Passively Synchronized Two-Color Mode-Locked Fiber Lasers

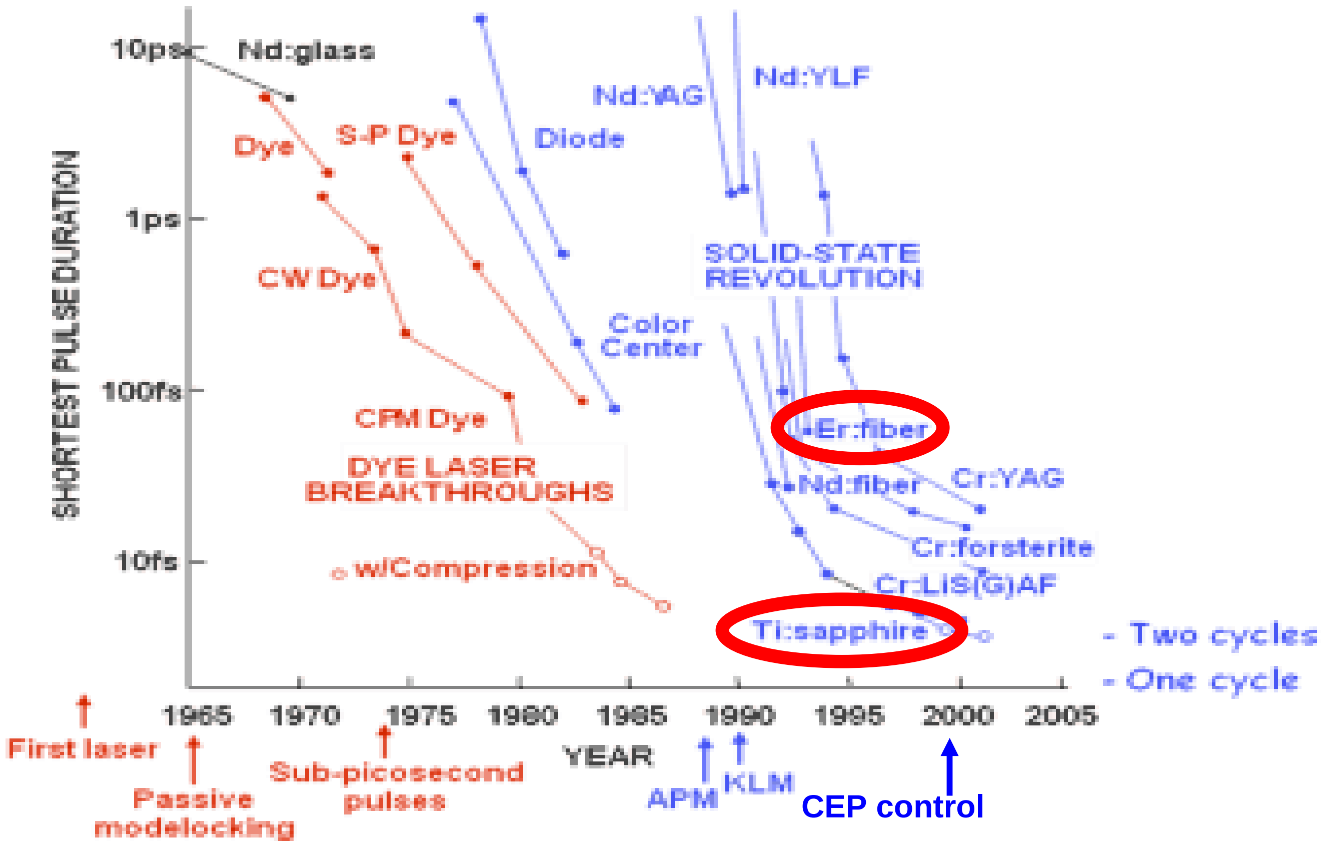
Wei-Wei Hsiang

Department of Physics, Fu Jen Catholic University

Outline

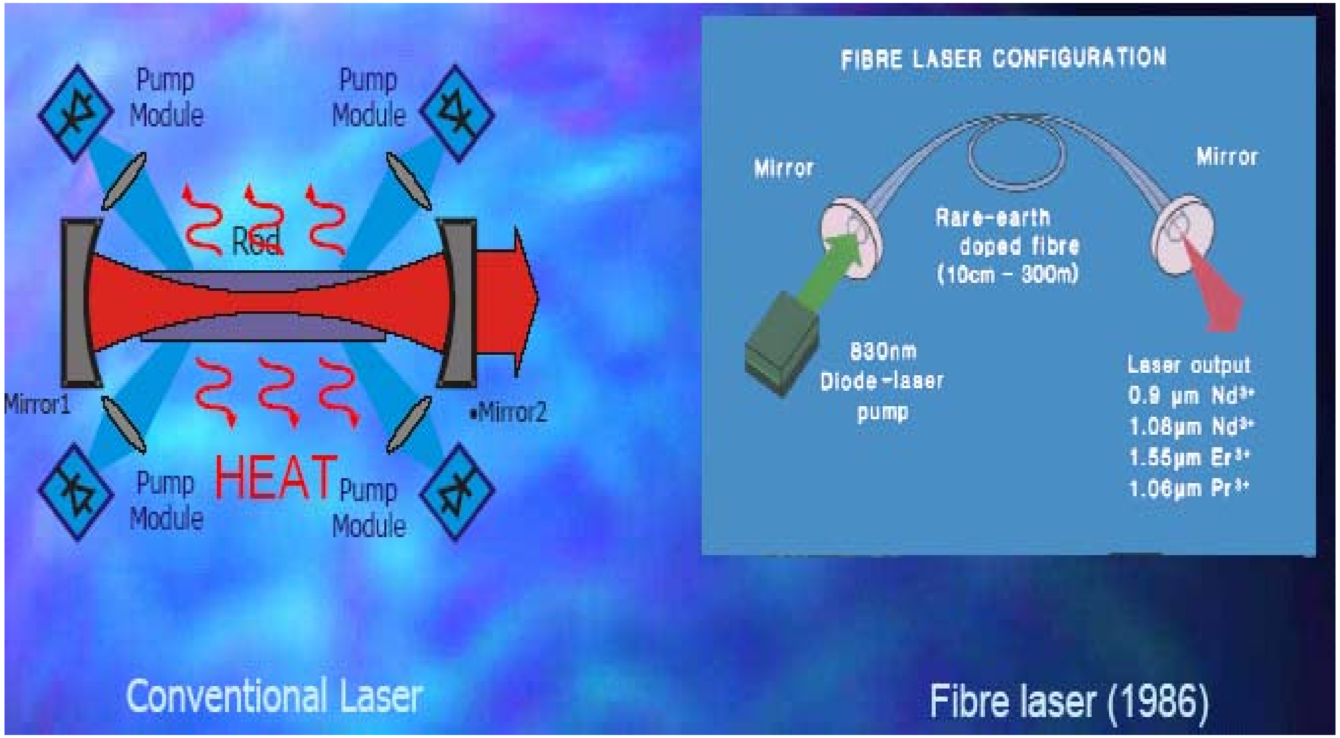
- Introduction
- Experimental setup
- Mechanism of the passive synchronization
- Synchronized multiple-pulse bound states
- Simultaneous CEO frequency measurement
- Summary

Progress in short pulse generation



Ref: http://www.rle.mit.edu/oqe/research_ultrashortpulse.htm

Fiber lasers versus solid-state lasers



Cavity: mirrors, free space
Gain medium: crystals (cooling**)**

Cavity: optical fibers, fiber Bragg grating, ring cavity
Gain medium: rare-earth-doped fibers

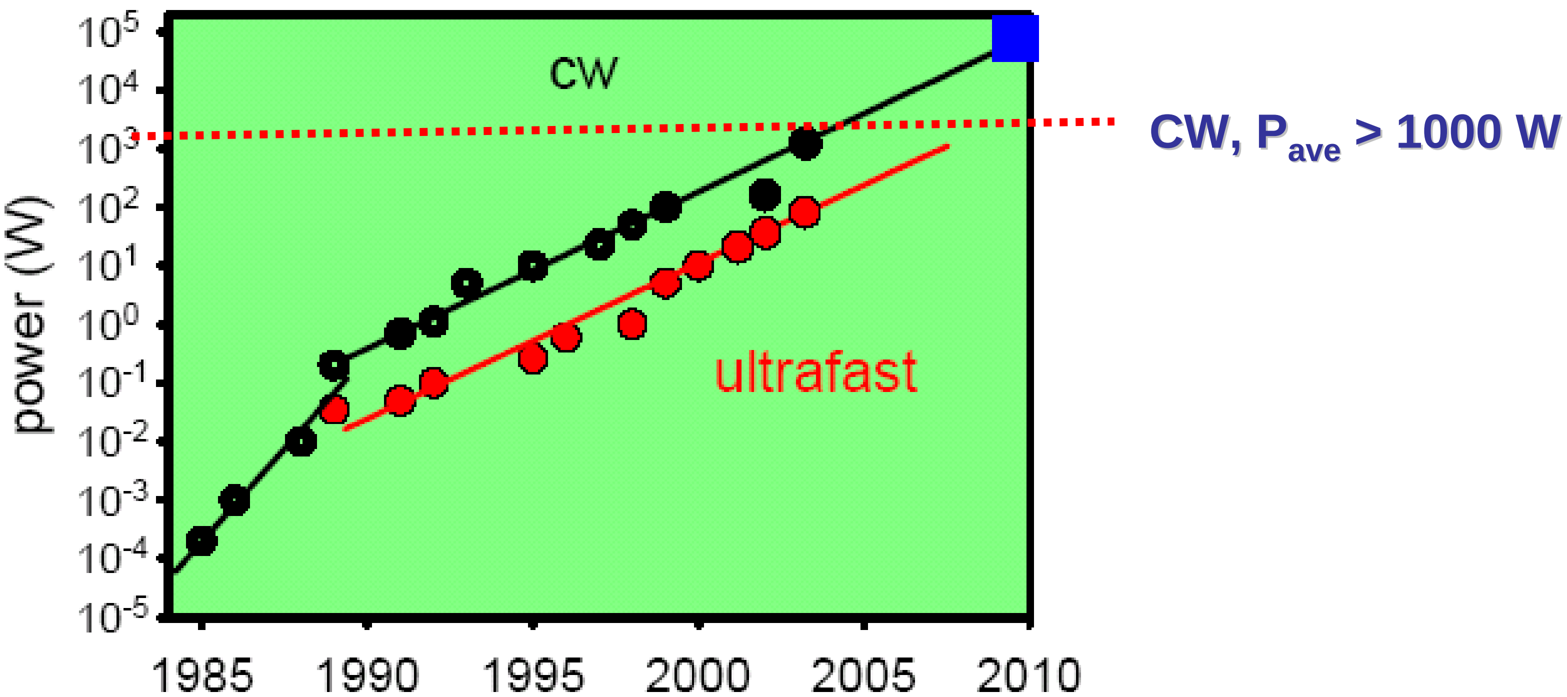
Ref: D. Payne

Development of fiber laser power

Key Components:

- Pump laser diodes (cheaper now)
- Large-mode-area (LMA) double cladding (DC) Yb-doped fibers
- Special fiber devices: power/signal combiner, FBG, end cap,…

All-fiber→ turnkey and maintenance free



Mode-locked ultrashort lasers and applications

Mode-Locked Lasers

Time domain
- Ultrashort pulse duration
- High peak intensity

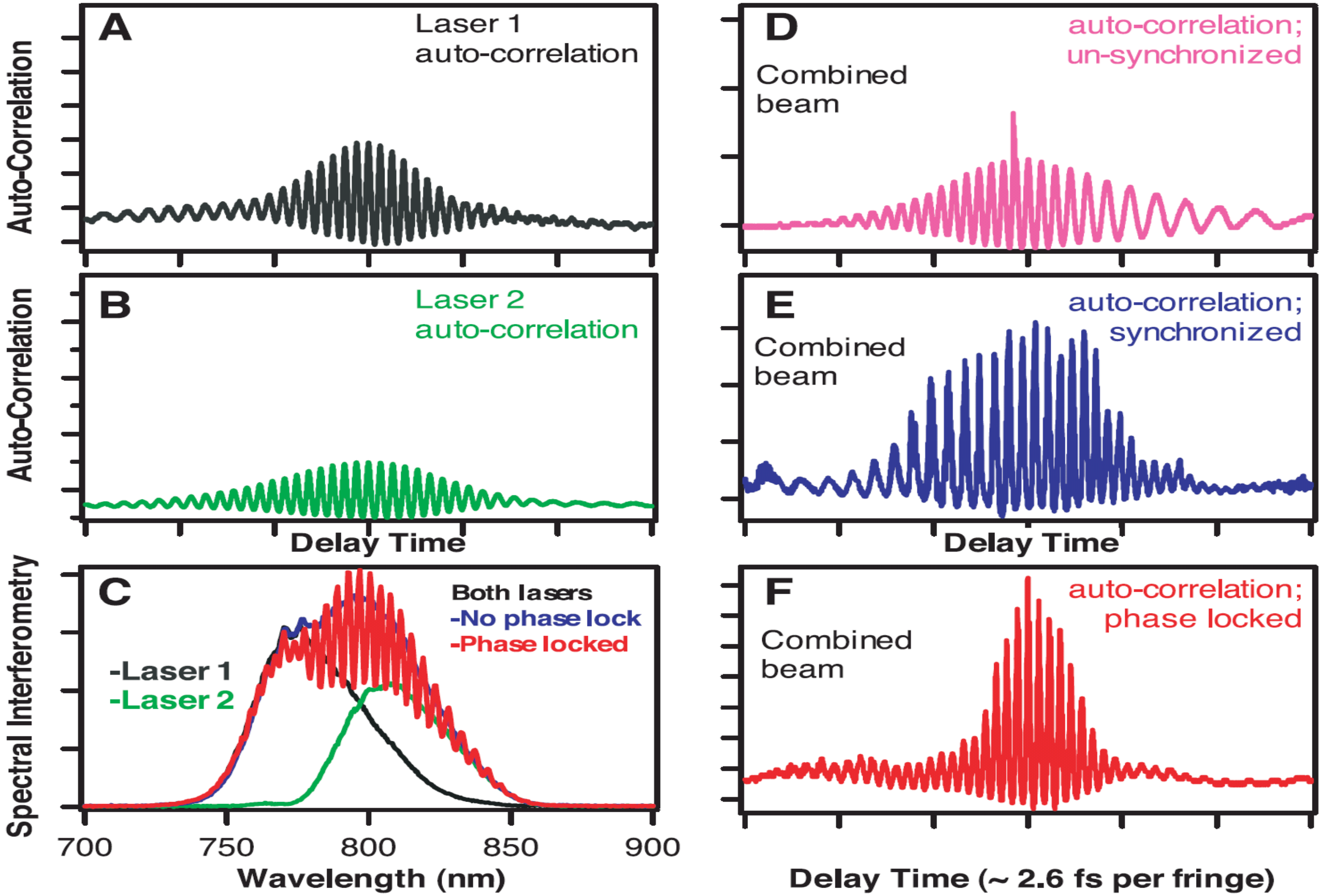
Frequency domain
- Broad spectrum
- Even-spaced frequency combs

Science
- Time-resolved experiment
- High-filed physics
- Extreme nonlinear optics

Science
- Optical frequency metrology/synthesis
- Optical clocks
- Frequency comb spectroscopy

Technology and industry
- *Laser micromachining*
- Optical coherence tomography
- Multiphoton microscopy
- High-speed communication and testing

Motivation

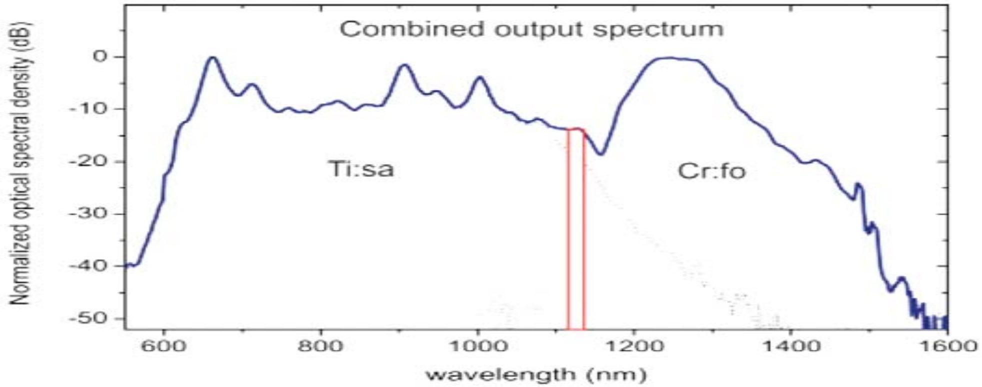


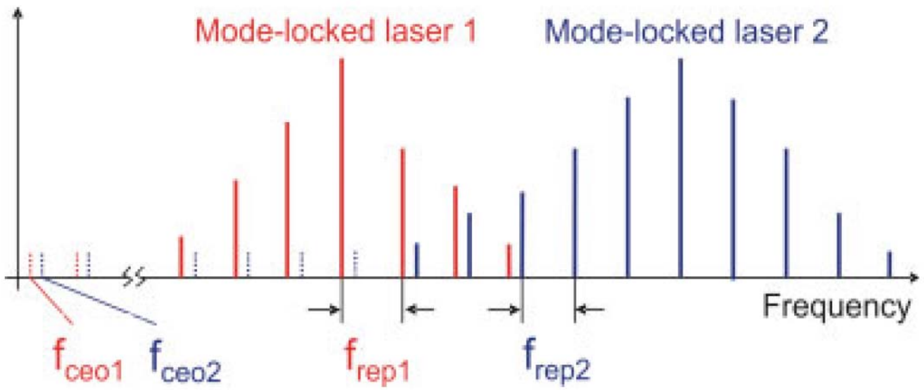
Ref: Science, **293**, 1286 (2001).

