Saturable absorption by carbon nanotubes on silica microtoroids for stable mode locking

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1. Introduction
   - Optical microcavities
   - Carbon nanotubes (CNTs) as saturable absorber
   - Objective of study

2. Fabrication of CNTs on silica microtoroids

3. Evaluation of saturable absorption characteristics of CNTs by pump-probe experiment

4. Conclusion
Optical microcavities

Whispering Gallery Mode (WGM)

- Microcavities have high-Q factors with small mode volumes.
- These properties are attractive for various applications that require strong interaction between light and matter (i.e. Raman, four wave mixing).

Applications

- Microlasers with high repetition rate
- Nonlinear optics devices
- Chemical or bio sensors

Silica
Vahala group (Caltech)

AIN
Tang group (Yale)

Crystalline
(CaF₂, MgF₂, etc)
Kippenberg group (EPFL, Swiss), Makei group (OE Waves)
The combination of saturable absorber and microcavities would allow us to realize a pulsed output.

Nano-carbon materials (CNT, Graphene) are good candidate for passive and ultra-fast (~100 fs) saturable absorber with showing broadband absorption.

Bandgap of CNT can be controlled by controlling its diameter and chirality.
Previous research

Objective

Saturable absorption by carbon nanotubes on silica microtoroids for stable mode locking

- Selective growth of CNTs on silica microtoroids by chemical vapor deposition (CVD).
- Investigation of saturable absorption characteristics by counter-propagating pump-probe experiment.
Outline

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Selective fabrication of CNTs by CVD
Sample observation

Digital microscope VHX-6000 (KEYENCE)

SEM top view

SEM side view

INSPECT S50 (FEI)
Accelerating voltage: 2-20 kV
Raman spectrum and mapping

- RBM (Radial Breathing Mode)
  - Intensity / a.u.
  - Wavelength: 532 nm
  - Power: 1.5 mW

G/D ratio = 7

- D band

inVia Raman microscope (Renishaw)
Wavelength: 532 nm
Power: 1.5 mW
CNT diameter vs bandgap

CNT diameter:
\[ d = \frac{248}{\omega_{RBM}} \text{ [nm]} \]

<table>
<thead>
<tr>
<th>( \omega_{RBM} )</th>
<th>( d / \text{nm} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>146.8</td>
<td>1.69</td>
</tr>
<tr>
<td>171.0</td>
<td>1.45</td>
</tr>
<tr>
<td>182.3</td>
<td>1.36</td>
</tr>
<tr>
<td>229.2</td>
<td>1.08</td>
</tr>
</tbody>
</table>

\[ \Delta E \sim 0.8 \text{ eV} \]

We prepared a device that operates in telecommunication band (~0.8 eV = 1550 nm).

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Method

Absorption coefficient

\[ Q_{\text{total}} \approx Q_{\text{absorption}} = \frac{2\pi n}{\alpha \lambda_0} \quad \Leftrightarrow \quad \alpha = \frac{2\pi n}{Q \lambda_0} \]

- \( Q \): Quality factor
- \( \alpha \): Absorption coefficient
- \( n \): Refractive index
- \( \lambda_0 \): Resonant wavelength

Power density

\[ I = \frac{P_{\text{cav}}}{S} \]

\[ P_{\text{cav}} = |a|^2 / T_{\text{roundtrip}} = |a|^2 \times \text{FSR} \]

\[ |a|^2 = \frac{\kappa_{\text{ext}}}{\Delta^2 + \left( \frac{\kappa_0 + \kappa_{\text{ext}}}{2} \right)^2 P_{\text{in}}} \]

- \( \Delta = \omega_{\text{pump}} - \omega_{\text{res}} \): Detuning
- \( P_{\text{in}} \): Input power
- \( \kappa_0 \): Intrinsic cavity decay rate
- \( \kappa_{\text{ext}} \): Coupling rate

Theory of microresonator based frequency comb generation

By T. Herr, doctor thesis

In experiential, \( Q, P_{\text{in}} \) and \( \Delta \) are measured.
(Critical coupling condition is satisfied.)
Counter-propagating pump-probe experiment

Pump: 1-80 mW
Probe: 50-200 μW

λ: 1550.767 nm
Q ~ 4.0 \times 10^5
Transmission spectra

\[ Q: 4.7 \times 10^5 \]
\[ 4.5 \times 10^5 \]
\[ 4.4 \times 10^5 \]
\[ 3.8 \times 10^5 \]
\[ 3.8 \times 10^5 \]
\[ 3.8 \times 10^5 \]

Frequency /THz

193.30 193.31 193.32

Wavelength /nm

1550.90 1550.85 1550.80 1550.75 1550.70

\[ P_{\text{in}} /\text{mW}: \]
\[ 4.3 \]
\[ 2.1 \]
\[ 1.1 \]
\[ 0.54 \]
\[ 0.25 \]
\[ 0.13 \]
Absorption coefficient vs power density

\[ \alpha(I) = \frac{\alpha_S}{1 + I/I_S} + \alpha_{NS} \]

\( \alpha_S: 0.042 \text{ cm}^{-1} \)

\( I_S: 25.9 \text{ MW/cm}^2 \)

\( \alpha_{NS}: 0.107 \text{ cm}^{-1} \)

Modulation depth: 28%
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Conclusion

- CNTs are fabricated on the silica microtoroids selectively by CVD.
- Characteristics of CNT as saturable absorber is evaluated by the counter-propagating pump-probe experiments.
- The saturable absorption is observed, and the $\alpha_S$ and $I_S$ are as 0.042 cm$^{-1}$ and 25.9 MW/cm$^2$, respectively.

Future plans

Robust mode-locked frequency combs in various gains such as Raman and rare-earth ions.
Acknowledgment

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