
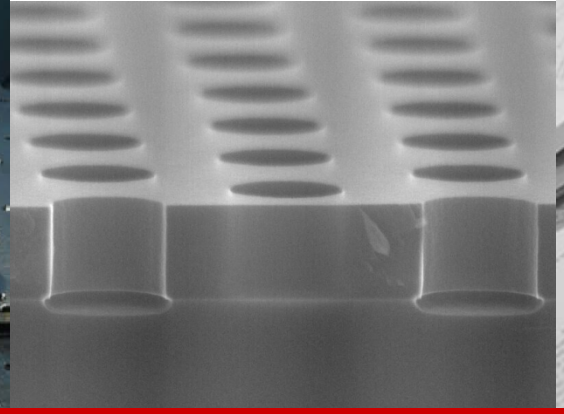


75th Anniversary Science & Technology Keio University

CLEO 2013 CF2I.7 @ Room C3 & C4 (San Jose Convention Center)

High-Q sapphire WGM cavities fabricated by crystal growth

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Outline

- ✓Introduction
- ✓Fabrication & optical measurement of crystalline WGM cavities
- ✓Numeral analysis
- ✓Summary

High Q/V crystalline WGM cavity fabrication

Crystalline cavities fabricated w/ precise machining

C. Y. Wang *et al.*, Nature Commun. **4,** 1345 (2013).

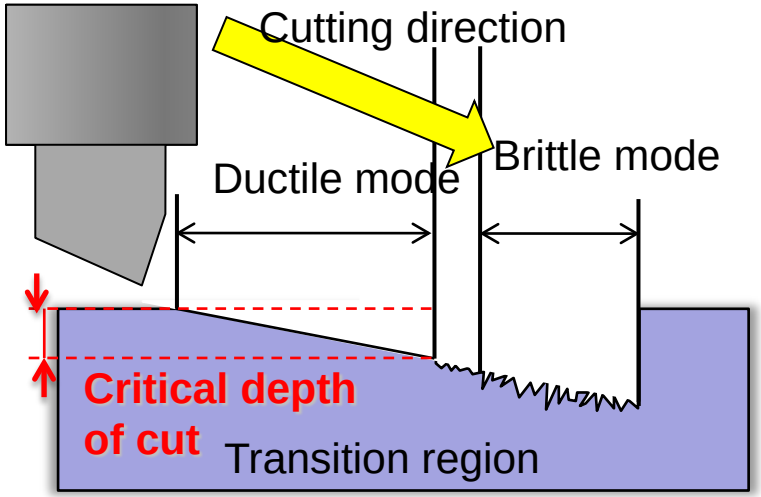
J. Hofer *et al.*, Phys. Rev. A **82**, 031804(R) (2010).

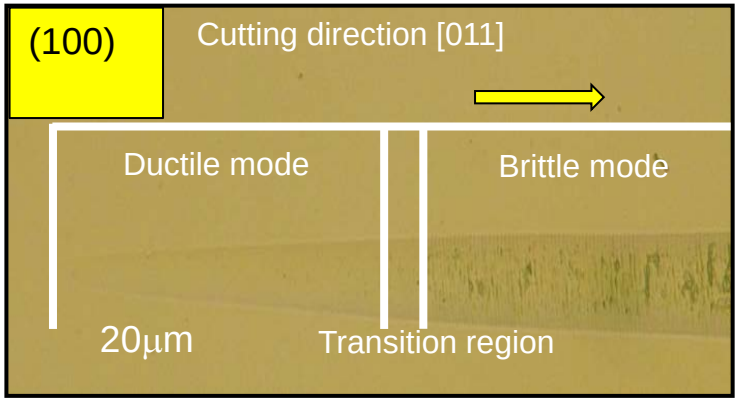
Q factor: $10^9 \sim 10^{10}$

Size: **mm order**

Precise machining processing

Y. Mizumoto, *et al.*, Procedia Eng. **19,** 264 (2011).





➢ brittle, fragile and inflexible

✓ Expensive machining needed
✓ Difficult to make small cavity

Motivation & Objectives

Motivation

- ✓ Easy & inexpensive fabrication
- ✓ Fabrication of small cavity

Laser-heated pedestal growth (LHPG)

① Fabricate crystalline WGM cavity
② Achieve cross-sectional shape control
③ Understand effect of different cross-sections
(circular → hexagonal)

Laser-heated pedestal growth (LHPG)

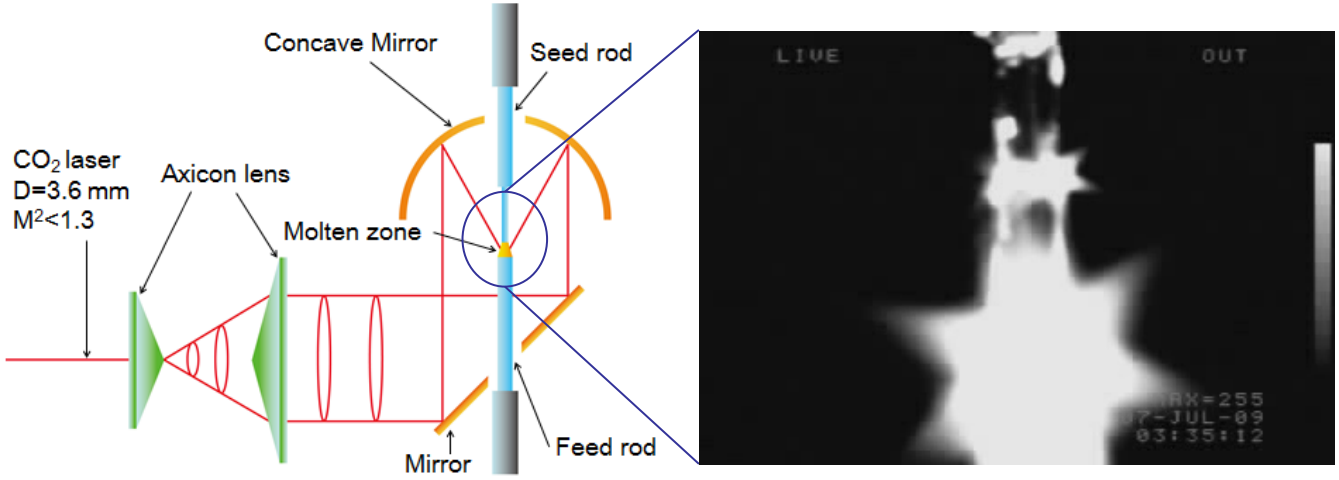
Original LHPG:

✓Fabrication of uniform crystal rods possible
✓Fabrication of rods w/ diameter < 100 μm possible
✓Fabrication of rods w/ smooth surface possible

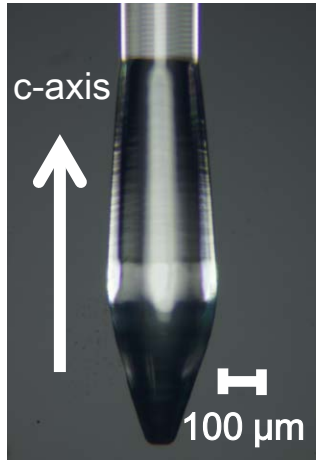
Modified LHPG:

✓Form bulge by changing growth rate (it allows WGM excitation)

