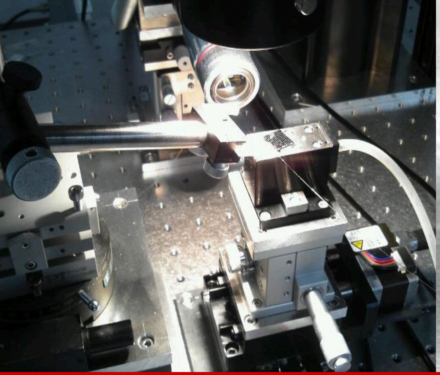
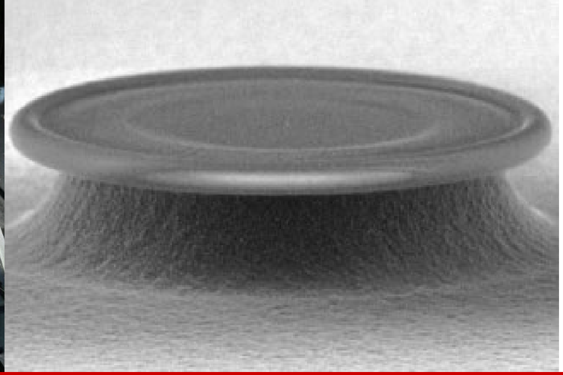
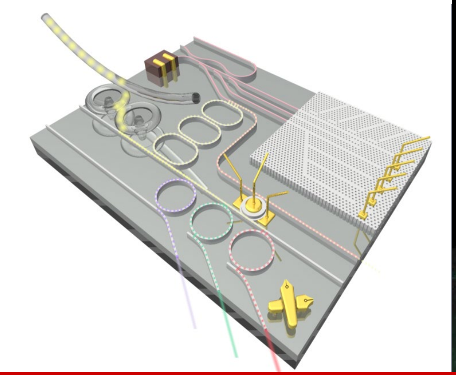





Session 4P10b: Optics and Fiber Laser
20/06/2019 Room 12 - Mezzanine

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

Tomoki S. L. Prugger Suzuki[1], Shun Fujii[1], Rammaru Ishida[1], Riku Imamura[1], Mizuki Ito[1], Hideyuki Maki[2,5], Lan Yang[3], Sze Yun Set[4] and Takasumi Tanabe[1]

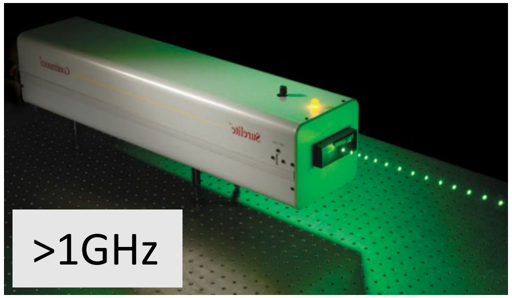
1. Electronics and Electrical Engineering,Keio Univ.
2. Applied Physics and Physico-Informatics, Keio Univ.
3. School of Engineering and Applied Science, Washington Univ. in St. Louis
4. Research Center for Advanced Science and Technology , The University of Tokyo
5. JST-PRESTO

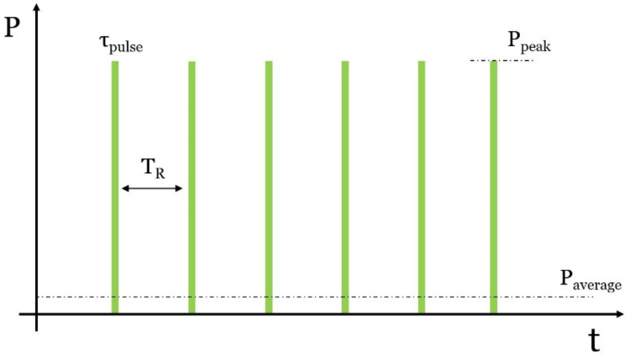
Outline

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

Background & Motivation

High repetition rate Modelocked Lasers (HR ML)



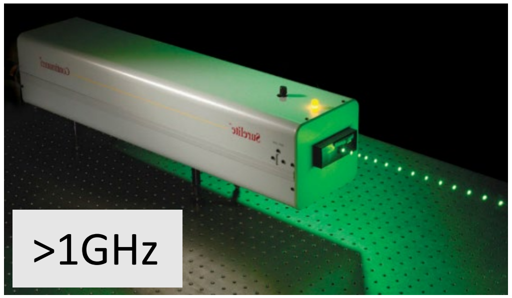


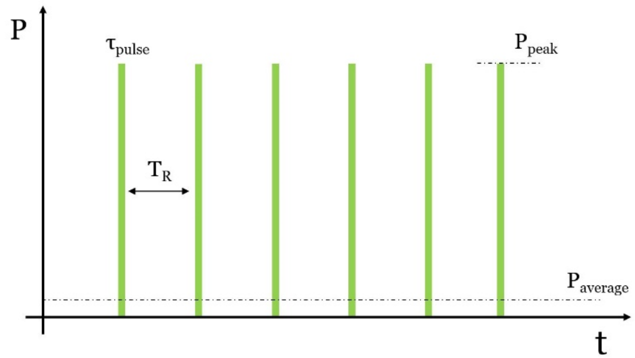
Applications

- Laser processing
- Optical communication
- Optical signal processing
- LIDAR and remote sensing
- Spectroscopy

Background & Motivation

High repetition rate Modelocked Lasers (HR ML)





Applications
- Laser processing
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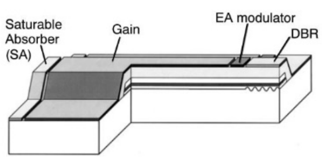
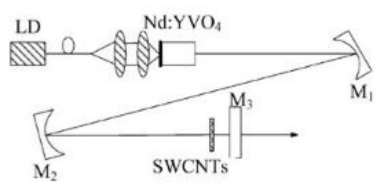
HR ML platforms

Semiconductor ML Laser



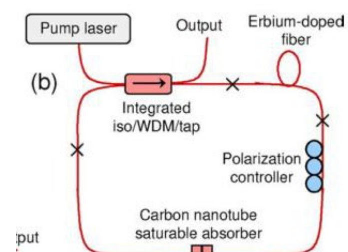
Ogura, I. et al., *Optical and Quantum Electronics* **33,** 709–725 (2001).

ML Bulk Laser



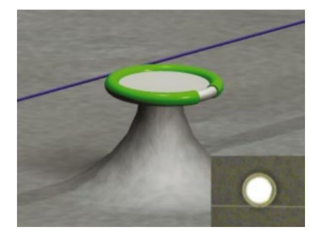
Liu, Y. et al., *Applied Physics B: Lasers and Optics* **104,** 835–838 (2011)

ML fiber ring Laser



Nicholson, J. et al., *IEEE Photonics Technology Letters* **20,** 2123–2125 (2008)

WGM microlaser



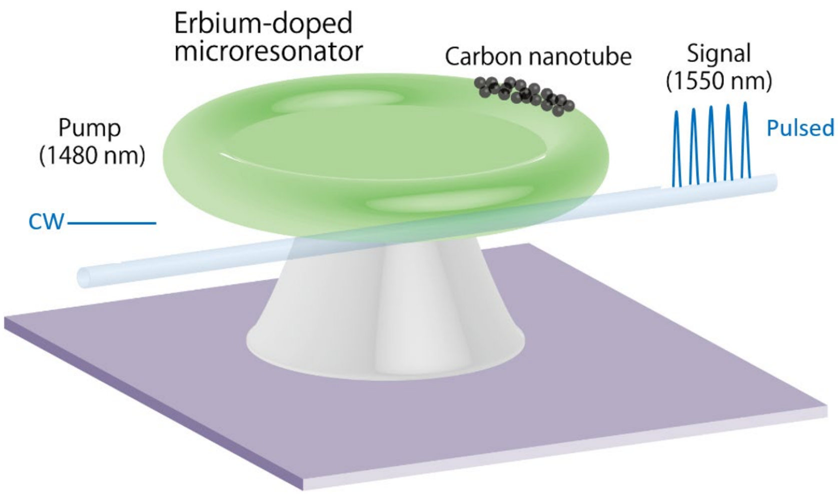
Yang, L. et al., *Applied Physics Letters* **83,** 825–826 (2003).

