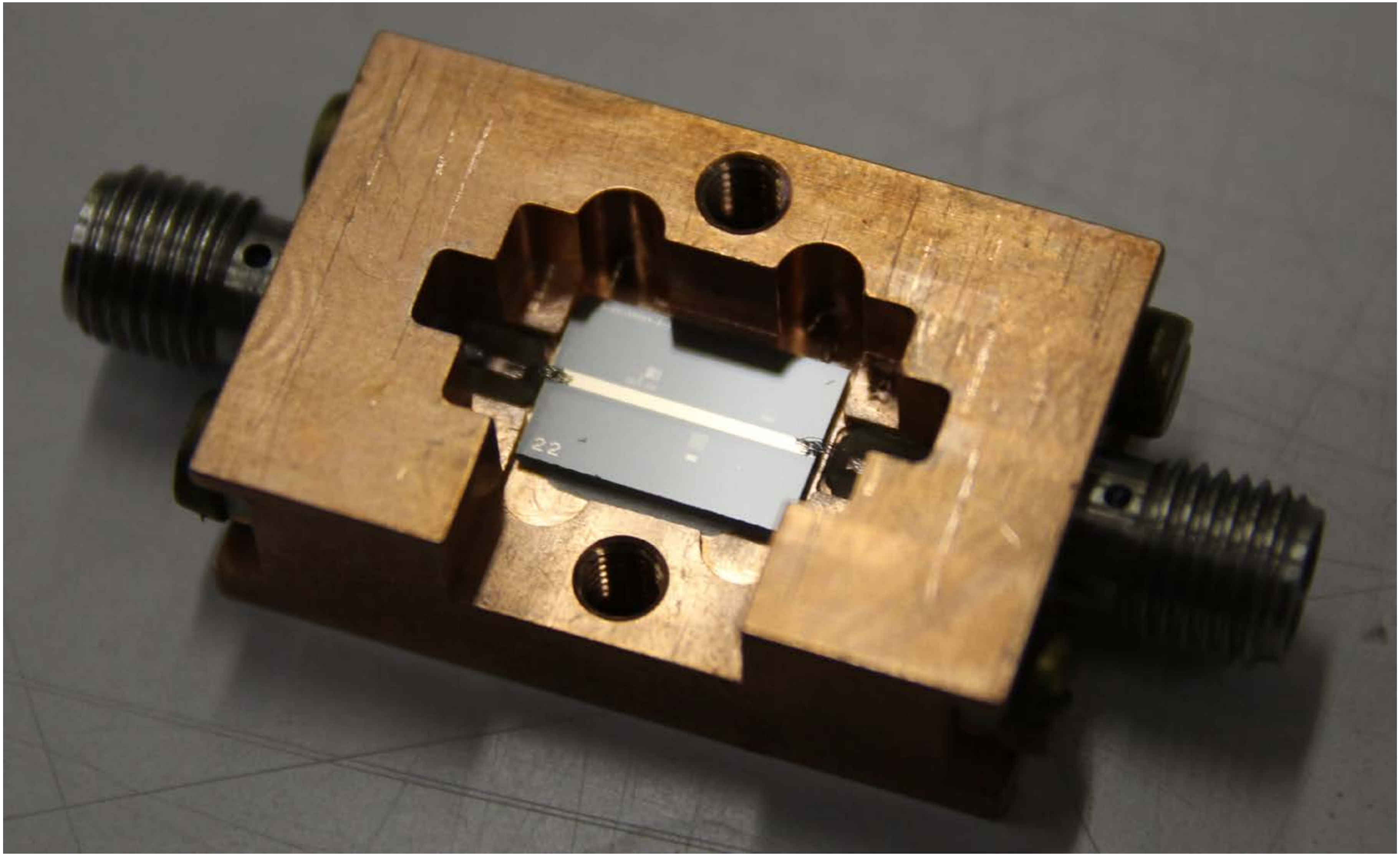
L. D. Tóth et al., arXiv:1602.05180, accepted to Nature Physics

Circuit layout

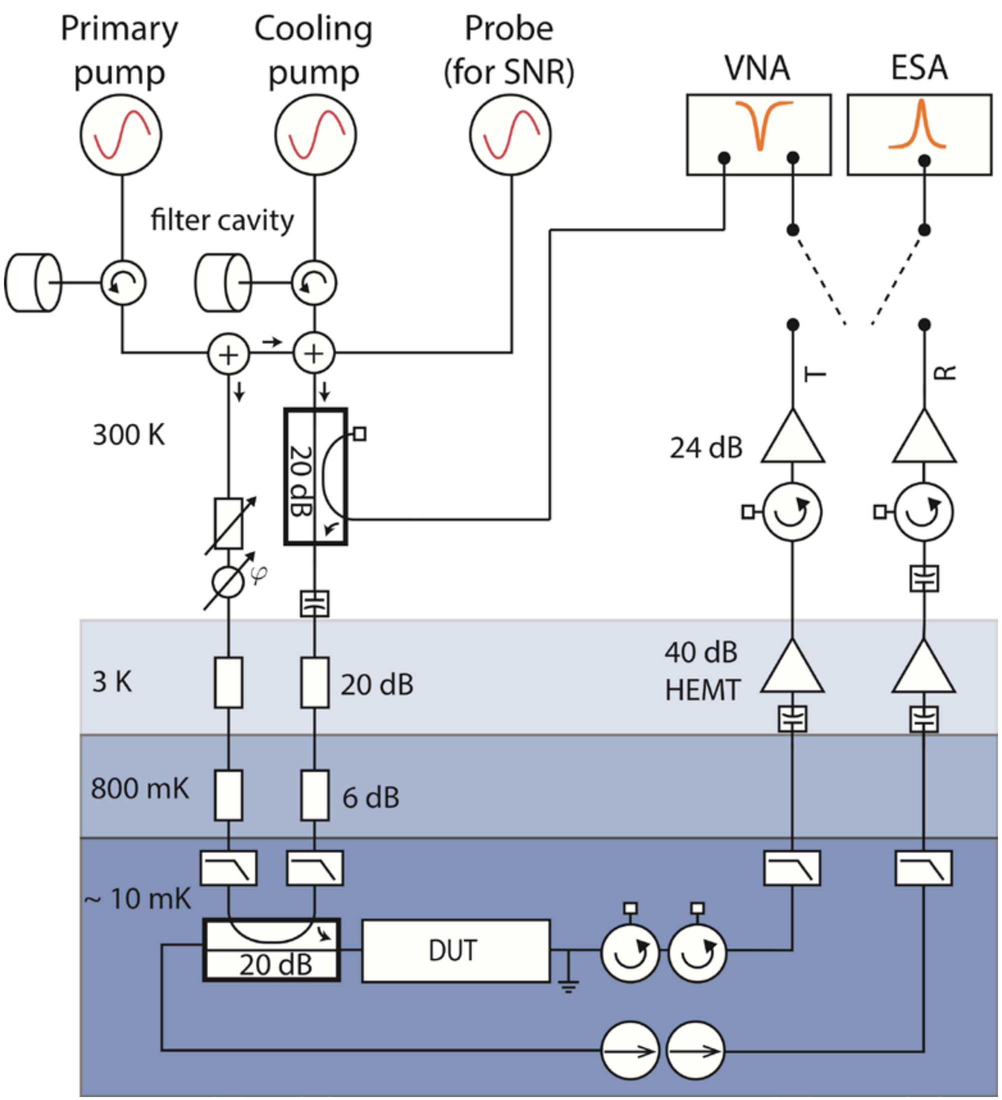


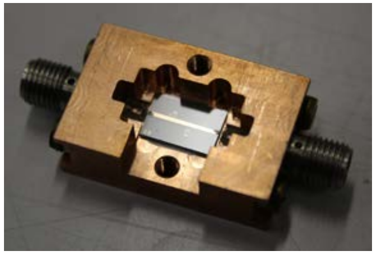
L. D. Tóth et al., arXiv:1602.05180, accepted to Nature Physics

Measurement setup



Measurement setup





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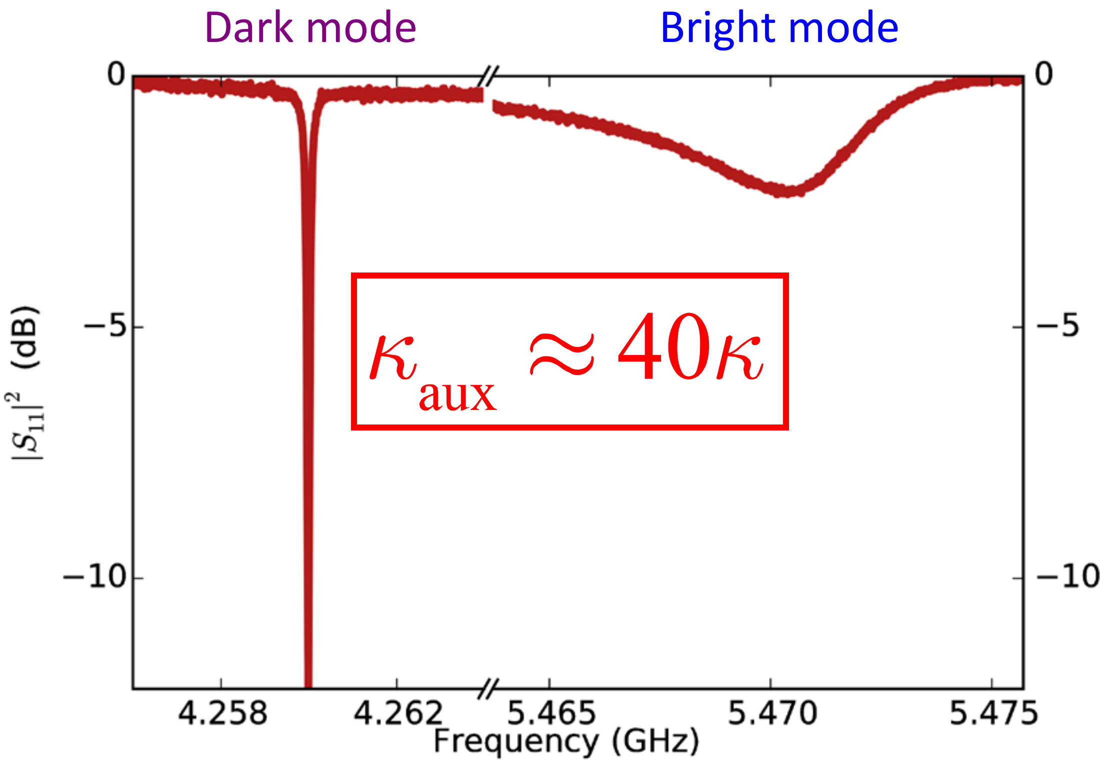
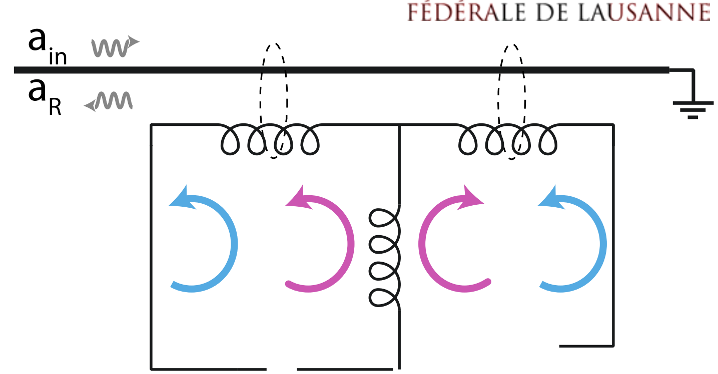
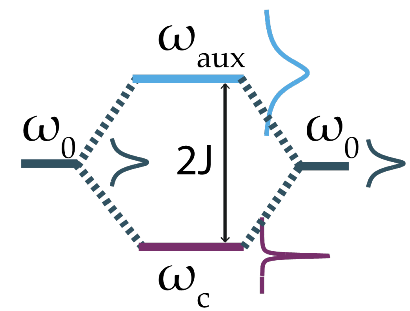
Device characterization







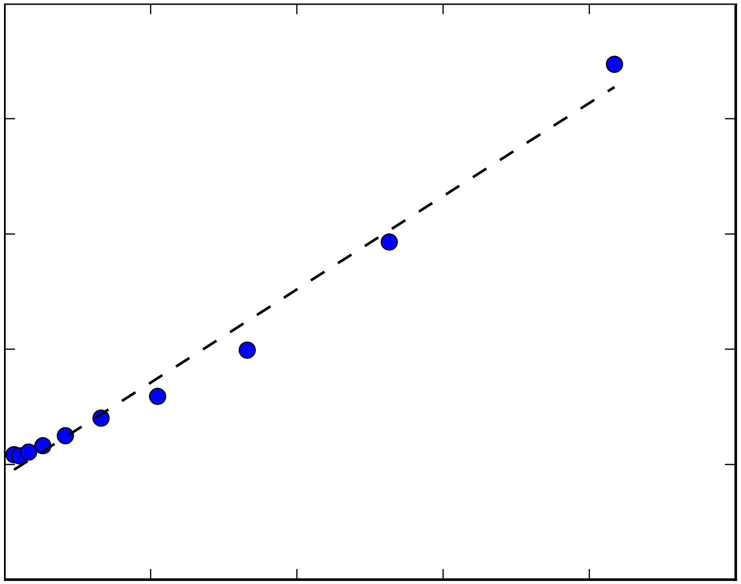
$\omega_c / 2\pi$	$\kappa / 2\pi$	$\omega_{aux} / 2\pi$	$\kappa_{aux} / 2\pi$	$\Omega_m / 2\pi$	$\Gamma_m / 2\pi$	$g_0 / 2\pi$
4.3 GHz	118 kHz	5.4 GHz	4.4 MHz	5 MHz	~ 30 Hz	~ 120 Hz

