
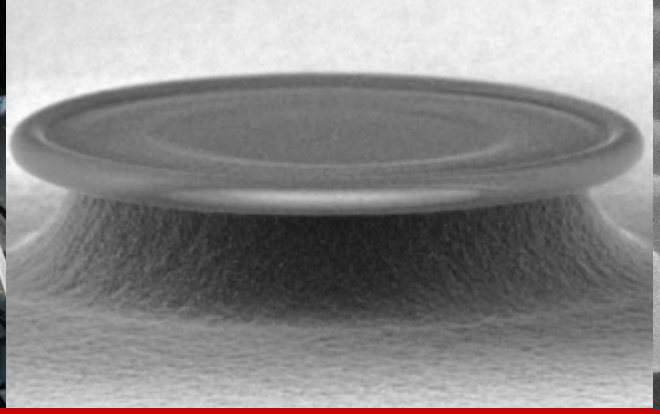
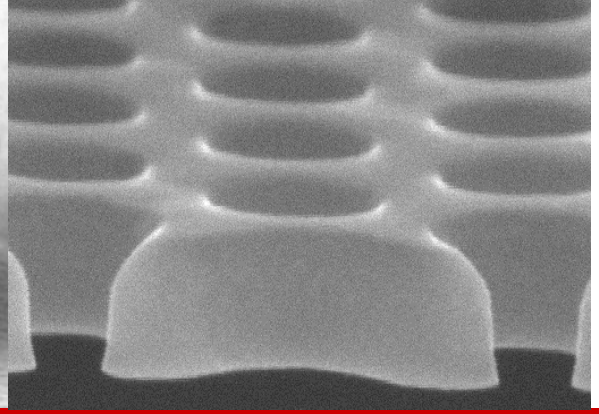
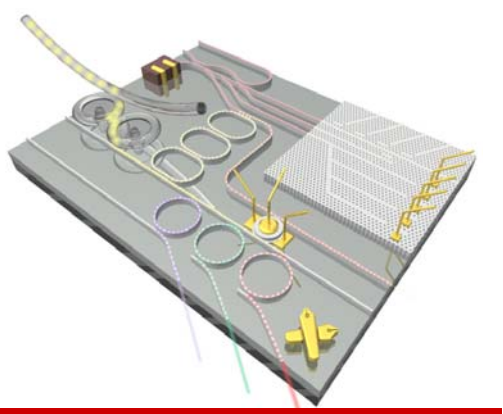

CLEO/Europe - EQEC 2015

Fabrication of Crystalline WGM Microcavity using Ultra-precision Machining to Reveal the Size Dependence of Thermo-opto-mechanical Oscillation

Electronics and Electrical Engineering, Keio University, Japan

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June 23, 2015, 17:15~17:30

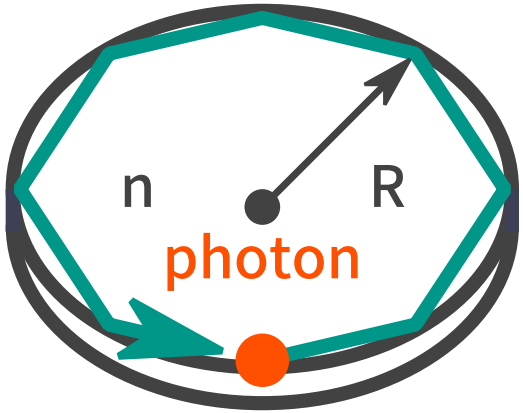
Whispering gallery mode (WGM) microcavity

High Q & small V are preferred

$$Q = \left(Q_{\text{scat}}^{-1} + Q_{\text{abs}}^{-1} + Q_{\text{coup}}^{-1} + \cdots\right)^{-1}$$

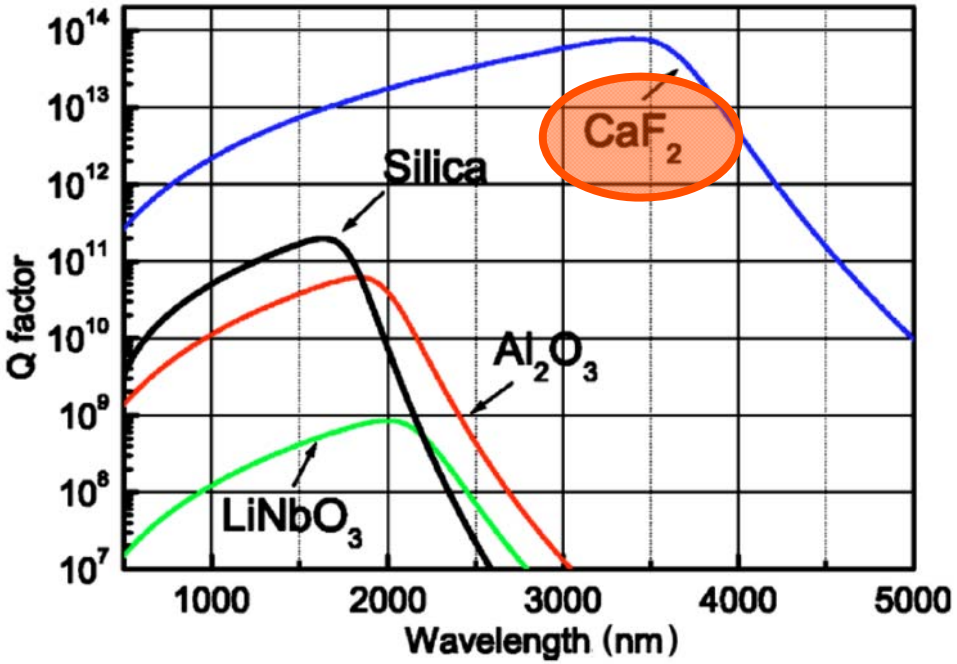
Q_{abs}: Material absorption dependent

WGM microcavity



circulating & trapped

Q_{abs} of various materials



A. A. Savchenkov, *et al.*, Phys. Rev. A **70**, 051804 (2004).

CaF_2 microcavity:

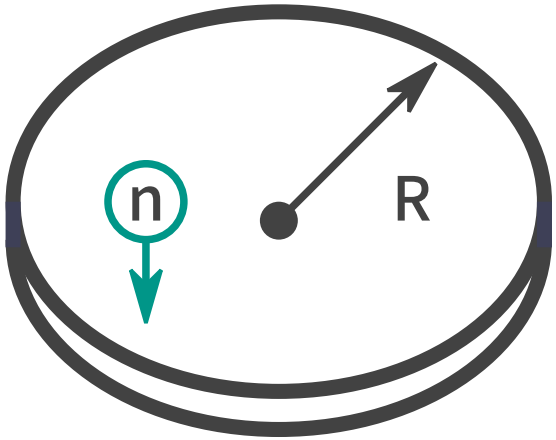
Pros: Very high-Q ($Q > 10^9$)

Cons: Mechanical polishing

Thermo-opto-mechanical (TOM) oscillation

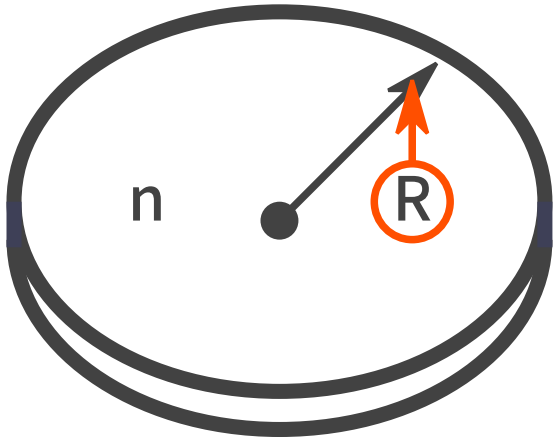
Origin: Negative thermo-optic coefficient (dn/dT) of CaF_2

Thermo-optic effect



n decreases
→ L becomes **smaller**

Thermal expansion effect

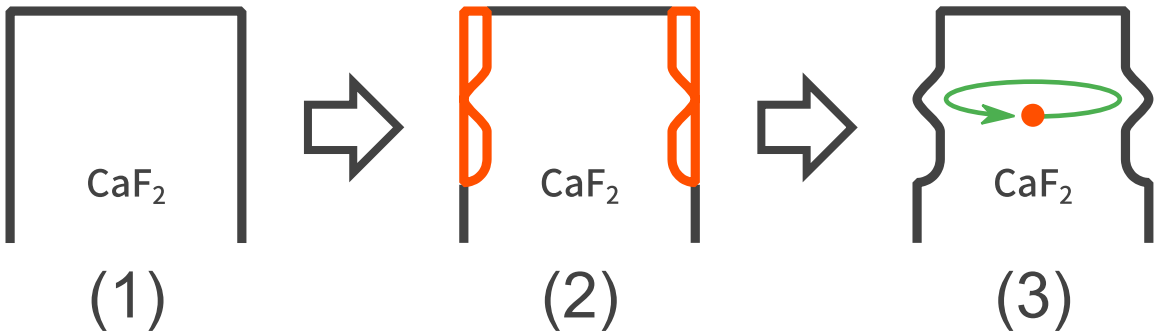


R increases
→ L becomes **larger**

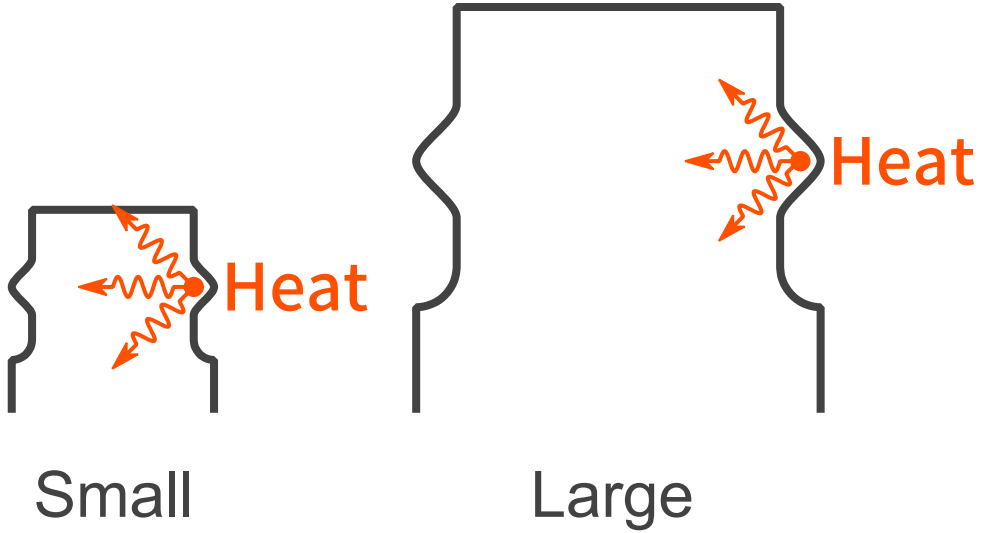
n : refractive index, R : radius, L : cavity length

