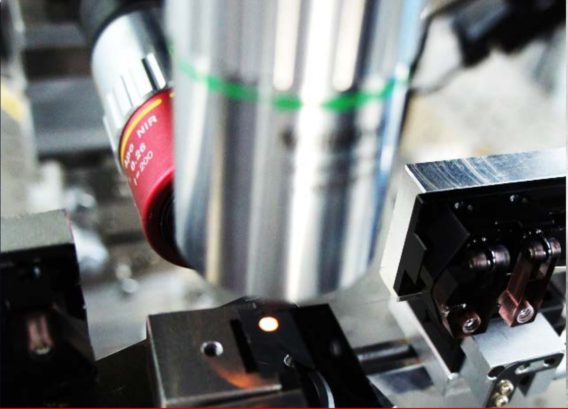
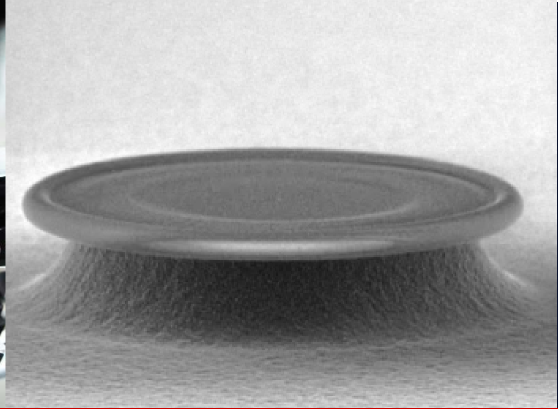
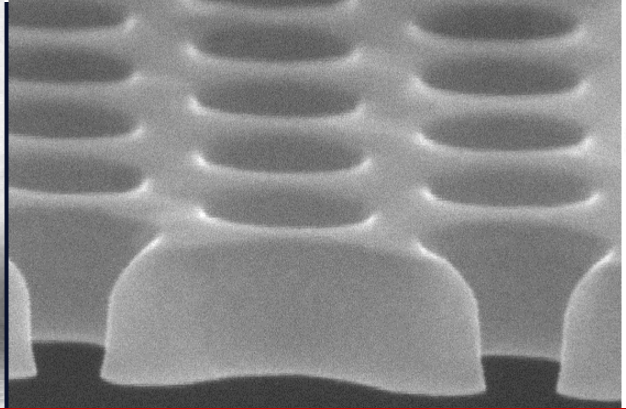
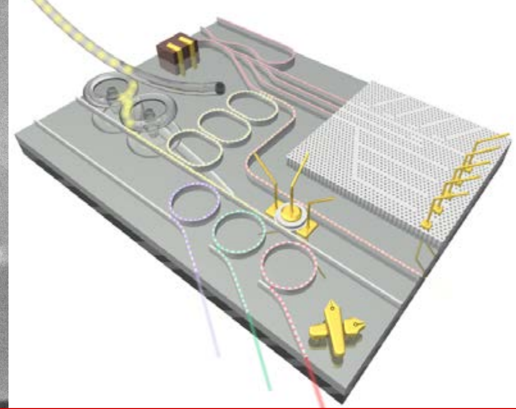





M1E-07

Numerical Simulation of Dark Soliton Generation in Coupled Microcavity System

ICO-24 August 21 2017

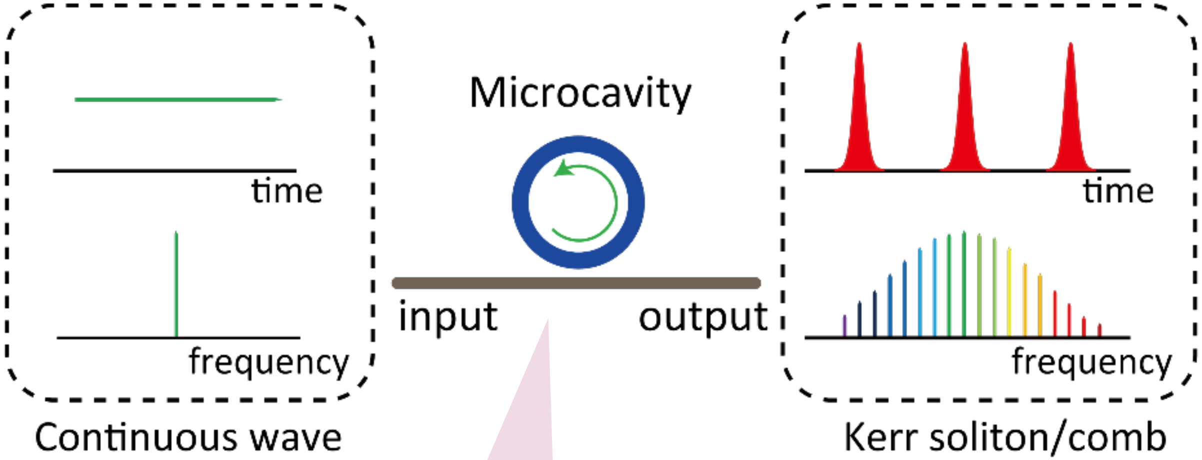
Shun Fujii, Yusuke Okabe, Takumi Kato, Ryo Suzuki, Yoshihiro Honda, Atsuhiro Hori, and Takasumi Tanabe

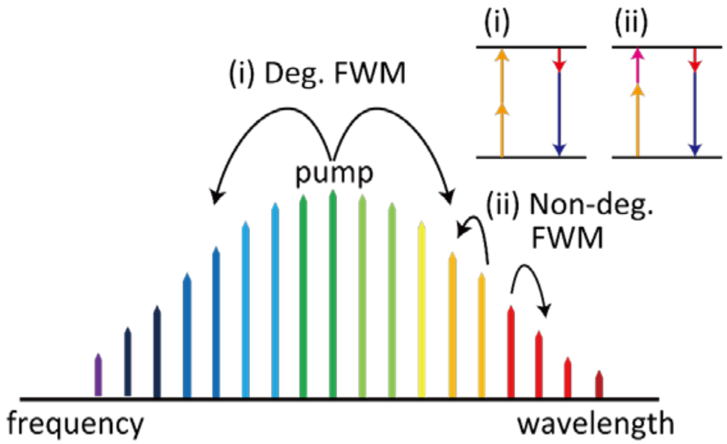
Department of Electronics and Electrical Engineering,
Faculty of Science and Technology, Keio University, Japan

Outline

1. Background
   - Mode-locked Kerr soliton comb (bright/dark)
   - Mode coupling induced dark soliton
2. Modeling of nonlinear coupled mode equation
3. Simulation results for dark soliton formation
4. Summary

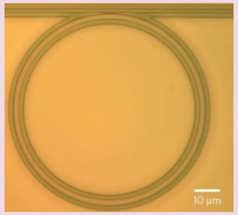
Mode-locked Kerr comb (Temporal soliton)

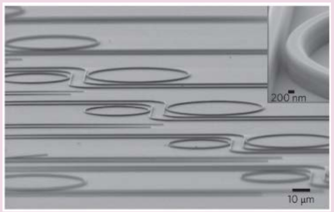




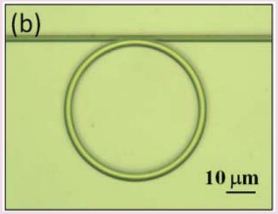
Cascaded four-wave mixing (FWM)

