The 6th Advanced Lasers and Photon Sources (ALPS’17)

Tuning Supermode Splitting for Stimulated Brillouin Scattering

Yoshihiro Honda¹, Wataru Yoshiki¹, Tomohiro Tetsumoto¹, Shun Fujii¹, Kentaro Furusawa², Norihiko Sekine² and Takasumi Tanabe¹

¹Faculty of Science and Technology, Keio University
²National Institute of Information and Communications Technology
Stimulated Brillouin Scattering (SBS)

**Background**

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

**SBS applications**

- High coherence lasers
- Microwave synthesizers

**Schematic representation of SBS process**

\[
\omega_L = \omega_S - \Omega
\]

- SBS frequency shift \(\approx 11\text{GHz}\)
- Brillouin gain width \(\approx 50\text{MHz}\)

**Simplified model**

- Pump
- Acoustic Wave \(\Omega\)
- Stokes Wave \(\omega_S\)

\((\text{SiO}_2)\)

Stimulated Brillouin Scattering (SBS)

Background

- Light storage
- Slow light generation

Applications of SBS

- High coherence lasers
- Microwave synthesizers


\[ \omega_L = \omega_S - \Omega \approx 11\text{GHz} \]
\[ \text{SBS frequency shift} \]
\[ \omega_L \approx \omega_S \]
\[ \Omega \approx 50 \text{MHz} \]

Pump
Stokes Wave
Acoustic Wave

Properties

- High Q
- Small mode volume \( V_m \)
- Small device size

Microcavities

- Crystalline (CaF\(_2\))
  \( Q > 10^{10} \)
  \( V \approx 10000 \text{ um}^3 \)

- Si\(_3\)N\(_4\) microring
  \( Q \approx 10^6 \)
  \( V \approx 1000 \text{ um}^3 \)

- Silica toroid
  \( Q \approx 10^8 \)
  \( V \approx 1000 \text{ um}^3 \)

Schematic representation of the SBS process

- High Q
- Small mode volume \( V_m \)
- Small device size

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

Applications

- Microwave synthesizers
- High coherence lasers

Brillouin lasing

- Low threshold power
- Small device size
SBS in microcavities

Method 1

Brillouin gain spectrum
Brillouin frequency shift
Pump

Frequency

Resonant mode FSR

Brillouin frequency shift = Resonant mode FSR

Brillouin lasing

CaF$_2$

SiO$_2$

$\nu_{FSR} = \frac{c}{\pi n R}$

5.52 mm

6.02 mm


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

Method 2

Brillouin gain spectrum
Brillouin frequency shift
Pump

Frequency

Mode number (n)
Mode number (n+m)

Brillouin frequency shift = High-order mode spacing

Brillouin lasing

TeO$_2$

SiO$_2$

C. Guo, H. Xu et al., OL 40, 4971- (2015)

SBS in microcavities

**Method 1**
- Precise control of cavity size

- $\nu_{FSR} = \frac{c}{\pi n}$

- Materials: CaF$_2$, SiO$_2$, TeO$_2$

**Method 2**

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

- C. Guo, H. Xu et al., OL 40, 4971- (2015)

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

Our work

Precise size control
Low threshold
Small footprint

SBS in coupled microcavities

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

Increasing coupling

Tunable
Silica toroid microcavities

Fabrication

1. Photolithography
2. Cutting
3. XeF₂ dry etching
4. Laser reflow
5. Finish

- Precisely control coupling strength by changing distance between toroids

Side View

Top View
Tuning resonant frequency

- Thermo-optic (TO) effect

- Tuning two different resonant frequencies

Couple tapered fiber to each cavity, and measure each resonant wavelength.

Increasing temperature (C1)

Resonance wavelength red-shifted.

Fabrication
Supermode splitting

Calculation

- Mode overlap
- Phase matching condition

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

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
SBS in coupled cavities

Experiments

We achieved …

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

Experimental setup
Results

SBS in coupled cavities

(a) We experimentally demonstrated SBS in coupled microcavities for the first time.
(b) We achieved a threshold power of about 50 mW.
SBS in coupled cavities

Results

- We experimentally demonstrated SBS in coupled microcavities for the first time.
- We achieved a threshold power of about 50 mW.
## Comparison with other Brillouin lasing

### Coupled silica toroid microcavities (This work)

<table>
<thead>
<tr>
<th>Material</th>
<th>SiO$_2$</th>
<th>CaF$_2$</th>
<th>SiO$_2$</th>
<th>SiO$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threshold power</td>
<td>50 mW</td>
<td>3 µW</td>
<td>40 µW</td>
<td>8 µW</td>
</tr>
<tr>
<td>Device size</td>
<td>110 µm</td>
<td>5.5 mm</td>
<td>6 mm</td>
<td>172 µm</td>
</tr>
<tr>
<td>$Q$</td>
<td>$2 \times 10^6$</td>
<td>$4 \times 10^9$</td>
<td>$\sim 1 \times 10^9$</td>
<td>$\sim 3 \times 10^7$</td>
</tr>
<tr>
<td>On-chip</td>
<td>✓</td>
<td>×</td>
<td>✓</td>
<td>×</td>
</tr>
<tr>
<td>Precise cavity size control</td>
<td>Not needed</td>
<td>Needed</td>
<td>Needed</td>
<td>Needed</td>
</tr>
</tbody>
</table>
Comparison with other Brillouin lasing

Threshold power for SBS

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

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

Coupled silica toroid microcavities (This work)

<table>
<thead>
<tr>
<th>Material</th>
<th>SiO₂</th>
<th>CaF₂</th>
<th>Wedge resonator</th>
<th>Microsphere</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threshold power</td>
<td>500 μW</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Device size</td>
<td>110 μm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q</td>
<td>2 × 10⁷</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>On-chip</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Precise cavity size control</td>
<td>Not needed</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Results

Threshold power relation

\[\bar{V} = \bar{V}_0 \exp \left( \frac{W}{\eta} \right)\]
Conclusions

- 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 50 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)