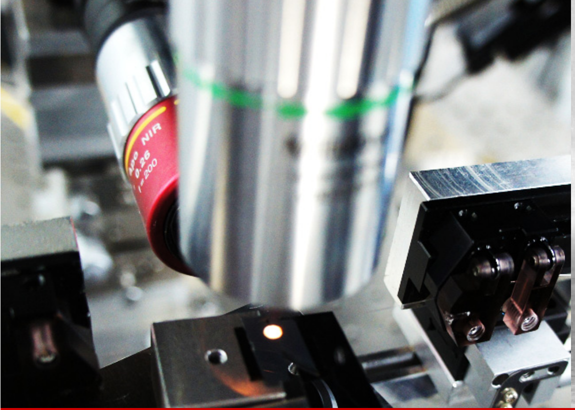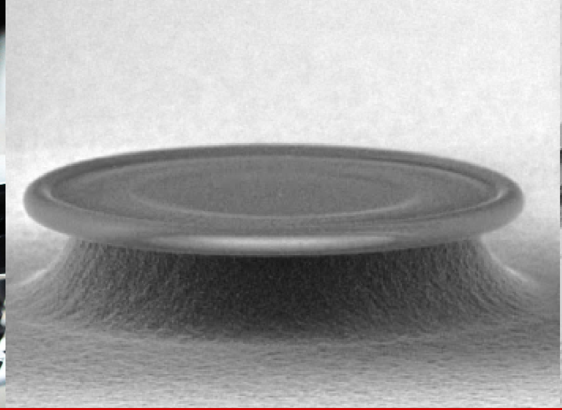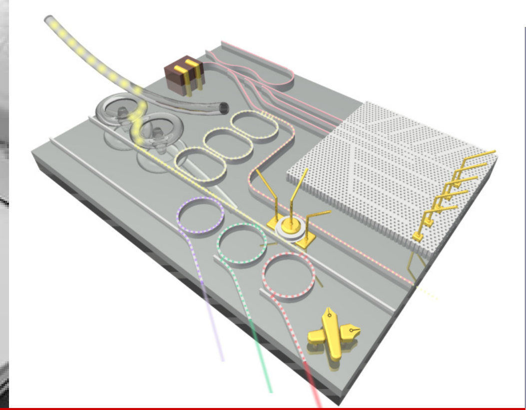

Progress In Electromagnetics Research Symposium (PIERS)
[2P_13 SC3 Optical Microcavities Aug. 9, 2016]

The effect of Raman scattering in Kerr comb generation in a Silica Toroidal Microcavity

Takumi Kato, Tomoya Kobatake, Akitoshi Chen-Jinnai, Atsuhiro Hori, and Takasumi Tanabe

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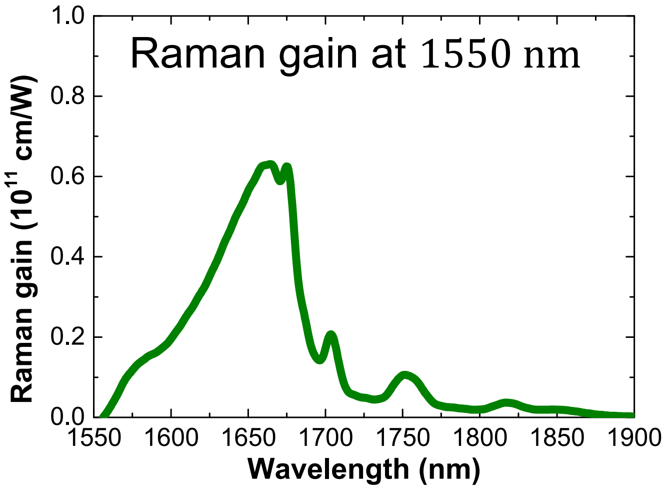
Keio University, Japan

Outline

- Background & Motivation
  - Raman scattering in Kerr comb generation
- Numerical modeling
  - Simultaneous Lugiato-Lefever Equations
- Numerical results
  - Dependence on Q factor
  - Raman soliton generation
- Summary

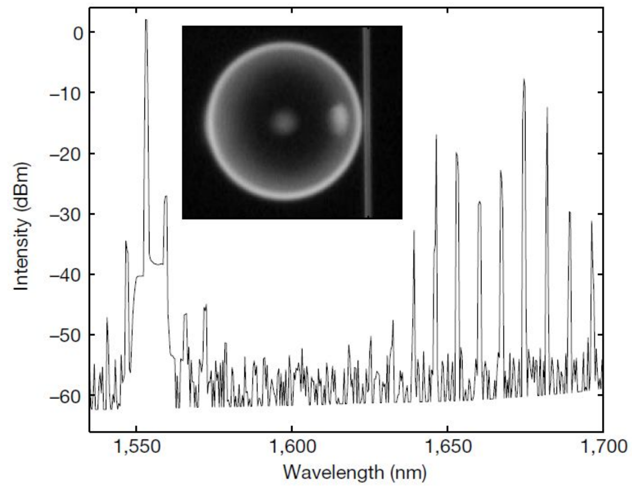
Raman lasing in high-Q silica microcavity

- Stimulated Raman Scattering(SRS)
  - Third-order nonlinearity χ^3
  - Competing FWM process
  - Silica has broad Raman gain



D. Hollenbeck, and C. Cantrell, JOSA B **19,** 2886 (2002).

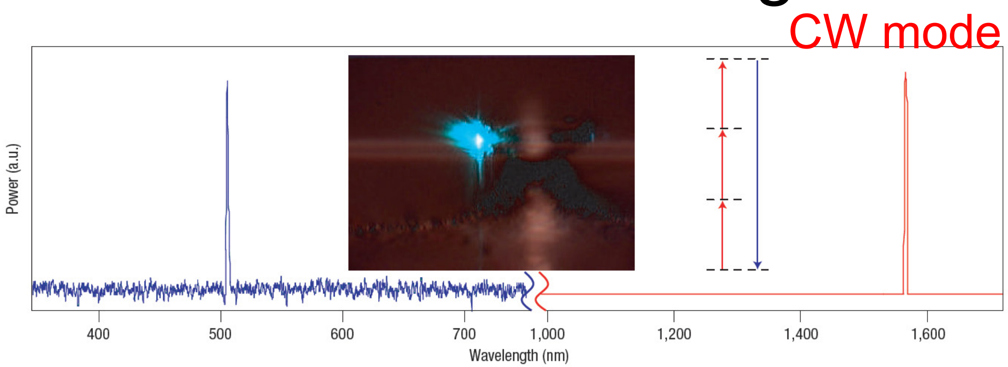
- Raman lasing in high-Q silica microcavity
  - small input power (~ μW)
  - high conversion efficiency
  - Often observing Multi-mode lasing



S. Spillane, *et al.,* Nature **415,** 621 (2002).

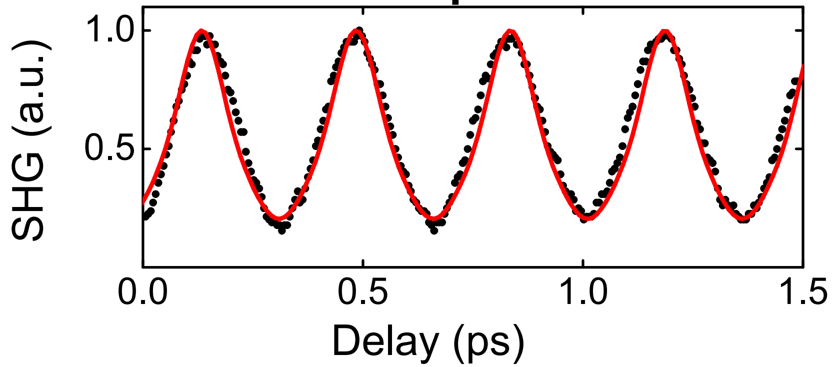
Visible comb generation with soliton pulse