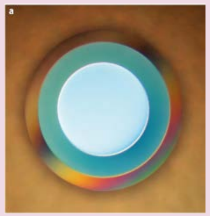
Third-order nonlinear materials





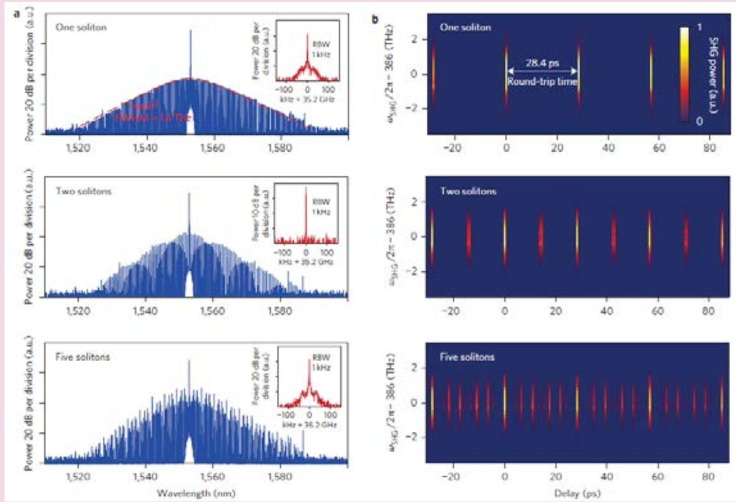
SiN(EPFL,Pardue) Diamond(Harvard) MgF_2(EPFL)





AlN(Yale) CaF_2(OE waves) SiO_2(Caltech)

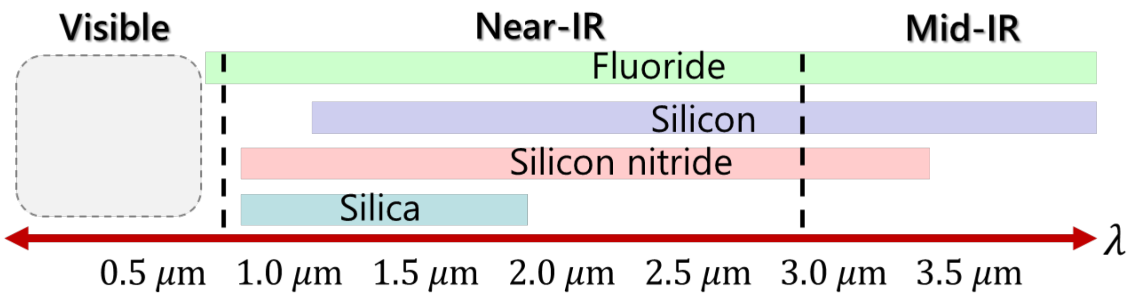
First observation of temporal soliton (2014)



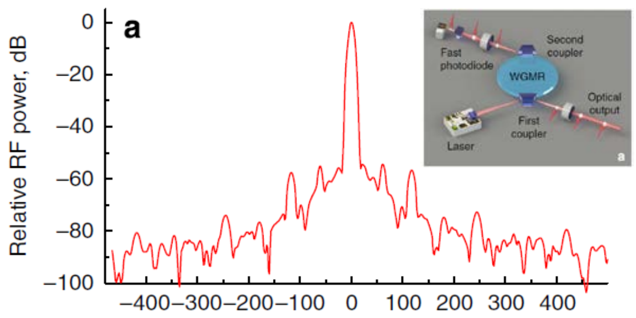
T. Herr, *et al.* Nat. Photonics **8**, 145 (2014).

Applications of mode-locked Kerr comb

- *On-chip integrated*
- *Low phase noise*
- *Low power consumption*
- *High repetition rate (>GHz)*

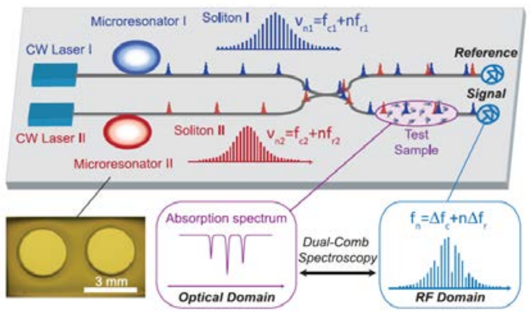


Low-noise microwave generation



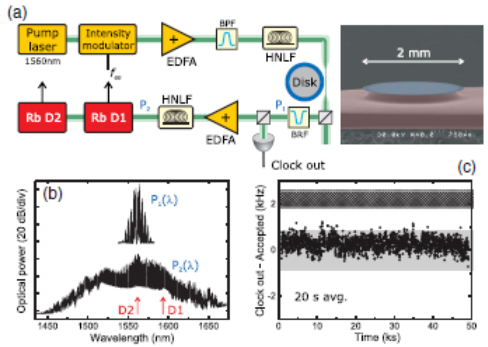
W. Liang, *et al.* Nat. Commun. **6**, 7957 (2015).

Dual-comb spectroscopy



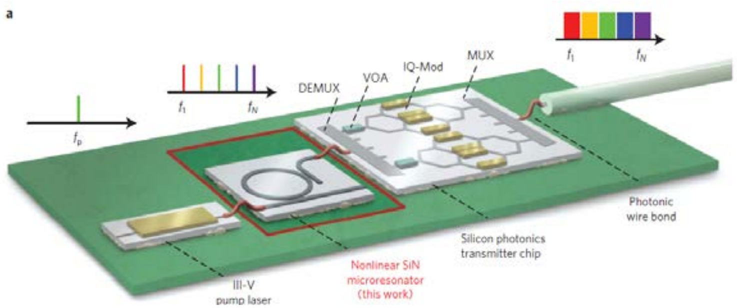
M.-G. Suh, *et al.* Science **354**, 600 (2016).

Microcomb optical clock



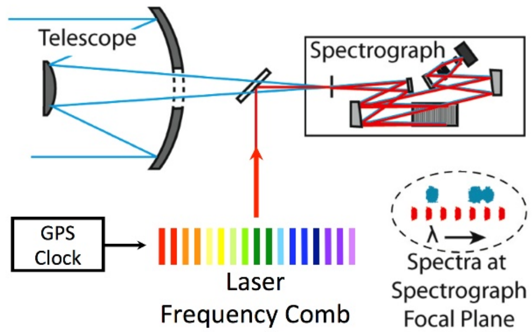
S. B. Papp, *et al.* Optica **1**, 10 (2014).

Coherent telecommunication



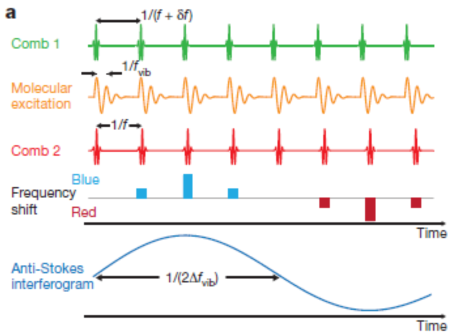
J. Pfeifle, *et al.* Nat. Photonics **8**, 375 (2014).

