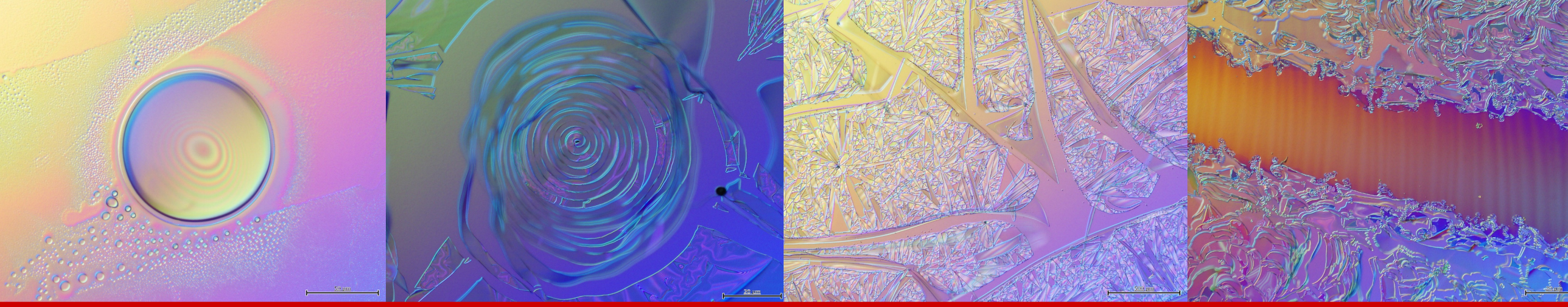

CK-3.5

CLEO/Europe-EQEC 2019 | Jun. 23th

Saturable Absorption with CNT Coupled WGM and Fabrication of Er-doped Microresonator for On-chip Mode-locked Laser

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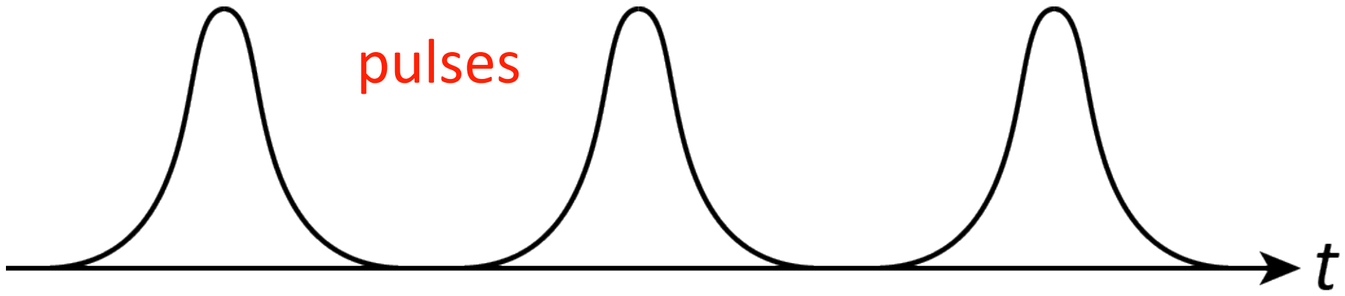
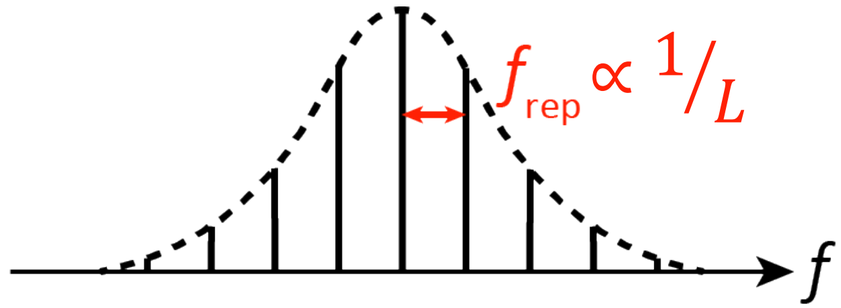
Outline

- Background & Objective
- Numerical model
- Saturable absorption of CNT
- Er-doped microresonator
- Summary

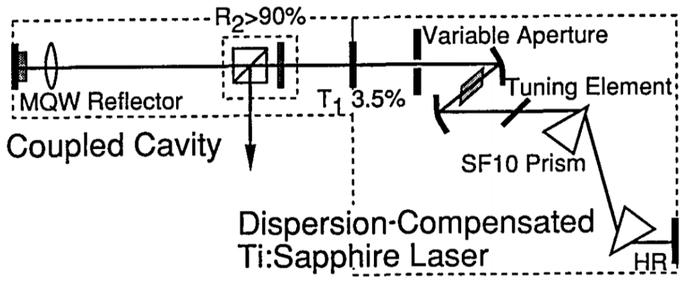
Background: mode-locked laser





laser type	solid-state	semiconductor (MIXSEL)	fiber	microcavity
pulse width	~ 100 fs	~ 1 ps	~ 1 ps	~ 100 fs
repetition rate	~ 100 MHz ○	~ 10 GHz ○	~ 200 MHz △	< 1000 GHz ◎
wavelength	850 nm ×	650 ~ 2200 nm ○	1550 nm ◎	1550 nm ◎
footprint	×	○	△	◎

[1]



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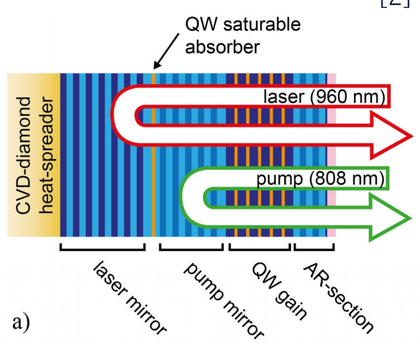

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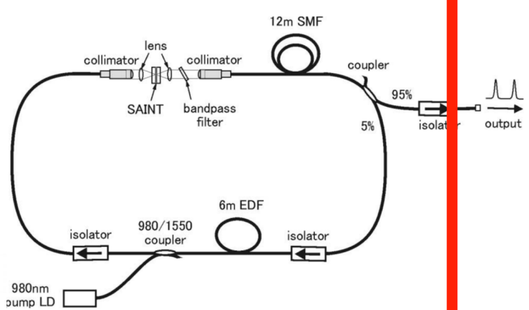
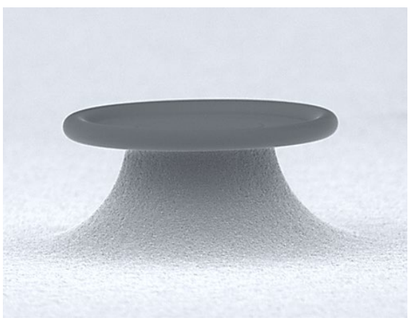


