Attosecond Timing

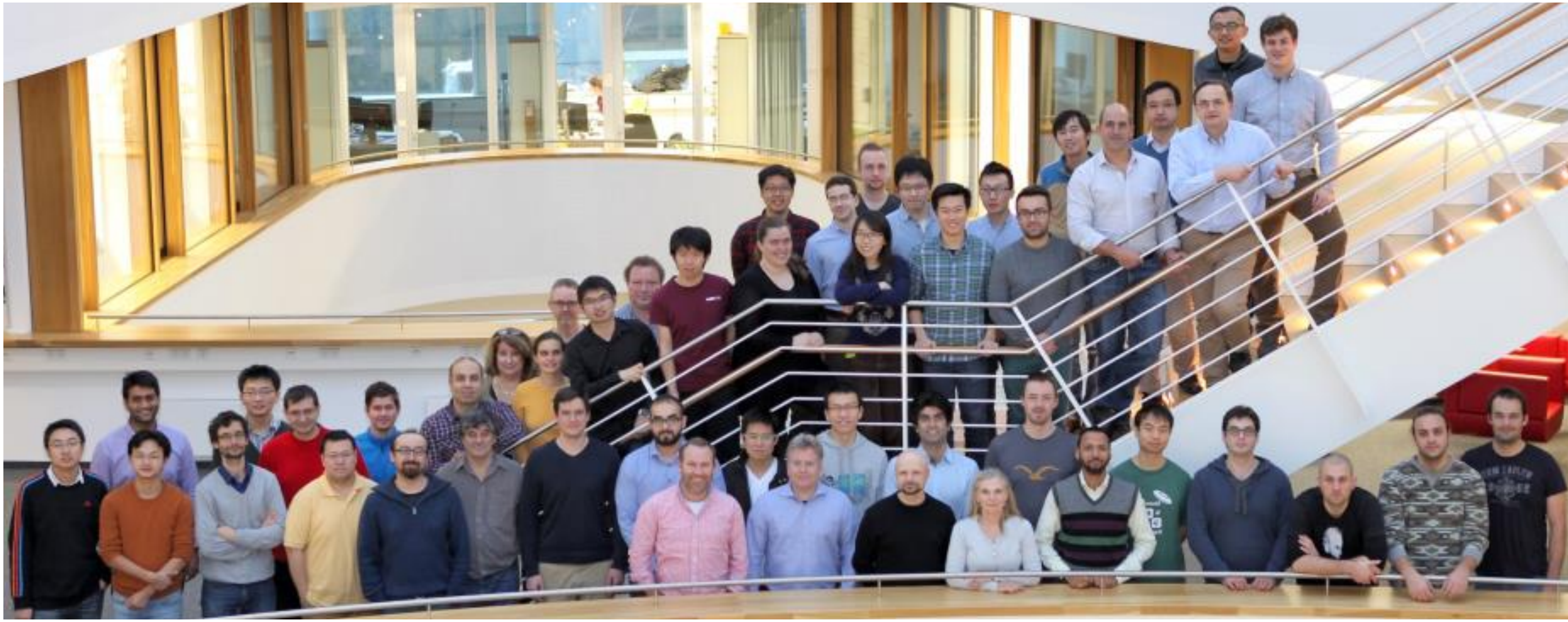
Franz X. Kärtner[1,2], Kemal Shafak[1,2] and Ming Xin[1]

Center for Free-Electron Laser Science (CFEL), DESY, Hamburg, Germany
Ultrafast Optics and X-Rays Group

Department of Physics and The Hamburg Center for Ultrafast Imaging,
University of Hamburg, Germany
and
Cycle GmbH