Experimental setup



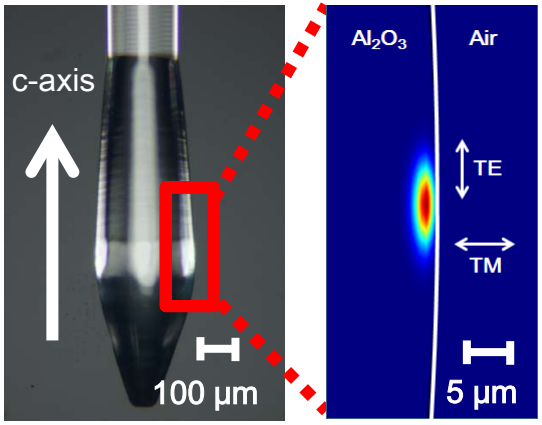
Fabricated cavity



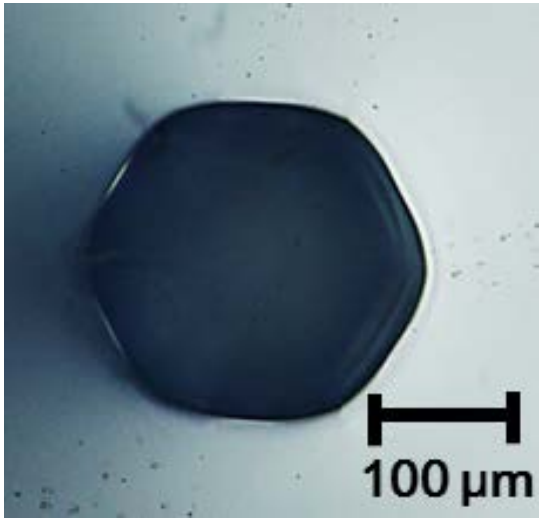
$$D_{grown} = D_{feed} \times \sqrt{v_{feed}/vseed}$$