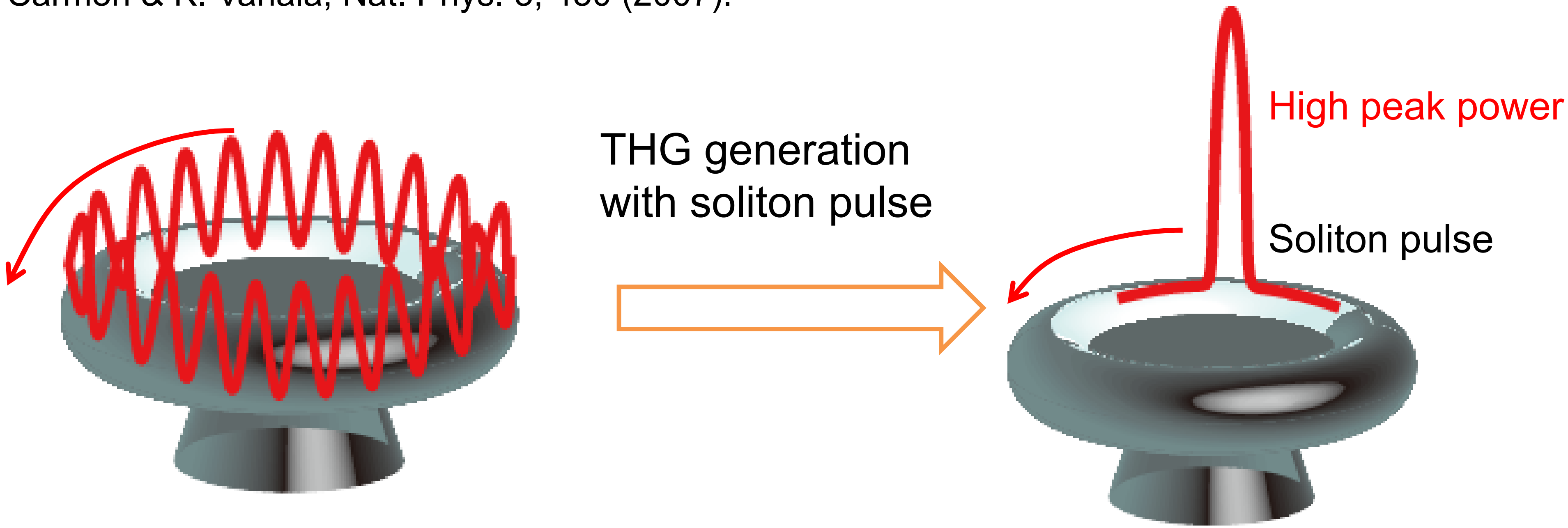
▶Efficient third-harmonic generation



T. Carmon & K. Vahala, Nat. Phys. 3, 430 (2007).

▶THG with pulsed mode

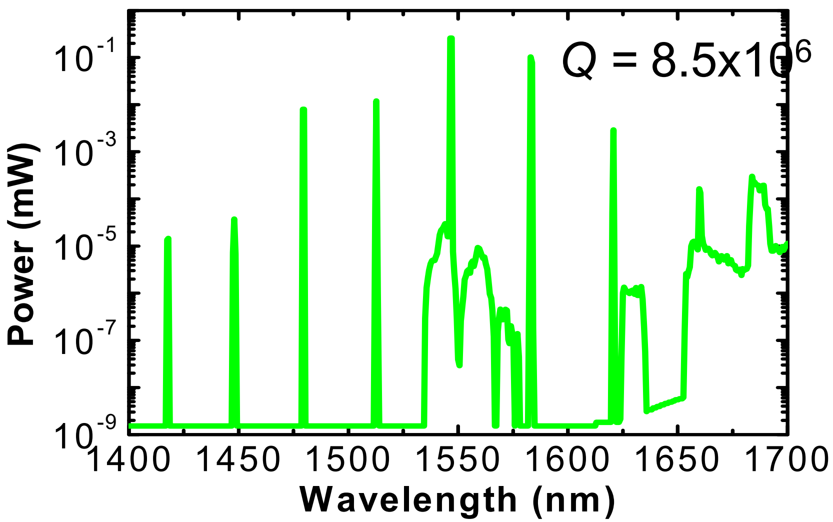


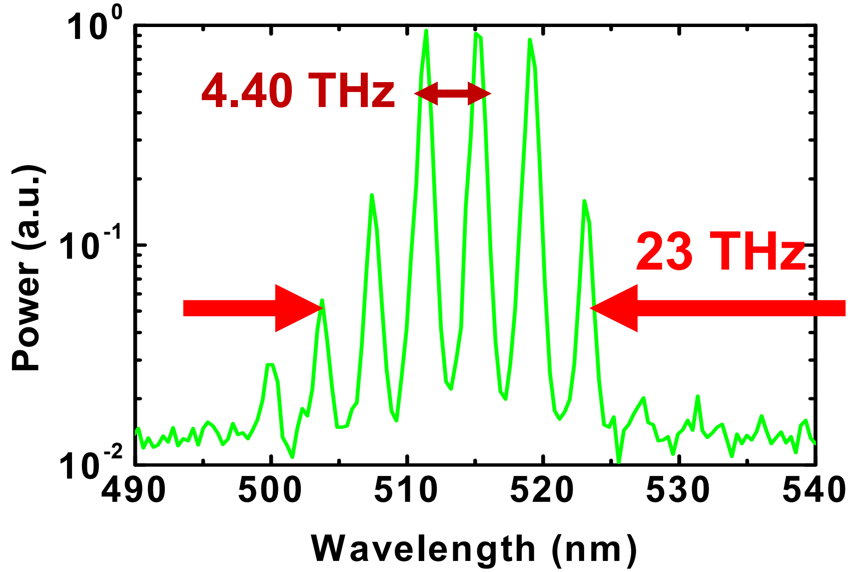


Potential for improving THG efficiency

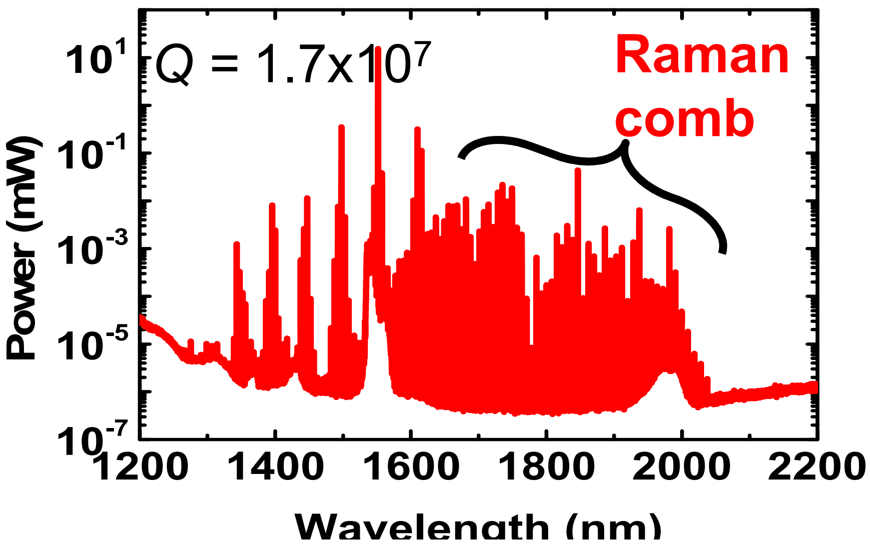
Broad bandwidth generation

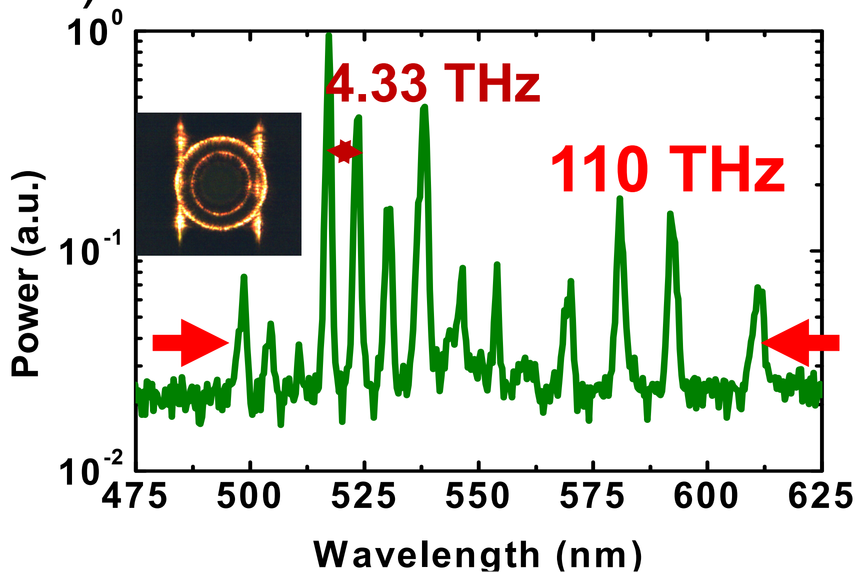
▶w/o Raman comb (Input: 1545.93 nm, 0.94 W)





