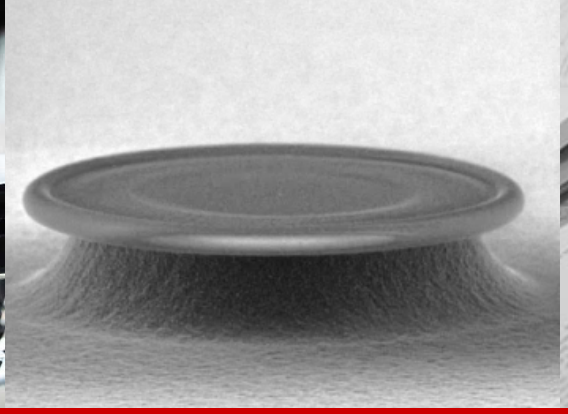
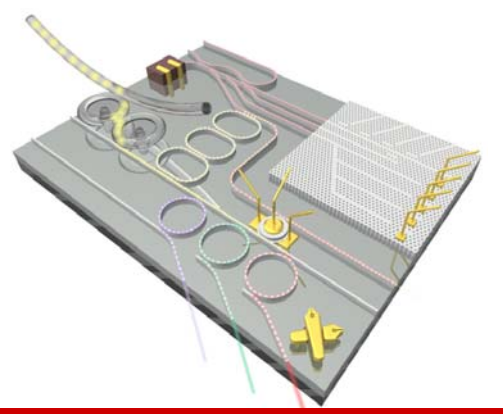





Conference on Lasers and Electro-Optics 2016 (CLEO2016)
[STu4Q.2]

Broadband visible comb generation via third harmonic generation assisted by stimulated Raman scattering

Takumi Kato, Akitoshi Chen-Jinnai, Shun Fujii,
and Takasumi Tanabe

Department of Electronics and Electrical Engineering,
Faculty of Science and Technology,
Keio University, Japan

Outline

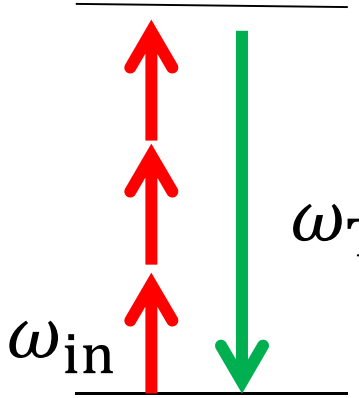
- Background & Motivation
  - visible light emission with high-Q microcavity
- Numerical calculation
  - Lugiato-Lefever Equation including third-harmonic generation
- Experimental results
  - with silica toroid microcavity
- Summary

Visible light emission with high-Q microcavity

- Third harmonic generation(THG)

$$\omega_{\mathrm{TH}} = 3\omega_{\mathrm{in}}$$

$$P_{\mathrm{TH}} \propto \left(\frac{Q}{V}\right)^3$$

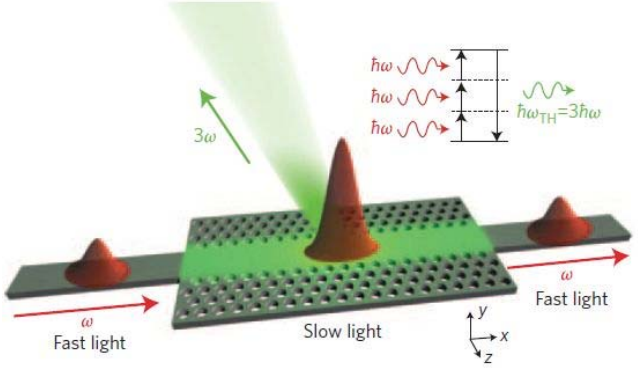


- Third-order nonlinearity χ^3
- TH power is scaled cubically with pump power.

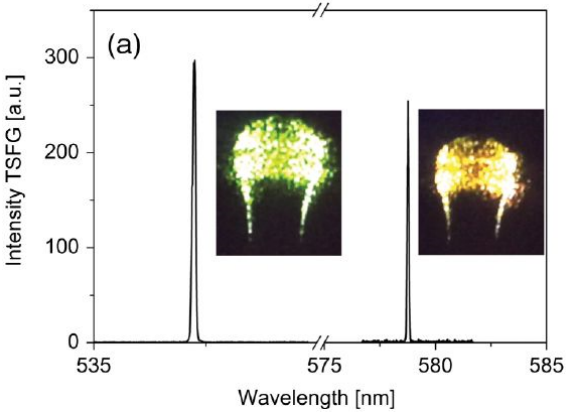
T. Carmon, and K. Vahala, Nat. Phys. **3,** 430 (2007).

- High-Q microcavity for THG

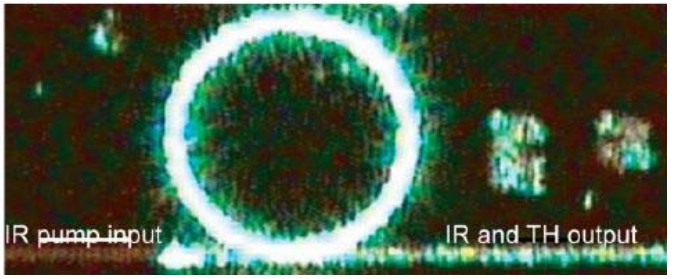
- ☐ Silicon photonic crystal
- ☐ Silica microsphere
- ☐ Silica microtoroid
- ☐ Silicon-nitride microring



B. Corcoran, *et al.*, Nat. Photon. **3,** 206 (2009).



T. Carmon, and K. Vahala, Nat. Phys. **3,** 430 (2007).
D. Farnesi, *et al.*, Phys. Rev. Lett. **112,** 093901 (2014).
D. Farnesi, *et al.*, Proc. SPIE 8960, p. 896008 (2014).