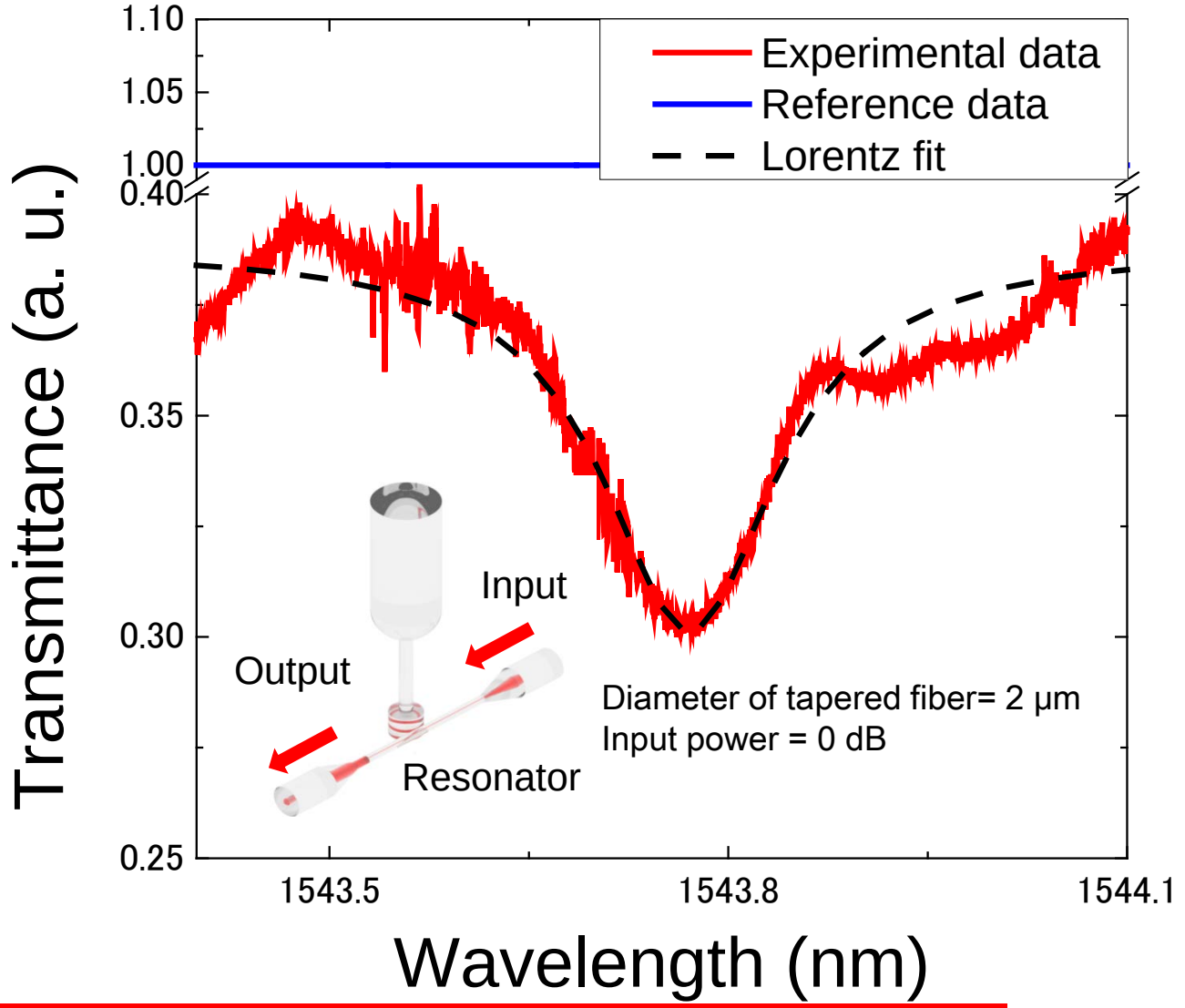
✓ WGM cavity fabricated

Optical characteristics



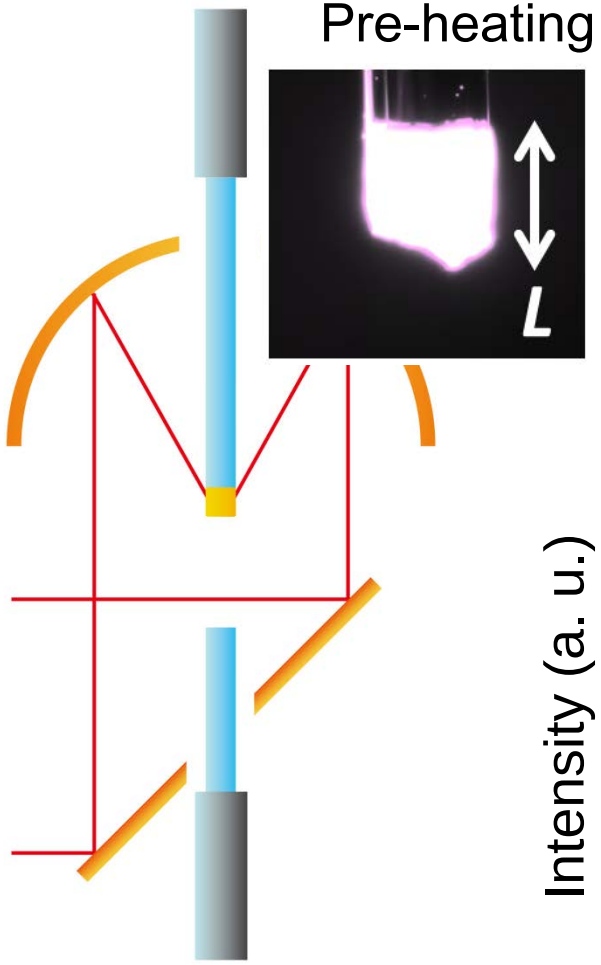
$V_{eff} = 1.28 \times 10^{-2}$ mm^3



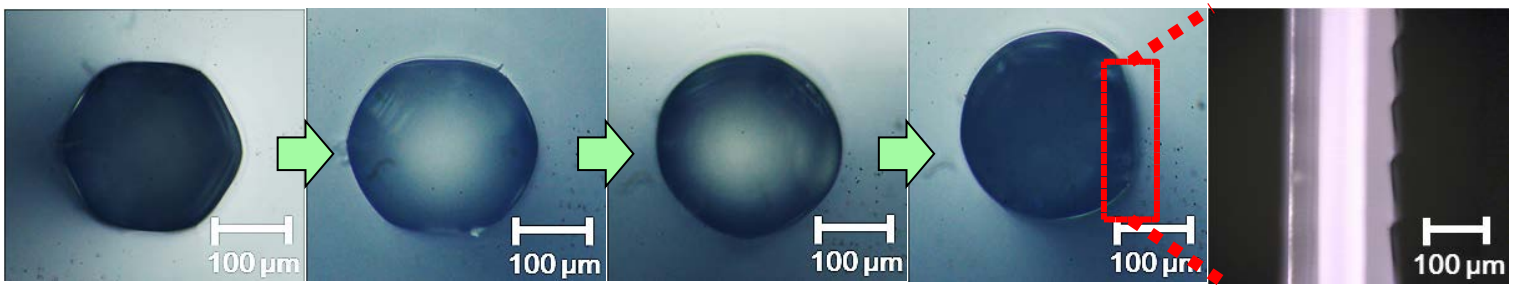


- ✓ Q = 8.5×10^3 achieved
- ✓ Is cross-sectional shape critical to achieve high Q?

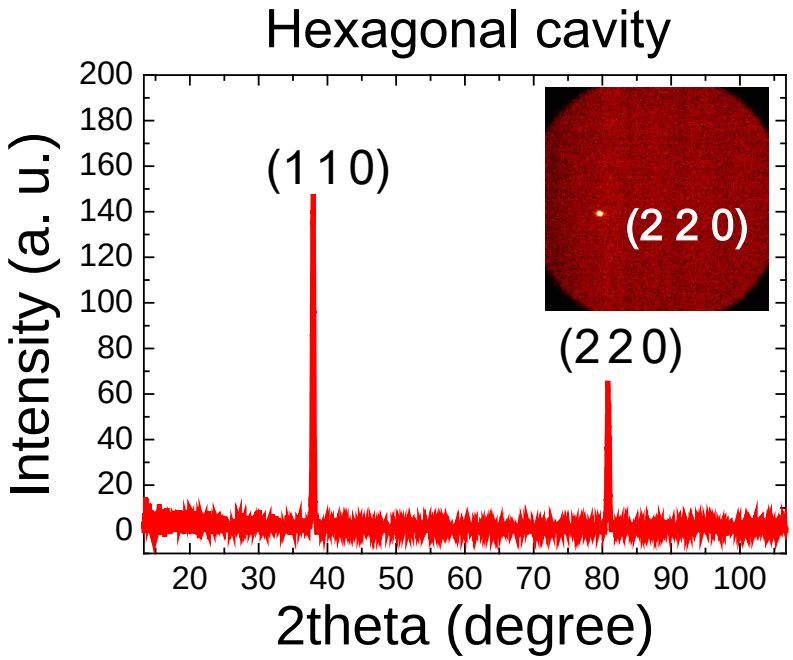
Pre-heating method: cross-sectional shape control

