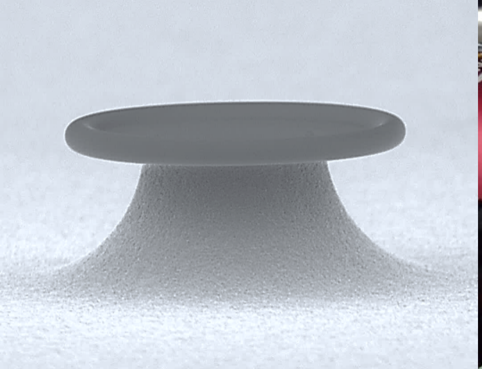

The 5th Advanced Lasers and Photon Sources (ALPS'16)
ALPS1-3, May 17, 2016

Effects with Kerr comb in silica toroid microcavity: Raman scattering and third harmonic generation

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Tomoya Kobatake, Shun Fujii and Takasumi Tanabe

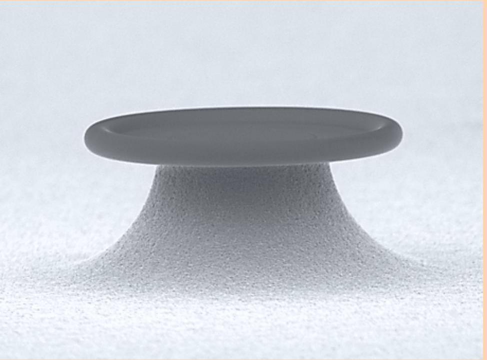
Faculty of Science and Technology,
Keio University

JSPS KAKENHI under Grant 16J04286, 15H05429.

Kerr frequency comb

Kerr comb

Microcavity



- ✓ Small size & Low cost
- ✓ High repetition rate (10GHz-1THz)
- ✓ Large bandwidth
- ✓ Low threshold power

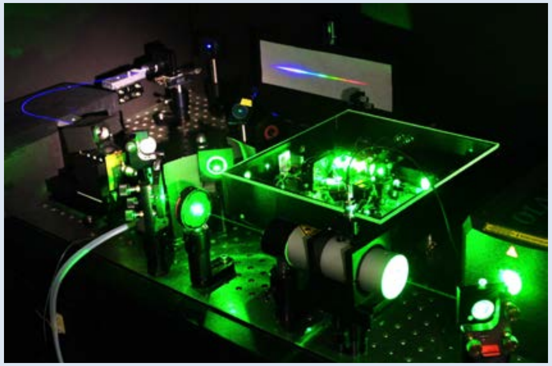
Threshold pump power of four-wave mixing

$$P_{\mathrm{threshold}} \propto V/Q^2$$

V : Mode volume
Q : Quality factor

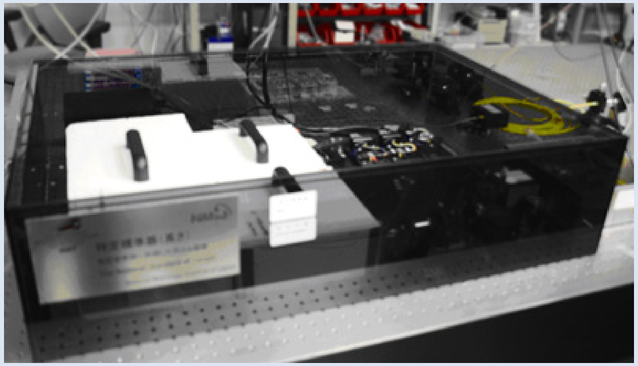
Conventional frequency comb sources

Ti:Sapphire laser



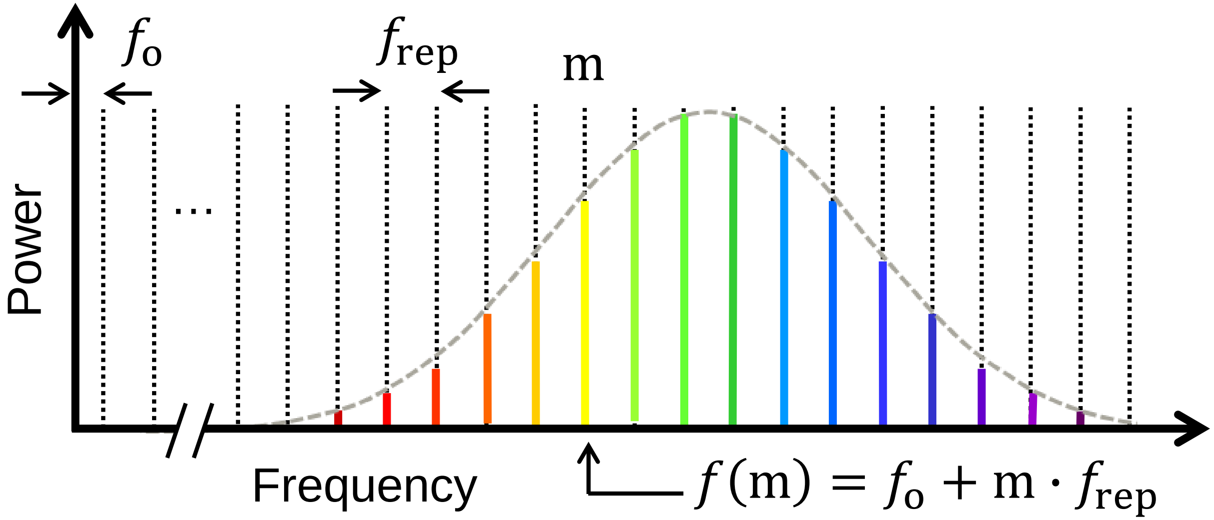
http://www.mpq.mpg.de/~haensch/comb/index.html

