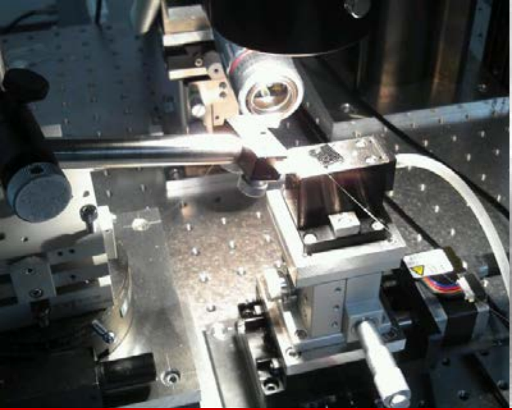
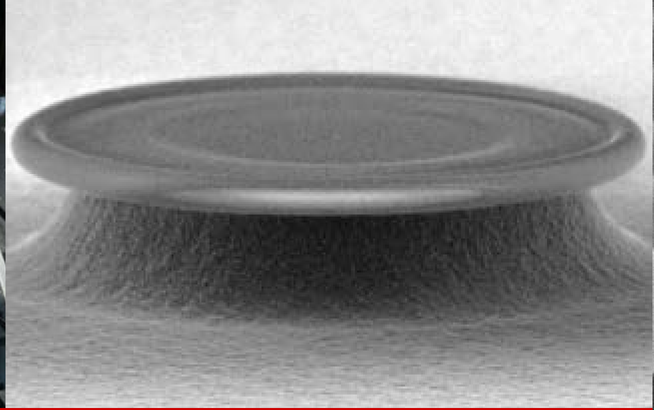
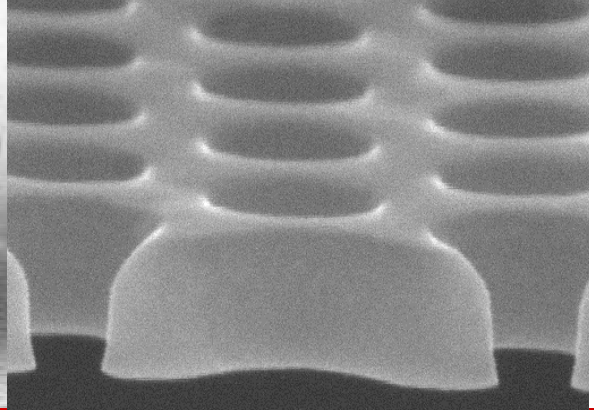
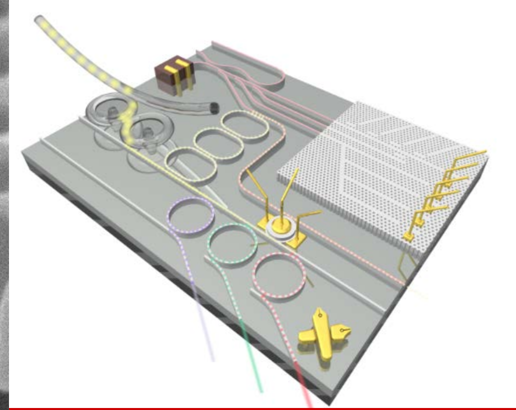

Conference on Lasers and Electro-Optics 2016 (CLEO2016)
[STu3Q.1]

The effect on Kerr comb generation in mode coupled WGM microcavity

Shun Fujii, Yusuke Okabe, Wataru Yoshiki, Takumi Kato, Akitoshi Chen-Jinnai, Tomoya Kobatake and Takasumi Tanabe

Department of Electronics and Electrical Engineering,
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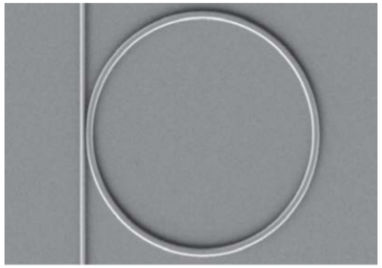
Keio University, Japan

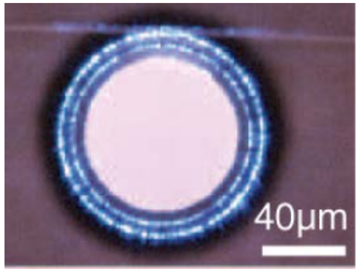
Outline

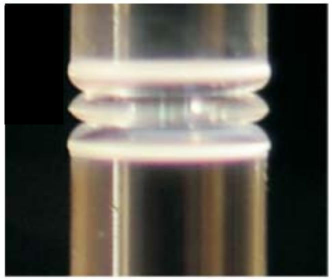
- **Background**
  - Microcavity Kerr frequency combs
  - Kerr combs with mode coupling
  - CW-CCW mode coupling
- **Objective & Method**
- **Results**
  - CW-CCW comb measurement
  - Numerical simulation of CW-CCW comb
- **Summary & Conclusion**

Microcavity Kerr frequency combs

Microcavities as frequency Kerr comb platforms


SiN ring


Silica toroid


Silica rod


MgF_2


CaF_2

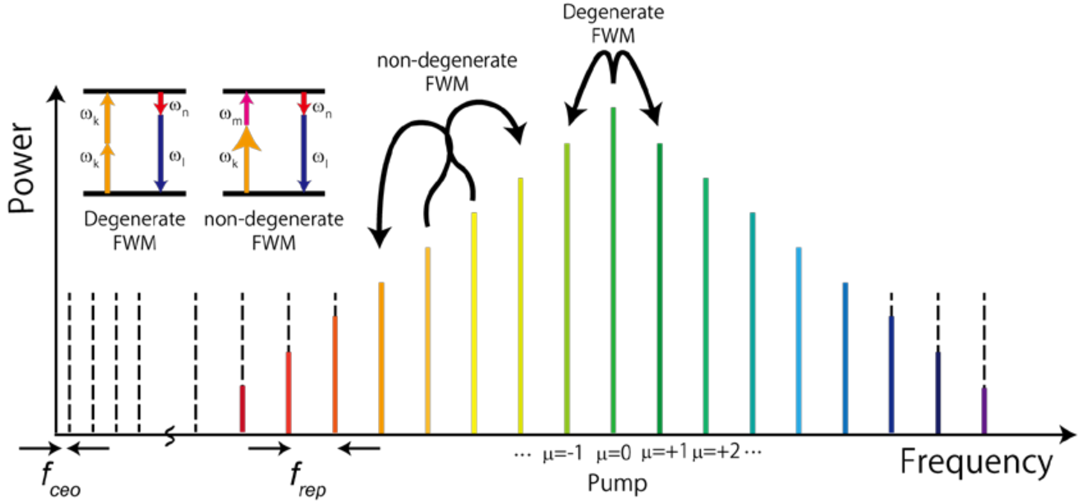
D. J. Moss et al., Nat. Photon. **7** P. Del'Haye et al., Phys. Rev. Lett. **107** S. Papp et al., Phys. Rev. X **3** http://k-lab.epfl.ch/page-102897-en.html J. Hofer et al., Phys. Rev. A **82**