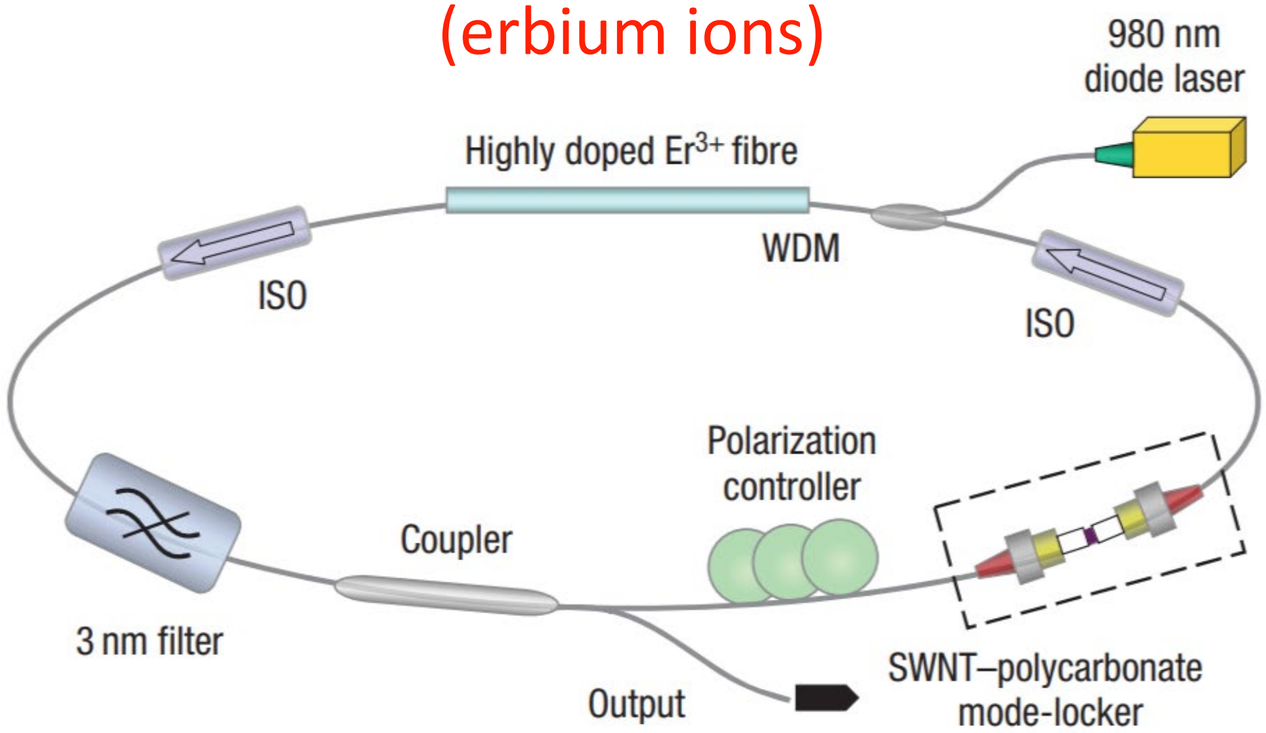


[1] U. Keller, *et al.*, Opt. Lett., **16**, 13, 1022-1024 (1991) [2] M. Mangold, *et al.*, Opt. Express 22, 6099-6107 (2014)
[3] Sze Y. Set, IEEE J. Sel. Top. Quantum Electron., **10**, 1, 137-146 (2004)

Background: mode-locked fiber ring system

gain medium (erbium ions)

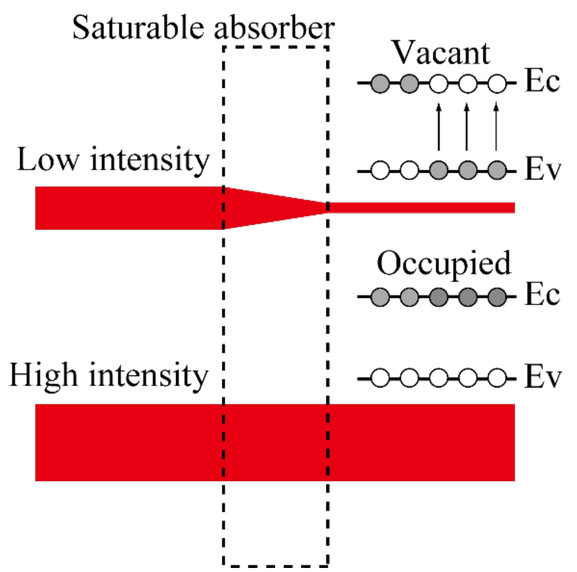
pump (CW)

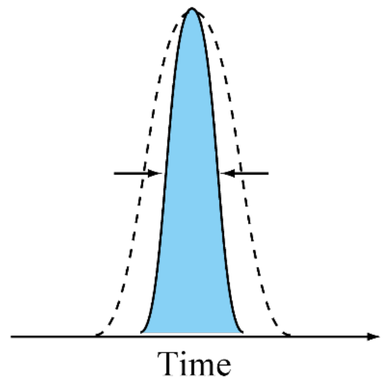


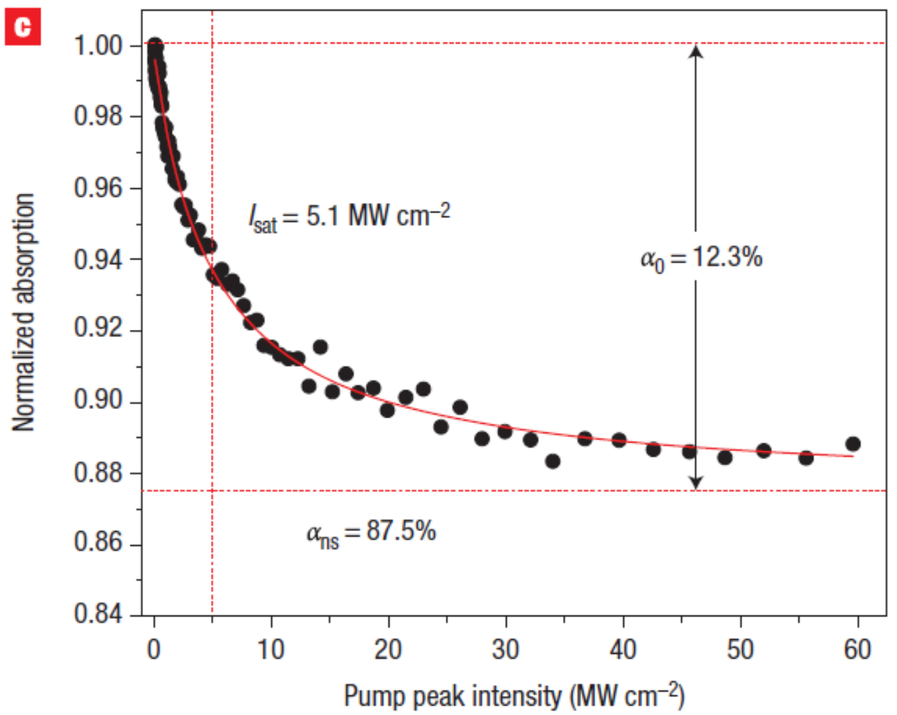
lasing at 1550 nm

saturable absorber (carbon nanotube)