J. Levy, *et al.*, Opt. Express **19,** 11416 (2011).

Visible comb generation

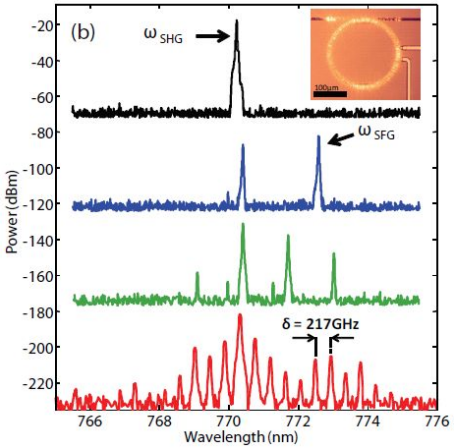
- Visible comb with 2nd order nonlinearity χ^2 & χ^3
  - Silicon nitride ring

    S. Miller, *et al.*, Opt. Express **22,** 26517 (2014).
  - Aluminum nitride ring

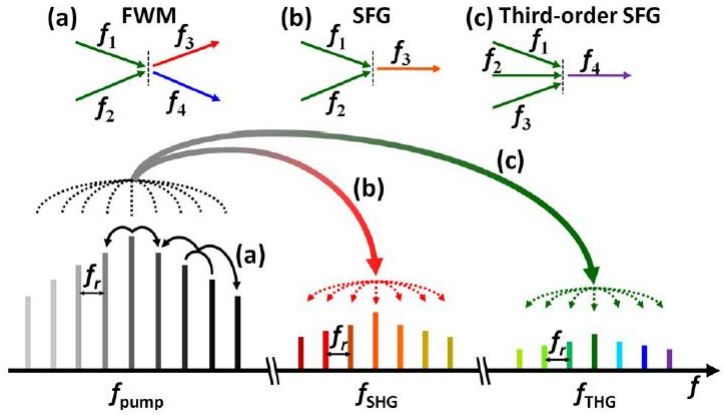
    H. Jung, *et al.*, Optica **1,** 396 (2014).

  Use χ^2 & χ^3 simultaneously
  - Theoretical work (SHG comb)

    F. Leo, *et al.*, Phys. Rev. A **93,** 043831 (2016).



S. Miller, *et al.*, Opt. Express **22,** 26517 (2014).

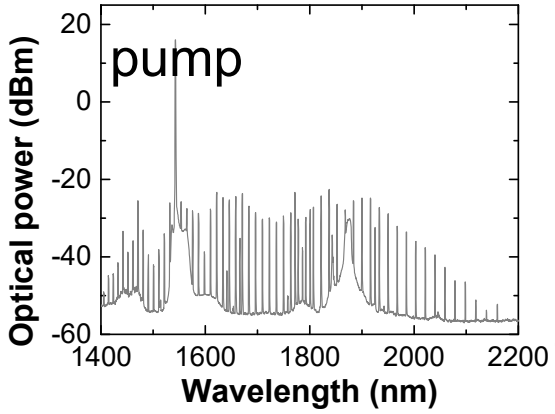


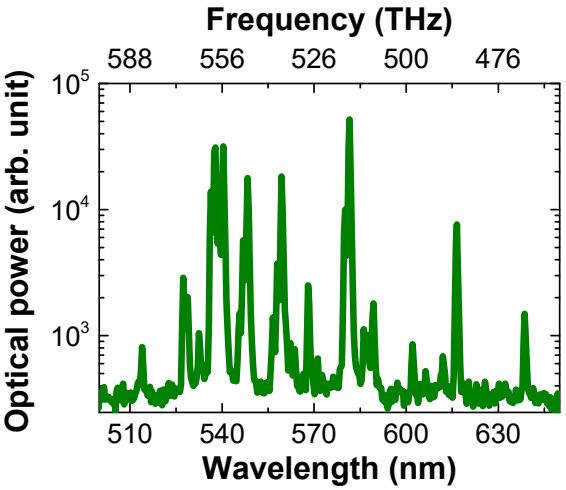
H. Jung, *et al.*, Optica **1,** 396 (2014).

- Visible comb with THG and Raman
  - Silica microsphere

    D. Farnesi, *et al.*, Proc. SPIE 8960, p. 896008 (2014).
  - **Silica microtoroid**

  Use χ^3 (Kerr & Raman) simultaneously





Motivation & objective

Motivation: visible comb generation with a silica toroid cavity

Application:

- Visible comb for frequency metrology, spectroscopy, & biological imaging

Physics:

- Relation between THG and Kerr-Raman effects is not well known.