On-chip ← ***χ^3 nonlinearity*** → ***High-Q***

Nonlinear threshold

$$\boxed{P_{NL} = \frac{V}{Q^2}}$$

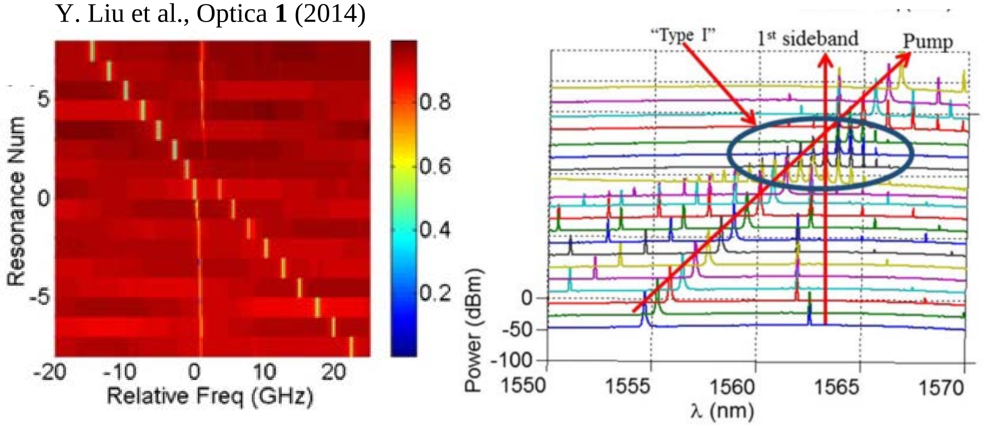
$\propto$ Small mode volume
High quality factor



Kerr combs with mode coupling

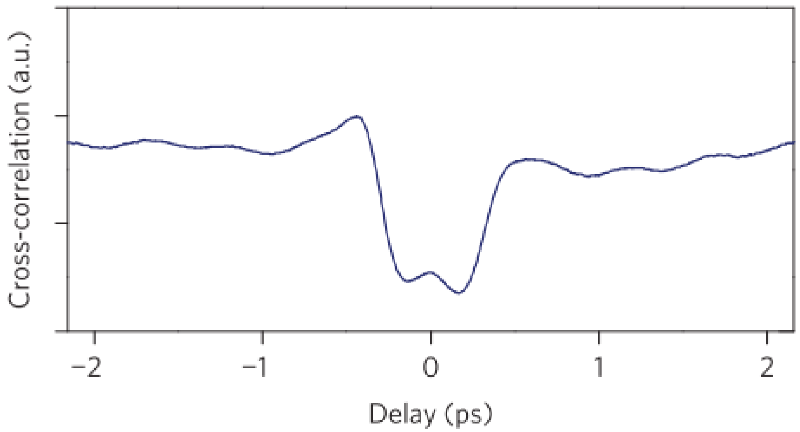
Kerr comb in normal dispersion with mode coupling

Y. Liu et al., Optica **1** (2014)



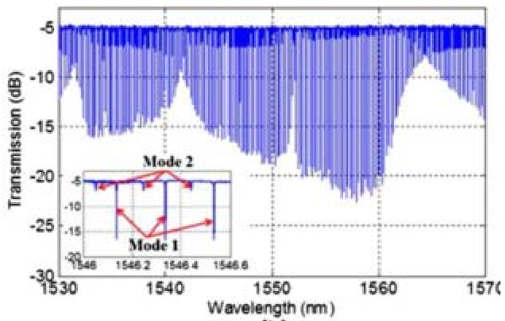
Mode coupling assisted Type-I comb

X. Xue et al., Nat. Photon. **10** (2015)



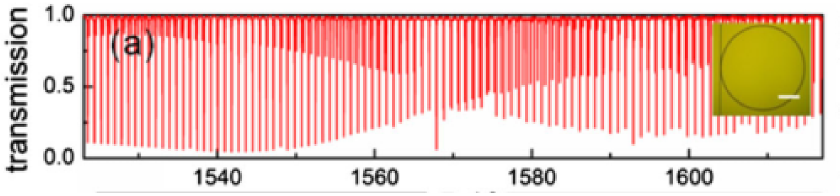
Dark pulse Kerr comb

<u>TE-TE interaction</u>



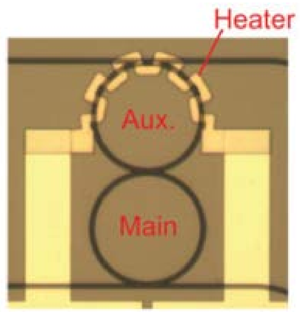
Y. Liu et al., Optica **1** (2014)

<u>TE-TM interaction</u>



S.-W. Huang et al., Phys. Rev. Lett. **114** (2015)

<u>Two-cavity mode</u>



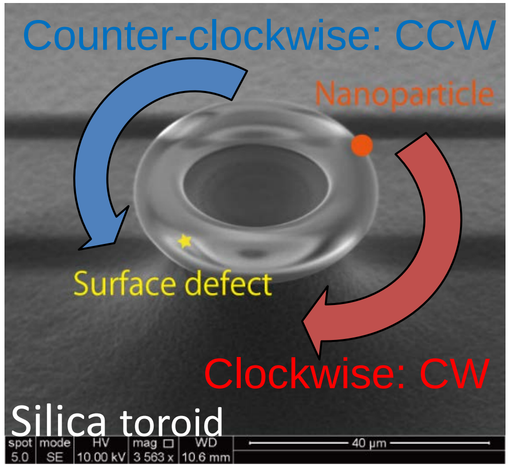
X. Xue et al., Laser Photonics Rev. **9** (2015)

Such <u>mode interactions</u> are used to change local dispersion

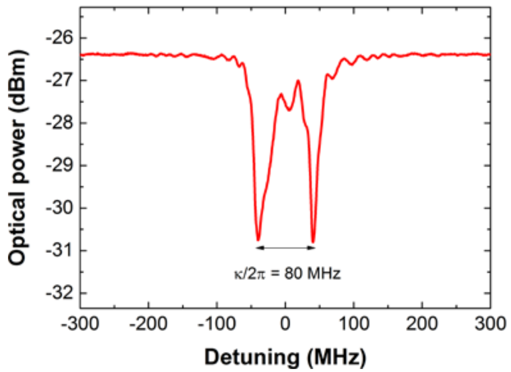
CW-CCW mode coupling

CW-CCW mode coupling

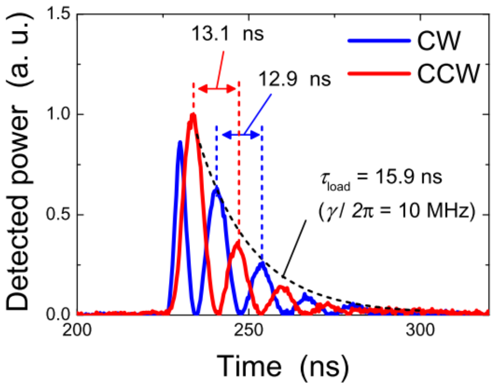
- Coupling using two counter propagating modes
- CCW mode induced by surface defects / nanoparticles etc..
- Application to label free sensing