Fiber laser



https://www.aist.go.jp/index_ja.html

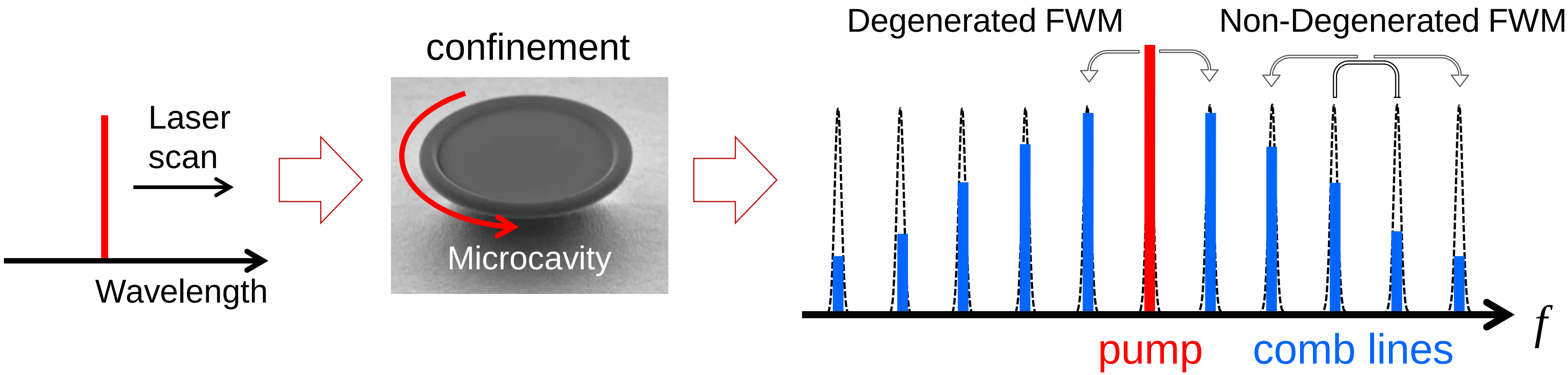
Large size & High cost



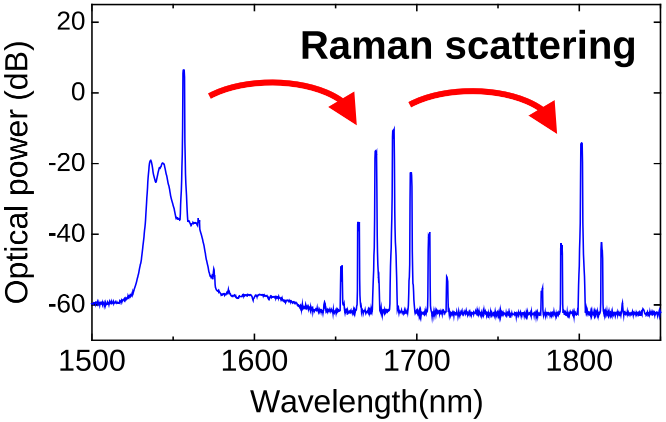
$$f(\mathrm{m}) = f_o + \mathrm{m} \cdot f_{\mathrm{rep}}$$

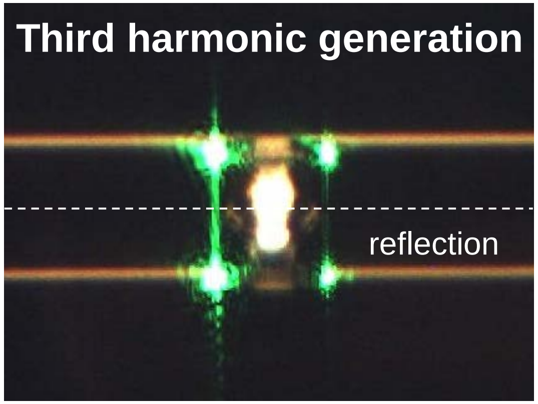
Generation scheme & Effects with Kerr comb

Cascaded FWM occurs by pumping the microcavity with CW laser

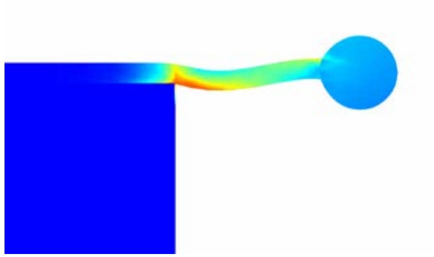


The strong optical confinement simultaneously causes other effects



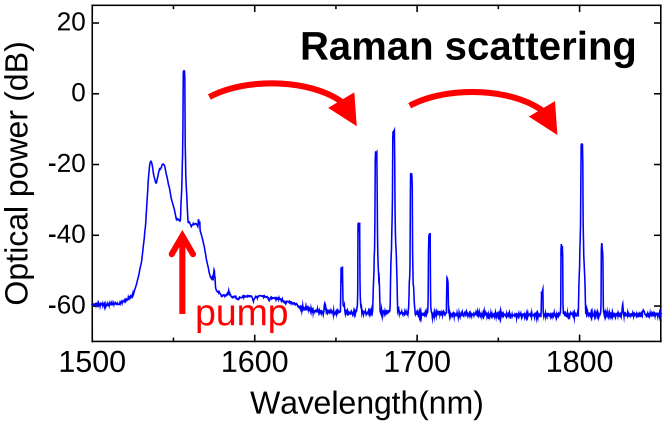


Cavity optomechanics



Raman scattering

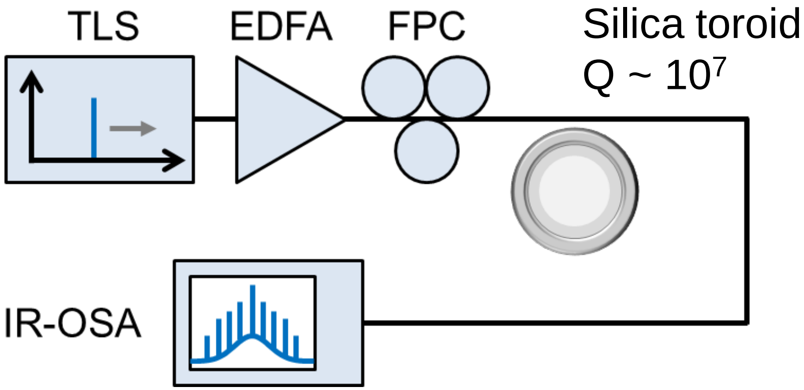
Typical experimental result



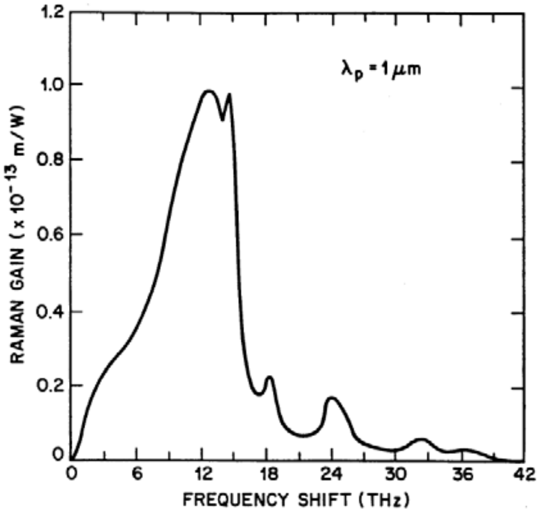
Raman scattering results from the delayed molecular response of the host medium

Silica: $\Omega_R/2\pi \sim 13\ \mathrm{THz}$

Experimental setup



Raman gain spectrum



G. Agrawal, “Nonlinear Fiber Optics”, Academic Press

Motivation

Microcavity with $\chi^{(3)}$ causes Kerr and/or Raman effects when the cavity is pumped above a threshold power.