Saturable absorption







F. Wang, *et al.*, Nat. Nanotechnol., **3**, 738-743 (2008)

Realizing this system with microcavity

cavity length : 13.3 m → 200 μm

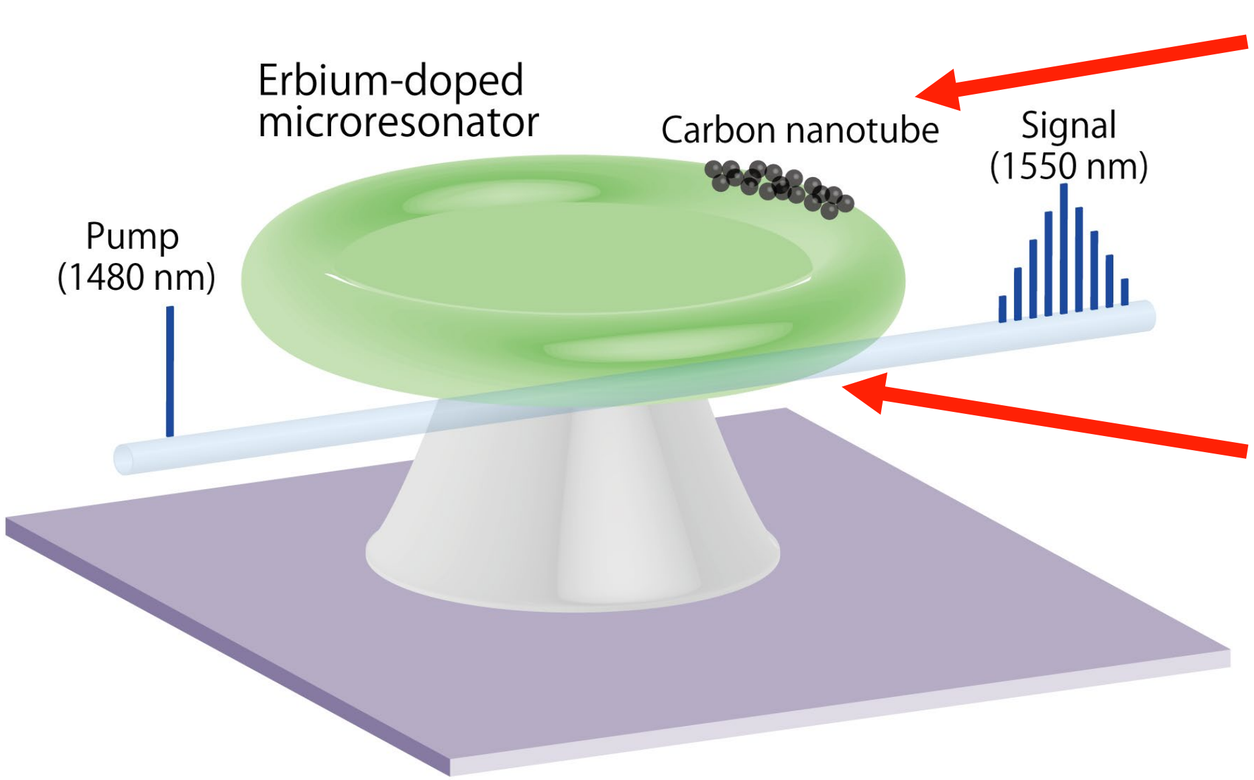
repetition rate : 15 MHz → 1000 GHz

F. Wang, *et al.*, Nat. Nanotechnol., **3**, 738-743 (2008)

Objective:

Mode-locked laser with microresonator

- high repetition rate (> GHz)
- small footprint
- on-chip integrability



1. Passive mode-locker

CNT(saturable absorber)