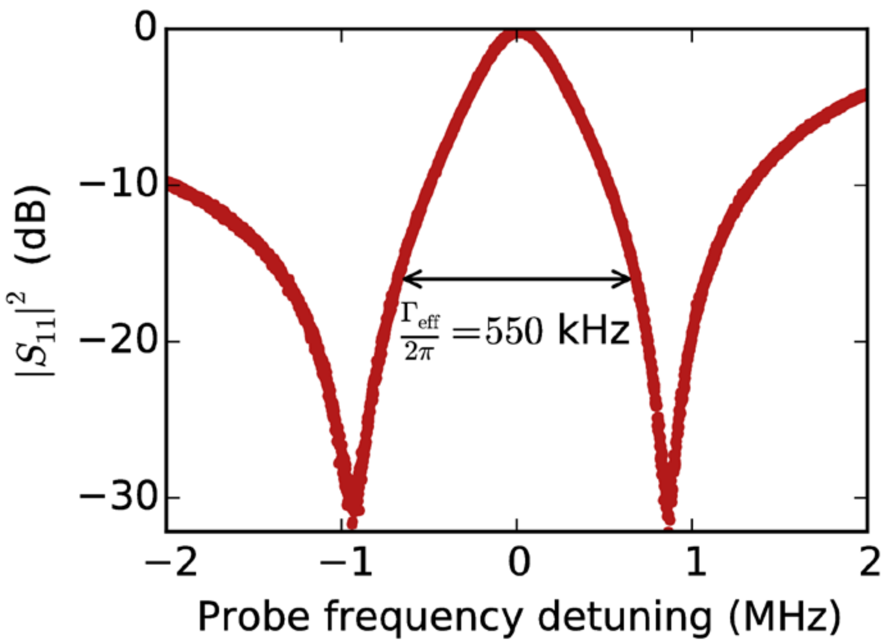
With these parameters we can easily damp the mechanics to $\Gamma_{eff} \sim 2\pi \times 550$ kHz ≈ 5κ

$$\Omega_m \gg \Gamma_{eff} \gg \kappa$$

L. D. Tóth et al., arXiv:1602.05180, accepted to Nature Physics

Preparation of a dissipative reservoir





- Prepare of a dissipative reservoir
  by increasing Γ_{eff} / 2π to 550 kHz

- Create close to Markovian dissipative bath
  for electromagnetic mode

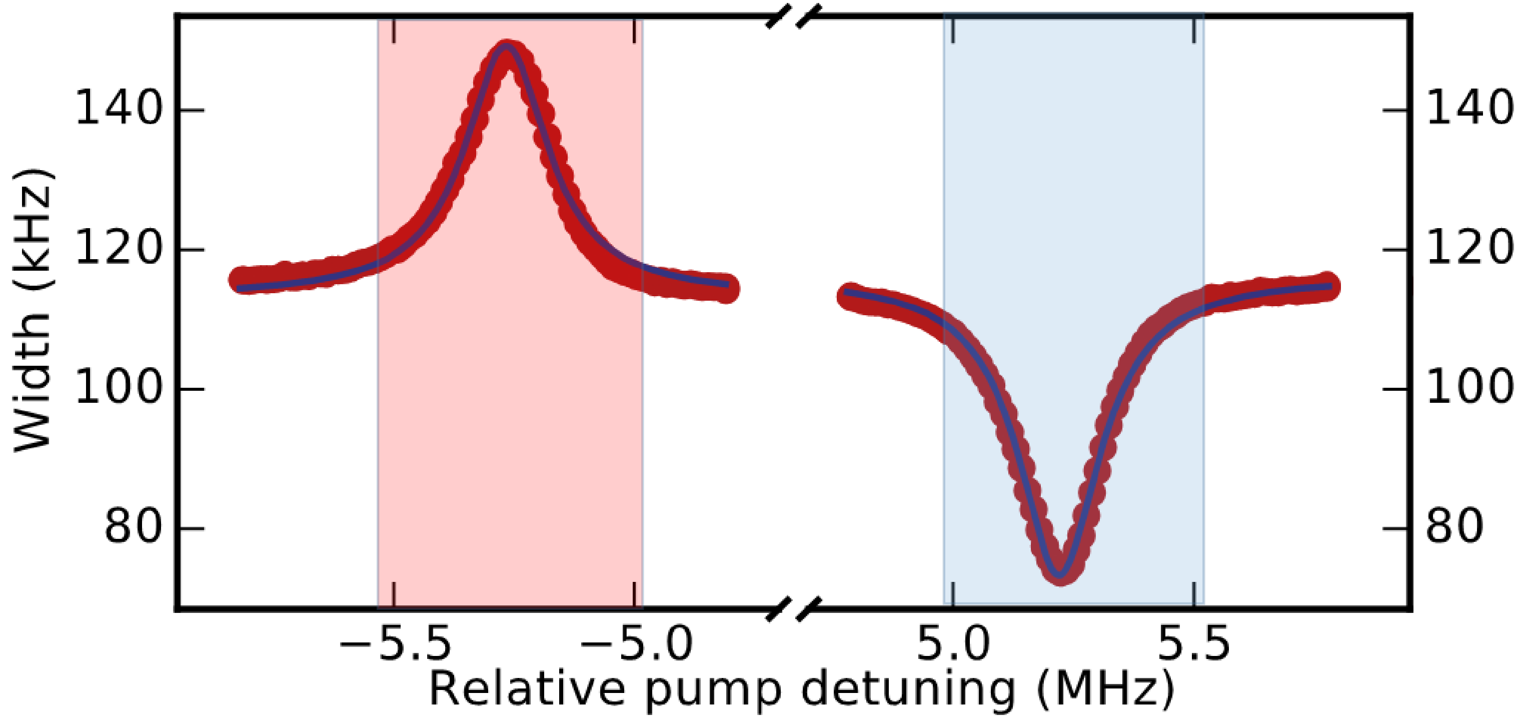
κ ux

$$\Omega_m \gg \Gamma_{\text{eff}} \gg \kappa$$

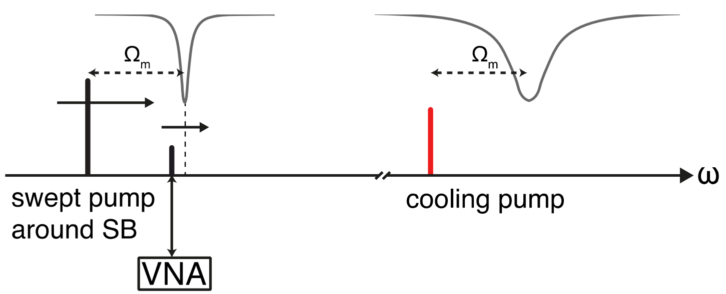
L. D. Tóth et al., arXiv:1602.05180, accepted to Nature Physics

Electromagnetic dynamical backaction

Fix pump power (5 dBm) and sweep detuning



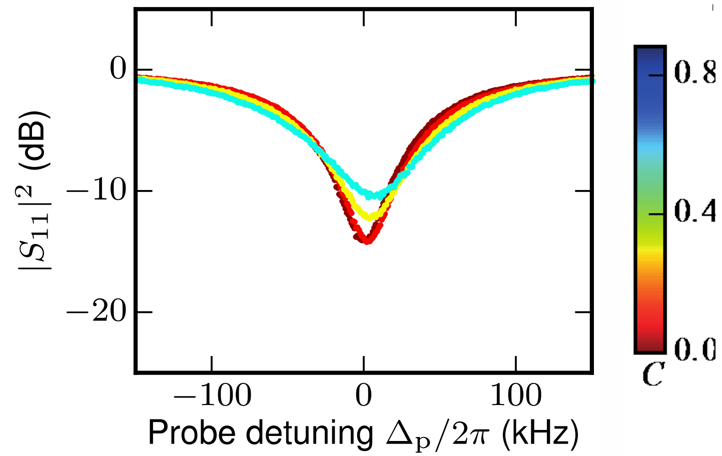
$$\kappa_{om} = \frac{\Gamma_{\text{eff}} g_0{}^2 n_p}{(\Gamma_{\text{eff}}/2)^2 + (\Delta + \Omega_m)^2} - \frac{\Gamma_{\text{eff}} g_0{}^2 n_p}{(\Gamma_{\text{eff}}/2)^2 + (\Delta - \Omega_m)^2}$$

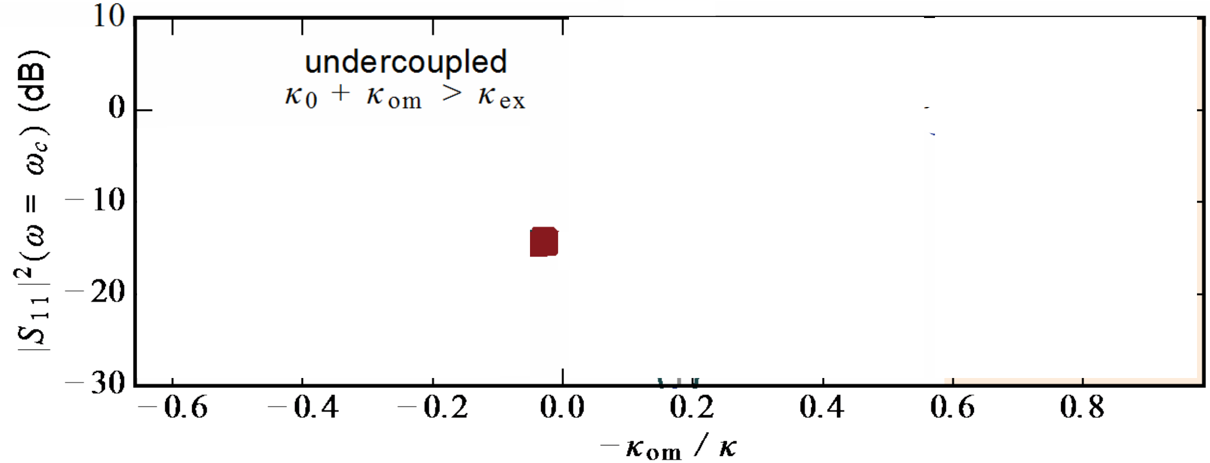


L. D. Tóth et al., arXiv:1602.05180, accepted to Nature Physics

(De)amplification by mechanical reservoir engineering

$$\Delta = -\Omega_m$$





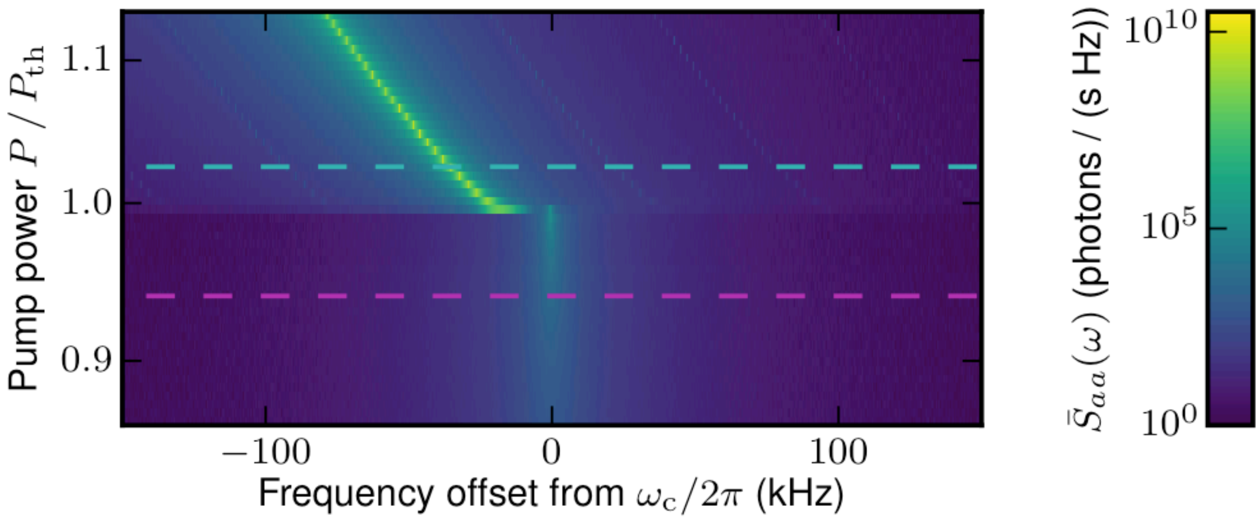
$$\kappa_{om} = \pm \mathcal{C}\kappa$$

$$S_{11}(\omega = \omega_c) = \frac{\kappa_0 - \kappa_{ex} + \kappa_{om}}{\kappa_0 + \kappa_{ex} + \kappa_{om}}$$