Objectives

- ☐ **Understand the physics and clarify the method for obtaining visible comb via THG (numerical study)**
- ☐ **Experimental demonstration**

Outline

- Background & Motivation
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  - LLE including third harmonic generation
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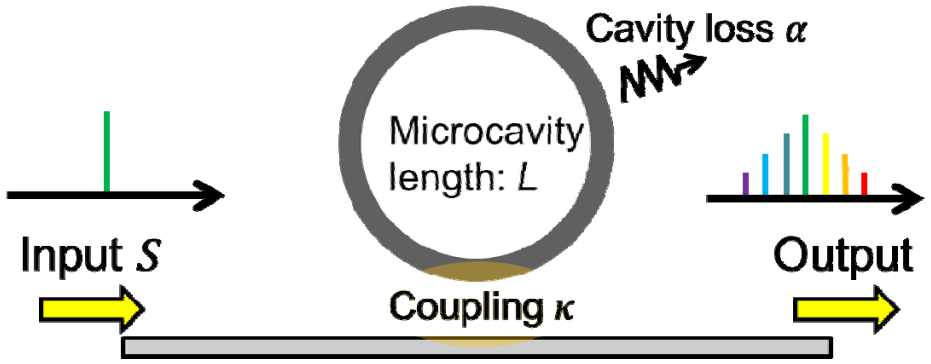
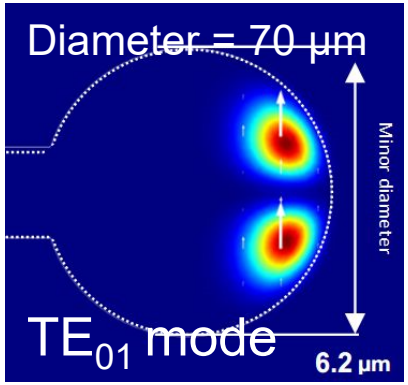
- Summary

Numerical model

- Lugiato-Lefever model including THG





δ: detuning
β: dispersion
γ: nonlinearity
J: mode overlapping
ϕ: phase mismatching

IR (fundamental mode)

$$t_R \frac{\partial E_{IR}}{\partial r} = \left\{ -\frac{\alpha_{IR}}{2} - \frac{\kappa_{IR}}{2} - i\delta_{IR} + iL \sum_{k\geq 2} \frac{\beta_{IR}^{(k)}}{k!} \left(i\frac{\partial}{\partial t} \right)^k \right\} E_{IR}$$

$$+\mathrm{i}\gamma_{IR} L\left(|E_{IR}|^2 E_{IR} + 2J_1 |\boldsymbol{E_{TH}}|^2 E_{IR} + J_2 (E_{IR}^*)^2 \boldsymbol{E_{TH}} \exp(-i\boldsymbol{\phi} L)\right) + \sqrt{\kappa_{IR}} S_{\mathrm{in}}$$

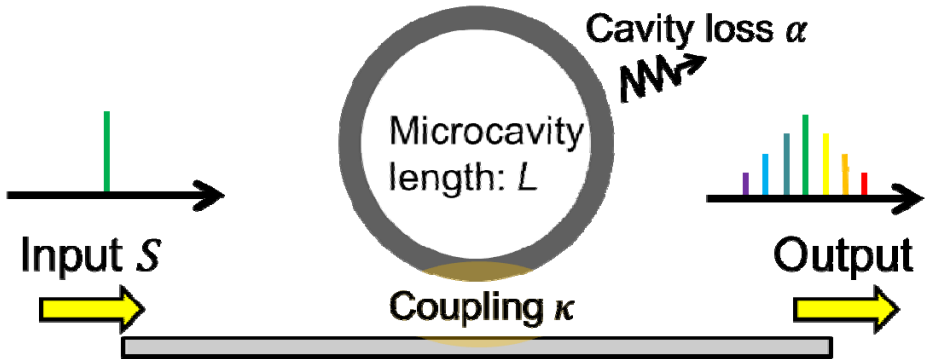
TH (THG mode)

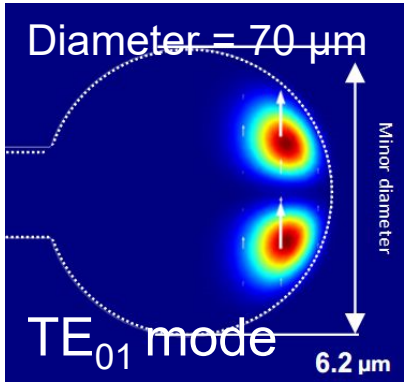
$$t_R \frac{\partial E_{TH}}{\partial r} = \left\{ -\frac{\alpha_{TH}}{2} - \frac{\kappa_{TH}}{2} - i\delta_{TH} - i(\beta_{TH}^{(1)} - \beta_{IR}^{(1)}) + iL \sum_{k\geq 2} \frac{\beta_{TH}^{(k)}}{k!} \left(i\frac{\partial}{\partial t} \right)^k \right\} E_{TH}$$

$$+\mathrm{i}\gamma_{TH} L\left(|E_{TH}|^2 E_{TH} + 2J_3 |E_{IR}|^2 E_{TH} + J_4 \boldsymbol{E_{IR}^3} \exp(i\boldsymbol{\phi} L)\right)$$