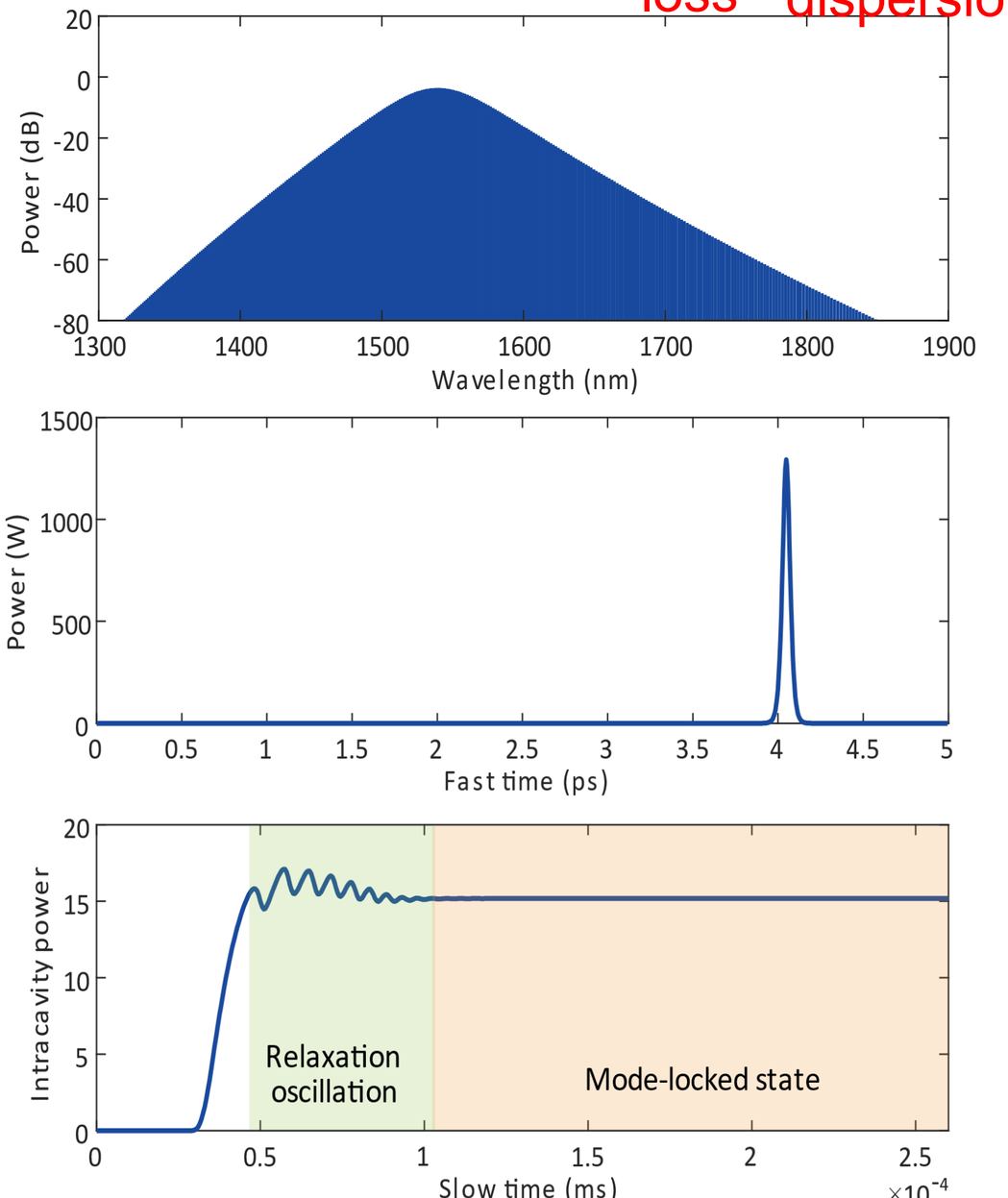
2. Gain medium

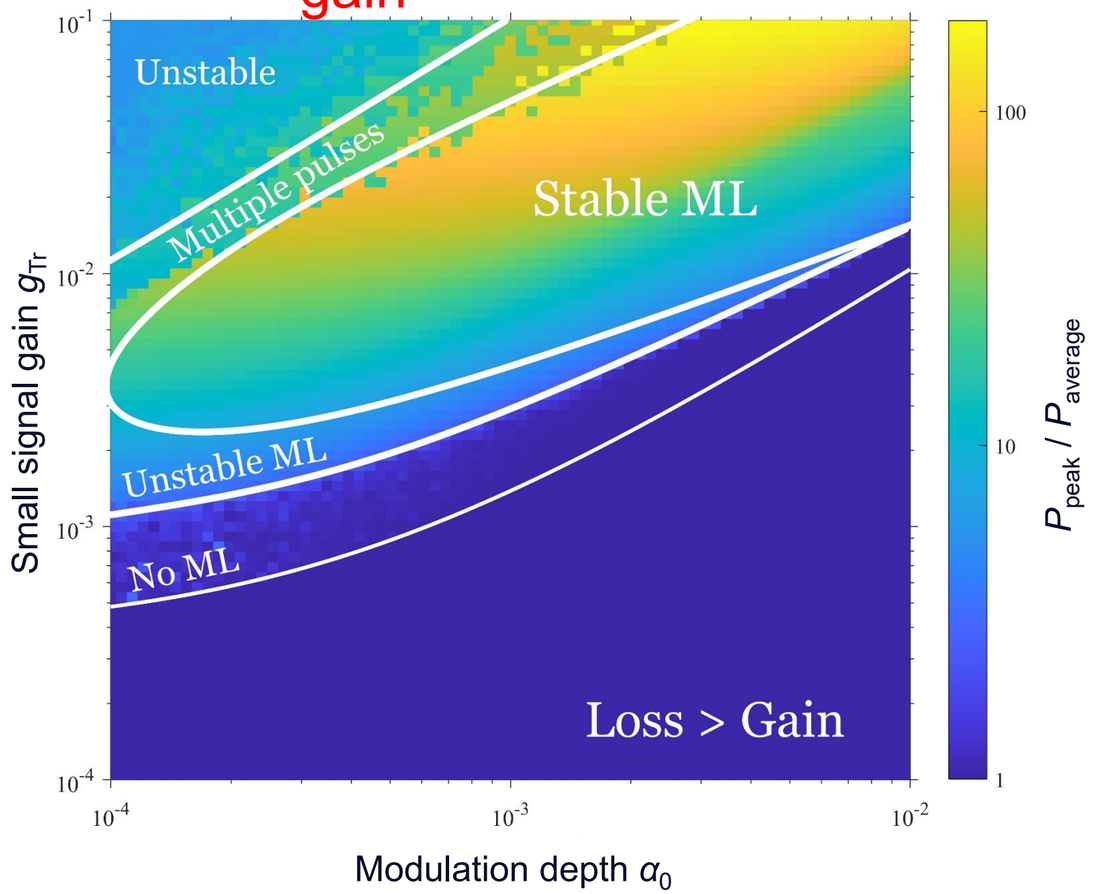
Erbium ions

Numerical model

Model: Nonlinear Schrödinger equation

$$t_R \frac{\partial E(t,\tau)}{\partial t} = \left[\underbrace{-\frac{\alpha_{\mathrm{tot}}}{2}}_{\text{loss}} \underbrace{-\frac{iL}{2}\beta_2 \frac{\partial^2}{\partial \tau^2}}_{\text{dispersion}} \underbrace{+ iL\gamma|E|^2}_{\text{SPM}} \underbrace{+ g(t) + \frac{g(t)}{{\Omega_g}^2}\frac{\partial^2}{\partial \tau^2}}_{\text{gain}} \underbrace{- q(t,\tau)}_{\text{SA}} \right] E$$