	Semiconductor ML Laser	ML Bulk Laser	ML fiber ring Laser	WGM microlaser
F_{rep}	F_{rep}> 10GHz	F_{rep}> 100 GHz	F_{rep}< 1GHz	✖
Fabrication & Cost	✖	✖	O	O
Integration	O	✖	O	O

http://www.directindustry.com/prod/continuum/product-27505-84814.html

Objective of the research

Modelocking of Whispering Gallery Mode Microlaser



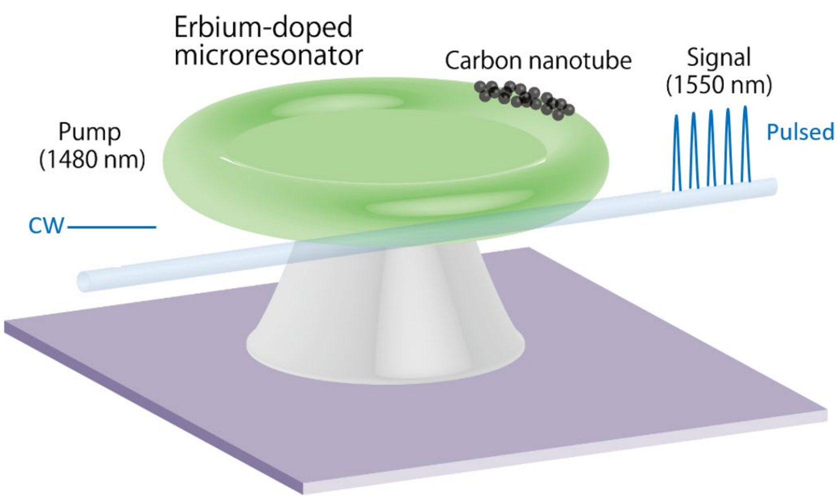
$$Repetition\ rate \propto \frac{1}{size}$$

D=300μm → 220GHz

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

Objective of the research

Modelocking of Whispering Gallery Mode Microlaser



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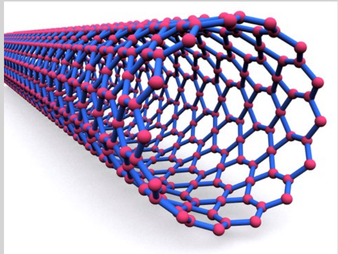
Carbon nanotubes (CNT) as saturable absorber



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

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

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

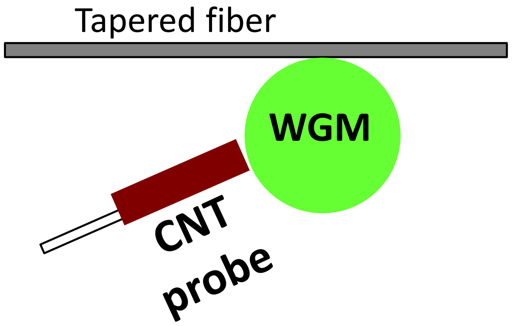
Outline

- 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

CNT integration methods	Chemical Vapor Deposition (CVD)	CNT-embedded polymer coating	CNT probe
Q factor	✖	△	○
fabrication	✖	△	○
SA properties	△	○	◎

Kumagai, T. *et al.* *Journal of Applied Physics* **123,** (2018)



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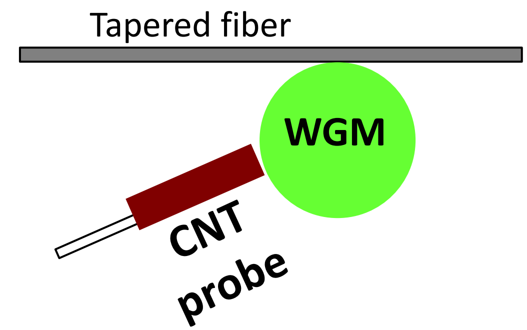
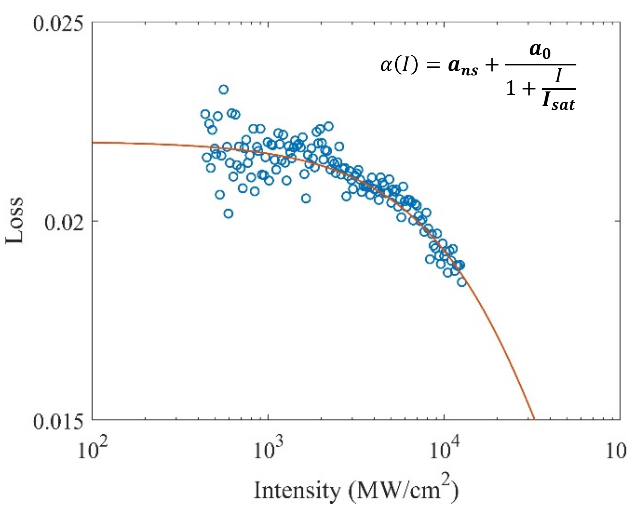
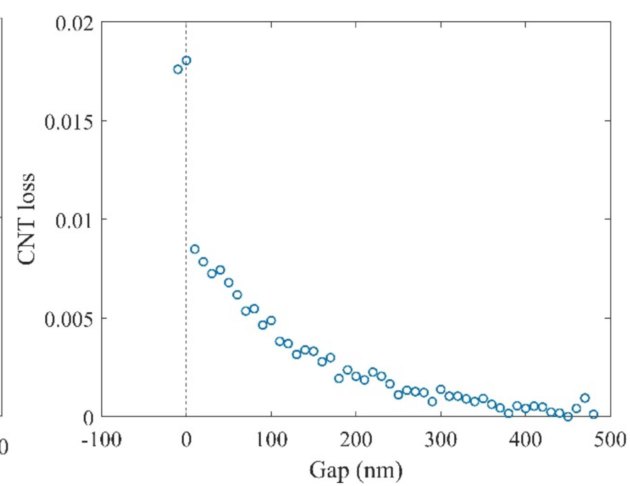


CNT probe as saturable absorber





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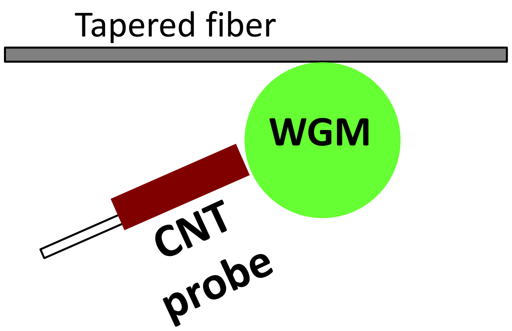
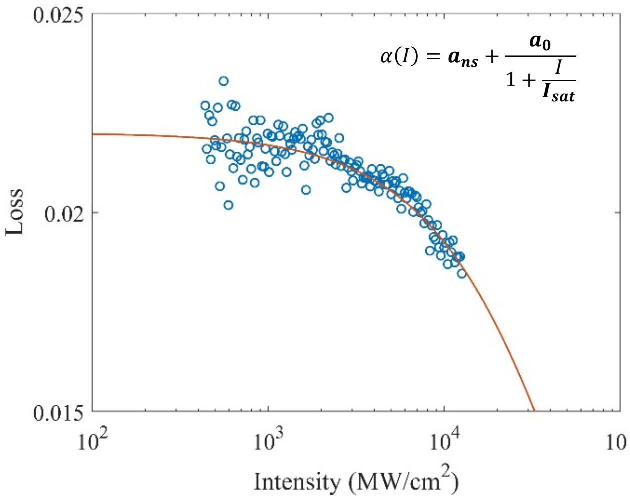
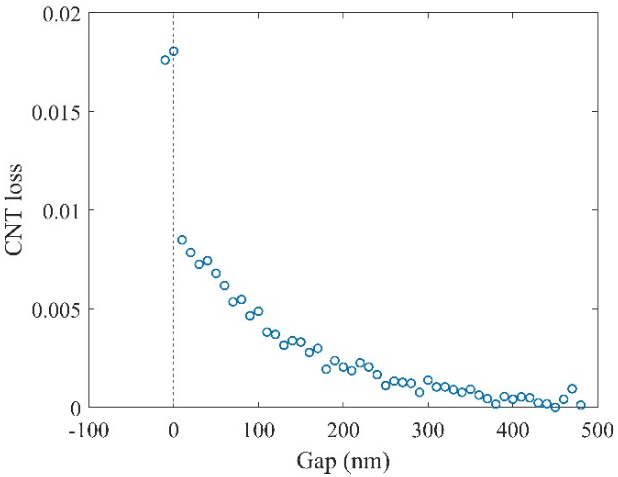