Numerical model

- Lugiato-Lefever model including THG

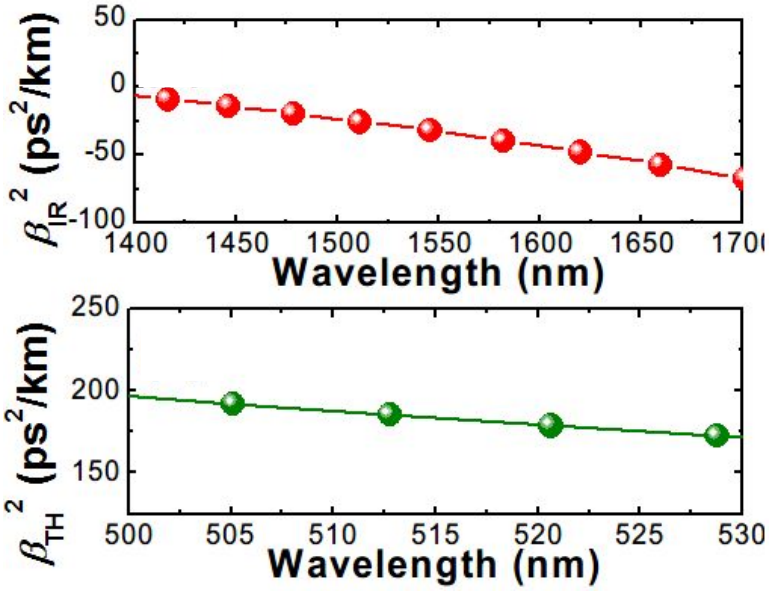




δ: detuning
β: dispersion
γ: nonlinearity
J: mode overlapping
ϕ: phase mismatching

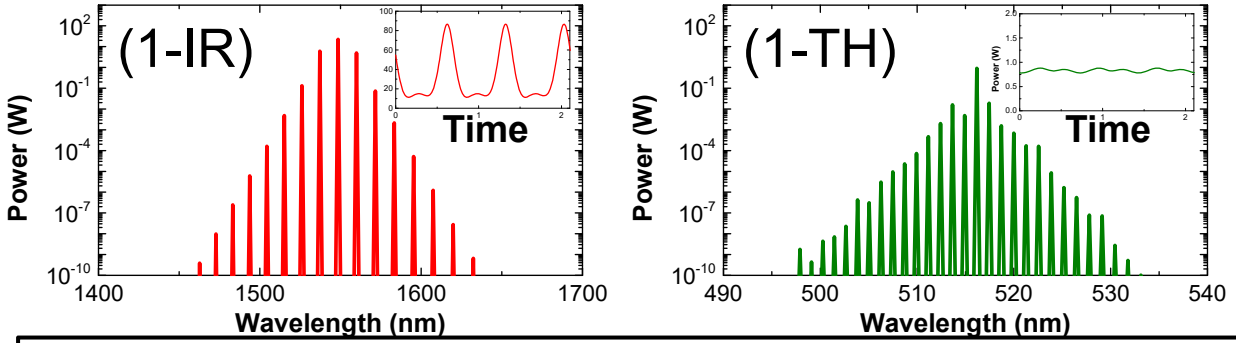
Parameter	
L	633 μm
Q_{IR}	5×10^6
Q_{TH}	5×10^6
γ_{IR}	1.92×10^{-2} /Wm
γ_{TH}	6.42×10^{-3} /Wm
P_{in}	40 mW
Mode area	4.63 μm^2
$\hat{\phi}(\omega)$	$\beta_{TH}(3\omega) - 3\beta_{IR}(\omega)$