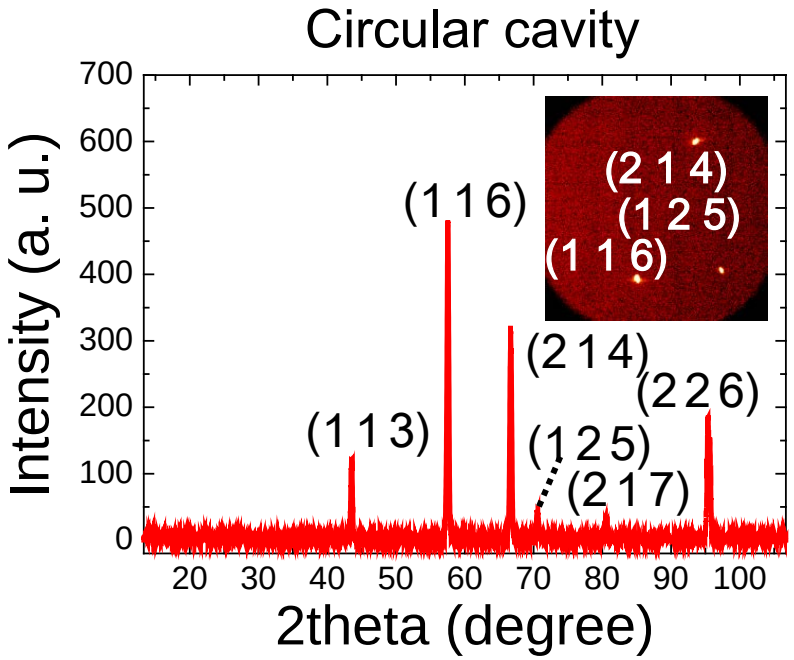


Side view



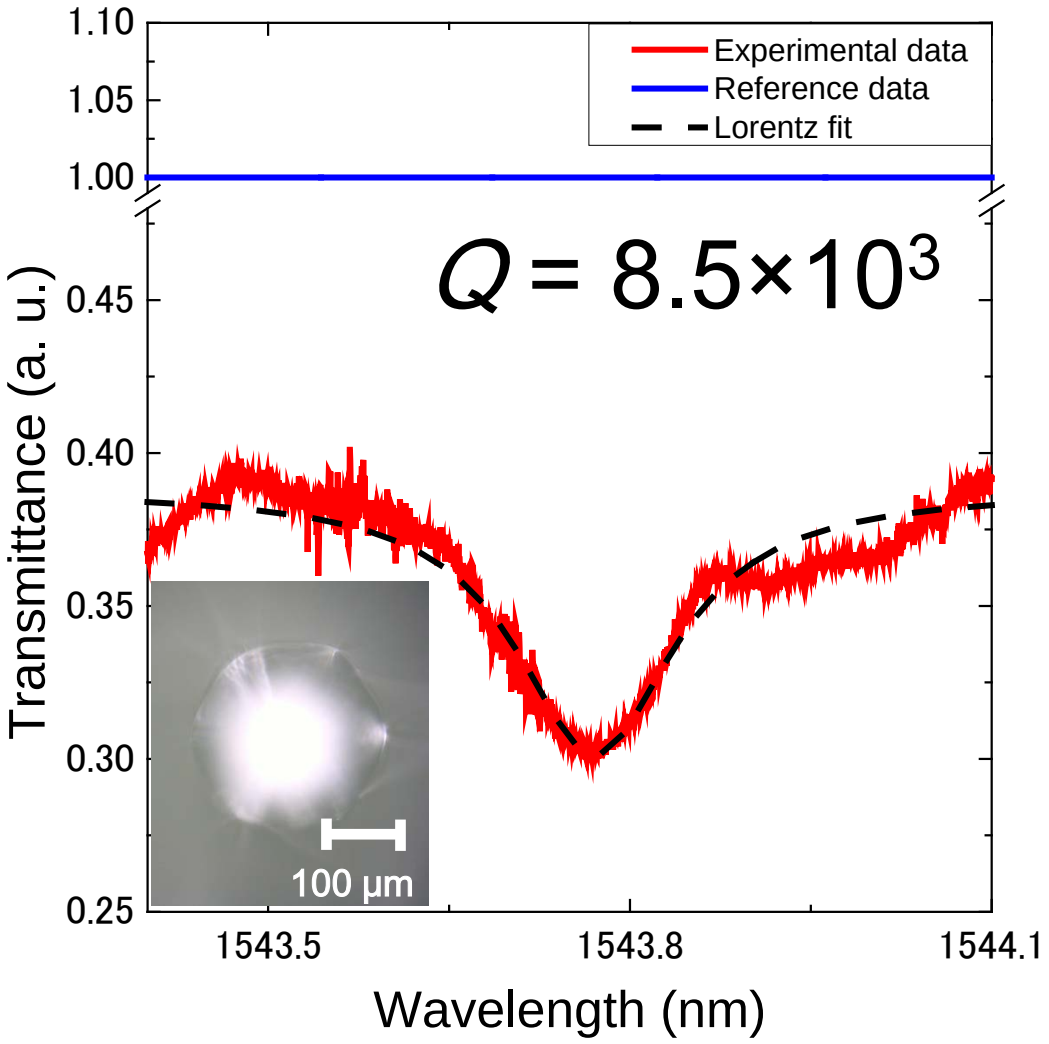
L = 0.10 mm 0.70 mm 0.78 mm 0.80 mm

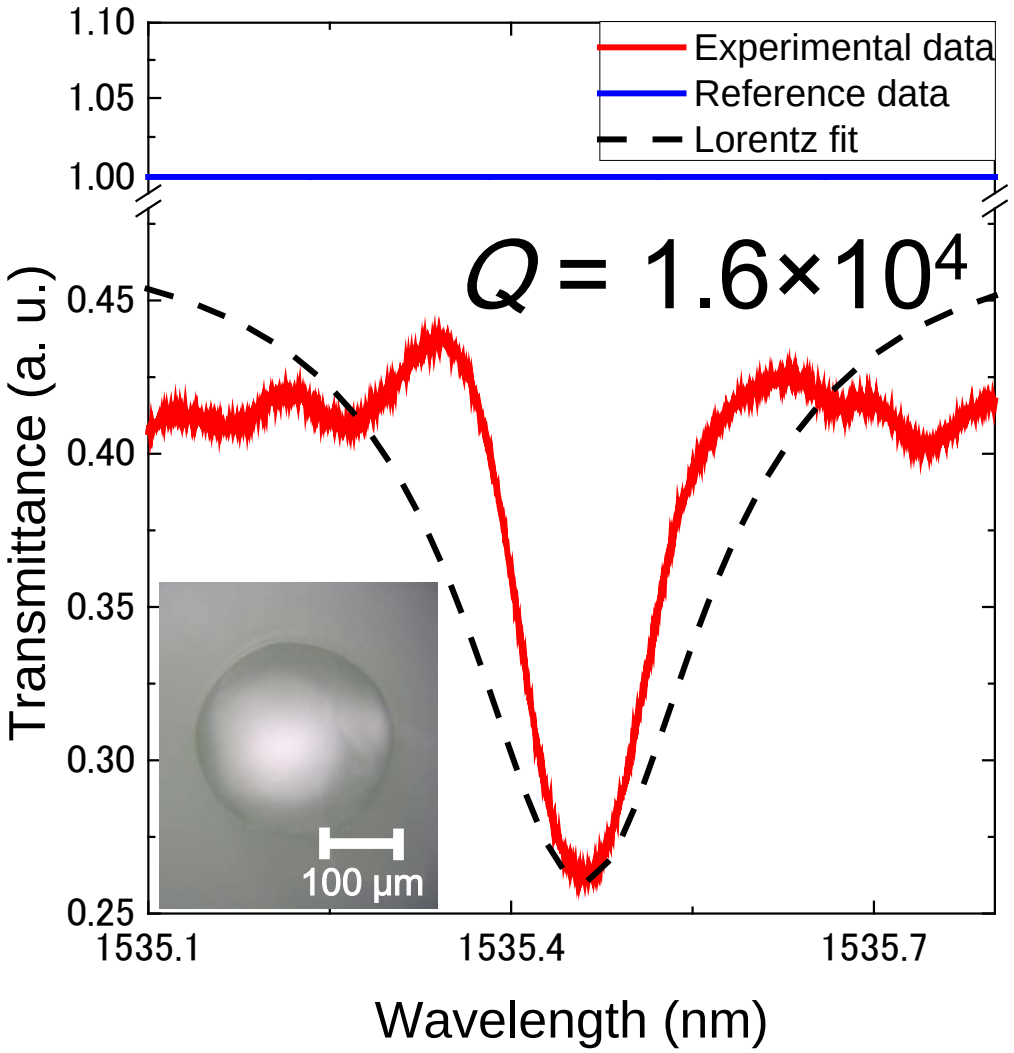




✓ Cross-sectional shape control demonstrated

Optical measurement

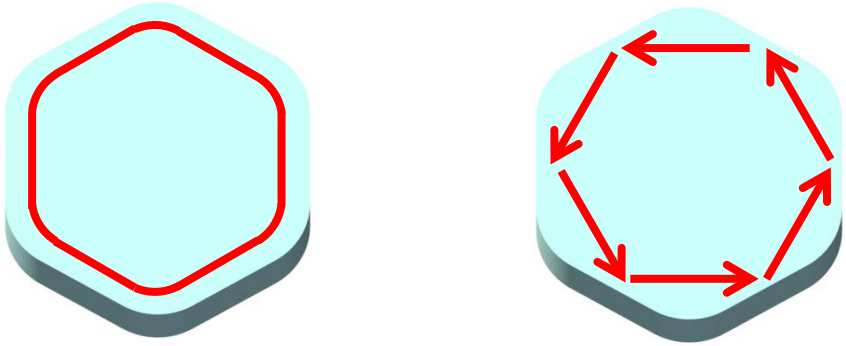




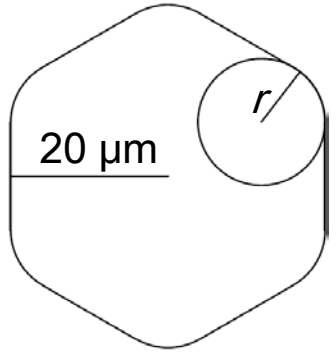
✓ High Q is obtained for circular cavity