However, these effects have almost been investigated separately.

Nonlinear Schrödinger equation

$$t_{\mathrm{R}}\frac{\partial E}{\partial t}=\left\{-\frac{1}{2}\underbrace{(\alpha_{\mathrm{i}}+\alpha_{\mathrm{c}})}_{\text{cavity loss}}-i\underbrace{\delta}_{\text{detuning}}+\underbrace{iL\sum_{k\geq 2}\frac{\beta_{k(m)}}{k!}\left(i\frac{\partial}{\partial\tau}\right)^{k}}_{\text{dispersion}}\right\}E+i\gamma L{\color{red}N}+\underbrace{\sqrt{\alpha_{\mathrm{c}}}E_{\mathrm{in}}}_{\text{coupling}}$$

$${\color{red}N}=\underbrace{|E|^{2}E}_{\text{Kerr}}$$

We added Raman effect to the simulation model of Kerr comb

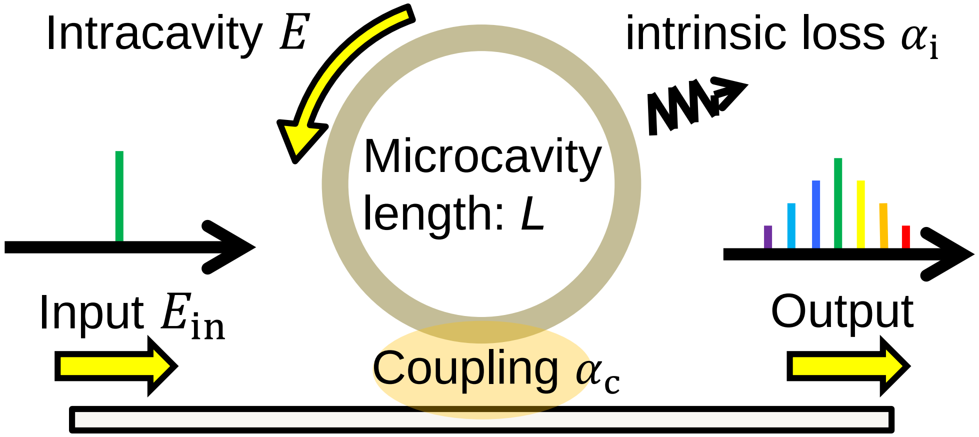
$${\color{red}N+(\text{Raman effect})}$$

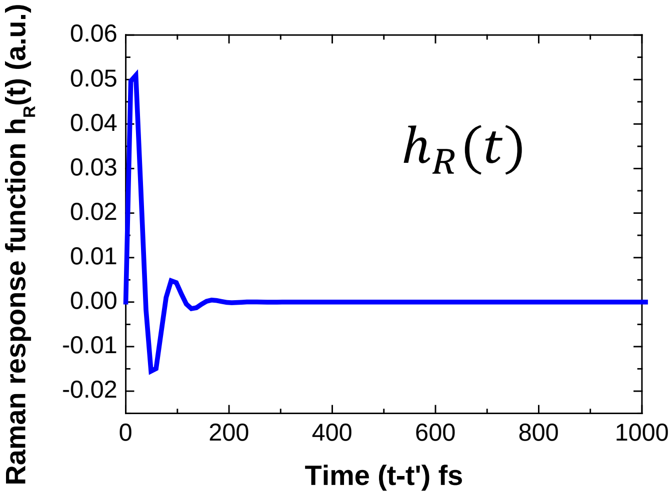
Calculation with Raman

Nonlinear Schrödinger equation + Raman effect

$$t_{\mathrm{R}} \frac{\partial E}{\partial t} = \left\{ -\frac{1}{2}\underbrace{(\alpha_{\mathrm{i}} + \alpha_{\mathrm{c}})}_{\text{cavity loss}} - \underbrace{i\delta}_{\text{detuning}} + \underbrace{iL \sum\nolimits_{k\geq 2} \frac{\beta_k}{k!}\left(i\frac{\partial}{\partial \tau}\right)^k}_{\text{dispersion}} \right\} E + i\gamma L N' + \underbrace{\sqrt{\alpha_{\mathrm{c}}}E_{\mathrm{in}}}_{\text{coupling}}$$

$$N' = \underbrace{(1 - f_{\mathrm{R}})|E|^2 E}_{\text{Kerr}} + \underbrace{f_R E \int_{-\infty}^{\infty} h_{\mathrm{R}}(t')|E(t-t')|^2\, dt'}_{\text{Raman}}$$