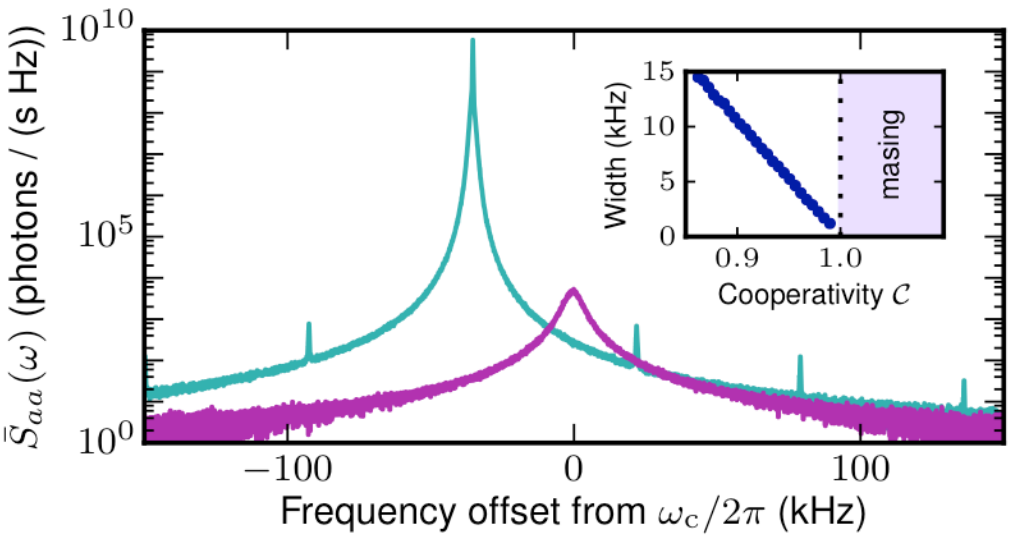
Demonstrates electromagnetic control over the *cavity damping rate*, via mechanical dissipative reservoir

L. D. Tóth et al., arXiv:1602.05180, accepted to Nature Physics

Maser using a mechanical dissipative reservoir



- Linewidth narrows as we increase pump power
- Above threshold, the noise turns into self-sustained oscillations in the cavity



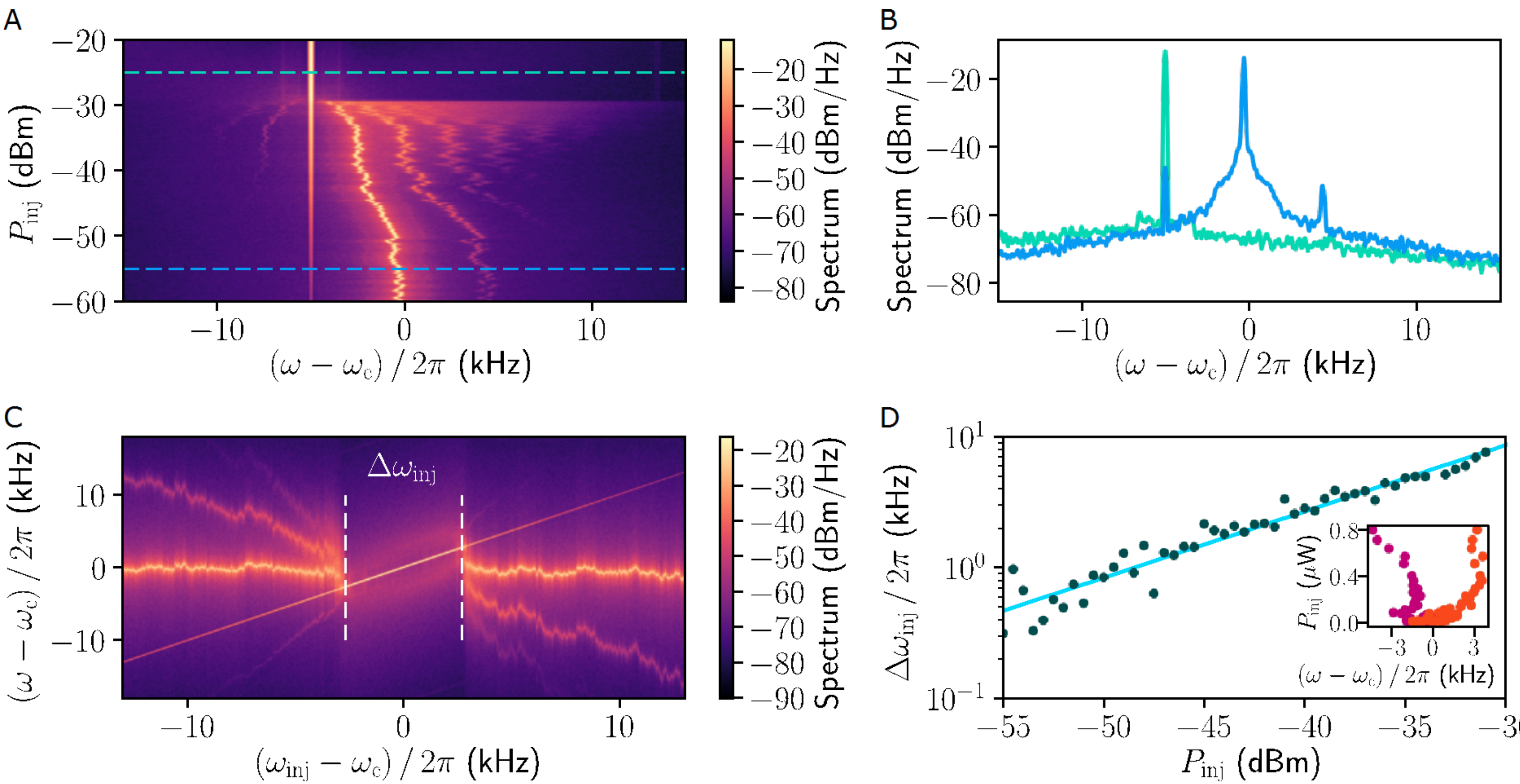
$$\bar{S}_{aa}(\omega) = \frac{1}{2} + \frac{\mathcal{C}\kappa_{\mathrm{ex}}\kappa(n_{\mathrm{eff}}+1)}{\left(\frac{\kappa_{\mathrm{eff}}}{2}\right)^2 + (\omega-\omega_{\mathrm{c}})^2}$$

$$\kappa_{\mathrm{eff}} = (1-\mathcal{C})\kappa$$

First observation of dynamical backaction on an *electromagnetic* mode

L. D. Tóth et al., arXiv:1602.05180, accepted to Nature Physics

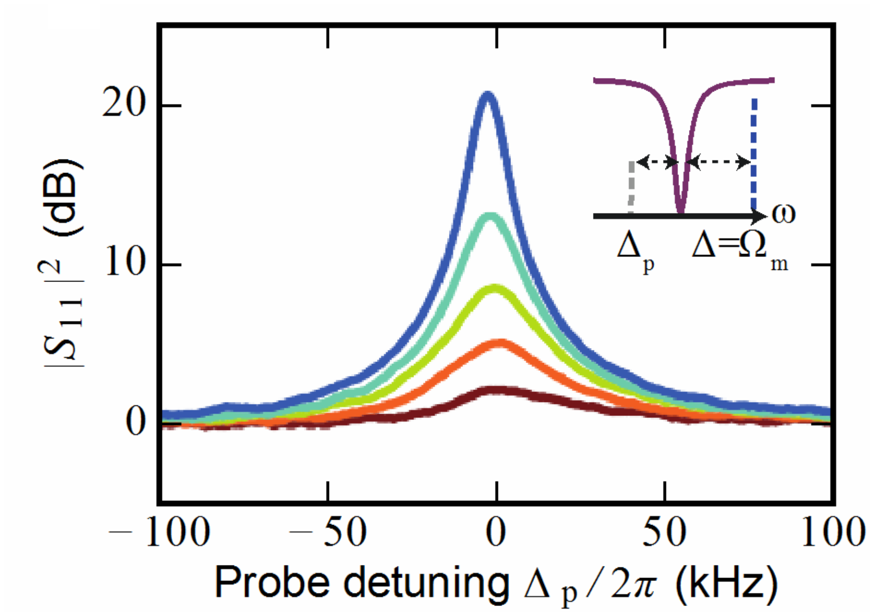
Injection locking

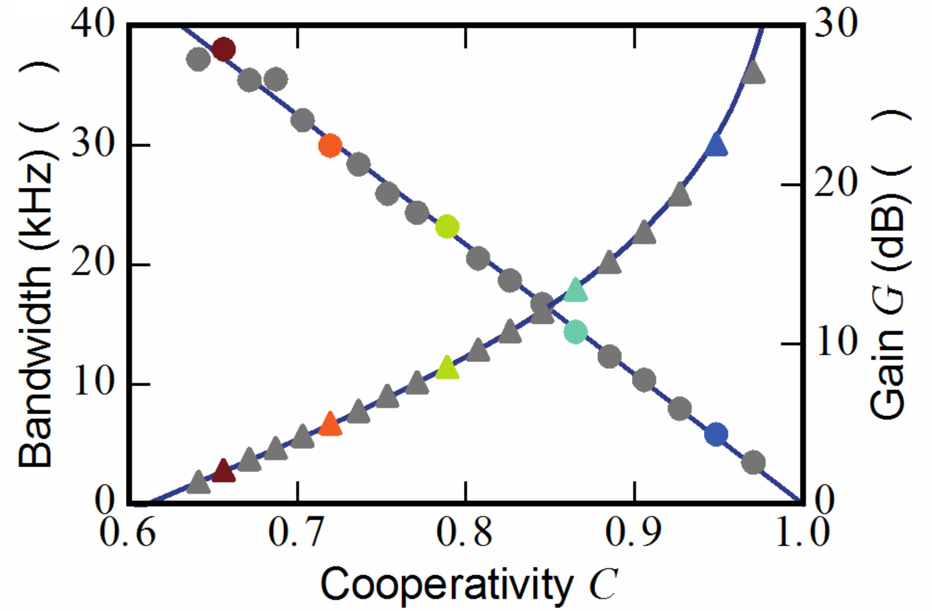


First maser with mechanical gain medium

R. Adler, Proceedings of the IRE 34, 351 (1946)
L. D. Tóth et al., *in preparation* (2017)

Amplification by mechanical reservoir engineering





$$\mathcal{G} = \left|S_{11}(\omega_c)\right|^2 = \left|\frac{\left(2\kappa_{ex}/\kappa - 1\right) + \mathcal{C}}{1-\mathcal{C}}\right|^2$$

$$\kappa_{eff} = (1-\mathcal{C})\kappa$$

L. D. Tóth et al., arXiv:1602.05180, accepted to Nature Physics

Noise added by the electromechanical amplifier (chip B)

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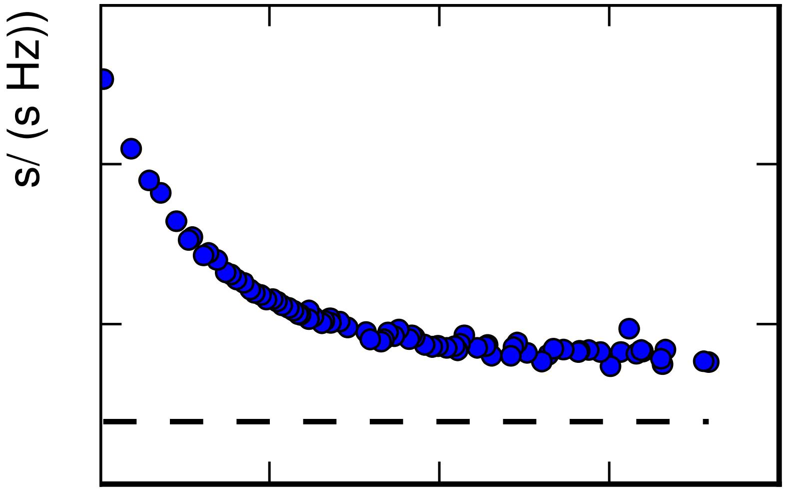
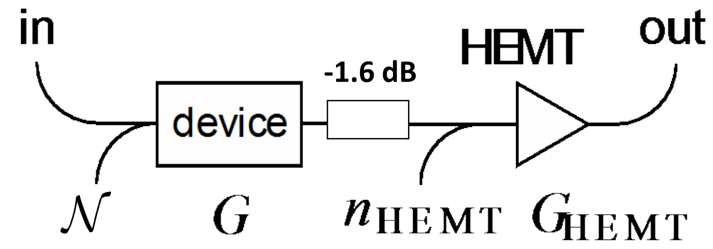




$$N = \alpha\mathcal{N} + n_{\mathrm{HEMT}} / \mathcal{G}$$

$$\mathcal{N}_{\mathrm{QL}} = \frac{1}{2} + \frac{\kappa_0}{\kappa_{ex}} \approx 0.81$$

$$\mathcal{N} = \frac{4\mathcal{C}\frac{\kappa_{\mathrm{ex}}}{\kappa}\left(n_{\mathrm{eff}} + \frac{1}{2}\right) + 4\frac{\kappa_{\mathrm{ex}}\kappa_0}{\kappa^2}\cdot\frac{1}{2}}{\left(\mathcal{C} - 1 + \frac{2\kappa_{\mathrm{ex}}}{\kappa}\right)^2}$$

The system noise is (2.07 ± 0.03) × QL

n_{HEMT} = 22.5 ± 0.25 quanta

n_{eff} ≈ 0.41 quanta

L. D. Tóth et al., arXiv:1602.05180, accepted to Nature Physics

Outline

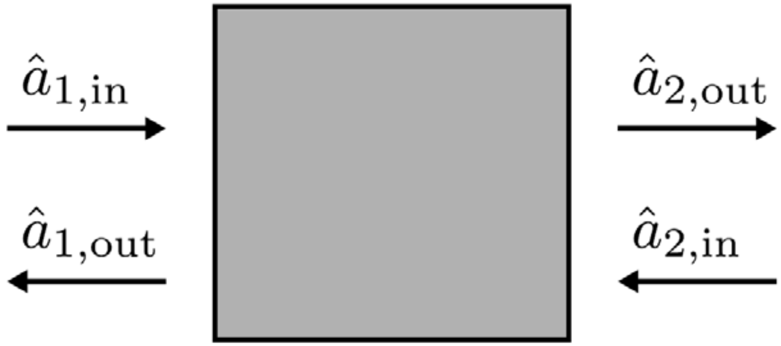
1. Progress on realization of coherent microwave-to-optical link