Astro-comb calibration



National Institute of Standards and Technology

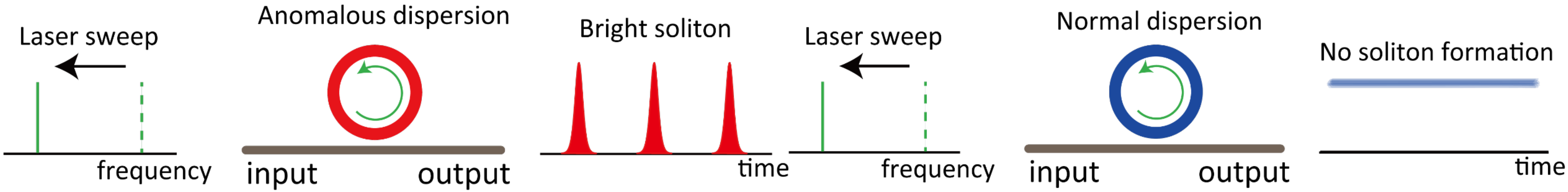
High-speed bio-imaging (CARS)



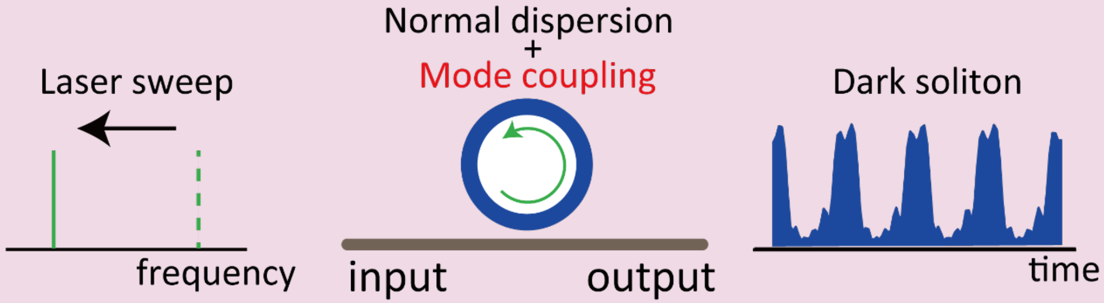
T. Ideguchi, *et al.* Nature **502**, 355 (2013).

Mechanism of bright/dark soliton formation

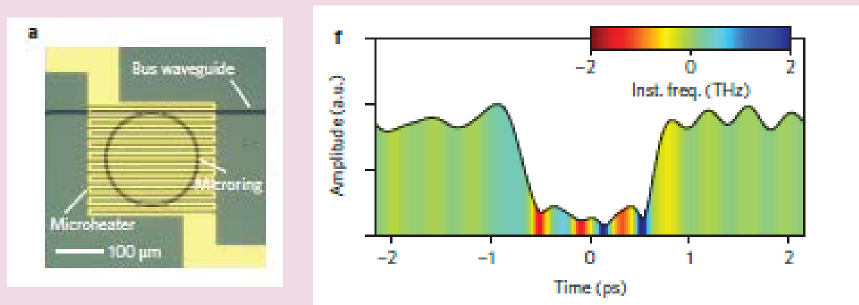
“Laser sweeping” is a way of forming solitons in an *anomalous* dispersion cavity