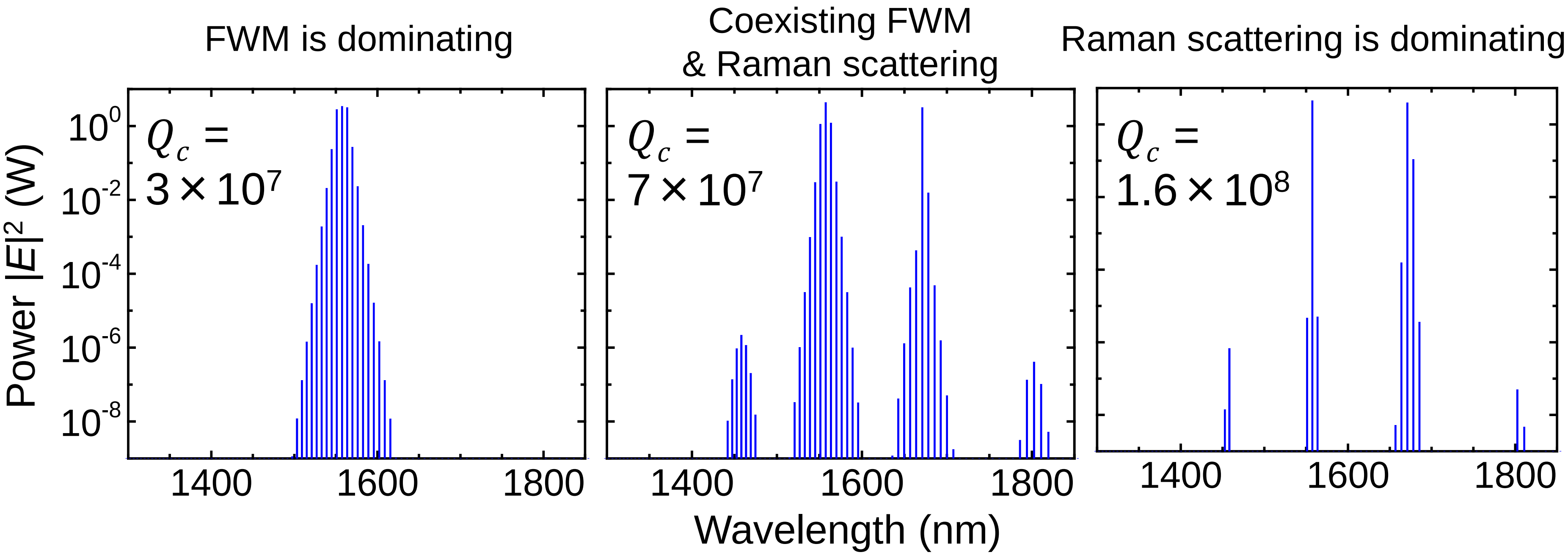




t_{R}: roundtrip time, δ_0: detuning, β_k: k$^{\mathrm{th}}$order dispersion, γ : nonlinear coefficient
f_R: contribution of delayed Raman response, h_R: Raman response function

Calculation results

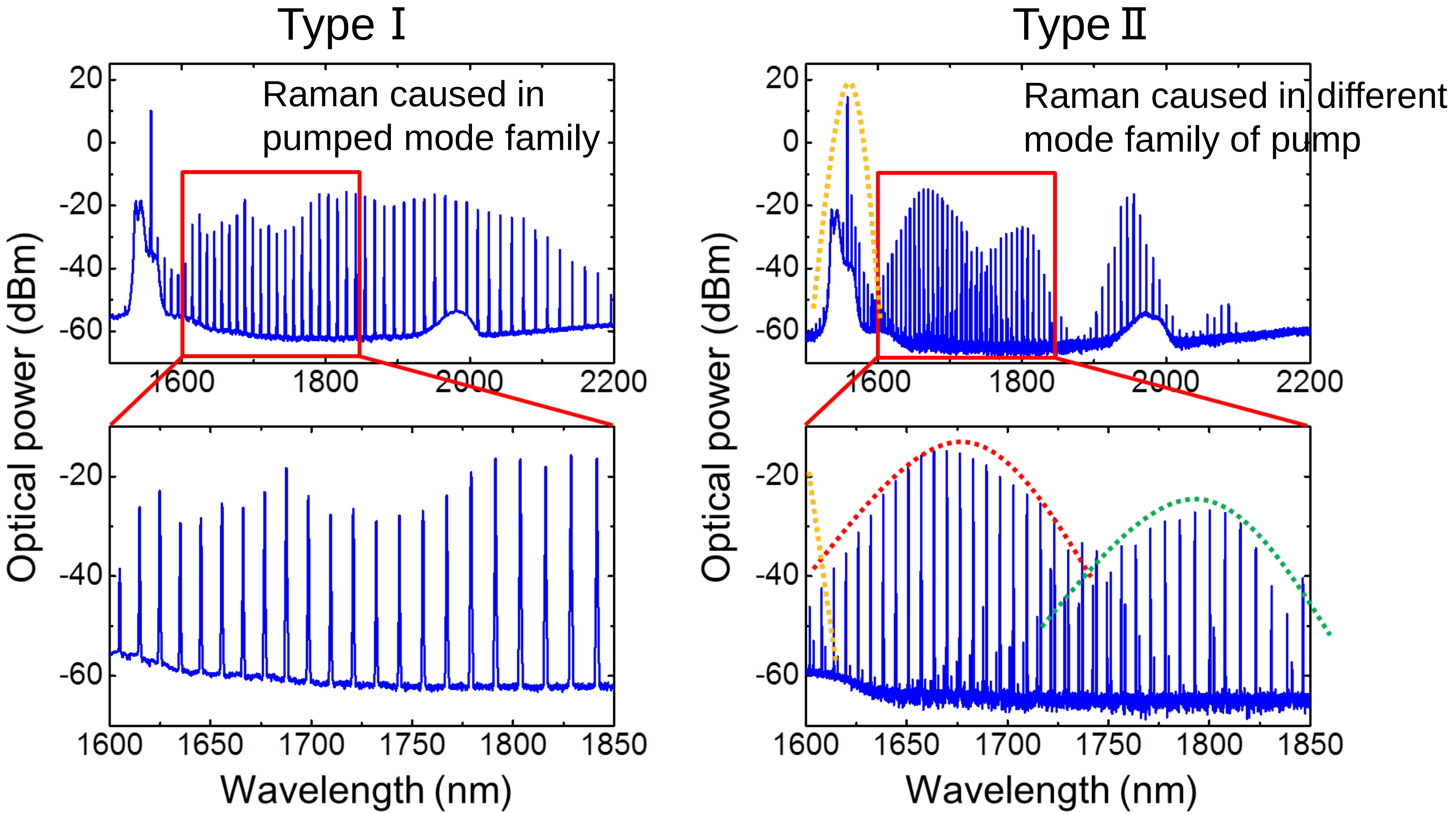
$$Q_c \propto \alpha_c^{-1}$$



strong ⇐ coupling ⇒ weak

Coupling control enables to generate FWM or Raman scattering selectively.

Experimental results



Pump
~ 500 mW

Stimulated Raman scattering had two types of formation.
However, we could not reveal the condition to decide the type.

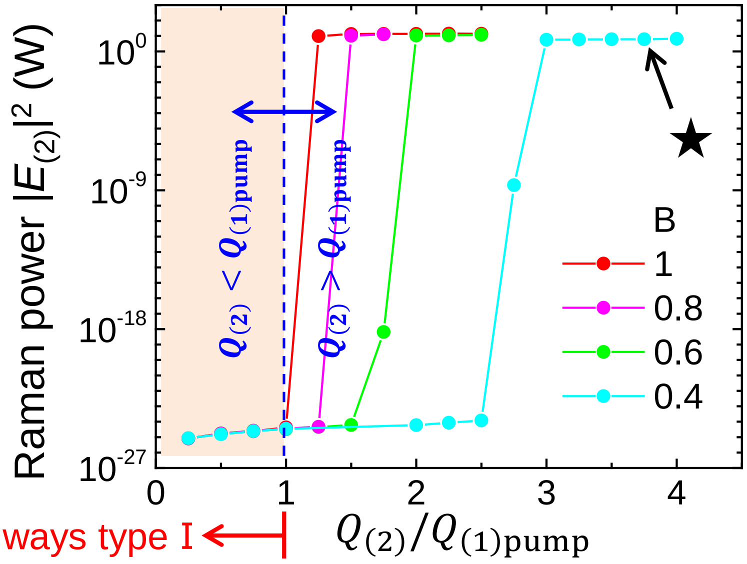
Calculation with Raman and XPM (two modes)

$$t_\mathrm{R}\frac{\partial E_{(1)}}{\partial t} = \left\{-\frac{1}{2}\left(\alpha_{\mathrm{i}(1)} + \alpha_{\mathrm{c}(1)}\right) - i\delta_{(1)} + iL\sum_{k\geq 2}\frac{\beta_{k(1)}}{k!}\left(i\frac{\partial}{\partial\tau}\right)^k\right\}E_{(1)} + i\gamma_{(1)}LN_{(1)} + \sqrt{\alpha_{\mathrm{c}(1)}}E_\mathrm{in}$$

