### Detailed program for ITN Workshop in Diavolezza, 01-05. February 2015

#### Wednesday 04.02.2015

<table>
<thead>
<tr>
<th>Time</th>
<th>Speaker's name</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>0:00</td>
<td>Breakfast</td>
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</tr>
<tr>
<td>8:30-9:00</td>
<td>Raphael Van Laer (UGent)</td>
<td>Brillouin scattering and optomechanics in silicon photonic wires</td>
</tr>
<tr>
<td>9:10-10:00</td>
<td>Dries Van Thourhout, Paul Tiebot, Jesper Halatsion (UGent)</td>
<td>New integrated platforms for optomechanics</td>
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<tr>
<td>10:00-10:30</td>
<td>Coffee break</td>
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<tr>
<td>10:30-10:50</td>
<td>Paul S coder (IBM)</td>
<td>Nanophotonics at IBM Research</td>
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<tr>
<td>11:00-11:30</td>
<td>Katharina Schneider (IBM)</td>
<td>Optomechanics with a slotted photonic crystal nanobeam cavity</td>
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<tr>
<td>11:40-12:00</td>
<td>Ilia Koren (IBM)</td>
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<tr>
<td>12:10-12:30</td>
<td>Amir Ghadimi (EPFL)</td>
<td>Localizing the vibrational mode of a nanomechanical beam</td>
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<tr>
<td>12:30</td>
<td>Lunch</td>
<td></td>
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<tr>
<td>18:30</td>
<td>Dinner</td>
<td></td>
</tr>
<tr>
<td>19:45-20:30</td>
<td>Florian Marquardt (FAU)</td>
<td>Topological phases in optomechanics</td>
</tr>
<tr>
<td>20:45-21:15</td>
<td>Stefan Walter (FAU)</td>
<td>Synchronization in the quantum regime</td>
</tr>
<tr>
<td>21:20-22:00</td>
<td>Talitha Weiss (FAU)</td>
<td>Quantum synchronization of two optomechanical systems</td>
</tr>
<tr>
<td>22:00-22:30</td>
<td>Xufeng Song (Aalto)</td>
<td>Graphene optomechanics at microwave frequencies</td>
</tr>
</tbody>
</table>
Light and sound couple in a feedback loop

“Stimulated Brillouin scattering (SBS)"

Gain

Frequency

Stokes seed

Acoustic wave

A Brillouin waveguide

No cavity!

Pump photon annihilated

Stokes photon created

Phonon created

Pump field

Optical forces

Stokes seed

Scattering

Pump photon annihilated

Stokes seed

Frequency

10 GHz

Sound is the gateway to a slow timescale

Tunable delay

Data Storage

Write pulse

Read pulse

Acoustic wave


Spectral purification

Pump (MHz)

Frequency (Hz)


Microwave synthesis

Pump


Overview

Brillouin scattering in silicon nanowires
Recent experimental demonstration

Brillouin scattering vs. cavity optomechanics
Transition from Brillouin waveguide to dispersive optomechanical cavity

Prospects
From silicon photonics to silicon phononics
Distinguish between localized and propagating acoustic phonons

Backward
High-group-velocity phonons

Stokes \rightarrow \text{Phonon} \rightarrow \text{Pump} \rightarrow \text{K}_p

Forward
Low-group-velocity phonons

Stokes \rightarrow \text{Phonon} \rightarrow \text{Pump} \rightarrow \text{K}_p

Forward scattering is dominant in silicon wires, unlike in conventional silica fibers

Brillouin scattering was unexplored territory in silicon nanowires

Suspended silicon nanowire

Strong nonlinearity
Predicted gain up to 10 dB/(mW cm)

Reasonably fast response
In the microwave domain

Tailorable properties
Phononic resonance depends heavily on waveguide geometry

Confining not only light, but also sound

The historical development of SBS

1920: First predictions
1964: First observation of SBS in quartz & sapphire
1970: Optical fibres
1976: First Brillouin laser ("reversed regime")
2006: Photonic crystal fibres
2010: Crystalline WGM resonators
2011: Chalcogenide rib waveguides
2012: Silica wedge disks
2013: Silicon nitride/silicon waveguide
2014: Silicon nanowires
Confining not only light, but also sound

