Accelerator and Detector R&D Meeting
August 22-23, 2011

Pulsed Timing and Synchronization Systems

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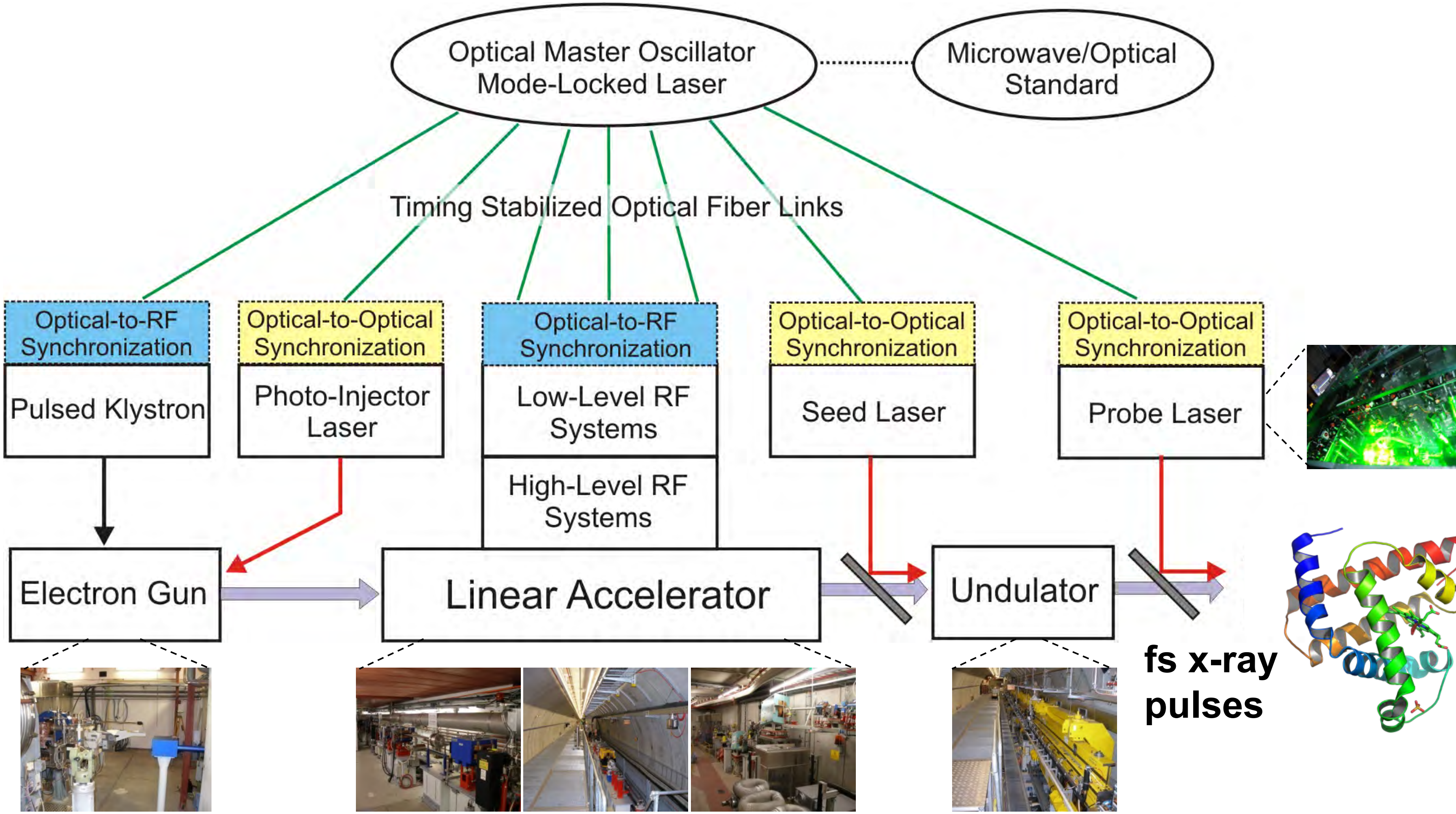
Outline

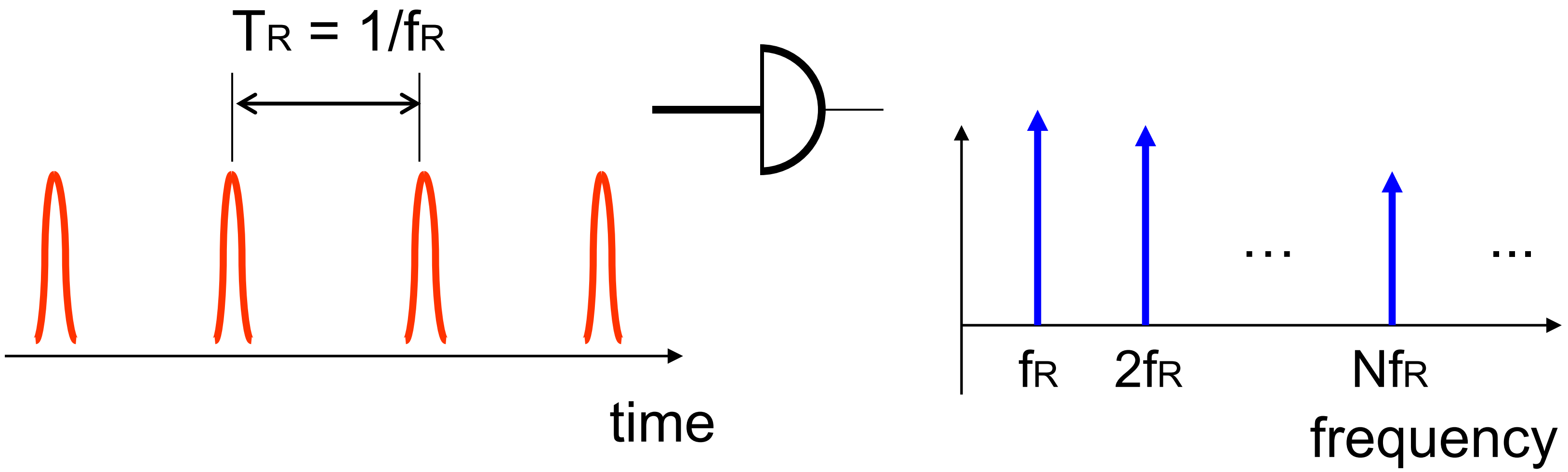
- Synchronization System Layout for X-ray FELs
- Low Jitter of Femtosecond Lasers
- Timing Distribution Over Stabilized Fiber Links
- Optical-to-Optical Synchronization
- RF-Extraction and Locking to Microwave References
- Attosecond Timing with Solid State Lasers

Timing Distribution and Synchronization



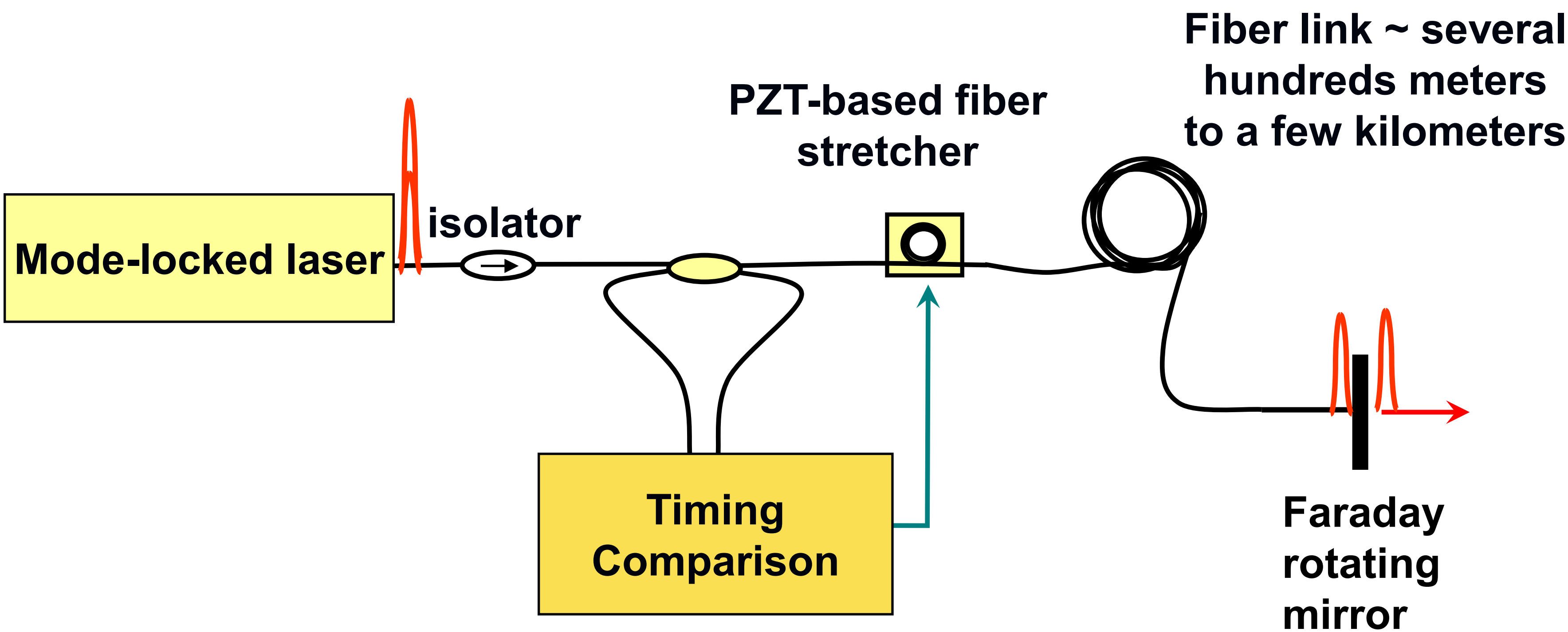
J. Kim et al, FEL 2004.