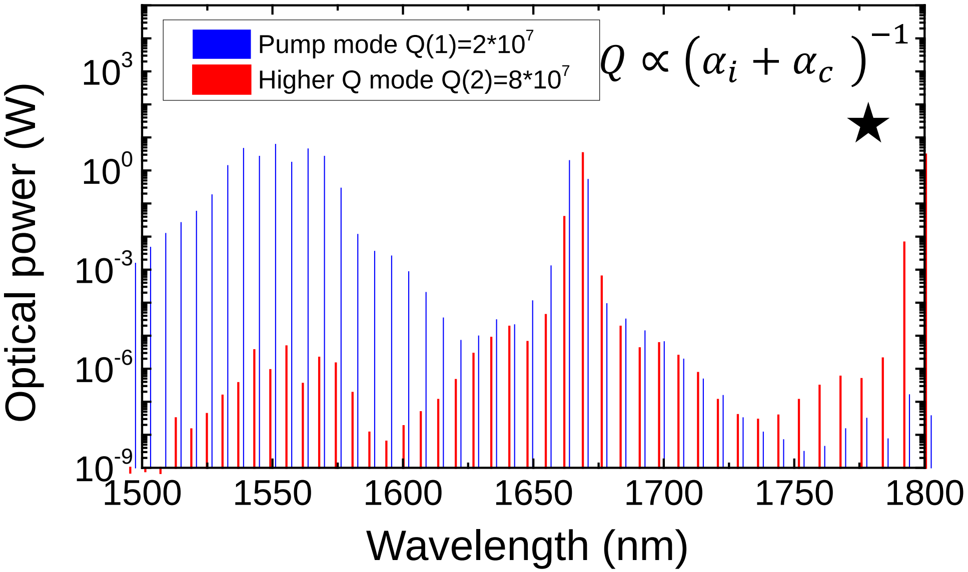
$$t_\mathrm{R}\frac{\partial E_{(2)}}{\partial t} = \left\{-\frac{1}{2}\left(\alpha_{\mathrm{i}(2)} + \alpha_{\mathrm{c}(2)}\right) - i\delta_{(2)} + iL\sum_{k\geq 2}\frac{\beta_{k(2)}}{k!}\left(i\frac{\partial}{\partial\tau}\right)^k\right\}E_{(2)} + i\gamma_{(2)}LN_{(2)}$$

$$N_{(1)} = (1-f_\mathrm{R})\left(\left|E_{(1)}\right|^2 + 2B\left|E_{(2)}\right|^2\right)E_{(1)} + f_R\left\{\begin{matrix} E_{(1)}\int_{-\infty}^{\infty} h_\mathrm{R}(t')\left|E_{(1)}(t-t')\right|^2 dt' \\ +E_{(1)}B\int_{-\infty}^{\infty} h_\mathrm{R}(t')\left|E_{(2)}(t-t')\right|^2 d + E_{(2)}B\int_{-\infty}^{\infty} h_\mathrm{R}(t')E_{(1)}(t-t')E_{(2)}^*(t-t')\,dt' \end{matrix}\right\}$$

$$N_{(2)} = (1-f_\mathrm{R})\left(\left|E_{(2)}\right|^2 + 2B\left|E_{(1)}\right|^2\right)E_{(2)} + f_R\left\{\begin{matrix} E_{(2)}\int_{-\infty}^{\infty} h_\mathrm{R}(t')\left|E_{(2)}(t-t')\right|^2 dt' \\ +E_{(2)}B\int_{-\infty}^{\infty} h_\mathrm{R}(t')\left|E_{(1)}(t-t')\right|^2 d + E_{(1)}B\int_{-\infty}^{\infty} h_\mathrm{R}(t')E_{(2)}(t-t')E_{(1)}^*(t-t')\,dt' \end{matrix}\right\}$$