CNT probe as saturable absorber



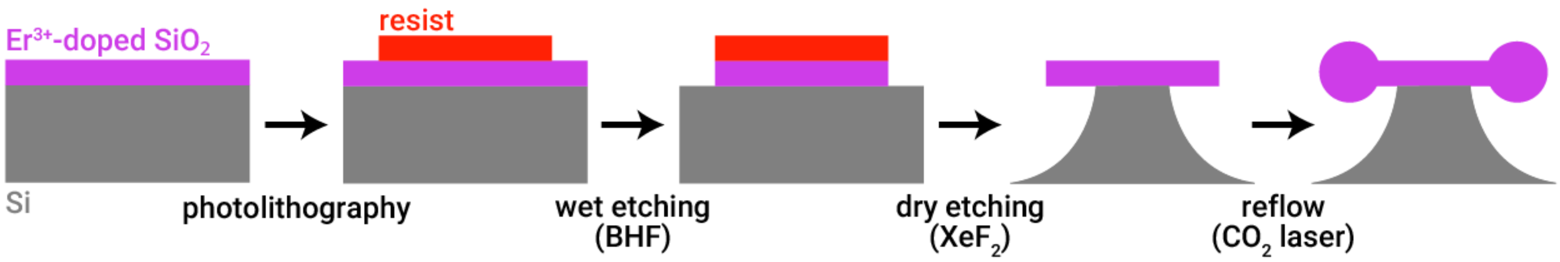


- ✓ Low loss
- ✓ Simple fabrication
- ✓ **Adjustable SA parameters**

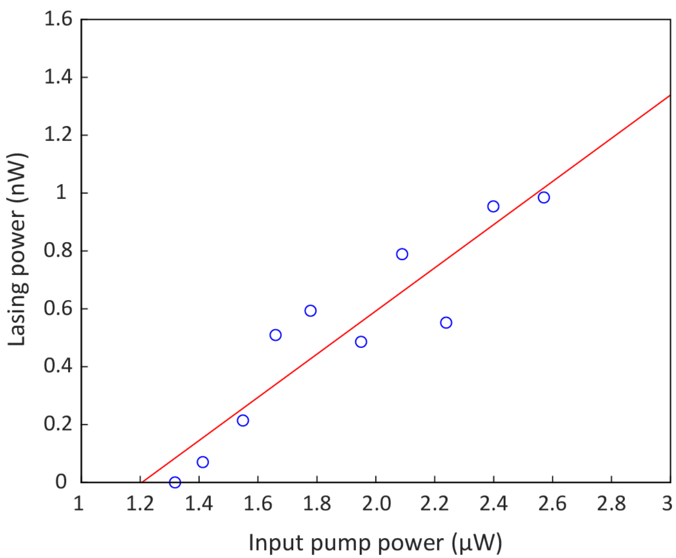
Er^{3+}-doped WGM microtoroid

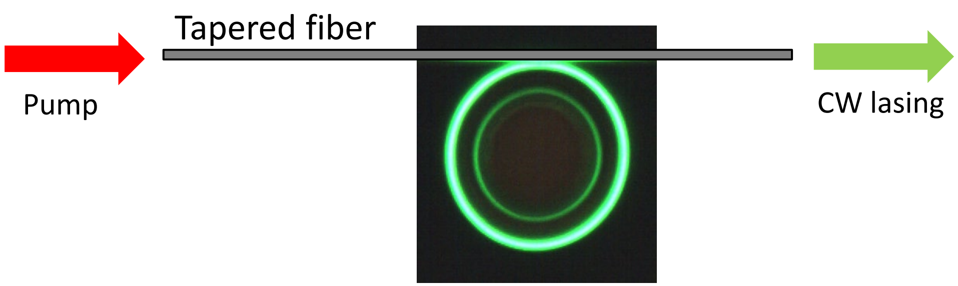
Fabrication by **sol-gel method**

Sigoli, F. A., *Journal of Non-Crystalline Solids*, *352*(32–35), 3463–3468 (2006).



Evaluation





$Q = 10^7$ (@1545nm)

Diameter: 40 μm

Er concentration: 1.9×10^{18} cm^{-3}

Threshold power: 1.2 μW

Er^{3+}-doped WGM microtoroid

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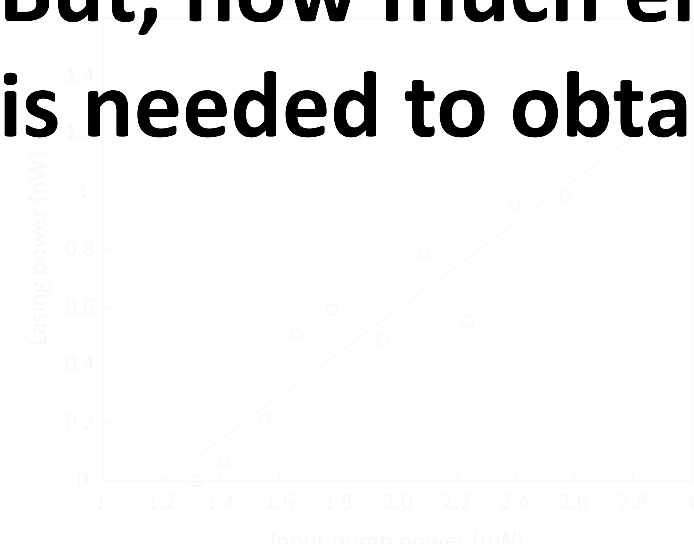

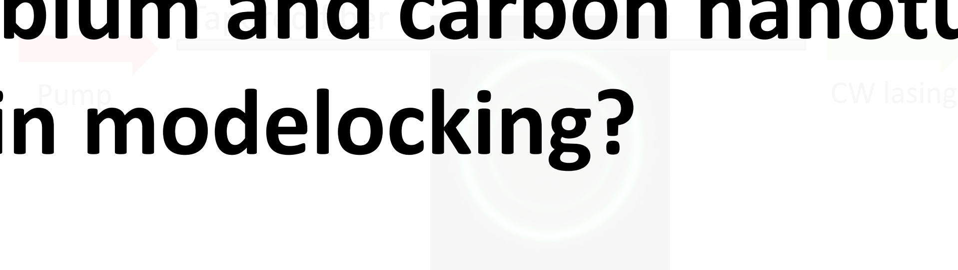

$Q = 10^7$ (@1545nm)

Diameter: 40 μm

Er concentration: 1.9×10^{18} cm^{-3}

Threshold power: 1.2 μW

But, how much erbium and carbon nanotube is needed to obtain modelocking?

Outline

- Background & Motivation
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Modelocked WGM microlaser - simulation

Modified Nonlinear Schrödinger Equation

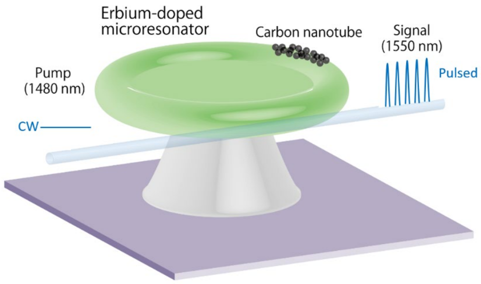
$$\frac{\partial}{\partial T}A(T,t) = \left(-iD\frac{\partial^2}{\partial t^2} + i\delta|A|^2\right)A(T,t) + \left((g + \frac{g}{\omega_g^2}\frac{\partial^2}{\partial t^2}) - (l + q(T,t))\right)A(T,t)$$

Dispersion

Self-Phase Modulation (SPM)

Gain

Loss (Q factor)+ saturable absorber



Modelocked WGM microlaser - simulation

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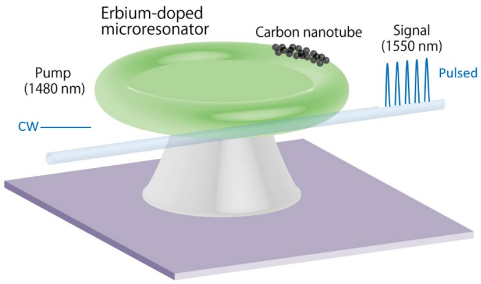