Why Optical Pulses (Mode-locked Lasers)?



- **Real marker in time and RF domain**, every harmonic can be extracted at the end station.
- Suppress Brillouin scattering and undesired reflections.
- **Optical cross correlation** can be used for link stabilization or for optical-to-optical synchronization of other lasers.
- Pulses can be directly used to **seed amplifiers, EO-sampling**, ….
- **Group delay is directly stabilized,** not optical phase delay.
- After power failure system can **auto-calibrate!**

Timing-Stabilized Fiber Links

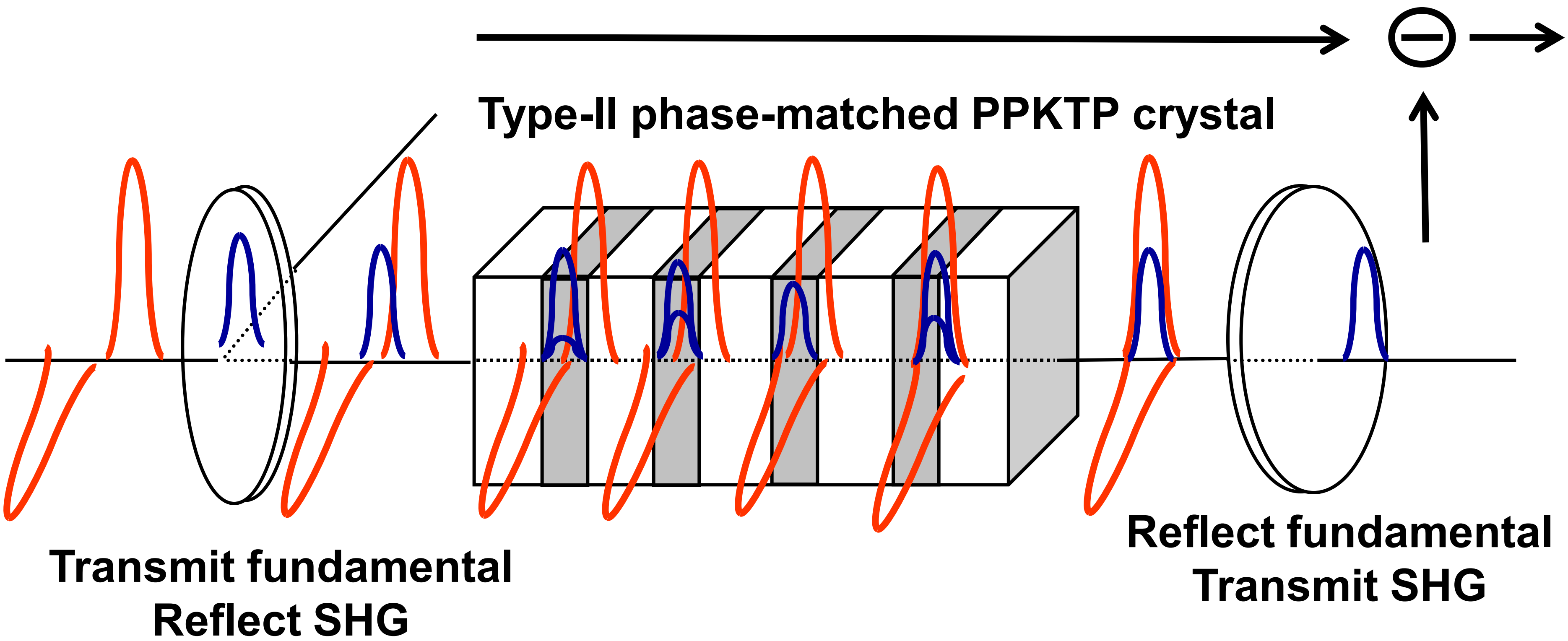


Cancel fiber length fluctuations slower than the pulse travel time (2nL/c).

1 km fiber: travel time = 10 μs → ~100 kHz BW

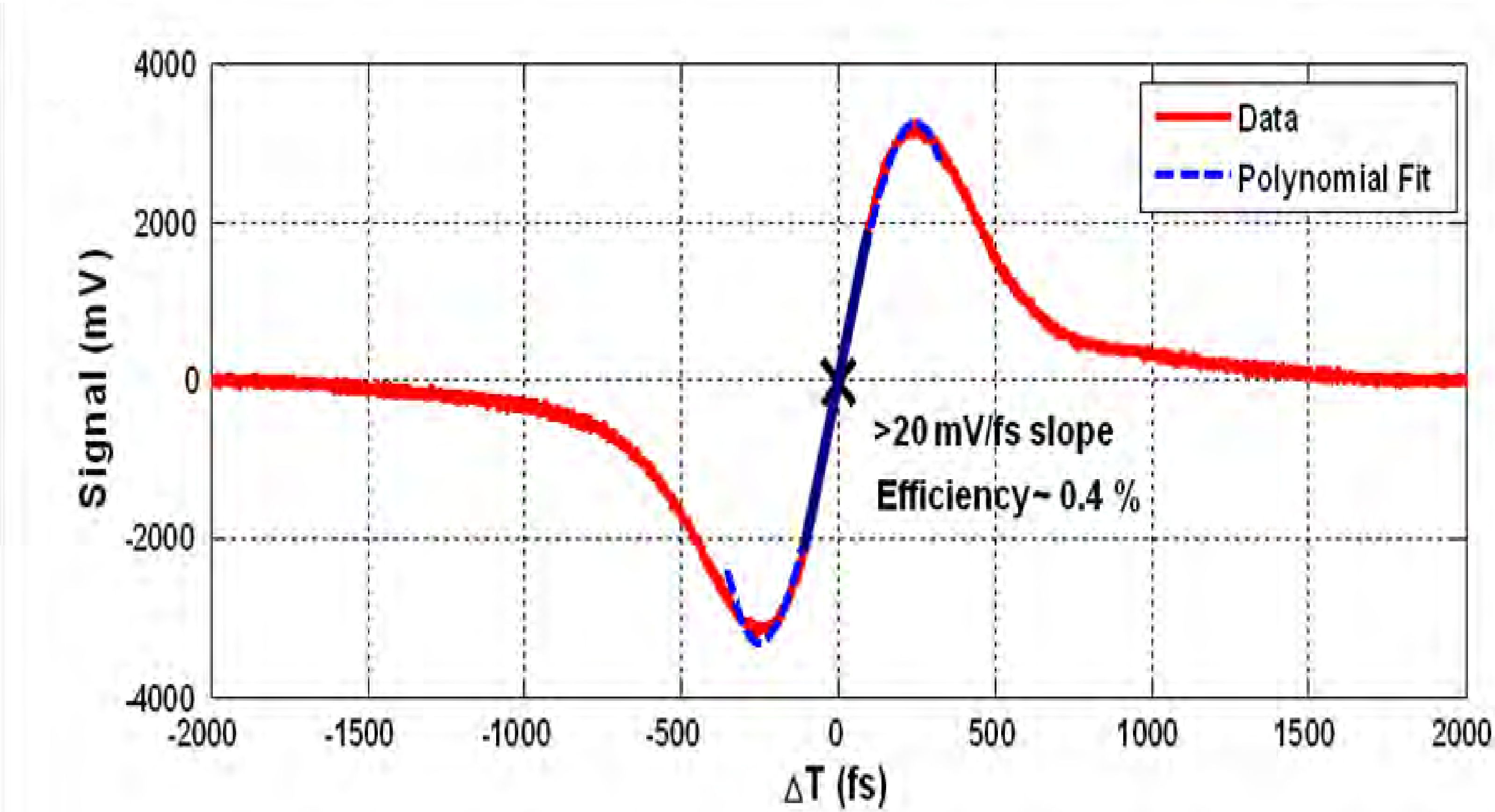
Single-Crystal Balanced Cross-Correlator