Frequency domain



Time domain

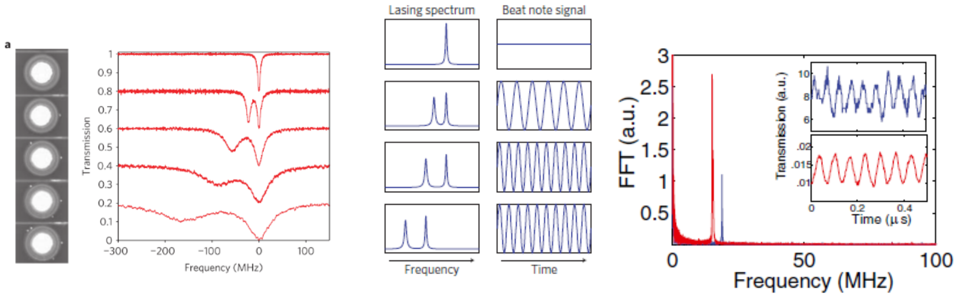


W. Yoshiki et al., Opt. Express **23** (2015)

Mode splitting

Energy exchange

Sensing applications



J. Zhu et al., Nat. Photon. **13**

L. He et al., Nat. Nanotech.. **6**

S. K. Özdemir et al., PNAS, **111**

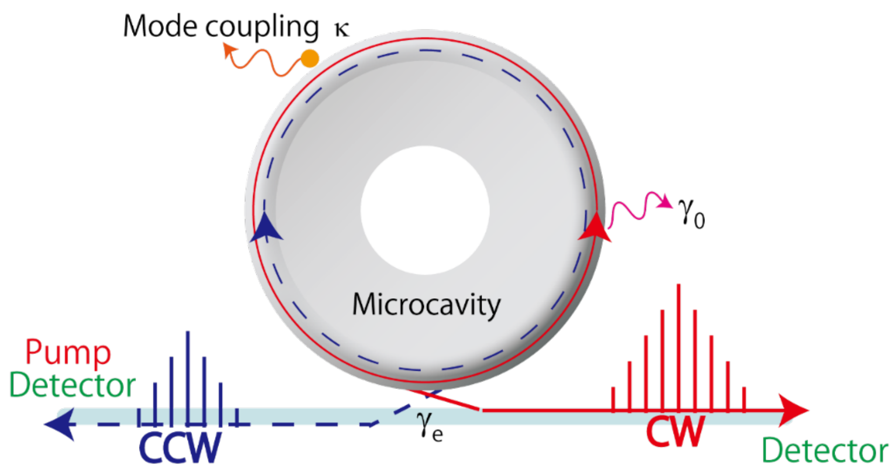
Transmission spectrum

Erbium & Raman lasing

Motivation & Method

<Objective>

1. Kerr comb generation in WGM microcavity
2. Spontaneous CW-CCW mode coupling



Understand relationship between CW-CCW coupling and Kerr comb generation

<Method>

Experiment

- Compare CW-CCW comb spectra
- Transmission spectrum of each mode

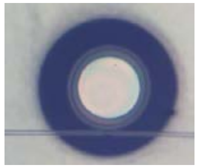
Simulation

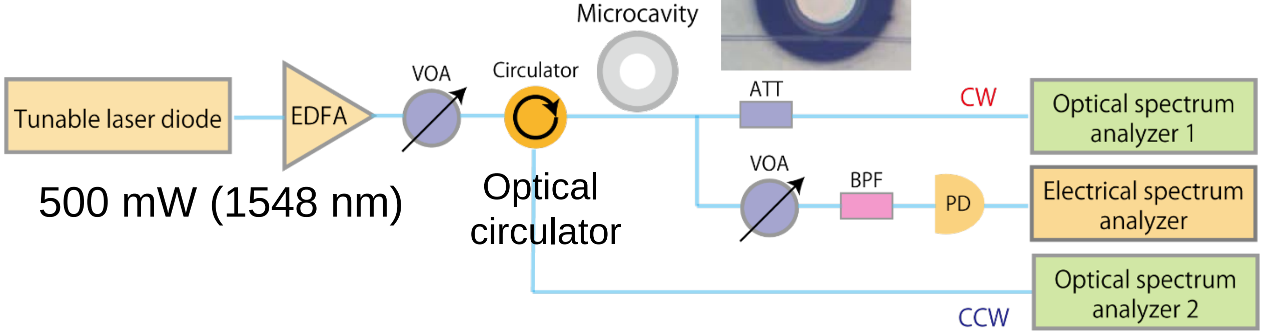
- Time domain spectrum of CW-CCW comb using coupled mode equations

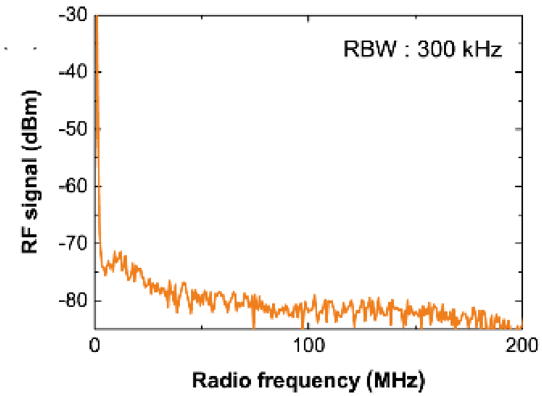
CW-CCW comb measurement

Silica toroid ($Q = 2 \times 10^7$)