1. Microwave amplification in the reversed dissipation regime of cavity optomechanics

2. Nonreciprocal microwave optomechanical circuit

3. Wideband Josephson parametric amplifiers

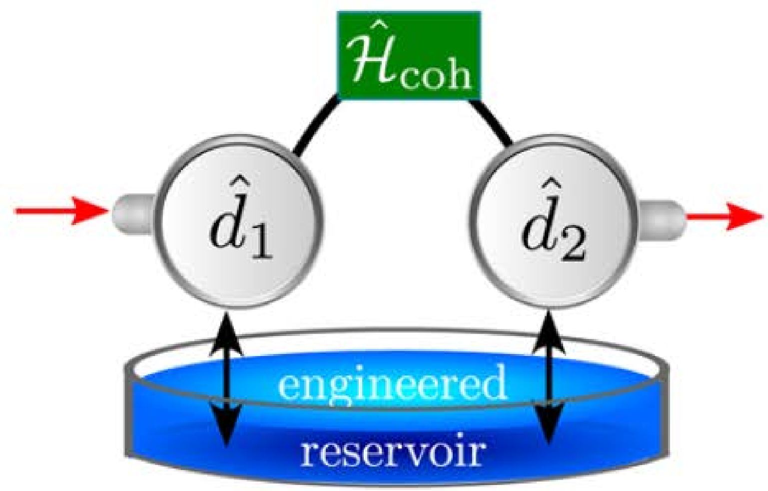
Nonreciprocal circuits



$$a_{i,\mathrm{out}} = S_{ij} a_{j,\mathrm{in}}$$

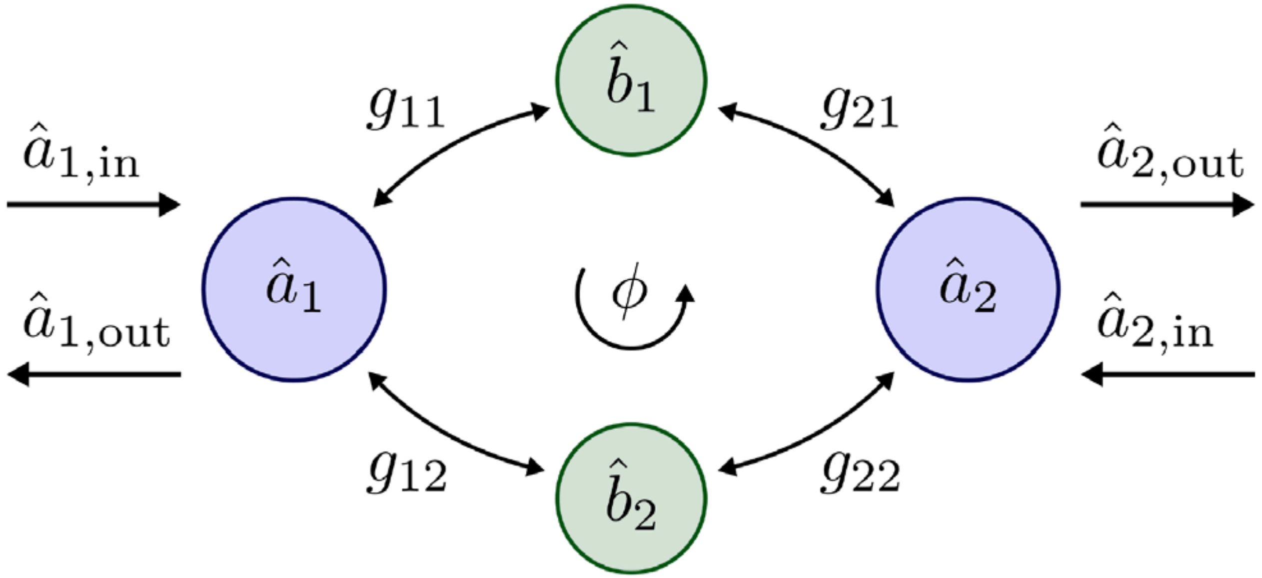
System is nonreciprocal if:

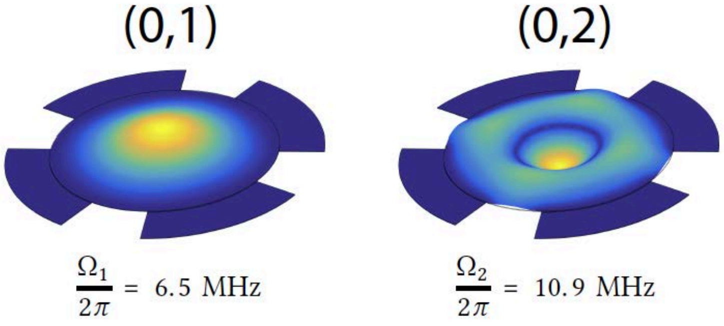
$$|S_{12}| \neq |S_{21}|$$



Ranzani & Aumentado, NJP 17, 023024 (2015)
Metelmann & Clerk, PRX 5, 021025 (2015)

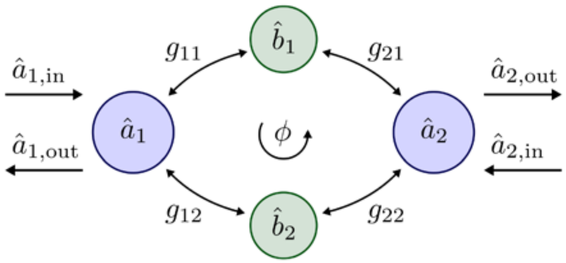
Nonreciprocity with purely optomechanical interaction





N. R. Bernier et al., arXiv:1612.08223

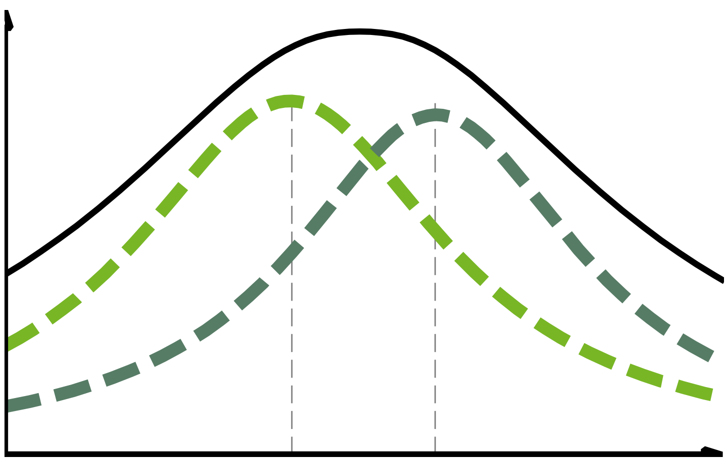
Theoretical description

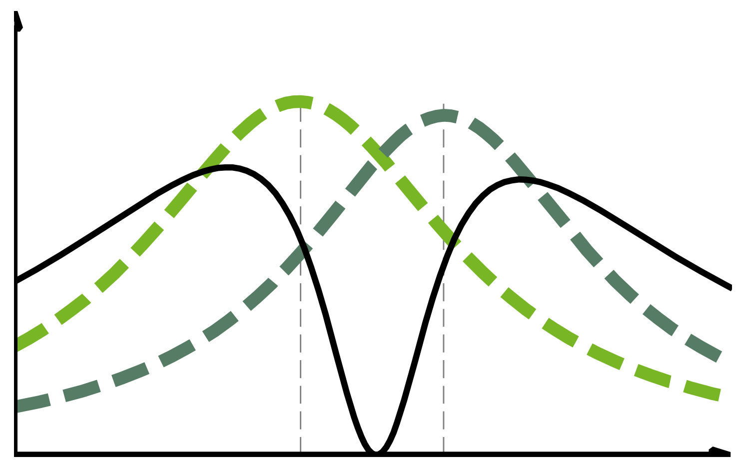


$$\frac{S_{12}(\omega)}{S_{21}(\omega)} = \frac{g_{11}\left(\frac{1}{\Gamma_1 - i2(\delta+\omega)}\right)g_{21} + g_{12}\left(\frac{1}{\Gamma_2 + i2(\delta-\omega)}\right)g_{22}e^{+i\phi}}{g_{11}\left(\frac{1}{\Gamma_1 - i2(\delta+\omega)}\right)g_{21} + g_{12}\left(\frac{1}{\Gamma_2 + i2(\delta-\omega)}\right)g_{22}e^{-i\phi}}$$

$$|S_{21}|^2_{\max} = \frac{\kappa_{\mathrm{ex},1}\kappa_{\mathrm{ex},2}}{\kappa_1\kappa_2}\left(1 - \frac{1}{2\mathcal{C}}\right)$$

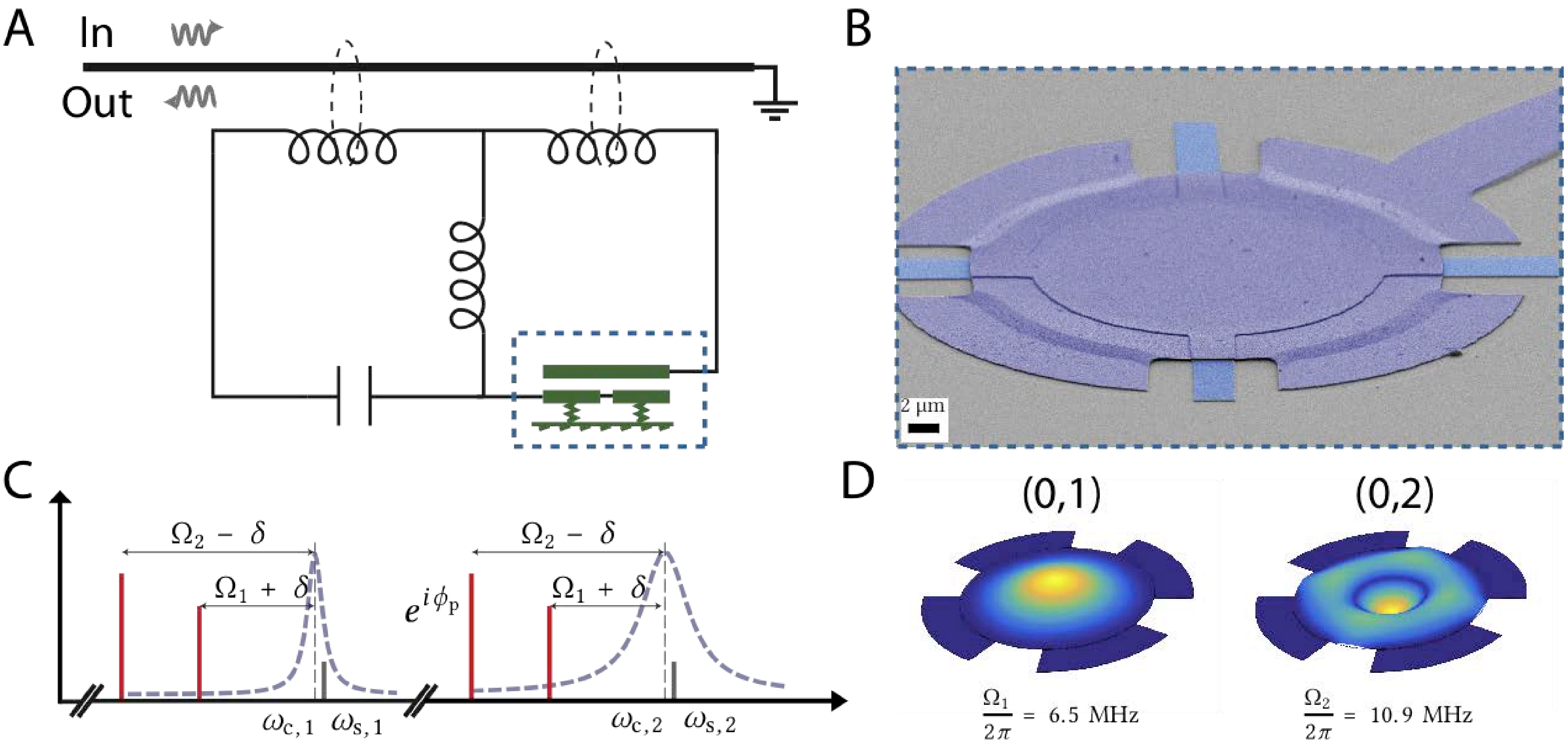
$$\frac{\Gamma}{2\delta} = \tan\frac{\phi}{2}$$