Mode-coupling induced dark soliton

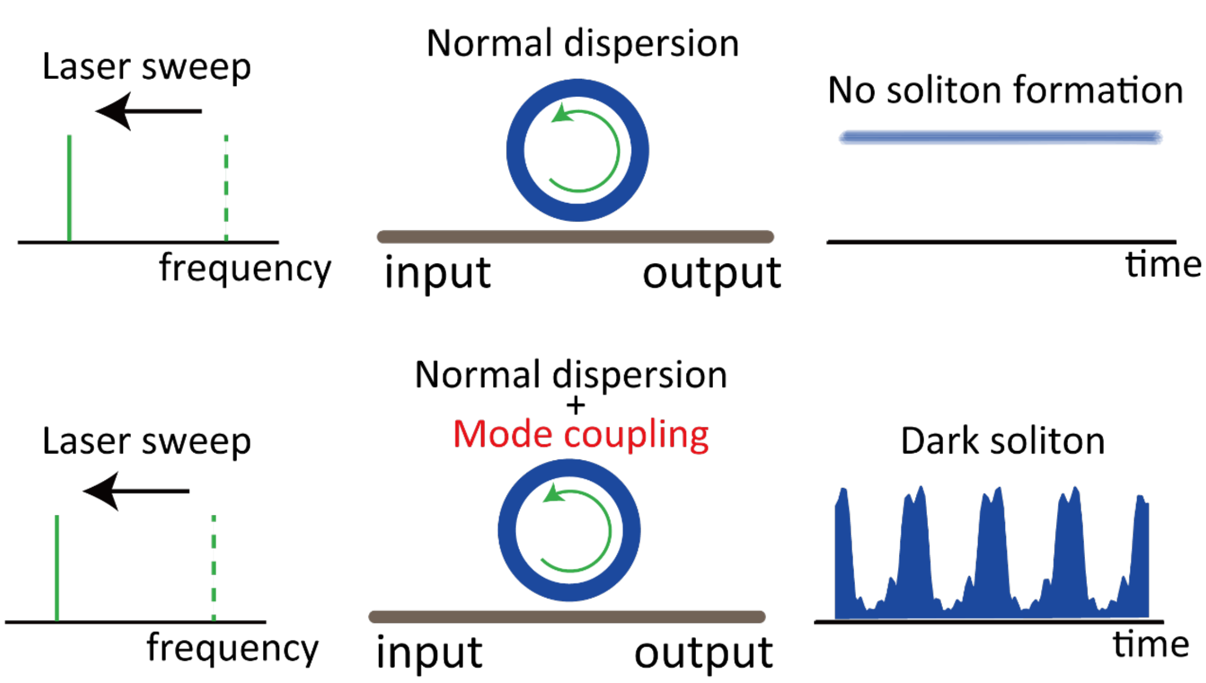


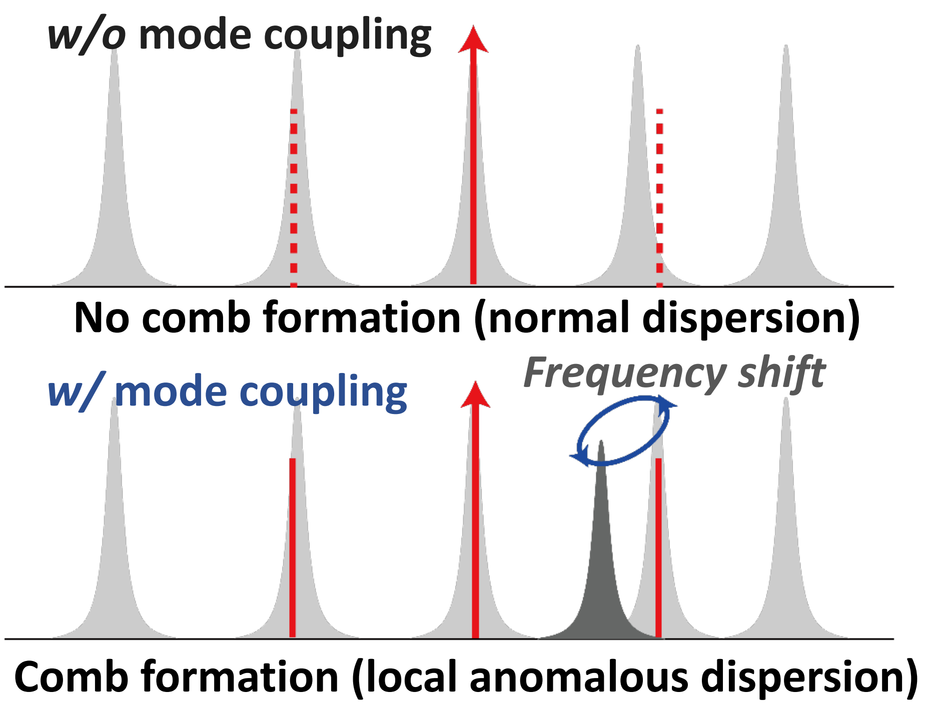
First observation of dark soliton (2015)

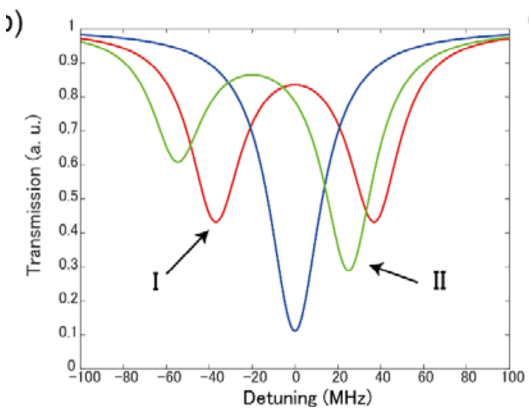


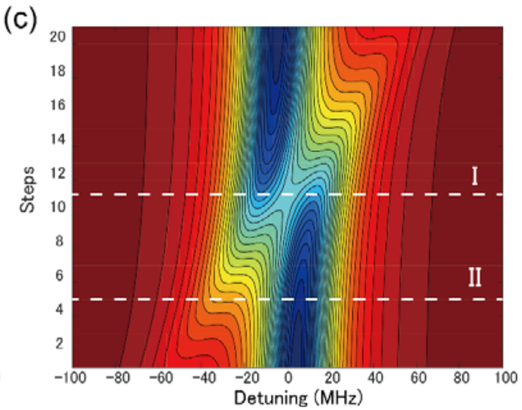
X. Xue, *et al.* Nat. Photonics **9**, 594 (2015).

Mode coupling induced dark soliton formation



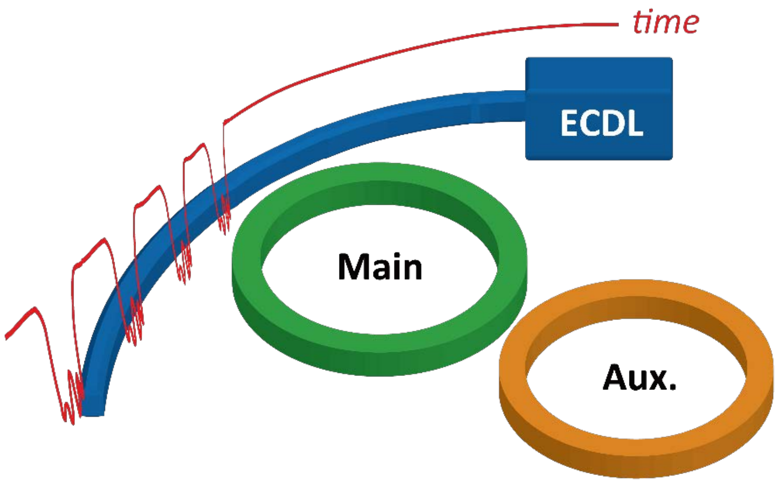




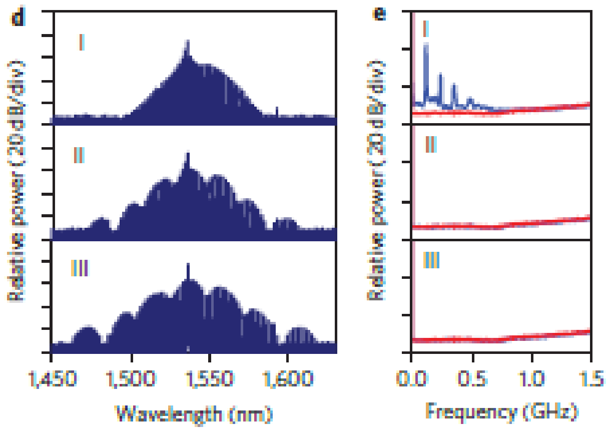


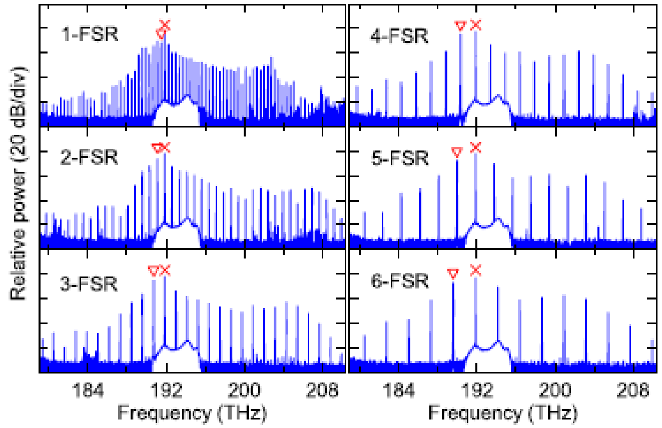
1. **Strong interaction between resonance modes**
2. **Frequency shift induced by mode coupling**
3. **Local dispersion change to *anomalous disp.***

Objective and Motivation



Follow experimental studies on dark soliton





X. Xue, *et al.* Nat. Photonics **9**, 594 (2015). X. Xue, *et al.* Laser Photon. Rev. **9**, L23 (2015).

- **Complete full numerical model of mode-coupling induced Kerr comb generation**
- **Find and propose optimal parameters for future experiments**
- **Investigate new features of complex phenomenon of dark soliton**

Modeling of NCLE for Kerr comb simulation

$$\frac{da_\mu}{dt} = -\left[\frac{\gamma_A}{2} + i(\omega_{\mu A} - \omega_p - \mu D_1)\right] a_\mu + i g_A \sum_{j,k} a_j a_k a_{j+k-\mu}^* + f\delta_\mu$$