T. Schibli et al, OL 28, 947 (2003)



J. Kim et al., Opt. Lett. 32, 1044 (2007)

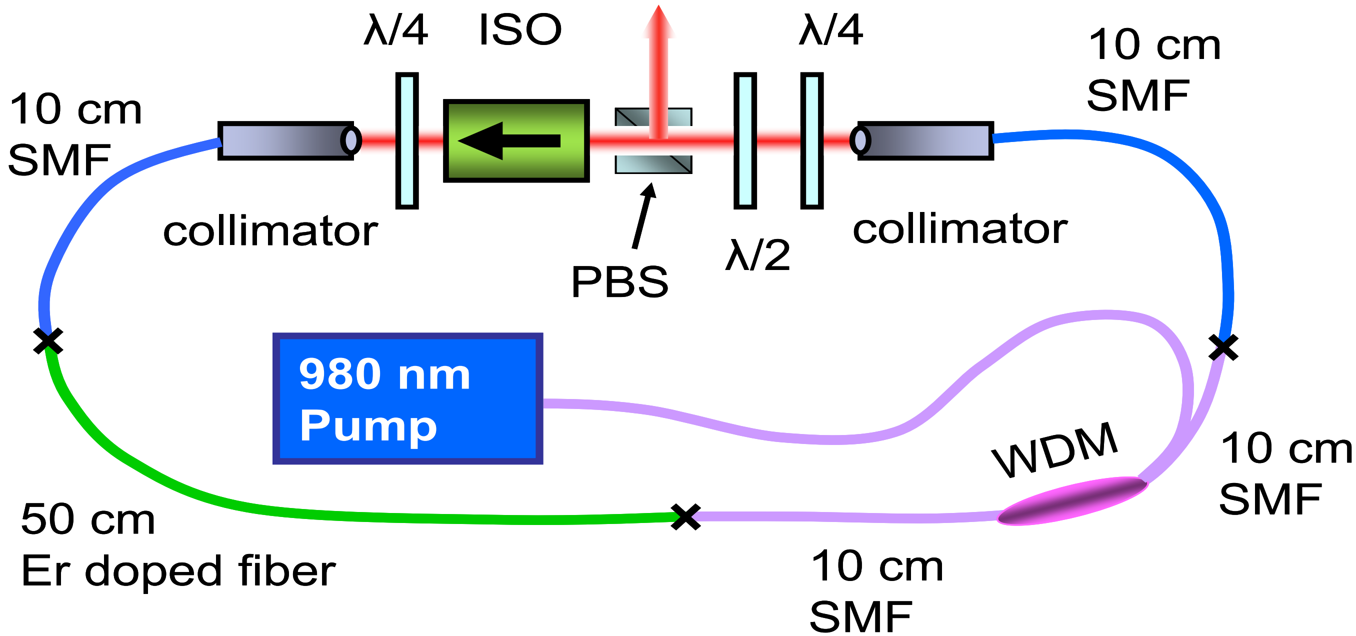
Single-Crystal Balanced Cross-Correlator



80 pJ, 200 fs
1550nm input pulses
at 200 MHz rep. rate

In comparison:
Typical microwave mixer
Slope ~1 μV/fs @ 10 GHz
Greatly reduced thermal drifts!