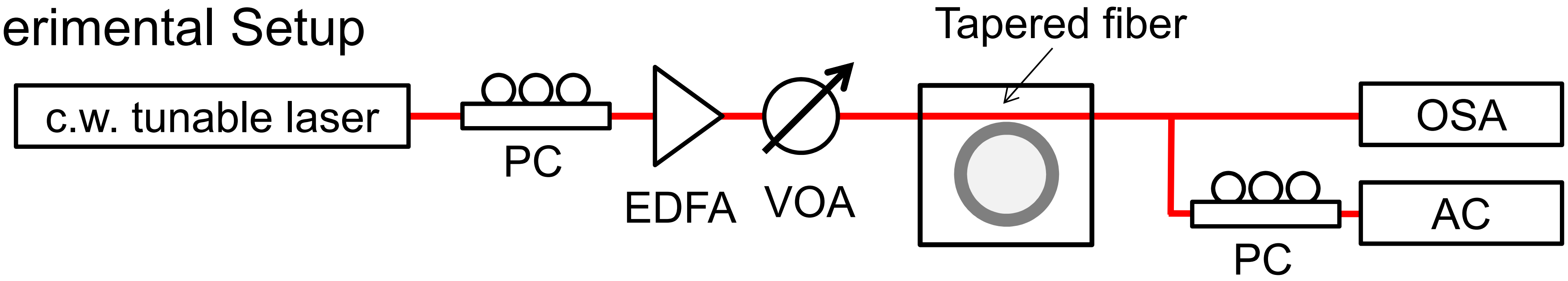
▶w/ Raman comb (Input: 1551.59 nm, 1 W)

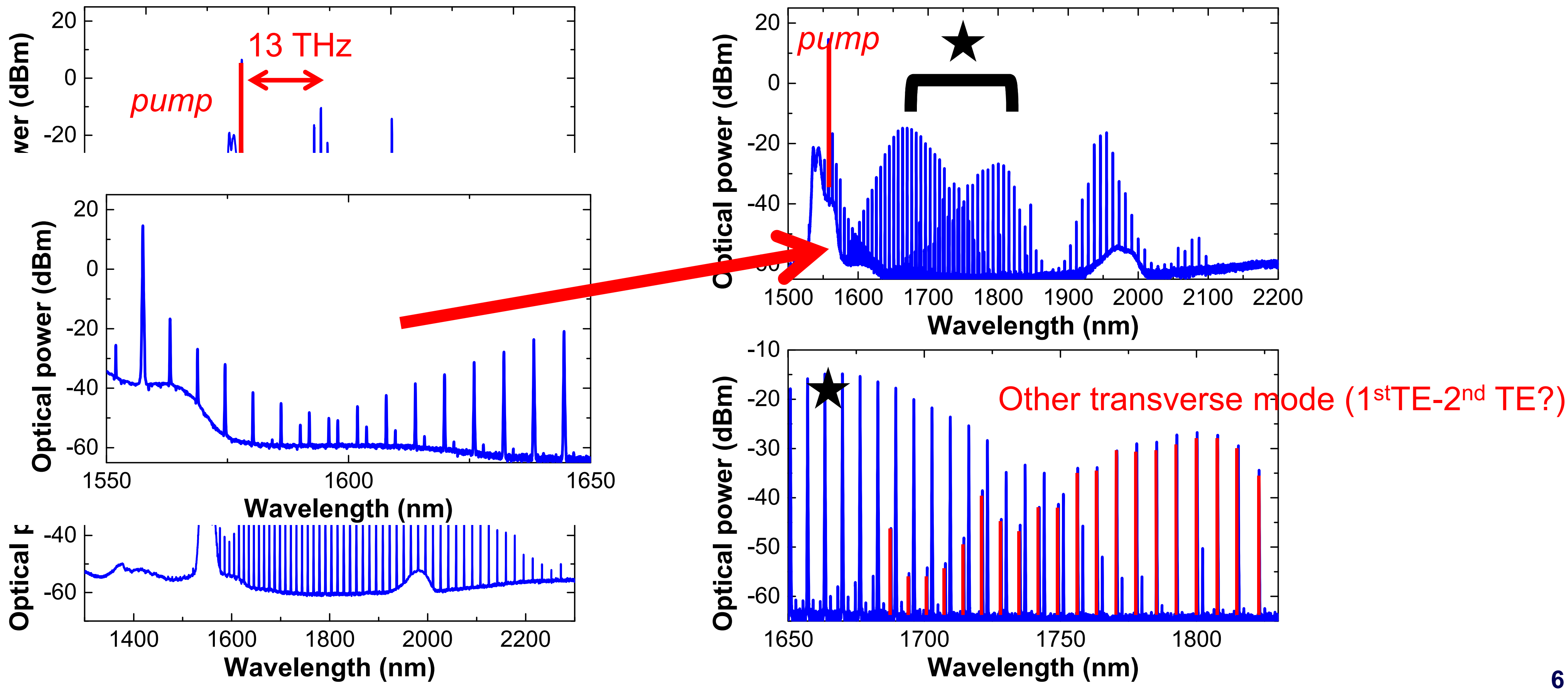




Raman scattering in Kerr comb generation

Experimental Setup





Motivation & objective

Motivation:

Application:

Two-comb modes have possibilities to apply dual comb applications.

Physics:

Raman scattering in Kerr comb in silica cavity is still unclear.

Objectives

- □ **Develop a numerical model considering 2 modes interacting with Raman scattering.**
- □ **Compare numerical/experimental results**