Coherent ultrashort pulse synthesis

Requirements:

- Pulse timing synchronization
- Optical phase locking (stringent requirements on carrier-envelope phase coherence)





Ref: Laser & Photon. Rev., 1–25 (2009)

Pulse timing synchronization

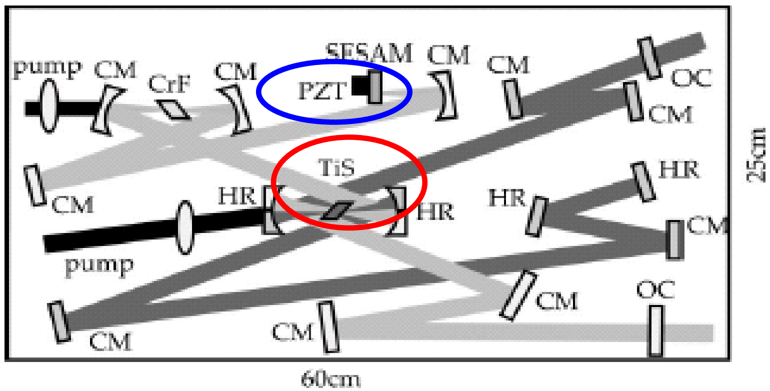
Round time $T_R = L_c / v_g$

- Passive synchronization: cross phase modulation, sub-fs timing jitter
- Active synchronization: electronic feedback control, sub-fs timing jitter
- Hybrid synchronization: combines (1) and (2), sub-fs timing jitter

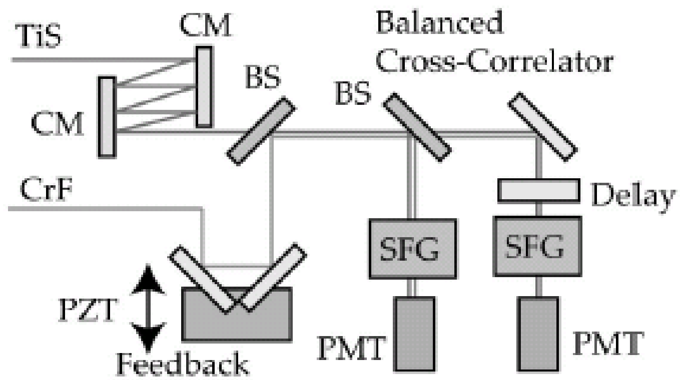
1408 OPTICS LETTERS / Vol. 30, No. 11 / June 1, 2005

100-attosecond timing jitter between two-color mode-locked lasers by active–passive hybrid synchronization

Dai Yoshitomi, Yohei Kobayashi, Hideyuki Takada, Masayuki Kakehata, and Kenji Torizuka
National Institute of Advanced Industrial Science and Technology, 1-1-1 Umezono, Tsukuba 305-8568, Japan



(a)

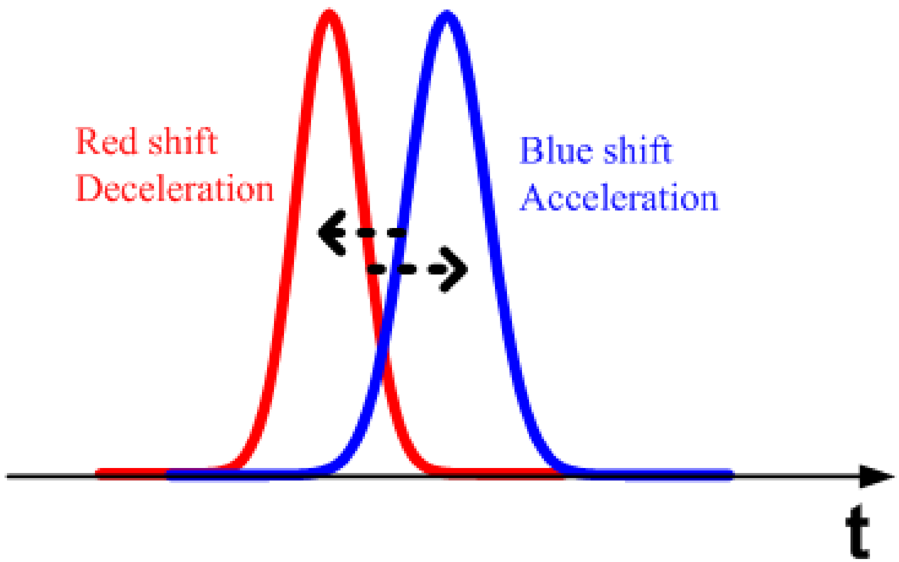


Passive synchronization

- Third-order nonlinearity: cross-phase modulation (XPM)
- Advantages: simplicity, fast response time

In the medium with ***anomalous*** **GVD**

1. The pulse in the front sees the leading edge of the other pulse, and vice versa.
2. Red shift leads to deceleration, and vice versa.



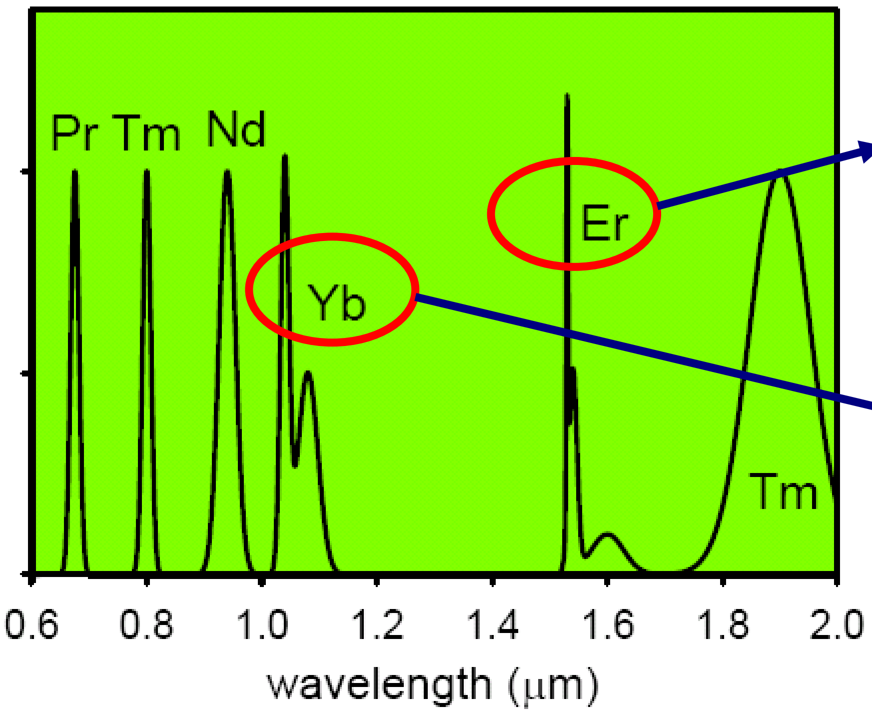
$$P_{NL} = \varepsilon_0 \chi^{(3)} : EEE$$

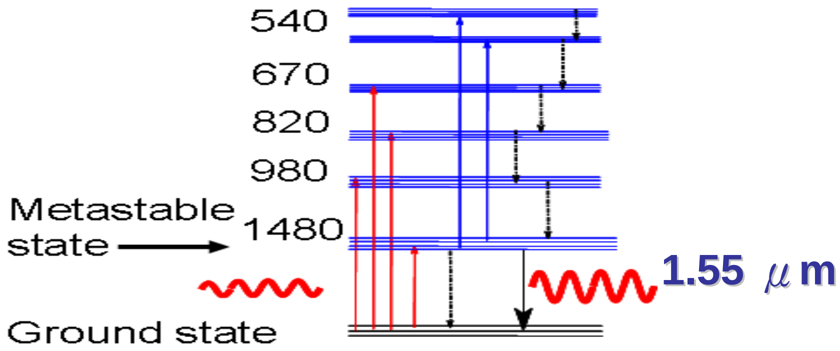
$$n_1 = n_0 + n_2 (I_1 + 2I_2)$$

$$\delta\phi_{XPM} = -2n_2 k I_2 d$$

$$\delta\omega_{XPM} = -2n_2 k d \frac{dI_2}{dt}$$

Rare-earth-doped fibers





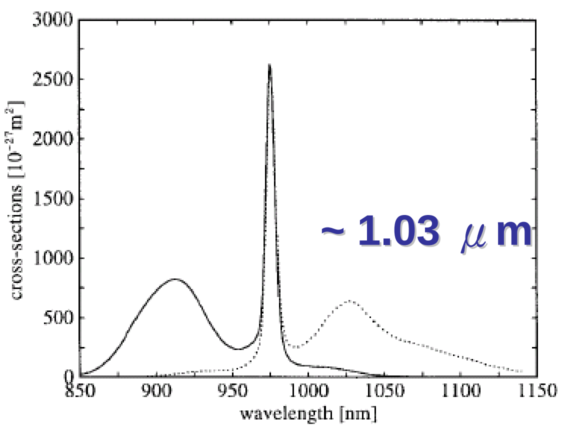


Fig. 1. Absorption (solid) and emission (dotted) cross sections of Yb in germanosilicate glass.

Ref: IMRA

Two cavity GVDs with opposite signs

- For two cavity GVDs with opposite signs, can passive synchronization achieve between them?
- If they can, what is the underlying mechanism?

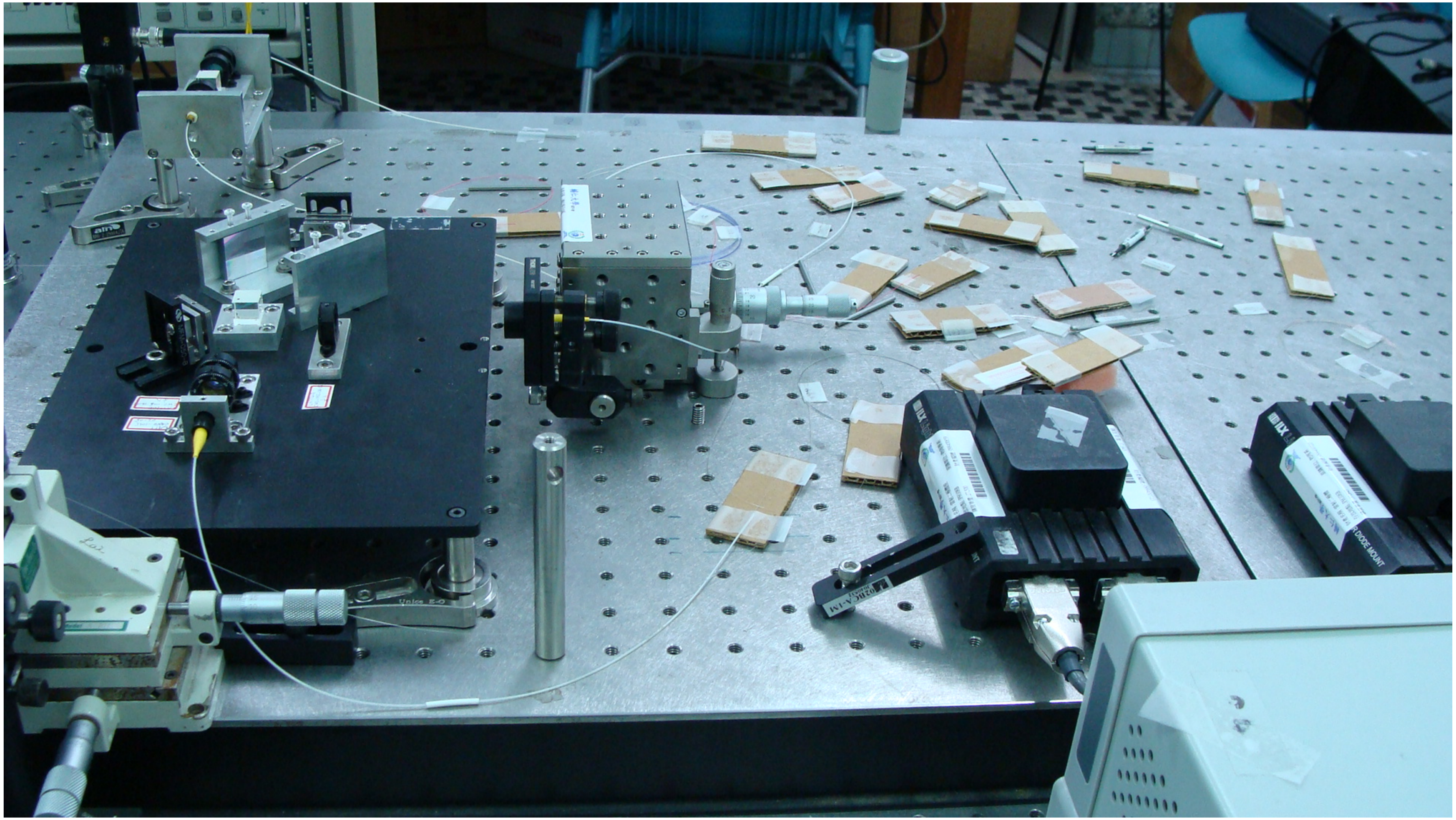
Examples:

--1035 nm self-similar or all-normal dispersion Yb-fiber laser

(normal cavity GVDs)

--1560 nm Er-fiber laser **(anomalous cavity GVDs)**

Experimental setup



Ref: W.-W. Hsiang, C.-H. Chang, C.-P. Cheng, and Y. Lai, Opt. Lett. **34**, 1967-1969 (2009).

P-APM mode-locked fiber laser

P-APM: Polarization additive-pulse mode-locking

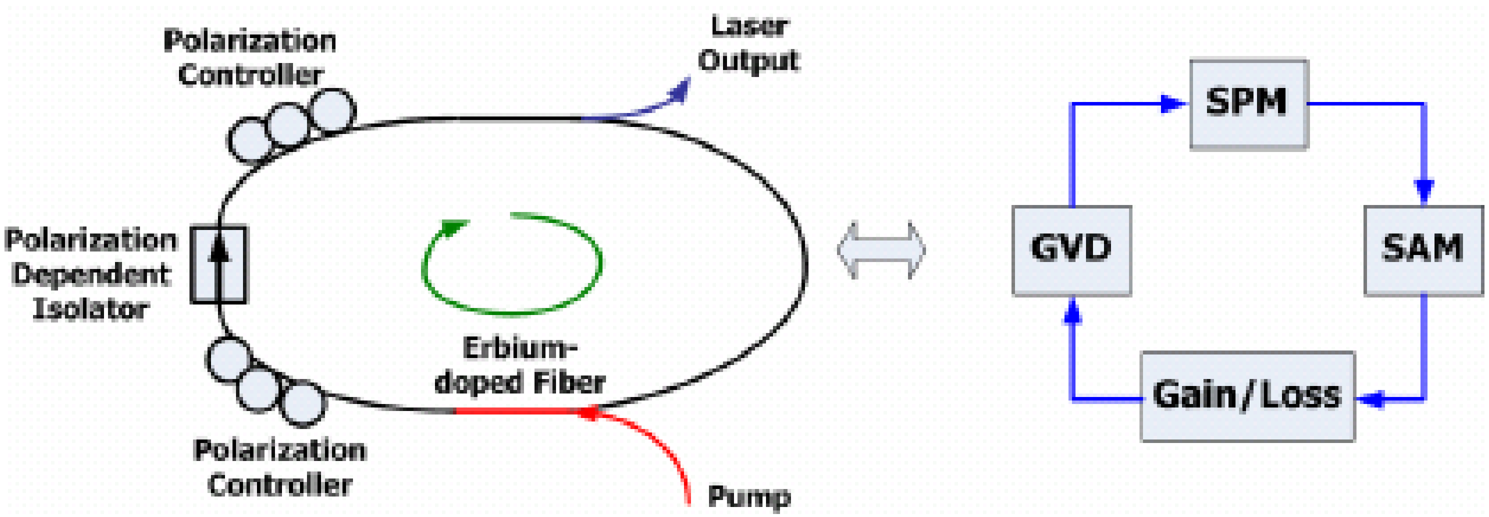


Fig. 2-1 Left: schematic diagram of the P-APM fiber laser. Right: equivalent ring cavity of the P-APM fiber laser.