200 MHz Soliton Er-fiber Laser

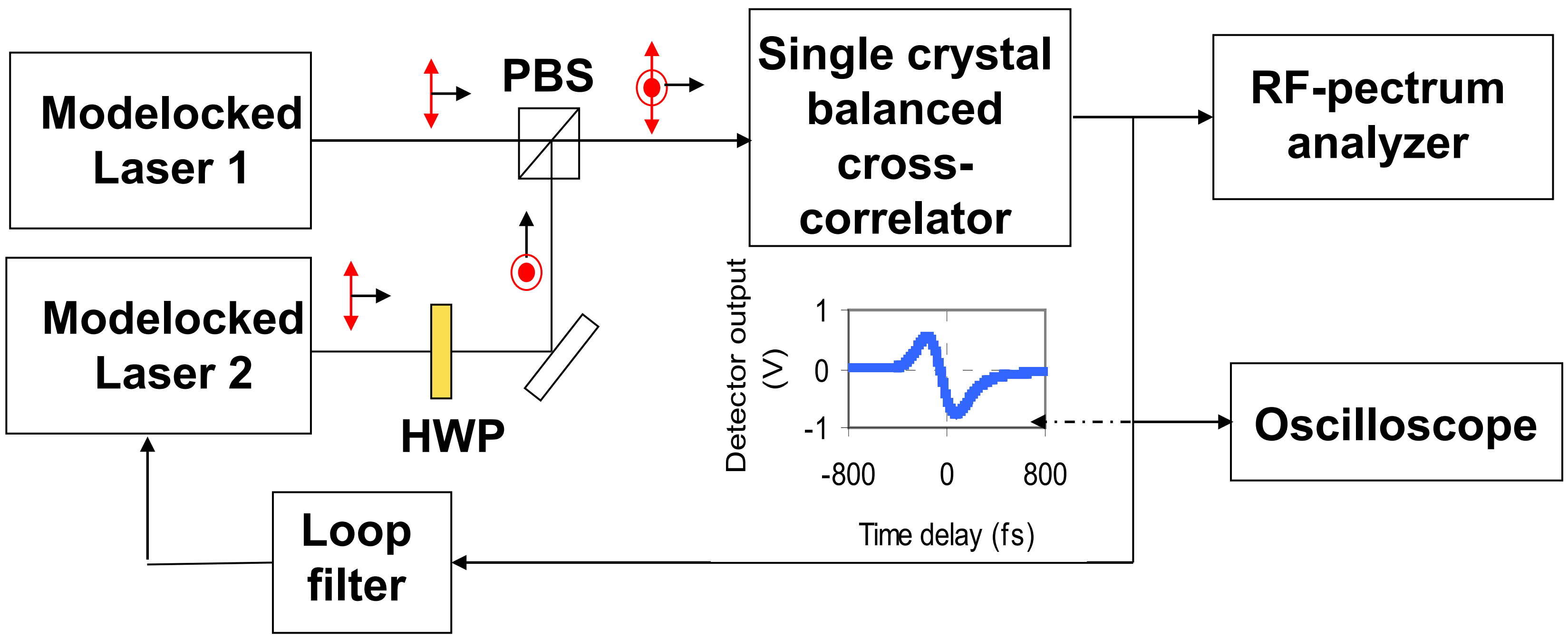


- **167 fs pulses**
- **200 pJ intracavity pulse energy**
- **50% loss**

K. Tamura et al. Opt. Lett. 18, 1080 (1993).
J. Chen et al, Opt. Lett. 32, 1566 (2007).

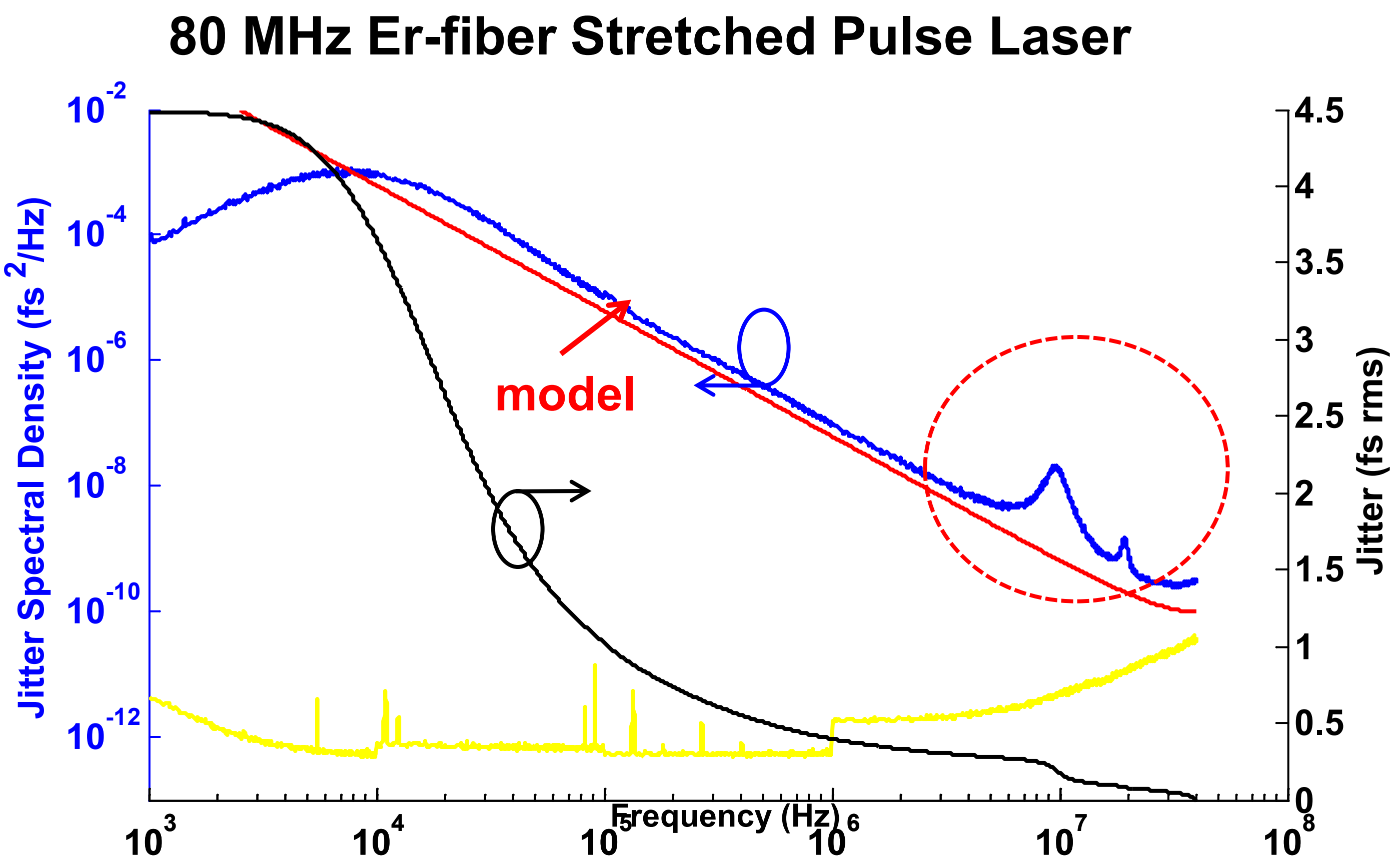
Timing Jitter of Fiber Lasers

Phase detector method → Timing Detector method



J. Kim, et al. , Opt. Lett. 32, 3519 (2007).

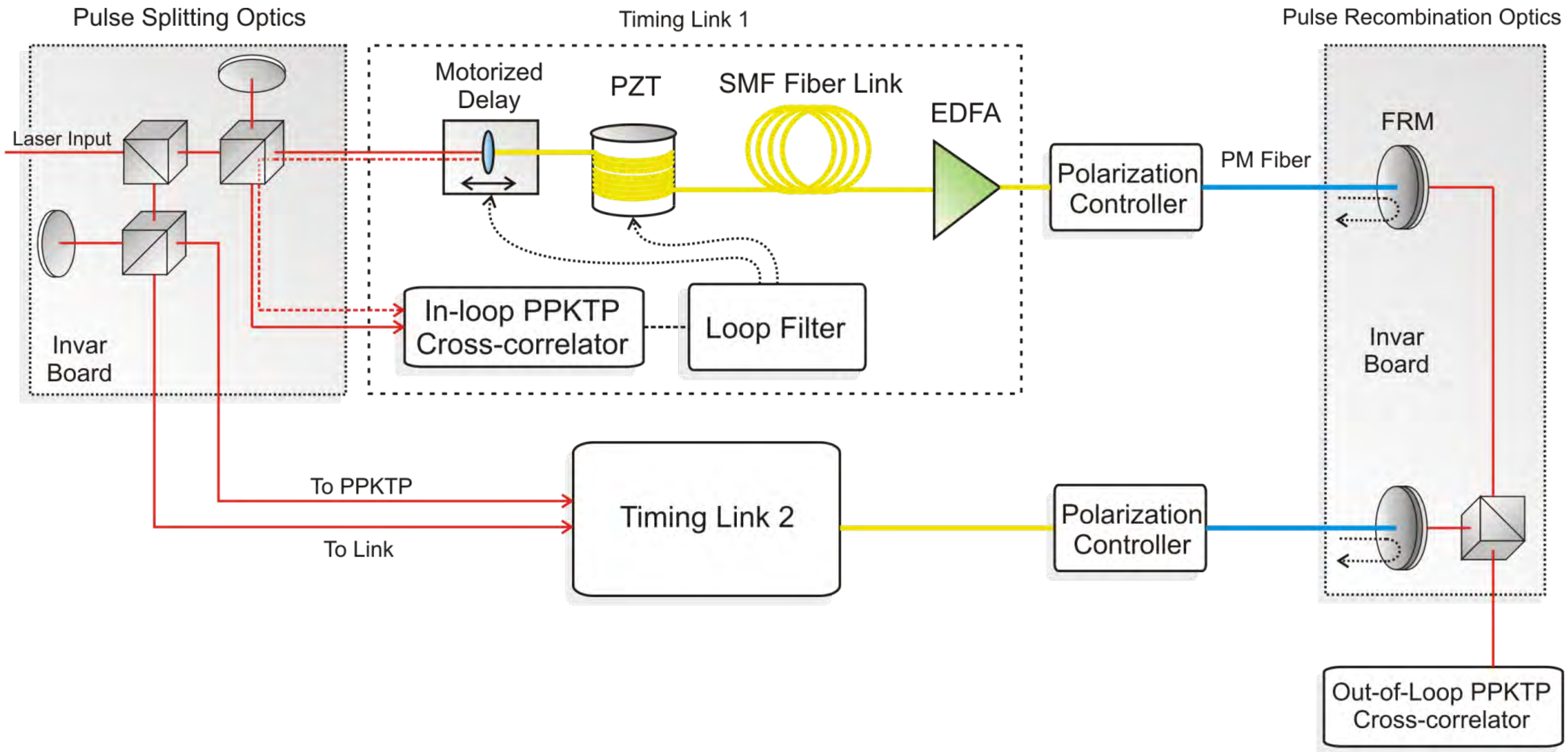
Timing Jitter in Stretched Pulse Lasers



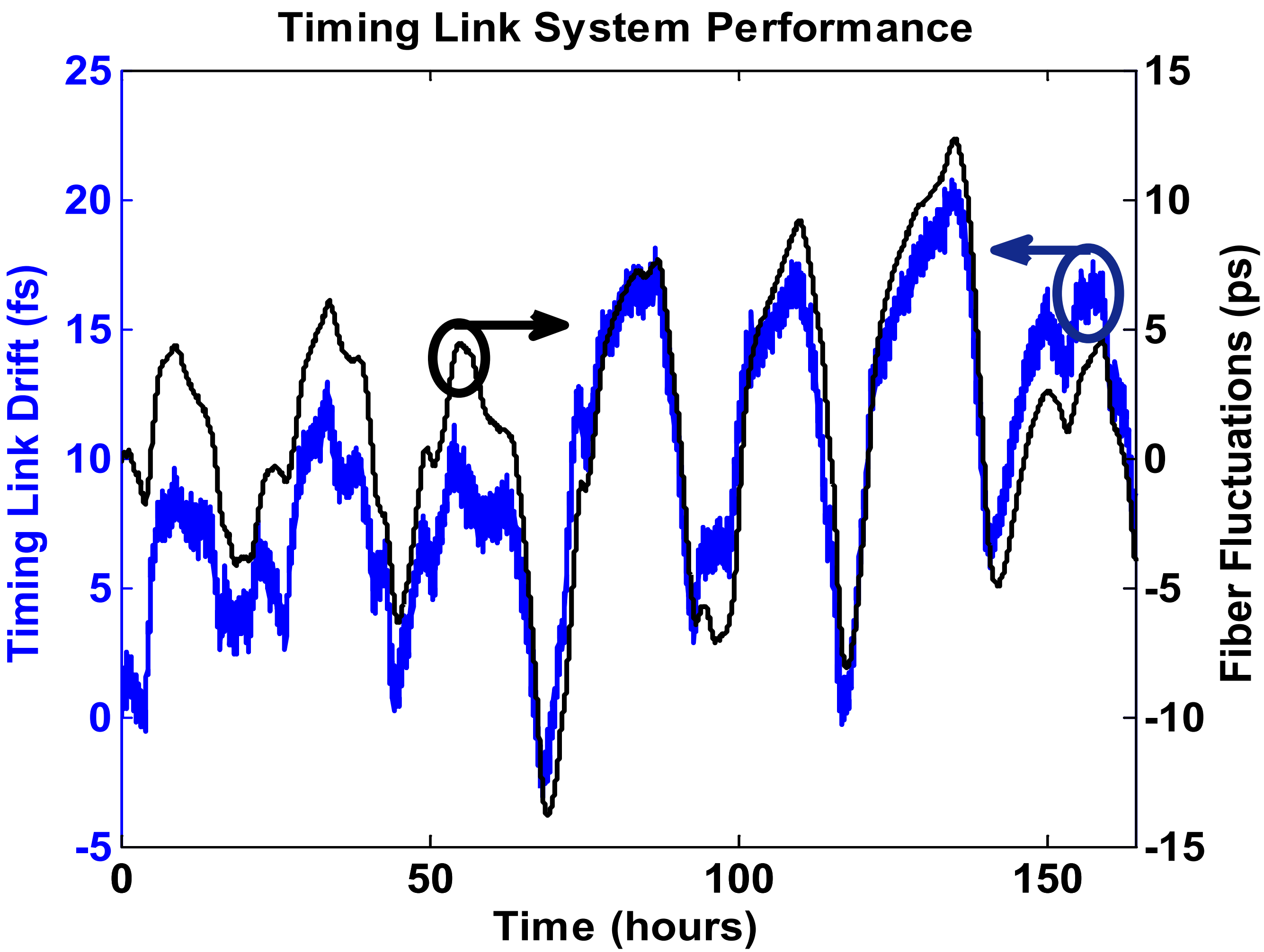
- 6 fs rms [10 kHz, 40 MHz]
- Additional noise present at $f_{rep}/2$ and $f_{rep}/4$

