Coupling of mechanical motion with frequency comb and Brillouin lasing in whispering gallery modes

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Outline

1. Brillouin laser in coupled WGMs


2. Optomechanics with micro-combs

High-Q whispering-gallery mode microcavities

1. Introduction

\[ Q = \omega \times \frac{\text{stored energy}}{\text{power in/out}} \]

\[ \propto \frac{Q}{V} \]
1. Brillouin laser in coupled WGMs


2. Optomechanics with micro-combs

Stimulated Brillouin Scattering (SBS)

- Schematic representation of SBS process
  - Pump: $\omega_L$
  - Acoustic Wave: $\Omega$
  - Stokes Wave: $\omega_S$
  - $\omega_L = \omega_S - \Omega$

- SBS applications
  - Light storage
  - Slow light generation
  - High coherence lasers
  - Microwave synthesizers

- SBS frequency shift: $\approx 11$ GHz
- Brillouin gain width: $\approx 50$ MHz

Stimulated Brillouin Scattering (SBS)

**Applications**
- Microwave synthesizers
- High coherence lasers

**Properties**
- High Q
- Small mode volume $V_m$
- Small device size

**Applications**
- Microwave synthesizers
- High coherence lasers

**Microcavities**
- Crystalline (CaF$_2$)
  - $Q > 10^{10}$
  - $V \approx 10000 \text{ um}^3$
- $\text{Si}_3\text{N}_4$ microring
  - $Q \approx 10^6$
  - $V \approx 1000 \text{ um}^3$
- Silica toroid
  - $Q \approx 10^8$
  - $V \approx 1000 \text{ um}^3$

**Brillouin lasing**
- Low threshold power
- Small device size

**Schematic representation of the SBS process**

**Background**
SBS in microcavities

**Method 1**

- Brillouin gain spectrum
- Brillouin frequency shift
- Pump
- Resonant mode FSR
- Brillouin frequency shift
- Brillouin lasing

\[ v_{FSR} = \frac{c}{\pi n R} \]

- CaF₂
- 5.52 mm
- SiO₂
- 6.02 mm

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**Method 2**

- Brillouin gain spectrum
- Brillouin frequency shift
- Pump
- Resonant mode FSR
- Brillouin frequency shift
- Brillouin lasing

- mode number (n)
- mode number (n+m)
- High-order mode spacing

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C. Guo, K. Che et al., OE 23, 32261- (2015)

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J. Li, K. Vahala et al., OE 20, 20170- (2012)
SBS in microcavities

Background

- Precise control of cavity size

Method 1
- Brillouin gain spectrum
- Brillouin frequency shift
- Pump

Method 2
- Brillouin gain spectrum
- Brillouin frequency shift
- Pump

Mathematical expression:

\[ \nu_{FSR} = \frac{c}{2L} \]

Images:

- CaF\textsubscript{2}
  - Resonator 1
  - 5.52 mm

- SiO\textsubscript{2}
  - 6.02 mm
  - J. Li, K. Vahala et al., OE 20, 20170- (2012)

- TeO\textsubscript{2}
  - C. Guo, H. Xu et al., OL 40, 4971- (2015)

- SiO\textsubscript{2}
  - C. Guo, K. Che et al., OE 23,25, 32261- (2015)
Objective

Our work

- Brillouin frequency shift in silica (11GHz)
- Mode splitting of supermodes

Brillouin lasing

SBS in coupled microcavities

Precise size control
- Low threshold
- Small footprint

Increasing coupling

Coupling gap

Cavity1

Cavity2

Pump

Relative frequency (MHz)

Transmission (a. u.)
Supermode splitting

Calculation

- Mode overlap
- Phase matching condition

Coupling coefficient

\[ \tilde{R}_{C1, C2} = \frac{\omega \varepsilon_0}{4} (n^2 - n_0^2) \times N_{C1} N_{C2} \iiint_{V_C} (E_{C1}(x, y, z) \cdot E_{C2}(x, y, z)) e^{i \Delta \beta z} \, dx \, dy \, dz \]


Supermode splitting is larger when the diameter of a microcavity is smaller.

Experimental results

Fabricated 55-μm-diameter silica toroid

Moved toroids close together

Achieved more than 10GHz mode splitting
We achieved ... Brillouin frequency shift in silica (11GHz) = Mode splitting of supermodes

Experimental setup

![Experimental setup diagram]

Transmission (a.u.)