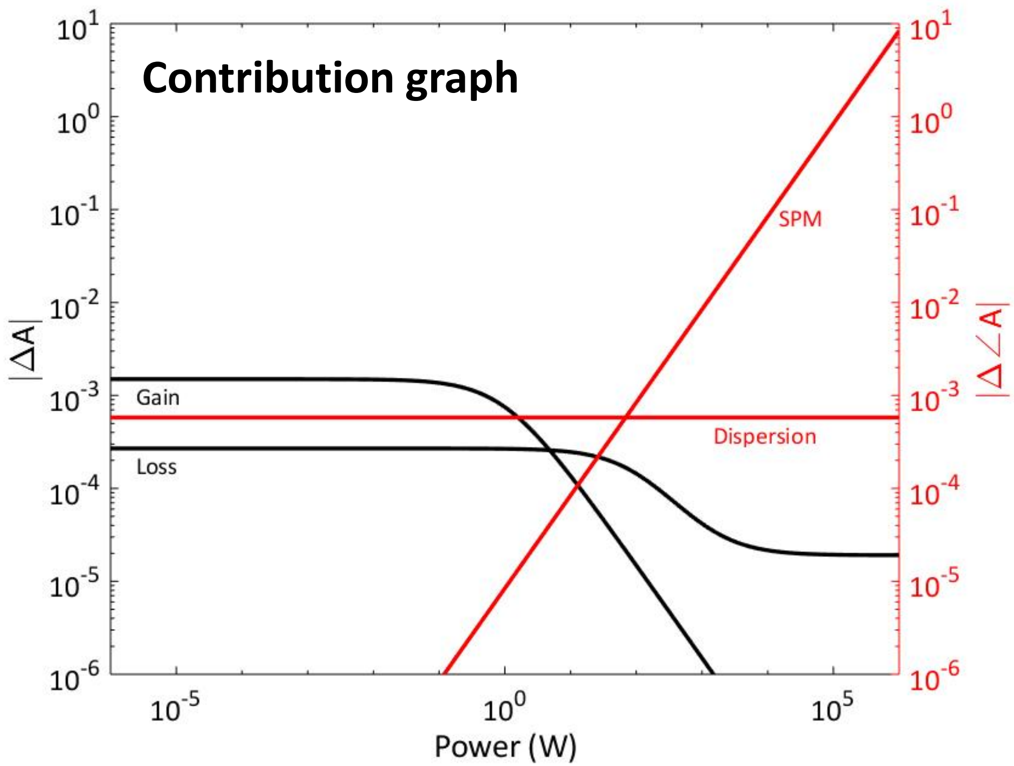

- ✓ Improved device understanding
- ✓ Predictive capability

Modelocked WGM microlaser - simulation

Modified Nonlinear Schrödinger Equation

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

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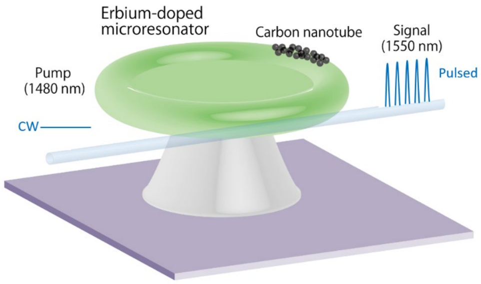
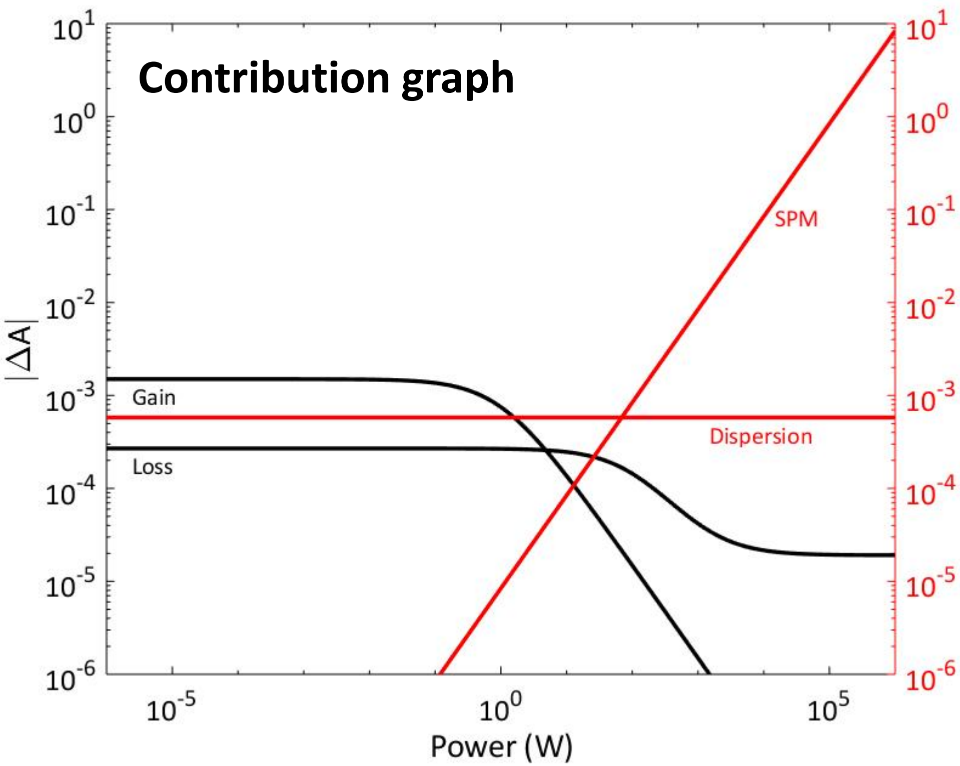
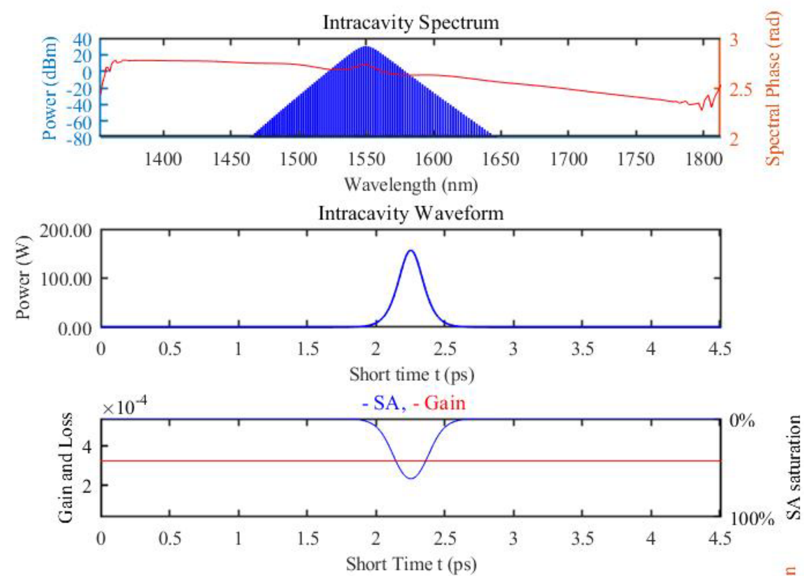