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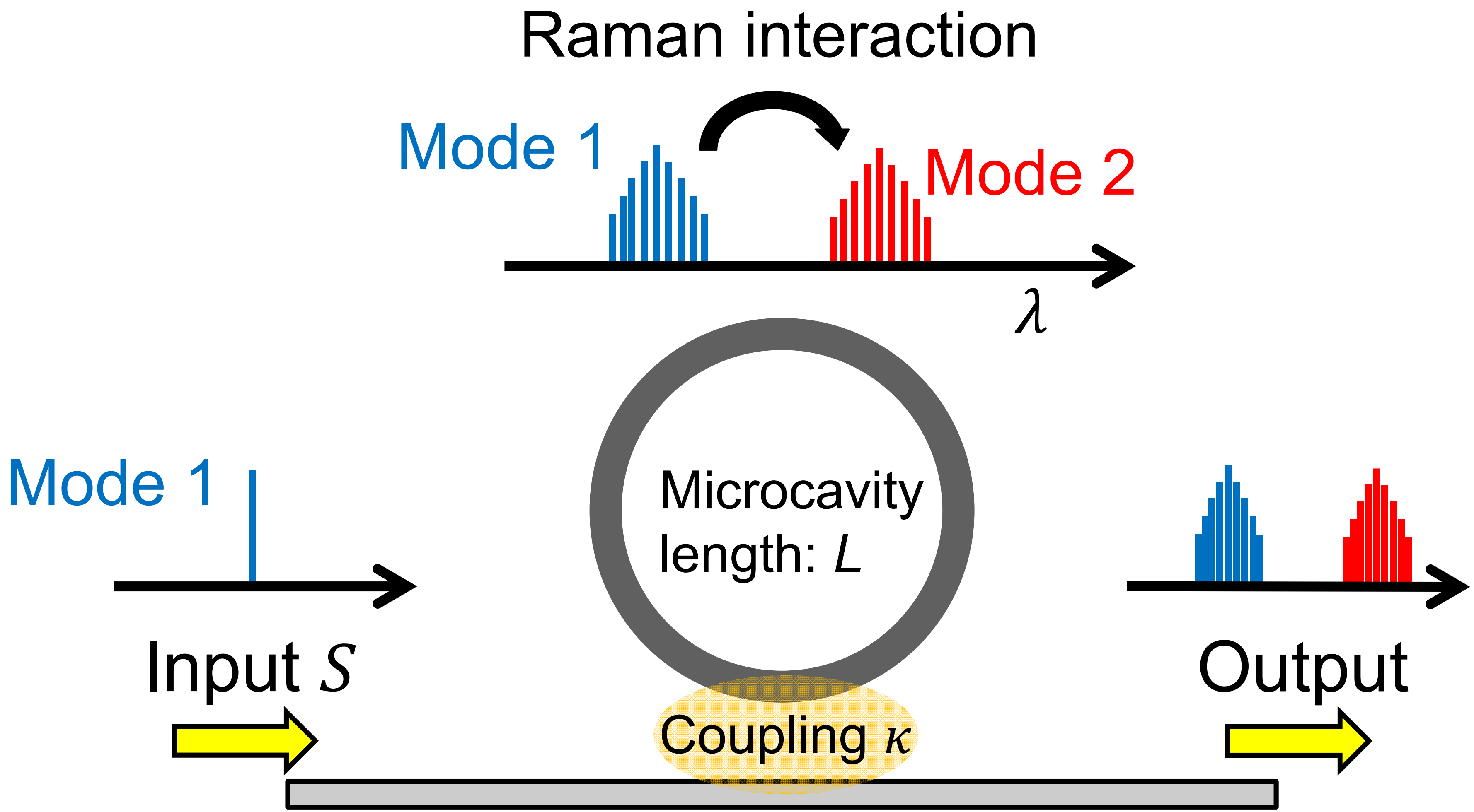
Numerical model

- Consider two modes that couple with Raman scattering



Simultaneous Lugiato-Lefever Equations

- Lugiato-Lefever equations with Raman interaction

Mode 1 (pump mode)

$$t_R \frac{\partial E_p}{\partial t} = \left\{ -\frac{\alpha_p}{2} - \frac{\kappa_p}{2} - i\delta_p + iL \sum_{k\geq 2} \frac{\beta_p^{(k)}}{k!} \left(-i \frac{\partial}{\partial t} \right)^k \right\} E_p + iL\boldsymbol{N_p} + \sqrt{\kappa_p} S_{\text{in}}$$

$$\boldsymbol{N_p} = (1 - f_R)\left(\gamma_p |E_p|^2 + 2\Gamma_p |E_s|^2\right) E_p + f_R \left\{ \begin{array}{c} \gamma_p E_p \int_{-\infty}^{\infty} h_R(t') |E_p(t - t')|^2 dt' \\ + \Gamma_p E_p \int_{-\infty}^{\infty} h_R(t') |E_s(t - t')|^2 dt' + \Gamma_p E_s \int_{-\infty}^{\infty} h_R(t') E_p(t - t') E_s^*(t - t') dt' \end{array} \right\}$$

Mode 2 (Raman mode)

$$t_R \frac{\partial E_s}{\partial t} = \left\{ -\frac{\alpha_s}{2} - \frac{\kappa_s}{2} - iL(\beta_s^{(1)} - \beta_p^{(1)}) \left(-i \frac{\partial}{\partial t} \right) + iL \sum_{k\geq 2} \frac{\beta_s^{(k)}}{k!} \left(-i \frac{\partial}{\partial t} \right)^k \right\} E_s + iL\boldsymbol{N_s}$$

$$\boldsymbol{N_s} = (1 - f_R)\left(\gamma_s |E_s|^2 + 2\Gamma_s |E_p|^2\right) E_s + f_R \left\{ \begin{array}{c} \gamma_s E_s \int_{-\infty}^{\infty} h_R(t') |E_s(t - t')|^2 dt' \\ + \Gamma_s E_s \int_{-\infty}^{\infty} h_R(t') |E_p(t - t')|^2 dt' + \Gamma_s E_p \int_{-\infty}^{\infty} h_R(t') E_s(t - t') E_p^*(t - t') dt' \end{array} \right\}$$

Simultaneous Lugiato-Lefever Equations

☐ Lugiato-Lefever equations with Raman interaction

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t_R: round trip
α_p : intrinsic loss
κ_p : external loss
δ_p : detuning
$\beta^{(2)}$: 2nd order dispersion

L: cavity length
N_p : nonlinear term
S_{in} : input power
f_R : contribution of Raman
γ, Γ : nonlinear coefficient
h_R: Raman response function

Simultaneous Lugiato-Lefever Equations

- Lugiato-Lefever equations with Raman interaction

t_R: round trip
α_p : intrinsic loss
κ_p : external loss
δ_p : detuning
$\boldsymbol{\beta}^{(1)}$: 1st order dispersion
$\beta^{(2)}$: 2nd order dispersion

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$$\boldsymbol{N_s} = (1-f_R)\left(\gamma_s|E_s|^2 + 2\Gamma_s\left|E_p\right|^2\right)E_s + f_R\left\{\begin{matrix} \gamma_s E_s\int_{-\infty}^{\infty} h_R(t')|E_s(t-t')|^2 dt' \\ +\Gamma_s E_s\int_{-\infty}^{\infty} h_R(t')\left|E_p(t-t')\right|^2 dt' + \Gamma_s E_p\int_{-\infty}^{\infty} h_R(t')E_s(t-t')E_p^*(t-t')dt' \end{matrix}\right\}$$

Supplements: nonlinear coefficient

$$\gamma = \frac{n_2\omega}{cA_{\mathrm{AA}}} \qquad \Gamma = \frac{n_2\omega}{cA_{\mathrm{AB}}}$$

n_2: nonlinear refractive index
A_{AA} : effective mode area (self)
A_{AB} : effective mode area (interaction)

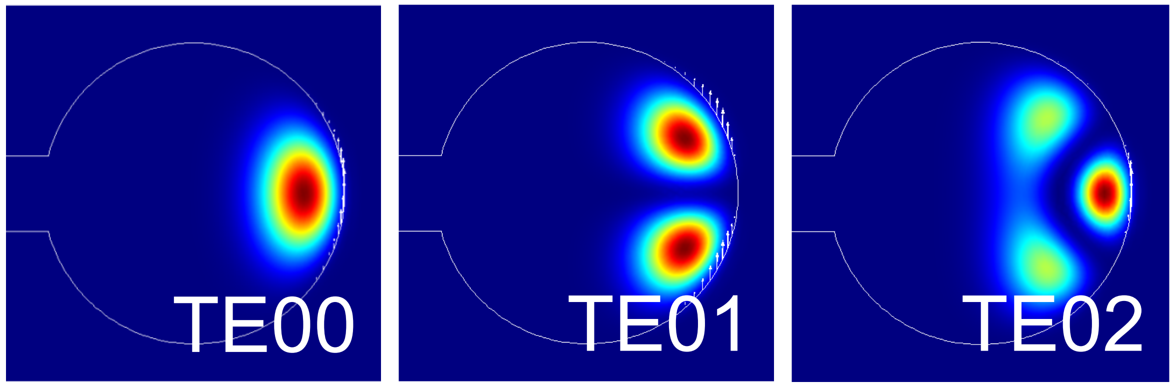
$$A_{AA} = \frac{\iint |A(x,y)|^2 dxdy * \iint |A(x,y)|^2 dxdy}{\iint |A(x,y)|^4 dxdy}$$