➢ Dispersion



Calculation results

1. $\delta_{TH} = 3\delta_{IR}$(perfect frequency matching), $\delta_{IR} = 0$

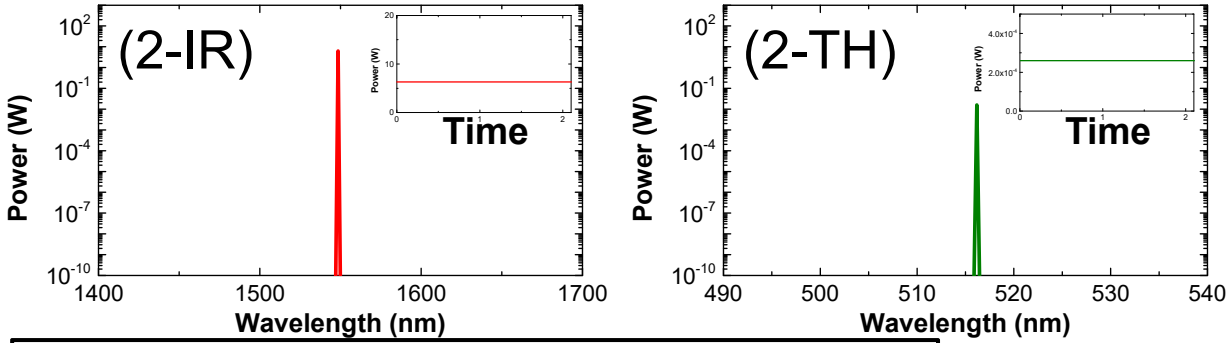


Efficiency: $P_{TH} = K(P_{IR})^3$

- Pulsed + frequency matching

$$K = 2.25 * 10^{-5}$$

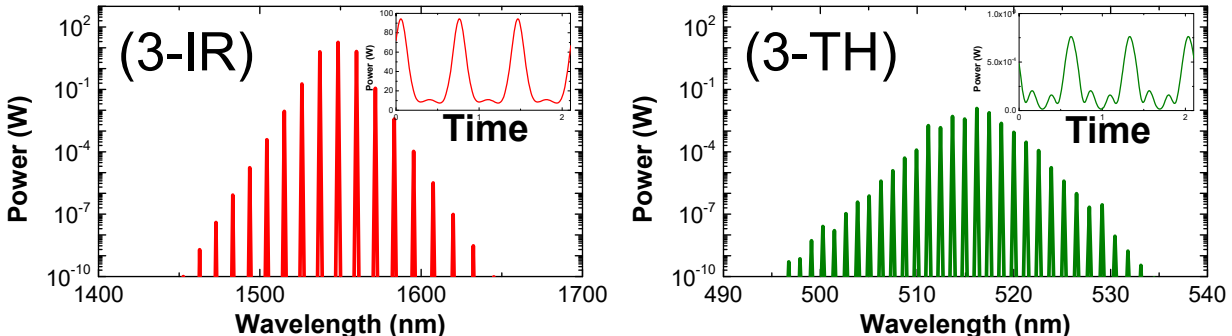
2. $\delta_{TH} = 3\delta_{IR}$(perfect frequency matching), $\delta_{IR} = 0.1$ GHz



- CW + frequency matching

