Soliton pulse formation in a calcium fluoride whispering gallery microcavity without frequency sweeping

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Optical Kerr frequency comb

Kerr comb
Microcavity

Conventional frequency comb sources
Ti:Sapphire laser
Fiber laser

- Small & Inexpensive
- High repetition rate (10GHz-1THz)
- Large bandwidth
- Low threshold pump

Threshold pump power for four-wave mixing

\[ P_{\text{threshold}} \propto \frac{V}{Q^2} \]

\( V \): Mode volume
\( Q \): Quality factor

Large & Expensive

\[ f(m) = f_0 + m \cdot f_{\text{rep}} \]
Soliton pulse generation w/ wavelength sweeping

**Kerr effect**

\[ n = n_0 + n_2 I : \text{positive} \]

**Thermo-optic coefficient**

\[
\frac{\partial n}{\partial T} > 0 : \text{positive} \quad \text{SiO}_2, \text{SiN}, \text{MgF}_2
\]

\[
\frac{\partial n}{\partial T} < 0 : \text{negative} \quad \text{CaF}_2
\]

Wavelength sweep is required for soliton

Background

SiN microring

MgF\textsubscript{2} bulk

Microcavity

Mode-locked pulse

Transmittance

Cold resonance

Effective blue-detuning

Triangular

Effective Red-detuning

Mode locked state “solitron step”

Pump scan

Wavelength

T. Herr et al., Nat. Photon. 6, 480 (2012)
Research goals

By utilizing negative thermo-optic (TO) effect,

- Can we obtain soliton pulse w/o frequency sweeping?

By utilizing ultra precision machining,

- Can we fabricate a dispersion controlled CaF$_2$ microcavity?
Thermo-opto-mechanical oscillation

$Q = 1.2 \times 10^7$

Model describing nonlinearities in CaF$_2$

Kerr effect + Thermal effects (TO/TE)

- 1. Lugiato-Lefever (LL) equation

$$t_R \frac{\partial E}{\partial t} = \left( -\frac{\alpha}{2} - \frac{\kappa}{2} \right) E + i2\pi r \frac{\beta}{2} \frac{\partial^2 E}{\partial \tau^2} + i2\pi r \gamma |E|^2 E + \sqrt{\kappa} S$$

- 2. Thermal rate equation (cavity temperature)

$$\frac{d\Delta T_m}{dt} = -\Gamma_m \Delta T_m + \gamma_m |E|^2 \quad (m = 1,2)$$

- 3. Resonant wavelength shift

$$\Delta \lambda = \lambda_0 \left( \frac{dn_1}{dT_1} \frac{\Delta T_1}{n_0} + \epsilon \Delta T_2 \right)$$

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_R$</td>
<td>round-trip time</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>intrinsic cavity loss</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>coupling loss</td>
</tr>
<tr>
<td>$\delta$</td>
<td>detuning of the input wavelength</td>
</tr>
<tr>
<td>$r$</td>
<td>cavity radius</td>
</tr>
<tr>
<td>$\beta$</td>
<td>dispersion of the cavity</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>nonlinear coefficient</td>
</tr>
<tr>
<td>$S$</td>
<td>input driving power</td>
</tr>
<tr>
<td>$\Delta T_1$</td>
<td>temperature change of the optical mode volume</td>
</tr>
<tr>
<td>$\Delta T_2$</td>
<td>temperature change of the entire cavity volume</td>
</tr>
<tr>
<td>$\lambda_0$</td>
<td>cold resonant wavelength</td>
</tr>
<tr>
<td>$d n_1 / d T_1$</td>
<td>TO coefficient</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>TE coefficient</td>
</tr>
<tr>
<td>$n_0$</td>
<td>refractive index of the cavity</td>
</tr>
</tbody>
</table>
Without thermal effects (only Kerr)

Calculation

With positive TO effect (SiO$_2$ microcavity)

It is difficult to stay in the soliton regime because of the TO effect.

Resonator model

\[ \frac{dn}{dT} = 1.05 \times 10^{-4} \]

Input = 5 mW

\[ Q_{\text{couple}} = 4 \times 10^7 \]

\[ Q_{\text{int}} = 4 \times 10^7 \]

radius = 42 μm
With negative TO effect (CaF₂ microcavity)

Easy to obtain soliton pulses by reverse scan.

\[ \frac{dn}{dT} = -1.15 \times 10^{-5} \]

Input = 70 mW
\[ Q_{\text{couple}} = 2 \times 10^7 \]
\[ Q_{\text{int}} = 2 \times 10^7 \]

radius = 500 μm
Soliton state w/o wavelength scan

Kerr + TO + TE

(1) Unstable  (2) 6 solitons  (3) 4 solitons

Principle of operation

Kerr effect

Negative TO effect

Soliton state
Fabrication of CaF$_2$ WGM cavity w/ cutting

**Precise machining process**

- Cutting direction [011]
- Ductile mode
- Brittle mode
- Critical depth of cut
- Transition region

**CaF$_2$ can be smoothly cut in ductile mode cutting**

**Lathe cutting**

- Diamond tool
- Collet chuck
- Workpiece
- Critical depth of cut
- $R_{rms} = 3 \text{ nm}$
- $Q = 1.2 \times 10^6$
Trapezoid shaped WGM microcavity

\[ \beta_2 (\text{ps}^2/\text{km}) \]

- Trapezoid (designed)
- Spheric (polished)
- Material dispersion (CaF\(_2\))

Wavelength (nm)

Power (W)

Time (ps)

Wavelength (nm)
Dispersion measurement

- Anomalous dispersion obtained

Experiment

- Anomalous dispersion obtained
Obtained soliton pulse without wavelength sweeping 
by using negative TO effect of CaF$_2$.

Fabricated a dispersion controlled CaF$_2$ microcavity 
with a computer controlled ultra precision machining

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