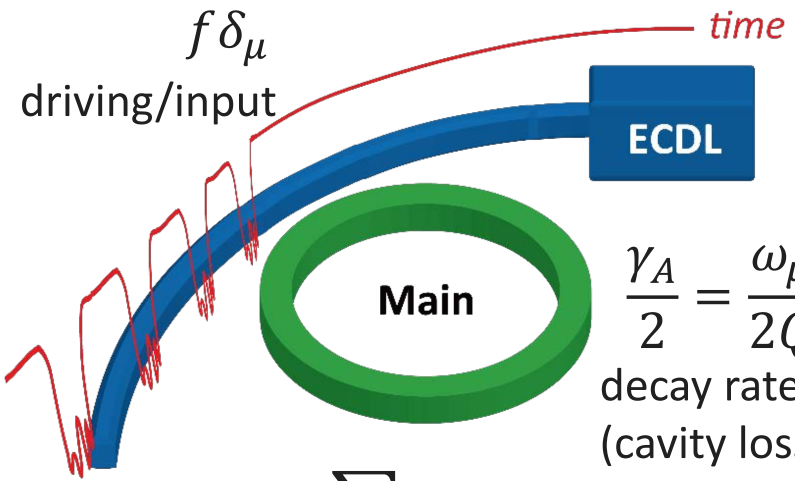
decay rate   detuning/dispersion   Kerr effects (SPM,FWM)   driving

μ : relative mode number a_μ : slowly varying amplitude of comb mode

g : nonlinear (Kerr) coefficient D_1 : free-spectral range ω_0 : center frequency

$f\delta_\mu$

driving/input



$$\frac{\gamma_A}{2} = \frac{\omega_\mu}{2Q}$$

decay rate
(cavity loss)

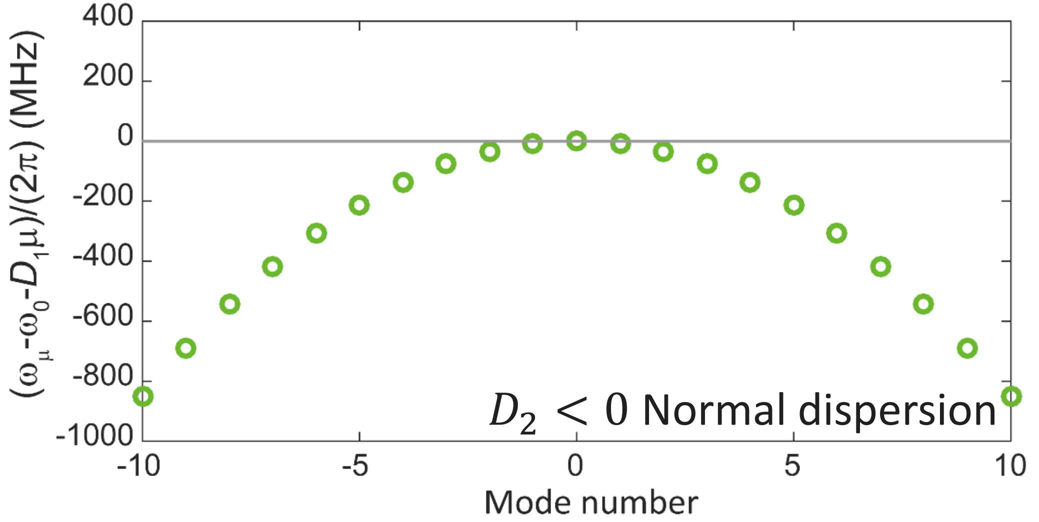
$$g_A \sum_{j,k} a_j a_k a_{j+k-\mu}^*$$

Kerr effects

✓ Discrete resonance frequencies (Taylor expansion)

$$\omega_\mu = \omega_0 + D_1\mu + \frac{1}{2}D_2\mu^2$$

D_2 : 2nd-order dispersion

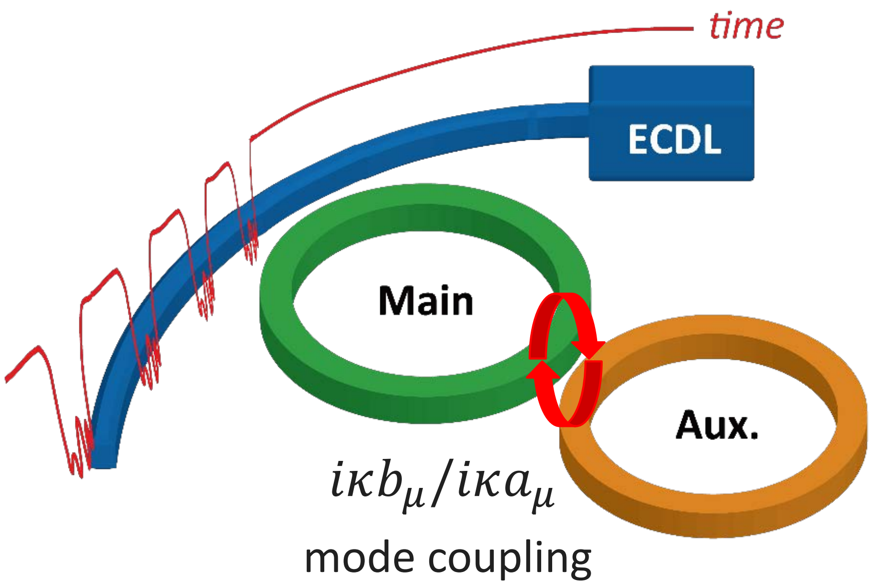


Modeling of NCLE with mode coupling term

$$\frac{da_\mu}{dt} = -\left[\frac{\gamma_A}{2} + i(\omega_{\mu A} - \omega_p - \mu D_1)\right] a_\mu + i g_A \sum_{j,k} a_j a_k a^*_{j+k-\mu} + f\delta_\mu + i\kappa b_\mu$$

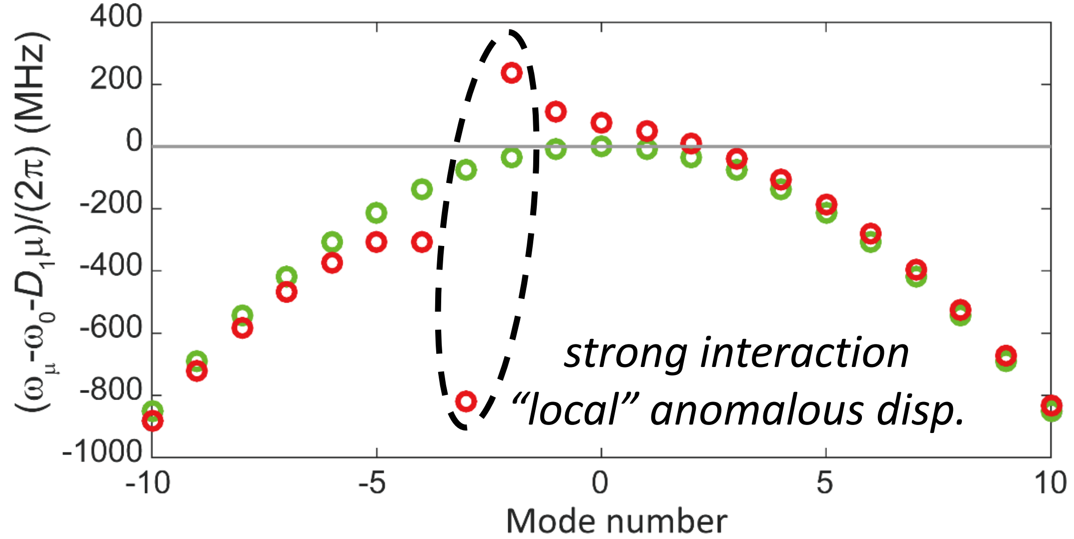
decay rate detuning/dispersion Kerr effects (SPM,FWM) driving mode coupling

$$\frac{db_\mu}{dt} = -\left[\frac{\gamma_B}{2} + i(\omega_{\mu B} - \omega_p - \mu D_1)\right] b_\mu + i g_B \sum_{j,k} b_j b_k b^*_{j+k-\mu} + i\kappa a_\mu$$



