Towards Mode-locking of an active Whispering-Gallery-Mode microresonator

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5. JST-PRESTO
Outline

• Background & Motivation
• Device Fabrication
• Numerical work
• Summary & Future work
Background & Motivation

High repetition rate Modelocked Lasers (HR ML)

Applications
- Laser processing
- Optical communication
- Optical signal processing
- LIDAR and remote sensing
- Spectroscopy
High repetition rate Modelocked Lasers (HR ML)

- Laser processing
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Frep & Cost

<table>
<thead>
<tr>
<th>F_{rep}</th>
<th>F_{rep}&gt; 10GHz</th>
<th>F_{rep}&gt; 100 GHz</th>
<th>F_{rep}&lt; 1GHz</th>
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</thead>
<tbody>
<tr>
<td>Fabrication &amp; Cost</td>
<td>✗</td>
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<td>O</td>
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<tr>
<td>Integration</td>
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Objective of the research

Modelocking of Whispering Gallery Mode Microlaser

- High repetition rate (>100GHz)
- Small footprint
- Low power consumption
- Cost effective
- On-chip integrability

Repetition rate $\propto \frac{1}{\text{size}}$

D=300μm $\rightarrow$ 220GHz
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Repetition rate $\propto \frac{1}{\text{size}}$

D=300$\mu$m → 220GHz

Carbon nanotubes (CNT) as saturable absorber

- Simple fabrication
- Cost effective
- Easy integration to fiber systems

$$\alpha(I) = a_{ns} + \frac{a_0}{1 + \frac{I}{I_{sat}}}$$

- $a_0$: Modulation depth
- $I_{sat}$: Saturation Intensity
- $a_{ns}$: Non-saturable loss
Outline

• **Background & Motivation**
  - WGM Modelocked Microlaser

• **Device Fabrication**
  - Carbon nanotube integration
  - Erbium doping technique

• **Numerical work**
  - WGM microlaser modelocking regime investigation

• **Summary & Future work**
# CNT integration

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### CNT probe as saturable absorber

\[
a(l) = a_{ns} + \frac{\alpha_0}{1 + \frac{l}{\ell_{sat}}}
\]

- Loss vs. Intensity (MW/cm²)
- CNT loss vs. Gap (nm)
## CNT integration

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**CNT probe as saturable absorber**

\[
\alpha(t) = \alpha_{ns} + \frac{\alpha_0}{1 + T_{sat}}
\]

- Low loss
- Simple fabrication
- Adjustable SA parameters
Er$^{3+}$-doped WGM microtoroid

Fabrication by sol-gel method

Evaluation

$Q = 10^7$ (@1545nm)
Diameter: 40 μm
Er concentration: $1.9 \times 10^{18}$ cm$^{-3}$
Threshold power: 1.2 μW
Er\textsuperscript{3+}-doped WGM microtoroid fabrication by sol-gel method:

- Er\textsuperscript{3+}-doped SiO\textsubscript{2}
- photolithography
- wet etching (BHF)
- dry etching (XeF\textsubscript{2})
- reflow (CO\textsubscript{2} laser)

Evaluation:

\[ Q = 10^7 \, (@1545\text{nm}) \]
Diameter: 40 μm
Er concentration: \(1.9 \times 10^{18} \text{ cm}^{-3}\)
Threshold power: 1.2 μW

But, how much erbium and carbon nanotube is needed to obtain modelocking?
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• Summary & Future work
Modelocked WGM microlaser - simulation

**Modified Nonlinear Schrödinger Equation**

\[
\frac{\partial}{\partial T} A(T, t) = \left( -iD \frac{\partial^2}{\partial t^2} + i\delta |A|^2 \right) A(T, t) + \left( (g + \frac{g}{\omega^2} \frac{\partial^2}{\partial t^2}) - (l + q(T, t)) \right) A(T, t)
\]

- Dispersion
- Self-Phase Modulation (SPM)
- Gain
- Loss (Q factor) + saturable absorber
Modelocked WGM microlaser - simulation

Modified Nonlinear Schrödinger Equation

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Contribution graph

- Improved device understanding
- Predictive capability
Modelocked WGM microlaser - simulation

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- Self-Phase Modulation (SPM)
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- Loss (Q factor) + saturable absorber

**Contribution graph**

- Improved device understanding
- Predictive capability
Modelocked WGM microlaser - simulation

\[ Q = 10^8 \]
\[ \beta_2 = -10 \text{ ps}^2/\text{km} \]

- Unstable regime
- Multiple pulses regime
- Stable modelocking regime
- No modelocking regime

Modelocking regime was investigated
Gain is limiting factor:

→ **Ultra high** $Q$ ($>10^7$) cavity is necessary for modelocking at low gain
  - Gain $>$ loss for CW lasing
  - Nonlinear loss by SA dominates loss for pulse formation
Modelocked WGM microlaser - simulation

Low gain

\[
\Delta |A| \quad \text{against} \quad \text{Power (W)}
\]

- **Gain**
- **Loss**
- **Dispersion**
- **SPM**
Modelocked WGM microlaser - simulation

- Low gain
- Decreased intracavity power
Modelocked WGM microlaser - simulation

Low gain
Decreased intracavity power
SPM is weak
Modelocked WGM microlaser - simulation

Low gain
Decreased intracavity power
SPM is weak
Weak dispersion is needed
Modelocked WGM microlaser - simulation

$Q=10^8$

$\alpha_0 = 0.0005$

Weak anomalous dispersion is necessary for modelocking at low gain
- Pulse formation is the result of gain and nonlinear loss action
- Careful cavity dispersion engineering is necessary
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- Pulse formation is the result of gain and nonlinear loss action
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Modelocked WGM microlaser - simulation

Adjustable by CNT probe

Gain < Loss

No ML

Stable ML

Unstable ML

Modulation depth $\alpha_0$
Summary & Future work

Modelocking of Whispering Gallery Mode Microlaser

[Device fabrication]

- We developed CNT integration method
  - CNT probe allows adjustable modulation depth

- We fabricated er-doped WGM microtoroids by sol-gel method
  - Low-threshold CW lasing was observed

[Numerical work]

- We investigated WGM microlaser modelocking regime
- Design guidelines for stable modelocking:

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<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Diameter</td>
<td>D=150μm</td>
</tr>
<tr>
<td>Q factor</td>
<td>&gt; 10^7</td>
</tr>
<tr>
<td>Saturable absorber</td>
<td>CNT probe (α₀ = 10^{-5} ~ 10^{-4})</td>
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Thank you for your attention.

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