J. Cox et al. Opt. Lett., 35, 3522 (2010)

2 Link Test System



1-week operation w/ Pol. Control

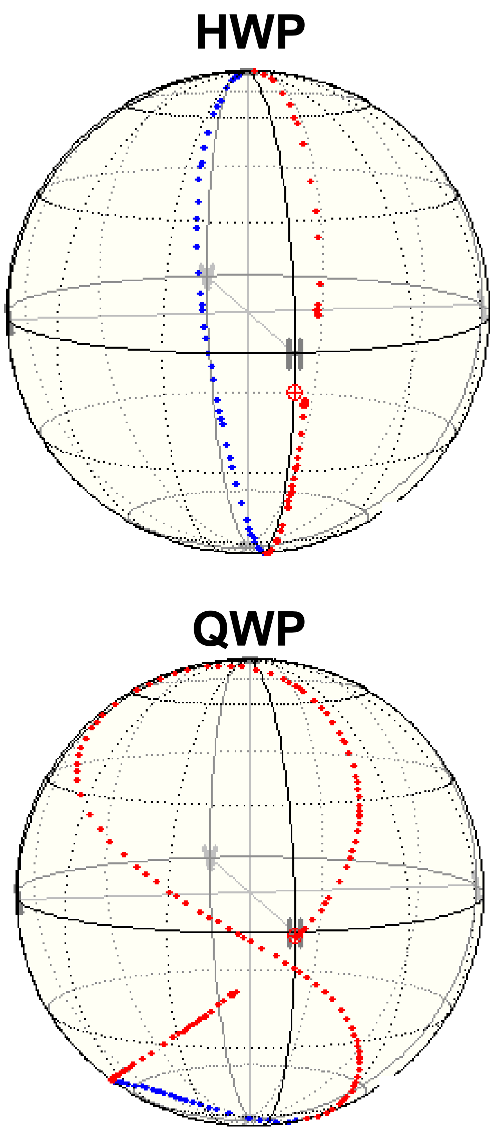


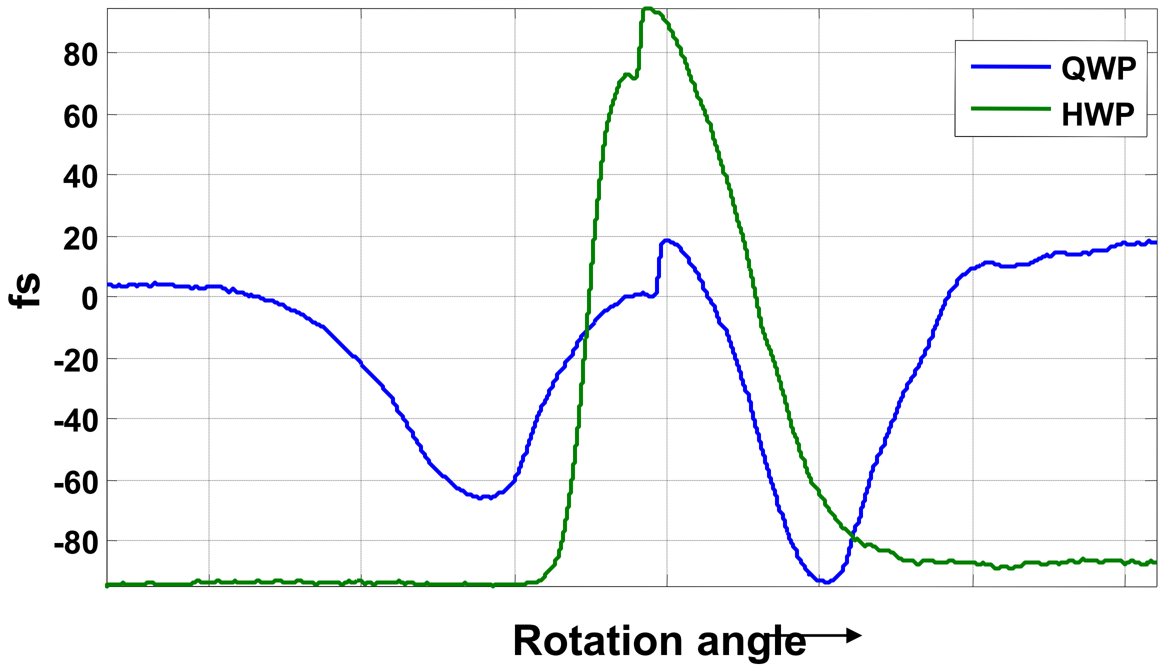
5 fs (rms) drifts over one week of operation

Similar Links deployed at FLASH

5-link system installed at FERMI @ Trieste, 10 days < 10 fs (IdestaQE and Menlosystems GmbH)

Differential Group Delay (PMD)

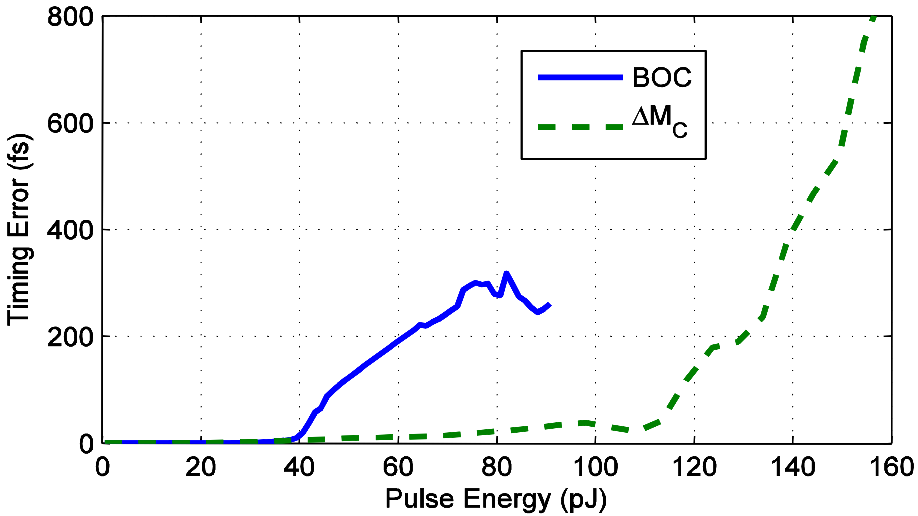




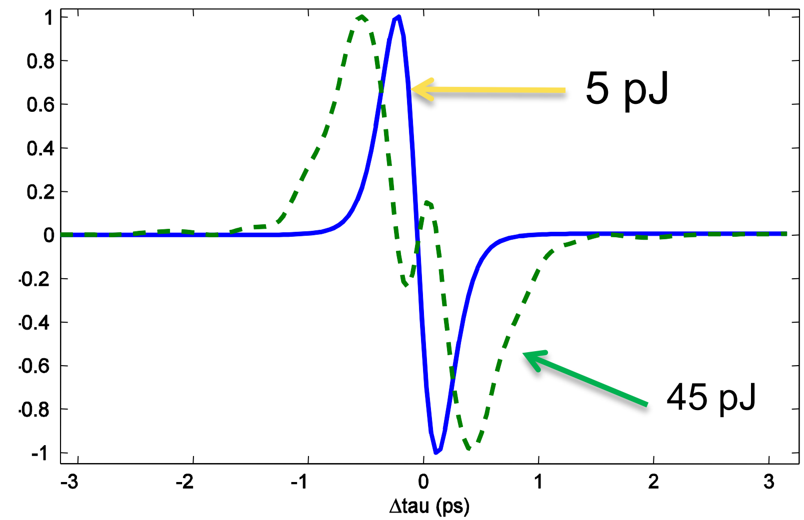
- Lower DGD in actual facility environment
- Can be reduced by eliminating fiber stretcher
- Can be eliminated with a PM fiber link

Non-linear Timing Link Error

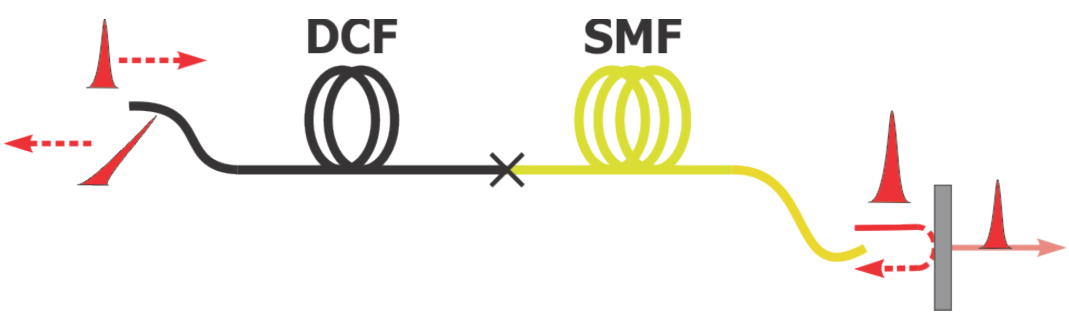
Timing Error vs. Pulse Energy



BOC Transfer Function



$$\frac{\partial A}{\partial z} = -i\frac{\beta_2}{2}\frac{\partial^2 A}{\partial T^2} + i\frac{\beta_3}{6}\frac{\partial^3 A}{\partial T^3} + i\gamma\left(|A|^2 A + \frac{i}{\omega_0}\frac{\partial}{\partial T}\left(|A|^2 A\right) - T_R A\frac{\partial |A|^2}{\partial T}\right)$$