Light confined by TIR
Total Internal Reflection because light moves faster in all surrounding materials

Sound not confined
No TIR because sound moves slower in all surrounding materials

Confining not only light, but also sound

Light confined by TIR
Total Internal Reflection because light moves faster in all surrounding materials

Sound confined by impedance mismatch
Z = mass density x speed

Confining not only light, but also sound

Light confined by TIR
Total Internal Reflection because light moves faster in all surrounding materials

Sound not confined
No TIR because sound moves slower in all surrounding materials

Remove the silicon dioxide
How to make it long?
The wire is a Fabry-Pérot cavity for sound

Also make it long: put the wire on a pillar

Middle road between minimal phonon leakage and a centimeter-scale interaction length

The phonons leak through the pillar

First demonstration of SBS in nanowire
Both electrostriction and radiation pressure drive the acoustic wave.

We also observed backward SBS.

\[
\text{Stokes seed} \rightarrow \text{Acoustic wave} \rightarrow \text{Electrostriction} \rightarrow \text{Moving boundary} \rightarrow \text{Strained bulk}
\]

\[
\frac{2\pi \text{ang}}{Q_m} = 0.37 \text{ W}^{-1}\text{m}^{-1} \\
Q_m = 971
\]

\[
\text{Stokes seed} \rightarrow \text{Scattering} \rightarrow \text{Electrostriction} \rightarrow \text{Moving boundary} \rightarrow \text{Strained bulk}
\]
Photon-phonon coupling huge in silicon wires

<table>
<thead>
<tr>
<th>Efficiency (m$^{-2}$ W$^{-1}$)</th>
<th>Coupling (m$^{-2}$ W$^{-1}$)</th>
<th>Loss (dB/cm)</th>
<th>Gain (dB/cm)</th>
<th>Gain (dB/mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8</td>
<td>0.8</td>
<td>2 x 10$^6$</td>
<td>3.5 x 10$^{-2}$</td>
<td>3</td>
</tr>
<tr>
<td>@ 10.8 GHz</td>
<td>Q = 540</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>1.5</td>
<td>7 x 10$^4$</td>
<td>3.2 x 10$^{-2}$</td>
<td>0.3</td>
</tr>
<tr>
<td>@ 1.8 GHz</td>
<td>Q = 122</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>304</td>
<td>1344</td>
<td>0.2</td>
<td>3.9</td>
<td>0.05</td>
</tr>
<tr>
<td>@ 7.7 GHz</td>
<td>Q = 226</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2328</td>
<td>1327</td>
<td>7</td>
<td>0.8</td>
<td>0.02</td>
</tr>
<tr>
<td>@ 1.3 GHz</td>
<td>Q = 1750</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3136</td>
<td>10344</td>
<td>2.6</td>
<td>2.3</td>
<td>0.1</td>
</tr>
<tr>
<td>@ 9.2 GHz</td>
<td>Q = 330</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

There is room for improvement by orders of magnitude

- Decrease optical losses
  Currently 2.6 dB/cm, lowest 0.7 dB/cm

- Increase efficiency
  Better phononic Q or light-sound overlap

Van Leeu et al. "Interaction between light and highly confined hypersonic in a silicon phononic nanowires" Nature Photon. (accepted)
Overview

Brillouin scattering in silicon nanowires
Recent experimental demonstration

Brillouin scattering vs. cavity optomechanics
Transition from Brillouin waveguide to dispersive optomechanical cavity

Prospects
From silicon photonics to silicon phononics

Different historical traditions

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<tr>
<td>Electrostriction/Strained bulk</td>
<td>Radiation pressure/Moving boundary</td>
</tr>
<tr>
<td>Optical response modified $\Gamma_{\text{in}} \gg \kappa$</td>
<td>Mechanical response modified $\kappa \gg \Gamma_{\text{in}}$</td>
</tr>
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</table>

Link?