Research goals

(1) Fabricate crystalline (CaF_2) WGM microcavities

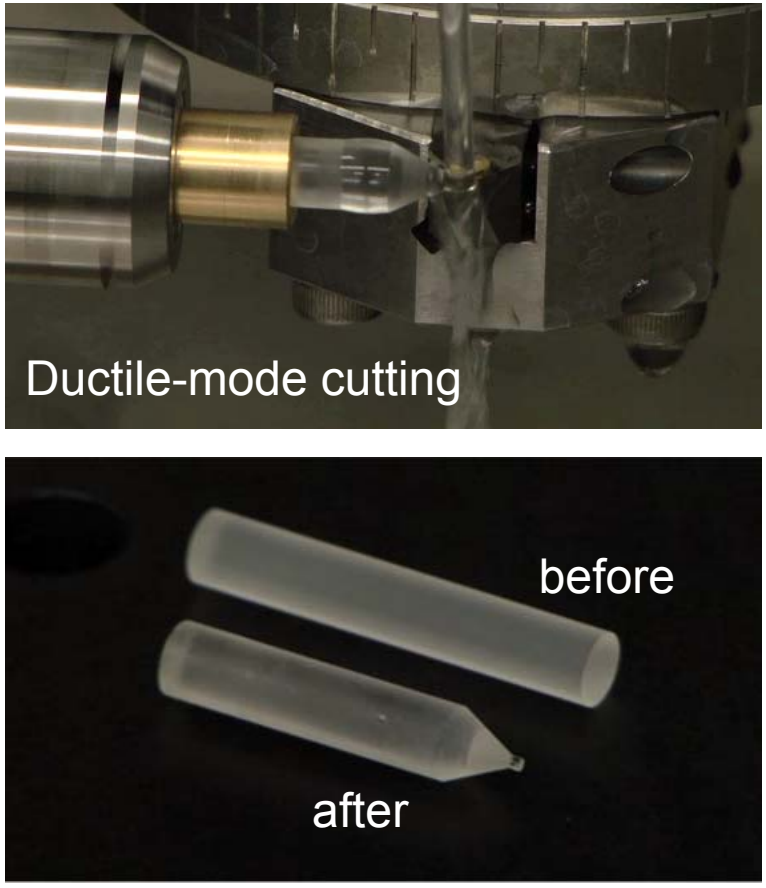


(2) Investigate size dependence of TOM oscillation



Fabrication: Lathe cutting

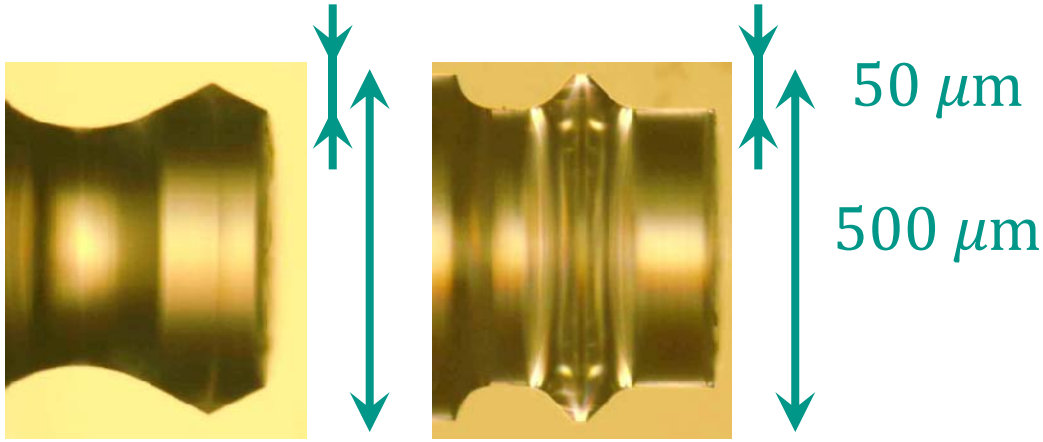
Ultra-precision cutting



Parameters:

- Cutting depth : $50\ \mathrm{nm}$
- Rotation speed : $1000\ \mathrm{min}^{-1}$

Fabricated CaF_2 microcavity



$$Q = \left(Q_{\mathrm{scat}}^{-1} + Q_{\mathrm{abs}}^{-1} + Q_{\mathrm{coup}}^{-1} + \cdots\right)^{-1}$$

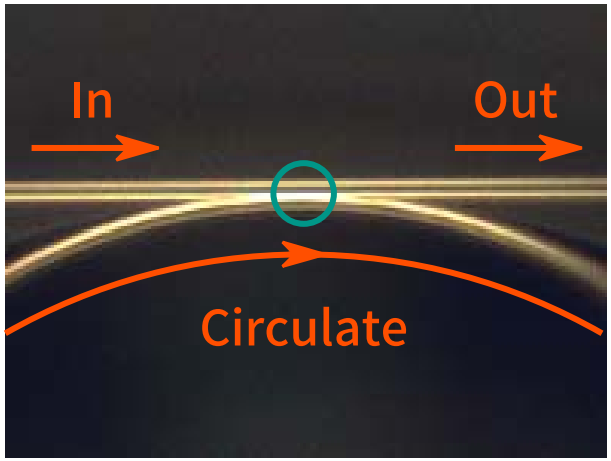
Q_{scat}: Surface scattering

surface roughness $(R_{\mathrm{rms}}) =$ **3 nm**

∵ **ultra-precision cutting**

Optical measurement & Surface roughness

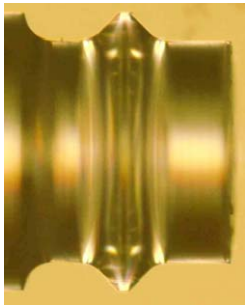
Q measurement

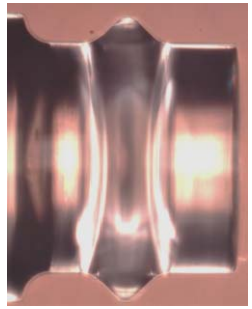


Parameters:

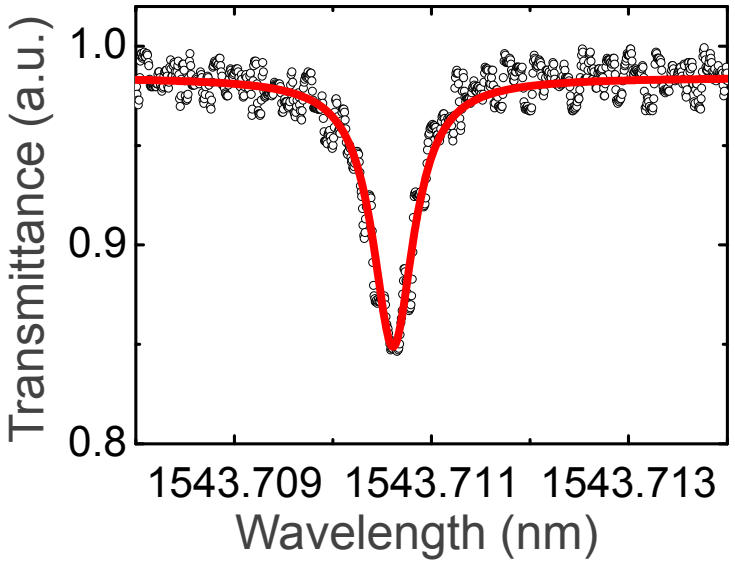
- Fiber diameter: 3~5 μm
- Input power: 1 mW
- Scan speed: 1 nm/s