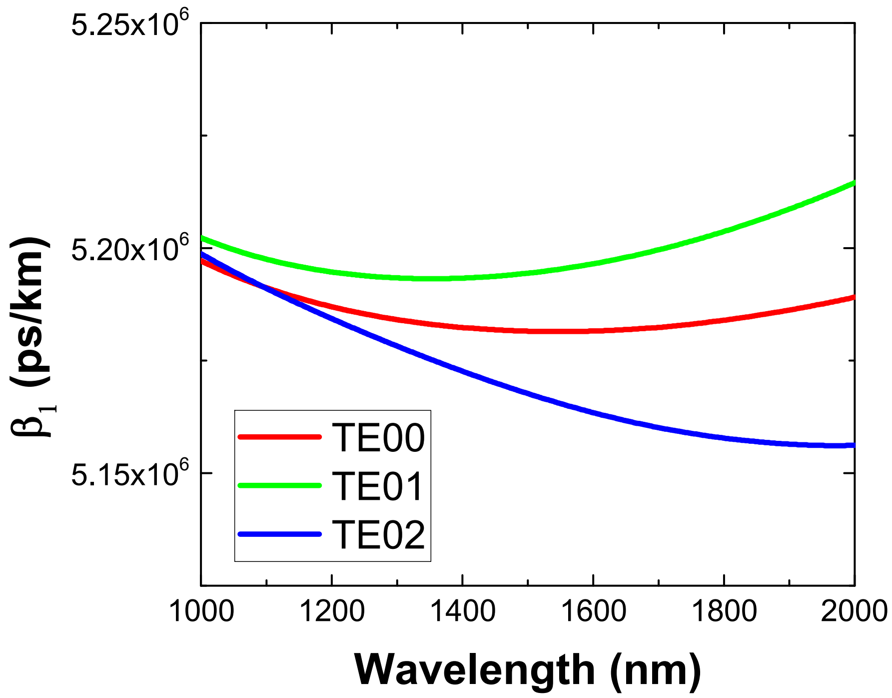
$$A_{AB} = \frac{\iint |A(x,y)|^2 dxdy * \iint |B(x,y)|^2 dxdy}{\iint |A(x,y)|^2 |B(x,y)|^2 dxdy}$$

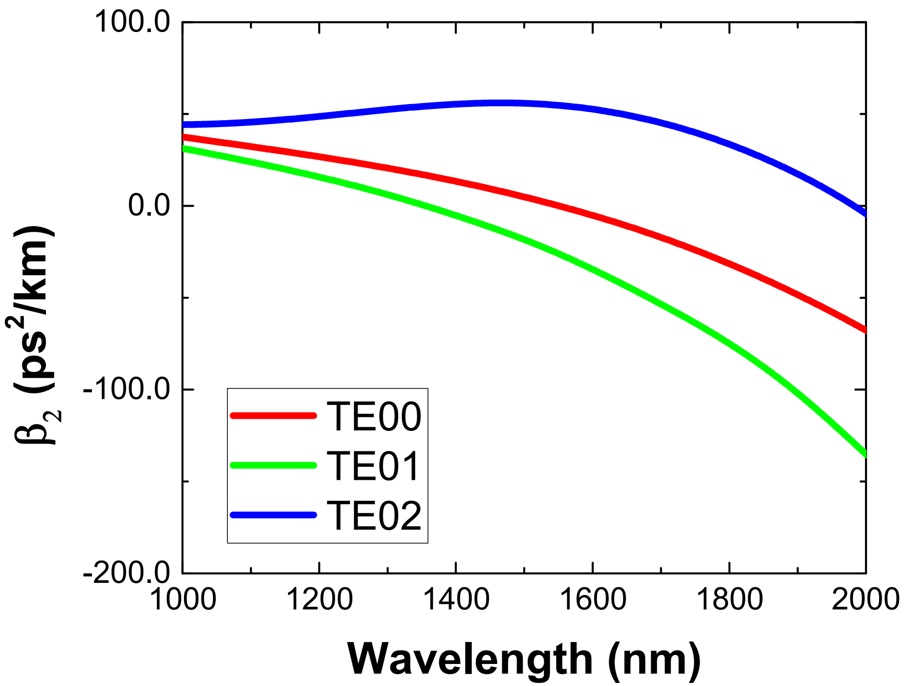
	Mode area (μm^2)
A_{TE00}	8.285
A_{TE01}	10.879
A_{TE02}	15.066
A_{TE00_TE01}	15.632
A_{TE01_TE02}	23.532
A_{TE02_TE00}	18.498

Parameters

Model: Silica toroid
Major *R*: 50 μm
Minor *R*: 4 μm
FSR: 600 GHz







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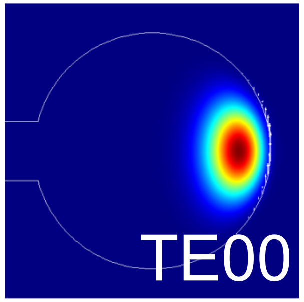
Dependence on Q factor

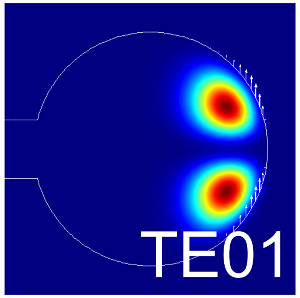
$P_{\text{in}} = 100\ \text{mW}$
$\delta_p = 1 \times 10^{-4}$