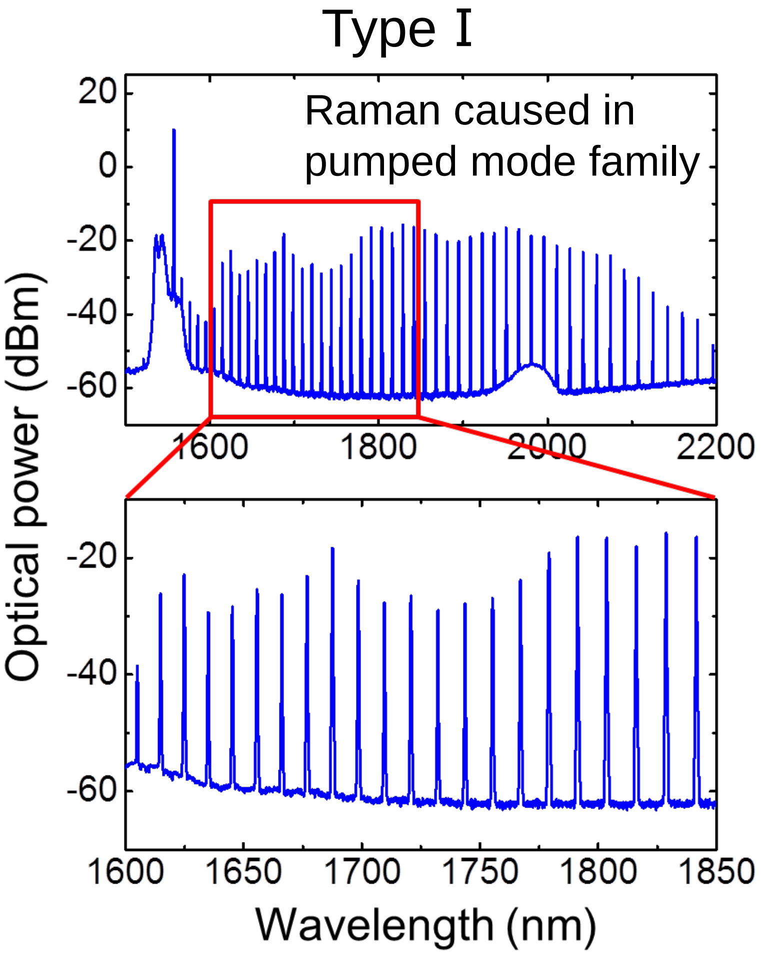
Always type I

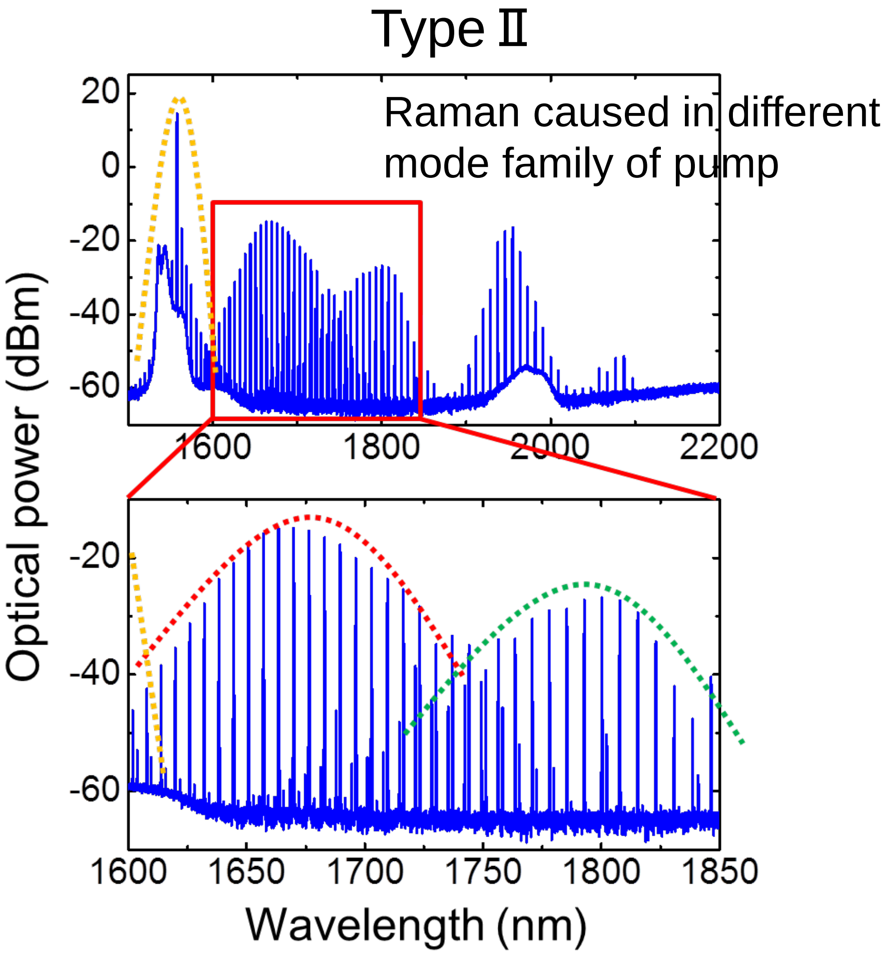


B: mode overlapping of different modes

When the highest Q mode (fundamental mode) is pumped, mode family of pump and Raman scattering is always the same

Experimental results





Pump
~ 500 mW

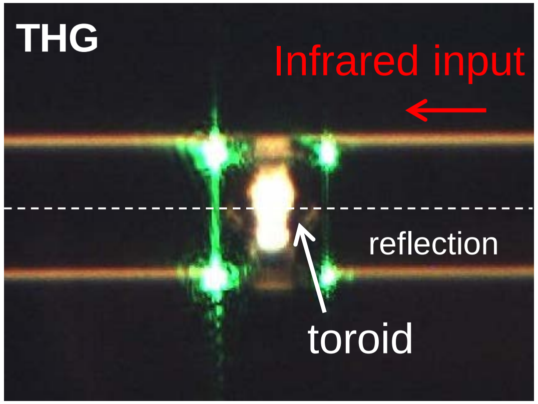
Taking the simulation result into account,

Highest Q mode (fundamental mode) was pumped

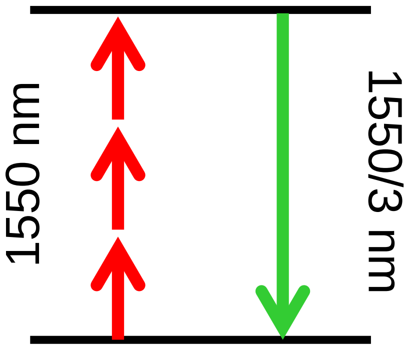
Low Q mode was pumped

Third harmonic generation (THG)