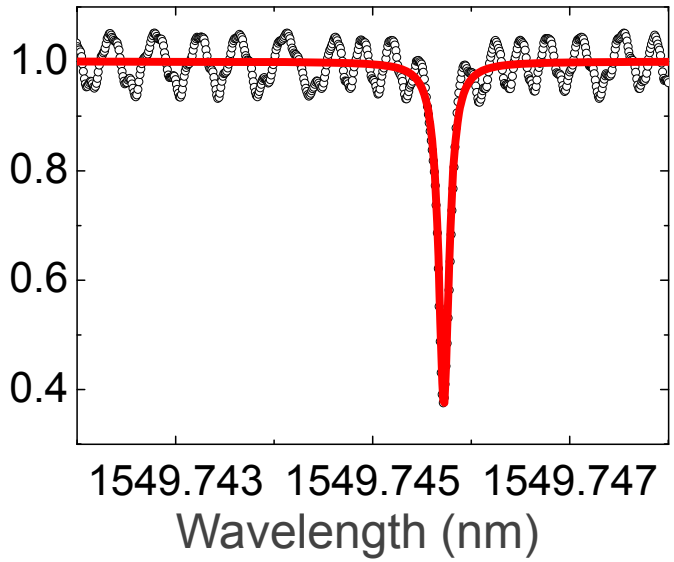
Before polishing → After polishing





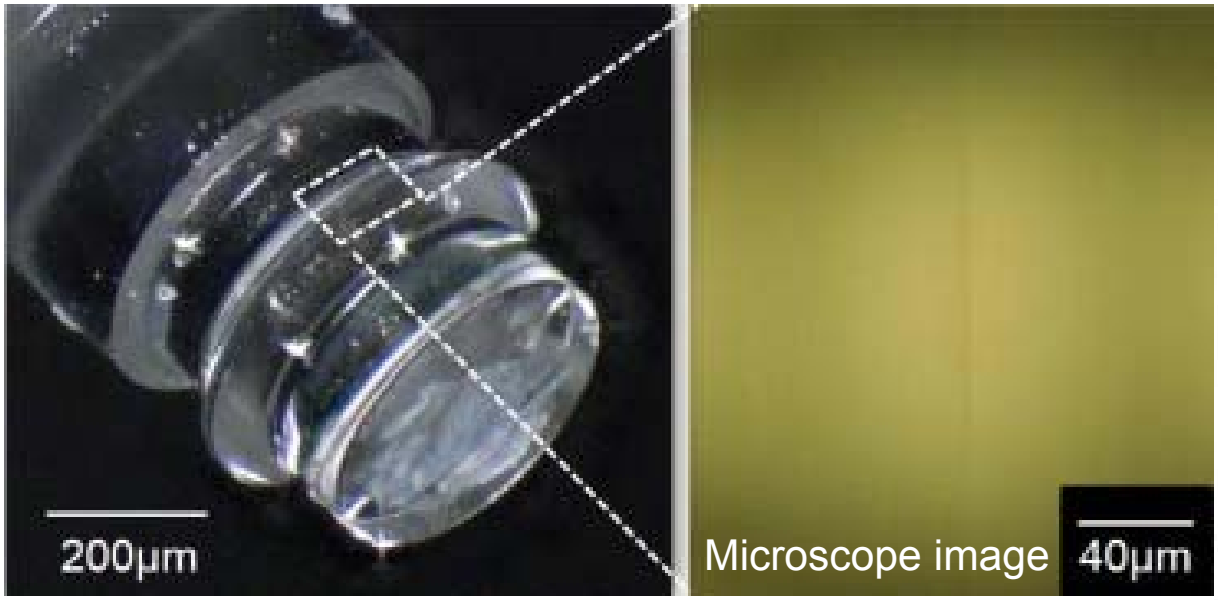
$R_{\mathrm{rms}} = 3$ nm → **Unchanged** → $R_{\mathrm{rms}} = 3$ nm