Pump mode: TE_{00}

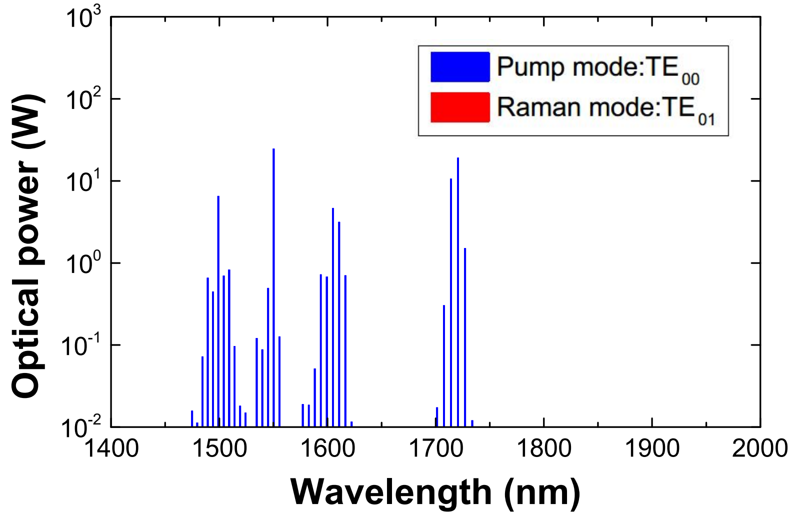


$Q_{\text{TE}_{00}} = 1 \times 10^8$

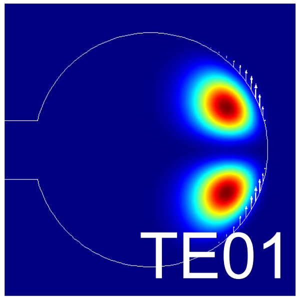
Raman mode: TE_{01}



$Q_{\text{TE}_{01}} = 2 \times 10^7$

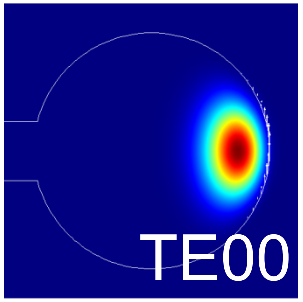


Pump mode: TE_{01}

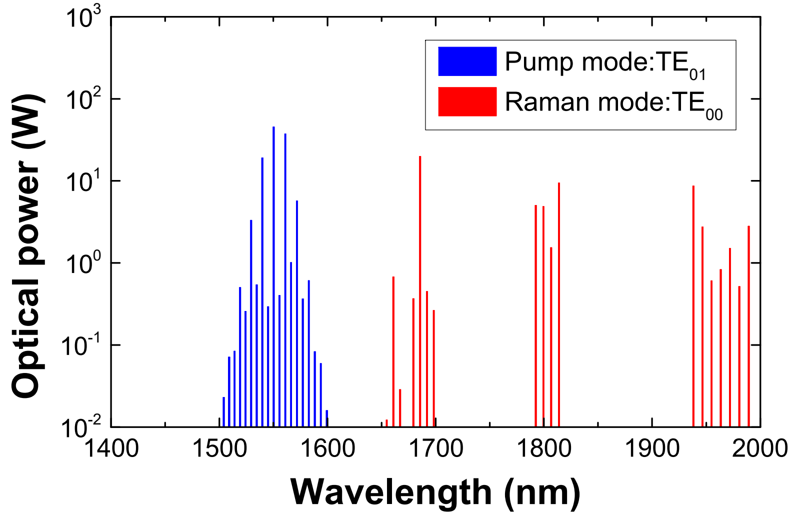


$Q_{\text{TE}_{01}} = 2 \times 10^7$

Raman mode: TE_{00}



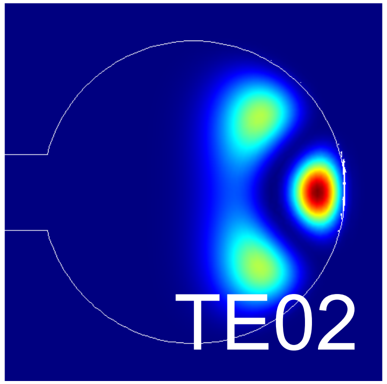
$Q_{\text{TE}_{00}} = 1 \times 10^8$



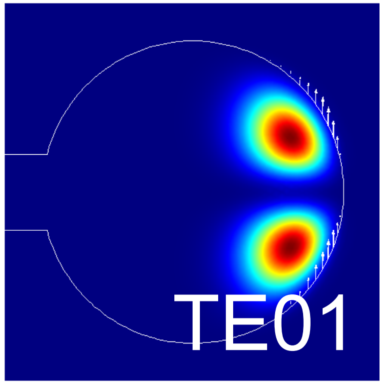
★Lower Q mode excites Higher Q mode Raman scattering.

Comparison with the experimental result

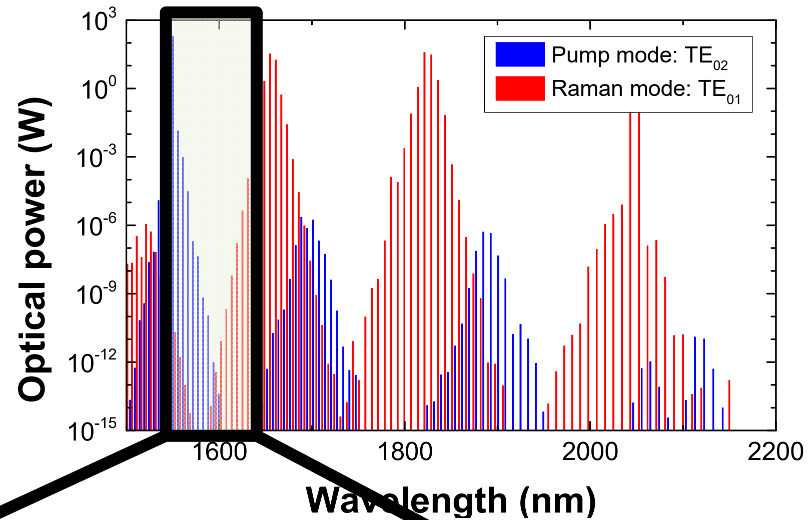
Pump mode: TE_{02} Raman mode: TE_{01} $P_{\mathrm{in}} = 1\,\mathrm{W}, \delta_p = 3.575 \times 10^{-4}$