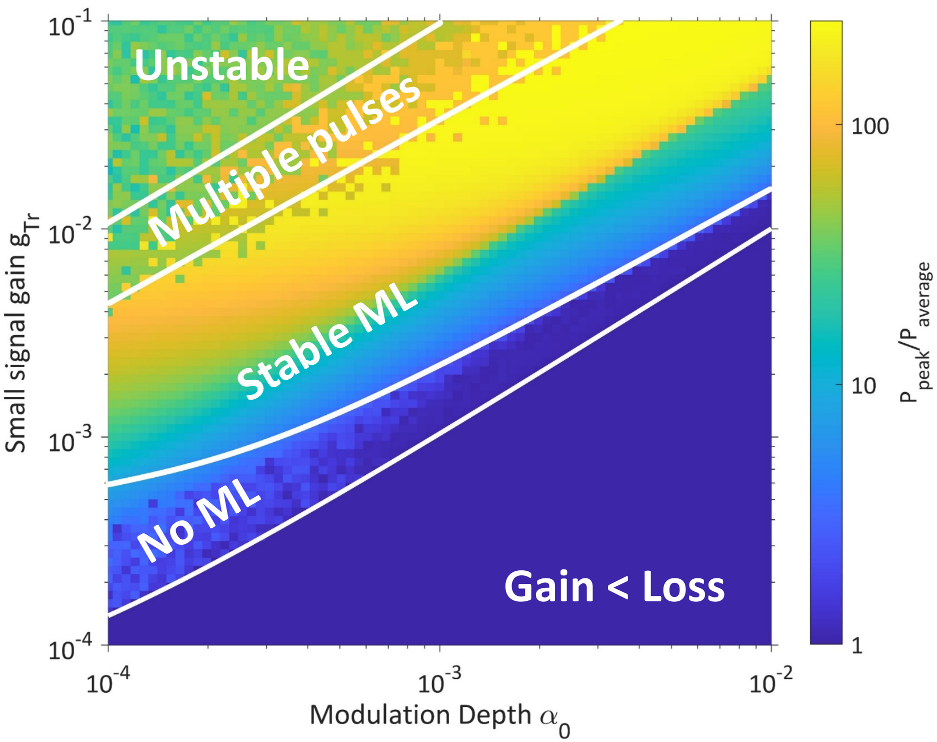


- ✓ Improved device understanding
- ✓ Predictive capability

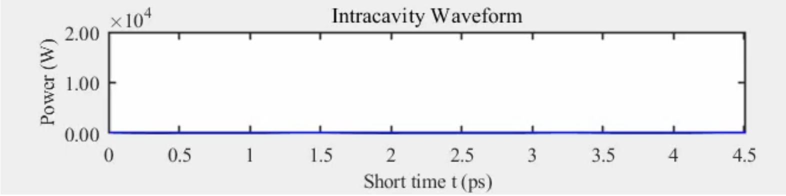
Modelocked WGM microlaser - simulation

$Q=10^8$

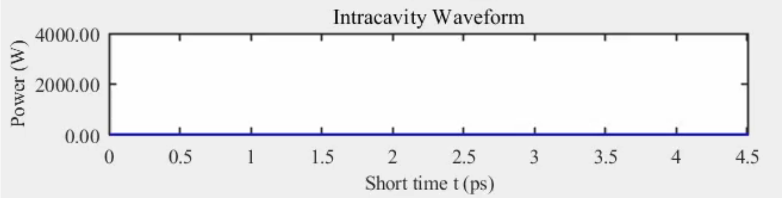
$\beta_2 = -10\ ps^2/km$



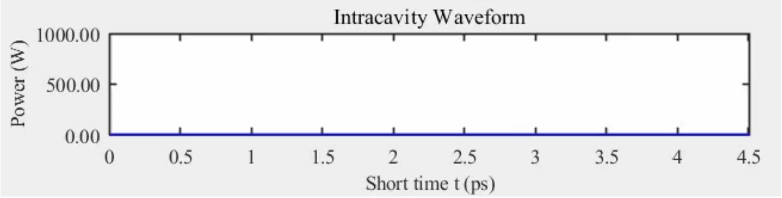
Unstable regime



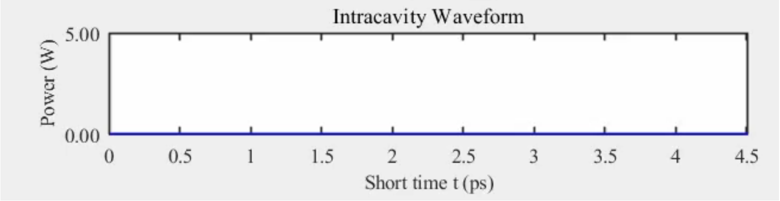
Multiple pulses regime



Stable modelocking regime