Passive mode-locking

Fast saturable absorber

- semiconductor saturable absorber mirror
- Kerr–lens mode-locking (KLM)
- **Polarization additive mode-locking (P-APM)**

Fast saturable absorber:

$$s(t) = \frac{s_0}{1 + I(t)/I_{sat}}$$

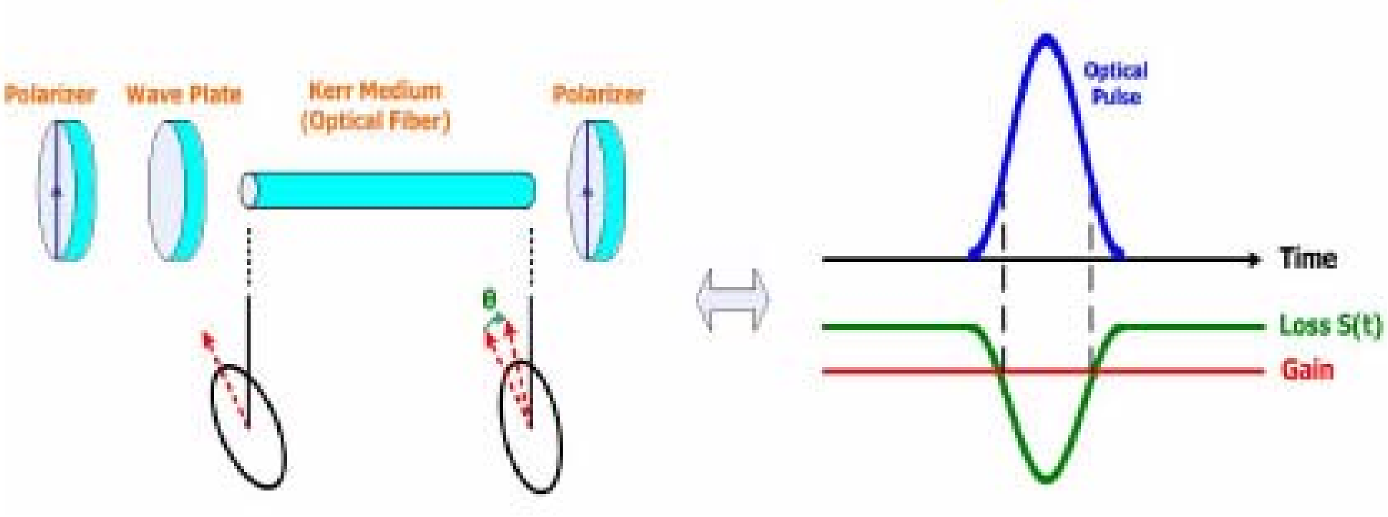
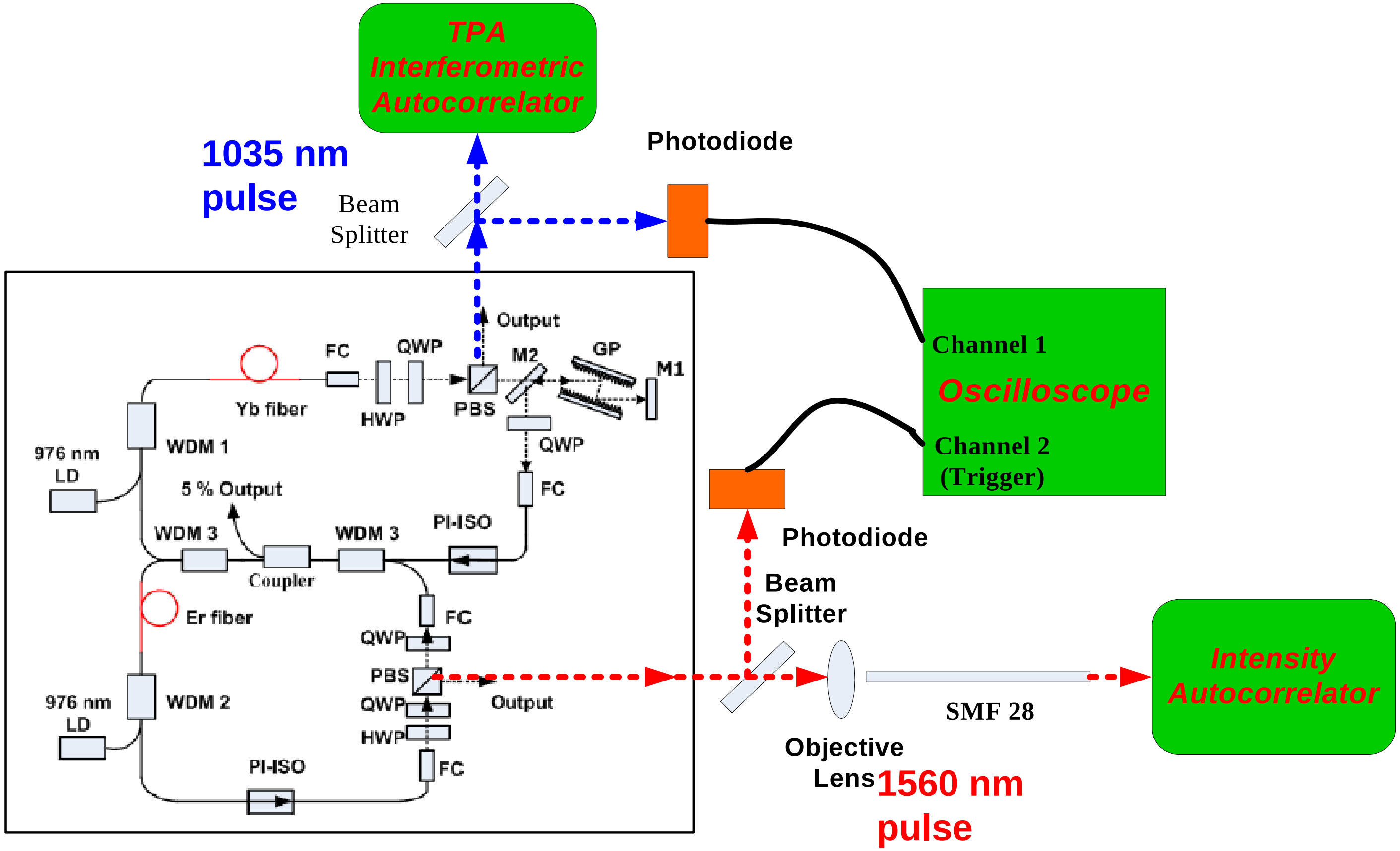


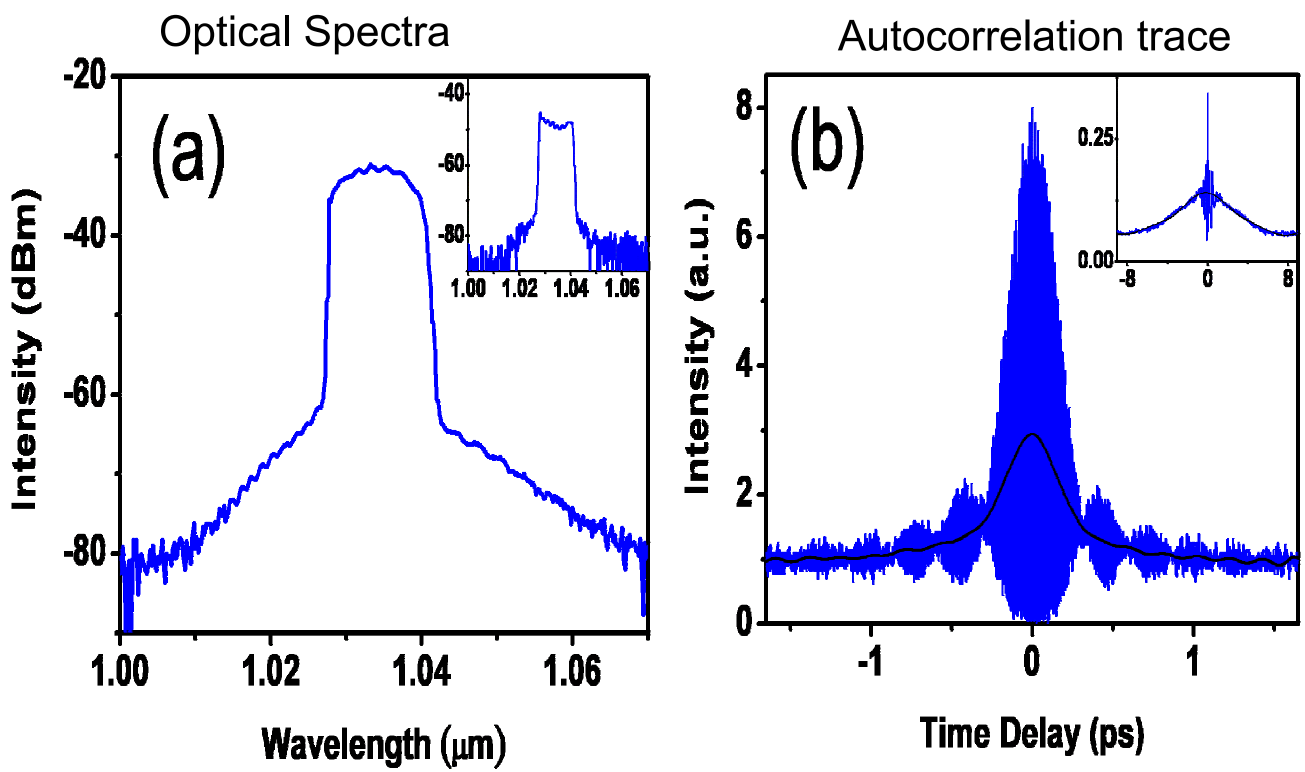
Fig. 2-2 Left: illustration of nonlinear rotation of elliptical polarization of P-APM. Right: the effect of saturable absorber achieved by P-APM.

Measurement of synchronized two-color pulse trains



- *Oscilloscope*: with the same trigger source
- *Frequency counter:* double-checking of rep. rate locking
- *Pulse width of 1560 nm pulses:* ~0.7ps, close to those measured at the center of the shared cavity
- *Pulse width of 1035 nm pulses:* several ps at the center of the shared cavity

Optical characteristics of self-similar Yb-fiber laser

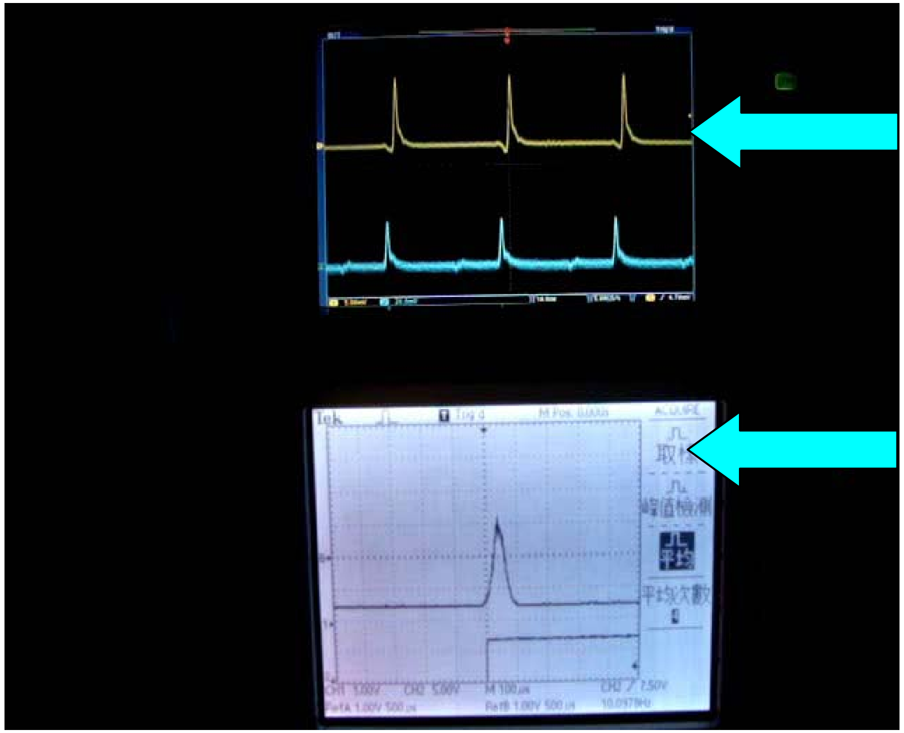


(a) Optical spectra: with a parabolic top and steep edges

(b) The original chirped (inset) and dechirped pulses from the rejection port of the PBS :

➔ the amount of anomalous GVD for dechirping: 0.186 ps^2 > 0.073 ps^2 of the intracavity grating pair

Synchronization : 1(Yb)+1(Er) pulses



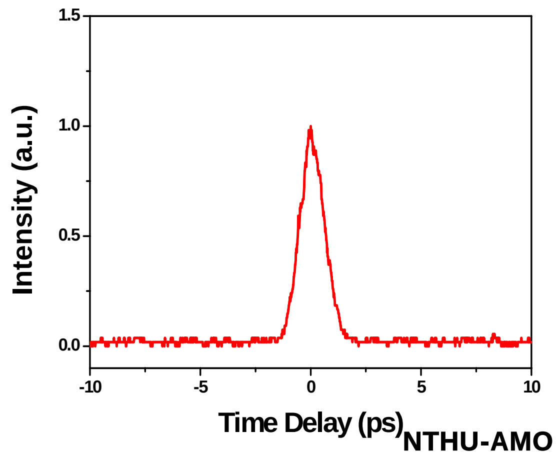
Oscilloscope traces:

Yellow: Yb-fiber laser

Blue: Er-fiber laser

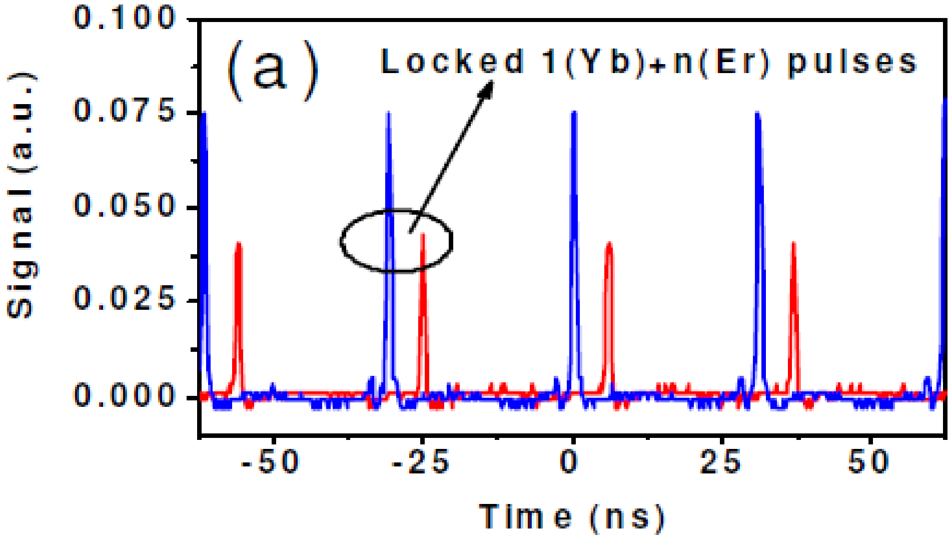
Autocorrelation trace:

Er-fiber laser



- Er-fiber laser: pump power of 70 mW
- Yb-fiber laser: pump power of 210 mW
- Low pumping power: single pulse in the fiber laser

Synchronization: 1(Yb)+n(Er) pulses



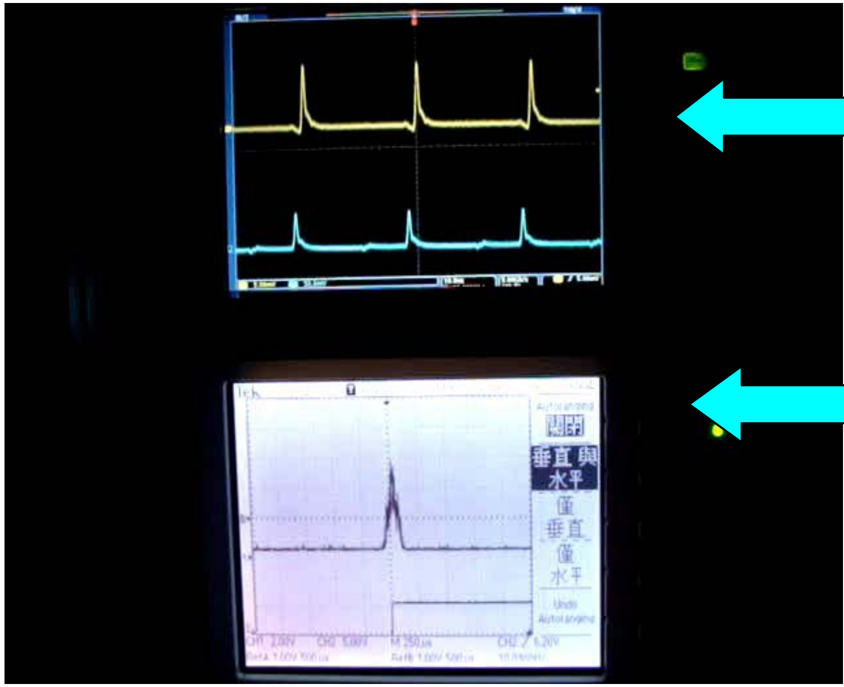
Blue curve: 1035 nm

Red curve: 1560 nm

Oscilloscope traces of the locked 1(Yb)+n(Er) pulses under passive synchronization