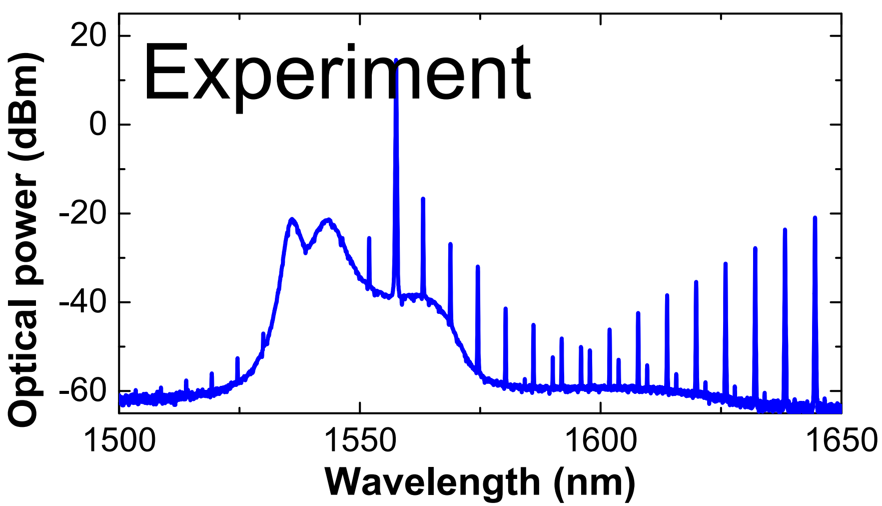


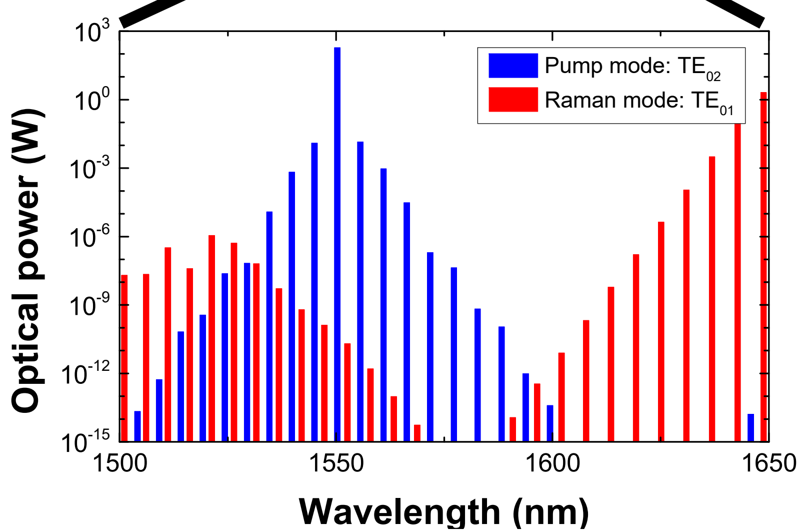
$Q_{\mathrm{TE}_{02}} = 7 \times 10^6$



$Q_{\mathrm{TE}_{01}} = 5 \times 10^7$

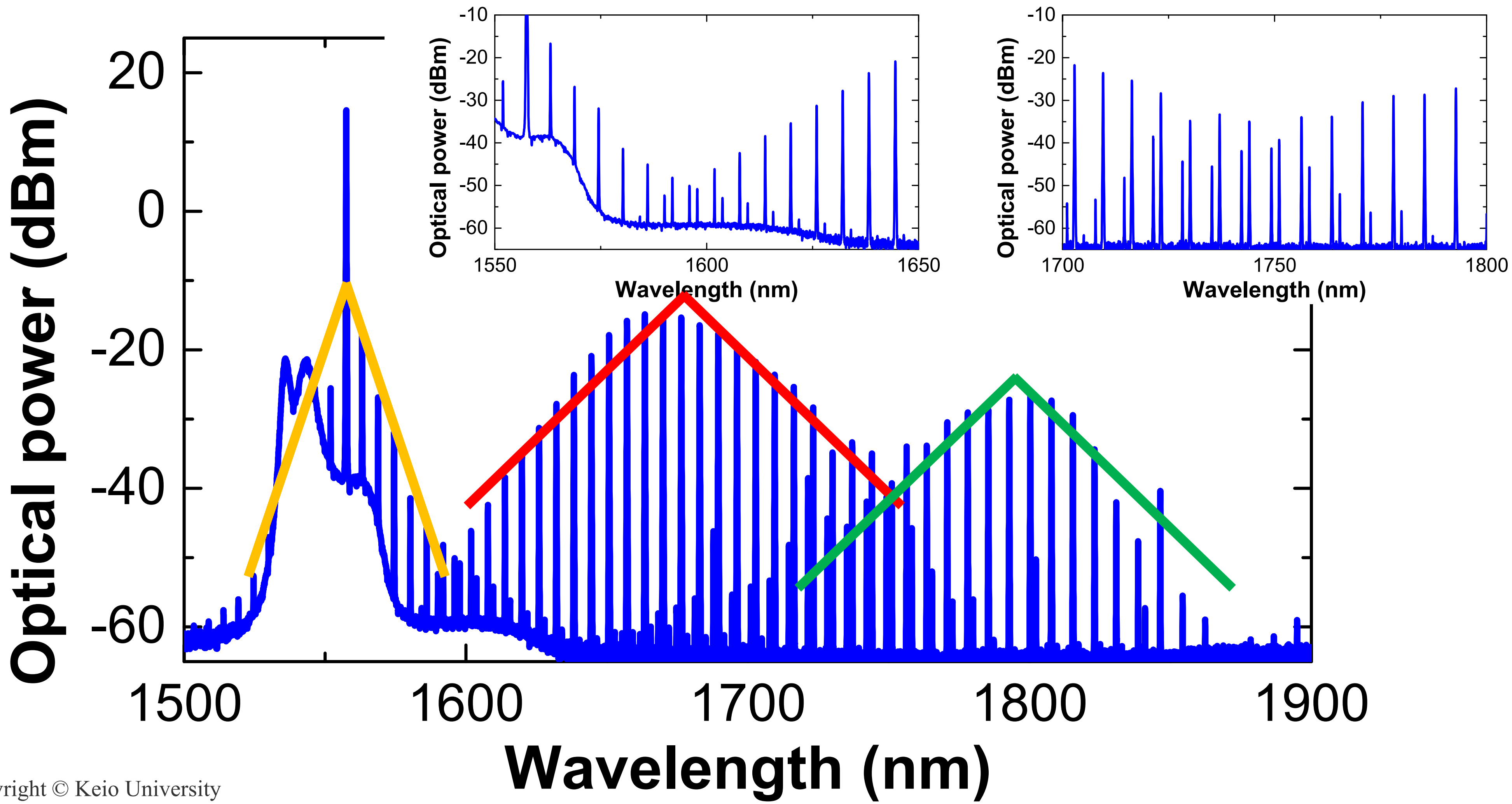






Three mode interaction

- Three mode interaction should be considered in this system.
  (ex: TE02→TE01→TE00)



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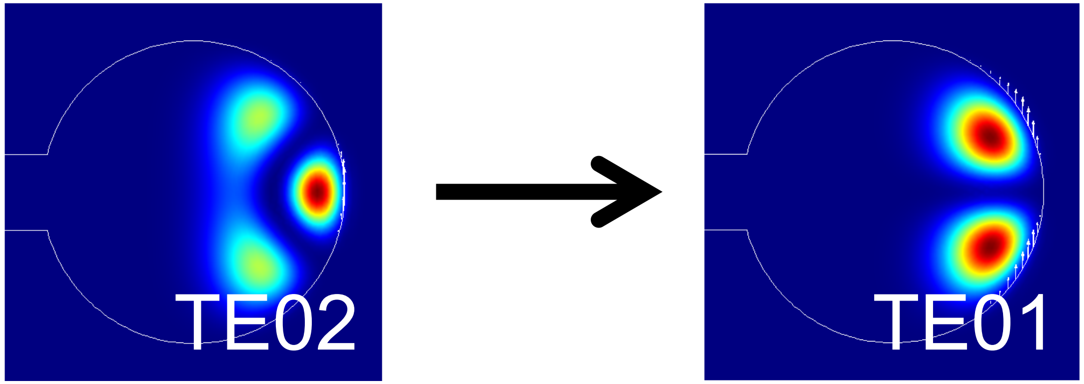
Raman soliton generation