- $Q_B \approx 2 \times 10^6$
- $\sim 11$ GHz
- $Q_P \approx 2 \times 10^6$

Pump

Frequency (THz)

OSA, PD, BPF, Circulator, PC, Coupled Cavities, EDFA, VOA, TLS, Function Generator, Oscilloscope
We experimentally demonstrated SBS in coupled microcavities for the first time.

We achieved a threshold power of about 50 mW (10 mW latest).
SBS in coupled cavities

- We experimentally demonstrated SBS in coupled microcavities for the first time.
- We achieved a threshold power of about 50 mW (10 mW latest).
## Results

### Comparison with other Brillouin lasing

<table>
<thead>
<tr>
<th>Coupled silica toroid microcavities (This work)</th>
<th>CaF₂ resonator</th>
<th>Wedge resonator</th>
<th>Microsphere</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Material</strong></td>
<td>SiO₂</td>
<td>CaF₂</td>
<td>SiO₂</td>
</tr>
<tr>
<td><strong>Threshold power</strong></td>
<td>10 mW</td>
<td>3 μW</td>
<td>40 μW</td>
</tr>
<tr>
<td><strong>Device size</strong></td>
<td>110 μm</td>
<td>5.5 mm</td>
<td>6 mm</td>
</tr>
<tr>
<td><strong>Q</strong></td>
<td>$2 \times 10^6$</td>
<td>$4 \times 10^9$</td>
<td>$\sim 1 \times 10^9$</td>
</tr>
<tr>
<td><strong>On-chip</strong></td>
<td>✓</td>
<td>✗</td>
<td>✓</td>
</tr>
<tr>
<td><strong>Precise cavity size control</strong></td>
<td>Not needed</td>
<td>Needed</td>
<td>Needed</td>
</tr>
</tbody>
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I. S. Grudinin et al., PRL, 102.4, 043902 (2009)
J. Lin et al., OE, 20.18, 20170-20180 (2012)
C. Guo, H. Xu et al., OL 40, 4971- (2015)
Comparison with other Brillouin lasing

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</tr>
</thead>
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<tr>
<td>Coupled silica toroid microcavities (This work)</td>
<td>500 μW</td>
<td>110 μm</td>
<td>2 × 10^7</td>
<td>✓</td>
<td>Not needed</td>
</tr>
<tr>
<td>CaF$_2$ resonator</td>
<td>50 mW</td>
<td>3 mm</td>
<td>500</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Wedge resonator</td>
<td>8 μW</td>
<td>6 mm</td>
<td>100</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Microsphere</td>
<td>4.5 mW</td>
<td>172 μm</td>
<td>2 × 10^7</td>
<td>×</td>
<td>×</td>
</tr>
</tbody>
</table>

Threshold power for SBS

\[
(P_{SBS})_{th} \propto \frac{V_m}{Q^2}
\]

- Improve threshold power by using mode pair with higher Q factor

Results
We achieved the 11GHz mode splitting of supermodes that matches the Brillouin frequency shift in silica in coupled silica toroid microcavities.

We experimentally demonstrated SBS in coupled microcavities and achieved a threshold power of 10 mW.

Acknowledgement

- Grant-in-aid from the Ministry of Education, Culture, Sports, Science and Technology (MEXT) for the Photon Frontier Network Program.
- Grant-in-aid from the Ministry of Education, Culture, Sports, Science and Technology (MEXT), (KAKEN 15H05429)
1. Brillouin laser in coupled WGMs


2. Optomechanics with micro-combs

Microresonator frequency comb generation

Microcavity frequency comb generation

- Laser Diode
- CW input
- SiO$_2$ WGM $\mu$-cavity
- Pulsed output
- Four-wave mixing
- Kerr comb generation w/ strong confinement of light

Silica toroid microcavity

Microcomb in toroid

- FSR ~ 414 GHz
- Degenerate FWM
- Non-degenerate FWM
- Pump
Cavity optomechanics

- Modulation by mechanical mode
  - $\omega_p$
  - $\omega_p, \omega_p \pm \Omega_m$
  - Pump
  - Oscillation

- Amplification and cooling by different pump detuning
  - Blue-detuning $\Rightarrow$ amplification
  - Red detuning $\Rightarrow$ cooling

Can observe optomechanical oscillation by measuring RF signal

$\Omega_m$, Radio frequency

Resonance modulation

Output power

Stokes

Red-detuning $\Rightarrow$ cooling

Blue-detuning $\Rightarrow$ amplification
Motivation

Optomechanical parametric oscillation (OMPO)

Blue-detuned pump: Amplification \( \Gamma_{\text{eff}} < 0 \)
Red-detuned pump: Damping \( \Gamma_{\text{eff}} > \Gamma_m \)

\[
\Gamma_{\text{eff}} = \Gamma_m + \Gamma_{\text{opt}}
\]