FLS Meeting 2018, March 5-9, Shanghai, China

Ultrafast Optics and X-Rays Group

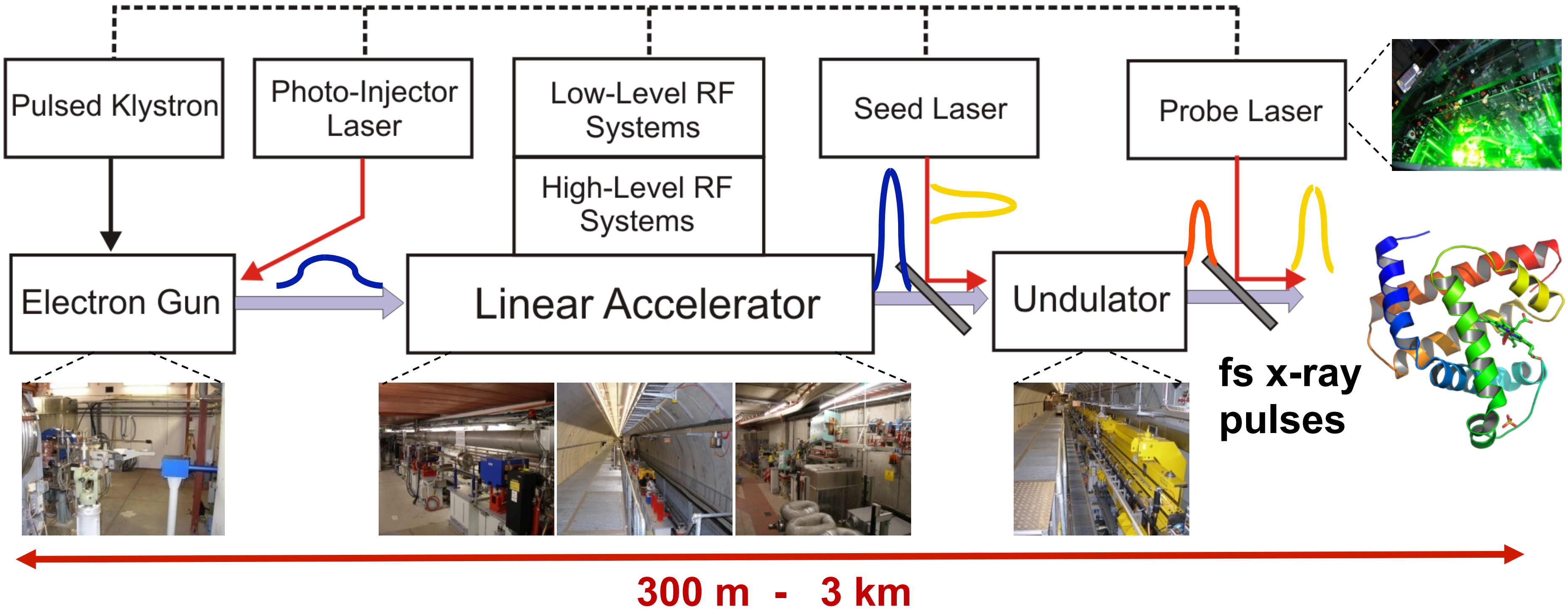


Early work: J. Kim (KAIST), J. Cox (Sandia Lab.), A. Benedick (MIT-LL), M. Peng (JPL)
Students: P. Callahan, K. Safak (Cycle), A. Kalaydzhyan, W. Wang (UCLA), T. Braatz
Postdocs: Q. Zhang and **Research Scientists:** M. Xin and O. Mücke

DESY: H. Schlarb, C. Sydlo, M. Felber, F. Ludwig, A. Winter
AdvR: P. Battle, B. Jones, T. Roberts, D. Walsh