Pump mode: TE_{02}

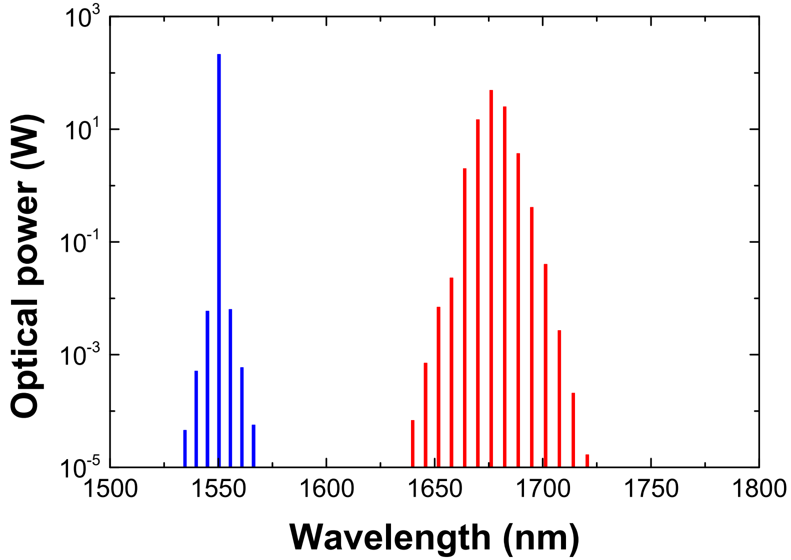
Raman mode: TE_{01}

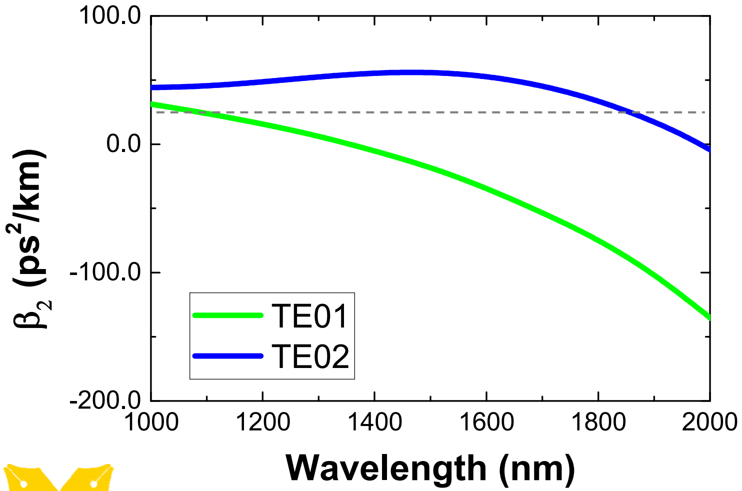


$Q_{TE_{02}} = 7 \times 10^6$

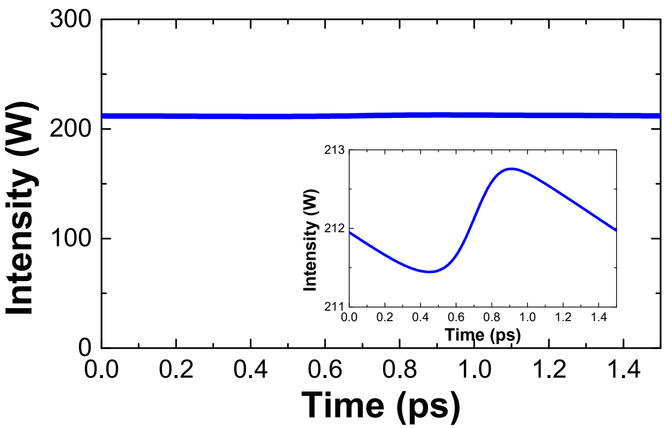
$Q_{TE_{01}} = 1.8 \times 10^7$

$P_{in} = 1\ \mathrm{W}, \delta_p = 3.575 \times 10^{-4}$

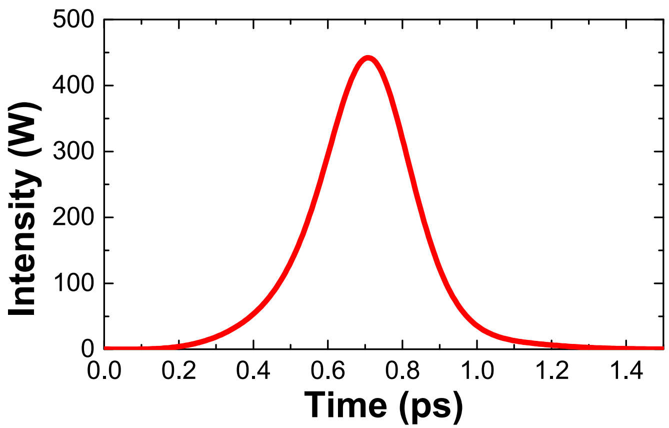




Pump mode



Raman mode

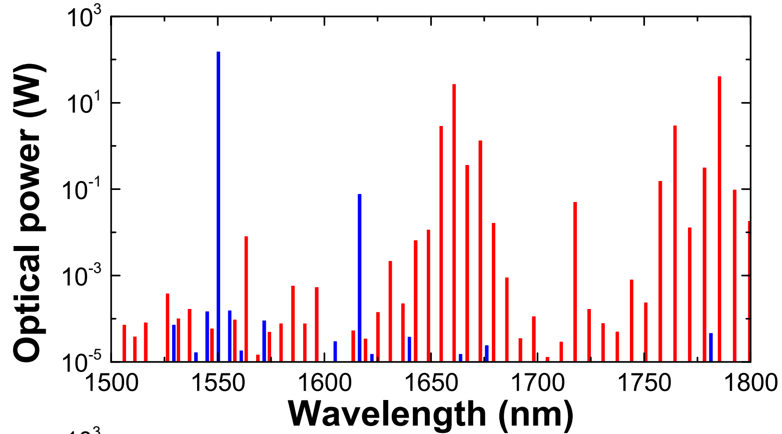


Raman soliton generation

□ Chaotic condition (too high-Q)

Pump mode: TE_{02} Raman mode: TE_{01}

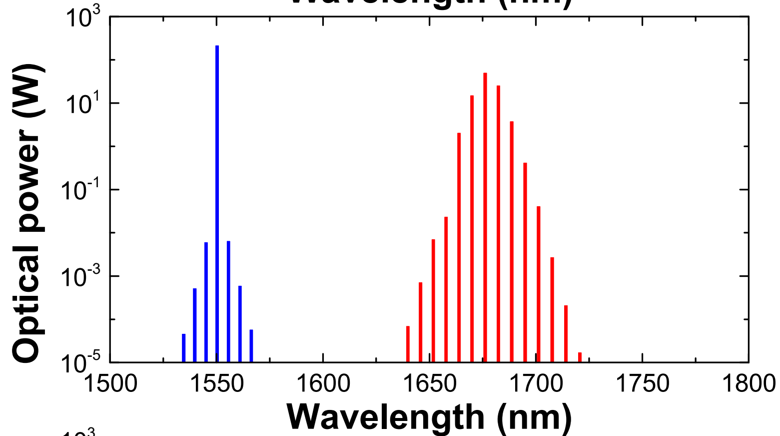
$Q_{TE_{02}} = 7 \times 10^6$ $Q_{TE_{01}} = 5.0 \times 10^8$



□ Soliton condition (reasonable Q)

Pump mode: TE_{02} Raman mode: TE_{01}

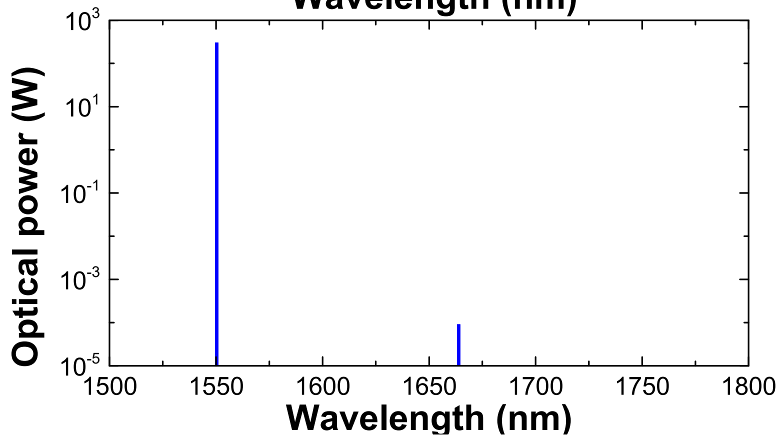
$Q_{TE_{02}} = 7 \times 10^6$ $Q_{TE_{01}} = 1.8 \times 10^7$



□ No excitation (too low-Q)

Pump mode: TE_{02} Raman mode: TE_{01}

$Q_{TE_{02}} = 7 \times 10^6$ $Q_{TE_{01}} = 9.0 \times 10^6$



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Summary

[Experiment]

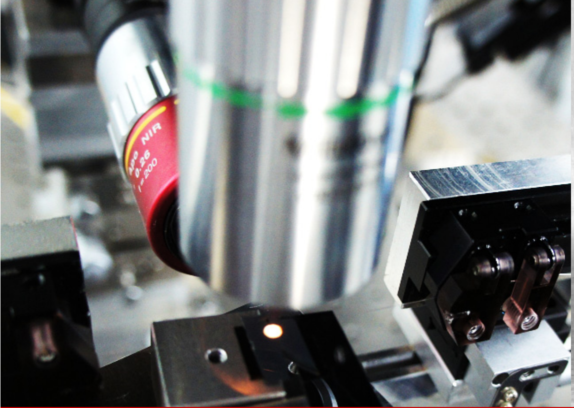
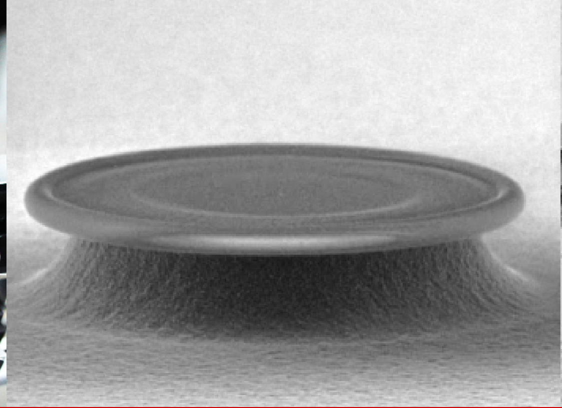
・We observed multi-mode generation through Raman scattering with silica toroidal microcavity.

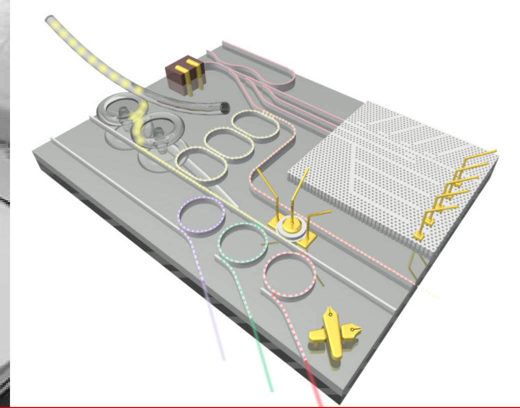
[Numerical simulation]

・We developed simultaneous LLE considering Raman effect.

・We considered TE_{00}, TE_{01}, and TE_{02} modes.

- Lower Q mode pumping excites Higher Q mode.
- Three mode interaction could be occurred.
- Raman soliton can achieve when Raman mode satisfies soliton condition.



Thank you very much

Acknowledgement

・Ministry of Education, Culture, Sports, Science and Technology (MEXT) (KAKEN 15H05429)

・Grant-in-Aid from the Ministry of Education, Culture, Sports, Science and Technology, Japan for the Photon Frontier Network Program.