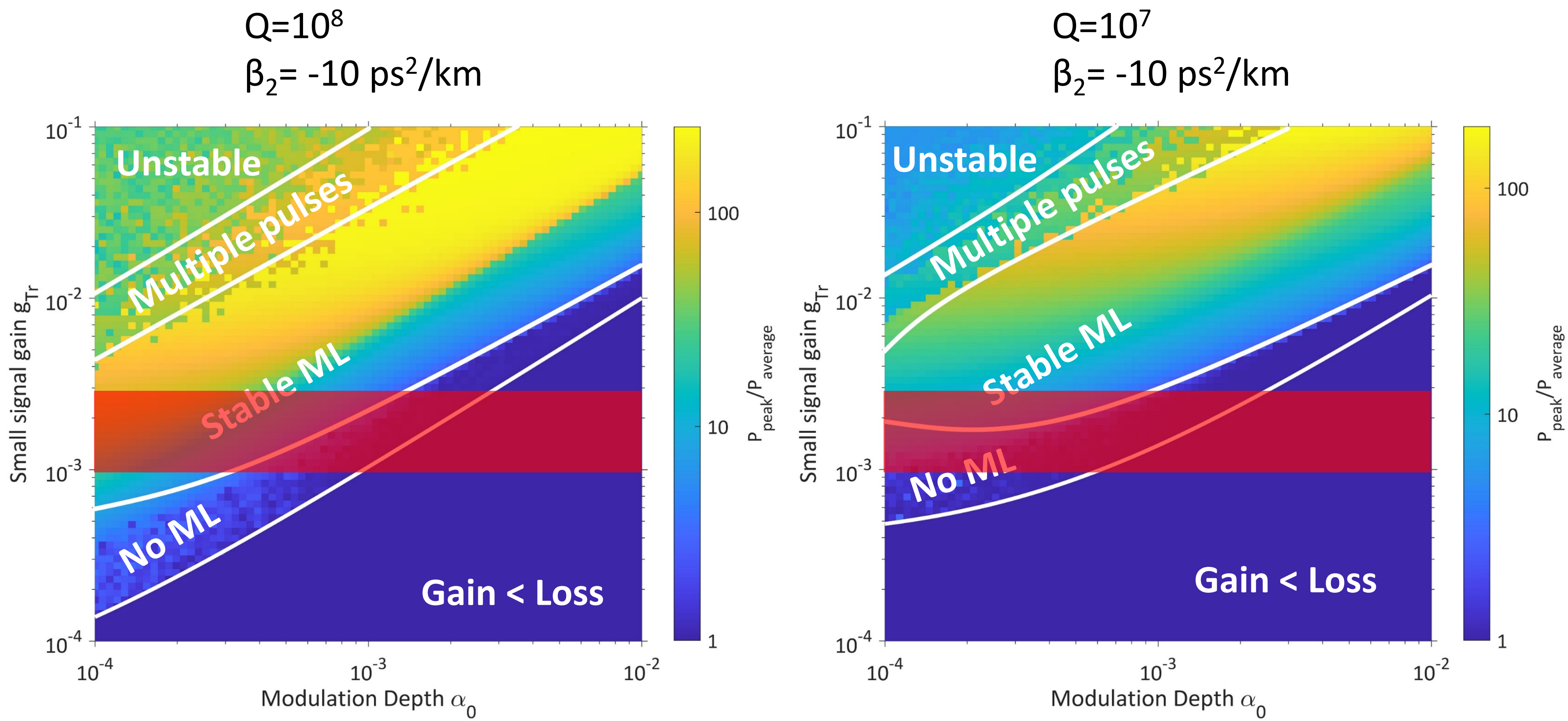


No modelocking regime



Modelocking regime was investigated

Modelocked WGM microlaser - simulation

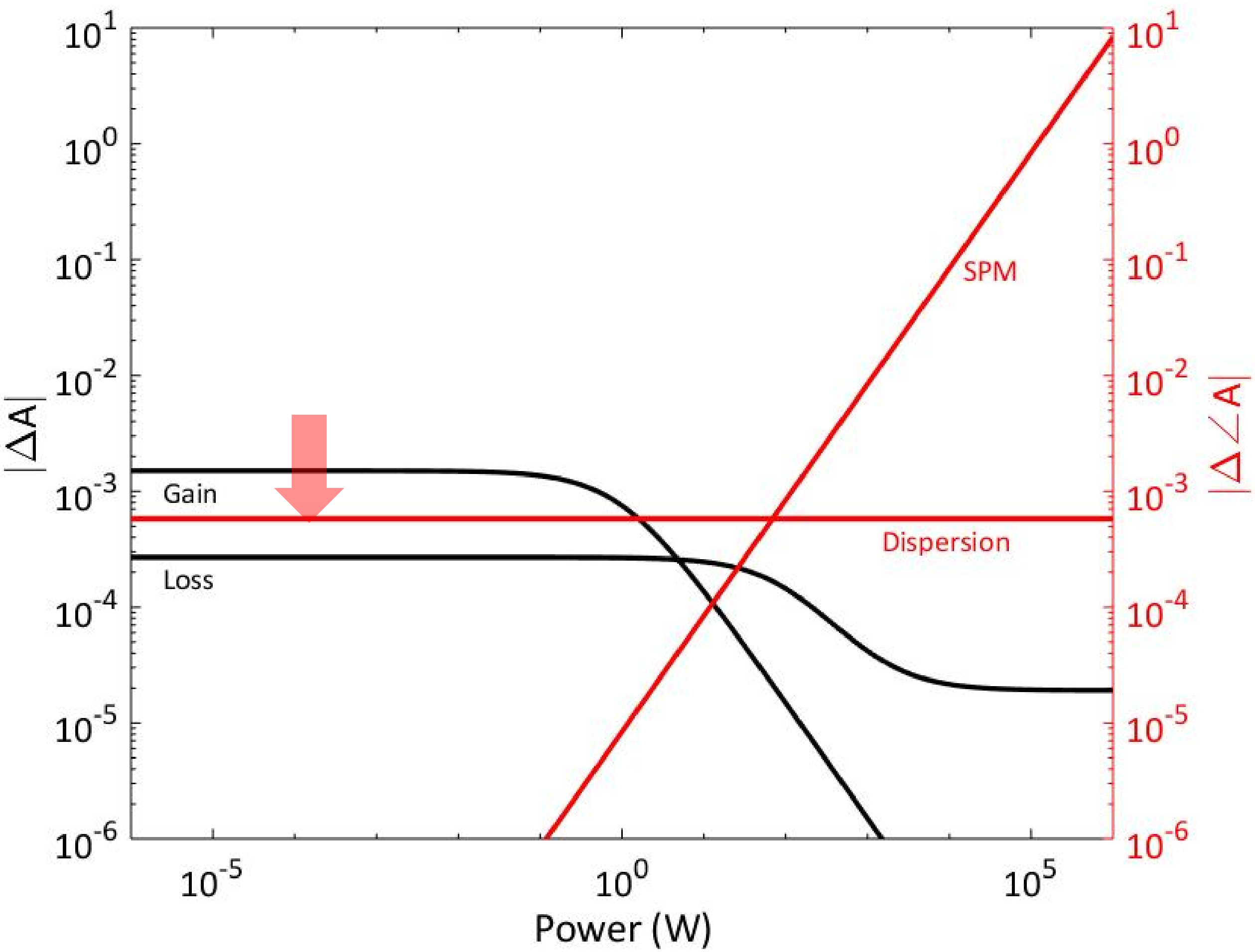


Gain is limiting factor:

→ **Ultra high Q** (>10^7) cavity is necessary for modelocking at low gain

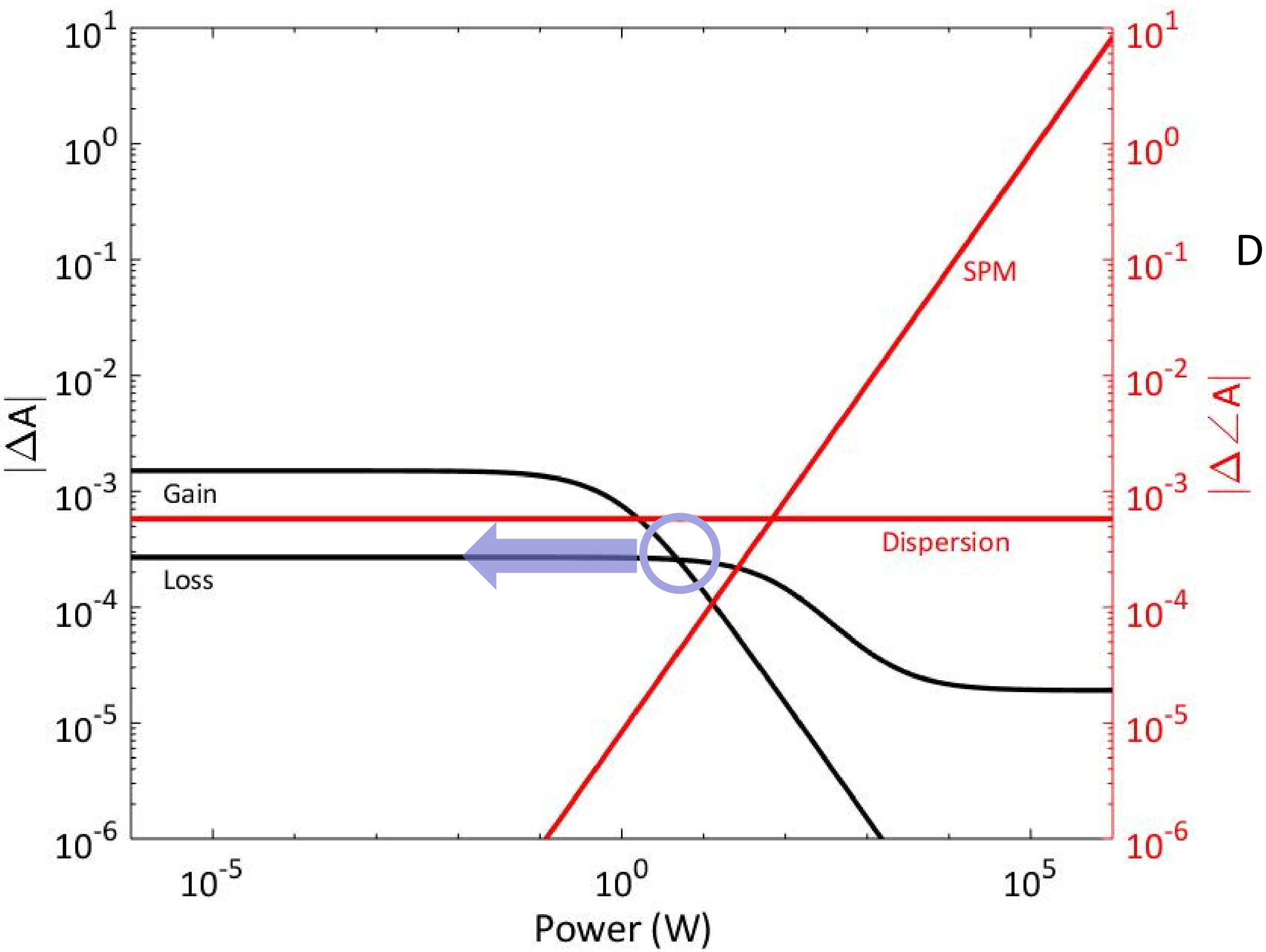
- Gain > loss for CW lasing
- Nonlinear loss by SA dominates loss for pulse formation