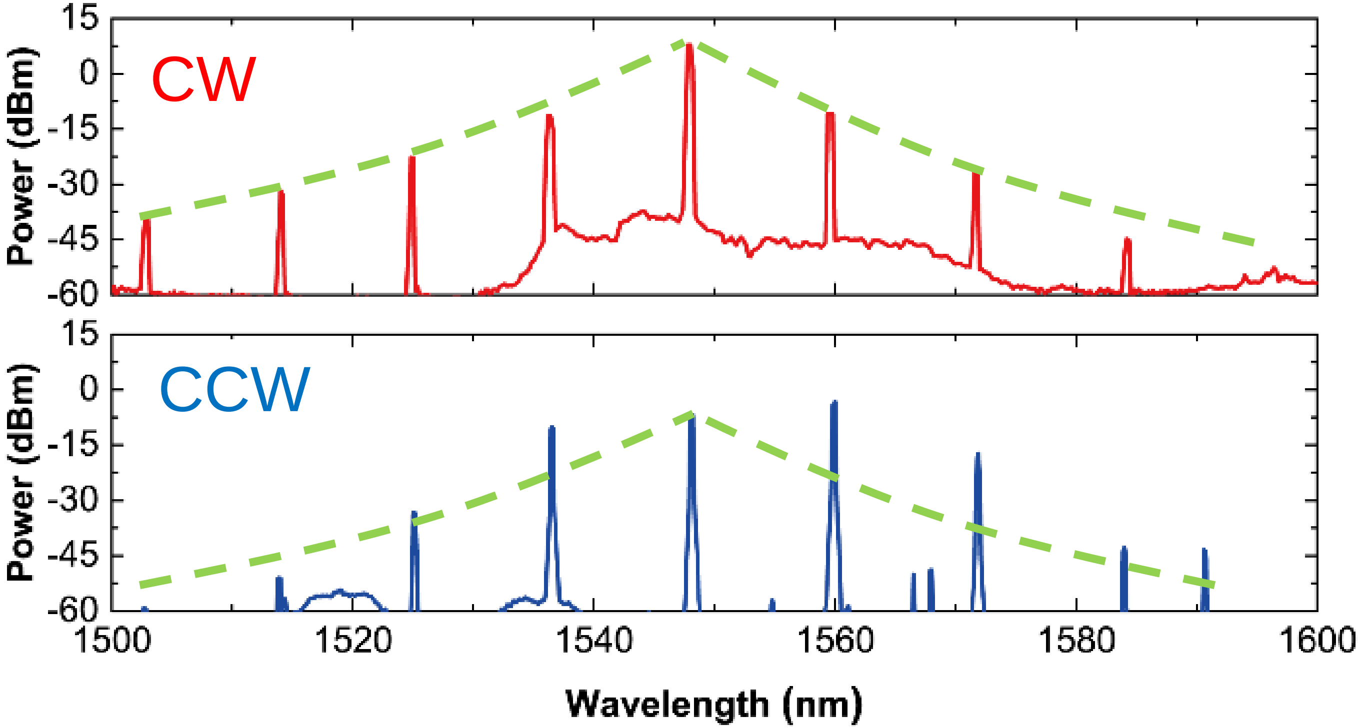
Experimental setup







Results



CW direction

Triangular envelope
Phase-locked ?

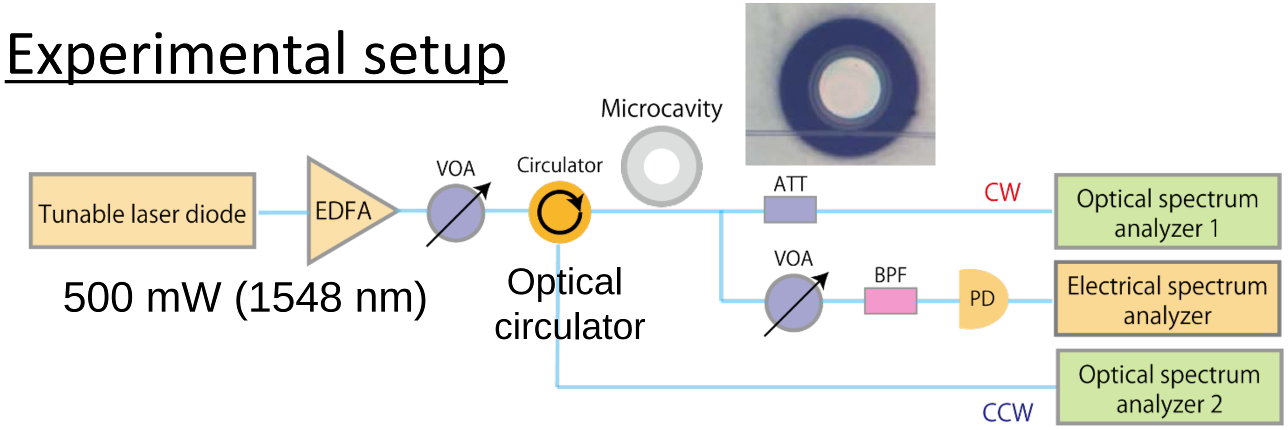
CCW direction

Envelope not smooth
unlike CW

CW-CCW comb measurement

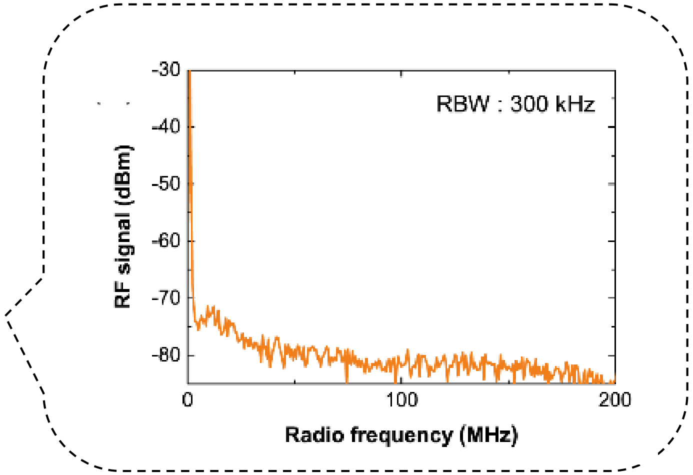
Silica toroid ($Q = 2 \times 10^7$)

Experimental setup

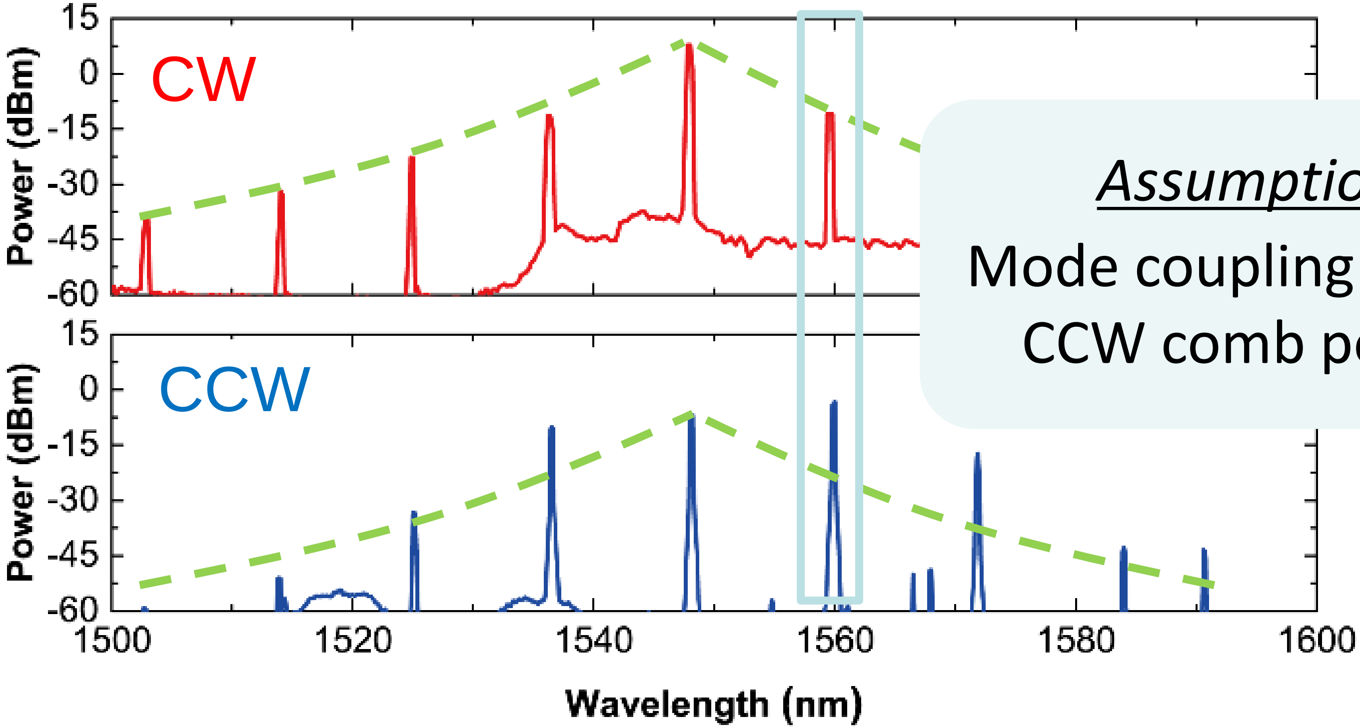


500 mW (1548 nm)