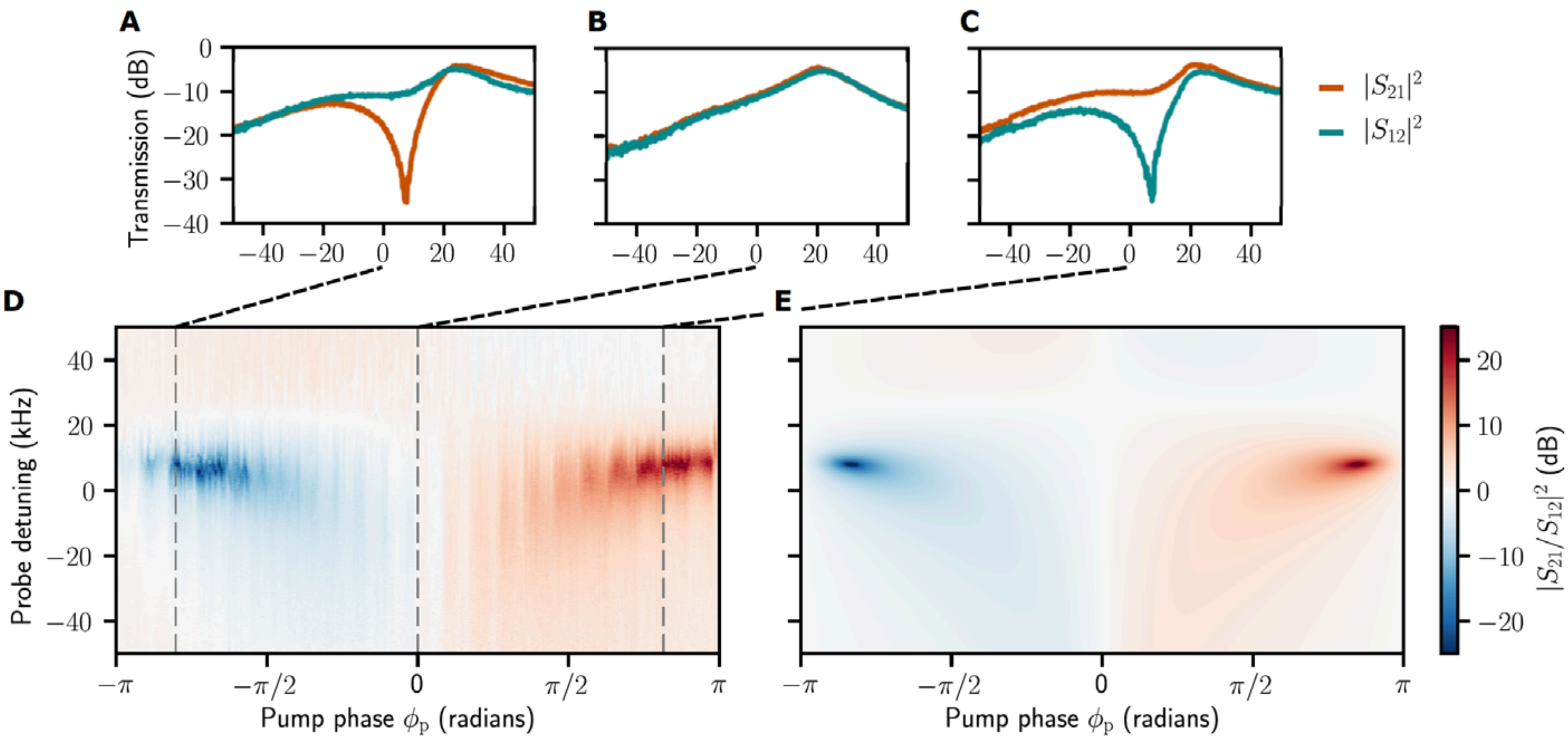
N. R. Bernier et al., arXiv:1612.08223

Circuit



N. R. Bernier et al., arXiv:1612.08223

Experimental results



Demonstrated reconfigurable optomechanical nonreciprocal circuit in microwave domain.

N. R. Bernier et al., arXiv:1612.08223

Summary

Coherent microwave-to-optical link

- Simulated direct microwave-to-optical converter using non-linear materials
- Suggested an architecture for a quantum converter using realistic parameters
- Developed a hybrid platform for integrated non-linear optical circuits
- Deliverable D1.2 *pending*

Electromechanics in the reversed dissipation regime

- Backaction on microwave light *via cold dissipative mechanical reservoir* (D1.3)
- Near-quantum-limited amplification of microwave field (D1.4)
- Maser action

- Reconfigurable nonreciprocal optomechanical circuit in microwave domain

Publications

1. A. Nunnenkamp et al., PRL 113, 023604 (2014)
2. C. Javerzac-Galy et al., PRA 94, 053815 (2016)
3. L. Chang et al., Optics Letters 42, 803 (2017)
4. L. D. Tóth et al., arXiv:1602.05180, accepted to Nature Physics
5. N. R. Bernier et al., arXiv:1612.08223

Outline

1. Progress on realization of coherent microwave-to-optical link

1. Microwave amplification in the reversed dissipation regime of cavity optomechanics

2. Nonreciprocal microwave optomechanical circuit

3. Wideband Josephson parametric amplifiers

Thank you for your attention

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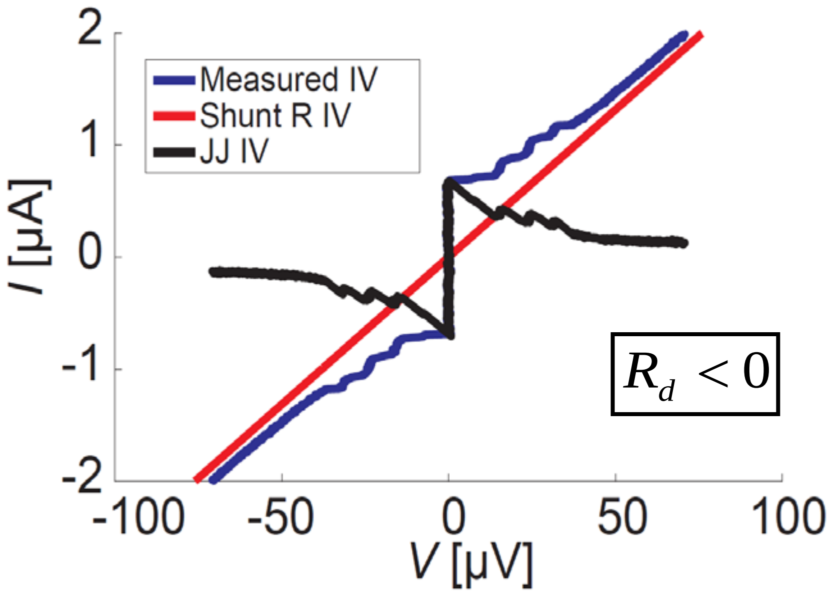
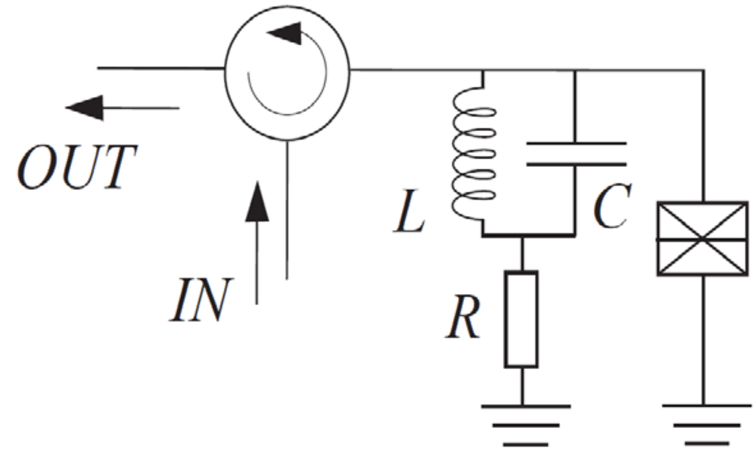
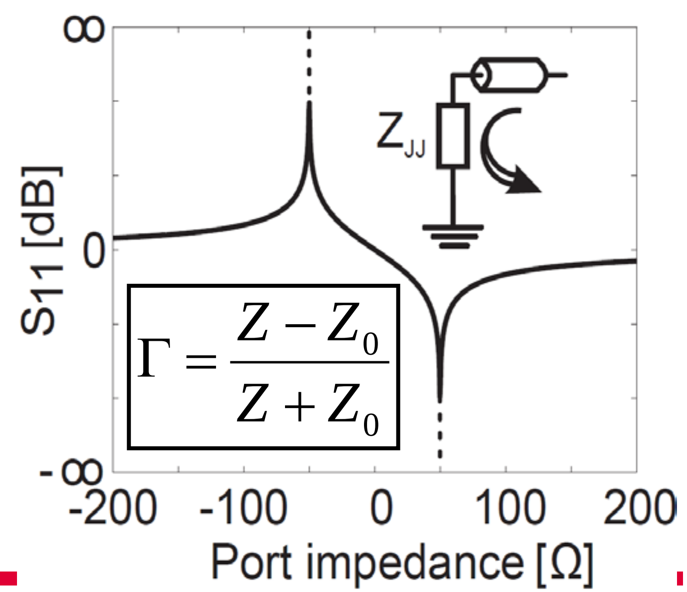
Original idea: wide-band single JJ Amplifier



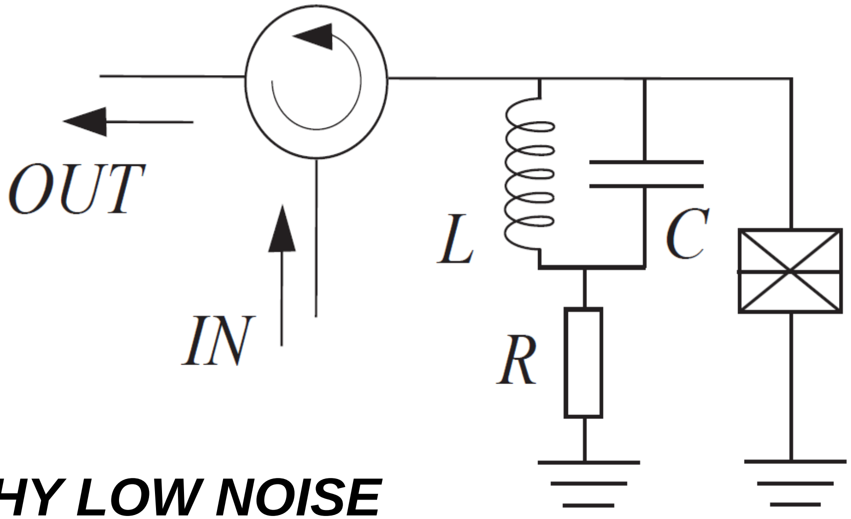


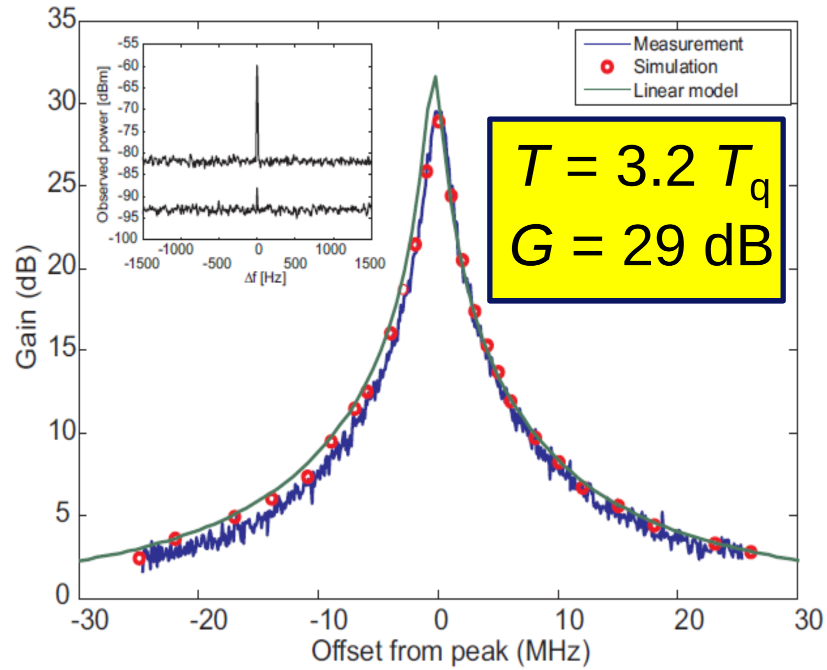
- Based on ***intrinsic negative resistance*** of a voltage biased Josephson junction.