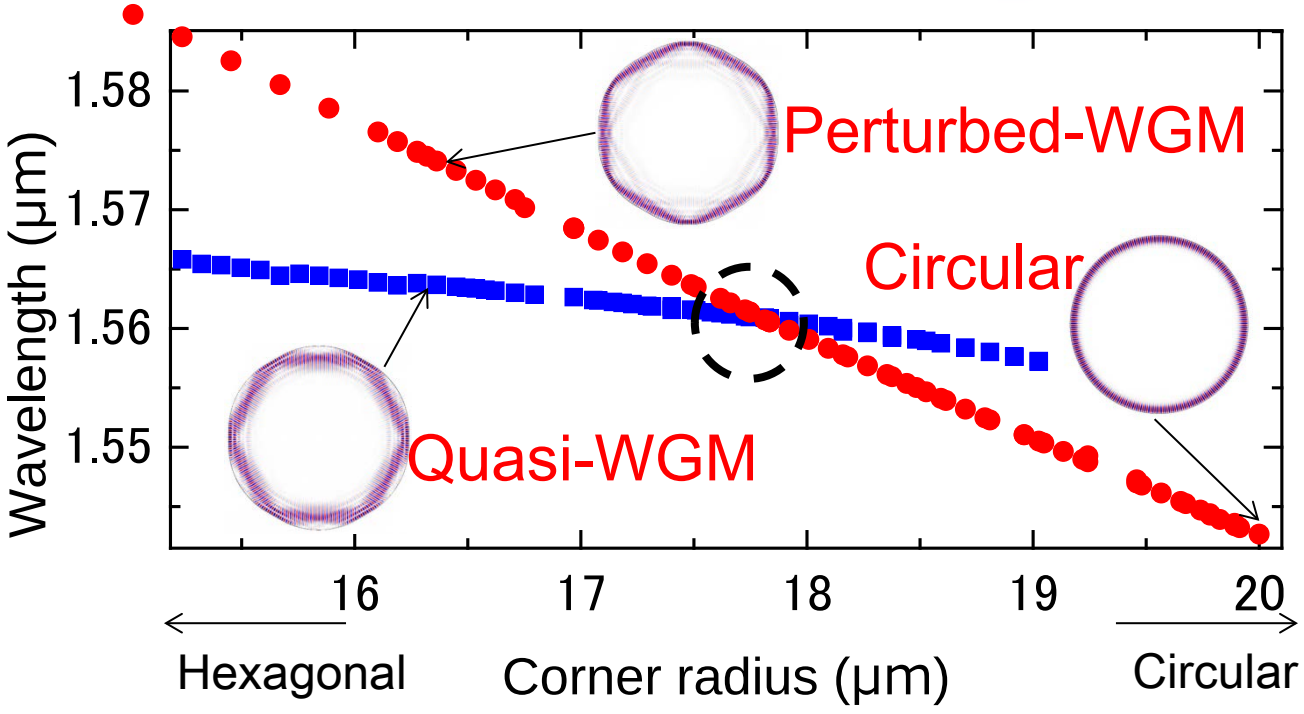
Mode mixing between different modes in hexagonal cavities

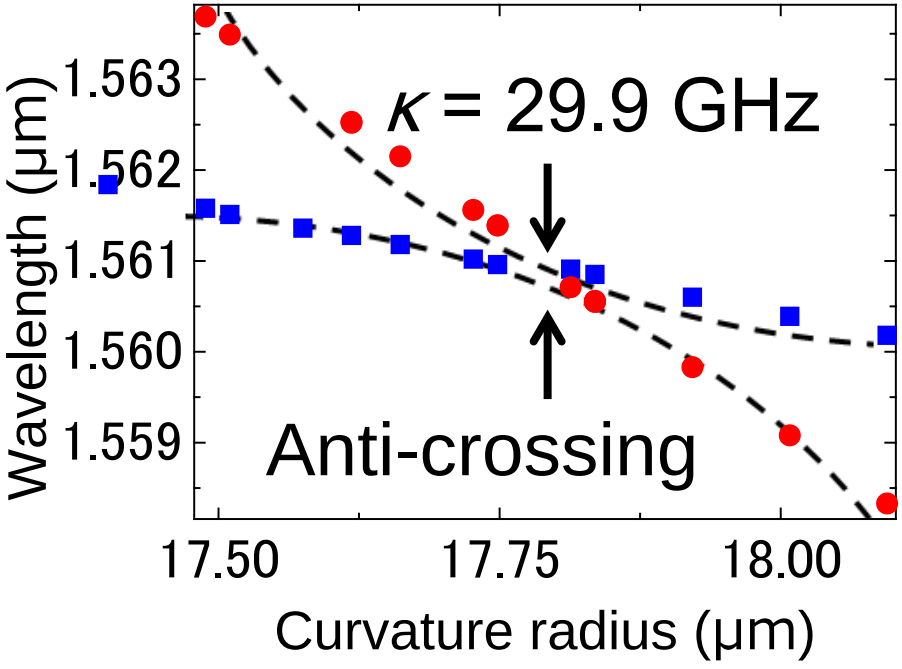
Perturbed - WGM **Quasi - WGM**



FDTD model



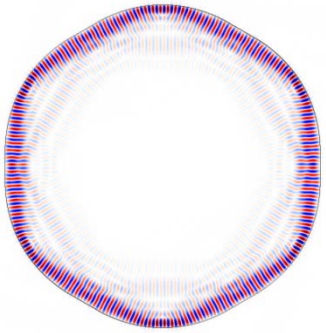




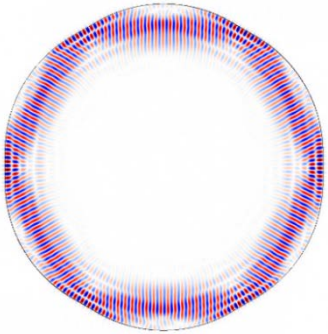
✓ Strong coupling occurs between perturbed & quasi modes

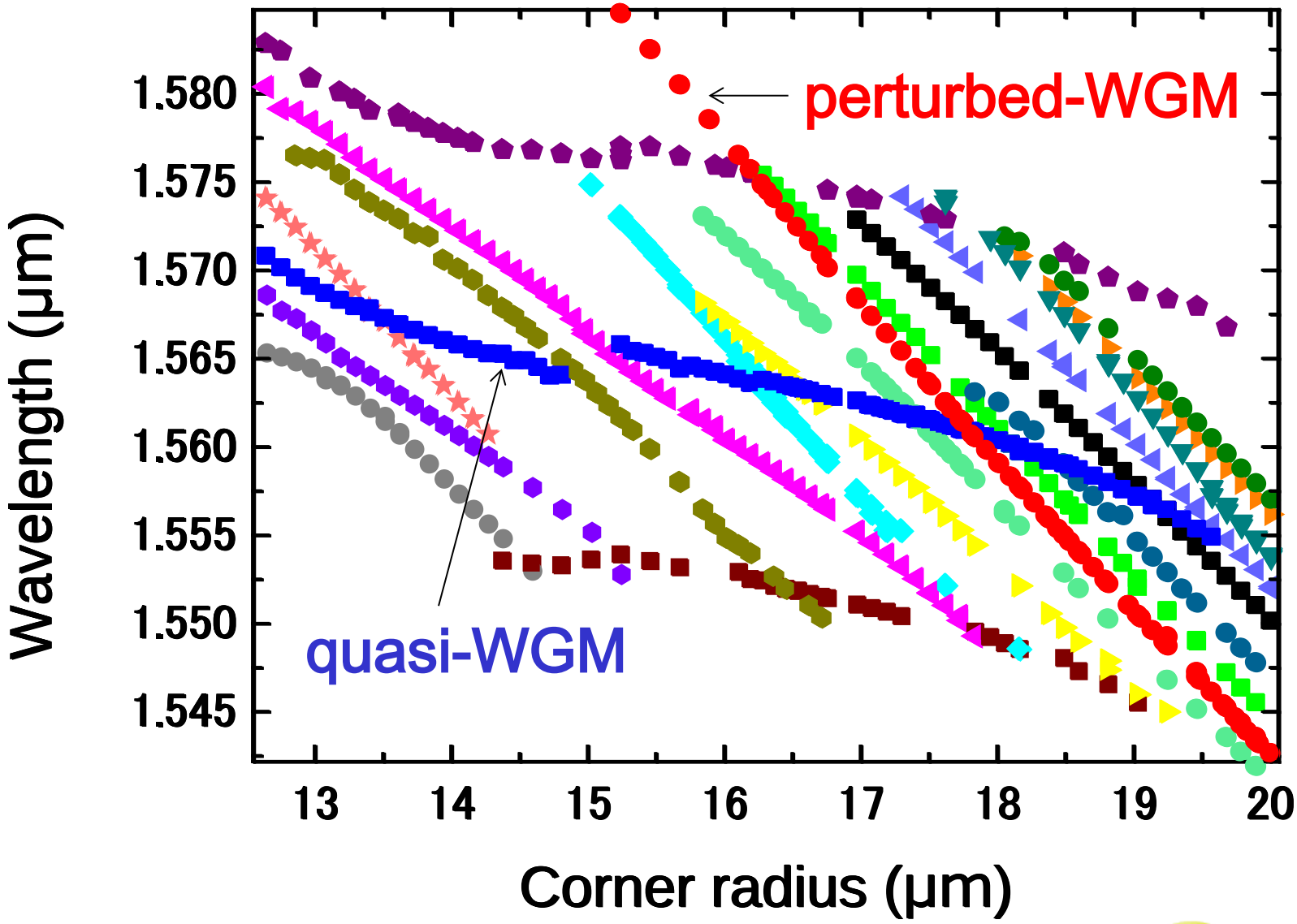
Modes in hexagonal cavities (cont...)

