Modelocking and Femtosecond Pulse Generation in Chip-Based Frequency Combs

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Outline

• Introduction
  ✿ Frequency combs
  ✿ Microresonator platforms

• Parametric combs in Silicon nitride structures
  ✿ Dispersion engineering & amplification
  ✿ Comb generation
  ✿ Modelocking dynamics & femtosecond pulse generation
  ✿ Pump-less comb source
Optical Frequency Combs

100’s of THz span with mHz precision

Direct link between optical and microwave frequencies


\[ f_m = m f_{rep} + f_{ceo} \]
Applications of Frequency-Comb Technology

- Optical communications & interconnects
- Optical clockwork
- Astronomical spectral calibration
- Chemical/biological sensing
- Tests of fundamental laws and constants ($R$, Lamb shift, fine-structure constant)
- Navigation (GPS)
- Very-long baseline interferometry
- Arbitrary-waveform generation
- Coherent control of molecules and reactions
Optical Frequency Comb Generation

Mode-Locked Femtosecond Laser

Spacing ~ 100 MHz

> 1 GHz Spacing

Supercontinuum Generation in Photonic Crystal Fibers

Comb Generation via Parametric Mixing in Microtoroids

Microresonator-Based Parametric Combs

**silica m-resonators**

**CaF$_2$ resonators**
Papp & Diddams, *PRA* (2011)

**silica m-spheres**

**Also:**

**Demonstrated properties in these platforms:**
- full stabilization to a reference [Del’Haye, et al., *PRL* (2008).]
- spacings as small as 2.6 GHz [Lee, et al., (2011)].

**Review article:** Kippenberg, Holzwarth, & Diddams, *Science* (2011)
Silicon-Nitride-Chip Microresonators

- CMOS-compatible material
- Fully monolithic and sealed structures and couplers
- High nonlinearity (10X silica)
Comb Generation in Silicon-Nitride Microrings

- Comb dynamics [Herr, et al, Nature Phot. ('12).]
- Waveform shaping [Ferdous, et al, Nature Phot. ('12).]
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Four-Wave Parametric Mixing

Energy conservation – restricts frequencies:
\[ 2\omega_p - (\omega_s + \omega_i) = 0 \]

Momentum conservation:
\[ Dk = 2k_p - (k_s + k_i) + Dk_{nl} \]
- wavevectors matching: dispersion, self- and cross-phase modulation

Requirement for gain: group-velocity dispersion \( D > 0 \) anomalous

\[ P^{(3)} = \chi^{(3)} E^3 \]

\[ E_i \propto \chi^{(3)} E_p^2 E_s^* \]
GVD can be tuned by varying waveguide shape and size.

FWM Gain in Si Nitride

- Dispersion engineered for anomalous GVD.
- 6-cm-long waveguide.
Frequency Comb Generation via Parametric Mixing in Microresonators

Continuous-wave pump $w_p$ interacts with the microresonator, leading to four-wave mixing, gain, and oscillation.

Energy levels: $w_p, w_1, w_2, w_3$.
Pulse Generation

Few ps pulses
Papps & Diddams

430 fs pulses,
External modulation
Ferdous et al.,

Few ps pulses,
External cavity
Peccianti et al.,
Characterization of Comb Dynamics
- Filter 25-nm section of comb centered at 1545 nm (red)
Comb Generation Dynamics

Comb Generation Dynamics

Temporal and Spectral Comb Generation Dynamics

![Graphs showing temporal and spectral comb generation dynamics.](image-url)
Transition to modelocking.
Transition to single-pulse modelocking.

Ultrashort Pulses at 99 GHz

- 99-GHz repetition rate
- 160-fs pulses

Dispersive Broadening Measurement

- Additional fiber lengths added after filtered comb output
- Dispersive broadening consistent with coherent transform-limited pulse.
Asynchronous, Single-Shot Characterization of Pulse Train

- PicoLuz ultrafast temporal magnifier used to measure pulse evolution

Single-Shot Characterization using Temporal Magnifier

Non-modelocked state

Modelocked state
< 0.5 Hz equidistance over 115 nm (14.5 THz)
- $3 \times 10^{-14} \times$ measurement bandwidth
- $3 \times 10^{-15} \times$ optical frequency

Soliton-Modelocking Mechanism

- Consistent with soliton modelocking.

**Theoretical Model for Comb Generation**

- Lugiato-Lefever model: NLSE with ring-resonator B.C.


\[
\frac{\partial}{\partial t} A = -(\alpha + i\delta) A - i \frac{L}{L_{DS}} \frac{\partial^2 A}{\partial \tau^2} + i \frac{L}{L_{NL}} |A|^2 A + \eta E_{in}
\]

Cavity loss & detuning

Dispersion

Nonlinearity

Pump

Multiple soliton solutions exist

\[ A(\tau) \sim C_1 + C_2 \sum_{j=1}^{N} \text{sech} \left[ (\tau - \tau_j) / \tau_0 \right] \]

Multiple Cavity-Soliton Formation

Temporal output varies with tuning of pump laser.

Modeling of Octave-Spanning Combs

- Includes higher-order dispersion and self-steepening for octave combs

\[ T_R \frac{\partial E(t,\tau)}{\partial t} = \sqrt{\kappa E_{in}} + \left[ -\frac{\alpha}{2} - \frac{\kappa}{2} - i\delta_0 + iL \sum_{k=2} \frac{\beta_k}{k!} \left( i \frac{\partial}{\partial \tau} \right)^k + i\gamma L \left( 1 + \frac{i}{\omega_0} \frac{\partial}{\partial \tau} \right) |E(t,\tau)|^2 \right] E(t,\tau) \]

- Consistent with experimental data from Okawachi et al. (2011).

Evolution to Modelocked State

- Evolution to stabilized single-pulse modelocking
- Each stage represents increase in pump detuning from on-resonance to $d_0 = 0.02$, 0.04, and 0.05642

Effect of Dispersion Tuning on Comb Bandwidth

- Vary waveguide width for dispersion engineering
- Width 1800 → 2400nm:
  - Anomalous $\beta_2$ decreases at pump $\lambda$
  - $\rightarrow$ BW increases
- Width 2400 → 2600nm:
  - ZDP approaches pump $\lambda$
  - $\rightarrow$ BW decreases
  - Proximity to ZDP shifts center of comb to higher frequencies
- Optimal waveguide has low, flat anomalous dispersion
Dual-Cavity-Based Parametric Frequency Comb Generation

- No tuning of CW pump required for comb generation
- Self-selection of cavity mode corresponding to microresonator mode
- Bandpass filter (6-nm bandwidth) used to control center wavelength
Dual-Cavity-Based Parametric Frequency Comb Generation

- No tuning of CW pump required for comb generation
- Self-selection of cavity mode at microresonator mode
- Bandpass filter (6-nm bandwidth) used to control center wavelength
- 90-THz bandwidth generation

Dual-Cavity-Based Parametric Frequency Comb Generation

- 6-nm filter replaced with 1.1 nm filter
- Center wavelength (a) 1544 nm and (b) 1558.7 nm
- Filter narrower than microresonator FSR to excite one mode

Silicon-Based Combs

- Highly flexible CMOS-compatible platform for combs from visible to mid-IR
- Highly compact, robust chip-based optical clock.
- Multiple-wavelength WDM CMOS-compatible source.
- Highly flexible, chip-based ultrashort pulse source.
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