JTu5A.48

Analysis of effect of interaction between transverse modes on Kerr frequency comb generation

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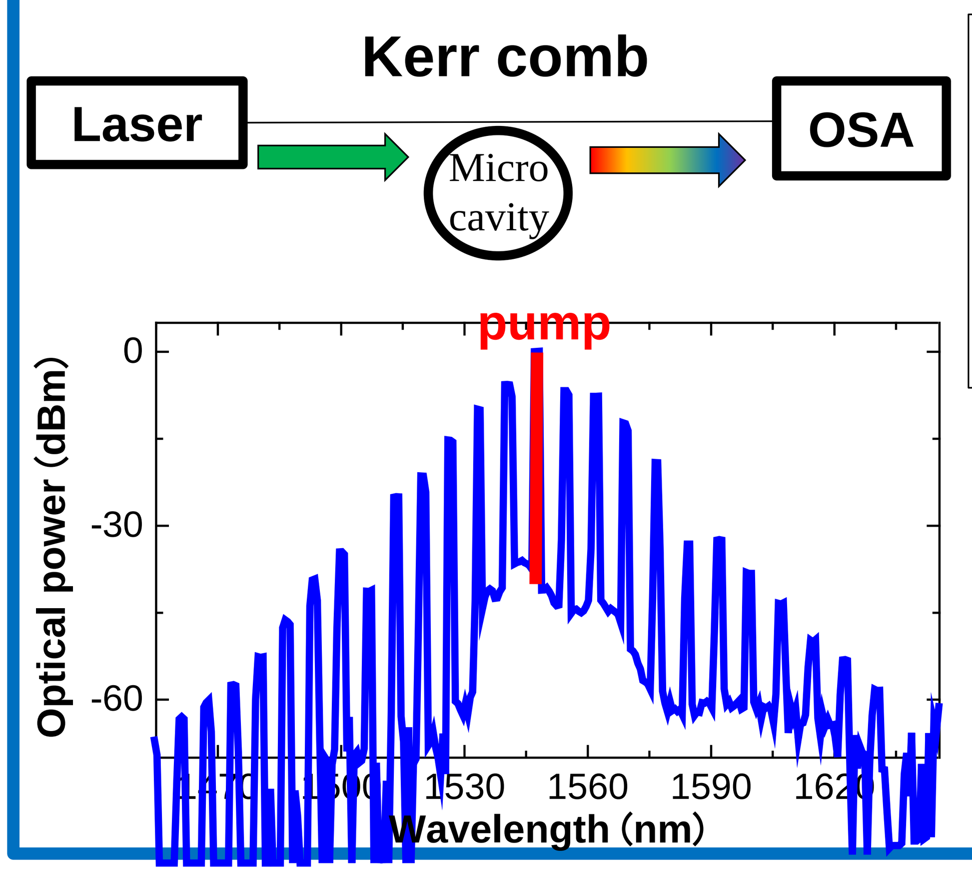
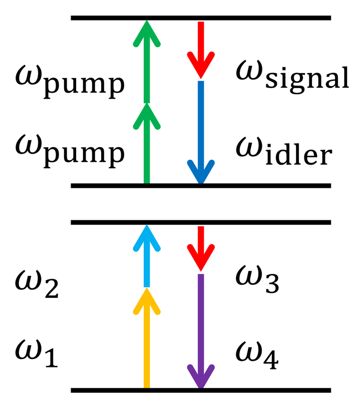
Abstract

We numerically studied the effect of the interaction between transverse modes on Kerr frequency comb generation. We expanded the Lugiato-Lefever mode to consider the effect of cross-phase modulation (XPM). We found that XPM can work for forming solitons in both modes, TE and TM modes. This means dual solitons can be achieved in one microcavity.