\[ g_0^2 = \frac{v_s v_p}{4L} \left( \frac{G_{\text{SBS}}}{Q_m} \right) \]

$G_{\text{SBS}}$ (W/m$^2$)

$g_0$ (Hz)

Cavity optomechanics
### Silica microspheres

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### Silica fibers

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### Silicon nanowires

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### Microtoroids

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Neglecting phonon propagation

\[ \frac{\partial \rho}{\partial t} + v_m \frac{\partial \rho}{\partial z} = -i \kappa \omega_m a_p a_s^* - \chi_m^{-1} \rho \]

Phonons don’t get far

Even high-group-velocity phonons \( \alpha_m^{-1} = \frac{v_m}{c_m} \approx 10 \mu \text{m} \)

Otherwise reduced SBS

Wolff, arXiv (2014)

In steady-state: Brillouin gain

\[ b = -i \kappa \omega_m \chi_m a_p a_s^* \]

\[ \frac{\partial a_s}{\partial z} = \frac{G_{\text{SBS}} p_p - \alpha_s a_s}{2} \]

\[ G_{\text{SBS}} = \frac{4}{\Gamma_m} \kappa \omega_m \kappa \omega_m \]

Acoustic slave wave

Fully determined by beat note

Gain on Stokes wave

Exponential build-up

\[ \frac{1}{v_p} \frac{\partial a_p}{\partial t} + \frac{\partial a_p}{\partial z} = -i \kappa \omega_m a_p a_s^* - \frac{\alpha_p}{2} a_p \]

\[ \frac{1}{v_b} \frac{\partial b}{\partial t} + \frac{\partial b}{\partial z} = -i \kappa \omega_m a_p a_s^* - \chi_m^{-1} b \]

\[ \chi_m^{-1} = \frac{\Gamma_p}{v_p} + i \Delta_m \]
Transition from waveguide to cavity

Mean fields
Average over roundtrip
\[ \overline{a}(t) = \frac{1}{L} \int_0^L a(z, t) \, dz \]

Boundary condition
The fields feed back into themselves

High-finesse limit
Mean-field approximation

\[ \hat{a} = -\left( \frac{\kappa}{2} + i \Delta \right) \overline{a} + v_g \sqrt{T} \zeta + \sqrt{\kappa_c} \sigma \]

\[ \kappa_c = \frac{\alpha}{2} \]

\[ \Delta = \frac{\omega - \omega_s}{2} \]

\[ T = \frac{1}{v_g} \]

Transition from waveguide to cavity

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\[ \kappa_c = \frac{\alpha}{2} \]

\[ \Delta = \frac{\omega - \omega_s}{2} \]

\[ T = \frac{1}{v_g} \]
**Link to the usual Hamiltonian**

\[
\hat{H}_{\text{int}}^{(\text{int})} = -i g \left( \hat{\delta} + \hat{\delta}^* \right) \left( \hat{b} + \hat{b}^* \right)
\]

\[
\hat{a}_\alpha = -\chi_\alpha^{-1} a \alpha - i \kappa_{\text{exciton}} a \alpha b^* + \sqrt{\kappa_{\text{exciton}}} a \alpha
\]

\[
\hat{b}_\alpha = -\chi_\alpha^{-1} b \alpha - i \kappa_{\text{exciton}} a \alpha b + \sqrt{\kappa_{\text{exciton}}} a \alpha
\]

Undepleted pump

\[
\delta \hat{a} = \delta a \exp(it)
\]

\[
\delta \hat{b} = \delta b \exp(it)
\]

Rotating-wave approximation

\[
\hat{a}_\alpha = \hat{a}_\alpha \exp(it)
\]

\[
\hat{b}_\alpha = \hat{b}_\alpha \exp(it)
\]

**Transition from waveguide to cavity**

\[
1 \frac{\partial a}{v_g \partial t} + \frac{\partial a}{\partial z} = \zeta - \frac{\alpha}{2} t
\]