- ***Damping*** for stable operation by
  1) frequency dependent shunt
  2) load impedance



Single Josephson Junction Amplifier (JPA I)





WHY LOW NOISE

- Direct noise coupling prevented by band stop filter

- ***Quantum noise*** from the Josephson frequency ***mixed down to the signal frequencies***

$$S_I(\omega) = \frac{I_C^2 S_I(\omega_J)}{2I^2}$$

Low I_c → *Low noise*

- Equally good as the best SQUID amplifiers

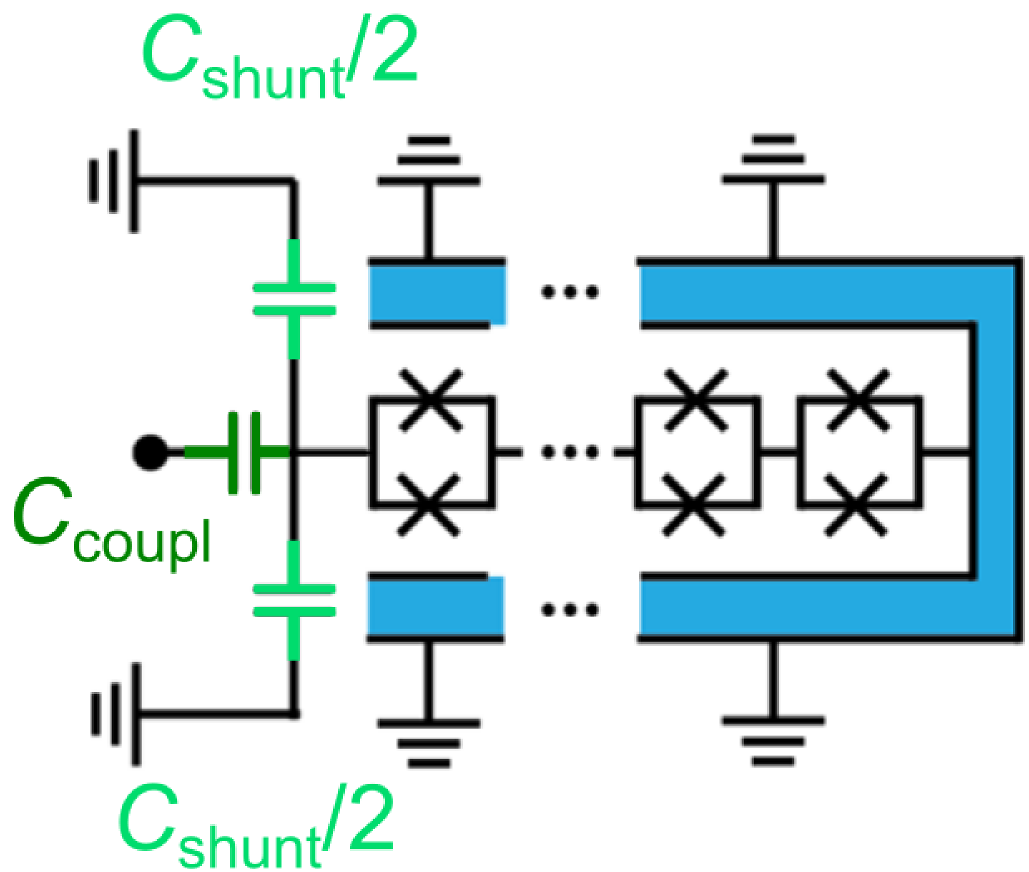
- No need for a high *f* pump generator as in parametric amplifiers

- ***Wide band operation unstable in practice***

P. Lähteenmäki, V. Vesterinen, J. Hassel, H. Seppä, and P. Hakonen, Scientific Reports **2**, 276 (2012).

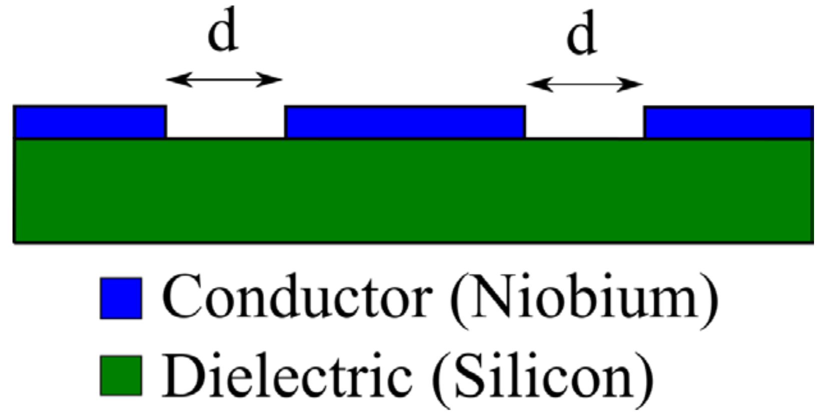
SQUID-array amplifiers (generation JPA II)

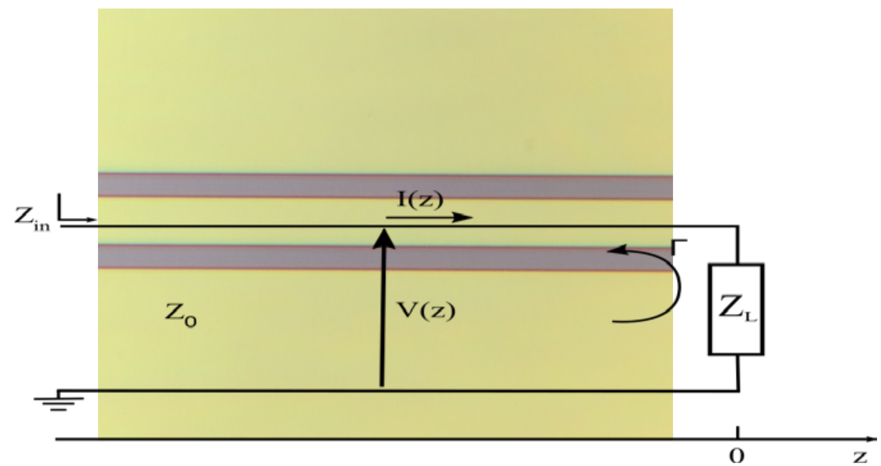
- Chain of SQUIDs embedded inside a resonator
- Resonance frequency tuned with magnetic flux generated with on-chip flux lines
- Number of SQUIDs: 1-255
- Noise temperature $\hbar\omega ... 2\hbar\omega$
- Resonance frequency $f(T)$
- Dissipation due to two level systems (TLS) in SiO_2



Optimization of materials for JPA amplifiers

- Transmission line resonators used to investigate material losses
- A piece of transmission line = resonator
- Larger resonator quality factor *Q* => longer photon lifetime => less losses
- Deposit material on top of the resonator & calculate capacitive participation ratio using SONNET circuit simulator





TLS-theory

- Two level systems (TLS) in dielectrics react resonantly to the electric field of the applied signal
- Relaxation effects caused by phonons minimal at microwave frequencies (~1 GHz) and millikelvin temperatures
- Resonant frequency shift vs temperature:

$$\frac{f_r(T)-f_r(0)}{f_r(0)}=\frac{F\delta_0}{\pi}\mathrm{Re}\left\{\Psi\left(\frac{1}{2}+\frac{\hbar\omega}{2\pi k_B T}\right)-\log\left(\frac{\hbar\omega}{2\pi k_B T}\right)\right\}$$

where F is the participation ratio, δ_0 the loss tangent at weak field and low temperature, and Ψ the Digamma function

TLS-theory, continued

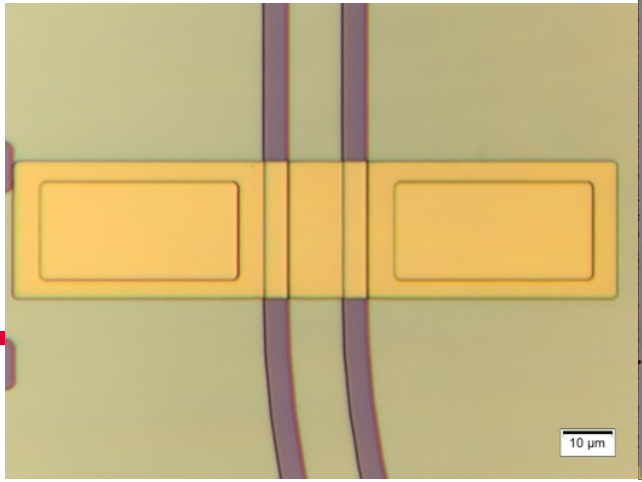
- The loss tangent δ_0 is linked to resonator internal quality factors:

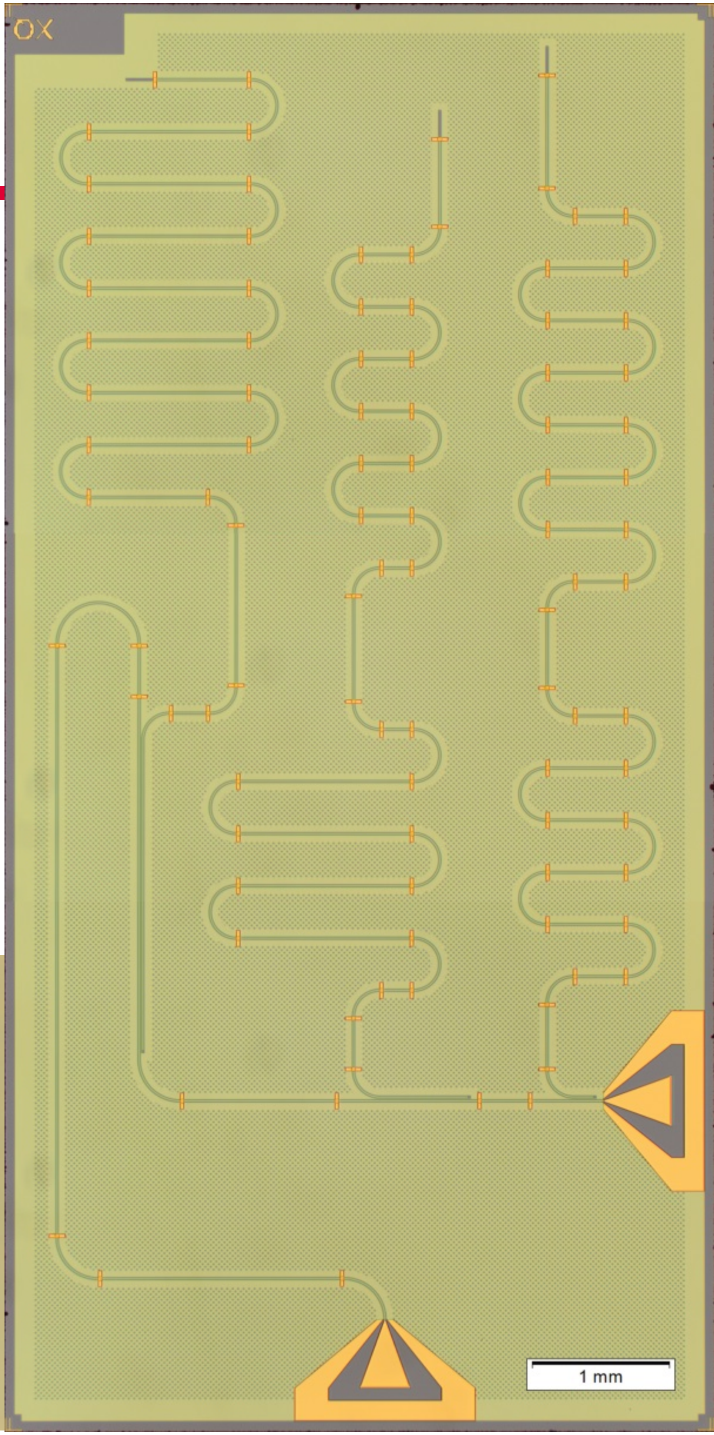
$$\frac{1}{Q_i} = F\delta_0 \frac{\tanh\left(\frac{\hbar\omega}{2\pi k_B T}\right)}{\sqrt{1+\left(\frac{E}{E_c}\right)^2}}$$

- The above formula can be used to determine the loss tangents from quality factors measured over a wide range of powers at a fixed temperature

Resonator chip design

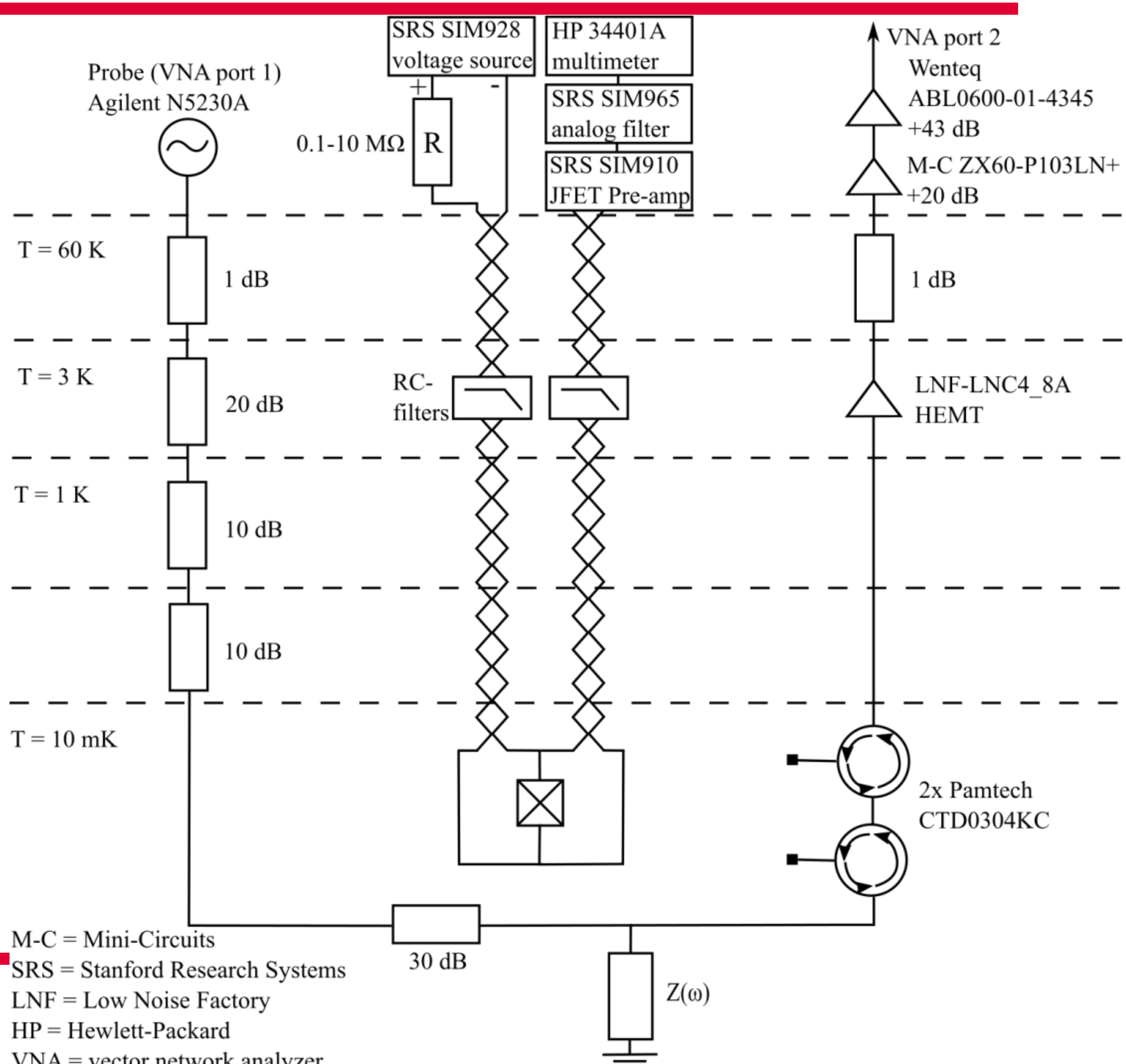
- A second niobium layer (yellow) covers the oxide on top of the first niobium (green)
- Three resonators with varying coupling connected to a feedline
- The multi-layer bridges connect the ground plane on both sides to guarantee equipotential