1. Yb-fiber laser: one single pulse circulating in the cavity with the fixed pump power of 210 mW
2. Er-fiber laser: n-pulse bound state, n=2 or 3 with the pump power > 100 mW

Time-separation narrowing: 1560 nm 2-pulse bound state



Oscilloscope traces:

Yellow: Yb-fiber laser

Blue: Er-fiber laser

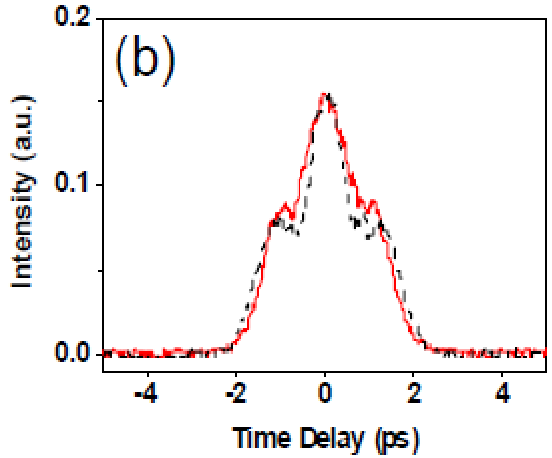
Autocorrelation trace:

Er-fiber laser

Time-separation narrowing

Red: under synchronization

Black: without synchronization



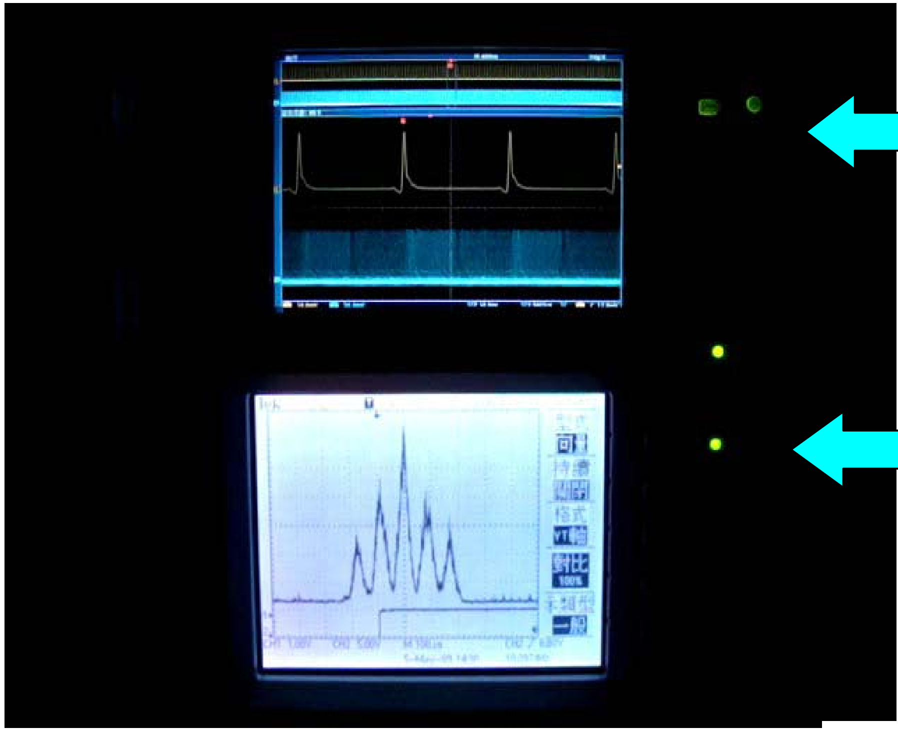
- Er-fiber laser: pump power of 105 mW:

  ➔ **2-pulse bound state**

- Yb-fiber laser: pump power of 210 mW:

  ➔ **single pulse**

Time-separation narrowing: 1560 nm 3-pulse bound state



Oscilloscope traces:

Yellow: Yb-fiber laser

Blue: Er-fiber laser

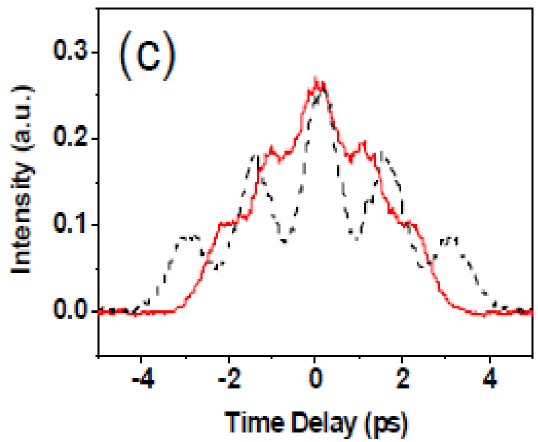
Autocorrelation trace:

Er-fiber laser

Time-separation narrowing

Red: under synchronization

Black: without synchronization



- Er-fiber laser: pump power of 145 mW:

  → **3-pulse bound state**

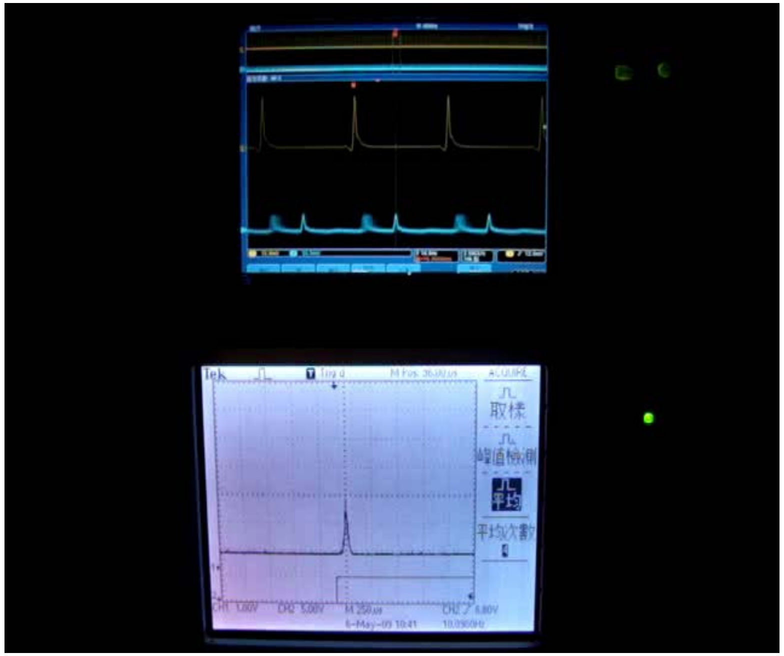
- Yb-fiber laser: pump power of 210 mW:

  → **single pulse**

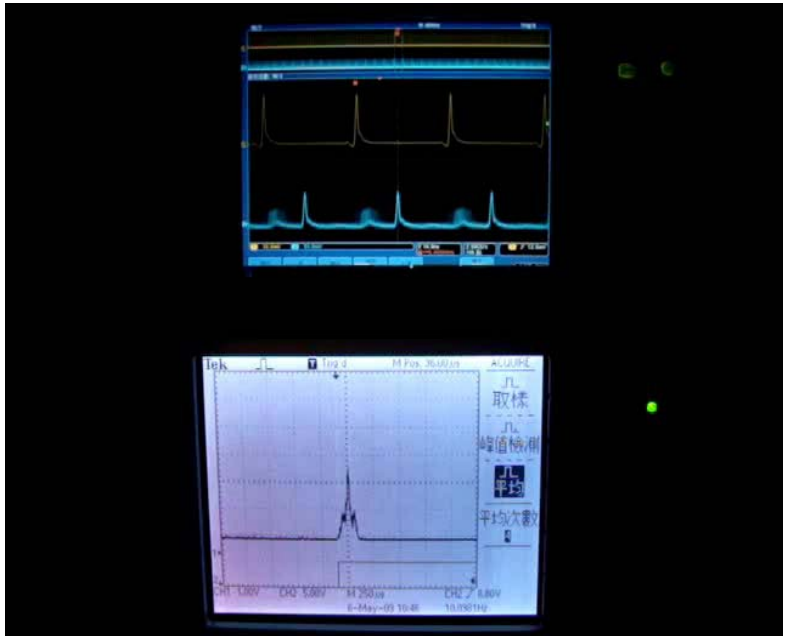
Periodic pulse collision

Oscilloscope traces :

Yellow: Yb-fiber laser Blue: Er-fiber laser



Locked 1(Er)+1(Yb) pulse are collided by a separate (Er) moving pulse.



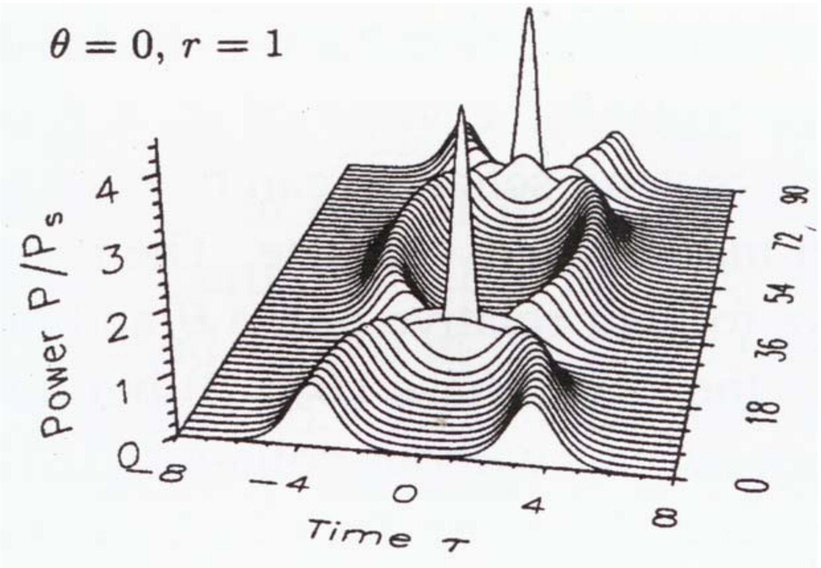
Locked 1(Er)+2(Yb) pulse are collided by a separate (Er) moving pulse.

Pulse collision: passing through or exchange ?

Conservative system: in-phase two identical solitons collision

$$i\frac{\partial\varphi}{\partial z}=-\frac{1}{2}\frac{\partial^2\varphi}{\partial t^2}-|\varphi|^2\varphi$$

$$\varphi(z=0,t)=\mathrm{sech}(t-d)+\mathrm{sech}(t+d)$$



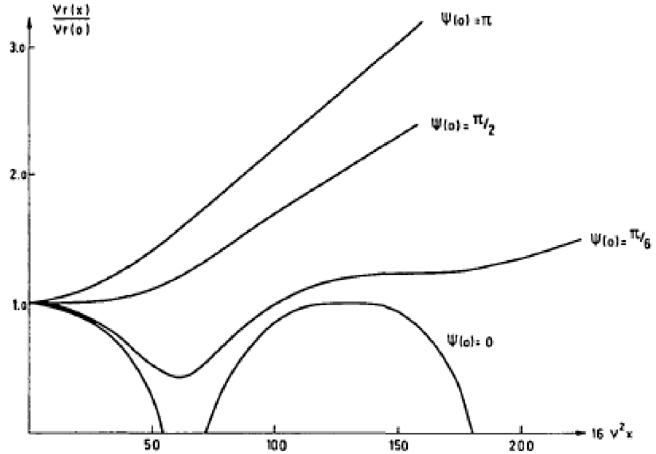


Fig. 1. Normalized distance between solitons for different initial phases $\psi(0) = 0, \pi/6, \pi/2$, and for $\nu r(0) = 3$.

Ref: G. P. Agrawal, “Nonlinear fiber optics”

Pulse collision: passing through or exchange ?

Dissipative system: mode-locked fiber lasers

$$\frac{\partial \varphi}{\partial z} = (g-l)\varphi + (d_r + id_i)\frac{\partial^2 \varphi}{\partial t^2} + (k_r + ik_i)|\varphi|^2 \varphi + (h_r + ih_i)|\varphi|^4 \varphi$$

Gain and loss — Gain dispersion and GVD — SAM and SPM — Saturation of SAM and SPM

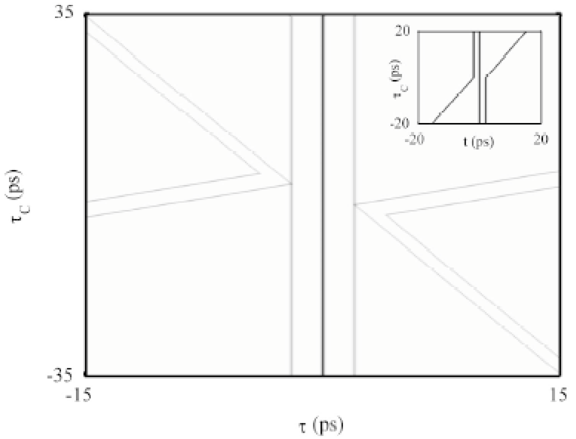


FIG. 3. Reconstruction of the measurement illustrated in Fig. 2 assuming the elastic collision dynamics illustrated in the inset (as seen in the reference frame moving with the central pulse).

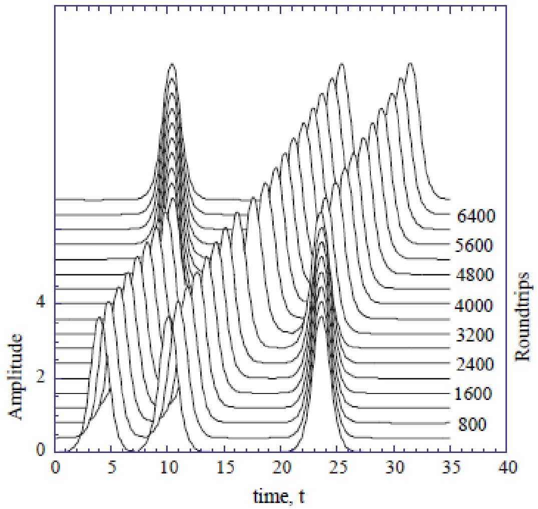


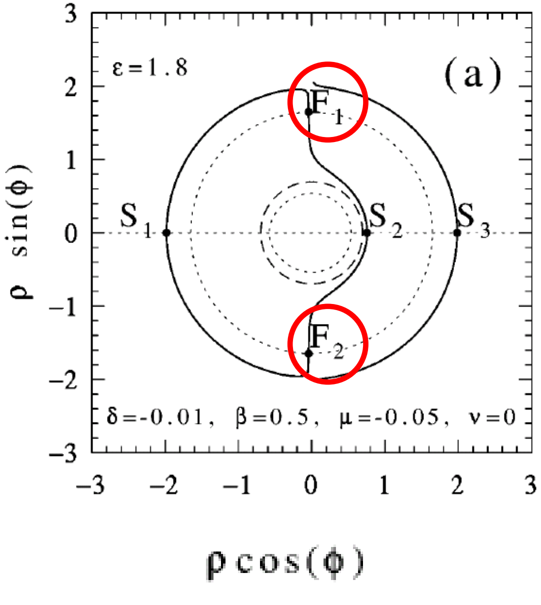
Fig. 7. "Elastic" collision of a pair of coupled dissipative solitons with a soliton singlet.

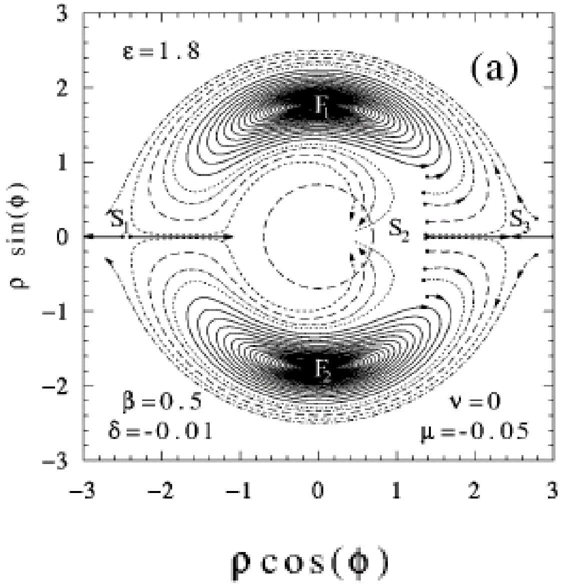
Ref [1]: V. Roy et al., Phys. Rev. Lett. **94**, 203903 (2005).
Ref [2]: P. Grelu et al., Opt. Express **12**, 3184 (2004).