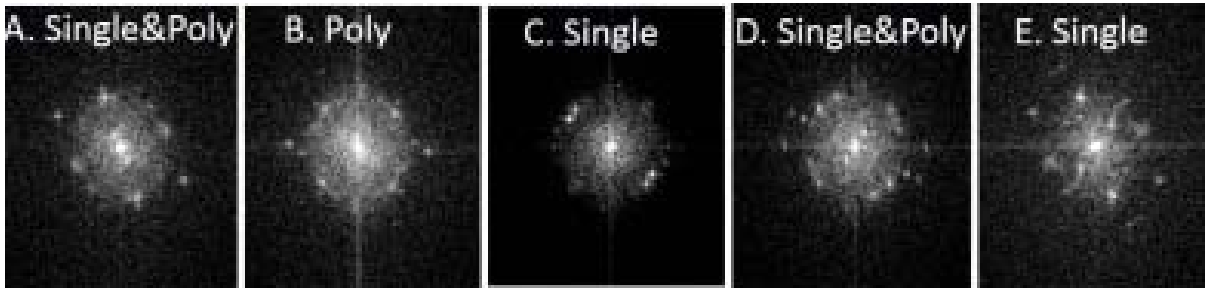




$Q = 3.0 \times 10^6$ → **Increased** → $Q = 1.2 \times 10^7$

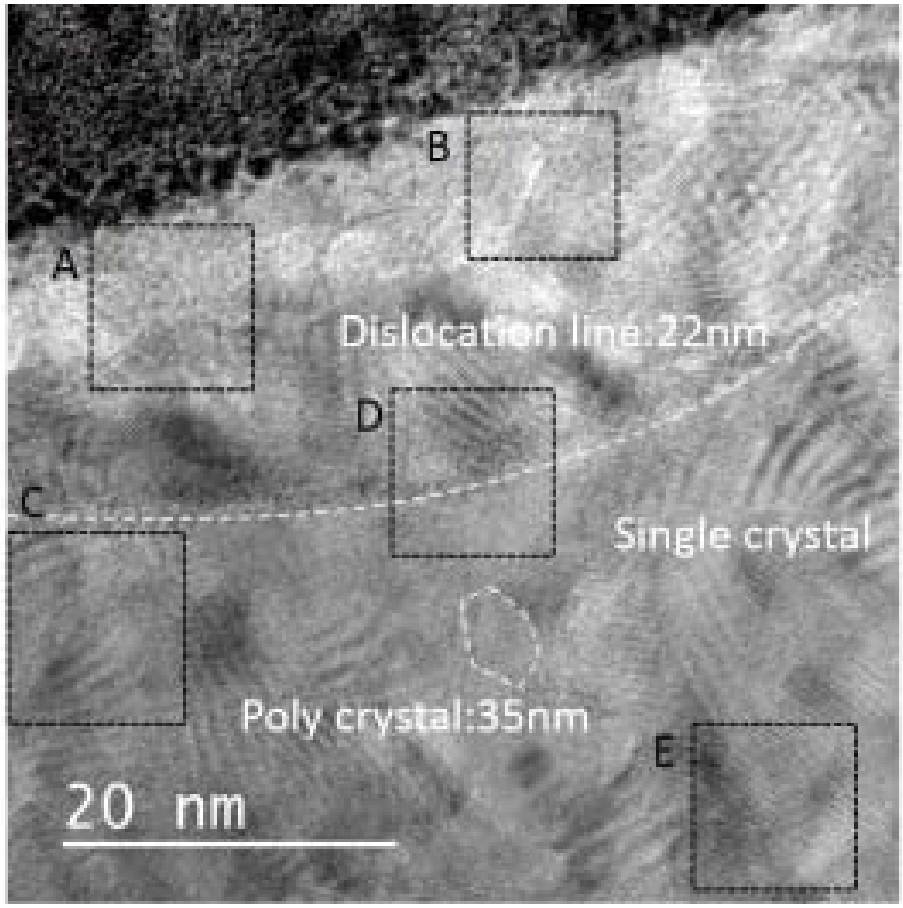
Surface: Dislocation loops





Diffraction images

TEM image



Y. Kakinuma, *et al.*, CIRP Annuals (2015) in press.

Polycrystalline layer must be removed

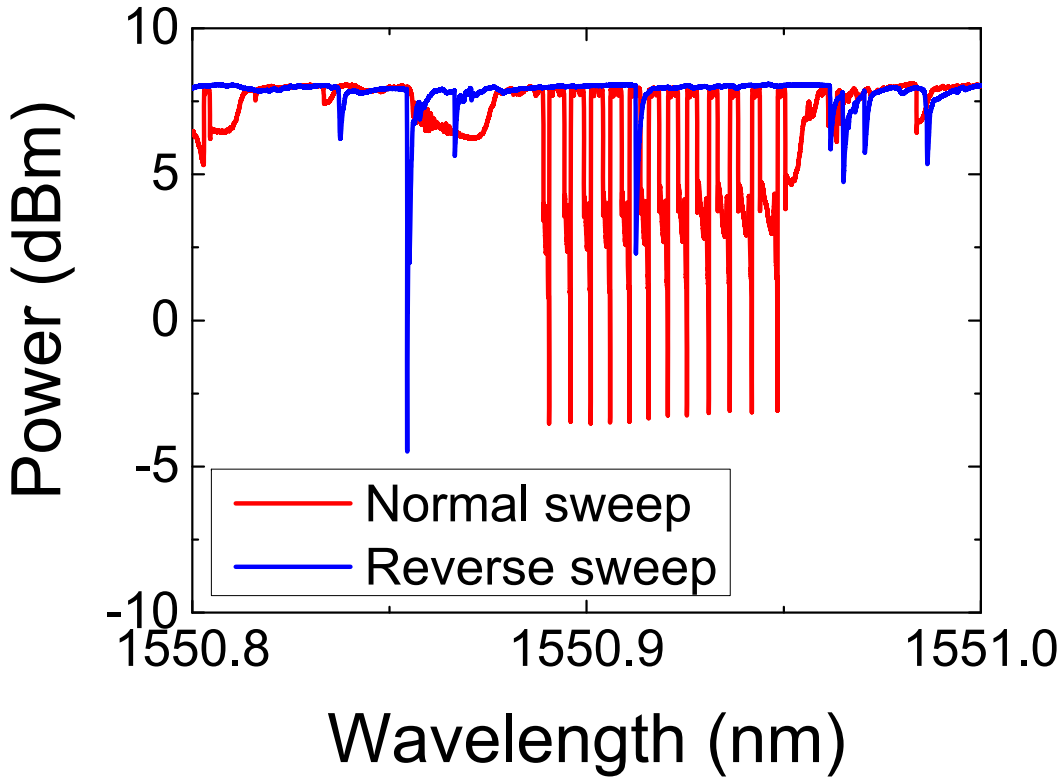
TOM oscillation: Wavelength scan

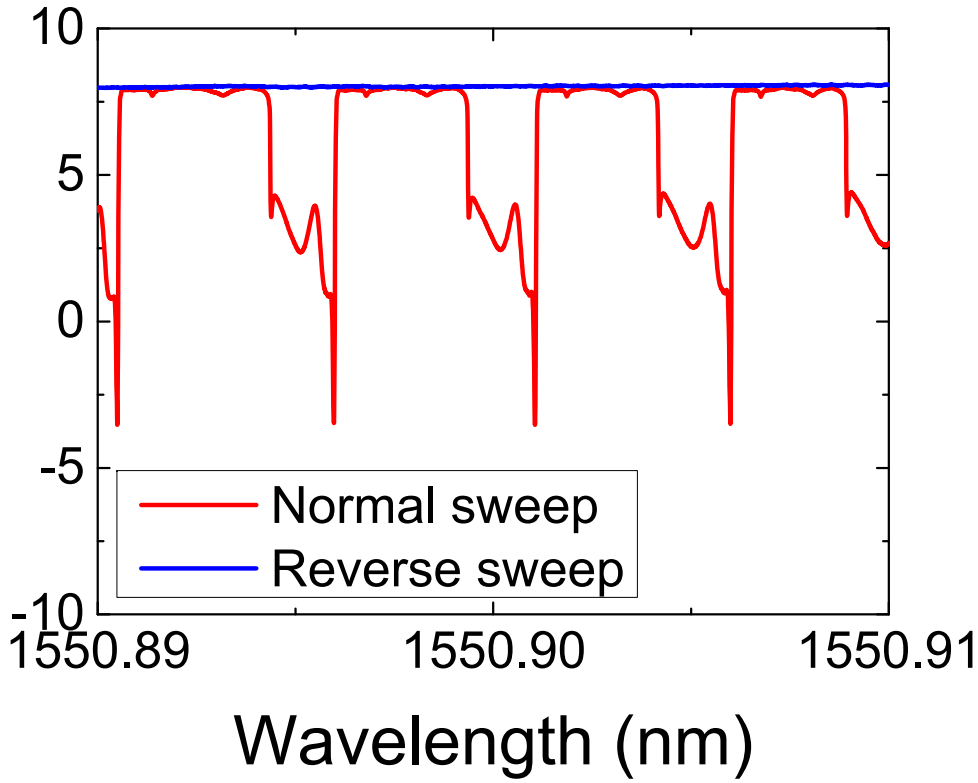
Normal sweep: from short λ to long λ

Reverse sweep: from short λ to long λ

Parameters:

- Input power: 1 W
- Scan speed: 0.5 nm/s





Oscillations observed when employing normal sweep

TOM oscillation: Principle

Resonant wavelength (λ_r) :

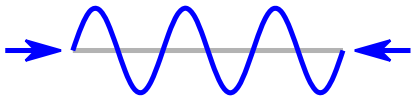
$$\lambda_r(t) = \lambda_0\left(1 + dn/dT_1 \cdot \Delta T_1(t) + \alpha \cdot \Delta T_2(t)\right) \cdots (1)$$

(ΔT : temperature change)

Fast response

$dn/dT_1 < 0$: **Thermo-optic (TO)**

$\Delta T_1(t)$: ΔT in optical mode volume

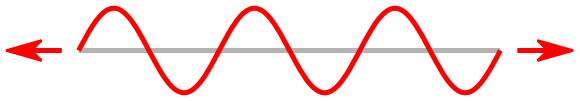


λ_r shifts toward short wavelength

Slow response

$\alpha > 0$: **Thermal expansion (TE)**

$\Delta T_2(t)$: ΔT in entire cavity volume



λ_r shifts toward long wavelength

Different time scales cause oscillations

TOM oscillation: Sweep direction dependency

Normal sweep

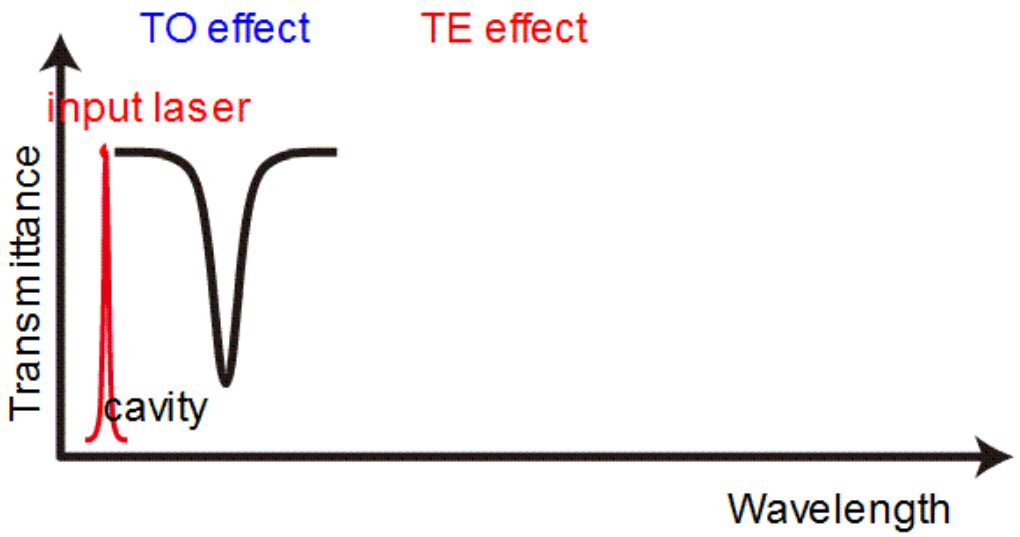
TO effect > TE effect

by turns

TO effect < TE effect

→ Oscillation starts

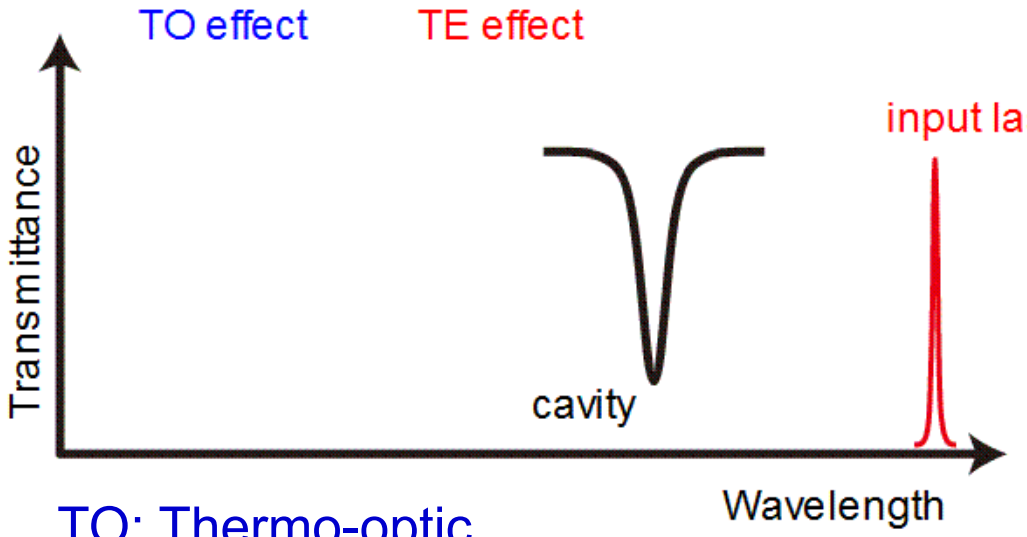
TO first TE follows



Reverse sweep

TO effect > TE effect

→ Oscillation do not occur

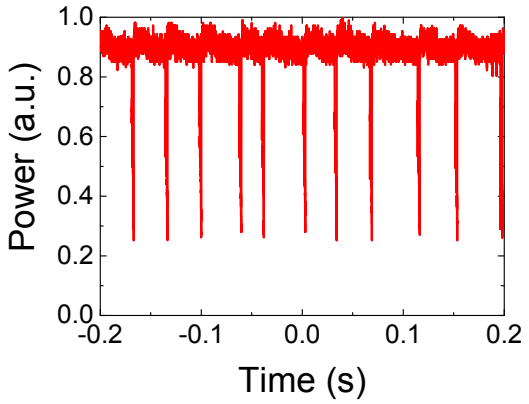


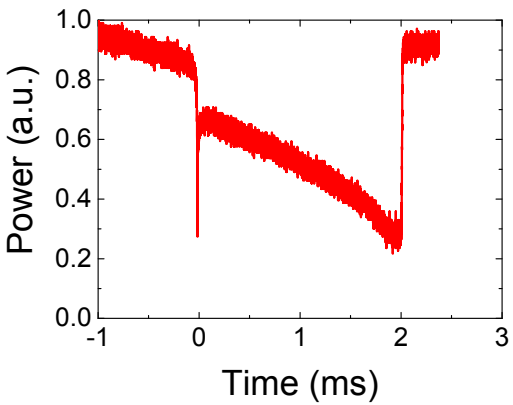
TO: Thermo-optic

TE: Thermal expansion

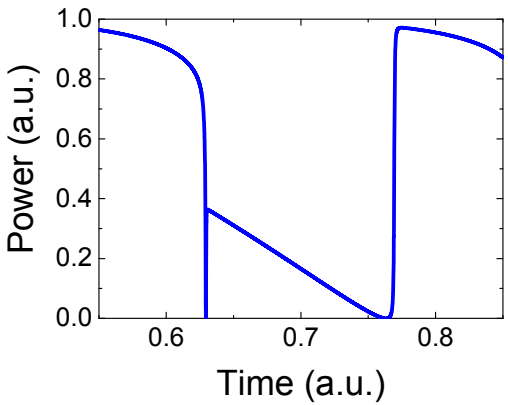
TOM oscillation: Fixed input wavelength

Experiment

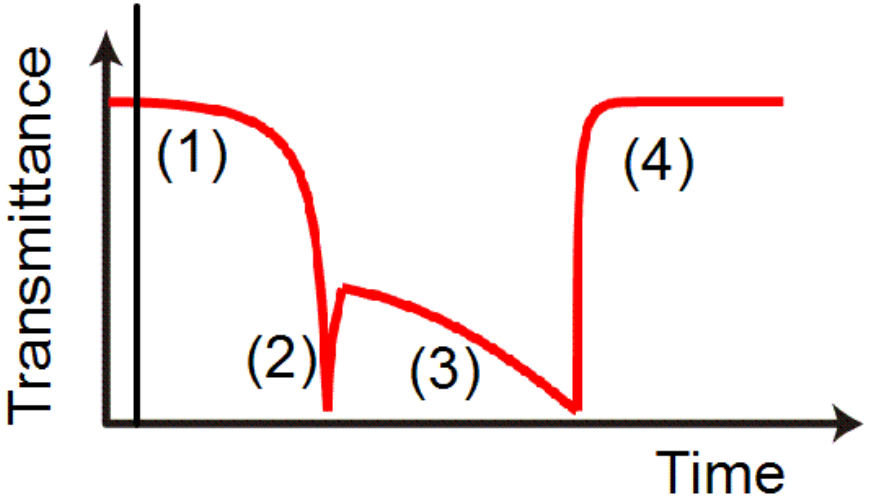


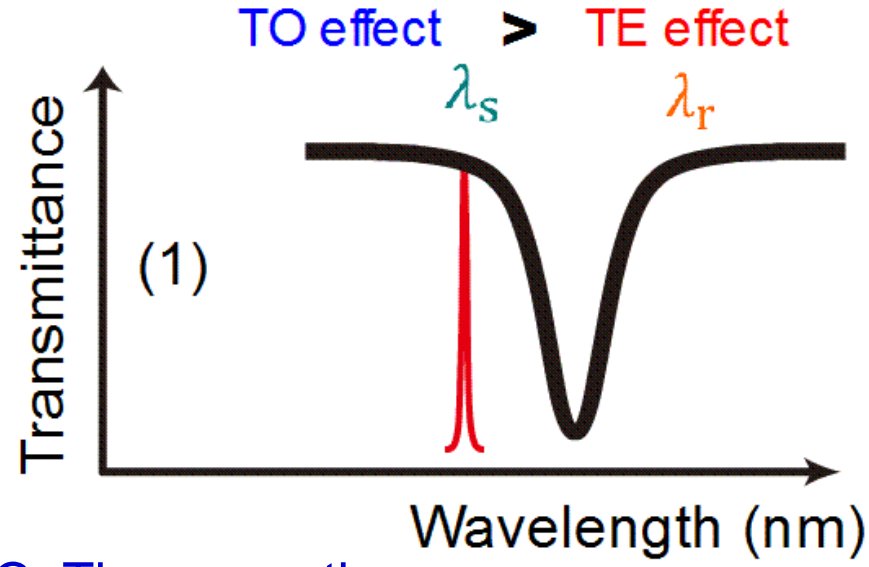


Simulation



Oscillatory behavior (λ_r : resonance, λ_s : input)