Optical circulator



Results



Assumption

Mode coupling affects CCW comb power

CW direction

ular envelope

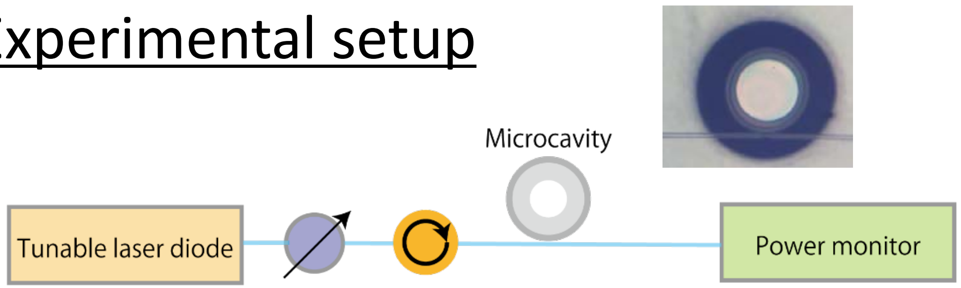
se-locked ?

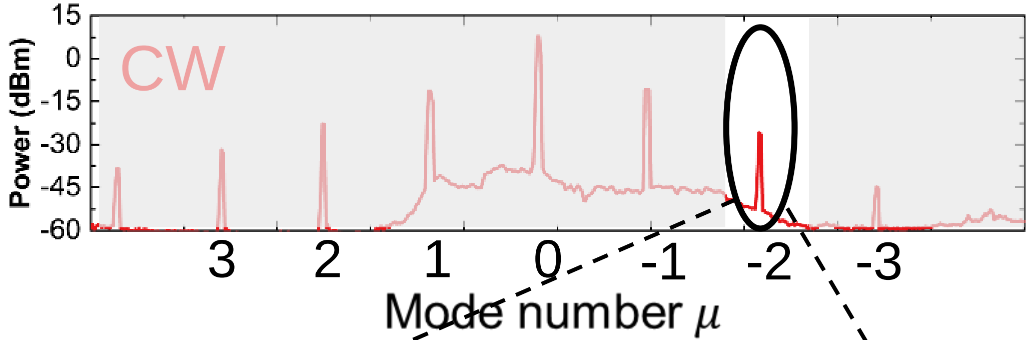
/ direction

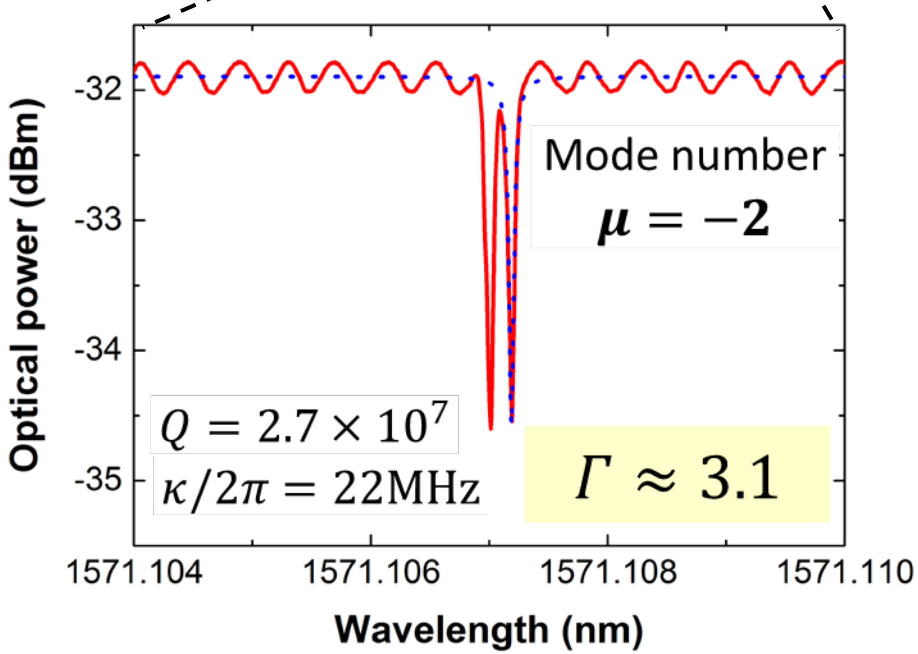
Envelope not smooth unlike CW

Mode splitting of each mode

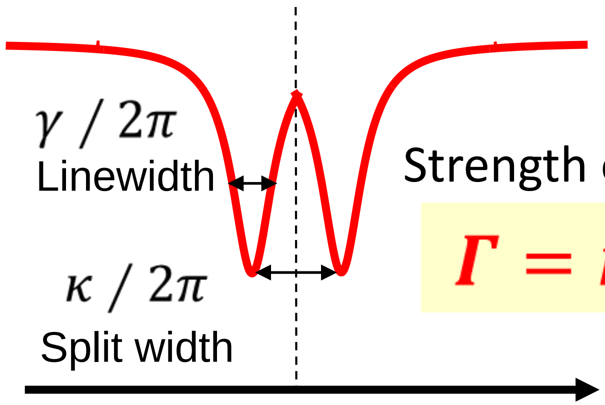
Experimental setup







Coupling parameter $\boldsymbol{\Gamma}$



Strength of coupling

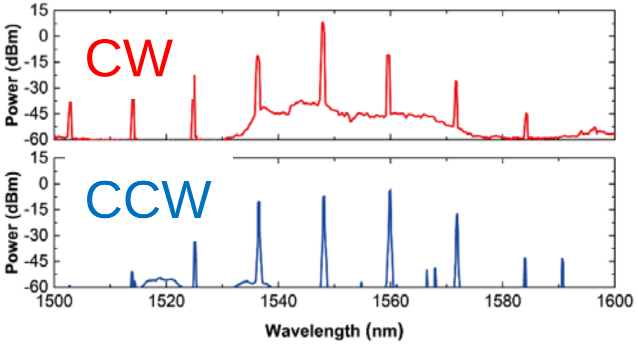
$$\boldsymbol{\Gamma = \kappa \,/\, \gamma_0}$$

$$\frac{da_{CW}}{dt} = \left(j\Delta\omega - \frac{\gamma}{2}\right) a_{CW} + j\frac{\kappa}{2} a_{CCW} + \sqrt{\gamma_e}\, s$$

$$\frac{da_{CCW}}{dt} = \left(j\Delta\omega - \frac{\gamma}{2}\right) a_{CCW} + j\frac{\kappa}{2} a_{CW}$$

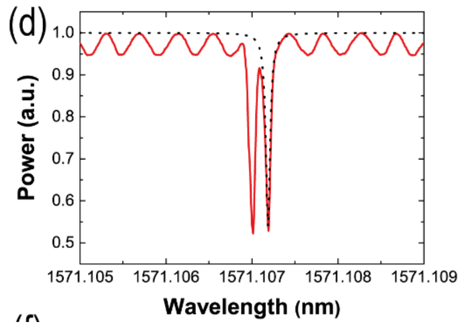
<u>Γ of each comb mode determined from transmission spectrum</u>