Mode coupling makes new resonance frequencies

coupling strength $\kappa = 1.05 \times 10^{10}\ (\mathrm{s}^{-1})$



Simulation results for normal-dispersion comb

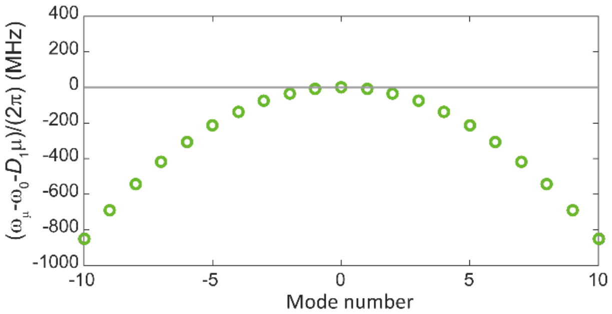
- ✓ Common parameters for SiN ring

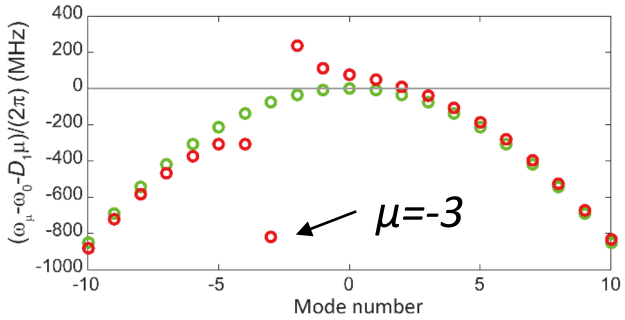
X. Xue, *et al.* Laser Photon. Rev. **9**, L23 (2015).

$\omega_0 = 191.9\ \mathrm{THz}$ $\quad P_{in} = 500\ \mathrm{mW}$

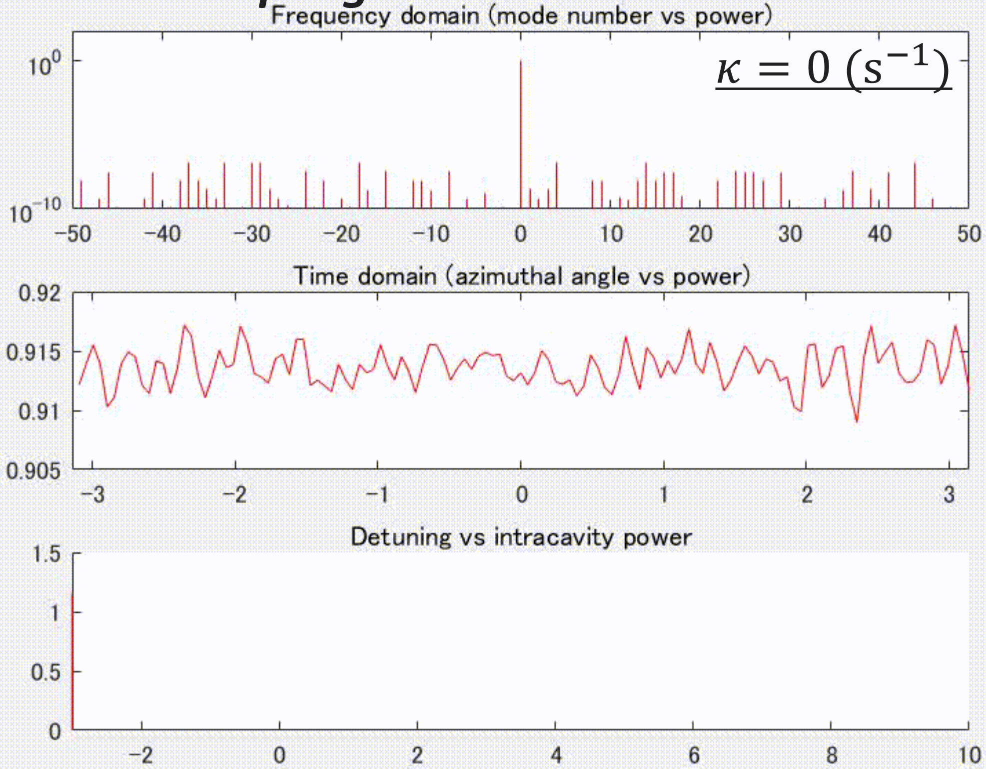
$D_1/2\pi = 378\ \mathrm{GHz}$ $\quad Q = 7.5 \times 10^5$