Modelocked WGM microlaser - simulation



Low gain

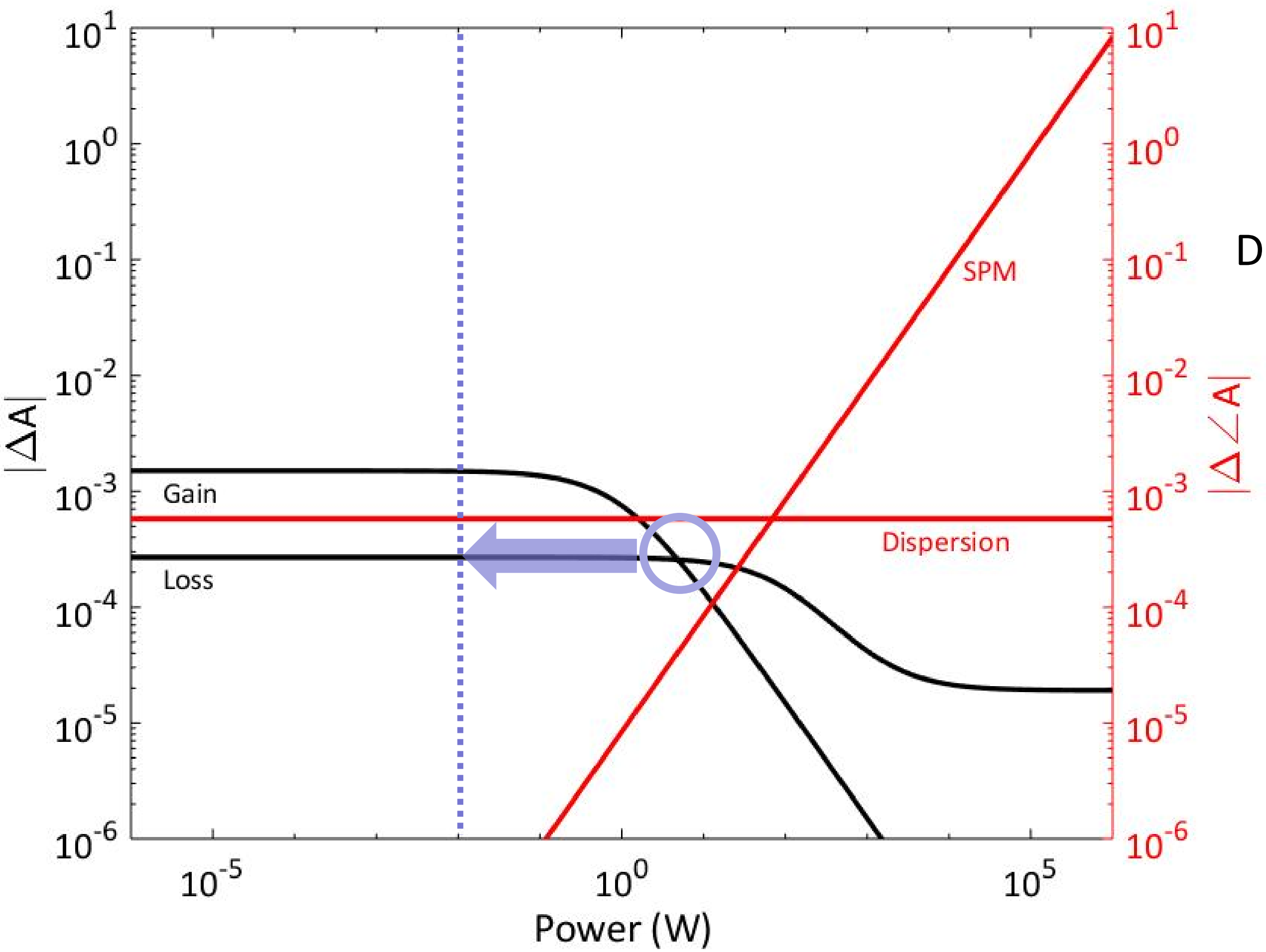
Modelocked WGM microlaser - simulation



Low gain

Decreased intracavity power

Modelocked WGM microlaser - simulation

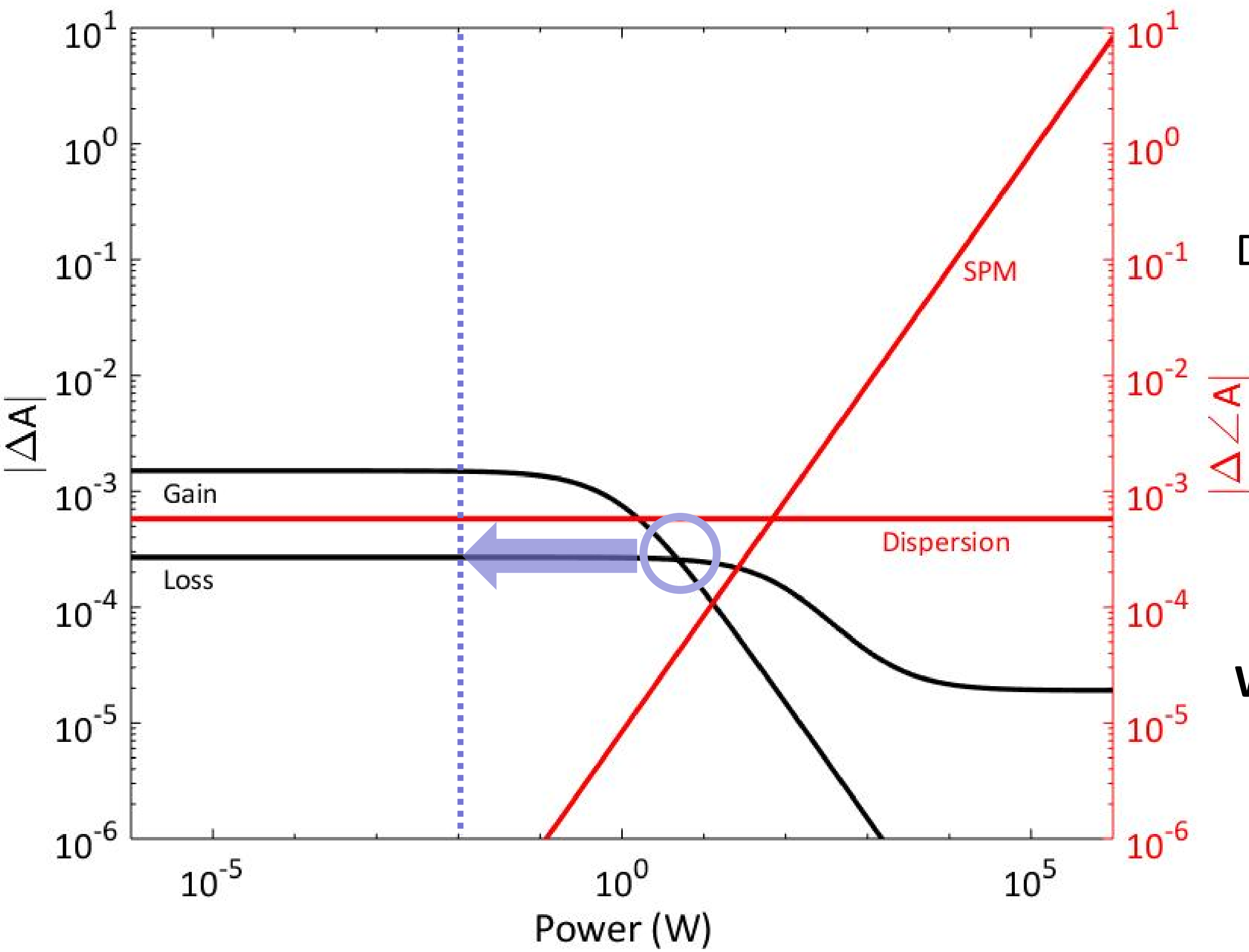


Low gain

Decreased intracavity power

SPM is weak

Modelocked WGM microlaser - simulation



Low gain

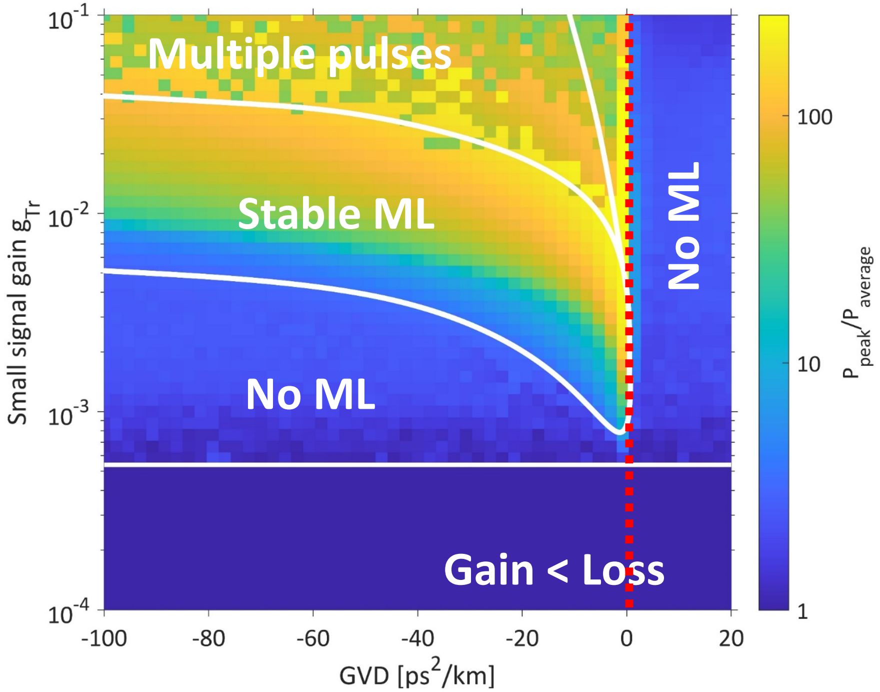
Decreased intracavity power

SPM is weak

Weak dispersion is needed

Modelocked WGM microlaser - simulation

$Q=10^8$
$\alpha_0 = 0.0005$



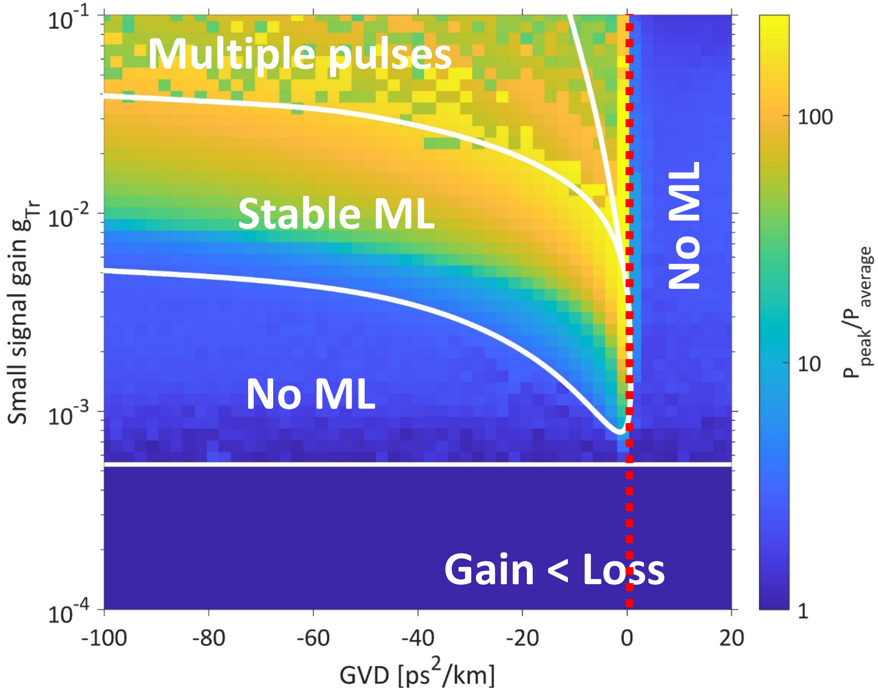
Weak anomalous dispersion is necessary for modelocking at low gain