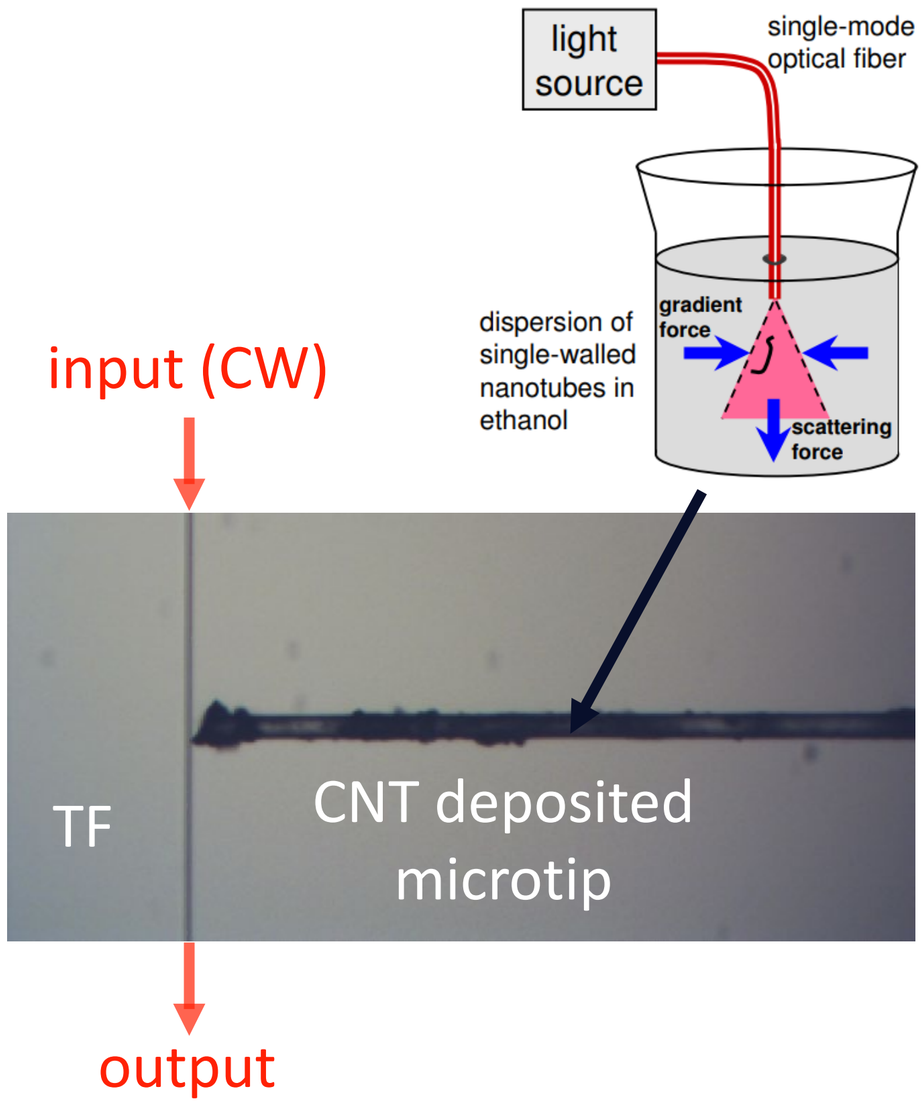
FSR = 200 GHz
$Q = 1 \times 10^7$

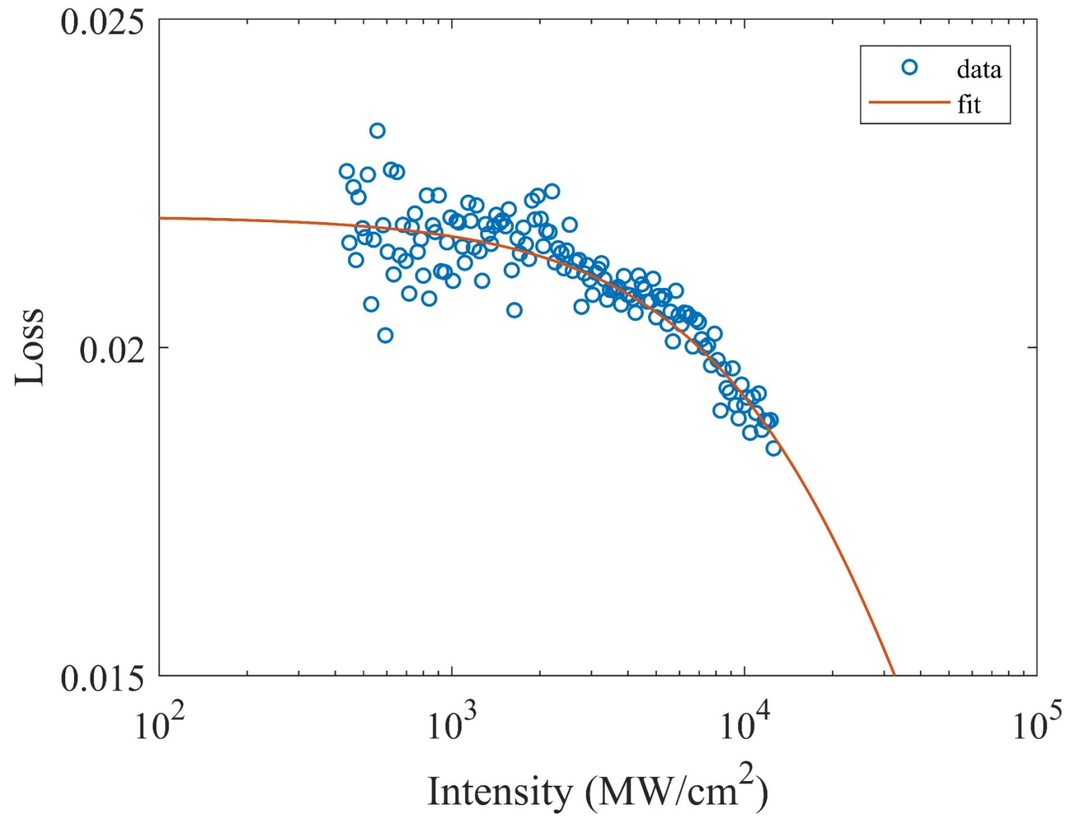
$\beta_2 = -10$ ps²/km
$g_0 = 0.01$
$q_0 = 0.049$

Saturable absorption of CNT

Optical deposition on fiber microtip

J. W. Nicholson, *et al*., Opt. Express, **15**, 15, 9176-9183 (2007)

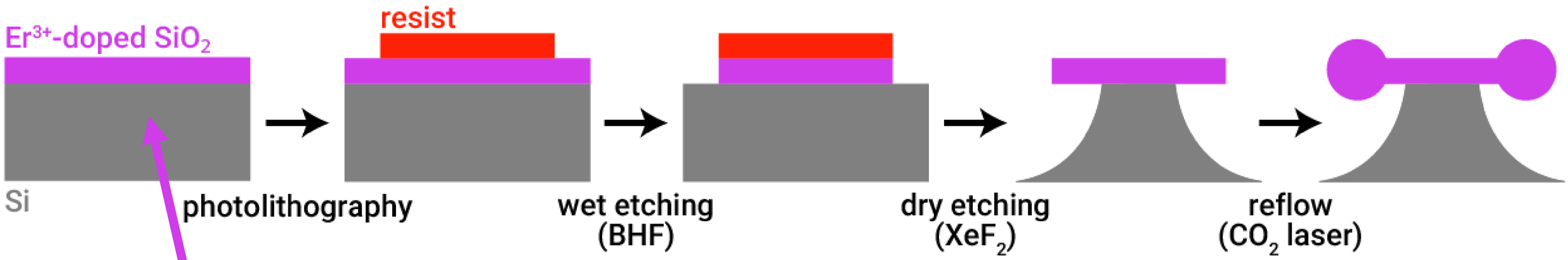




- By using optical deposited fiber tip, saturable absorption was observed
- By changing the gap distance between microtip and tapered fiber, the absorption can be controlled.

