Analysis and experiments on harmonic mode locking in an optical microcavity

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Outline

1. Background
   · Optical Kerr comb in microcavities (micro-comb)
   · Harmonic mode locking in fiber lasers

2. Harmonic-mode locking (calculation & experiment)
   · Numerical model: Split-step Fourier algorithm
   · Numerical study: Kerr bistability and mode locking
   · Experimental demonstration: Harmonic-mode locking

3. Summary
Background: Optical Kerr comb in a microcavity

★Optical Kerr comb
- Cascade Four wave mixing in a high-$Q$ optical microcavity
- The generation of temporal cavity solitons has been researched i.e. T. Herr et al., Nat. Photon. 8, 145 (2014).

◆Characteristics
- Using only single CW pump
- Need very low input power
- micro-size chip-based device


T. Kato CLEO_20140609 3/15
Harmonic-mode locking in an optical microcavity

★ Harmonic-mode locking in solid-state & fiber lasers

- Saturable absorber
- Fabry-Perot filter
- E/O modulator …

are required to achieve harmonic-mode locking

★ Harmonic-mode locking in an optical microcavity

Harmonic mode locking seems to be stable in spite of simple setup

1-FSR

3-FSR

Motivation & objective

Problem

Application:
- Allow us to have different repetition rates w/ harmonic mode-locking

Physics:
- Condition for harmonic-mode locking in a microcavity is not well known

Motivation

- Understand the physics and clarify the method to obtain harmonic mode locking (numerical study)
- Experimental demonstration
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Nonlinear microcavity model: Split-step Fourier algorithm

Cavity loss $\alpha$

Microcavity length: $L$

Coupling $\kappa$

Input $S$

Output

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

$r$: round trip number
$\beta$: dispersion
$t_R$: round trip time
$\gamma$: nonlinear coefficient
$\delta_0$: detuning of input

Material

Geometrical

Material + Geometrical

Dispersion

$\beta^2$ (psps/km)

Wavelength (nm)

$\lambda = 1550$ nm

$3 \, \mu m$

Material: silica

diameter: 84 $\mu$m
Harmonic mode locking depends on Kerr bistability

\[ Q_{\text{int}} = 1.0 \times 10^7 \quad \Delta = 2.2 \text{ (normalized detuning)} \quad \Delta = \frac{2\delta_0}{\alpha + \kappa} \]
\[ Q_\kappa = 5.0 \times 10^7 \quad d = 3 \, \mu\text{m (minor diameter)} \]

- Bistability influences the Kerr comb
- 2-FSR is only accessed through decreasing the input
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\[ \text{Average intracavity power (W)} \]

\[ \text{Input power (mW)} \]

Below threshold of Kerr bistable state
Harmonic mode locking depends on Kerr bistability

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3-FSR Harmonic mode locking

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Experiment: Harmonic-mode locking by reducing power

- Tunable laser
- EDFA
- Attenuator
- Optical power meter
- Silica toroid
- OSA

Tapered fiber

FSR: 800 GHz

Q factor: $> 2.0 \times 10^6$

1-FSR

3-FSR

2-FSR

Optical power (dBm)

Wavelength (nm)

1-FSR (chaotic)

input: 200 mW

input: 183 mW

input: 59 mW

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We found the way to control mode locked state, which is to control input power considering Kerr bistability.

We simulated a Kerr cavity model using a split-step algorithm.

In experiments, we achieved to control Kerr comb formation by changing only input power.
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