Background: Kerr frequency comb generation

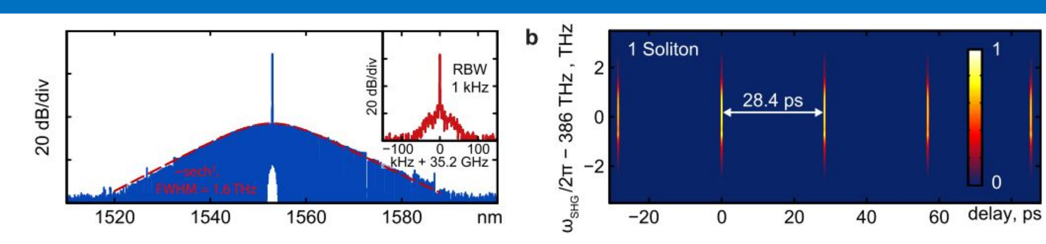


- High repetition rate (> 100 GHz)
- Small size (< 1 mm)
- Low power consumption



Temporal soliton generation

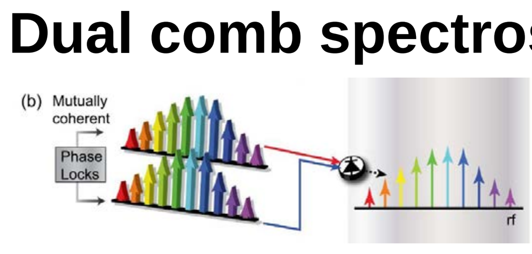
- Mode-locking mechanism is clear.
- Stabilization has been developed.



- Some material platforms (MgF_2, SiN, Silica…)
- Variable generation band (telecom, Mid-IR, Vis)

T. Herr, *et al.*, Nat. Photon. **8,** 145 (2014).
J. Jost, *et al.*, Optica **2,** 706 (2015).
J. Jost, *et al.*, Opt. Lett. **40,** 4723 (2015).

Dual comb spectroscopy



- Two comb source
- Coherent link is needed.

I. Coddington, *et al.*, Optica **3,** 414 (2016).

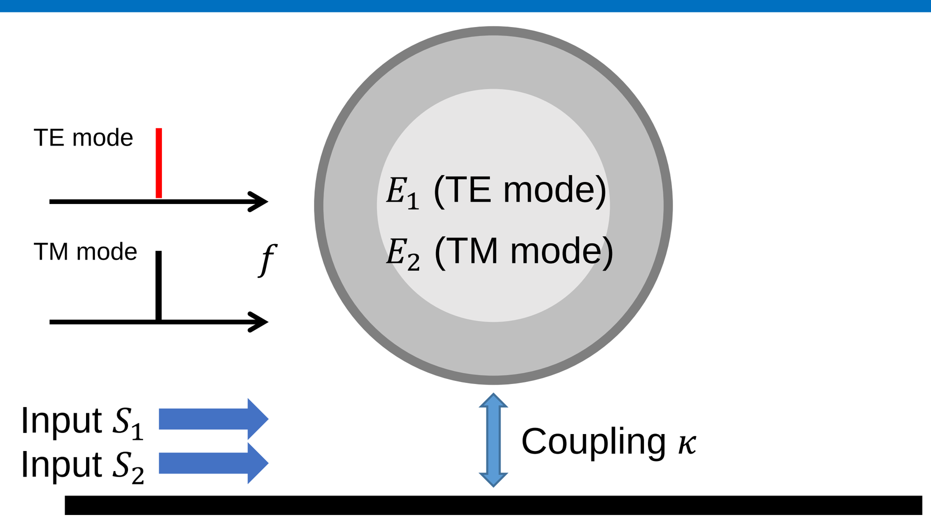
For dual comb light source…

- An μ-cavity supports some high-Q mode families.
- An μ-cavity requires comparatively low input power.

⇩

- Dual comb from dual input pumps could be achieved in one μ-cavity considering the interactions such as XPM.

Simulation Method: Transverse modes interaction



S : Input power
r: Round trip number
t_R: Round trip time
δ: Detuning
M: Mode number
κ: Coupling coefficient
β: Dispersion parameter
γ: Nonlinear parameter

$$t_R\frac{\partial E_{TE}}{\partial r}=\left(-\alpha_{TE}-i\delta_{TE}+iL\sum_{k\geq 2}\frac{\beta_{k\_TE}}{k!}\left(i\frac{\partial}{\partial T}\right)^k\right)E_{TE}+i\gamma_{TE}L(|E_{TE}|^2+PB|E_{TM}|^2)E_{TE}+\sqrt{\kappa_{TE}}S_{TE}$$

$$t_R\frac{\partial E_{TM}}{\partial r}=\left(-\alpha_{TM}-i\delta_{TM}+dLi\frac{\partial}{\partial T}+iL\sum_{k\geq 2}\frac{\beta_{k\_TM}}{k!}\left(i\frac{\partial}{\partial T}\right)^k\right)E_{TM}+i\gamma_{TM}L(|E_{TM}|^2+PB|E_{TE}|^2)E_{TM}+\sqrt{\kappa_{TM}}S_{TM}$$