$$K = 1.04 * 10^{-6}$$

3. $\delta_{TH} = 3\delta_{IR} + 100$ GHz, $\delta_{IR} = 0$ GHz



- Pulsed + frequency mismatching

$$K = 8.16 * 10^{-9}$$

Outline

- Background & Motivation
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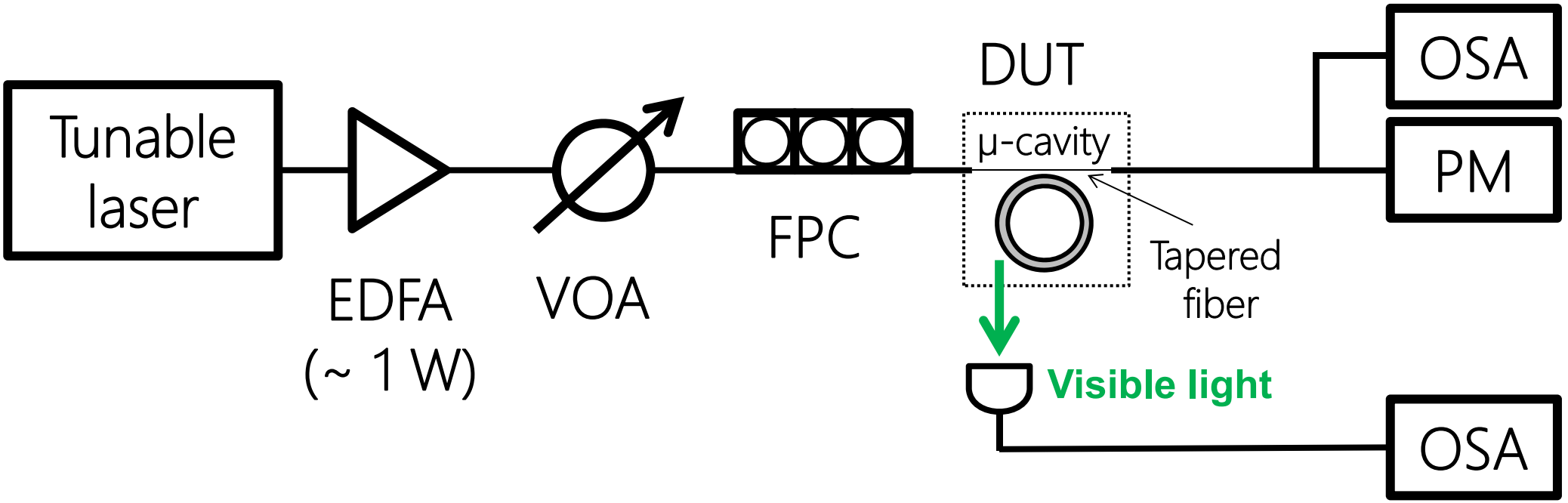
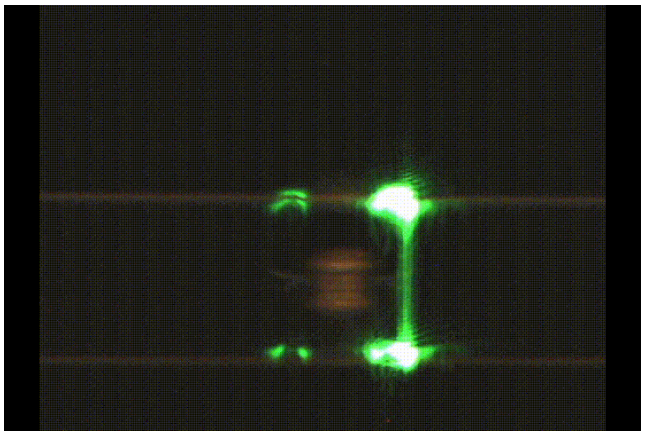
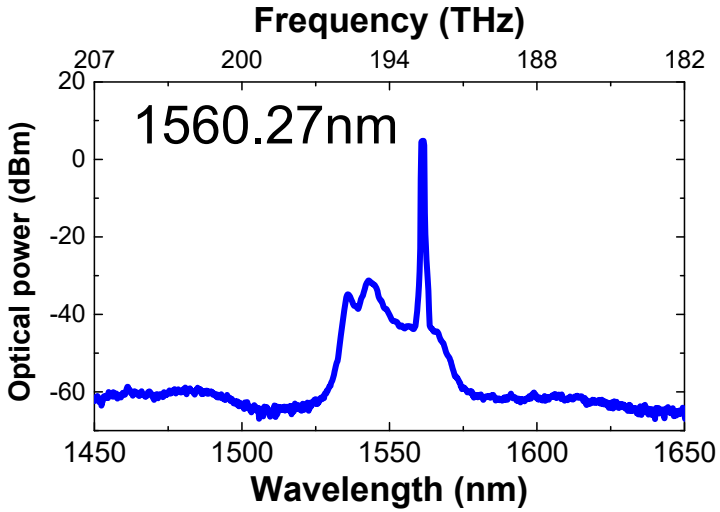
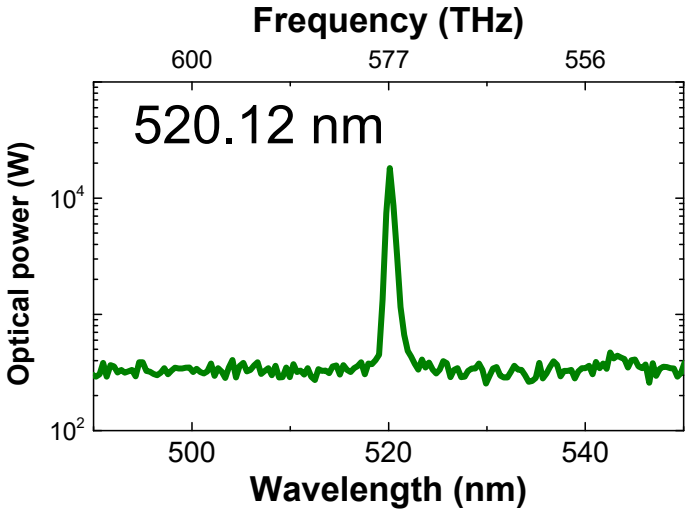
Experimental setup