perturbed-WGM



quasi-WGM

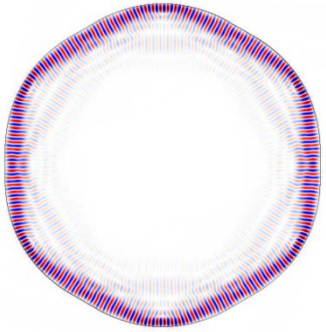




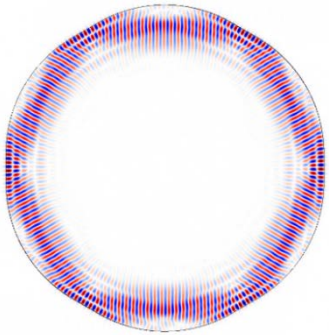
✓ A number of perturbed modes couple w/ quasi mode.

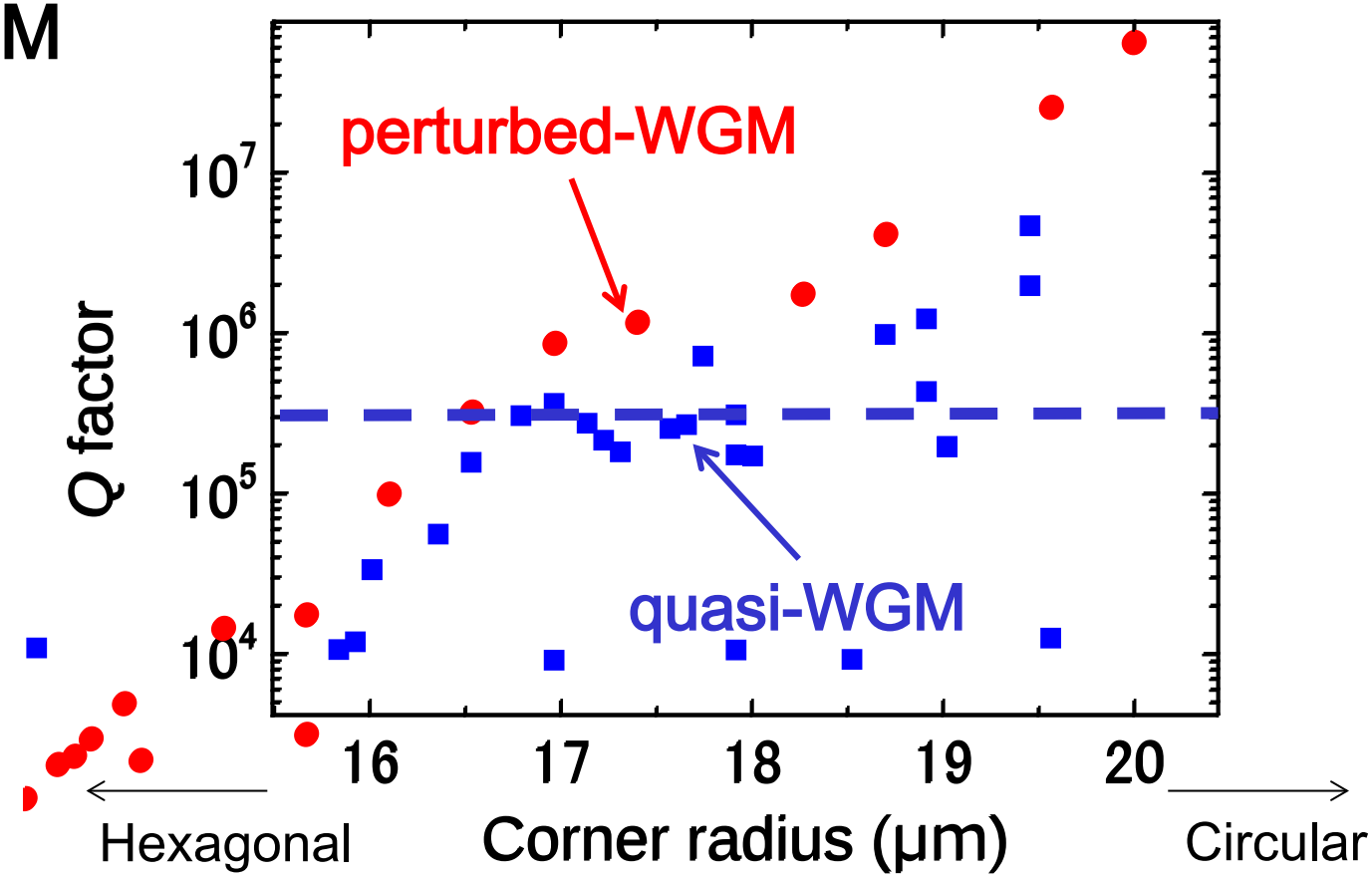
Q factors for different WGM modes

perturbed-WGM



quasi-WGM





- ✓ Low Q = quasi–WGM (due to strong mode mixing)
- ✓ High Q = perturbed–WGM (but only w/ round corner)

Summary

① Fabricated crystalline WGM cavity by LHPG

- ✓ $Q = 1.6 \times 10^{4}$
- ✓ $V = 1.28 \times 10^{-2}\ mm^{3}$

② Pre-heating allows the control of cross-sectional shape of the crystalline WGM cavity

③ Studied the effect of circle & hexagonal shape

- ✓ Mode coupling plays an important role to understand the low Q in quasi–WGM.
- ✓ High–Q is possible w/ perturbed–WGM when the corner is round.

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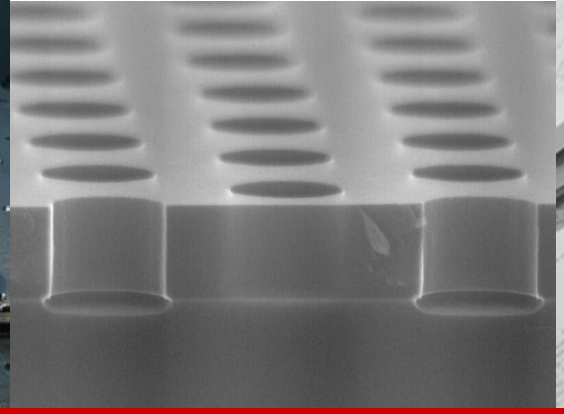


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Thank you very much.