・Calculate them alternatively with split-step Fourier method

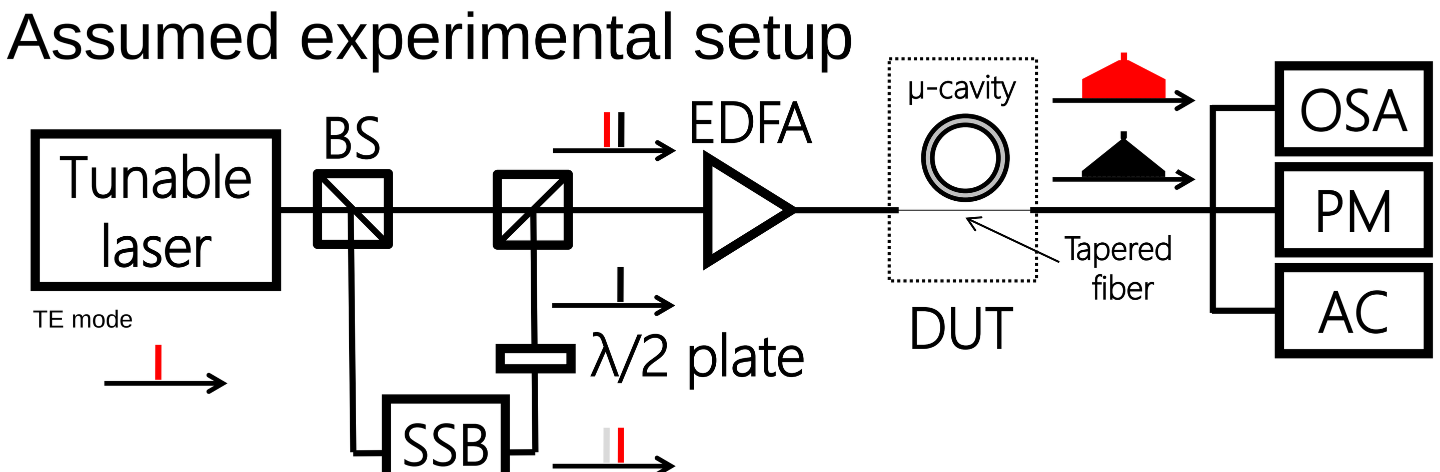
To be simple,
1. Mode overlapping is perfect. (B=1)
2. Group velocity mismatch is negligible. (d=0)
2. Each input is coherent. Detuning & cavity length are same.
3. Linear coupling is negligible (only XPM is the interaction)

<u>Mode interaction(XPM) coefficient ***P***</u>
- same polarization ***P=2***
- orthogonal polarization ***P=2/3***