Comparison of power and coupling



Normalized power ratio

$$P_\mu = \frac{\text{CCW peak power}_\mu}{\text{CW peak power}_\mu}$$



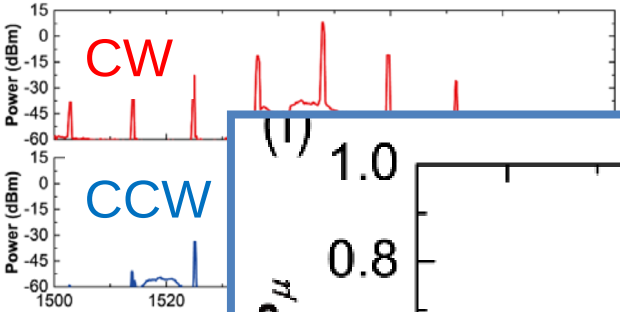
Coupling parameter

$$\Gamma_\mu = \kappa_\mu \,/\, \gamma_{0_\mu}$$

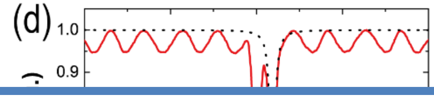
P_μ $\propto$ CCW (backscattering) power

Γ $\propto$ Strength of mode coupling

Comparison of power and coupling



Normalized power ratio

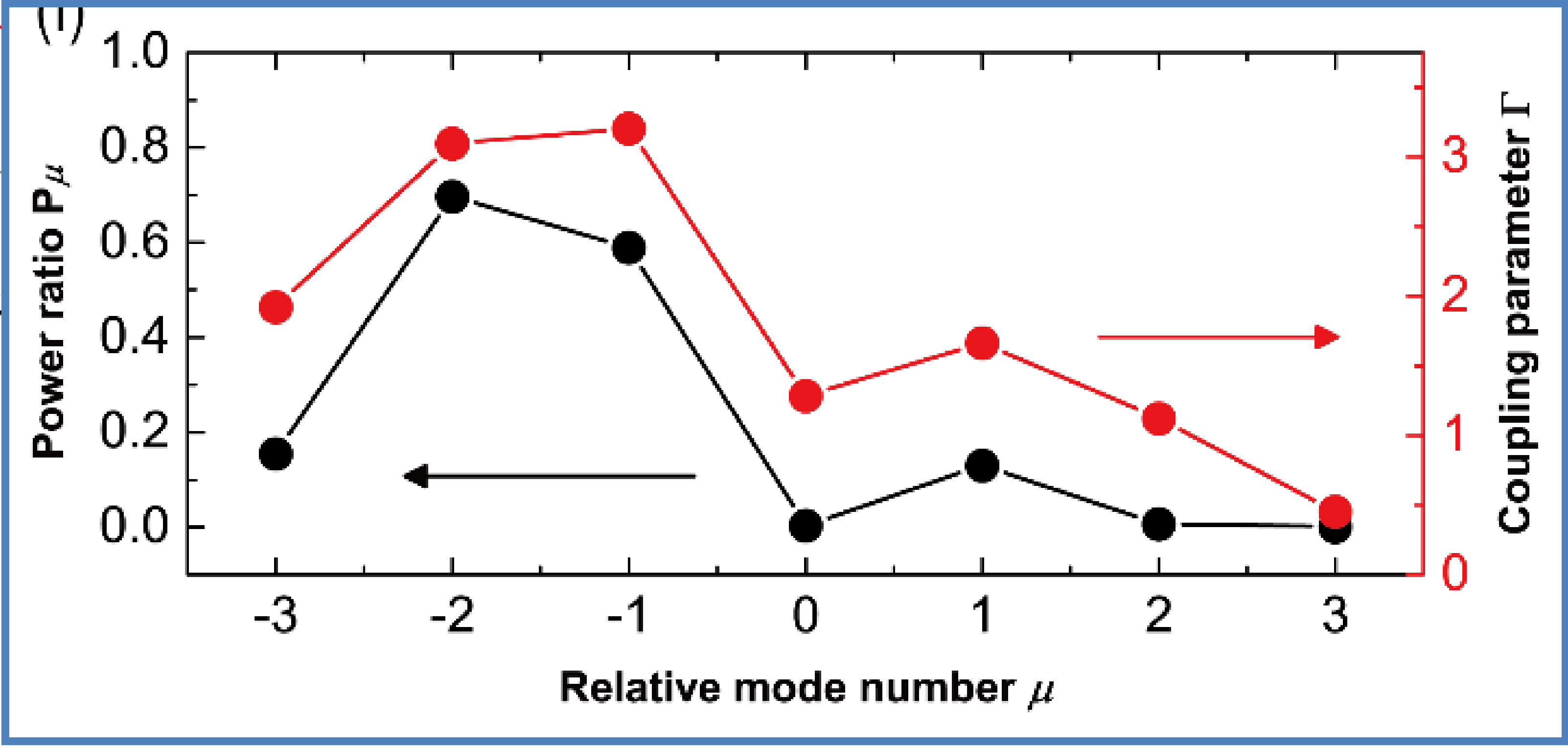


Coupling parameter

$= \kappa_{\mu} \,/\, \gamma_{0\mu}$

P_{μ}

e coupling

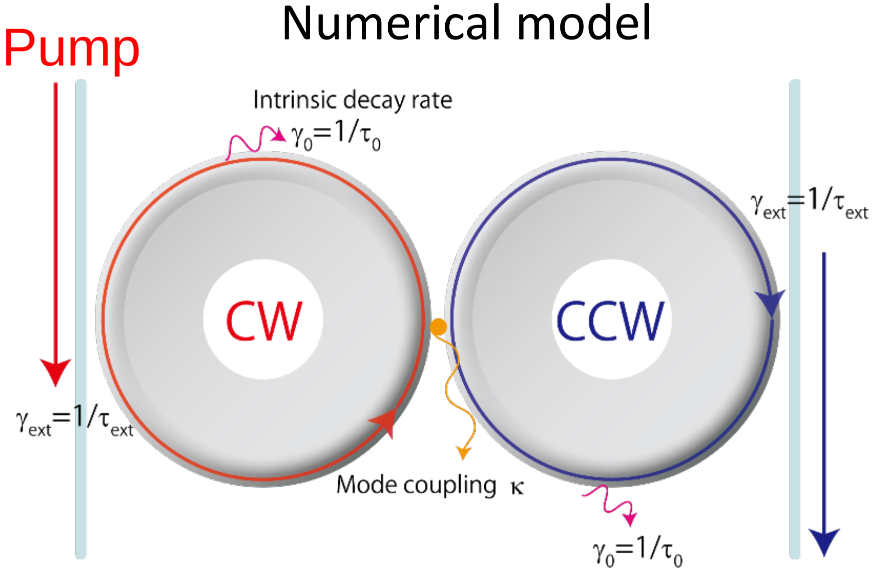


Strong correlation observed

- CCW combs generated by scattering of CW components
- CW comb (pumped) affected by coupling? → ***Question…***