The Timing Challenge

Seeded X-Ray FELs

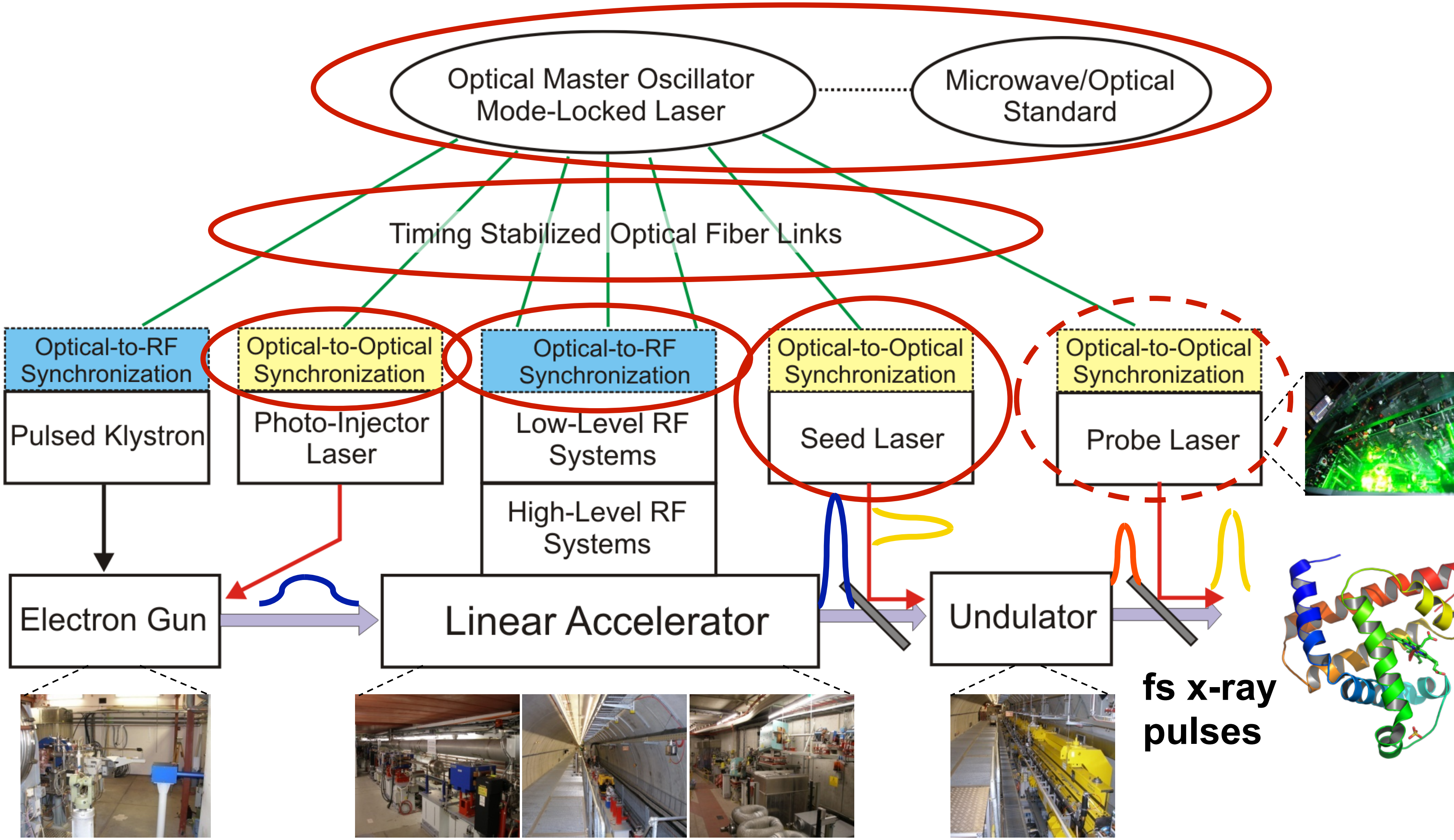


Long-term sub-10 fs synchronization over entire facility desired.