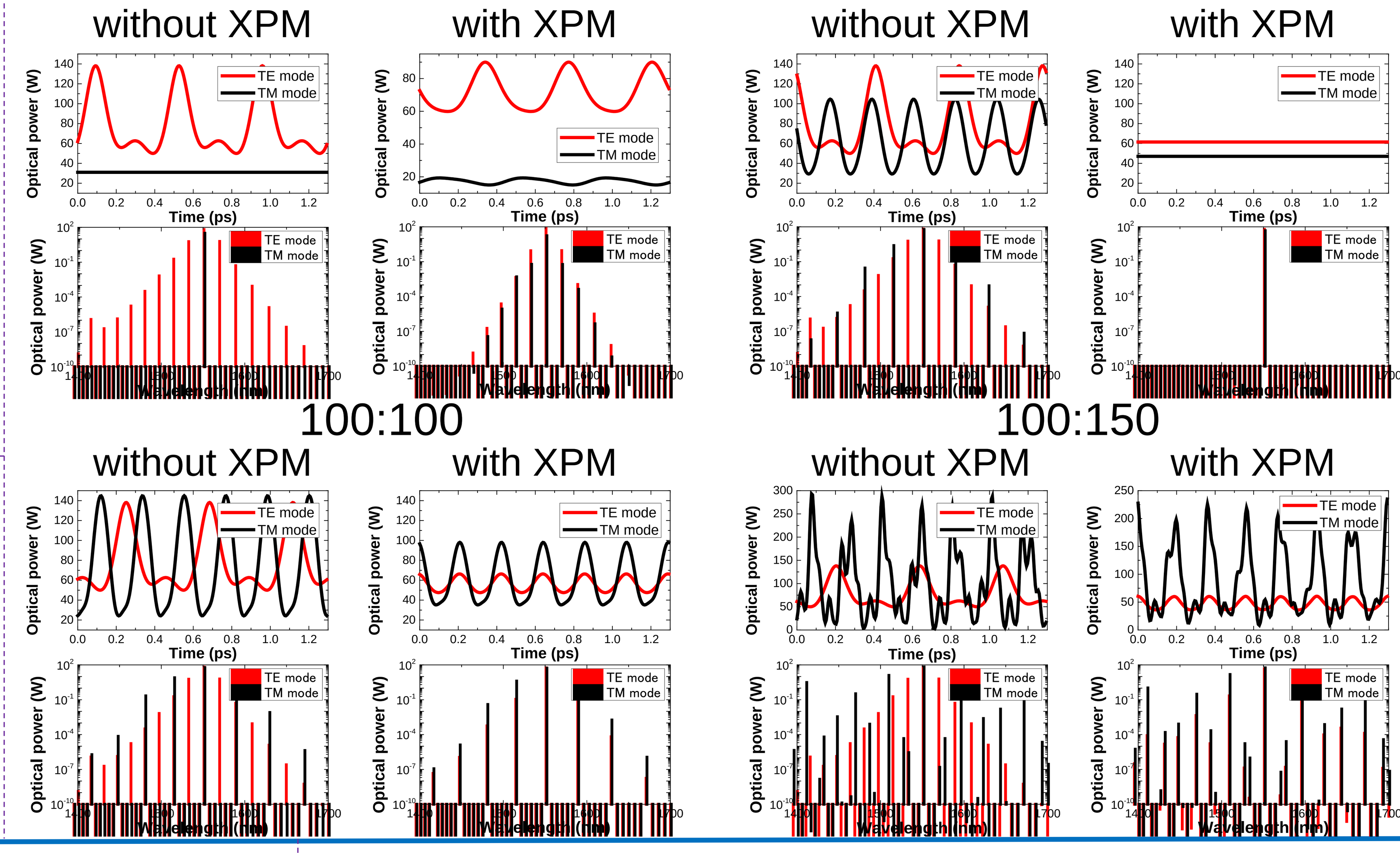
For example,
- 1st order TE × 1st order TM: ***P=2/3***
- 1st order TE × 2nd order TE: ***P=2***

Simulation Result

Assumed experimental setup



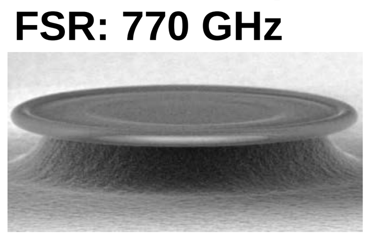
BS: Beam splitter
SSB: single side-band modulator
EDFA: Erbium-doped fiber amplifier
OSA: optical spectrum analyzer
PM: power meter
AC: auto-correlator

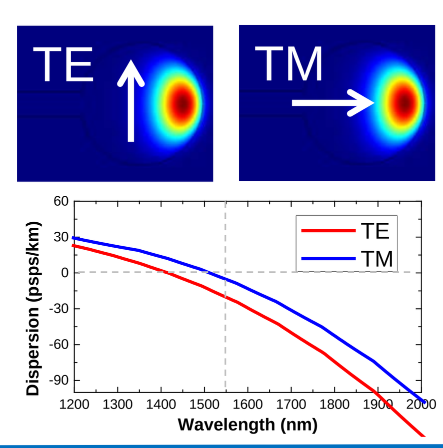


Calculation parameters

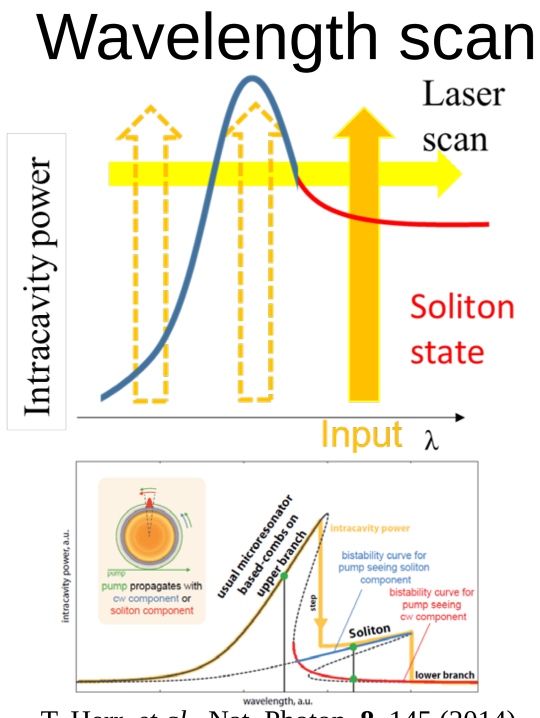
Q_{TE}	4.0*10^6
Q_{TM}	4.0*10^6
A_{eff-TE}	4.63 μm^2
A_{eff-TM}	4.96 μm^2
n_2	$2.2*10^{-10}$ 1/Wm