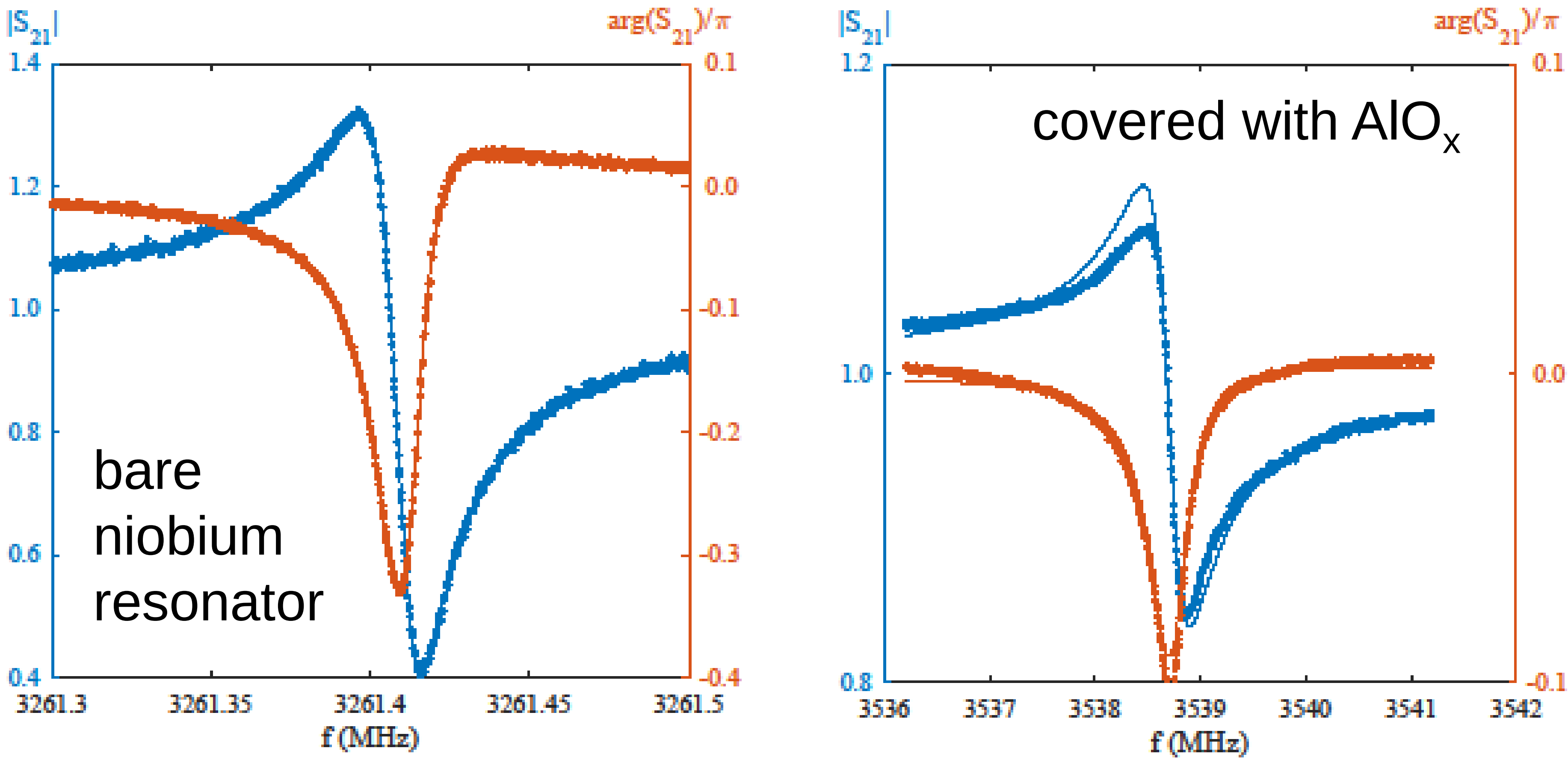
Measurement setup

- Transmission measurement
- The impedance mismatch $Z(\omega)$ of the resonators reflects some of the incident power and absorbs, dissipates, and radiates some of it.
- Resonator response: output power reduced at the resonance frequencies

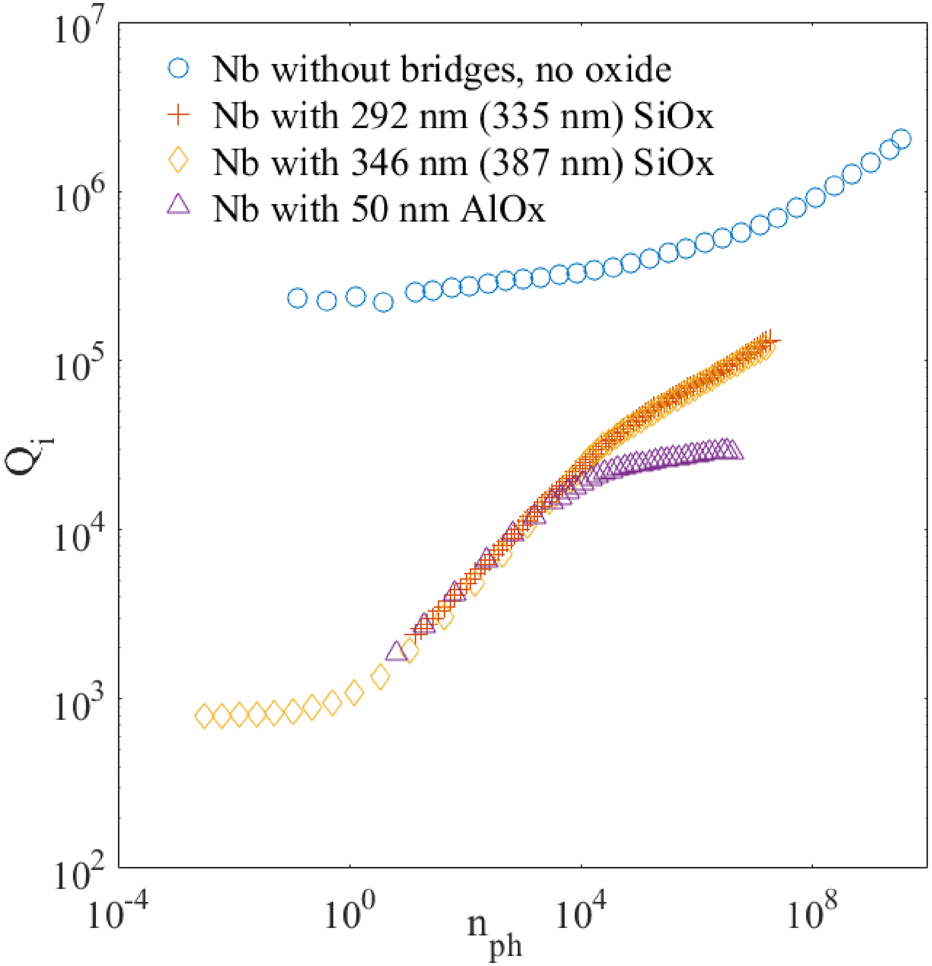


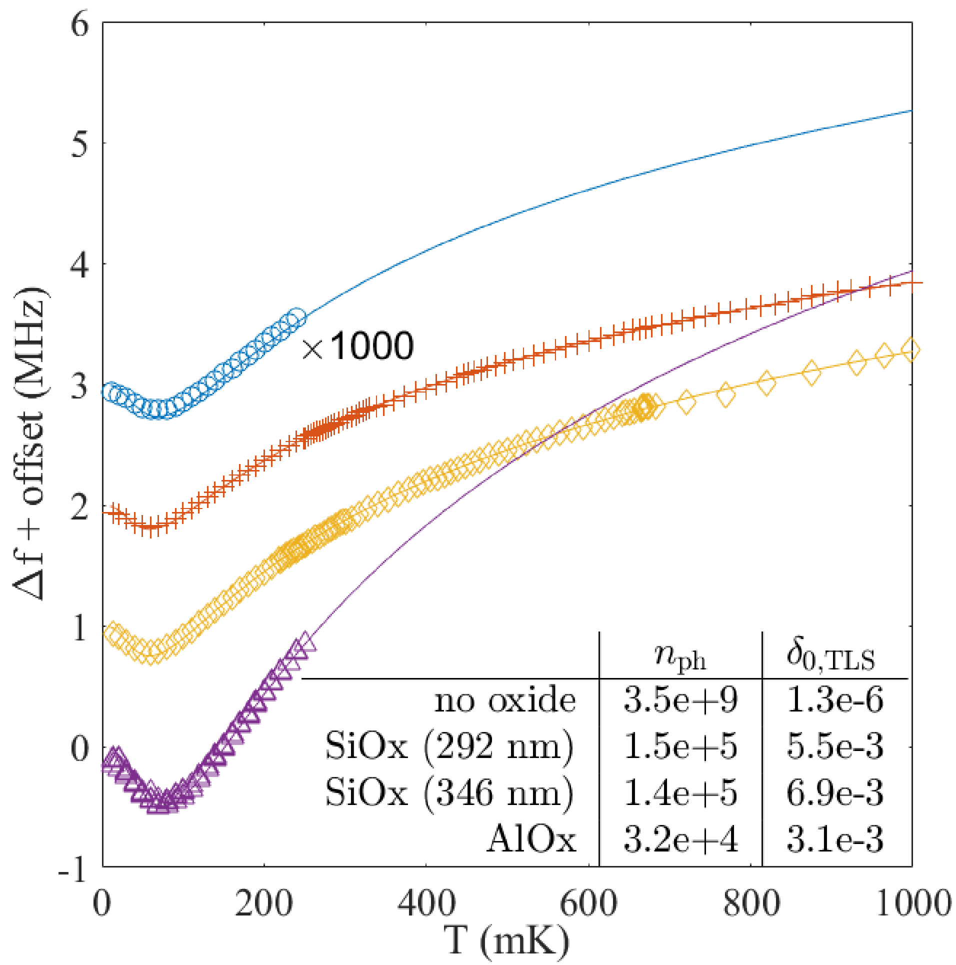
M-C = Mini-Circuits
SRS = Stanford Research Systems
LNF = Low Noise Factory
HP = Hewlett-Packard
VNA = vector network analyzer