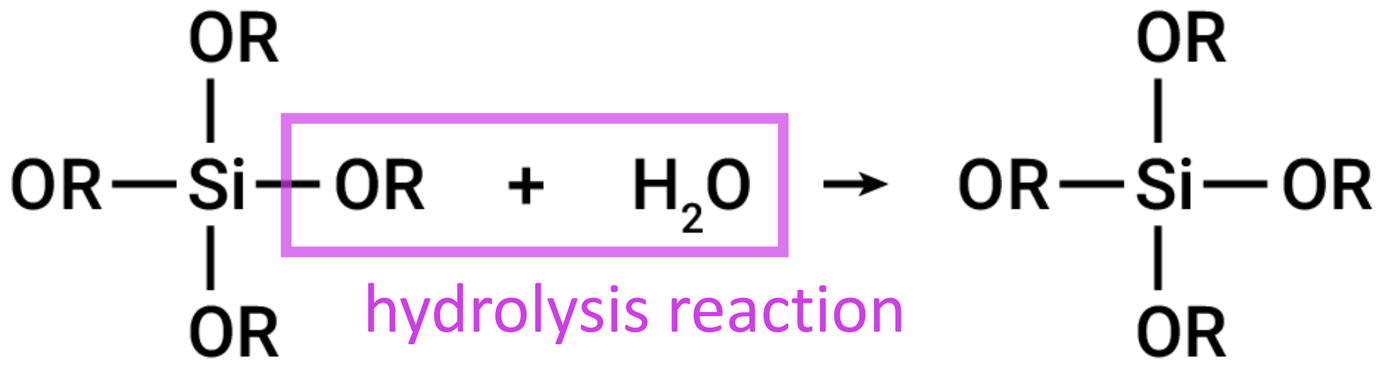
Er-doped microresonator: Process flow

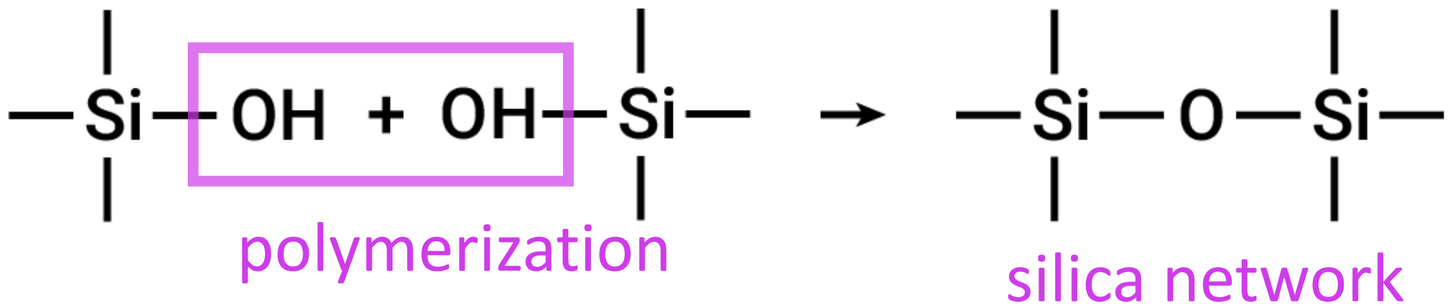
Fabrication flow of microtoroid by sol-gel method (cross-section).



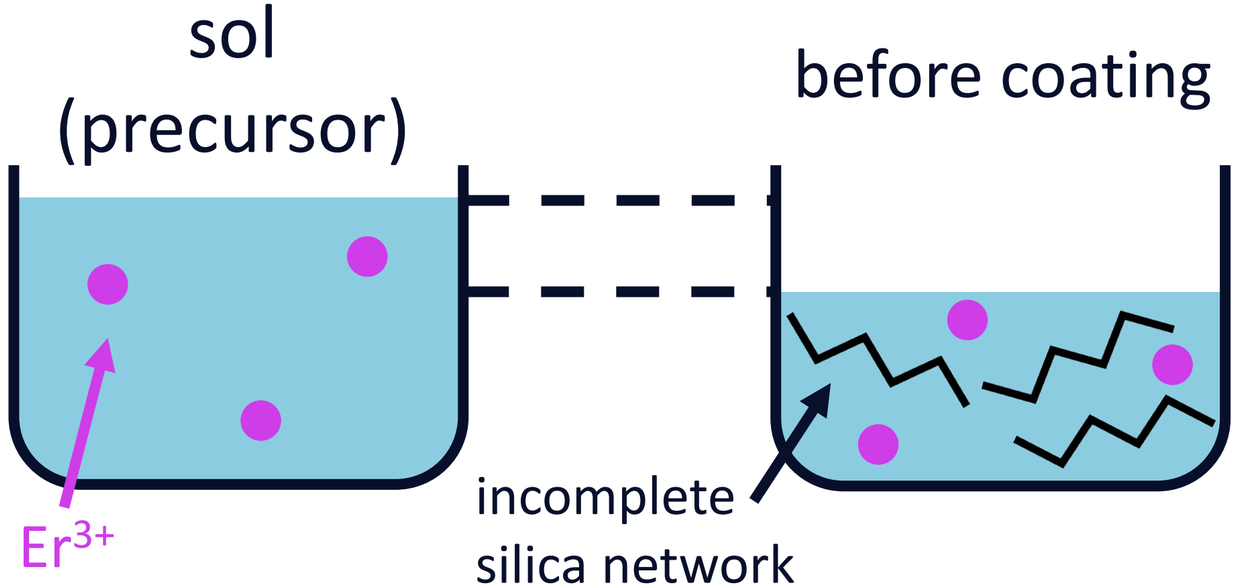
sol-gel method:

TEOS:

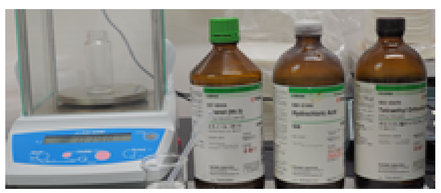




Er-doped microresonator: Process flow



Precursor mixing
- TEOS
- Ethanol
- H_2O
- HCl
- $Er(NO_3)_3 \cdot nH_2O$



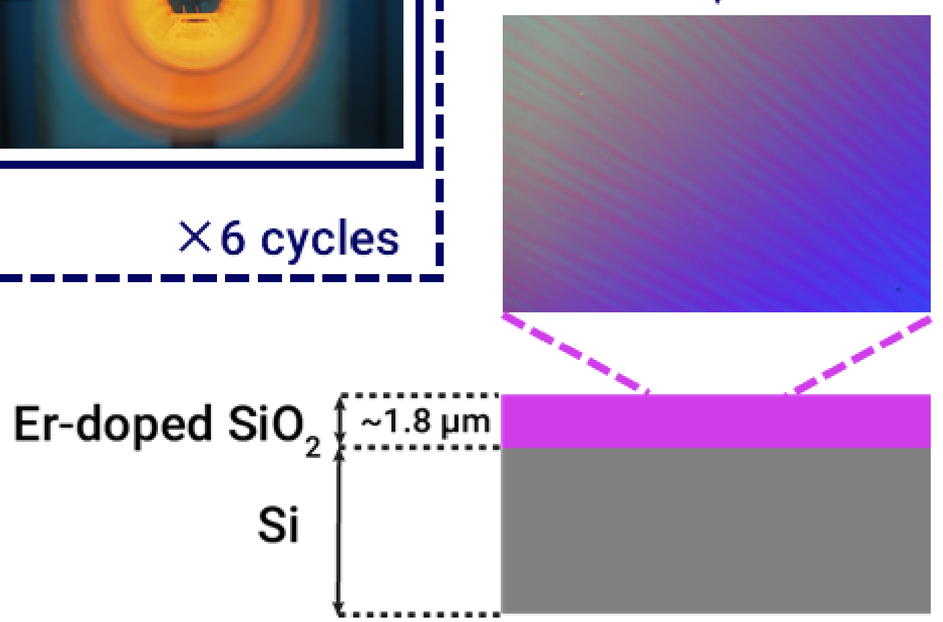
Cleaning
- Ethanol
- O_2 plasma ashing
- heating
  150°C, 3 min