Improvement of *Q*

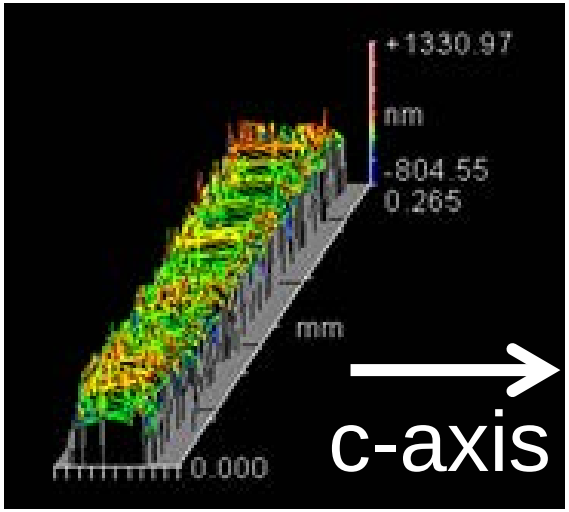
$$Q = 1.6 \times 10^4$$

$$Q\,\text{factor} \fallingdotseq \frac{3\lambda^3 \mathbf{a}}{8n\pi^2 B^2 \boldsymbol{\sigma}^2}$$

σ : Root Mean Square (RMS)
a : Radius of cavity
λ : Wavelength
B : Correlation length
n : Refractive index of material

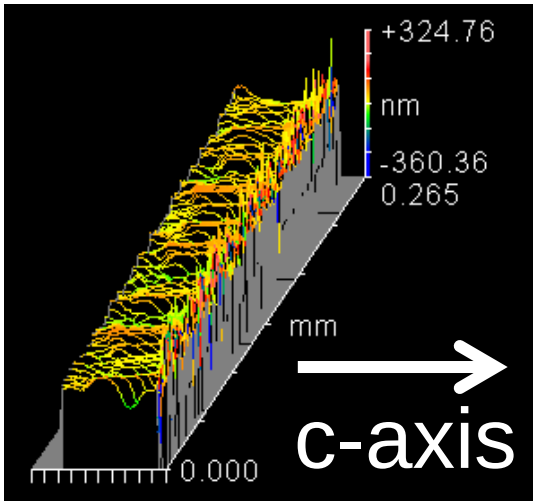
I. S. Grudinin, *et al.*, Optics Communications **265,** 33–38 (2006) .

RMS: 65 nm



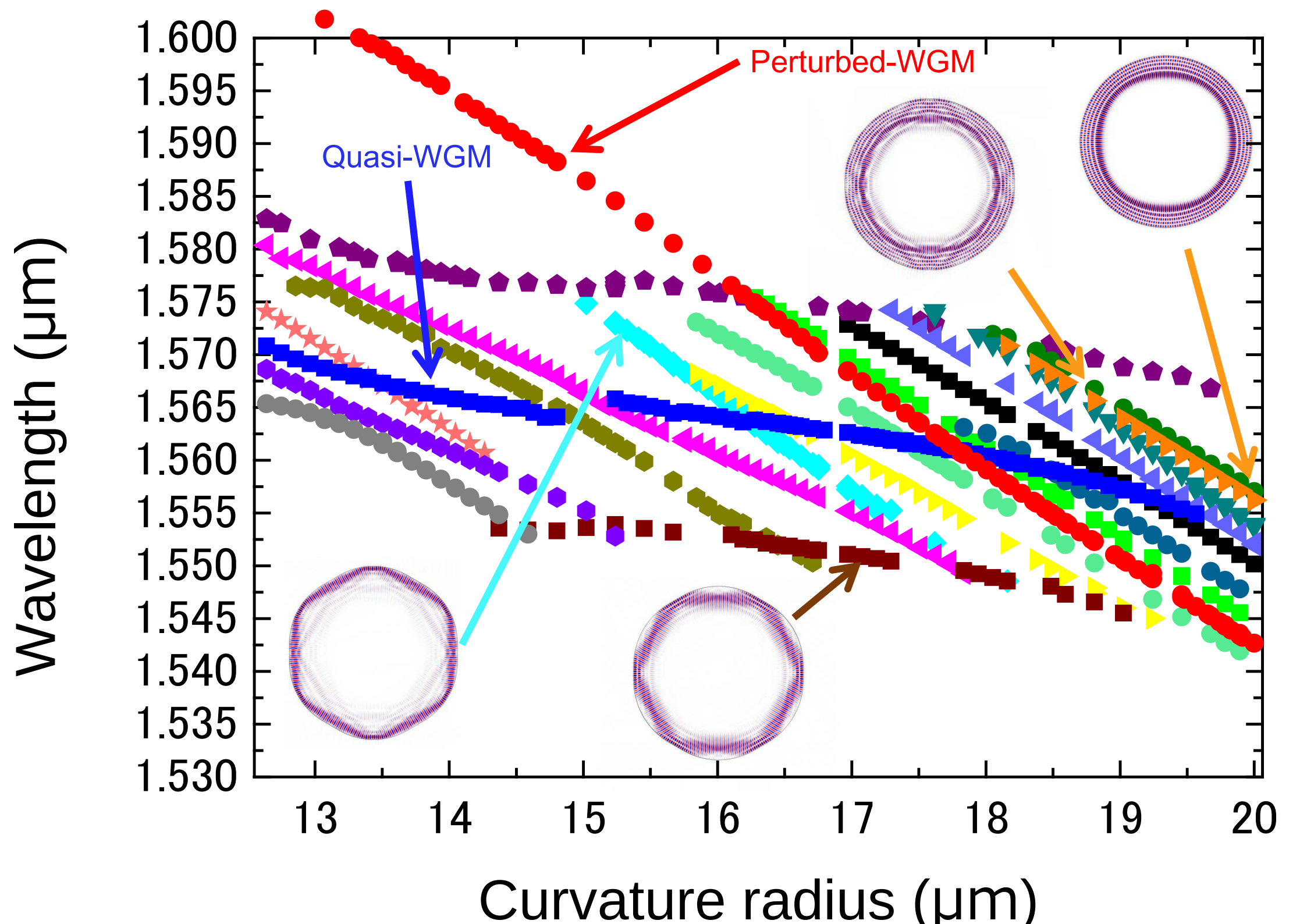
Pulling velocity
12 μm/s

RMS: 6 nm



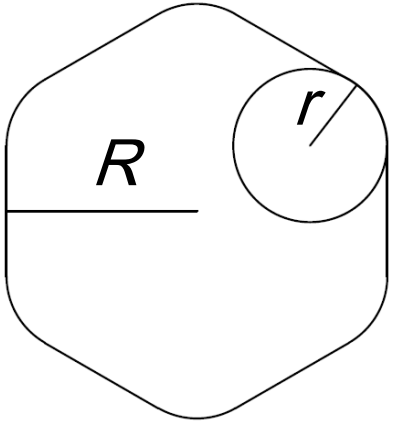
Pulling velocity
2 μm/s

Can achieve higher Q factor by improve of surface roughness.