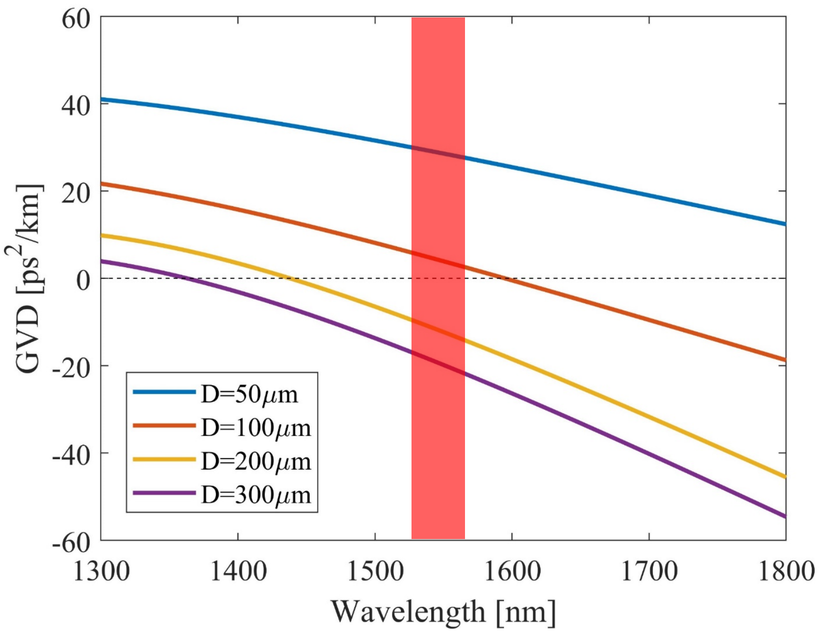
- Pulse formation is the result of gain and nonlinear loss action
- Careful cavity dispersion engineering is necessary

Modelocked WGM microlaser - simulation

Q=10^8

α_0= 0.0005





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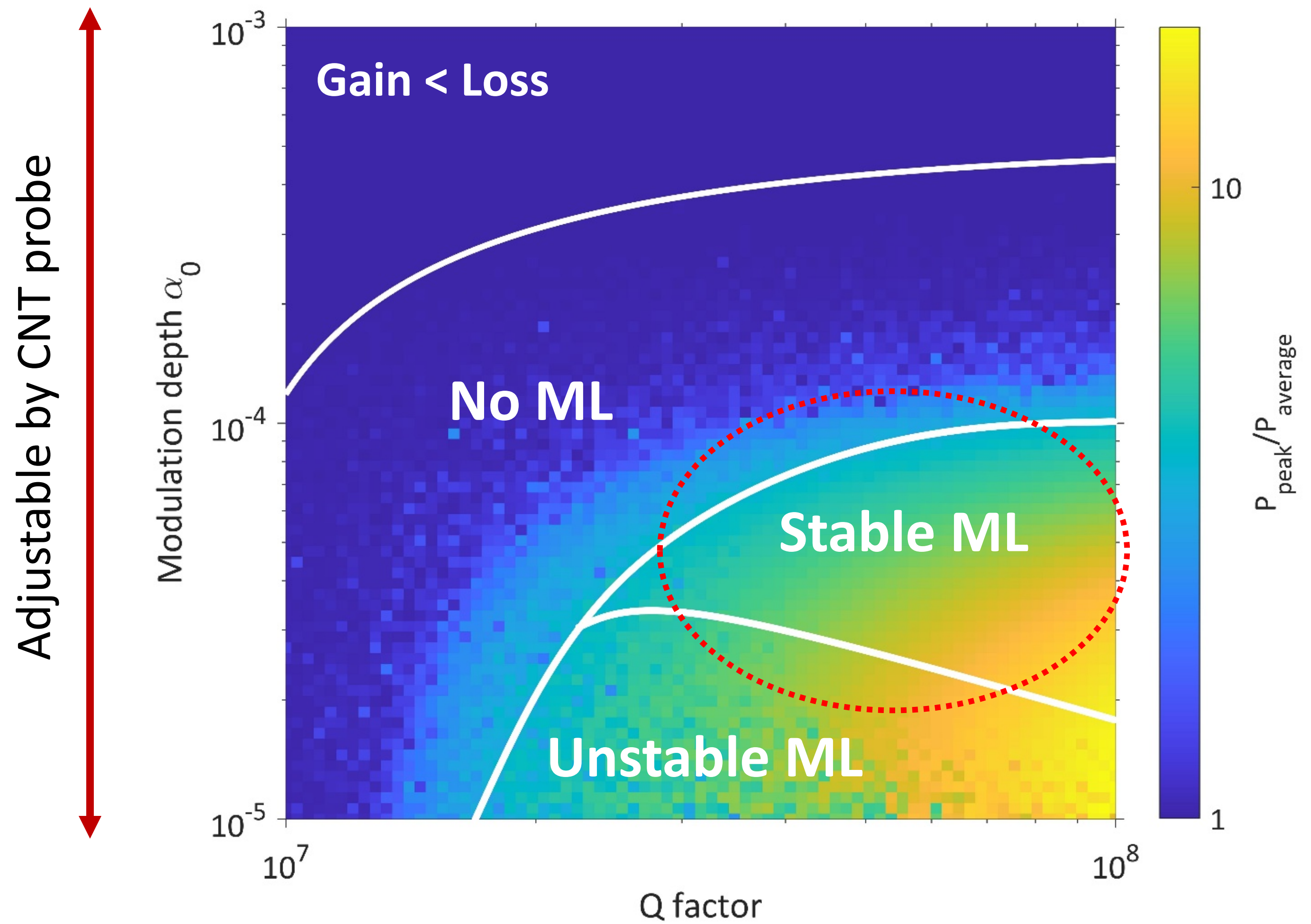
Modelocked WGM microlaser - simulation



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:

Diameter	D=150μm
Q factor	> 10^7
Saturable absorber	CNT probe ($\alpha_0 = 10^{-5} \sim 10^{-4}$)

Thank you for your attention.

This work was suported by JSPS KAKENHI (JP18K19036, JP19H00873), Amada Foundation, and MEXT Q-LEAP.