Microscope image

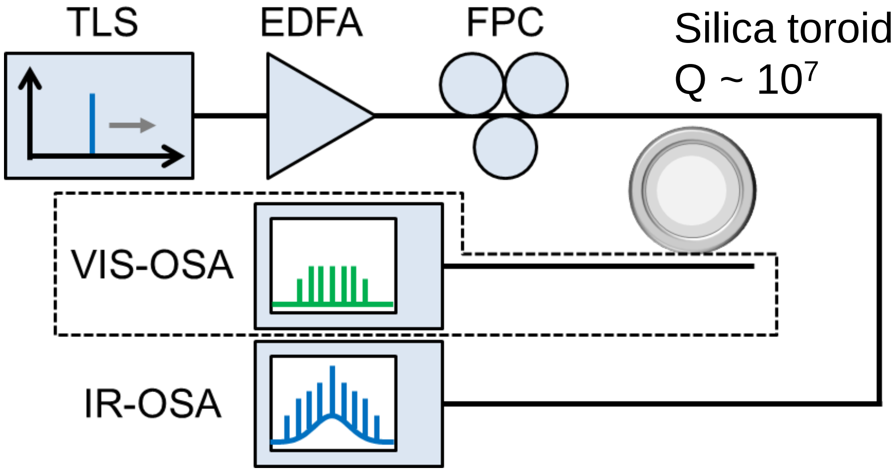


THG



THG allows emission at three times the pump frequency

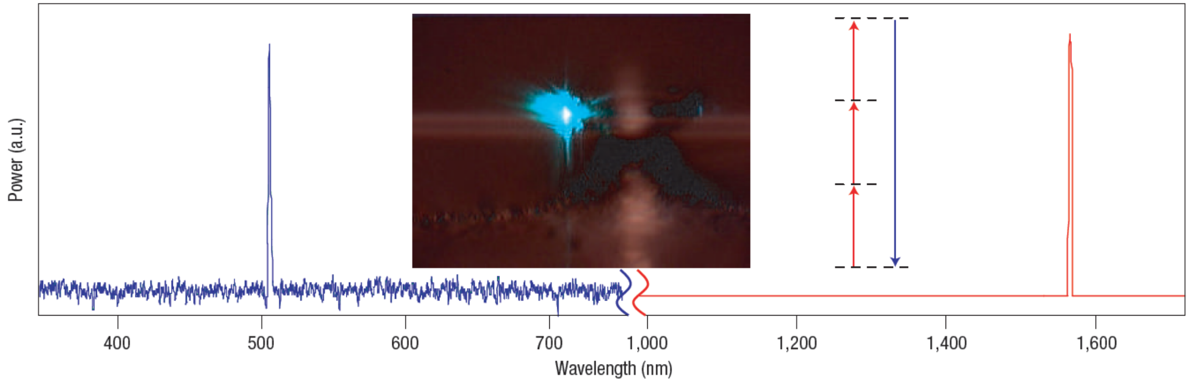
Experimental setup



Previous research of THG & Motivation

- THG

T. Carmon and K. J. Vahala, Nature Physics 3, 430 (2007)

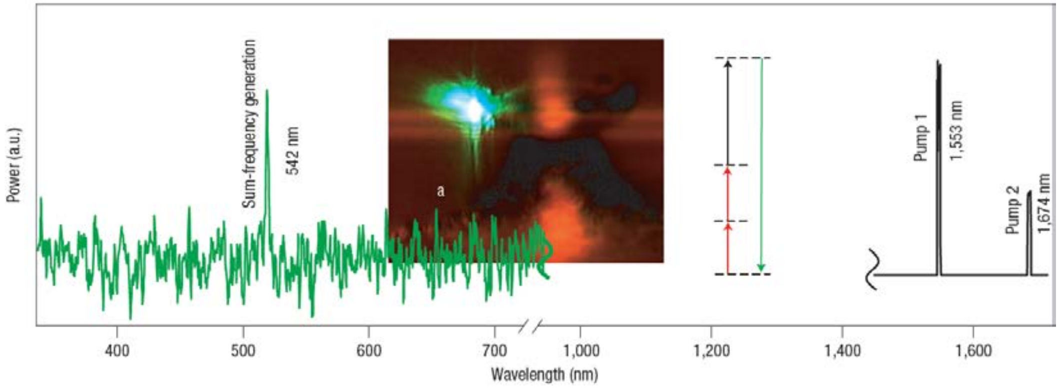


Infrared CW light

conversion

Visible CW light

- Sum frequency generation



Infrared two CW lights

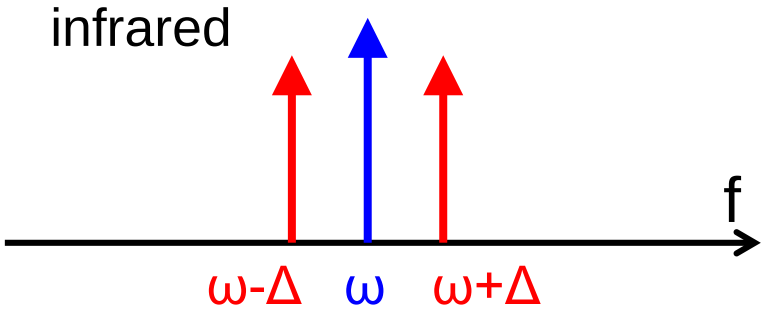
conversion

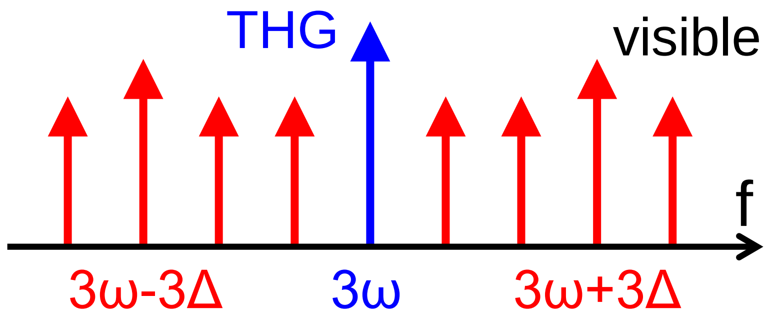
Visible CW light

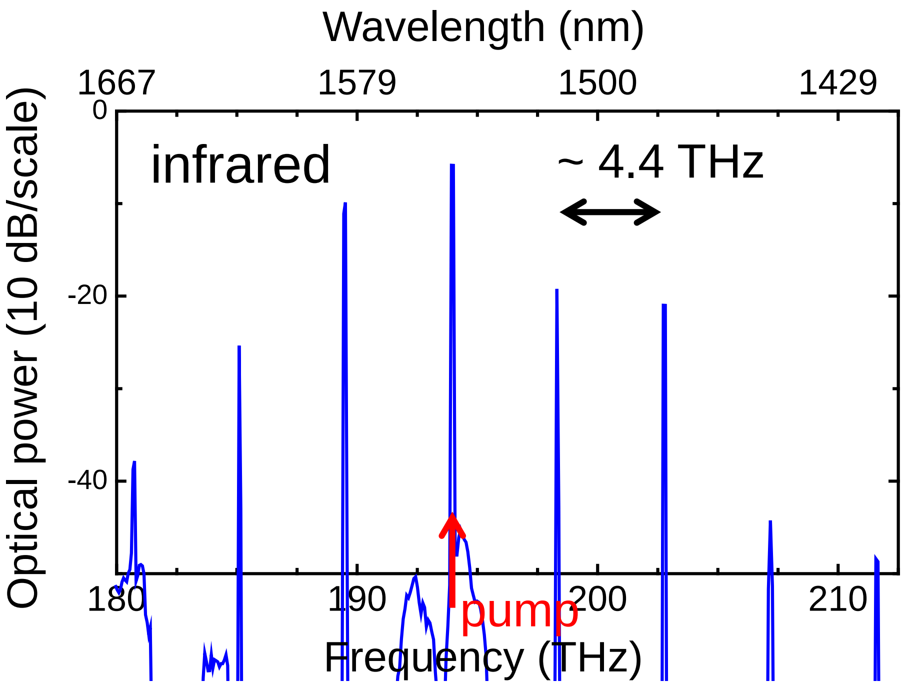
Motivation of our research:

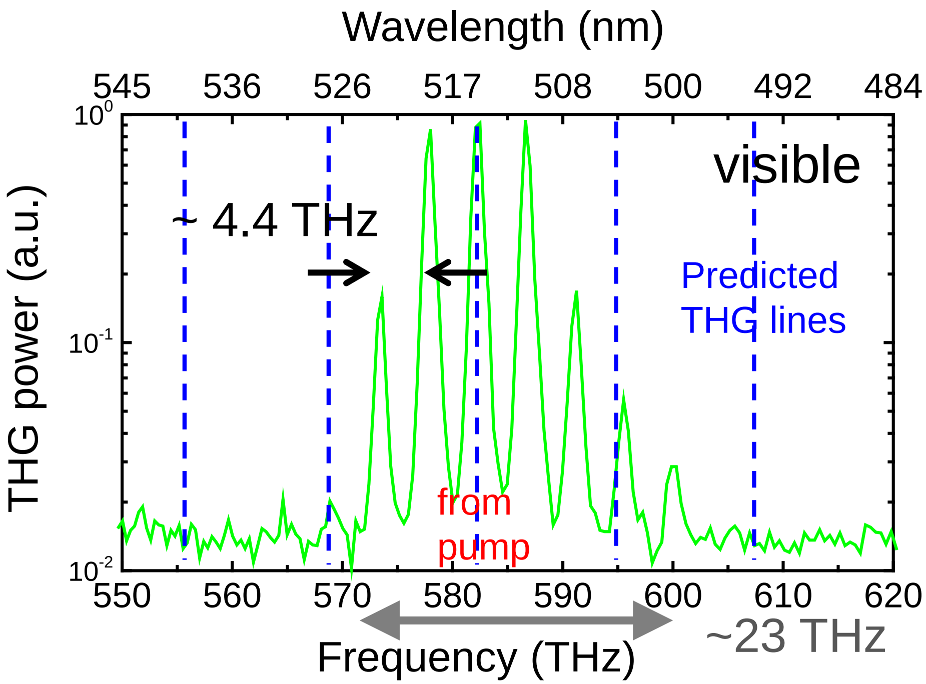
Can Kerr comb cause (THG and) sum frequency generation by pumping with only one CW light?

Experimental result







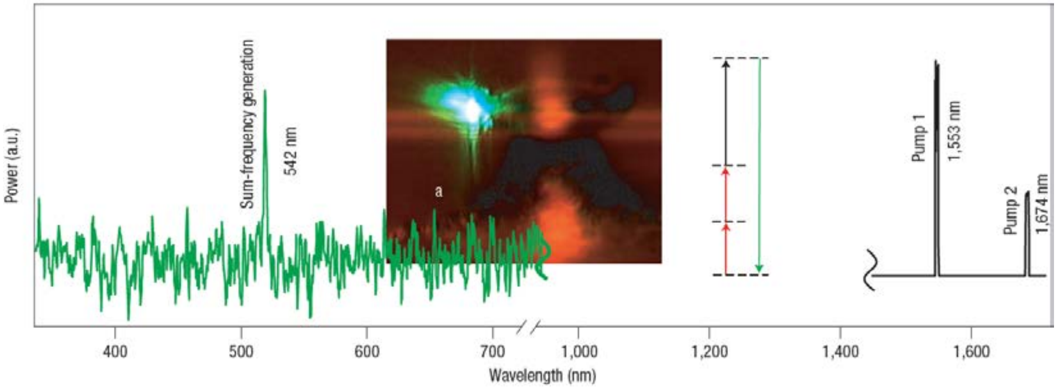


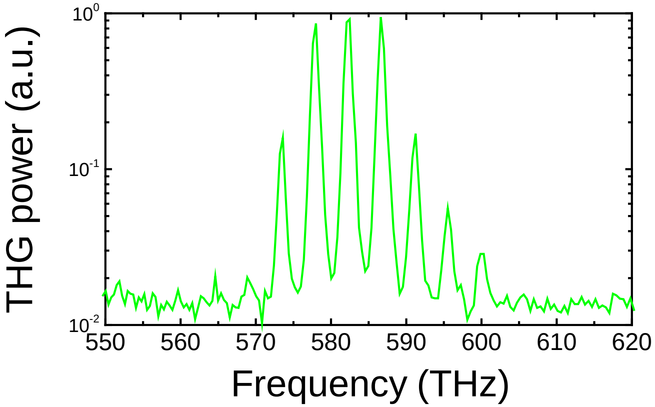
Kerr comb assists the generation of visible emission having multiple wavelengths with equal spacing

Summary of the THG result

In order to generate sum frequency generation

- **Previous research**
  Pumping by two CW lights
- **This research**
  Pumping by one CW light
  Kerr comb assists the generation of visible emission having multiple wavelengths with equal spacing





Conclusion

Raman scattering

① Model with Raman factor

Coupling control enables to generate FWM or Raman scattering selectively.

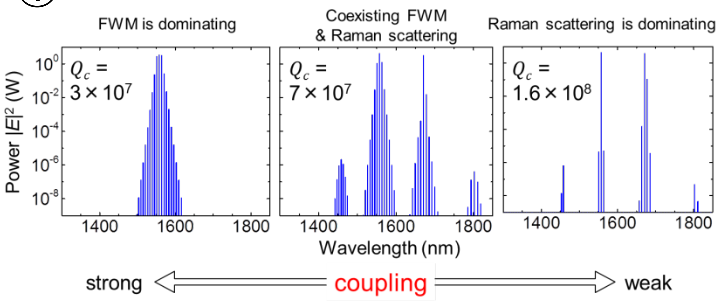
② Model with Raman and XPM factors for two modes

Mode family of pump and Raman scattering is always the same when the highest Q (fundamental) mode is pumped.

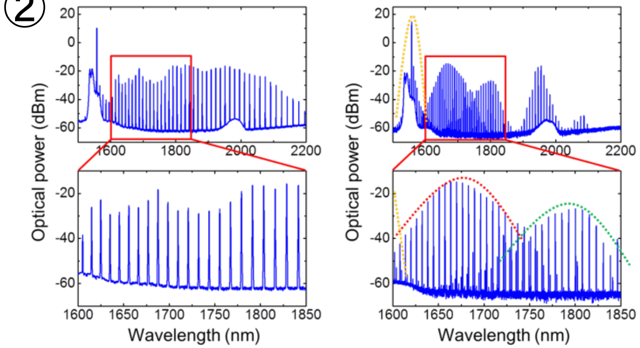
THG

③ Kerr comb assists the generation of visible emission having multiple wavelengths with equal spacing

①



②



③