Boundary condition

Mean fields
Average over roundtrip

\[
\bar{a}(t) = \frac{1}{L} \int_0^L a(z,t) dz
\]

\[
\alpha(L,t) = \alpha(0,t) \approx \left( \frac{\alpha + \mu}{2} + i\delta \right) a(t) - \sqrt{\mu} a(t)
\]

\[
\bar{a}(t) = -\left( \frac{\kappa}{2} + i\Delta \right) a + v_g \sqrt{\Gamma} \int_0^L a(z,t) dz + \sqrt{\kappa_a} a(z)
\]

Mean-field approximation

High-finesse limit

**Lasing vs. sasing**

\[
\gamma_a = \frac{1}{2} \left\{ \chi_a^{-1} - \chi_a^{-2} \right\} \pm \sqrt{\left( \chi_a^{-1} - \chi_a^{-2} \right)^2 + 4g^2}
\]

**Transition from waveguide to cavity**

\[
1 \frac{\partial a}{v_g \partial t} + \frac{\partial a}{\partial z} = \zeta - \frac{\alpha}{2} t
\]

\[
\frac{\partial b}{\partial t} = -i \kappa_{\text{exciton}} \omega b - \chi_a^{-1} b
\]

\[
\begin{align*}
\alpha_\alpha &= -\chi_\alpha^{-1} a \alpha - i \kappa_{\text{exciton}} a \alpha b^* + \sqrt{\kappa_{\text{exciton}}} a \alpha \\
\alpha_\beta &= -\chi_\beta^{-1} a \beta - i \kappa_{\text{exciton}} a \beta b + \sqrt{\kappa_{\text{exciton}}} a \beta \\
b_\alpha &= -\chi_\alpha^{-1} b \alpha - i \kappa_{\text{exciton}} a \alpha b + \sqrt{\kappa_{\text{exciton}}} a \alpha \\
b_\beta &= -\chi_\beta^{-1} b \beta - i \kappa_{\text{exciton}} a \beta b + \sqrt{\kappa_{\text{exciton}}} a \beta \\
\end{align*}
\]
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**Prospects**

From silicon photonics to silicon phononics

---

**Lasing vs. sasing**

\[
\gamma_s = \frac{1}{3} \left\{ \frac{(\chi_s^{\text{eff}} + \chi_m^{\text{eff}})}{\sqrt{(\chi_s^{\text{eff}} - \chi_m^{\text{eff}})^2 + 4g^2}} \right\}
\]

Weak coupling \( g \ll |\kappa_s - \Gamma_m| \)

Optical response barely modified
\( \chi_m^{-1} + g^2 \chi_s \approx \chi_s^{-1} \)

Mechanical response barely modified
\( \chi_m^{-1} + \Sigma_m \approx \chi_m^{-1} \)

Mechanical response can be strongly modified: "sasing"
\( \chi_m^{-1} + \Sigma_m = -g^2 \chi_s^{-1} \)

Optical response can be strongly modified: "lasing"
\( \chi_s^{-1} + \Sigma_s = -g^2 \chi_m^{-1} \)

---

**We are closer to sasing than lasing**

Close to transparency
Currently 2.6 dB/cm loss, 2.3 dB/cm gain

\( g \leq 0.9 \)

\( g_t/2\pi = 500 \text{ kHz} \)

Lasing harder than sasing
Need better optical Qs

\( \Gamma_m \ll \kappa_s \)

---

**Cooperativity is the roundtrip gain/loss ratio**

\[
C = \frac{4g_t^2}{\kappa_s \Gamma_m}
\]

\[
C = \frac{4g_t^2 m_cav}{\kappa_s \Gamma_m}
\]

Also holds for sasing!
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Increasing the acoustic Q

Inter-modal scattering
TE/TM eliminates clamping loss

Fully suspended wire
Shortness acceptable for cavities

Low-Q sometimes desirable
Slow light, lasing

Increase the coupling strength in 5-nm-gap silicon slots

Giant light-sound overlap
Less TPA, probably higher losses

Kerr-like optomechanics
Transition from Kerr-like to Brillouin-like

Broadband operation
Up to resonance frequency

\[ G_{SBS} \times 10 - 100 \text{ in best case} \]