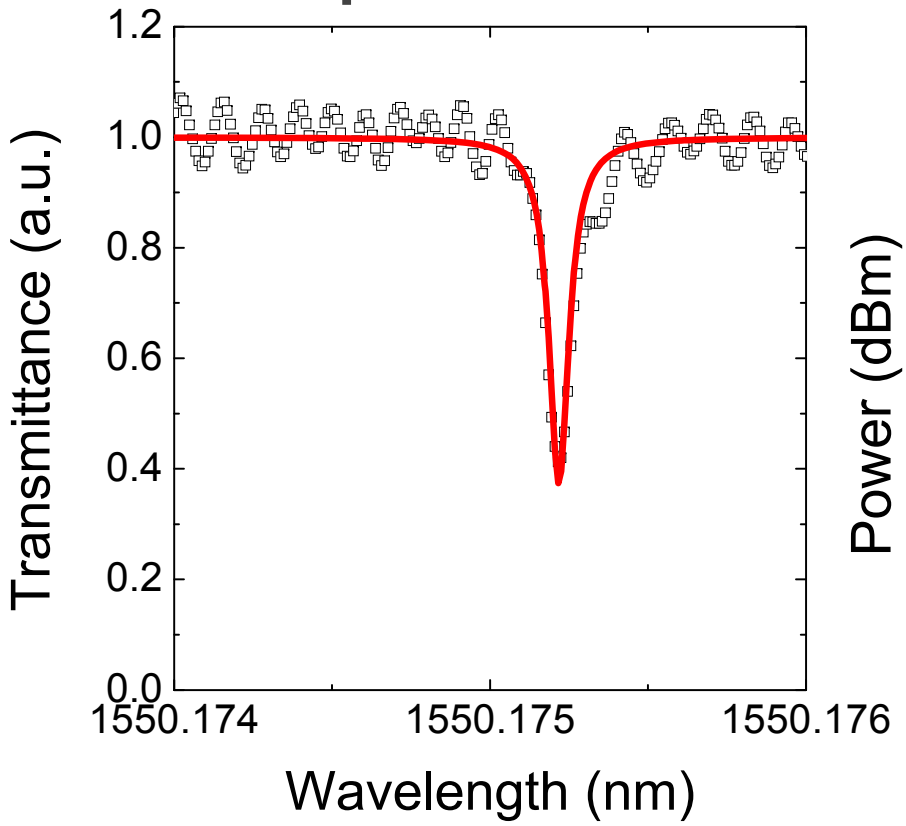


TO: Thermo-optic
TE: Thermal expansion

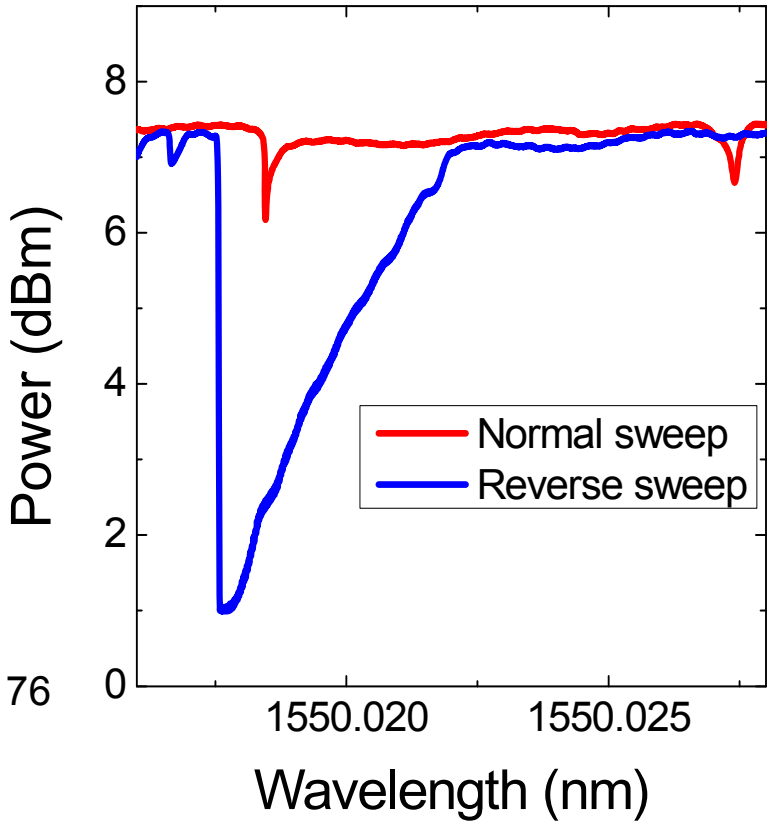
TOM oscillation: Size dependence (experiment)

Cavity

Spectrum



Nonlinear experiment



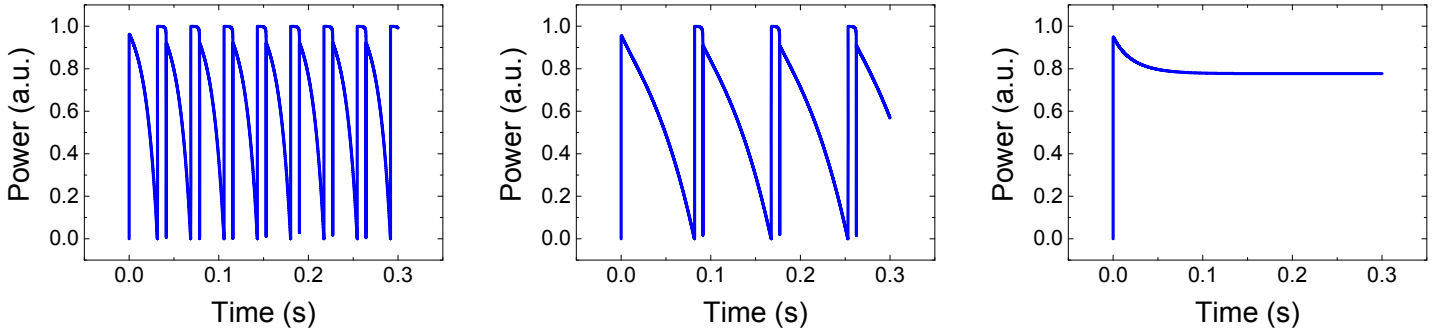
$$Q = 2.0 \times 10^7$$

No oscillation was observed

TOM oscillation: Size dependence (calculation)

Diameter (D)	500 μm	600 μm	700 μm

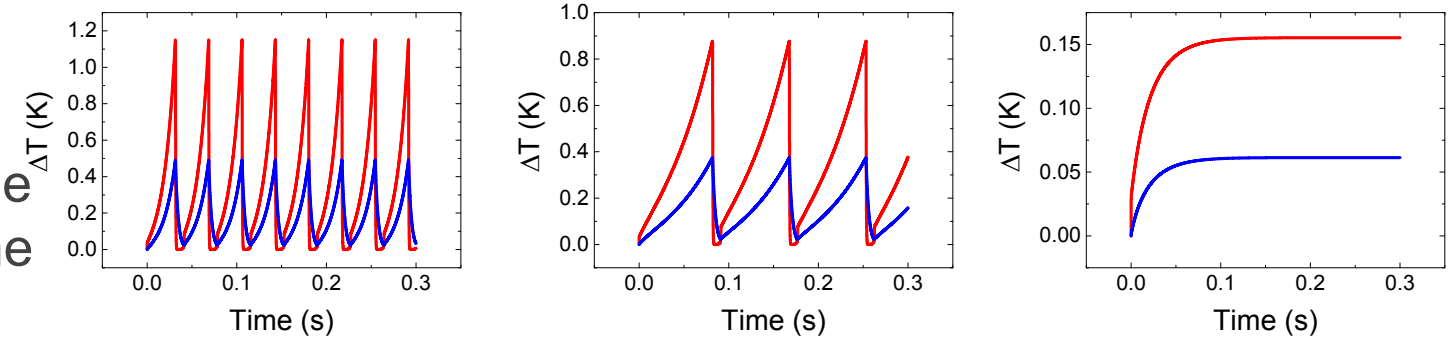
Transmittance



ΔT

— : mode volume

— : cavity volume



Diameter ∝ Thermal diffusion time ∝ Oscillatory frequency

No oscillation is observed when D is larger than 700 μm

Summary

Summary

… We demonstrated the fabrication of CaF_2 WGM microcavities with an ultra-precision cutting process

… We studied the size dependence and observed the TOM oscillation with a small cavity ($D < 700\ \mu m$)

