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) \( \omega_{TH} = 3 \omega_{in} \)
  - Third-order nonlinearity \( \chi^3 \)
  - TH power is scaled cubically with pump power.

- High-Q microcavity for THG
  - Silicon photonic crystal
  - Silica microsphere
  - Silica microtoroid
  - Silicon-nitride microring


Visible comb generation

- Visible comb with 2\textsuperscript{nd} order nonlinearity $\chi^2$ & $\chi^3$
  - Silicon nitride ring
  - Aluminum nitride ring
  - Theoretical work (SHG comb)

**Use $\chi^2$ & $\chi^3$ simultaneously**

- Visible comb with THG and Raman
  - Silica microsphere
  - Silica microtoroid

**Use $\chi^3$ (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
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Numerical model

- Lugiato-Lefever model including THG

**IR (fundamental mode)**

\[
t_R \frac{\partial E_{IR}}{\partial r} = \left\{ -\frac{\alpha_{IR}}{2} - \frac{\kappa_{IR}}{2} - i\delta_{IR} + iL \sum_{k \geq 2} \frac{\beta_{IR}^{(k)}}{k!} \left( i \frac{\partial}{\partial t} \right)^k \right\} E_{IR} 
+ i\gamma_{IR} L \left( |E_{IR}|^2 E_{IR} + 2J_1 |E_{TH}|^2 E_{IR} + J_2 (E_{IR}^*)^2 E_{TH} \exp(-i\phi L) \right) + \sqrt{\kappa_{IR}} S_{in}
\]

**TH (THG mode)**

\[
t_R \frac{\partial E_{TH}}{\partial r} = \left\{ -\frac{\alpha_{TH}}{2} - \frac{\kappa_{TH}}{2} - i\delta_{TH} - i(\beta_{TH}^{(1)} - \beta_{IR}^{(1)}) + iL \sum_{k \geq 2} \frac{\beta_{TH}^{(k)}}{k!} \left( i \frac{\partial}{\partial t} \right)^k \right\} E_{TH} 
+ i\gamma_{TH} L \left( |E_{TH}|^2 E_{TH} + 2J_3 |E_{IR}|^2 E_{TH} + J_4 E_{IR}^3 \exp(i\phi L) \right)
\]
Numerical model

- Lugiato-Lefever model including THG

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L$</td>
<td>633 µm</td>
</tr>
<tr>
<td>$Q_{IR}$</td>
<td>$5 \times 10^6$</td>
</tr>
<tr>
<td>$Q_{TH}$</td>
<td>$5 \times 10^6$</td>
</tr>
<tr>
<td>$\gamma_{IR}$</td>
<td>$1.92 \times 10^{-2}$ /Wm</td>
</tr>
<tr>
<td>$\gamma_{TH}$</td>
<td>$6.42 \times 10^{-3}$ /Wm</td>
</tr>
<tr>
<td>$P_{in}$</td>
<td>40 mW</td>
</tr>
<tr>
<td>Mode area</td>
<td>4.63 µm²</td>
</tr>
<tr>
<td>$\hat{\phi}(\omega)$</td>
<td>$\beta_{TH}(3\omega) - 3\beta_{IR}(\omega)$</td>
</tr>
</tbody>
</table>

Dispersion

\[
\beta_R^2(\text{ps}^2/\text{km}) \\
\beta_{TH}^2(\text{ps}^2/\text{km})
\]
Calculation results

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

   Efficiency: $P_{TH} = K(P_{IR})^3$
   - Pulsed + frequency matching
     $K = 2.25 \times 10^{-5}$

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

   - CW + frequency matching
     $K = 1.04 \times 10^{-6}$

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

   - Pulsed + frequency mismatching
     $K = 8.16 \times 10^{-9}$
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Experimental setup

- Tunable laser
- EDFA (~1 W)
- VOA
- FPC
- DUT (μ-cavity)
- Tapered fiber
- Visible light
- OSA
- PM

Graphs:
- Frequency (THz) vs. Optical power (dBm)
  - 1560.27 nm
  - 520.12 nm
- Frequency (THz) vs. Optical power (W)
  - 600 to 650
  - 500 to 540
Experimental results

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)**
  - Blue generation
  - 485 nm
  - Green generation
  - 110 THz
  - Yellow generation
  - Red generation

- **Anti-Stokes Raman scattering**
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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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