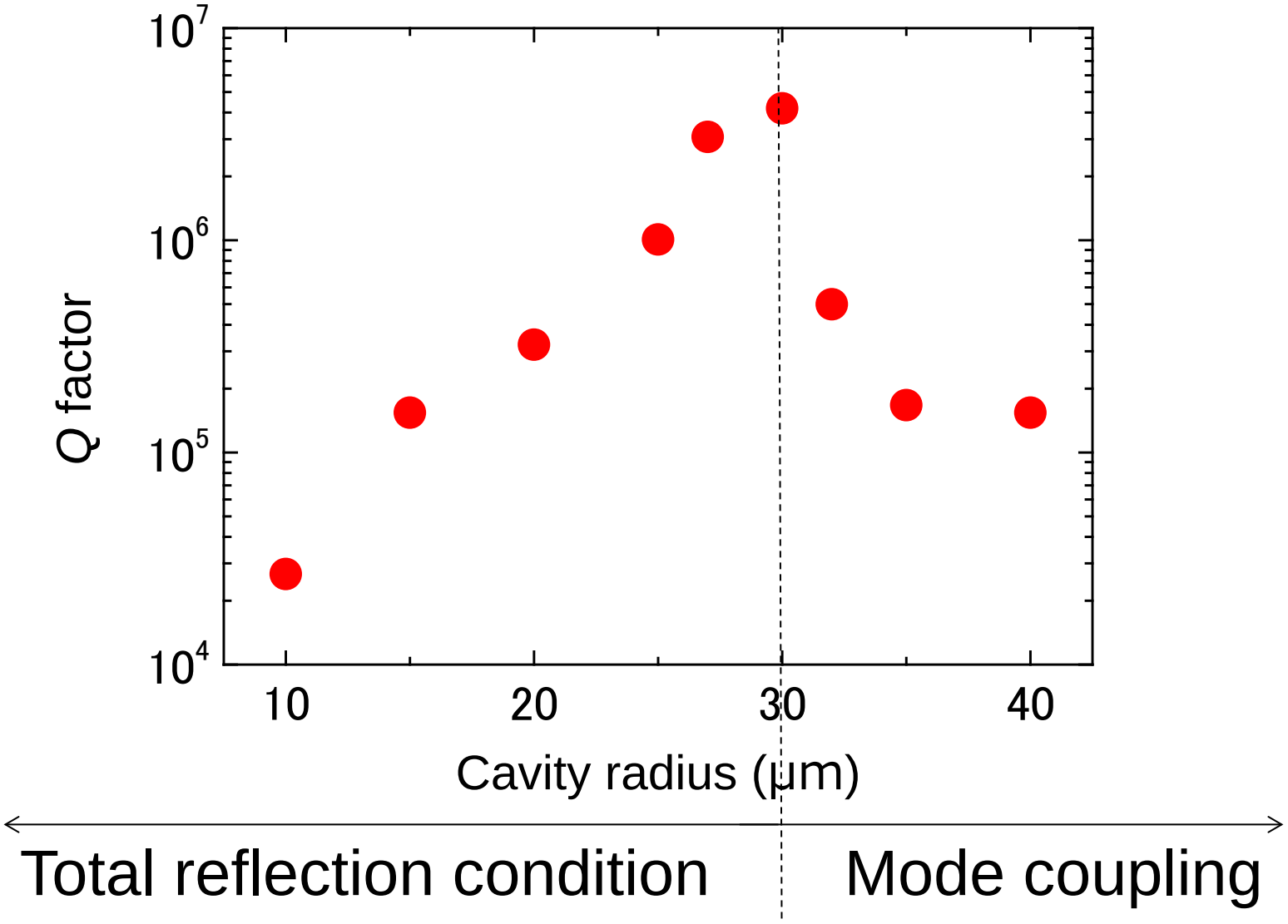

Perturbed-WGM
Quasi-WGM
Wavelength (μm)
1.600
1.595
1.590
1.585
1.580
1.575
1.570
1.565
1.560
1.555
1.550
1.545
1.540
1.535
1.530
13
14
15
16
17
18
19
20
Curvature radius (μm)

Optimization of diameter

Calculation model

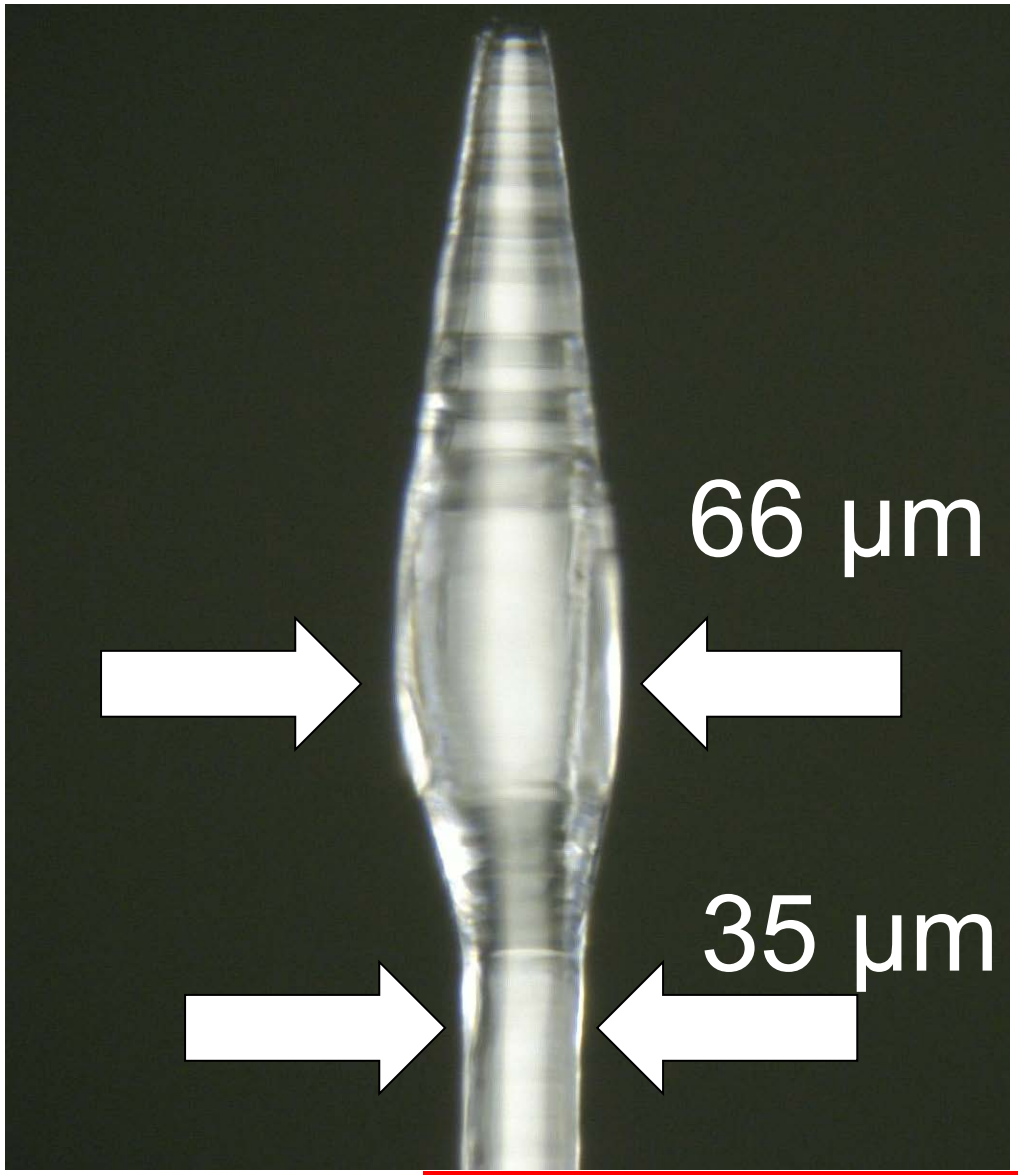


$r = 0.8 \times R$



The optimal radius of the perturbed WGM is 30 μm.

Miniaturization of the fabricated rods



Using LHPG method,
we can fabricate a sapphire rod with a diameter smaller than 3 μm.

R. S. Feigelson, W. L. Kway and R. K. Route, ”Single Crystal Fibers by the Laser-Heated Pedestal Growth Method,” SPIE **484,** 133 (1984).

Can fabricate at a smaller size.