$D_2/2\pi = -16\ \mathrm{MHz}$ $\quad Q_{ext} = 3.5 \times 10^6$



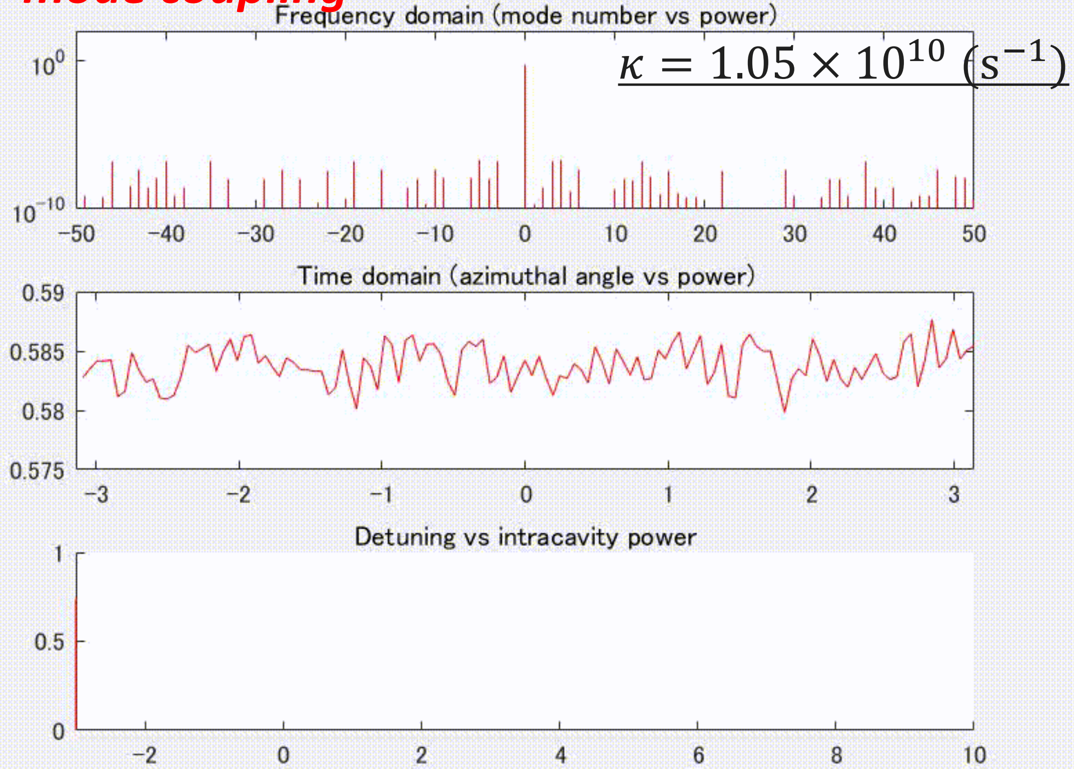


w/o mode coupling



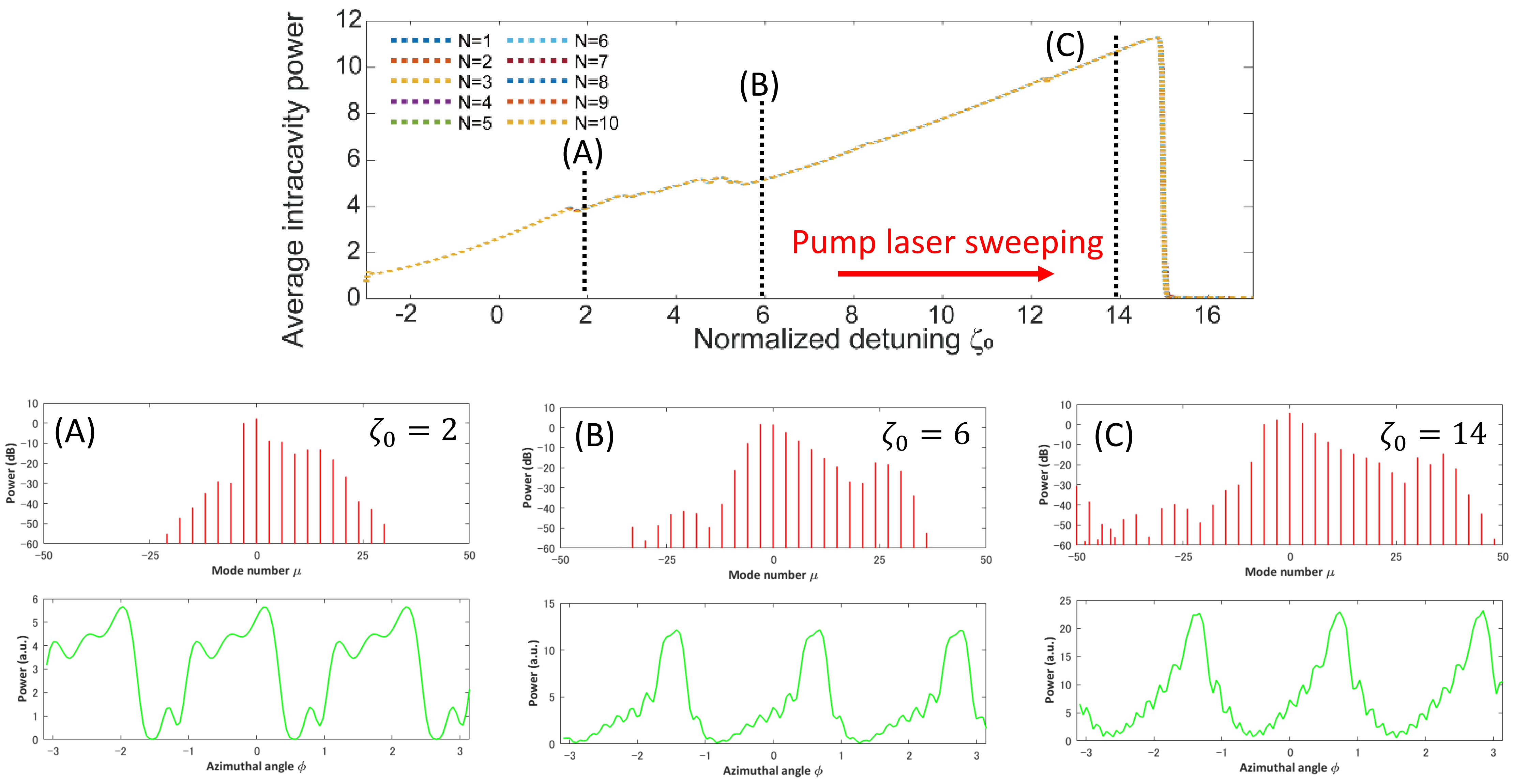
✓ ***No comb formation***

w/ mode coupling



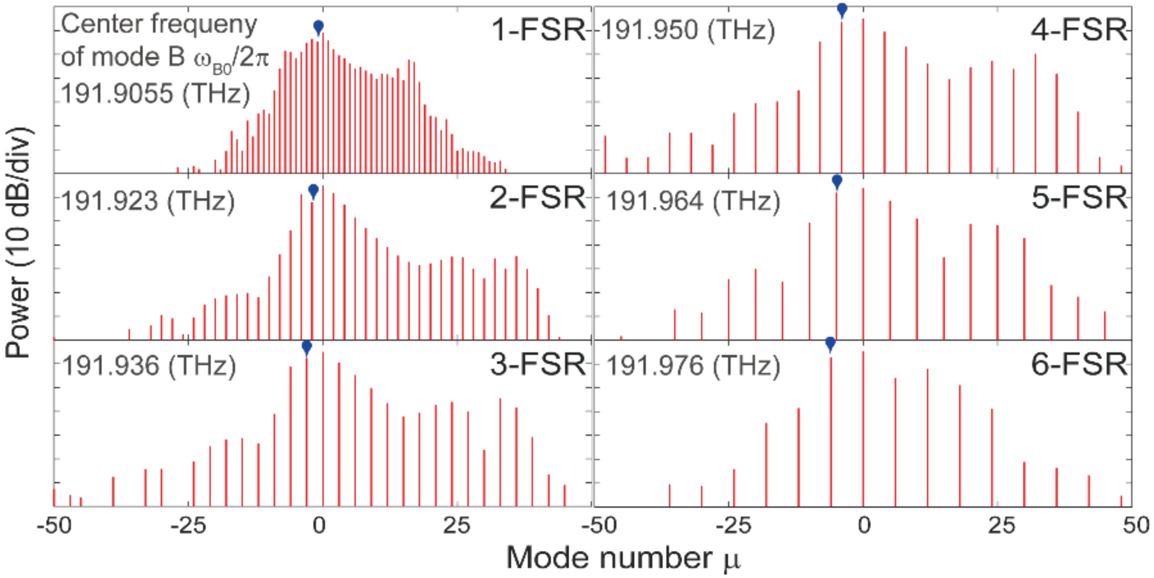
✓ ***3-FSR comb & dark pulse formation***