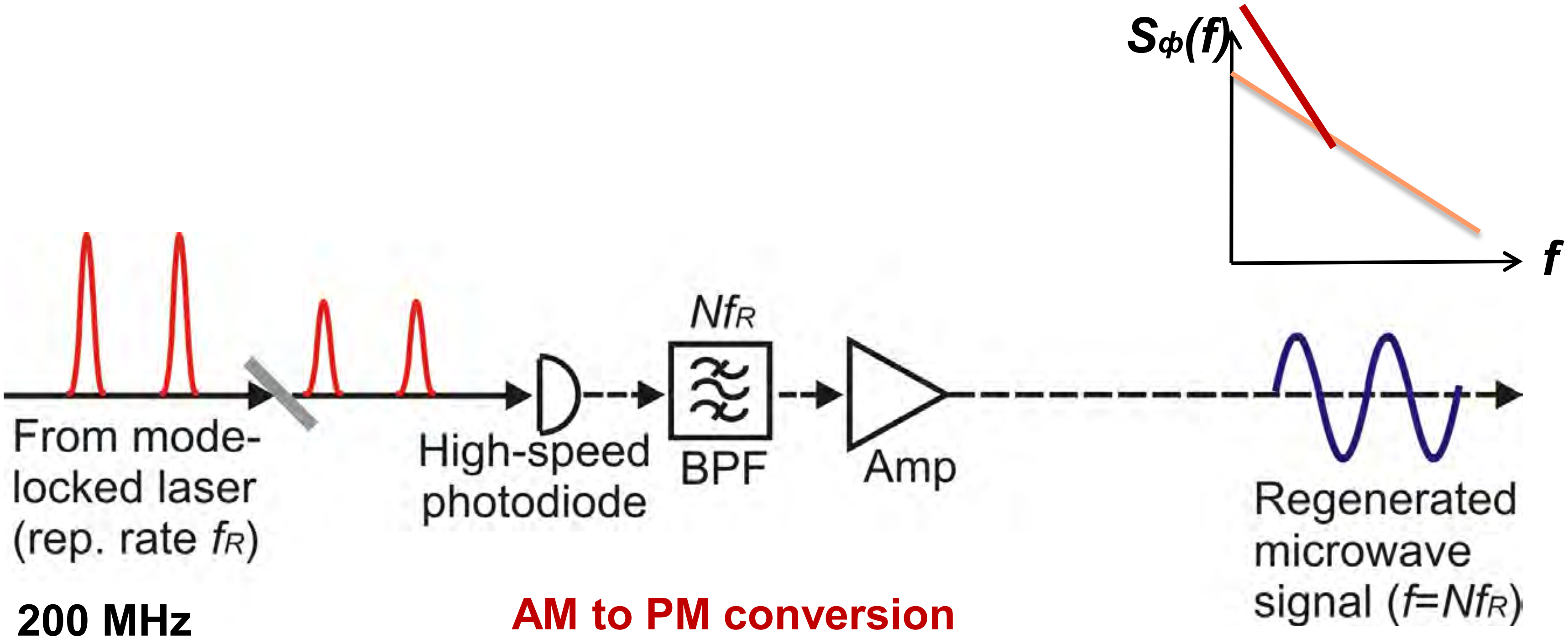
- 100 m SMF-28e with 14 m DCF
- Pulse splitting → 10 fs/pJ shift above 40 pJ
- NLSE solved with split-step & Runga-Kutta 4th order and adaptive step