Spin-coating
- 4000 rpm, 40 sec

Annealing
- 1000°C, 10 min
- N_2 atmosphere

×6 cycles

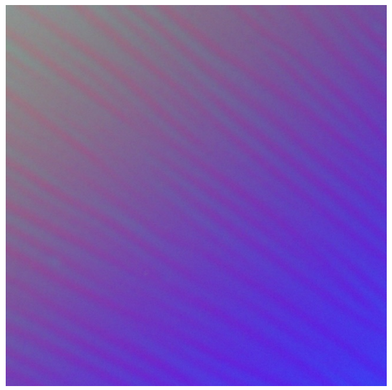
Annealing
- 1000°C, 1 hour
- N_2 atmosphere



Er-doped microresonator: Fabrication result

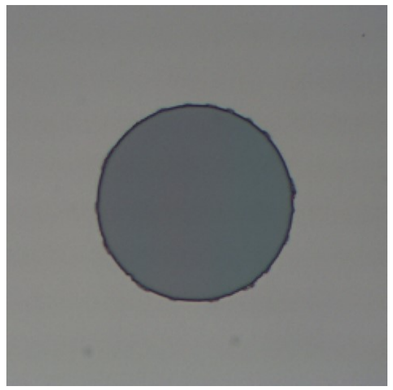
The thickness of sol-gel film is ~ 1.8 μm with 6 layers (~ 300 nm/layer).