Upcoming Attosecond FELs → sub-fs synchronization

Seeded FELs are a reality with FERMI

Timing Distribution, Seeding and Probing



J. Kim et al, FEL 2004.

Other approaches: R. Wilcox, LBNL, cw-distribution

Pulsed timing and synchronization

Femtosecond lasers are very low jitter:

- High intracavity pulse energy
- High Q Cavity
- 10 - 100 fs pulses, good time markers

→ sub-femtosecond jitter for f > 1kHz

Balanced optical cross correlation:

- High timing sensitivity (zeptoseconds)
- low drift (only dielectrics involved)
- attosecond laser to laser locks

→ attosecond laser-to-laser locks and fiber links

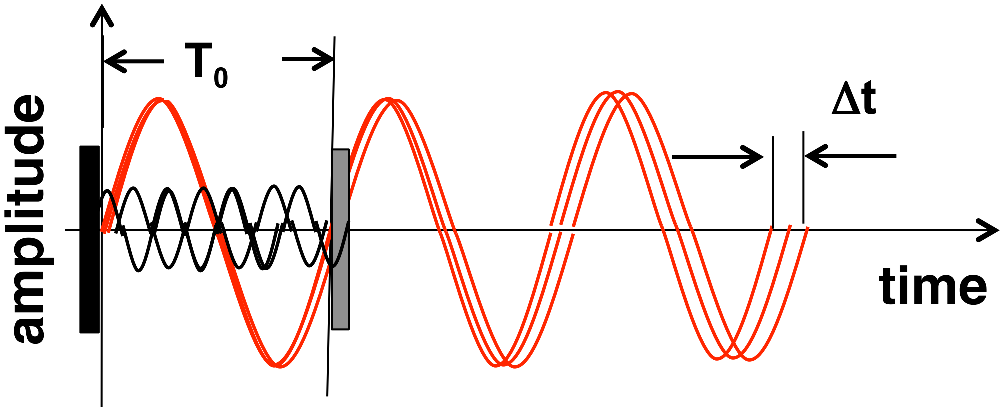
Balanced optical microwave phase detection:

- sub-femtosecond jitter microwaves

J. Kim, et al. Nat. Photonics 2, 733 (2008).
Light: Science & Applications, doi: 10.1038/lsa.2016.187.

Timing Jitter of Femtosecond Lasers

Electronic Oscillator



Dissipation-Fluctuation Theorem

$$\frac{d}{dt} < \Delta t_{RF}^2 > \approx T_0^2 \cdot \frac{1}{W_{mode}} \cdot \frac{kT}{\tau_{cav}}$$

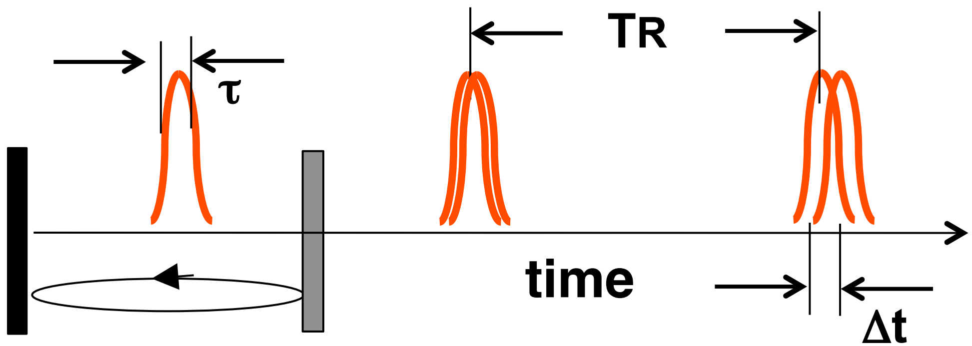
period ~100ps

cavity lifetime

10 $^{-6}$

Femtosecond Laser

pulse width ~100fs



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

Optical Cavity

10 $^{-4}$

$$\hbar\omega_c \sim 50kT$$

kT = **thermal energy**

$\hbar\omega_c$ = **photon energy**

H. A. Haus and A. Mecozzi, IEEE JQE *29, 983* (1993).
J. Kim and F. X. Kärtner, Laser & Phot. Rev., 1–25 (2009).

How Do We Measure Low Jitter?