Optical-to-RF Conversion

or

Optical-to-RF Locking

RF Extraction by direct detection

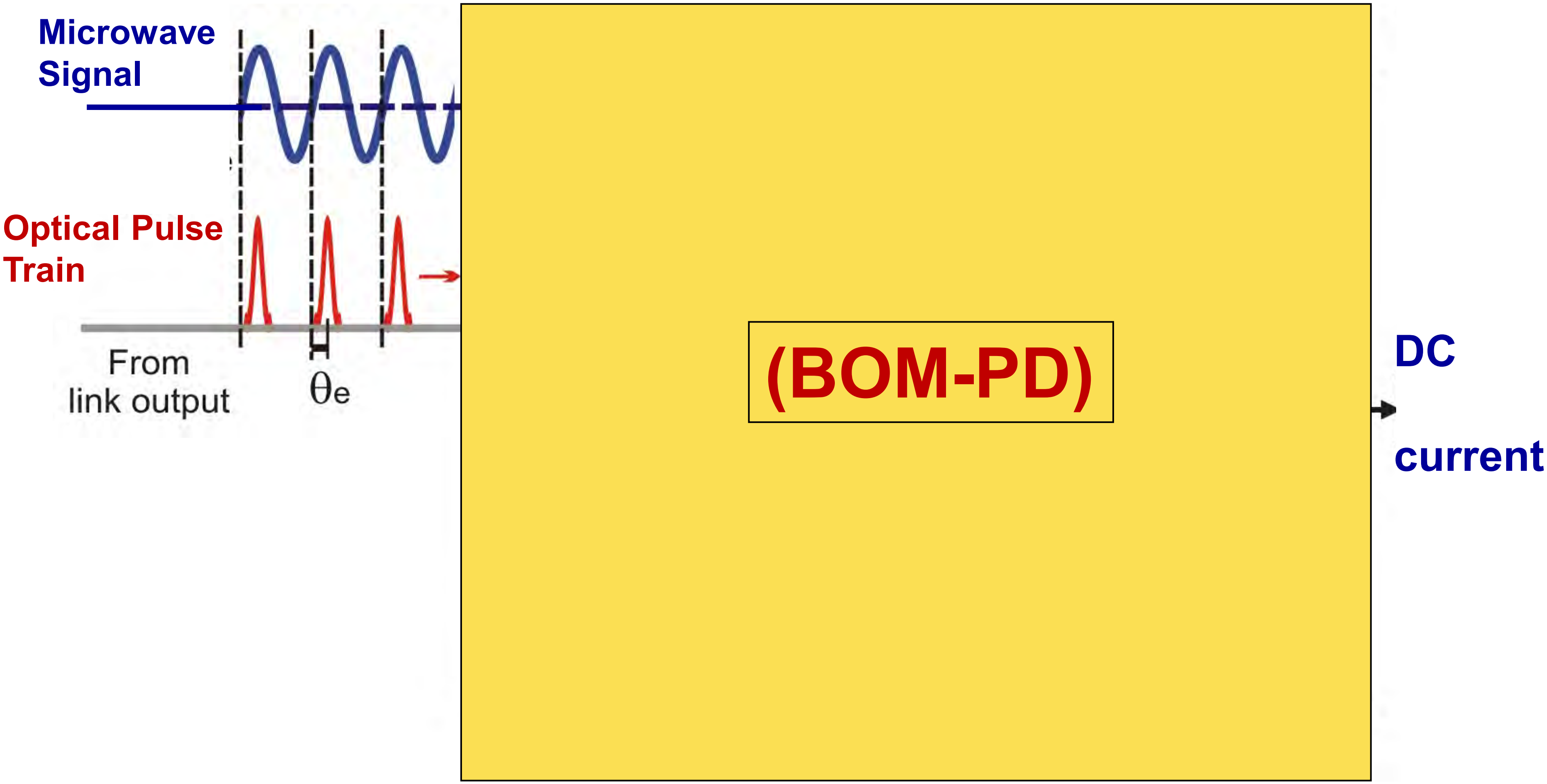


200 MHz
Er-fiber
ML laser

AM to PM conversion
Thermal Drift

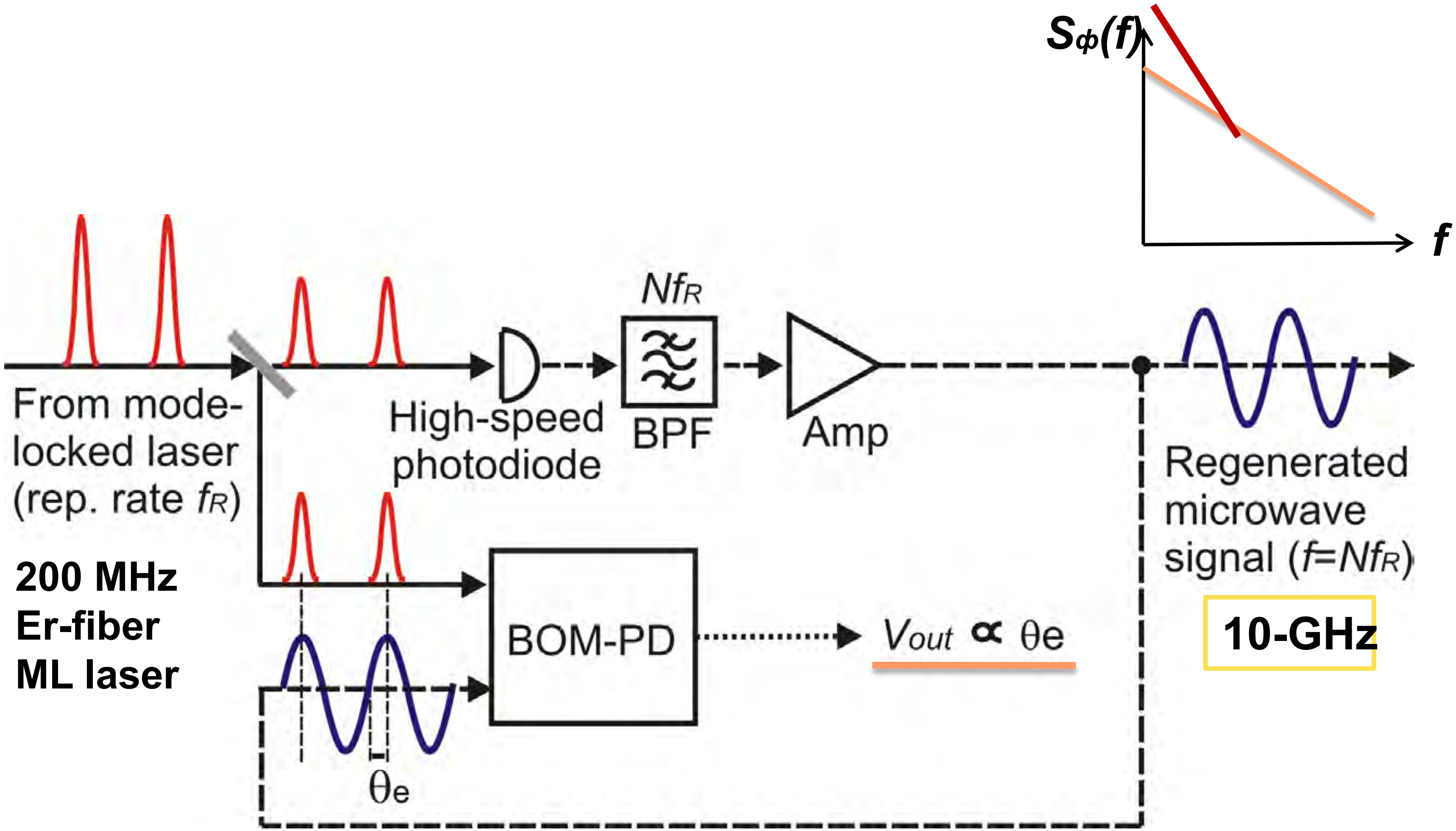
10-GHz

Balanced Optical-Microwave Phase Detector



Electro-optic sampling of microwave signal with optical pulse train

Delay-locked loop (DLL) for excess noise suppression



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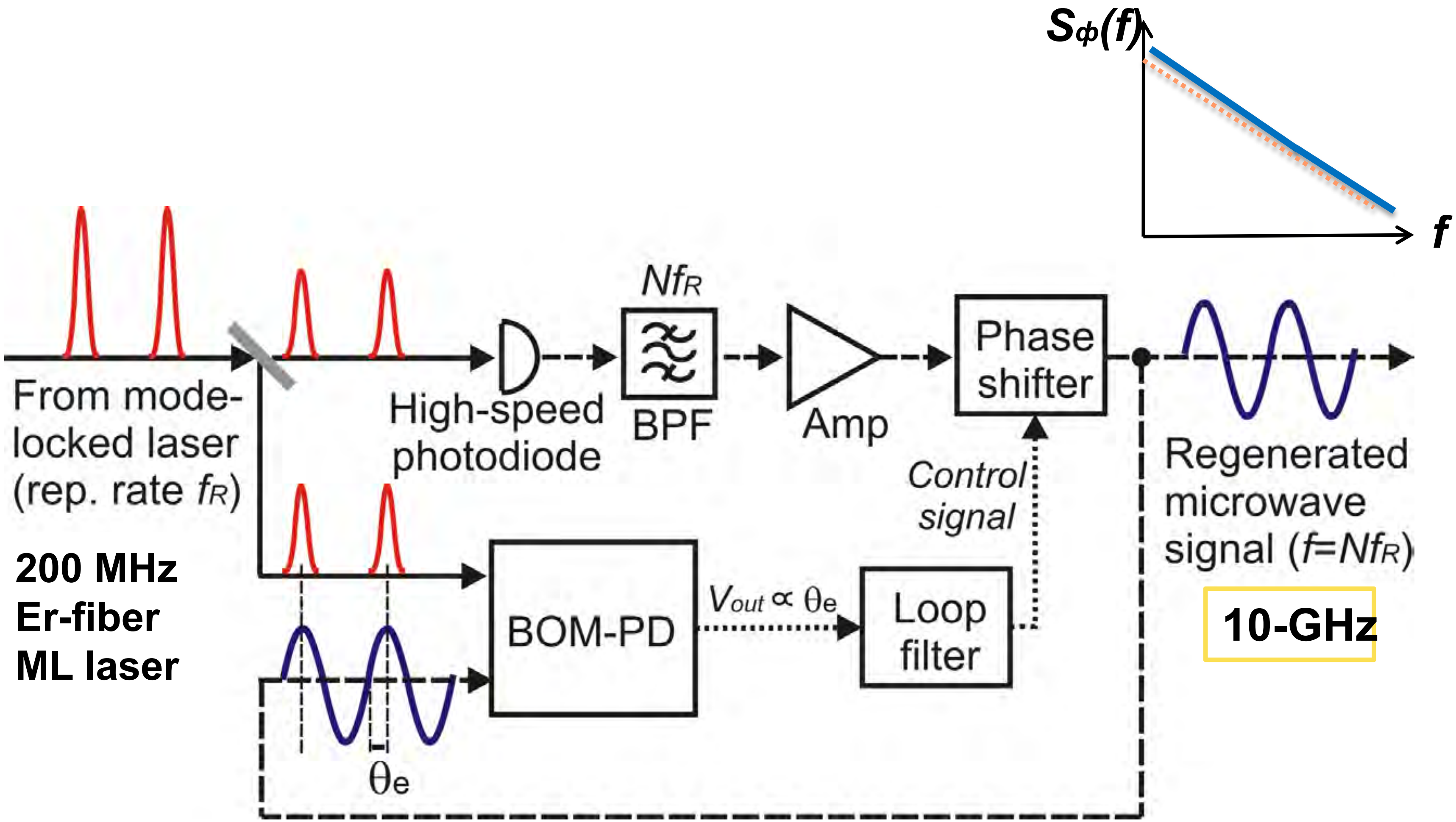
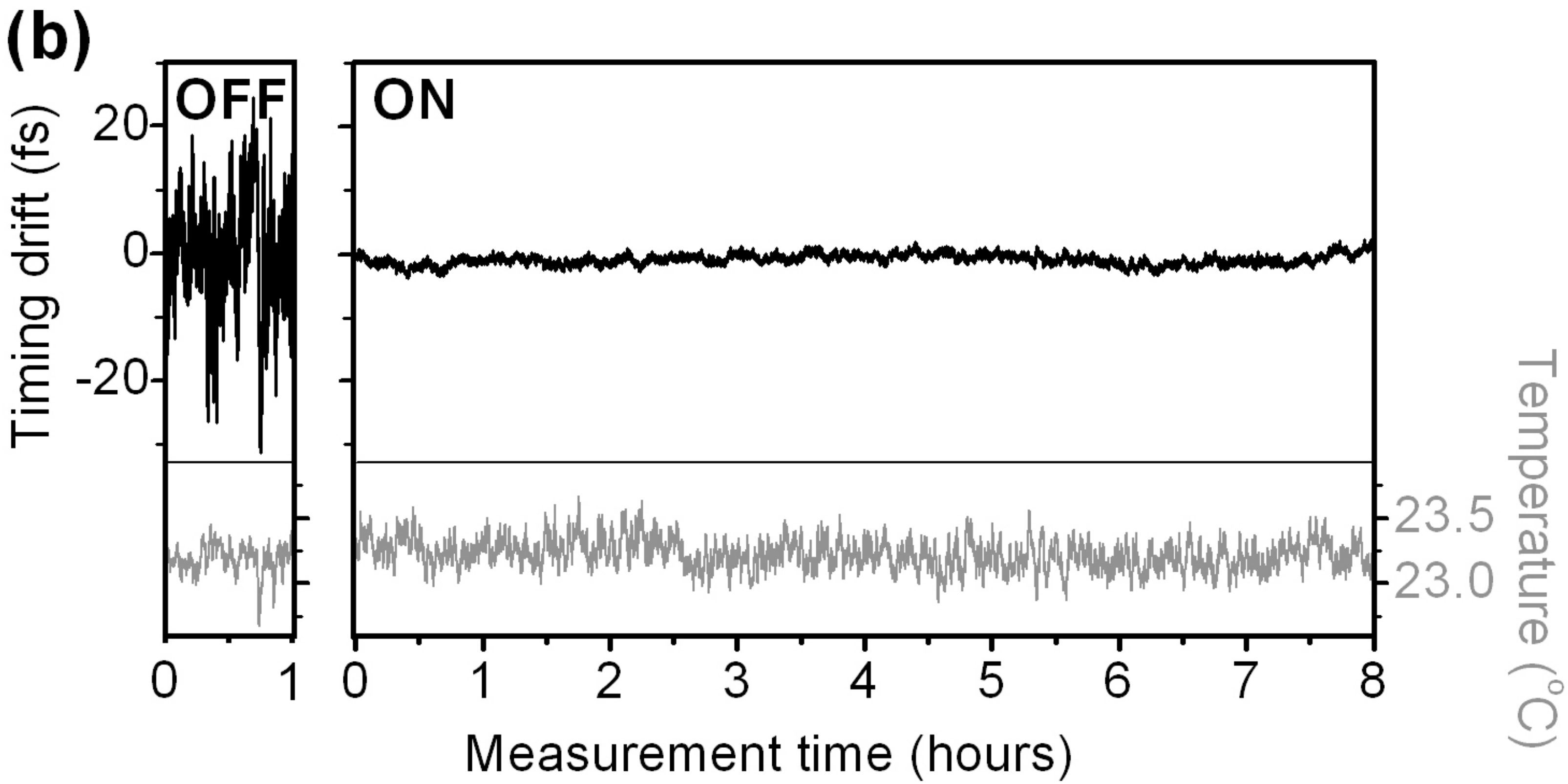


Delay Locked Loop: 3 fs drift over 8 hours

RMS timing jitter integrated in 0.1 Hz – 1MHz, 2.4 fs



J. Kim et al. Opt. Lett. 35, (2010).

Attosecond Jitter?