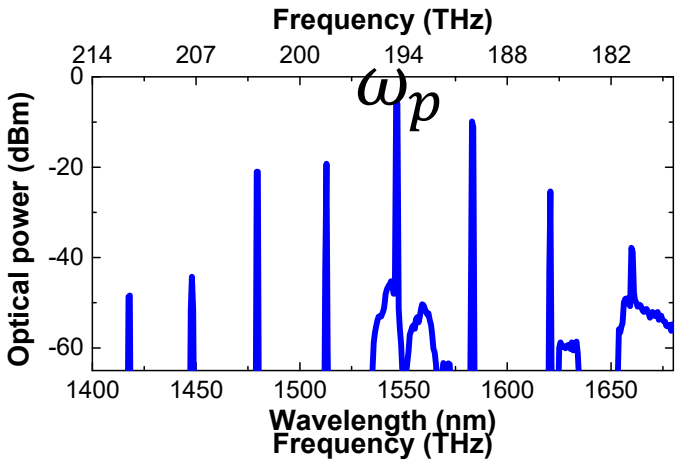


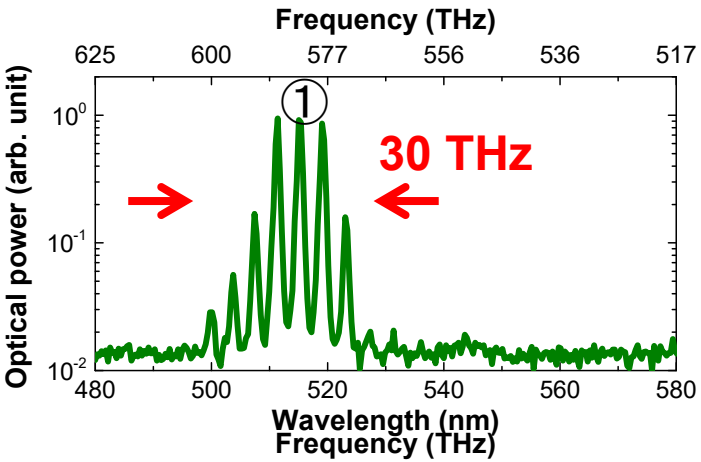


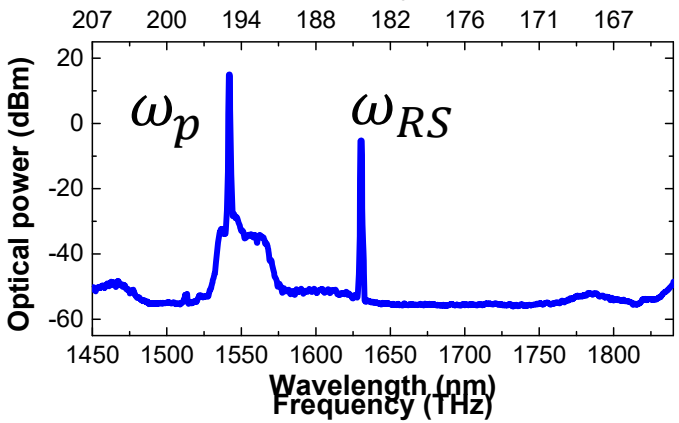


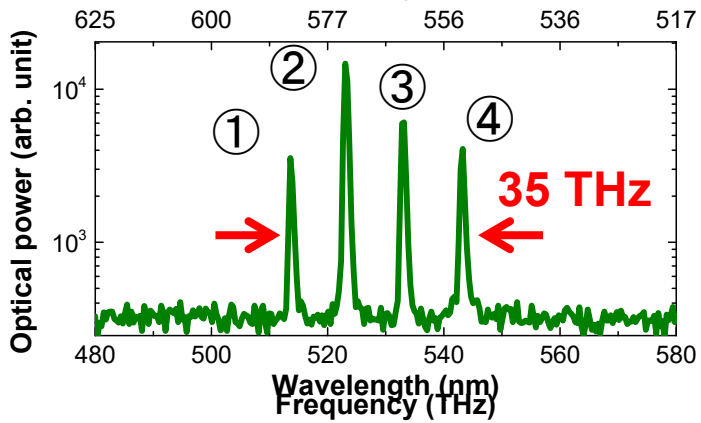


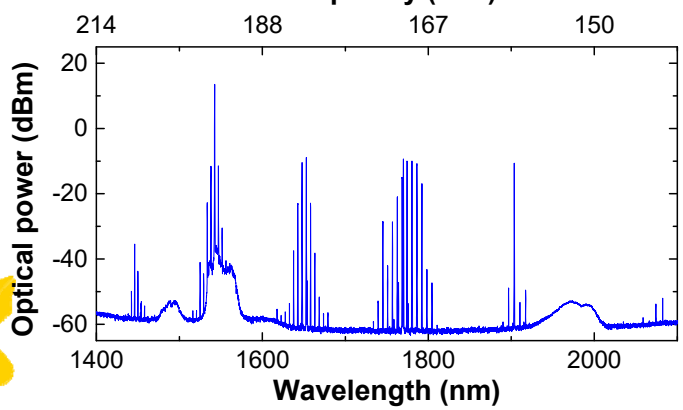
Experimental results

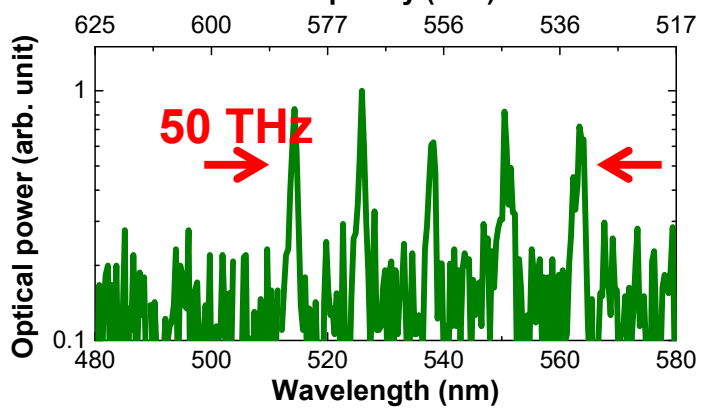










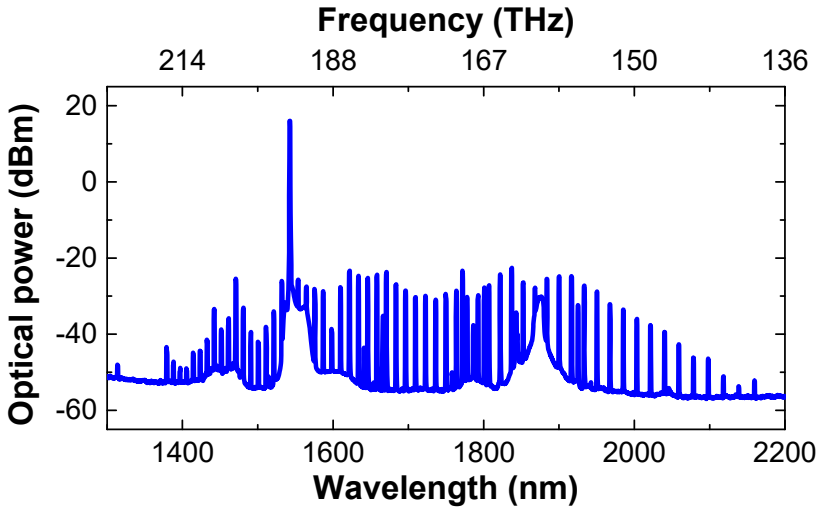


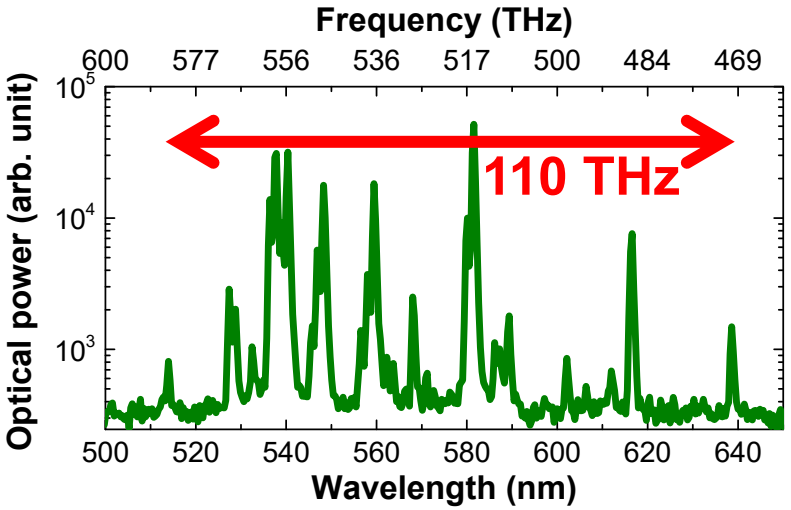
① $3\omega_p$

① $3\omega_p$
② $2\omega_p + \omega_{RS}$
③ $\omega_p + 2\omega_{RS}$
④ $3\omega_{RS}$