Numerical modeling of CW-CCW coupling

Numerical model



Coupled mode equations

A_μ, B_μ : Mode amplitude of cavities A&B

γ : Total loss g : nonlinear coefficient

κ : Coupling coefficient between A and B

δ : Kronecker delta A_{in}: Input amplitude

$Q_A = Q_B = 1 \times 10^7$

Silica toroid microcavity 80 µm

Coupled mode equations (Two-cavity coupled model)

$$\frac{\partial A_\mu}{\partial t} = -\frac{\gamma_{A_\mu}}{2}A_\mu + i g_A \sum_{\alpha,\beta,\gamma} A_\alpha A_\beta^* A_\gamma e^{i\left(\omega_{A_\alpha}-\omega_{A_\beta}+\omega_{A_\gamma}-\omega_{A_\mu}\right)t} + i\frac{\kappa_\mu}{2}B_\mu + \delta_\mu\sqrt{\gamma_{Aext}}A_{in}e^{i(\omega_{in}-\omega_{A_0})t}$$

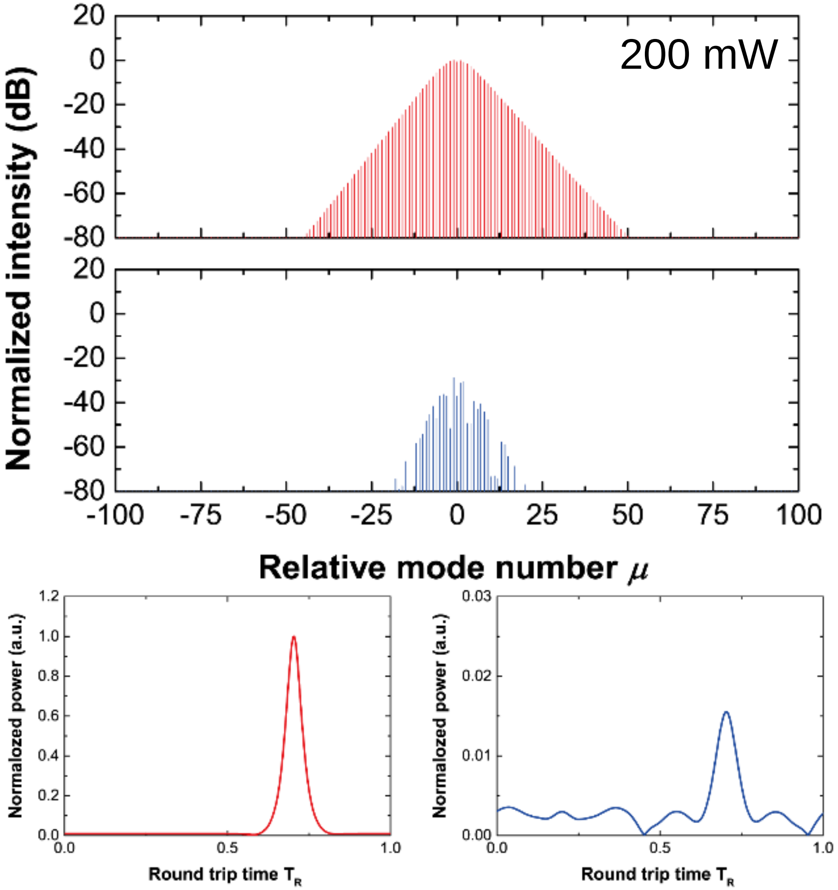
$$\frac{\partial B_\mu}{\partial t} = -\frac{\gamma_{B_\mu}}{2}B_\mu + i g_B \sum_{\alpha,\beta,\gamma} B_\alpha B_\beta^* B_\gamma e^{i\left(\omega_{B_\alpha}-\omega_{B_\beta}+\omega_{B_\gamma}-\omega_{B_\mu}\right)t} + i\frac{\kappa_\mu^*}{2}A_\mu$$

Pumped only CW direction

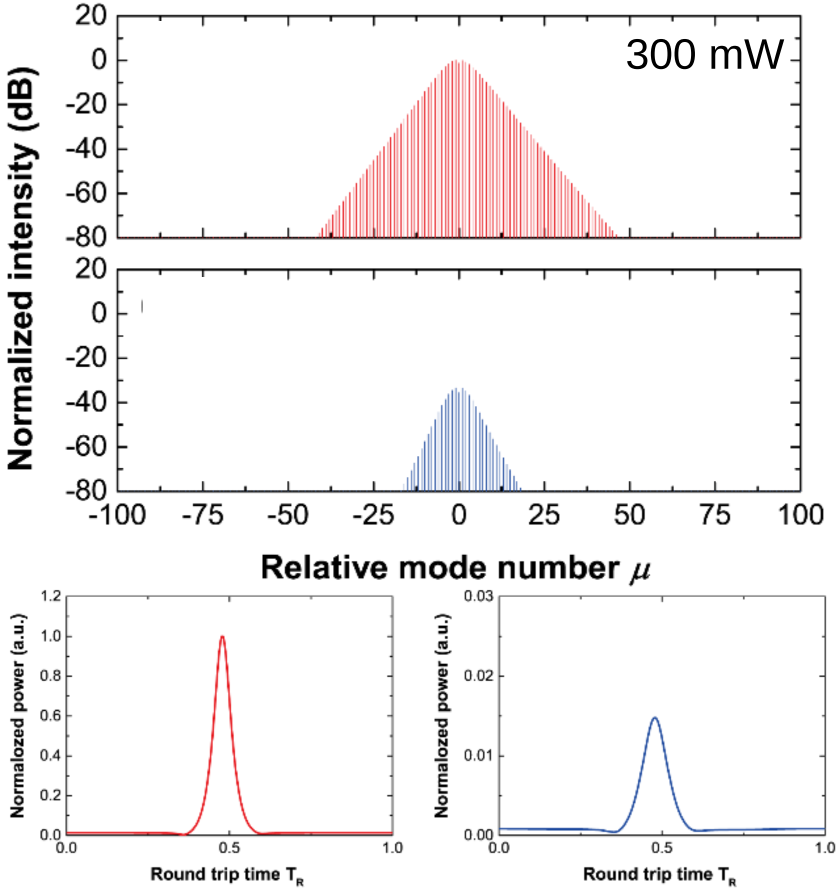
Loss FWM / Dispersion Mode coupling Input