forming sol-gel film

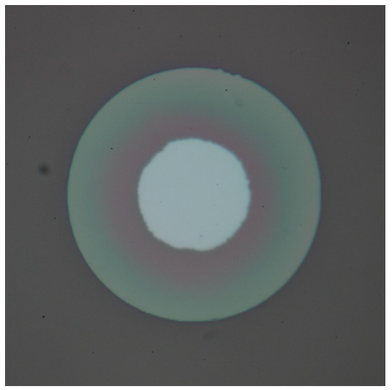


forming pattern

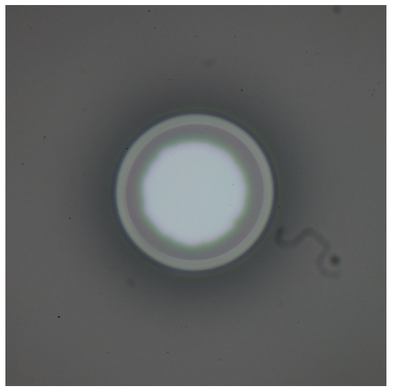
etching of silica layer



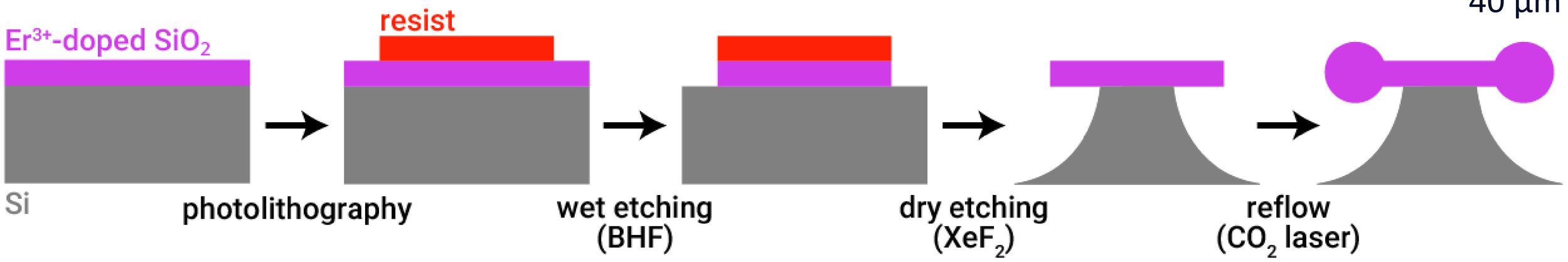
undercutting silicon pillar

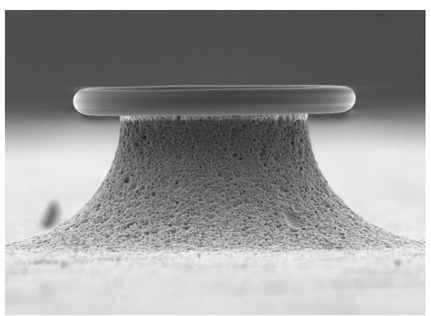


forming toroidal rim

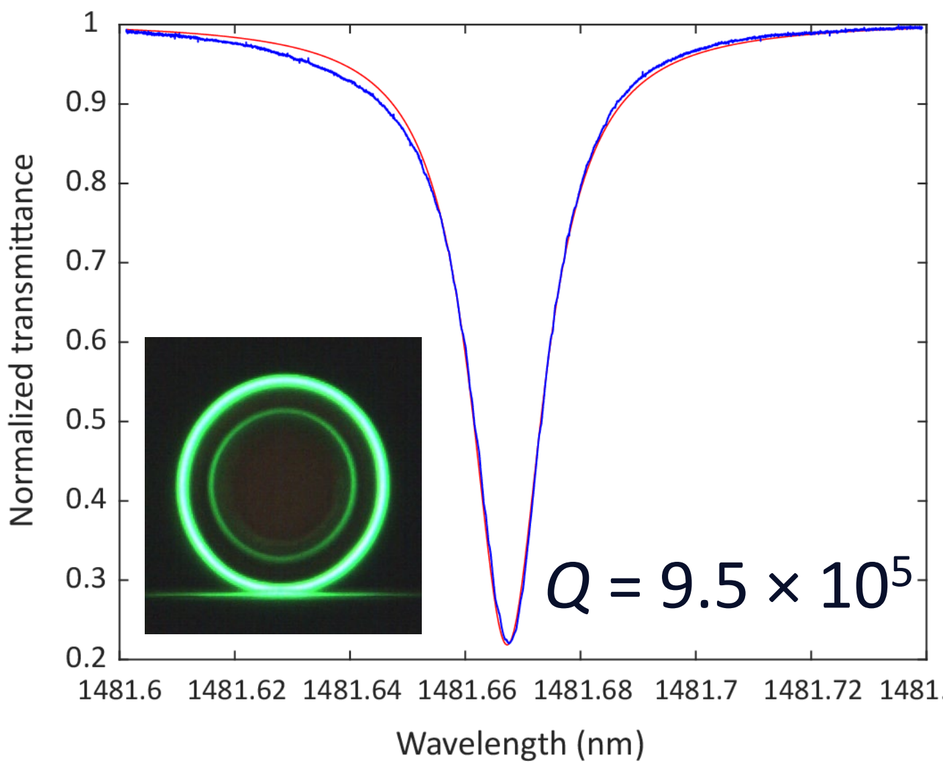


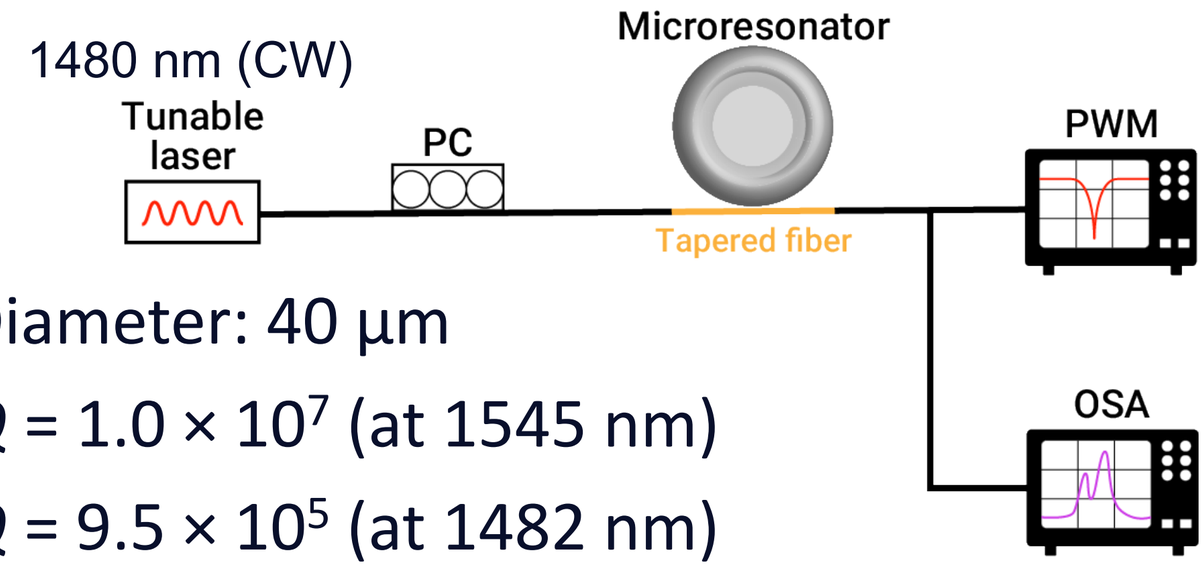
40 μm





Er-doped microresonator: Measurement





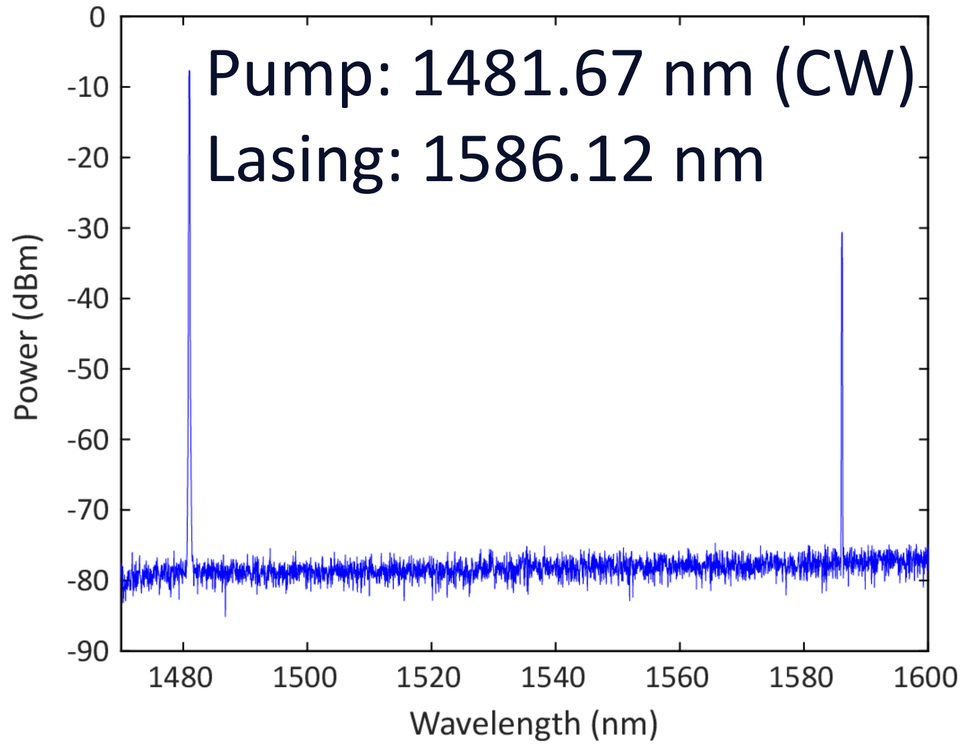
Diameter: 40 μm

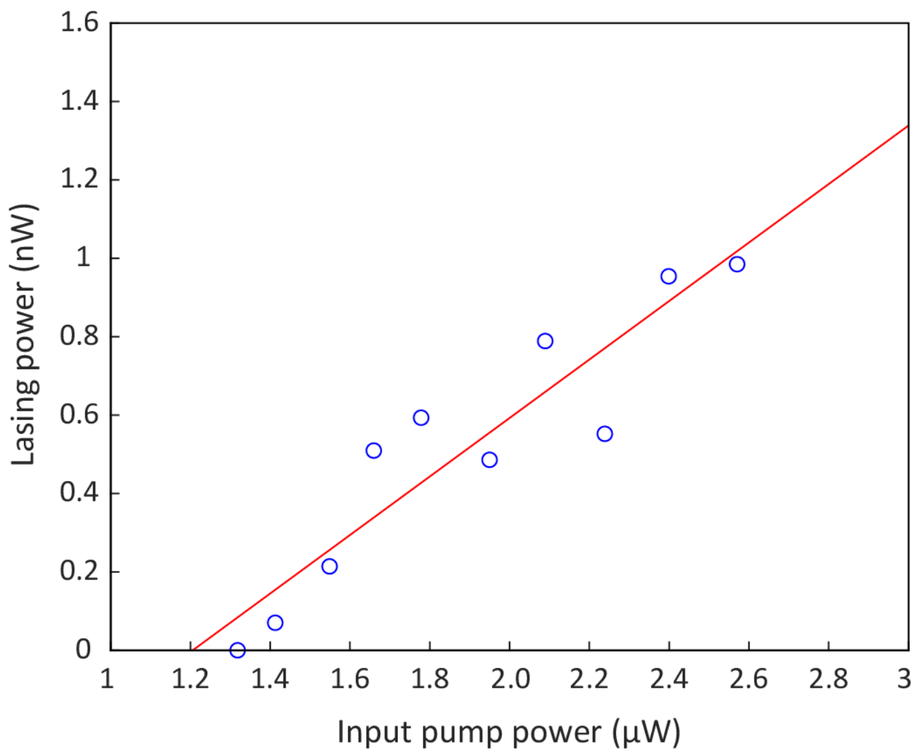
$Q = 1.0 \times 10^7$ (at 1545 nm)

$Q = 9.5 \times 10^5$ (at 1482 nm)

Er concentration: 1.9×10^{18} cm^{-3}

Threshold power: 1.2 μW





Summary

Objective:

On-chip mode-locked laser with CNT and Er-doped microresonator

Achievement:

- Saturable absorption of CNT
  - SA is obtained by using microtip
- Er-doped microresonator
  - Fabrication of Er-doped microtoroid
  - Lasing at ~ 1580 nm

Future plan:

- Measuring gain (g_0) of Er-doped microtoroid
- Integration of CNT and Er-doped microtoroid

Thank you.

Acknowledgement:

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