Multisoliton Solutions of the Complex Ginzburg-Landau Equation

$$i\psi_\xi + \left(\frac{D}{2} - i\beta\right)\psi_{\tau\tau} + (1 - i\epsilon)|\psi|^2\psi + (\nu - i\mu)|\psi|^4\psi = i\delta\psi$$

$$\psi(\tau) = \psi_0(\tau - \rho/2) + \psi_0(\tau + \rho/2)\exp(i\phi)$$





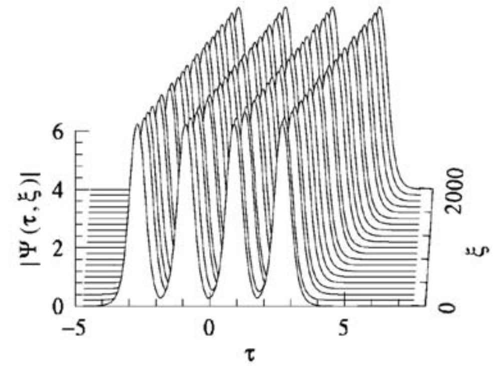


FIG. 4. Stable propagation of a four-soliton bound state. The equation parameters are the same as those in Fig. 3.

Ref: PRL **79**, 4047, 1997

Bound dissipative solitons with the external modulation

Complex Ginsburg-Landau equation with the external modulation

$$\frac{\partial \varphi}{\partial z} = (g-l)\varphi + (d_r + id_i)\frac{\partial^2 \varphi}{\partial t^2} + (k_r + ik_i)|\varphi|^2 \varphi + (h_r + ih_i)|\varphi|^4 \varphi + (a+ip)|\phi|^2 \varphi$$

external modulation

a: amplitude modulation from Yb-pulse

p: phase modulation from Yb-pulse

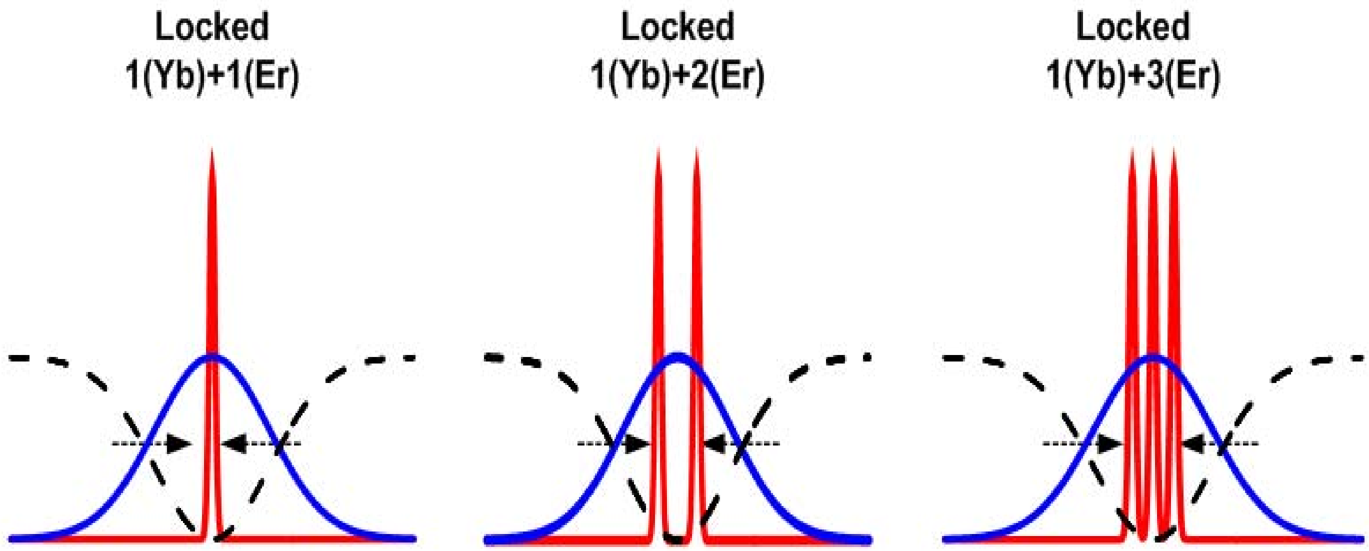
φ : Er-pulse envelope

ϕ : Yb-pulse envelope

Temporal walk-off effect?

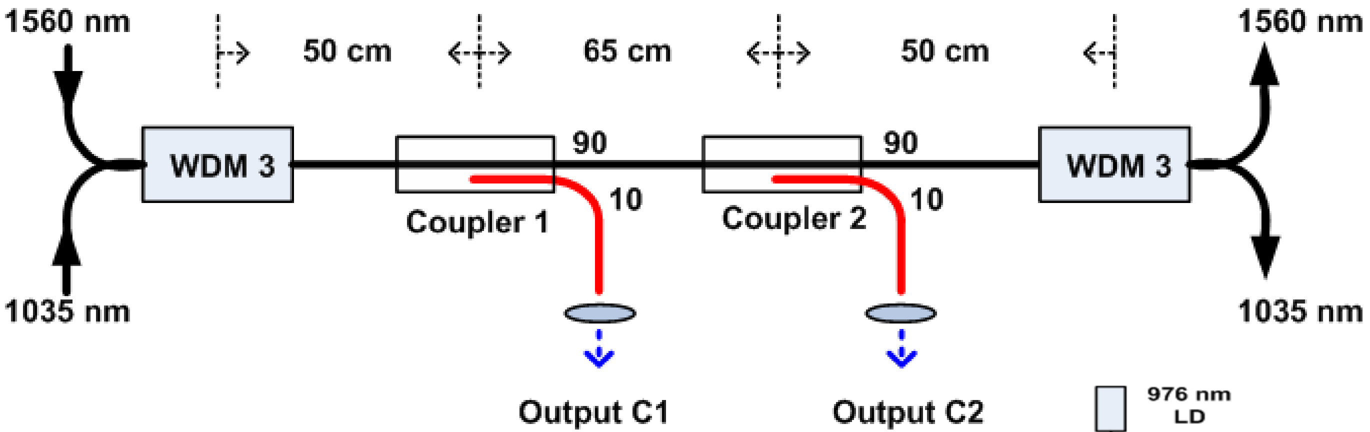
Mechanism of pulse-separation narrowing

- Are1560 nm multiple-pulse bound states trapped in the potential well ?
- What is the relative phase and relative position?
- Can the temporal wall-off be ignored?



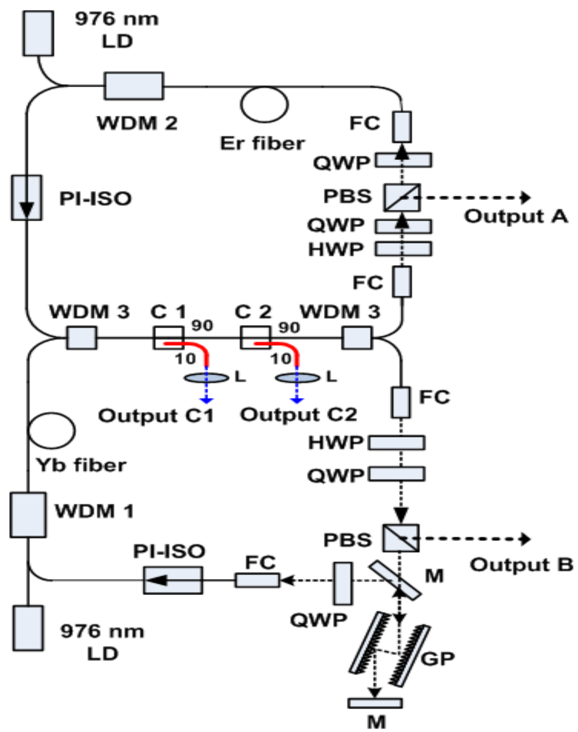
Blue curve: 1035 nm
Red curve: 1560 nm
Black curve: effective optical-induced potential well

Characterization of relative pulse position

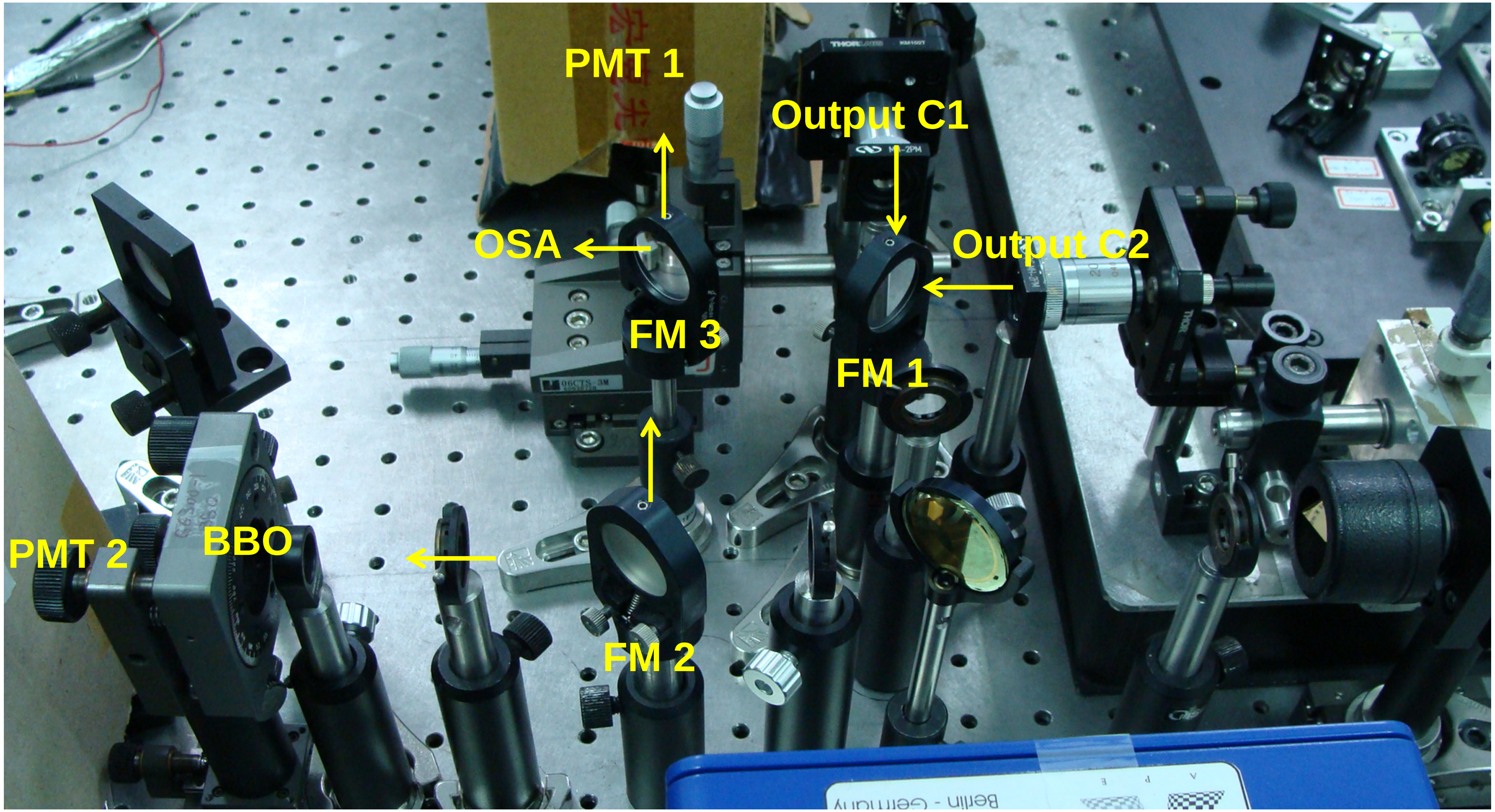


Measurements at output C1 and C2:

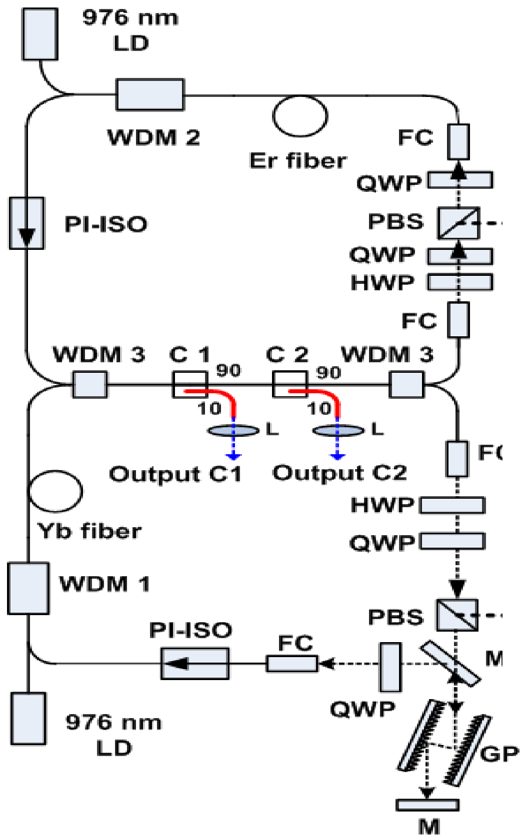
- 1 μm autocorrelator
- 1.5 μm autocorrelator
- Crosscorrelator
- Optical spectrum analyzer

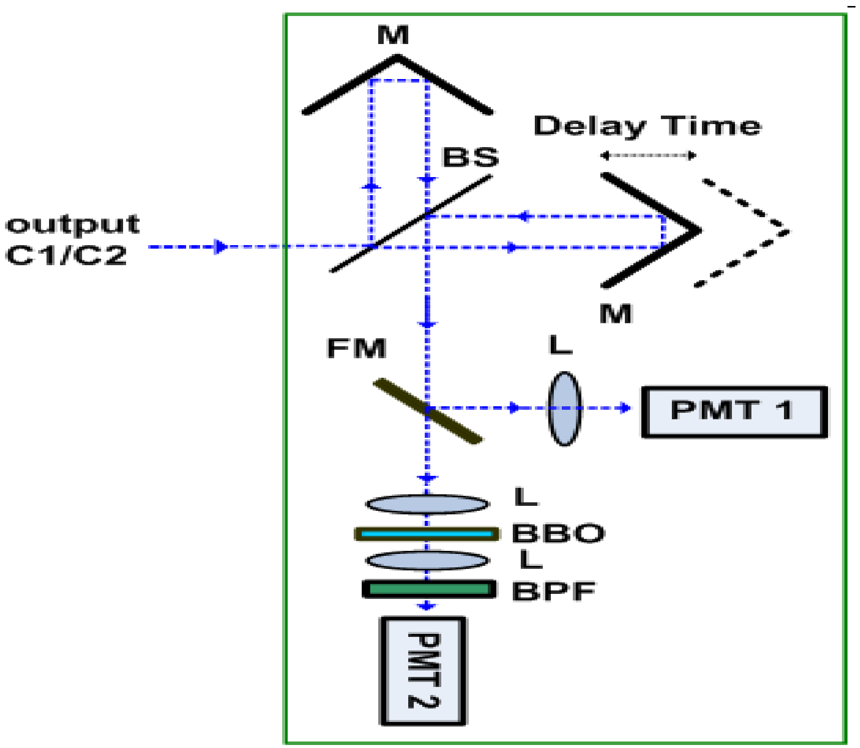


Characterization of relative pulse position



Crosscorrelator





- PMT 1: 1 μm autocorrelator
- PMT 2: crosscorrelator

Crosscorrelation trace

Incident fields on the BBO crystal:

$u_1(t)$ and $u_2(t)$: the complex envelopes of the 1.56 μm and 1.03 μm pulses respectively

$$u(t) = u_1(t)e^{-i\omega_1 t} + u_2(t)e^{-i\omega_2 t} + u_1(t+\tau)e^{-i\omega_1(t+\tau)} + u_2(t+\tau)e^{-i\omega_2(t+\tau)}$$

Sum-frequency generation in the BBO crystal:

$$SFG(t) \propto u_1(t)u_2(t)e^{-i(\omega_1+\omega_2)t} + u_1(t+\tau)u_2(t+\tau)e^{-i(\omega_1+\omega_2)(t+\tau)} + u_1(t)u_2(t+\tau)e^{-i(\omega_1+\omega_2)t-i\omega_2\tau} + u_1(t+\tau)u_2(t)e^{-i(\omega_1+\omega_2)t-i\omega_1\tau}$$