Simulation results for normal-dispersion comb



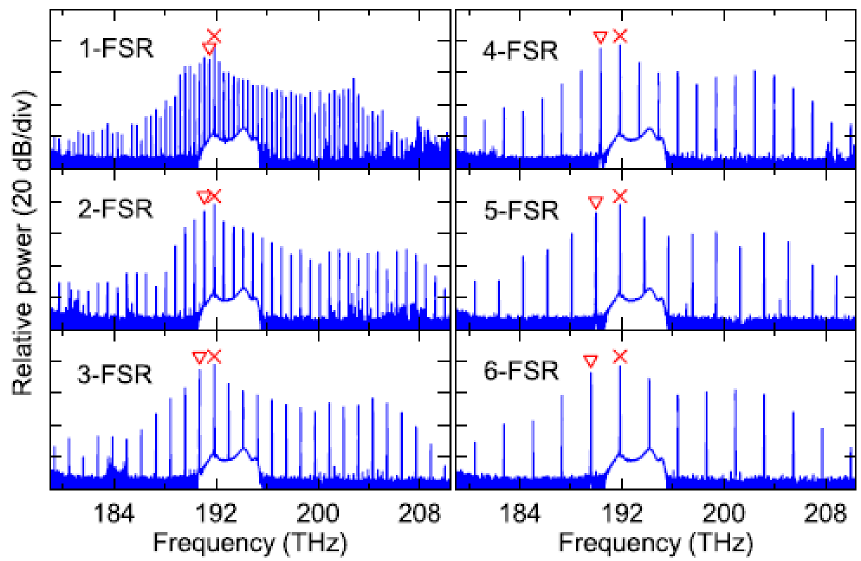
Simulation results for normal-dispersion comb

This work (simulation result)



Reference (experiment result)

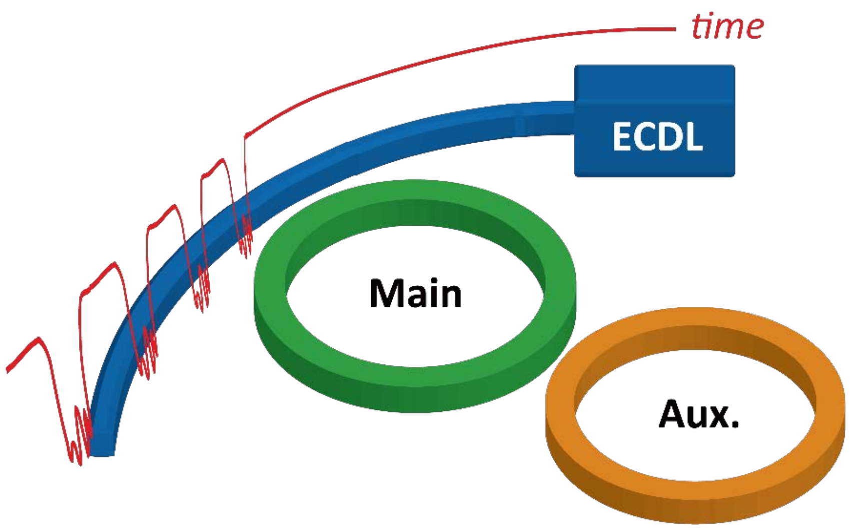
X. Xue, et al., Laser Photonics Review 9, L23-L25, (2015)

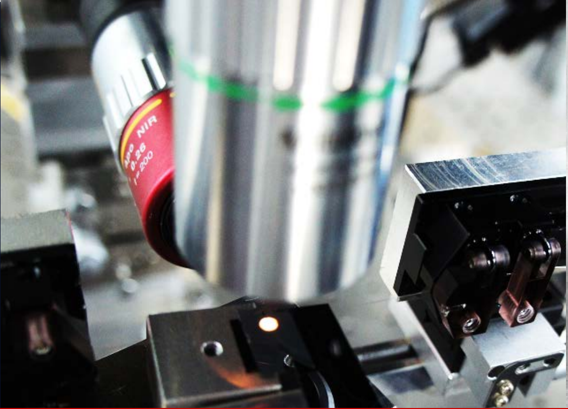
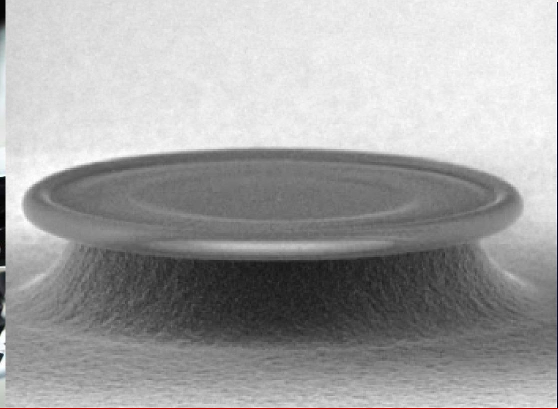
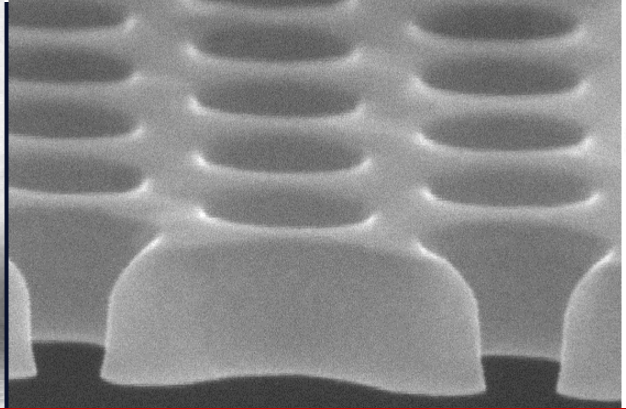
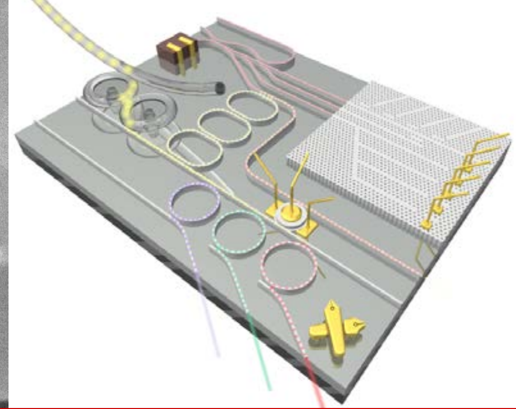


- ✓ **Shows good agreement previous experimental results**
- ✓ **Time domain analysis**
- ✓ **Allows top-down approach (“Calculation”→Fabrication→Experiment)**

Summary

- ◆ **Improved modeling of nonlinear coupled mode equation (NCLE)**
- ◆ **Calculation of normal-dispersion comb formation in coupled cavity model**
- ◆ **Time domain analysis of dark soliton formation**



Thank you

Funding information

1. Grant-in-aid from the Ministry of Education, Culture, Sports, Science and Technology (MEXT) for the Photon Frontier Network Program.
2. Grant-in-aid from the Ministry of Education, Culture, Sports, Science and Technology (MEXT), (KAKEN 15H05429)

Collaborator

Tomoyuki Miyaji (Meiji Univ.)