How do we get to Attosecond Jitter Lasers?

$$\frac{d}{dt} < \Delta t_{ML}^2 > \approx \tau^2 \cdot \frac{1}{W_{pulse}} \cdot \frac{\hbar\omega_c}{\tau_{cav}}$$

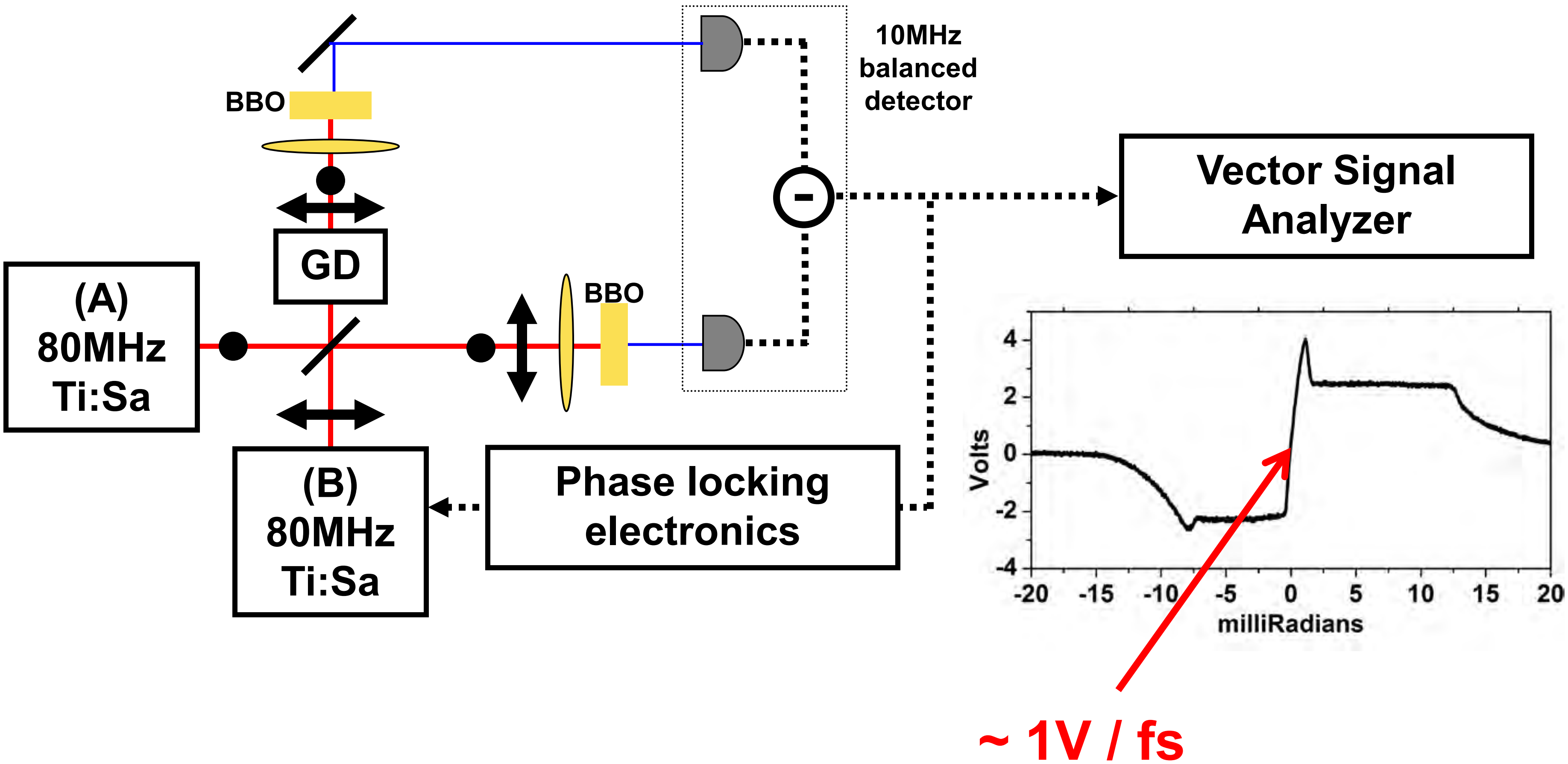
Intracavity losses down (Factor of 50)

Intracavity energy up (Factor of 50)

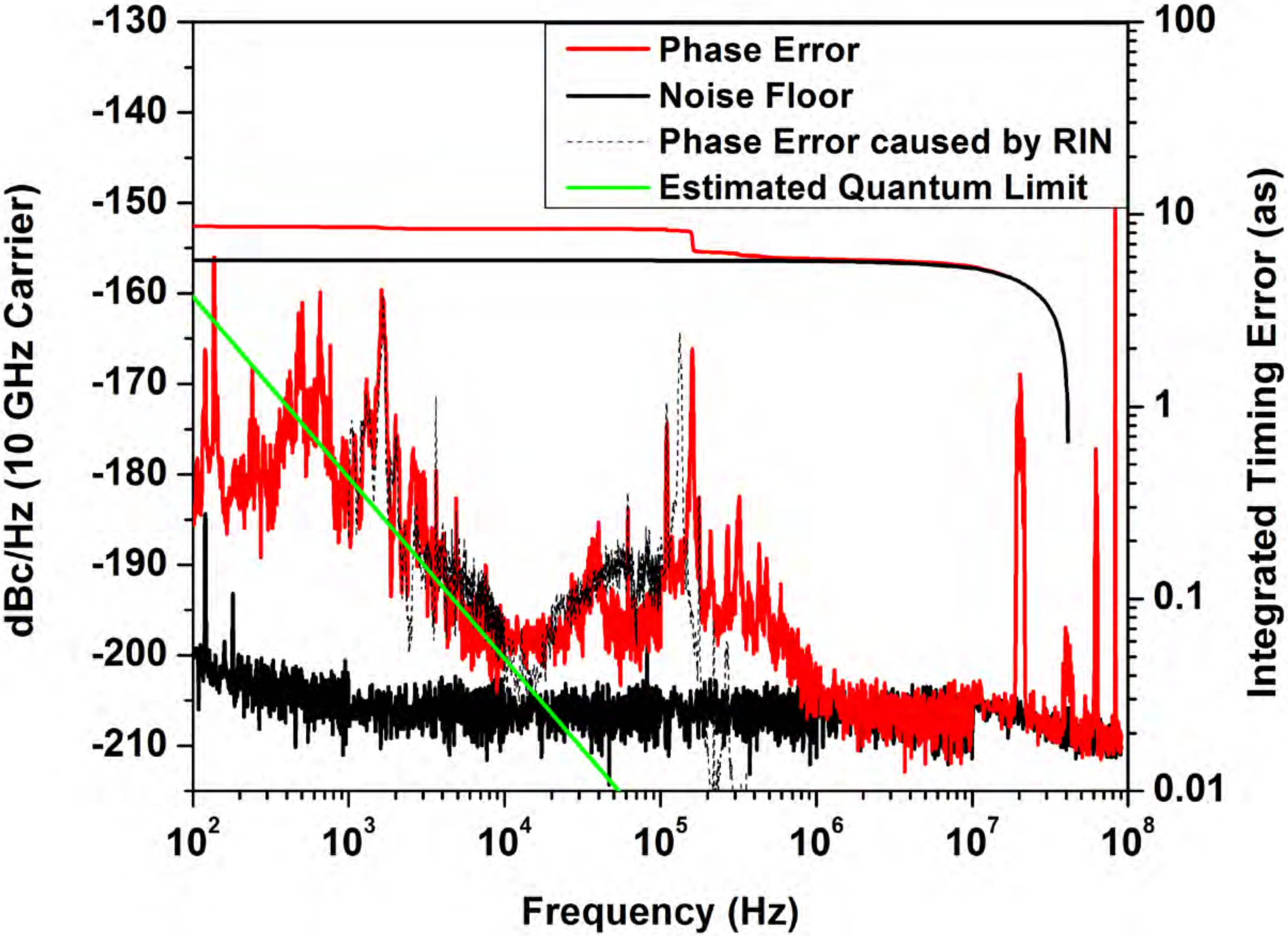
10-fs pulses (Factor of 100)

$\sim 10^6$ Is it true?

Timing Jitter of 10 fs Ti:sapphire Lasers



Timing Jitter and Laser Synchronization < 13 as



Conclusions

- Fundamental jitter in modelocked lasers is really low!
- Fiber lasers ~ 1 fs jitter for frequencies > 10 kHz
- Solid-state lasers ~ 10 as jitter for frequencies > 10 kHz (pump noise limited)

  Potential for < 1 as jitter!

- Long term stable timing distribution systems (X-ray FELs), 10 fs today
- Typical fiber lasers as master oscillators ~ 1 fs jitter [100 kHz]
  - 300 m Fiber Links over 10 h < 3 fs
  - Optical-to-Optical Synchronization over 12 h < 0.5 fs
  - Optical-to-Microwave Synchronization over 10 h < 3 fs

Thank You!