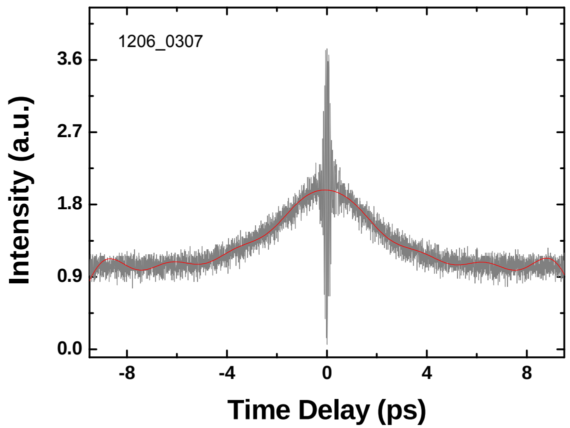
Crosscorrelation trace:

$$X(\tau) \propto \int_{-\infty}^{\infty} |SFG(t,\tau)|^2\, dt$$

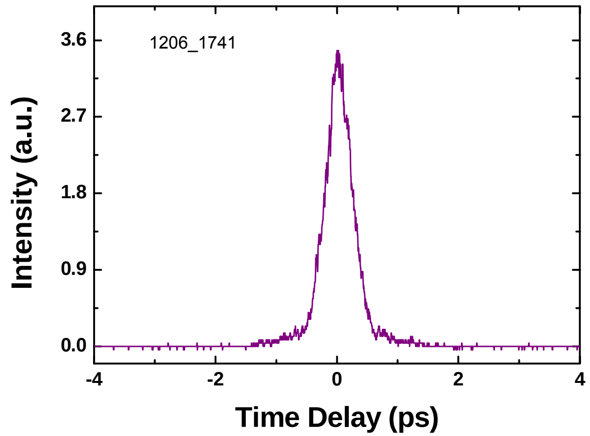
$$= 2I_0 + \int_{-\infty}^{\infty} I_1(t+\tau)I_2(t)dt + \int_{-\infty}^{\infty} I_1(t)I_2(t+\tau)dt + A(\omega_1) + B(\omega_2) + C(\omega_1+\omega_2) + D(\omega_1-\omega_2)$$

Measurement results at output C1

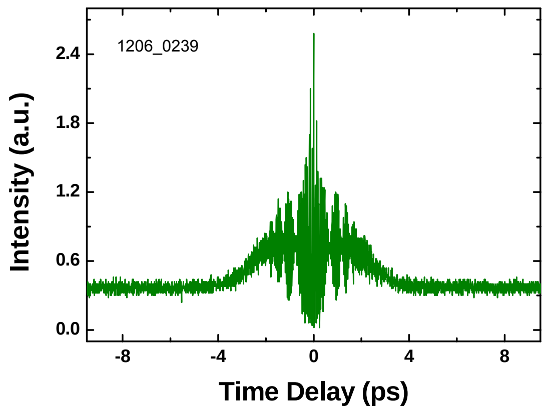
1 μm pulse: autocorrelation trace



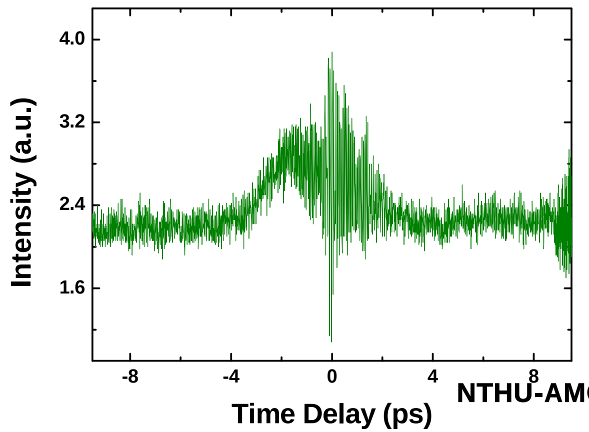
1.5 μm pulse: autocorrelation trace#



crosscorrelation trace



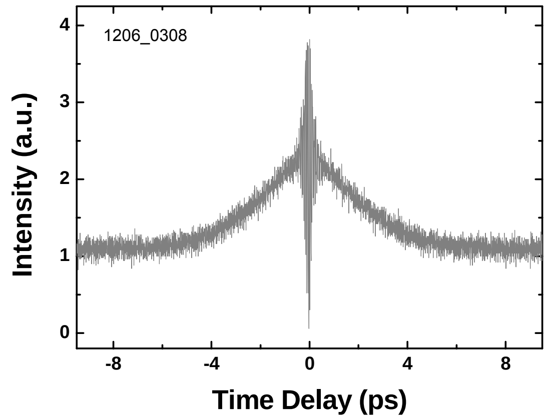
crosscorrelation trace with Si filter



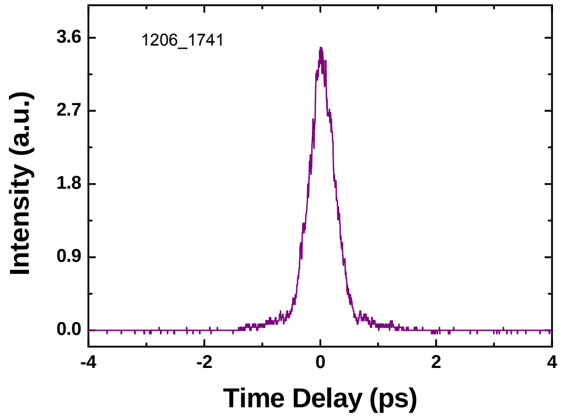
#: Measured at the rejection port of PBS

Measurement results at output C2

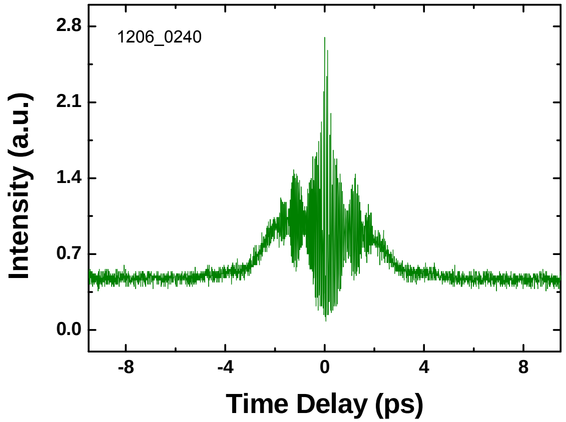
autocorrelation trace of 1 μm pulse



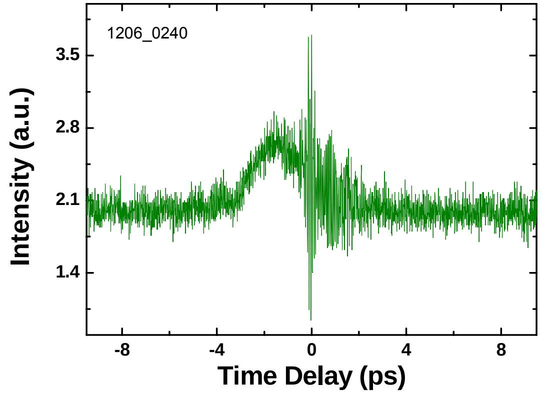
1.5 μm pulse: autocorrelation trace#



1 μm pulse: autocorrelation trace

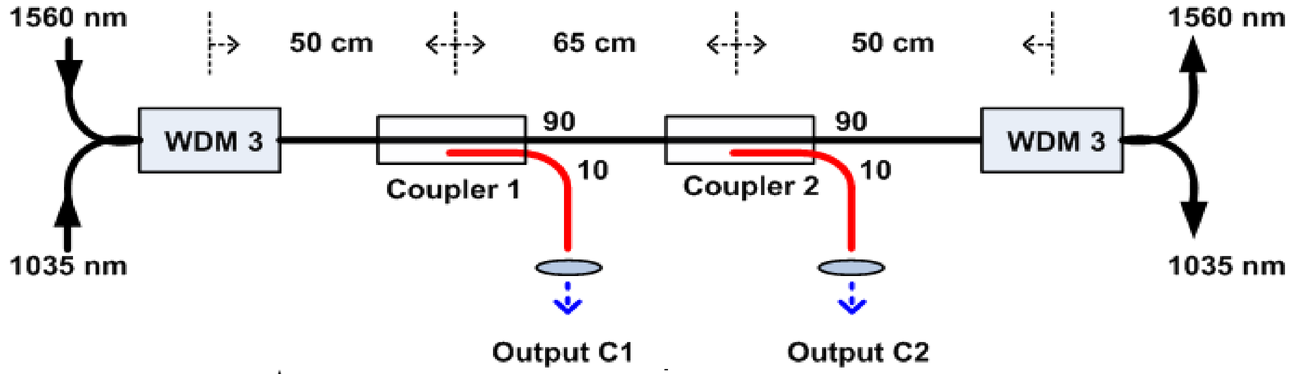


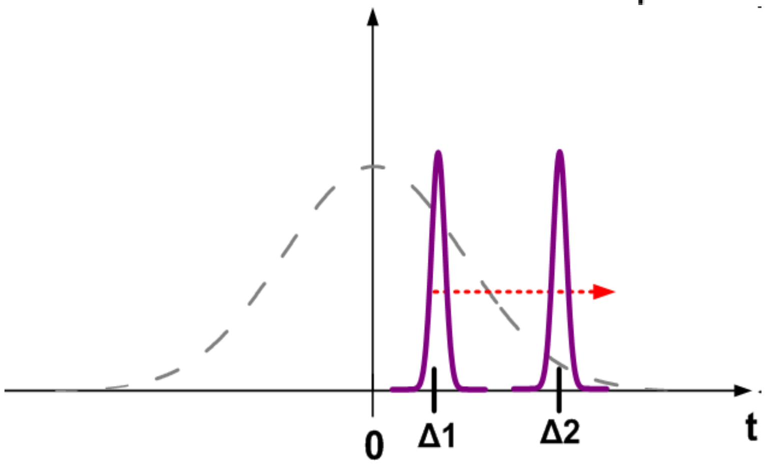
crosscorrelation trace with Si filter

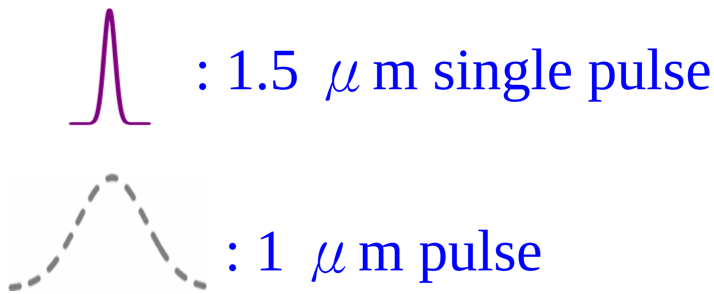


#: Measured at the rejection port of PBS

1560 nm single pulse



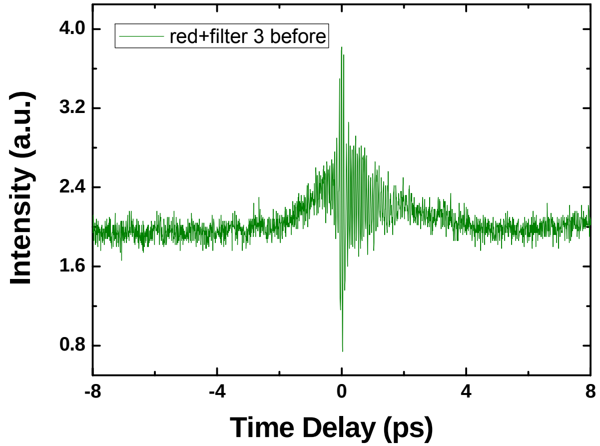




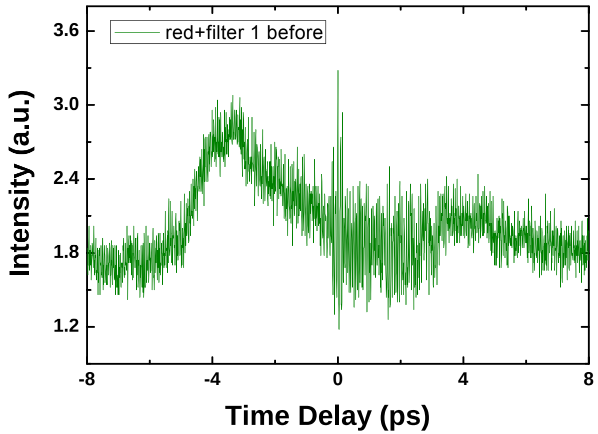
Temporal wall-off during co-propagation fiber: ~ 2.5 ps

Cavity length detuning (Initial rep. rate mismatch) versus relative position

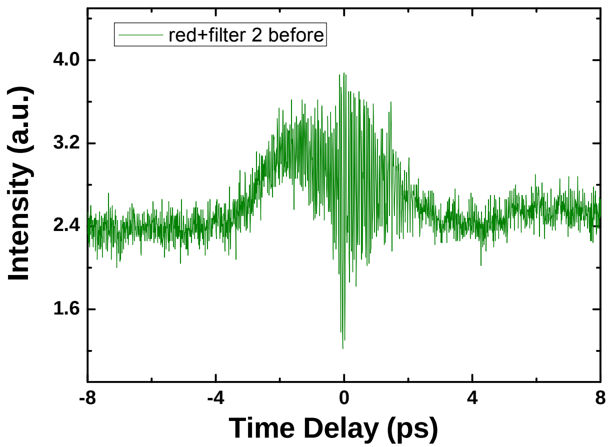
d = X_0



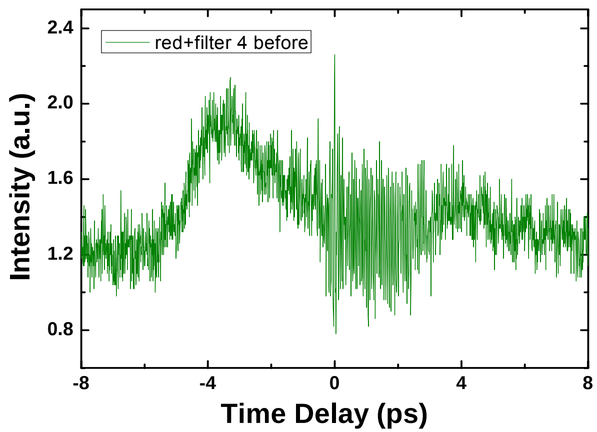
d = X_0+3 μm



d = X_0+1.5 μm

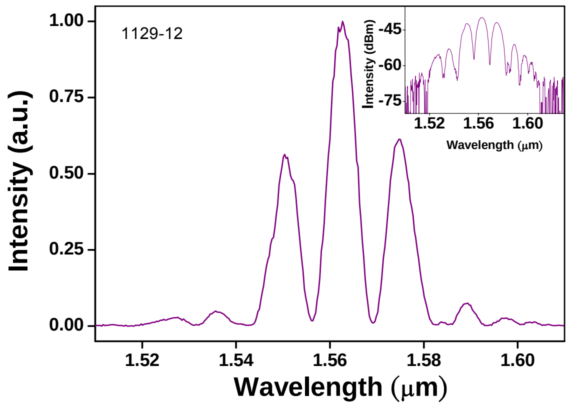


d = X_0+ 4 μm

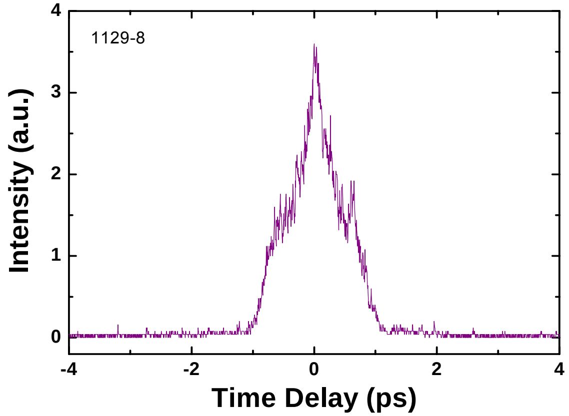


Measurement results at output C1

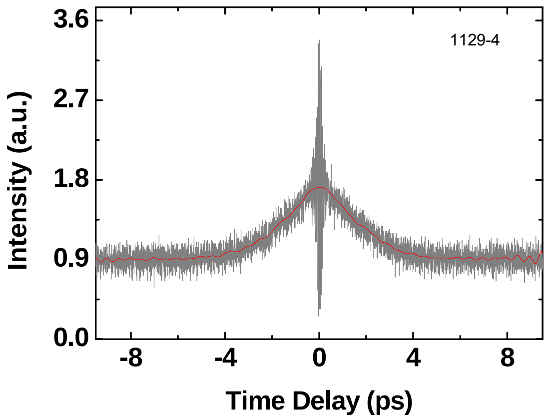
1.5 μm pulse: optical spectrum



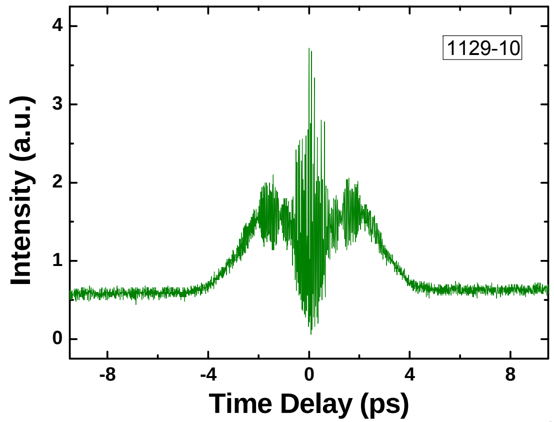
1.5 μm pulse: autocorrelation trace[#]