Silica toroid
Diameter: 60 μm
FSR: 770 GHz





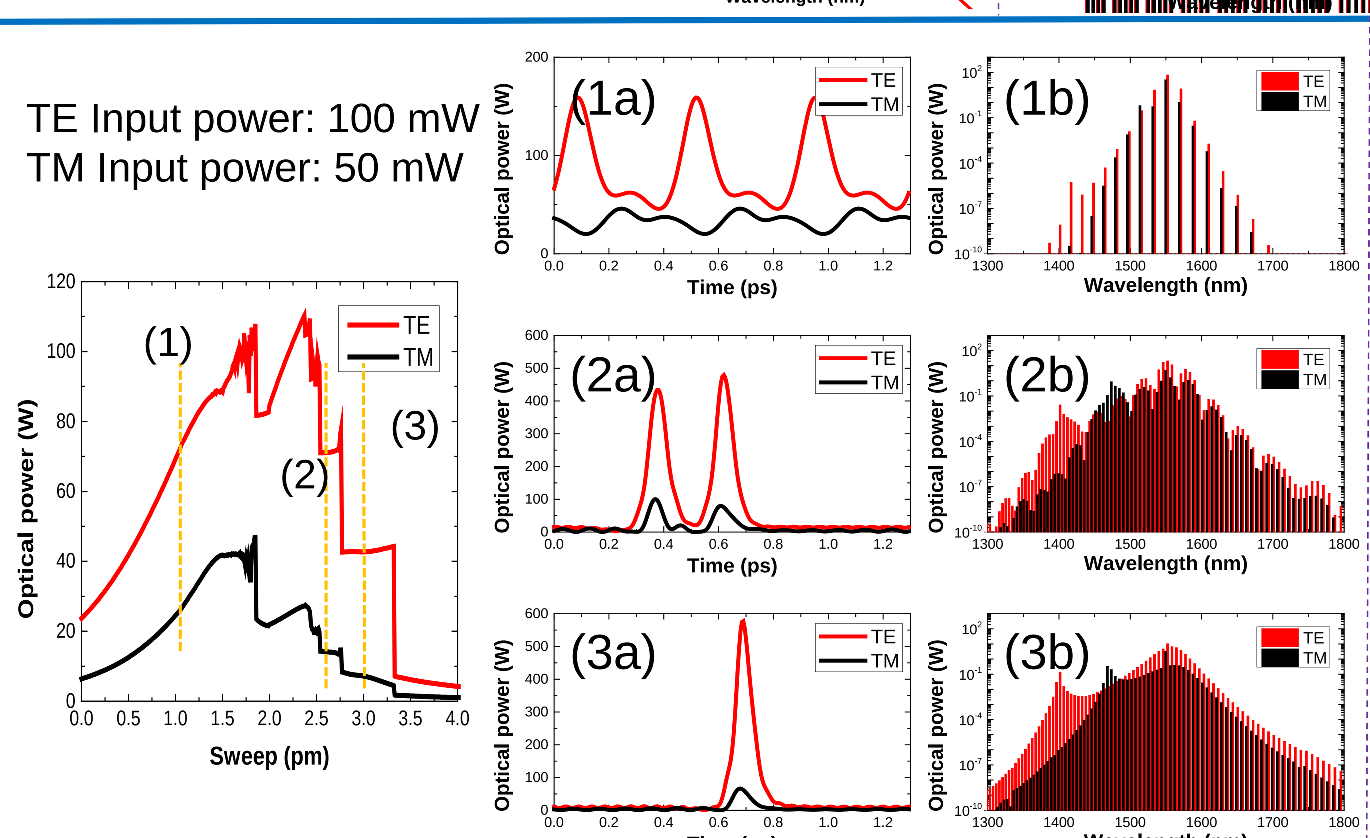
Wavelength scan



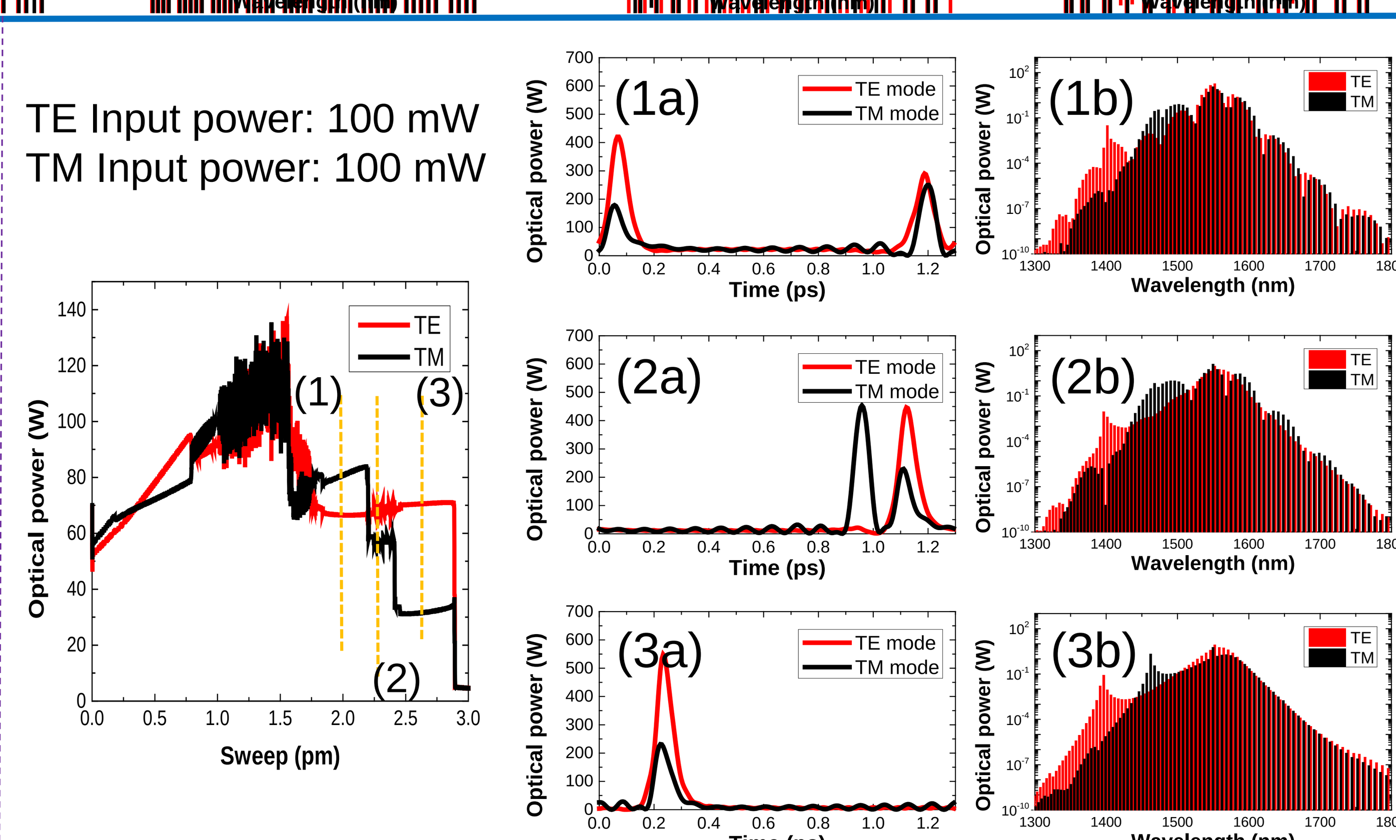
T. Herr, *et al.*, Nat. Photon. **8,** 145 (2014).

Laser scanning is required to reach the soliton state.

TE Input power: 100 mW
TM Input power: 50 mW



TE Input power: 100 mW
TM Input power: 100 mW



Conclusion

- ✓ Modelled the XPM effect with the SSFM calculation.
- ✓ Twin mode-locked pulses can be achieved with wavelength scanning method.
- ✓ Twin mode-locked pulses move forward at the same speed due to XPM effect that works like soliton trapping.

Acknowledgement

・Ministry of Education, Culture, Sports, Science and Technology (MEXT) (KAKEN 15H05429)
・Keio Program for Leading Graduate School "Science for Development of Super Mature Society"