Experimental results

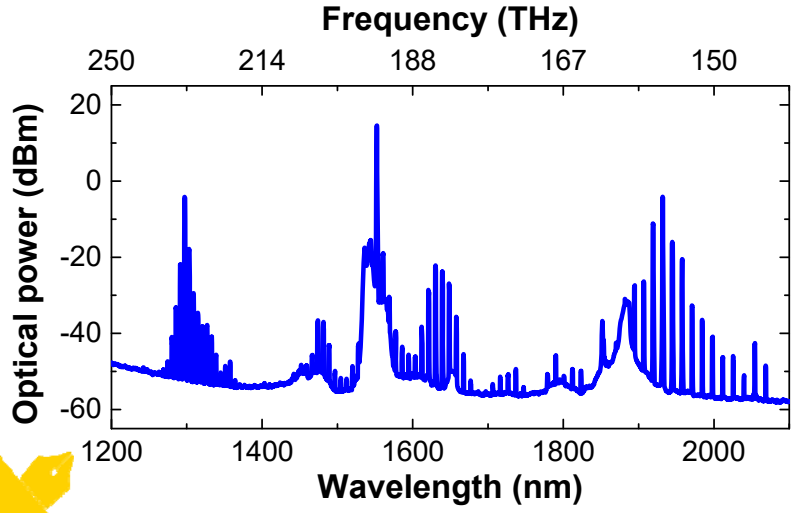
- Broad-IR Kerr comb (Four-wave mixing + Raman)

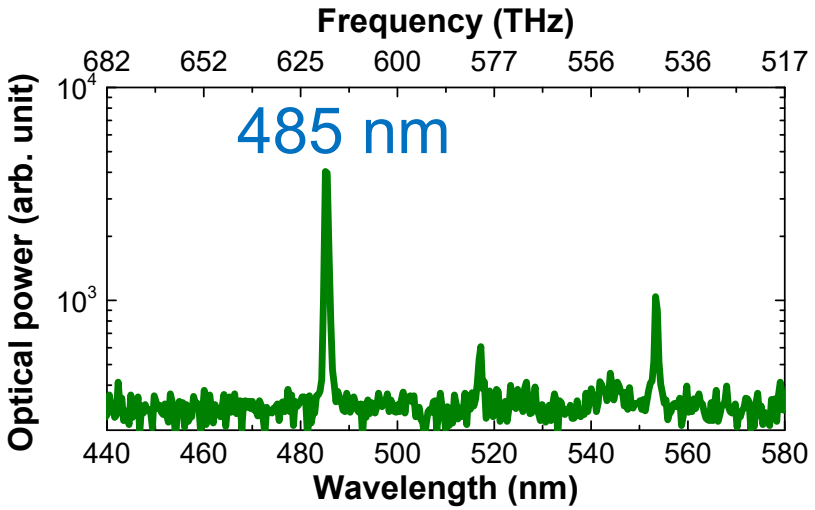




Green
Yellow
Red
generation

- Anti-Stokes Raman scattering





Blue
generation

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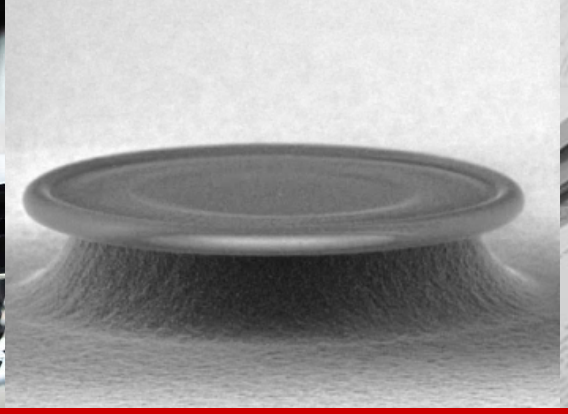
Summary

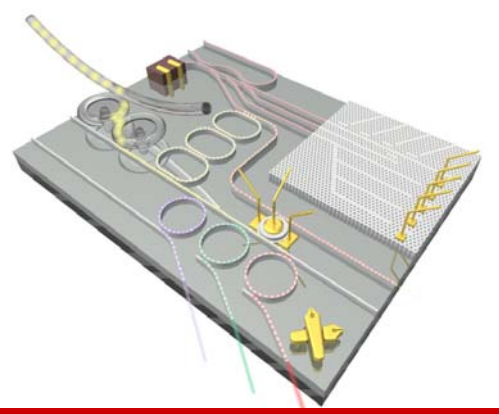
[Numerical simulation]

- We developed a LLE model including THG.
- We found that the efficiency of THG depends on not only whether frequency matching or not but also whether pulsed or CW in the fundamental mode.

[Experiment]

- We achieved to generate clear visible combs with only Four-wave mixing or only Raman scattering.
- We achieved to get broadband visible light using broad Kerr comb in the IR region with stimulated Raman scattering.



Thank you very much

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