1 μm pulse: autocorrelation trace



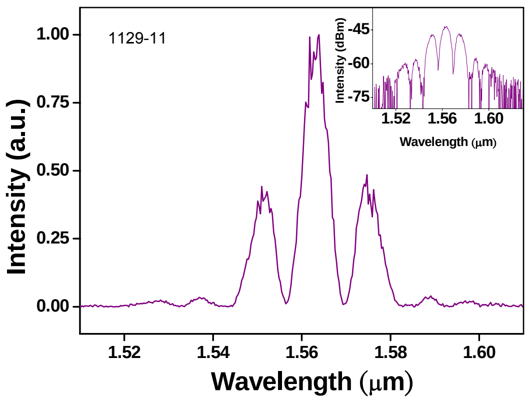
crosscorrelation trace



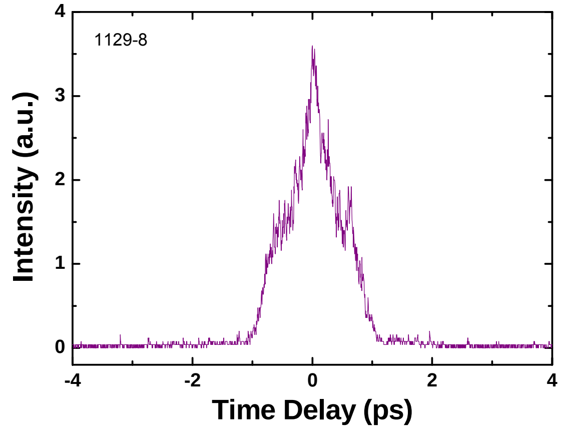
#: Measured at the rejection port of PBS

Measurement results at output C2

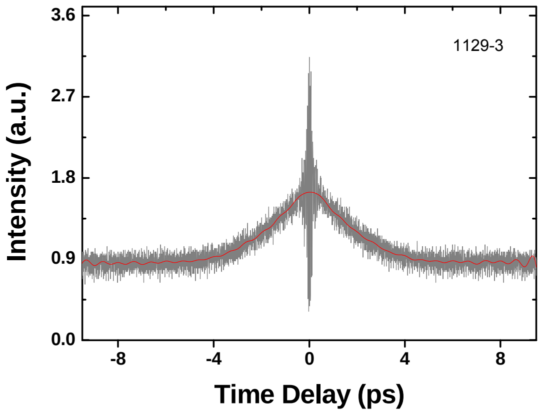
1.5 μm pulse: optical spectrum



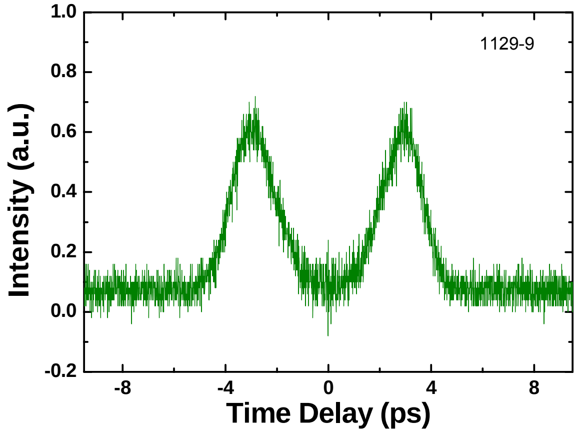
1.5 μm pulse: autocorrelation trace#



1 μm pulse: autocorrelation trace

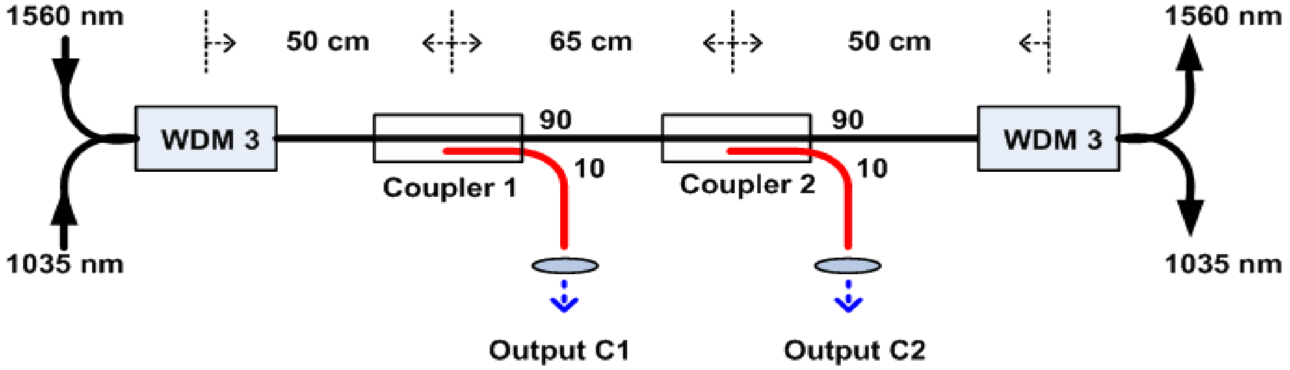


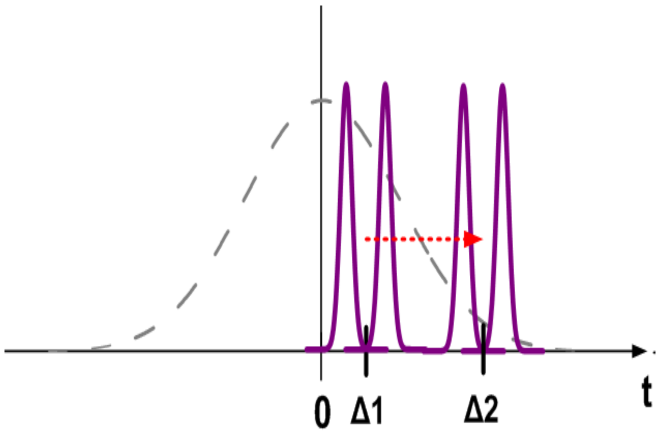
crosscorrelation trace

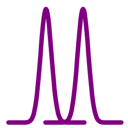


#: Measured at the rejection port of PBS

1560 nm 2-pulse bound state





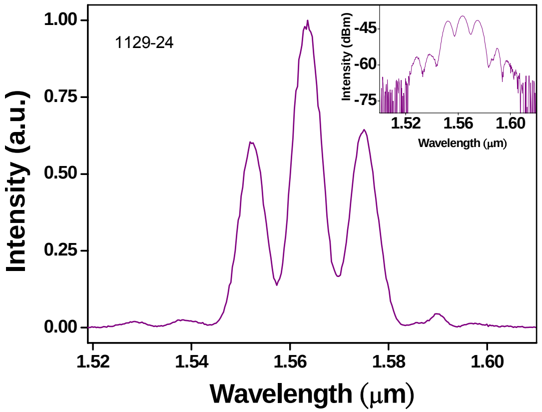
 : 1.5 μm 2-pulse bound state

 : 1 μm pulse

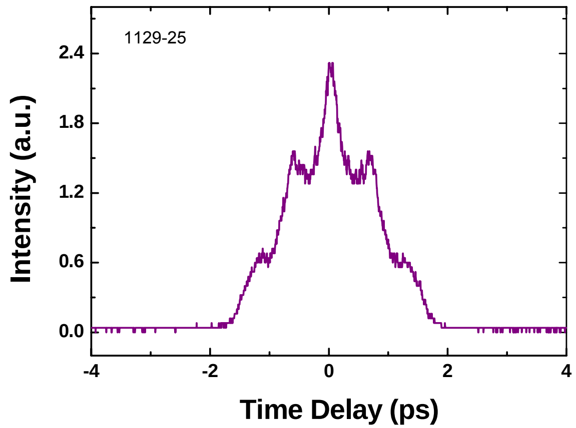
1. Two closely bound pulses: in phase
2. Temporal wall-off during co-propagation fiber: ~ 2.5 ps

Measurement results at output C1

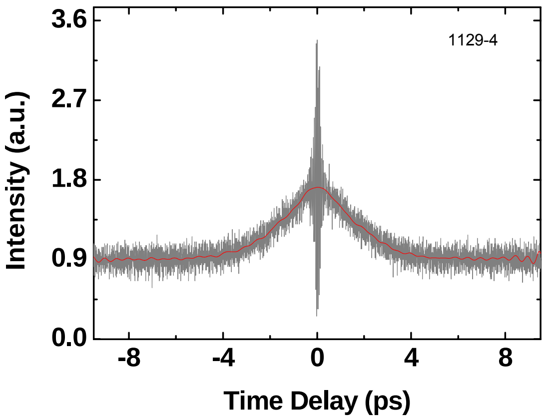
1.5 μm pulse: optical spectrum



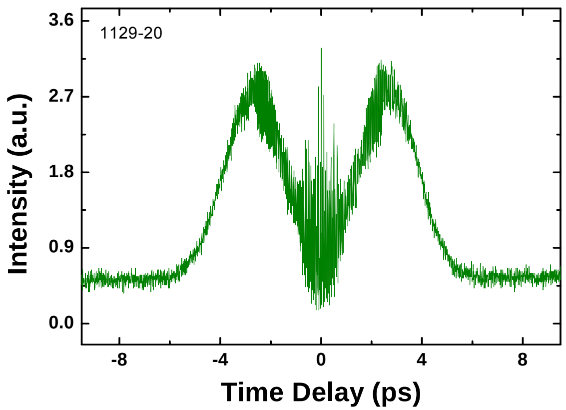
1.5 μm pulse: autocorrelation trace#



1 μm pulse: autocorrelation trace



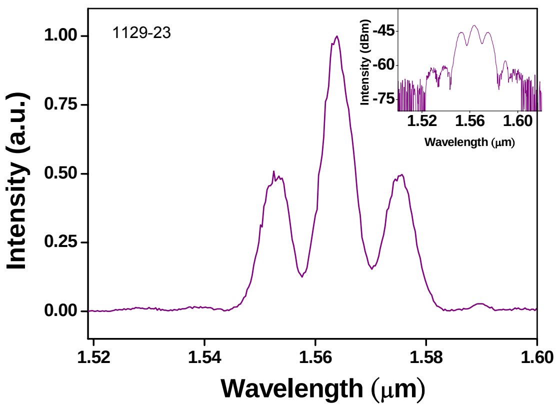
crosscorrelation trace



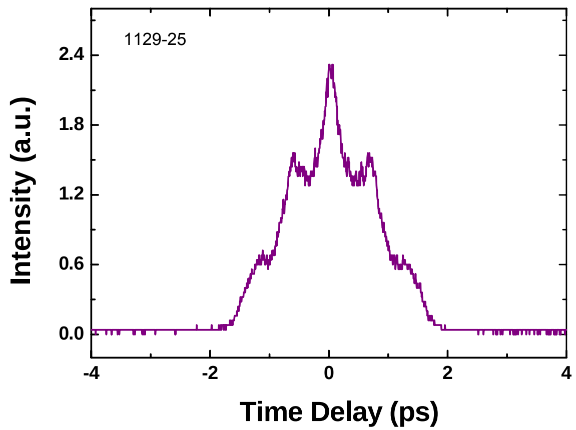
#: Measured at the rejection port of PBS

Measurement results at output C2

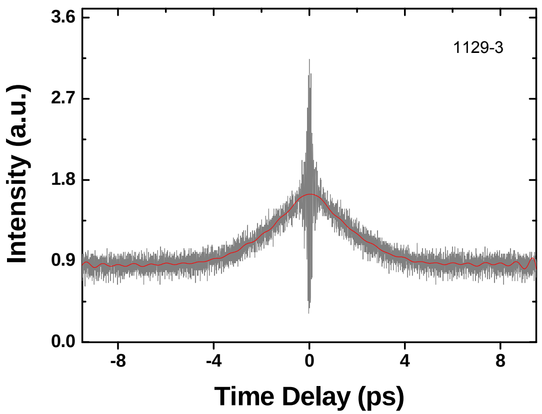
1.5 μm pulse: optical spectrum



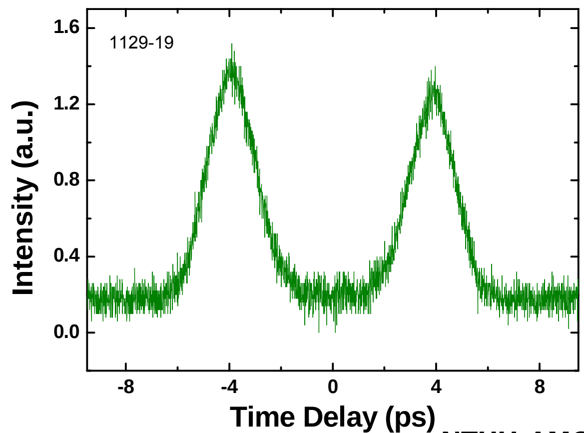
1.5 μm pulse: autocorrelation trace#



1 μm pulse: autocorrelation trace

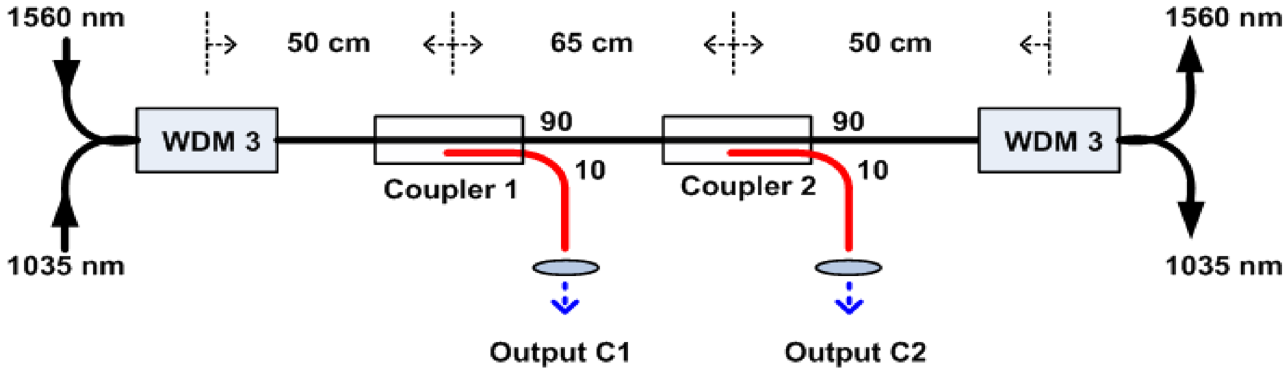


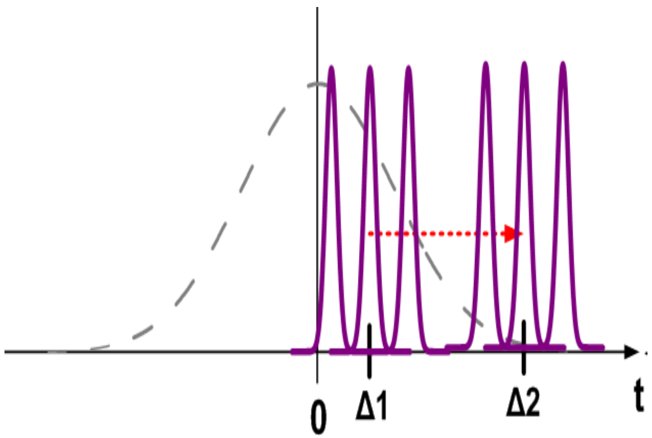
crosscorrelation trace

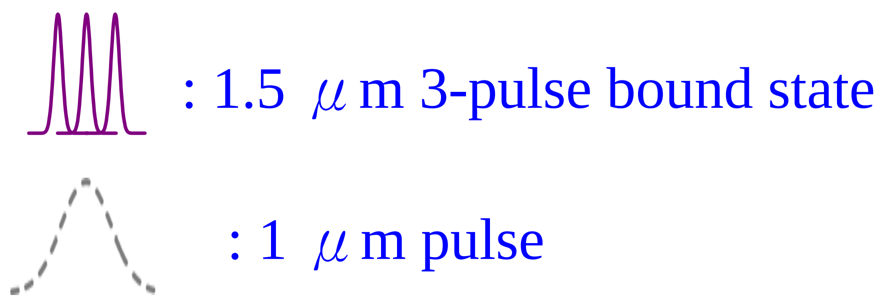


#: Measured at the rejection port of PBS

1560 nm 3-pulse bound state

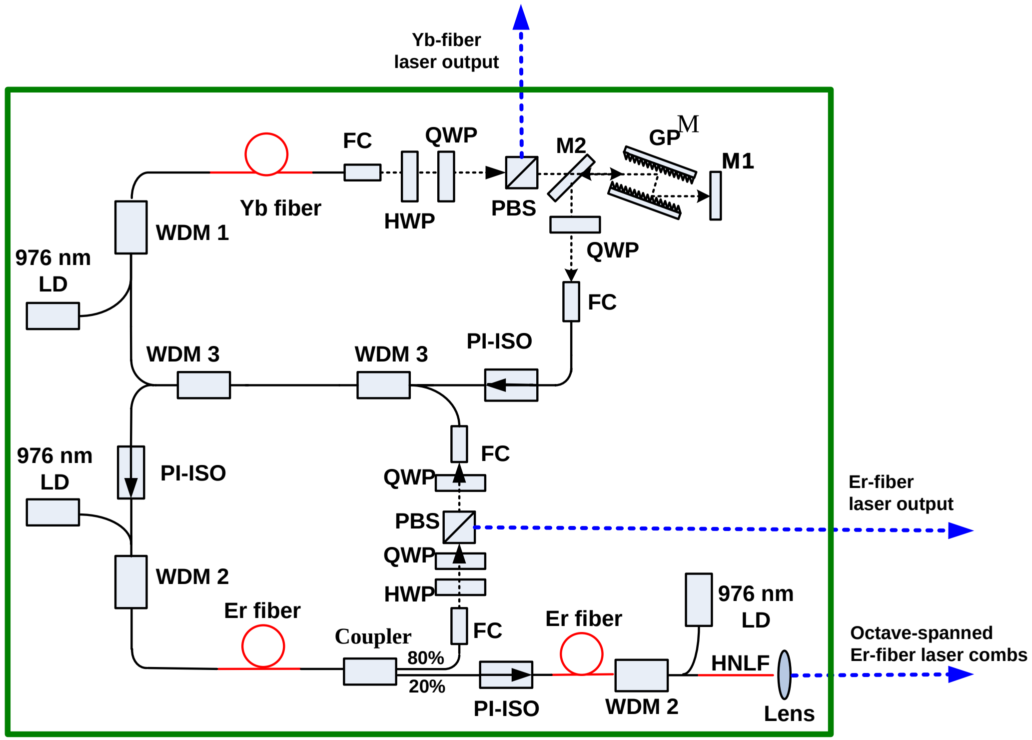






1. Three closely bound pulses: in phase
2. Temporal wall-off during co-propagation fiber: ~ 2.5 ps

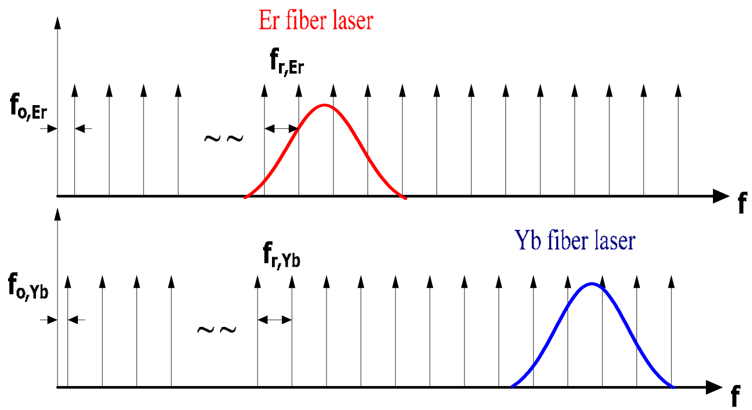
Carrier-envelope-offset (CEO) frequencies