Numerical simulation CW-CCW coupled Kerr comb

Coupling $\Gamma = 0 \sim 5$ **(Random)**



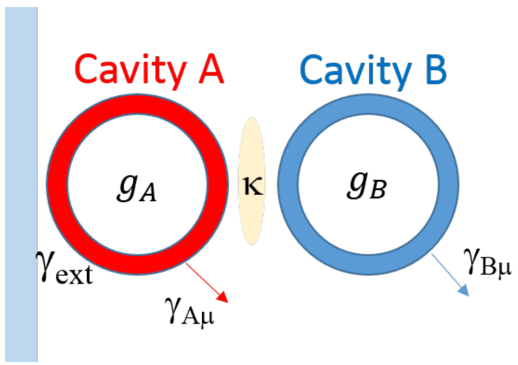
Coupling $\Gamma = 2.0$ **(Constant)**



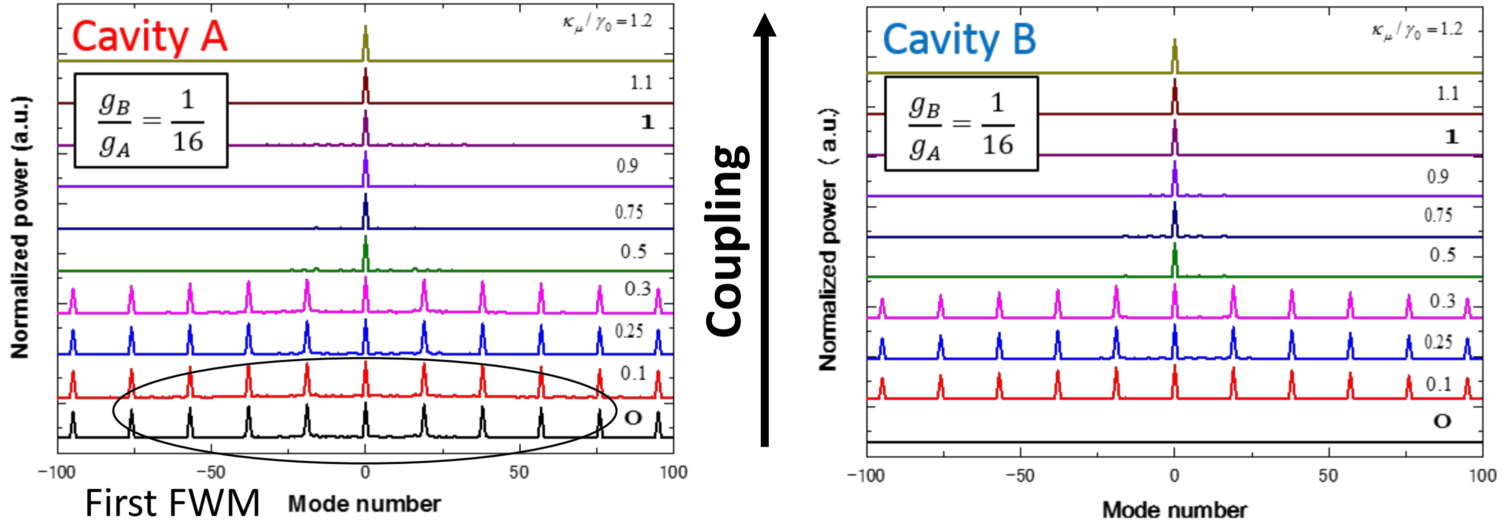
- ➢ Only CCW comb is affected by mode coupling
- ➢ Coherence decreases with random coupling

Coupled cavity model (Coupled mode equation)

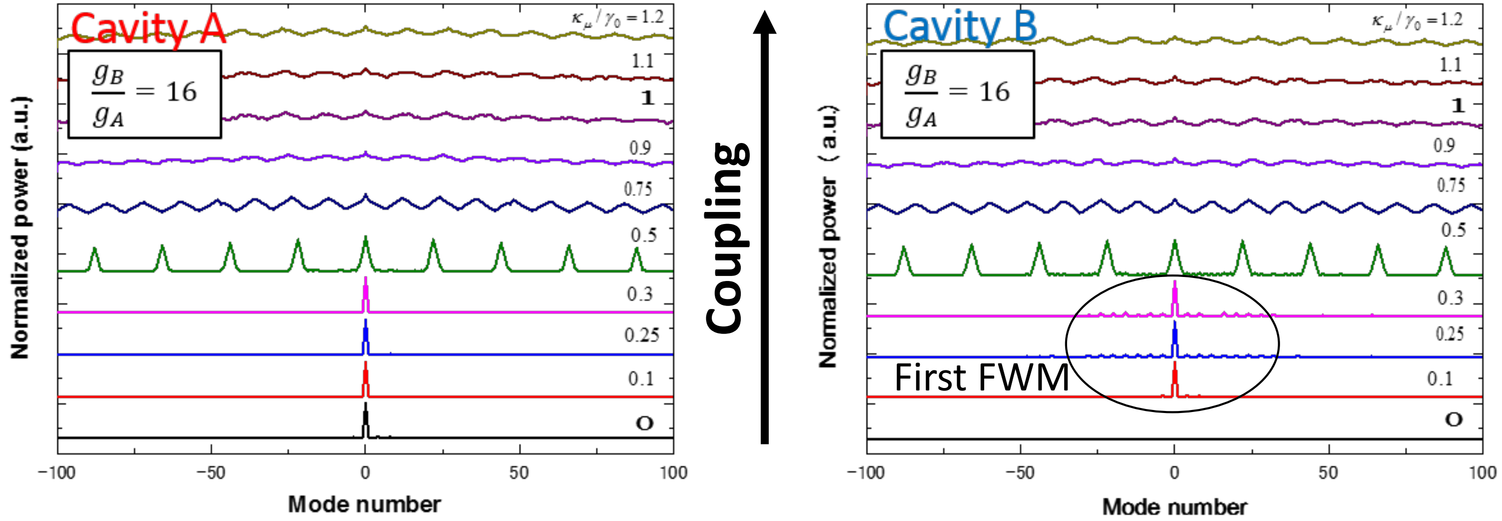
Numerical model



Nonlinear gain A >> B



Nonlinear gain A << B



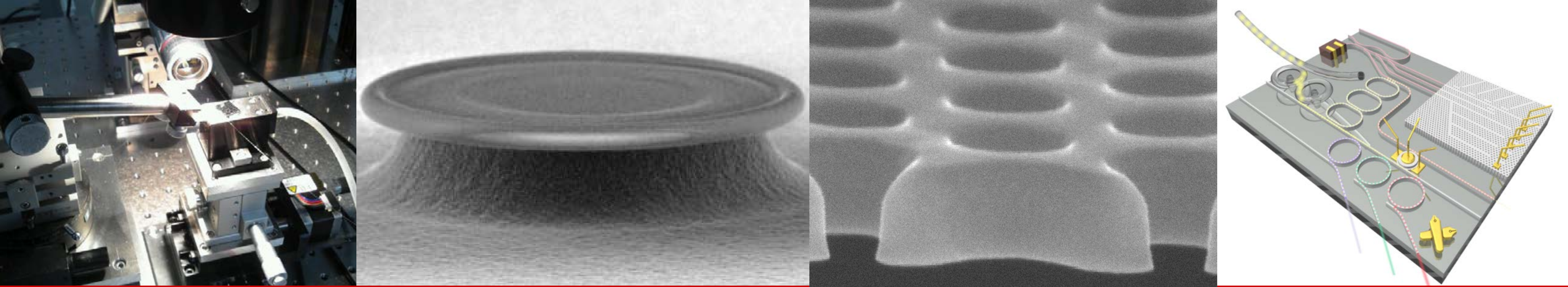
Summary & Conclusion

1. Demonstrated the relationship between the coupling strength and the backscattering comb components

→ Strong correlation between coupling and CCW comb

2. Investigated the impact of CW-CCW coupling on CW comb generation using CMEs for a coupled cavity system

→ No influence on CW comb & pulse formation
CCW pulse generation depending on conditions



STu3Q.1

Thank you very much

Acknowledgment

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Ministry of Education, Culture, Sports, Science and Technology (MEXT) (KAKEN 15H05429)

June 7, 2016