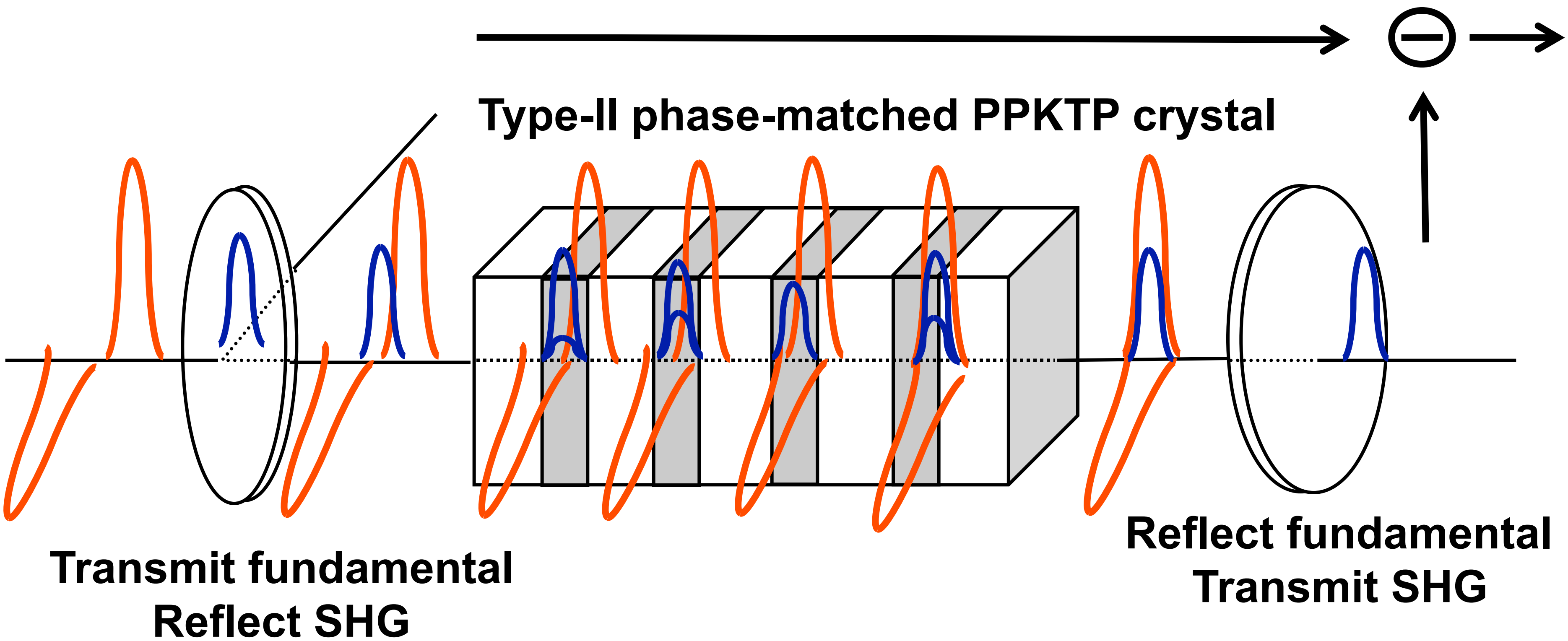
Sensitive Time Delay Measurements

by

Balanced Optical Cross Correlation

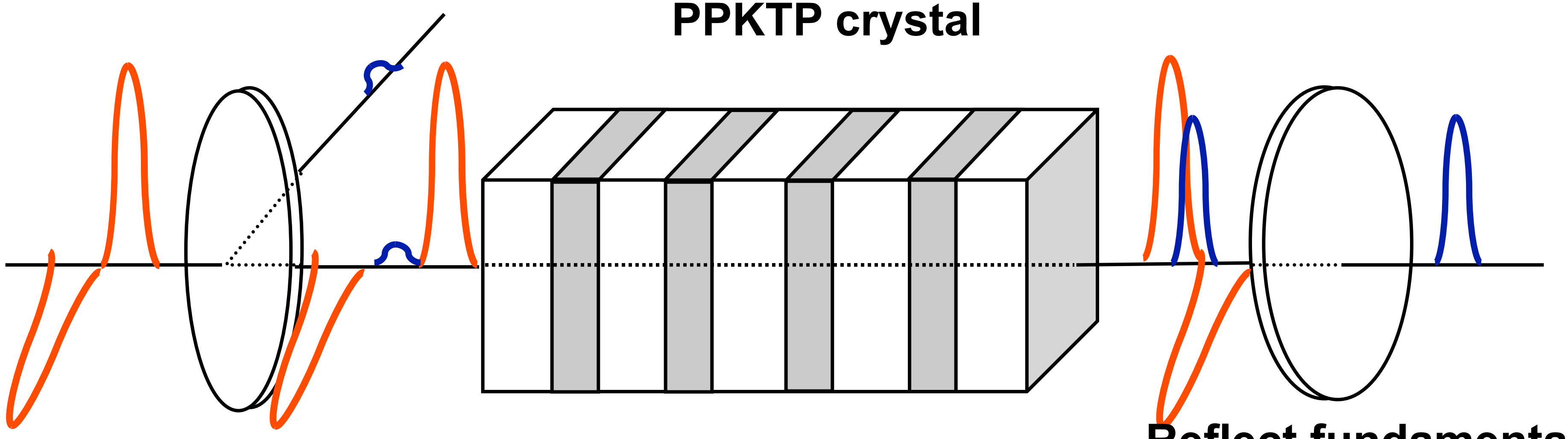
Single-crystal balanced cross-correlator