$$f_{Er} = mf_r + f_{o,Er}$$

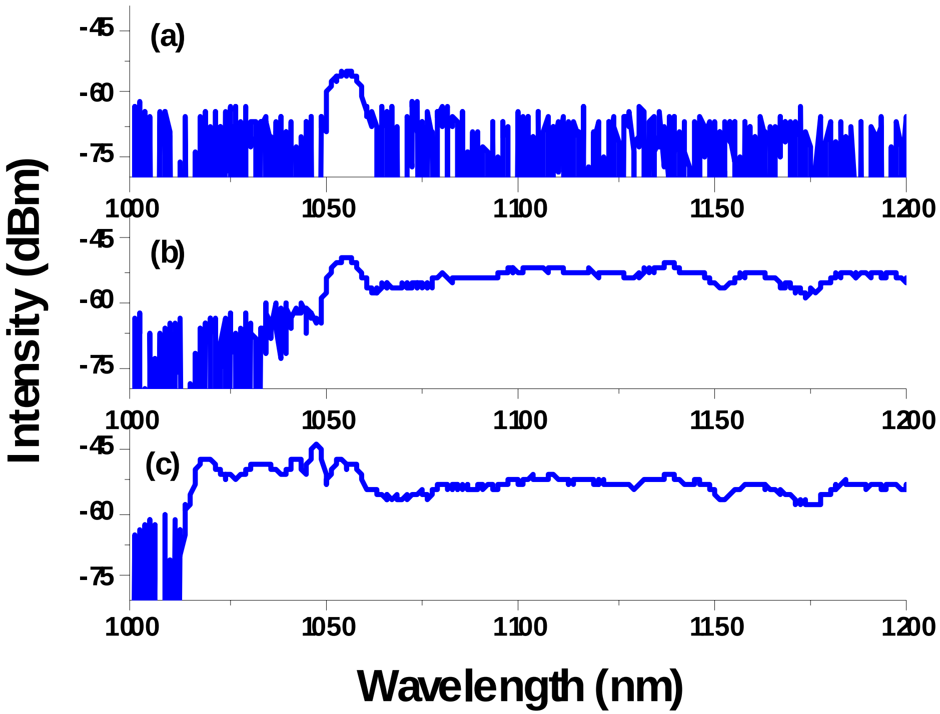
$$2f_{Er} = 2lf_r + 2f_{o,Er}$$

$$f_{Yb} = nf_r + f_{o,Yb}$$



Collaboration: Dr. J.-L. Peng, ITRI

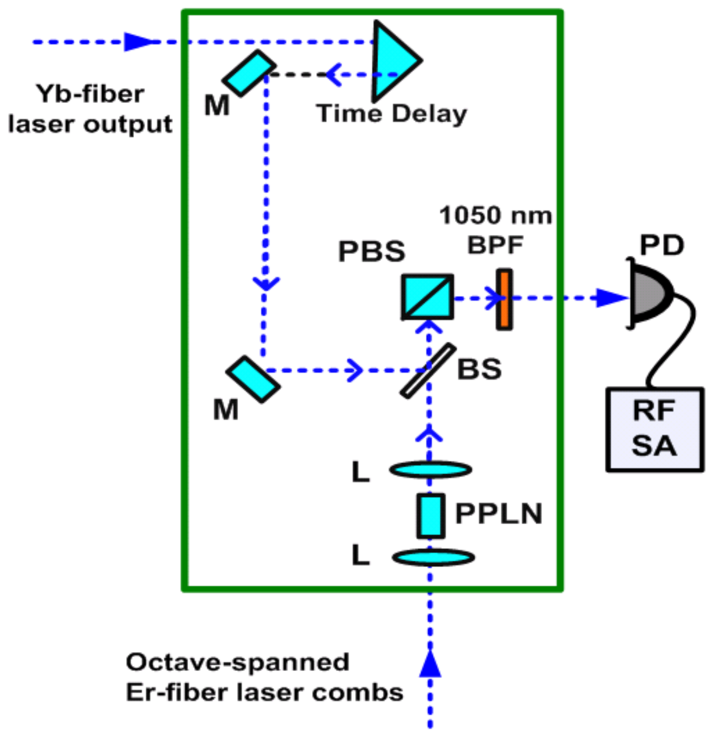
Octave supercontinuum (1030 nm-2200 nm)

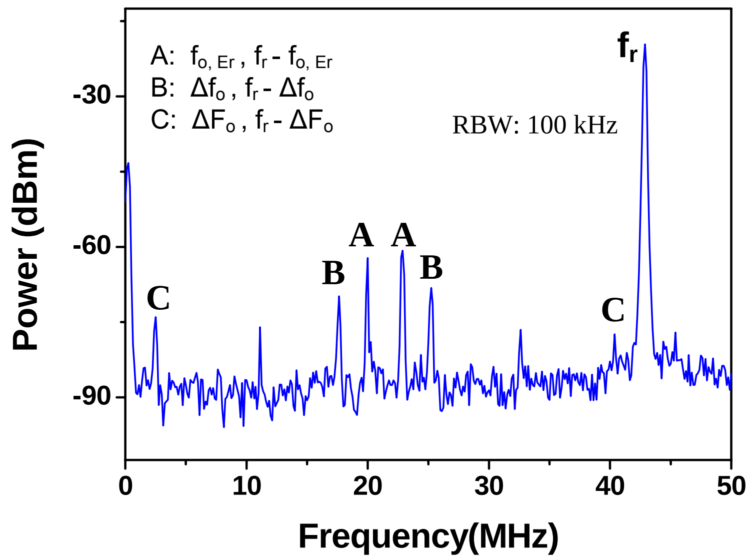


(a) Optical spectrum of the SHG around 1050 nm.
(b) Optical spectrum of the SHG around 1050 nm and the supercontinuum.
(c) Combined optical spectrum of the Yb-fiber laser, the SHG around 1050 nm, and the supercontinuum

Collaboration: Dr. J.-L. Peng, ITRI

Detection scheme (I)



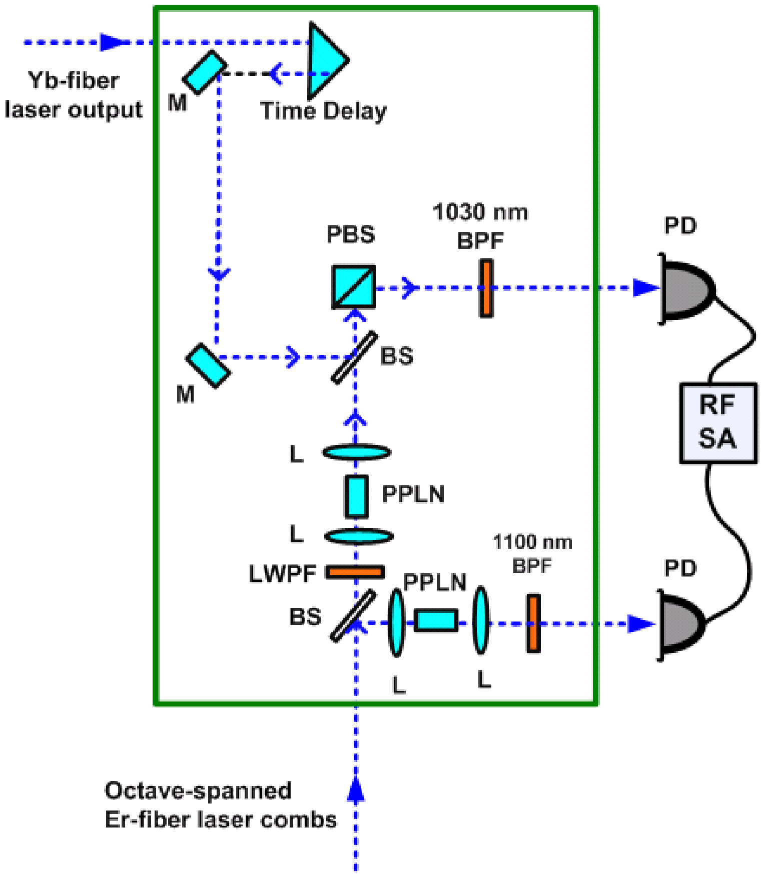


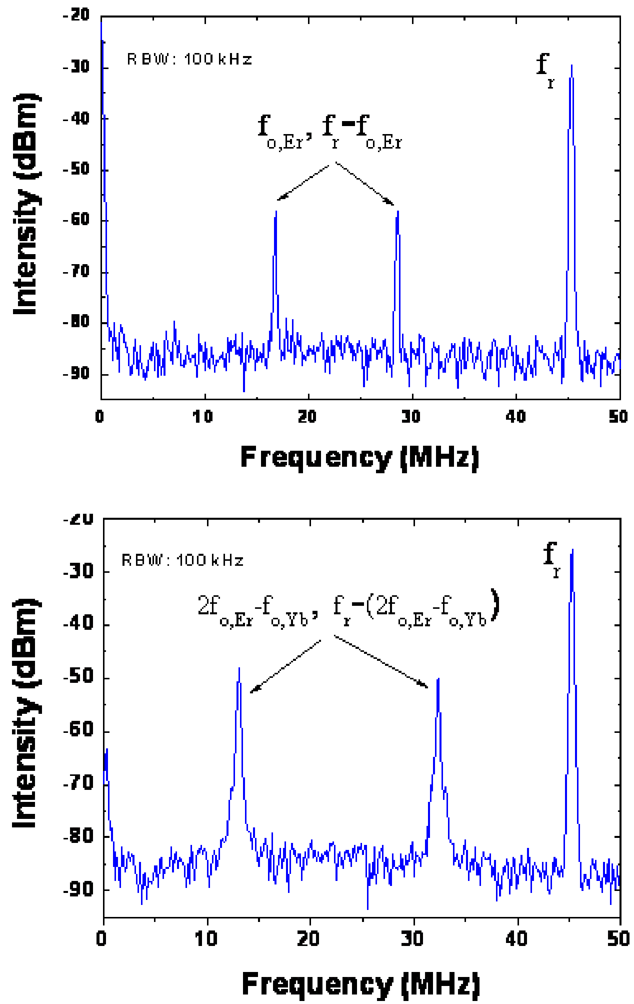
Simultaneous determination of both carrier-envelope offset (CEO) frequencies:

➔ Heterodyne beats between the Yb-fiber laser and the self-referenced Er-fiber laser combs around 1050 nm

Collaboration: Dr. J.-L. Peng, ITRI

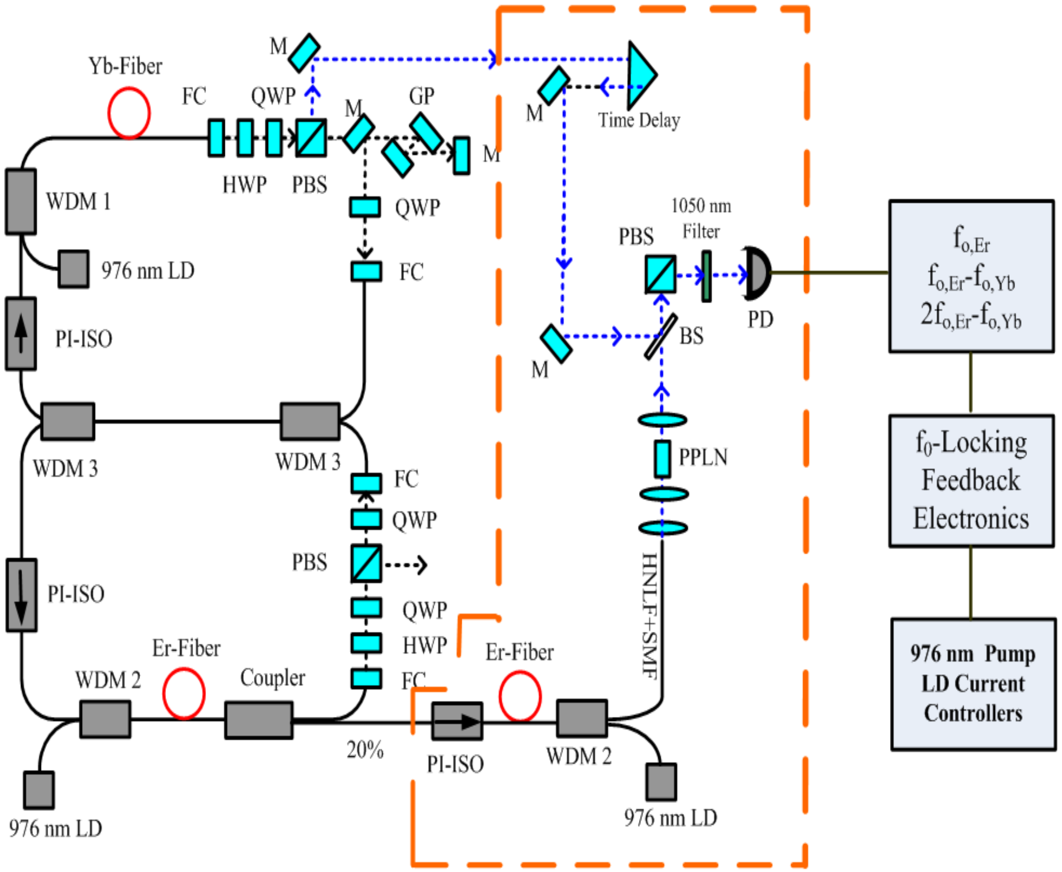
Detection scheme (II)





Collaboration: Dr. J.-L. Peng, ITRI

CEO frequency control



$$f_{Yb} = nf_r + f_{o,Yb}$$

$$f_{Er} = mf_r + f_{o,Er}$$

$$\Delta f_0 = f_{o,Er} - f_{o,Yb}$$

$$\Delta F_0 = 2 f_{o,Er} - f_{o,Yb}$$

Summary

- High power mode-locked fiber laser systems are (commercially) available now.
- Passive synchronization mechanism in two-color mode-locked fiber lasers
  - The relative position between 1560 nm and 1035 nm pulses depends on the repetition rate mismatch, the temporal walk-off, and the filtering effect.
  - The observed relative phase between 1560 nm closely bound multiple pulses is zero in our case.
  - The measured relative positions and phases may give some insight into the problem of dissipative solitons under the influence of the external modulation.
- Simultaneous carrier-envelope-offset (CEO) frequency measurement is achieved.
- Potential applications

  (1) CEP-stabilized Mid-IR pulses (frequency combs)

  (2) Coherent pulse synthesis

Acknowledgements

NSC
Prof. Y. Lai, NCTU
Prof. A. Kung, NTHU
Prof. R.-K. Lee, NTHU
Dr. L.-H. Peng, ITRI

研究生： 鄭堅伯, 張家豪, 吳家逸, 梁翰仁, 趙偉智, 林勇佑

Thank you for your attention!