Transmission data for quality factor estimates



Loss analysis

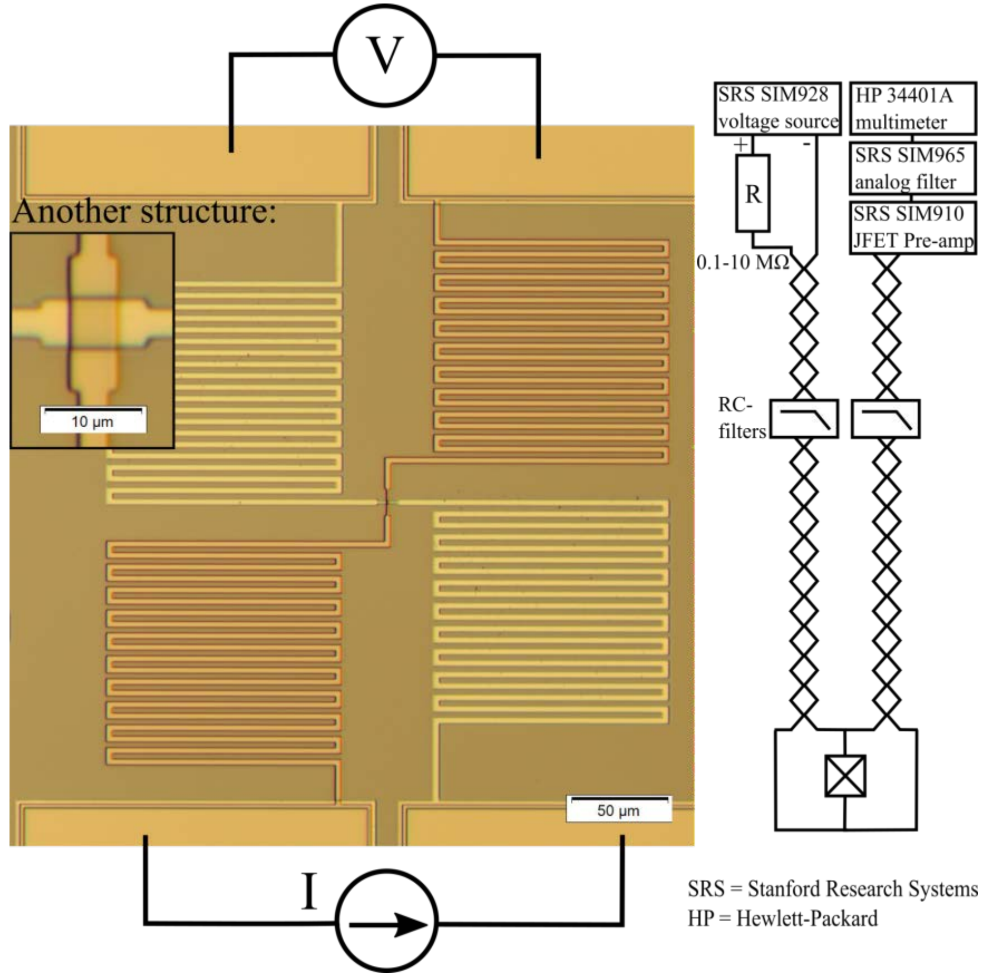




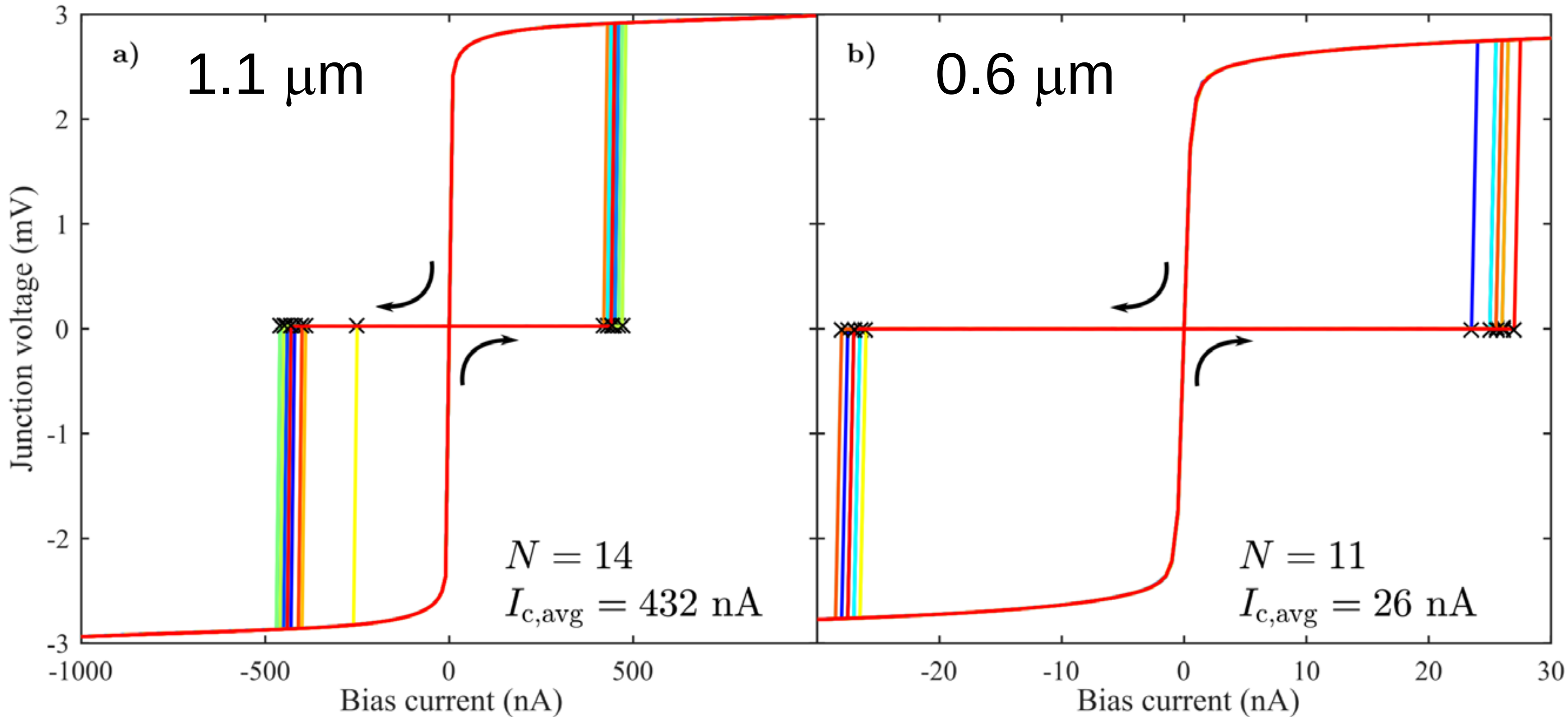
	n_{ph}	$\delta_{0,TLS}$
no oxide	3.5e+9	1.3e-6
SiOx (292 nm)	1.5e+5	5.5e-3
SiOx (346 nm)	1.4e+5	6.9e-3
AlOx	3.2e+4	3.1e-3

Testing of new CLIP junctions

- New junction process developed, CLIP = cross-layer patterning
- Based on standard tri-layer structure (Nb/Al-AlOx/Nb)
- Dielectric deposited only over the crossing points of two layers
- Contacts in one layer => number of SQUIDs even



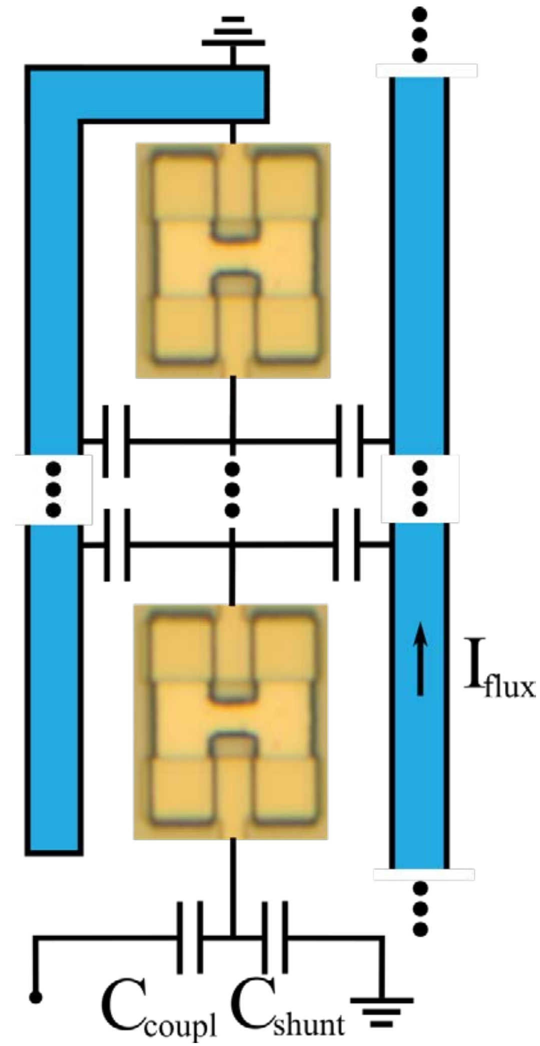
IV curves for CLIP-junctions



- Upsweeps take the lower path and downsweeps the upper path
- IV with gap behaviour and critical current density close to the target of 100 A/cm^2 => should work for a JPA

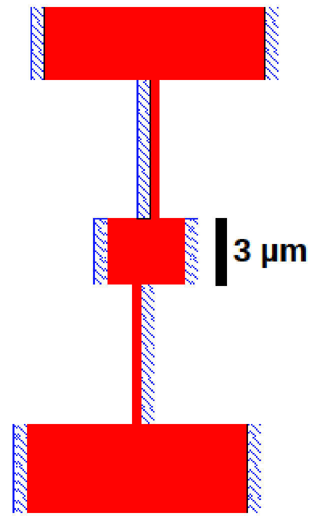
New generation JPA III

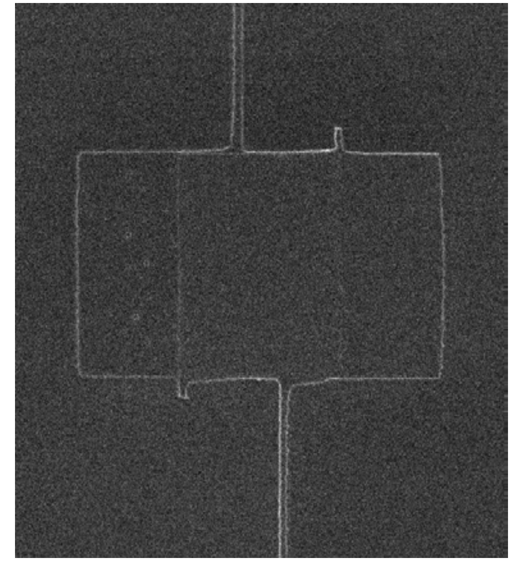
- 200 SQUIDs in series, lumped design (again) with shunt capacitances
- Structure designed without a lossy oxide layer, the other outer conductor acts as the flux line
- Single SQUID devices on the same chip
  - broadband external matching
- Traveling wave JPAs on the same chip
- Severe delays due to difficulties with ALD oxide

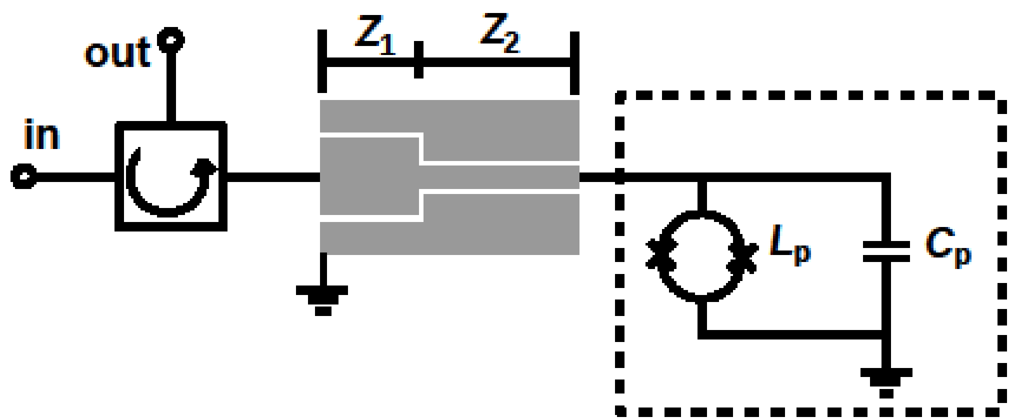


Impedance matched JPAs with Al junctions

- Started because of delays at VTT
- E-beam lithography
  - Junction area $\sim 10\ \mu\mathrm{m}^2$
  - Bridgeless shadow evaporation technique
- Integration possibilities
- First devices tested

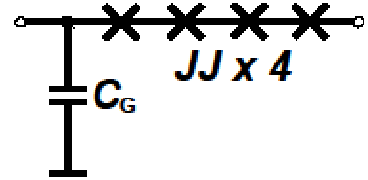


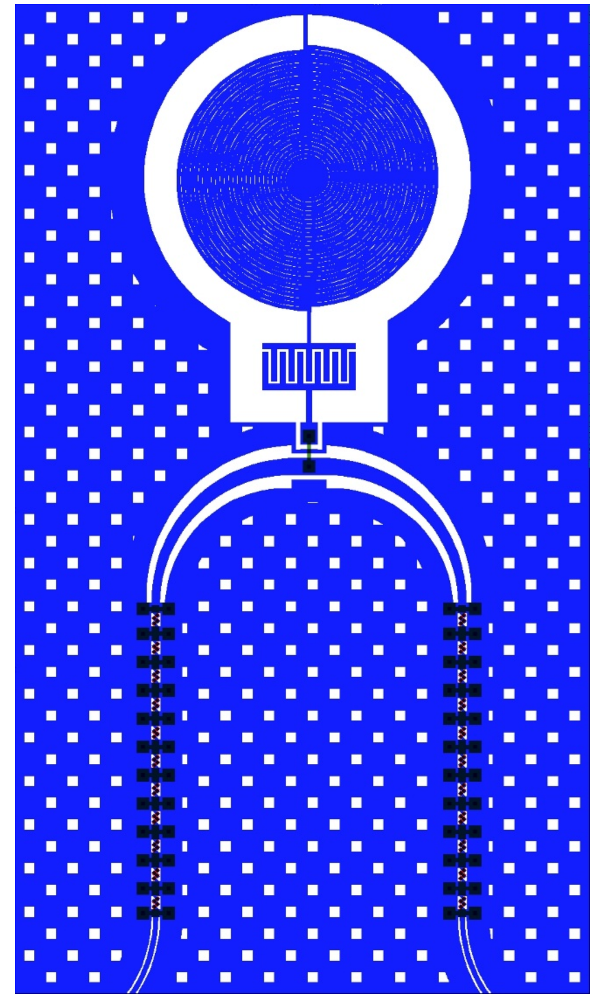




Traveling wave parametric amplifier

- Lumped element transmission line
  - Josephson inductance
  - Parallel plate capacitors
  - 1848 JJs in total
- Really wide bandwidth: up to several GHz
- ’Traveling’ pump tone
  - Nonlinearity causes distortion in pump tone
  - Compensated by λ/4 resonators
    - Phase shift at pump frequency
    - Signal and idler frequencíes left intact





Conclusions

- Resonator characterizations => proof that low quality factors and excess noise in previous JPAs because of TLSs in silicon dioxide
- ALD aluminium oxide slightly better than SiOx
- Demonstrated the applicability of the niobium CLIP-process in the facilities of VTT
- Constructed ”lumped” JPAs
  - basic characterization done
  - first amplifiers tested in the four wave mixing mode
- Full RF testing with 2ω pumping in the near future

Deliverable 1.4 pending