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



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

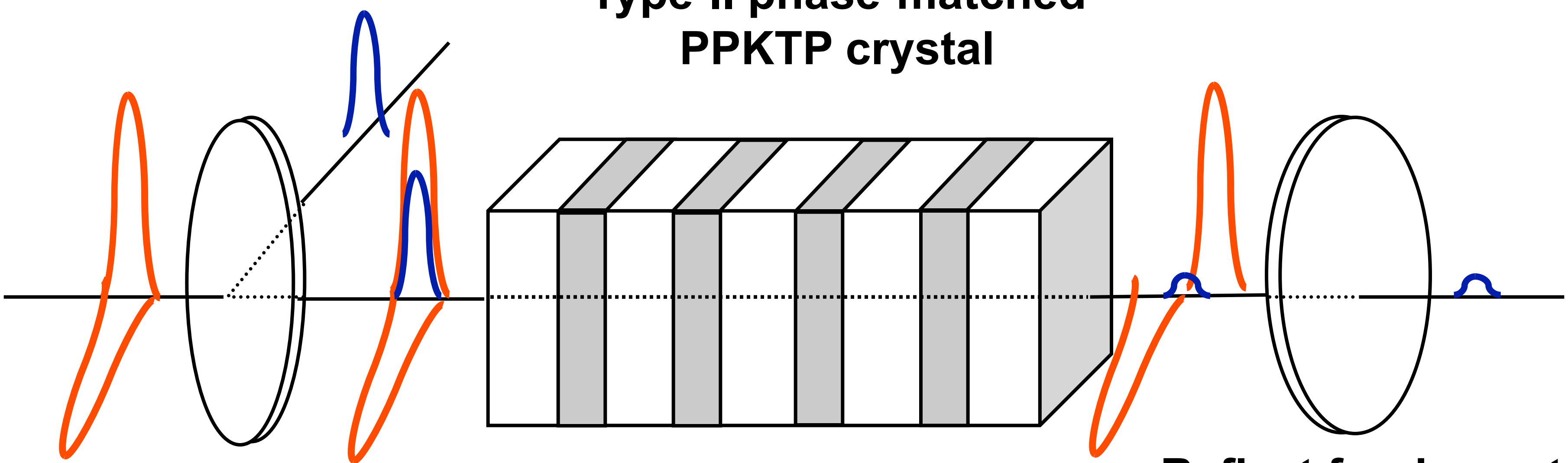
Single-crystal balanced cross-correlator



