Influence of Raman scattering on Kerr frequency comb in a silica toroidal microcavity

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Outline

• Background & Motivation
  - Kerr comb in a silica toroidal microcavity (experiment)
• Analysis on four-wave mixing and Raman gain (analysis)
• Simulation with a split-step algorithm (numerical calc.)
• Summary
Kerr frequency comb generation

- **Cascade FWM**

- **High-Q optical microcavity**

- **Merit**
  - Small size (~µm)
  - High-Q
  - Small mode volume

$$\chi^3$$ available

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Kerr comb in a silica toroidal microcavity

Experimental Setup

Result: Kerr comb

Result: Raman scattering

Result: Hybrid

FWM gain and Raman gain compete with each other.

Broadband Raman gain is peculiar to silica (amorphous).
Motivation

To find a way to control FWM and Raman scattering in a high-Q silica μ-cavity system

Previous researches (without the effect of FSR):
Comparison of threshold power b/w FWM and Raman scattering


This research (with the effect of FSR):
1. Analytically clarify FWM and Raman gain in a cavity mode
2. Numerically study competition b/w FWM & Raman gain
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Four-wave mixing gain

[Case 1: in fiber propagation]

\[ g(\Omega) = |\beta_2\Omega|\sqrt{\Omega_c^2 - \Omega^2} \]

\[ \Omega_c^2 = \frac{4\gamma P_0}{|\beta_2|} \]

\( \gamma \): nonlinear coefficient

\( \beta_2 \): second-order dispersion


[Case 2: in cavity resonance]

\[ g(\Omega) = \sqrt{(\gamma LP_0)^2 - (\delta_{\text{miss}})^2} \]

- detuning from a cavity mode

\[ \delta_{\text{miss}} = \delta_0 - \beta_2 L\Omega^2/2 - 2\gamma LP_0 \]

\( \delta_0 \): detuning of input


To achieve gain in a desired frequency, proper input power must be chosen.
Four-wave mixing gain in a cavity

\[ g(\Omega) = \sqrt{(\gamma L P_0)^2 - (\delta_{\text{miss}})^2} \]

\[ \delta_{\text{miss}} = \delta_0 - \frac{\beta_2 L \Omega^2}{2} - 2\gamma L P_0 \]

\[ \kappa P_{\text{input}} = (\gamma L)^2 P_0^3 - 2\delta_0 \gamma L P_0^2 + (\delta_0^2 + \alpha_{\text{tot}}^2) P_0 \]

- \( \gamma \): nonlinear coefficient
- \( \beta_2 \): second-order dispersion
- \( \delta_0 \): detuning of input
- \( L \): cavity length
- \( \kappa \): coupling coefficient
- \( \alpha_{\text{tot}} \): total loss

Input power (0~10 W)

FSR: 0.1 THz
Competition of FWM & Raman gain

Input power
- small
- medium
- high

1-FSR FWM
- Pump
- FWM gain

2-FSR FWM
- Raman scattering
- A condition dominated by Raman

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Raman gain in a silica toroidal microcavity

\[ g_{\text{raman}} = g_{\text{bulk}}^R \frac{P_0}{A_{\text{eff}}} L_{\text{eff}} - \text{loss} \]

\[ L_{\text{eff}} = \frac{1}{\alpha_{\text{tot}}} \{1 - \exp(-\alpha_{\text{tot}}L)\} \]


Model: Silica toroid, FSR = 1.1 THz, \( Q_{\text{int}} = 5 \times 10^7 \)

\[ g_{\text{bulk}}^R = 0.631 \times 10^{-11} \text{ at } \lambda_p = 1550 \text{ nm} \]

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Numerical simulation model

Nonlinear Schrödinger equation

$$t_R \frac{\partial E}{\partial r} = \left( -\frac{\alpha}{2} - \frac{\kappa}{2} - i\delta_0 + iL \sum_{k \geq 2} \frac{\beta_k}{k!} \left( i \frac{\partial}{\partial T} \right)^k + N \right) E + \sqrt{\kappa} S$$

$$N = i\gamma L \int_{-\infty}^{\infty} R(t') |E(t - t')|^2 dt'$$

$$R(t) = (1 - f_R)\delta(t) + f_R h_R(t)$$

$$h_R(t) = \frac{\tau_1^2 + \tau_2^2}{\tau_1 \tau_2^2} \exp\left(-\frac{t}{\tau_2}\right) \sin\left(\frac{t}{\tau_1}\right)$$

$r$: round trip number
$t_R$: round trip time
$\delta_0$: detuning
$\alpha$: cavity loss
$\kappa$: coupling loss
$L$: cavity length
$\beta$: dispersion
$\gamma$: nonlinear coefficient

$\tau_1 = 12.2$ fs
$\tau_2 = 32$ fs
$f_R = 0.18$
Simulation result on Kerr comb generation

There is good agreement with the gain analysis result

\[ P_{in} = 10 \text{ mW} \]

\[ Q_{coup} = 3 \times 10^7 \]

\[ Q_{coup} = 1 \times 10^8 \]

\[ Q_{coup} = 9 \times 10^8 \]
Experimental results

Wavelength detuning

Short

medium

Long

4-FSR

Raman only

3-FSR
Summary

1. We analyzed FWM and Raman gain in a cavity model with the effect of FSR.

2. We simulated a Kerr cavity model including Raman effect. There is a good agreement with gain analysis.

We found a way to control Four-Wave Mixing and Raman scattering by changing pump condition.
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