\( \Gamma_{\text{eff}} \): effective mechanical damping rate
\( \Gamma_m \): mechanical damping rate
\( \Gamma_{\text{opt}} \): optomechanical damping rate

\[
\Gamma_{\text{opt}} = |a_0|^2 g_{\text{om}} \left\{ \frac{\kappa}{\frac{1}{4} \kappa^2 + (\Delta \omega_0 + \Omega_m)^2} - \frac{\kappa}{\frac{1}{4} \kappa^2 + (\Delta \omega_0 - \Omega_m)^2} \right\}
\]

\( |a_0|^2 \): number of intracavity photon
\( \Delta \omega_0 \): laser detuning from resonance


What will happen when frequency comb is generated in an opto-mechanically coupled resonator?

- Turing pattern microcomb in a silica toroid microresonator
  - Blue-detuned pump ⇒ amplification of oscillations
  - Red-detuned comb ⇒ damping of oscillations

Pump is blue detuned
Microcomb and RF signals while scanning pump
Microcomb and RF signals while scanning pump
Cooling by the generated comb lines

\[ \Gamma_{\text{eff}} = \Gamma_m + \Gamma_{\text{opt}} \]

Single-optomechanical coupling with a resonance

\[ \Gamma_{\text{eff}} = \Gamma_m + \sum_{\mu} \Gamma_{\text{opt,}\mu} \]

Multi-optomechanical couplings with resonances

Four wave mixing ($D_1/2\pi$)

Optomechanical sidebands ($\Omega/2\pi$)

(Anomalous dispersion case)

Resonance mode

Pump scan
Comb detuning measurement

To calculate optomechanical damping rates in each resonance mode, the comb detuning $\Delta \omega_\mu$ and the number of intracavity photon $|a_\mu|^2$ are needed.

$$\Gamma_{\text{eff}} = \Gamma_m + \Sigma_\mu \Gamma_{\text{opt,}\mu}$$

$$\Gamma_{\text{opt,}\mu} = |a_\mu|^2 g_{\text{om}} \left\{ \frac{\kappa}{\frac{1}{4} \kappa^2 + (\Delta \omega_\mu + \Omega_m)^2} - \frac{\kappa}{\frac{1}{4} \kappa^2 + (\Delta \omega_\mu - \Omega_m)^2} \right\}$$

Comb detuning measurement

$$\Delta \omega_\mu \approx \Delta \omega_0 - \frac{1}{2} D_2 \mu^2$$

$$\Delta \omega_\mu = \omega_{\text{comb}} - \omega_\mu$$

![Diagram of photonic structure setup with TLD, EDFA, FPC, Toroid, MZI, OSA, OSC, BPF, PD, and coupling system connections.](image-url)
Pump detuning regime for OMPO

- Number of intracavity photon \(|a_\mu|^2\) is obtained by measurement or LLE simulation
- Comb detuning \(\Delta \omega_\mu\) follows the cavity dispersion \(D_2\)

\[
\Gamma_{\text{eff}} = \Gamma_m + \sum_\mu \Gamma_{\text{opt},\mu} \quad \Gamma_{\text{opt},\mu} = |a_\mu|^2 g_{\text{om}} \left\{ \frac{\kappa}{\frac{1}{4}\kappa^2 + (\Delta \omega_\mu + \Omega_m)^2} - \frac{\kappa}{\frac{1}{4}\kappa^2 + (\Delta \omega_\mu - \Omega_m)^2} \right\}
\]

Transmission while scanning pump wavelength

Pump detuning regime that suppresses OMPO can be estimated from the cavity dispersion value and LLE simulation result.
If only blue detuned pump light is present, optomechanical oscillations are always amplified. OMPO is suppressed when Turing pattern comb is generated, because all the lines appears in the red-detuning regime.

Single-optomechanical coupling with a resonance

\[ \Gamma_{\text{eff}} = \Gamma_m + \Gamma_{\text{opt}} \]

Multi-optomechanical couplings with resonances

\[ \Gamma_{\text{eff}} = \Gamma_m + \sum_{\mu} \Gamma_{\text{opt},\mu} \]
Summary

1. Brillouin laser in coupled WGMs

Achieved Brillouin lasing w/ 10 mW pump
Has potential to reduce down to 500 uW.

2. Optomechanics with micro-combs

Cooling is possible even w/ blue detuned pump when comb is present
Anomalous dispersion allows the cooling the cavity
Acknowledgement

The team

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