Nonlinear Parametric Oscillation Phase-matched via High-order Dispersion in High-Q Silica Toroid Microresonators

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Outline

1. Background
   - Optical parametric oscillator
   - Phase-matched four-wave mixing in microresonators

2. Numerical simulation of cavity dispersion

3. Experimental observation

4. Summary
Optical parametric oscillators (OPOs)

$\chi^{(2)}$ Nonlinear crystal

Difference frequency generation

$\chi^{(3)}$ Optical fiber OPO

High-Q Microresonators

Degenerated FWM


- On chip-scale (small)
- Low cost
- Low-power drive

20 resonators on a chip
Phase-matched FWM in microresonators

- Anomalous dispersion Kerr comb generation

- Initial FWM requires modulation instability gain
- MI gain requires *anomalous dispersion*
- Balance between Kerr effect and dispersion

Phase-matched FWM in microresonators

- Scheme in this work (Parametric sideband generation)
  - MI gain is achieved by unique phase-matching
  - Dispersion near the pump is normal
  - Phase-matching far from the pump mode

- Optical fiber OPO
- Bulk magnesium fluoride
- Silica microspheres

Definition of cavity dispersion

Resonance frequencies ($\mu$ is mode number)
$$\omega_\mu = \omega_0 + D_1 \mu + \frac{1}{2} D_2 \mu^2 + \frac{1}{6} D_3 \mu^3 + \frac{1}{24} D_4 \mu^4$$

Phase-matching condition (residual dispersion) for initial sidebands
$$\Delta \omega = \omega_\mu - \omega_0 - (\omega_0 - \omega_{-\mu}) = D_2 \mu^2 + \frac{D_4}{12} \mu^4 \to 0$$
$$\mu^2 = -\frac{12 D_2}{D_4} (D_2 \cdot D_4 < 0)$$

Fourth-order dispersion plays important role in phase-matched FWM!
Calculation method of cavity dispersion

Geometry dispersion
Finite-element method

Resonance frequency (Hz)

Sellmeier equation

Refractive index

Material dispersion

\[ n^2 = 1 + \sum_i \frac{A_i \cdot \lambda^2}{\lambda^2 - B_i^2} \]

A, B : coefficient (const.)

Silica toroid microresonator

Field distribution

Group velocity dispersion

2-TE

Major diameter

Minor diameter

1-TE

2-TM

Resonator A (Major 60 um Minor 4 um)
Resonator B (Major 25 um Minor 4 um)

\[ \beta_2 (ps^2/Km) \]

Wavelength (nm)
Phase-matching points depending on cavity geometry

Major diameter 120 um, Minor diameter 8 um, 1-TE mode

Total dispersion

Resonator A (1-TE)
FSR: $D_1/2\pi = 550$ (GHz)

$$1/D_2\mu^2 + 1/D_3\mu^3 + 1/24D_4\mu^4$$

Phase-matching condition

$$\Delta\omega' = 1/D_2\mu^2 + 1/12D_4\mu^4$$

Initial FWM occurs at the points $\Delta\omega = 0$

Phase-matching point!
Phase-matching points depending on cavity geometry

Phase-matched wavelength can be controlled by changing pump or geometry.

This method offers chip-scale arbitrary frequency generators (convertors)!
Fabrication process of silica toroid microresonator

1. Photolithography

2. HF wet etching

3. CO2 laser reflow

(Major diameter 20~200 μm)
(Minor diameter 3~12 μm)
Experimental setup and optical properties

### Experimental setup

- Tunable laser diode
- EDFA
- Polarization controller
- Microcavity
- Function generator
- PM or OSC
- OSA

### Transmission spectrum

\[ Q \approx 1 \times 10^7 \]

**Optical spectrum (anomalous dispersion Kerr comb)**

- Power (dBm)
- Wavelength (nm)
Observation of OPO in Resonator A

Major diameter 118 um  Minor diameter 9 um  1-TE mode

Simulation

Experiment

Phase-matched wavelength

Pump

Simulation

Experiment
Observation of OPO in Resonator B

Major diameter 54um   Minor diameter 8 um   2-TE mode

Simulation

Experiment

Phase-matched wavelength

Pump

Simulation

Power (dBm)

Frequency (THz)

Experiment

Resonator (Major 27um Minor 4 um, 2-TE) detuning 1

1999 1874 1763 1666 1578 1499 1427 1363 1303 1249 1199

10 0 -10 -20 -30 -40 -50

Frequency (THz)

Resonator (Major 27um Minor 4 um, 2-TE) detuning 2

1999 1874 1763 1666 1578 1499 1427 1363 1303 1249 1199

10 0 -10 -20 -30 -40 -50
Summary

- Demonstrated optical parametric oscillation in on-chip high-Q silica toroid microresonator

- Investigated the dependence of phase-matching condition on pump wavelength and cavity geometry

- Observed pure OPO signals and broadband four-wave mixing light by changing the pump wavelength
Thank you for your attention

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