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

Single-crystal balanced cross-correlator

Type-II phase-matched
PPKTP crystal

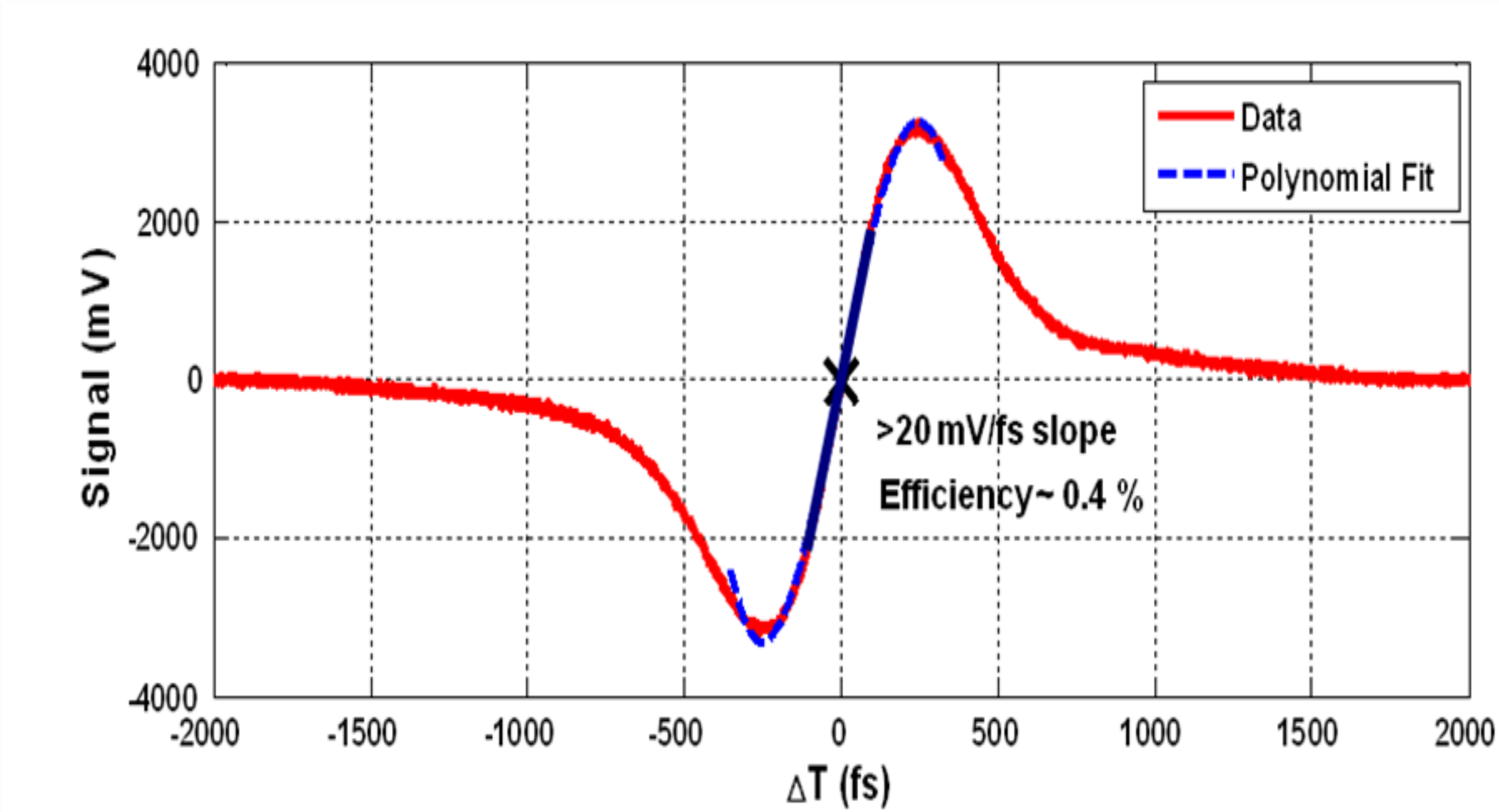


Transmit fundamental
Reflect SHG

Reflect fundamental
Transmit SHG

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

Single-crystal balanced cross-correlator

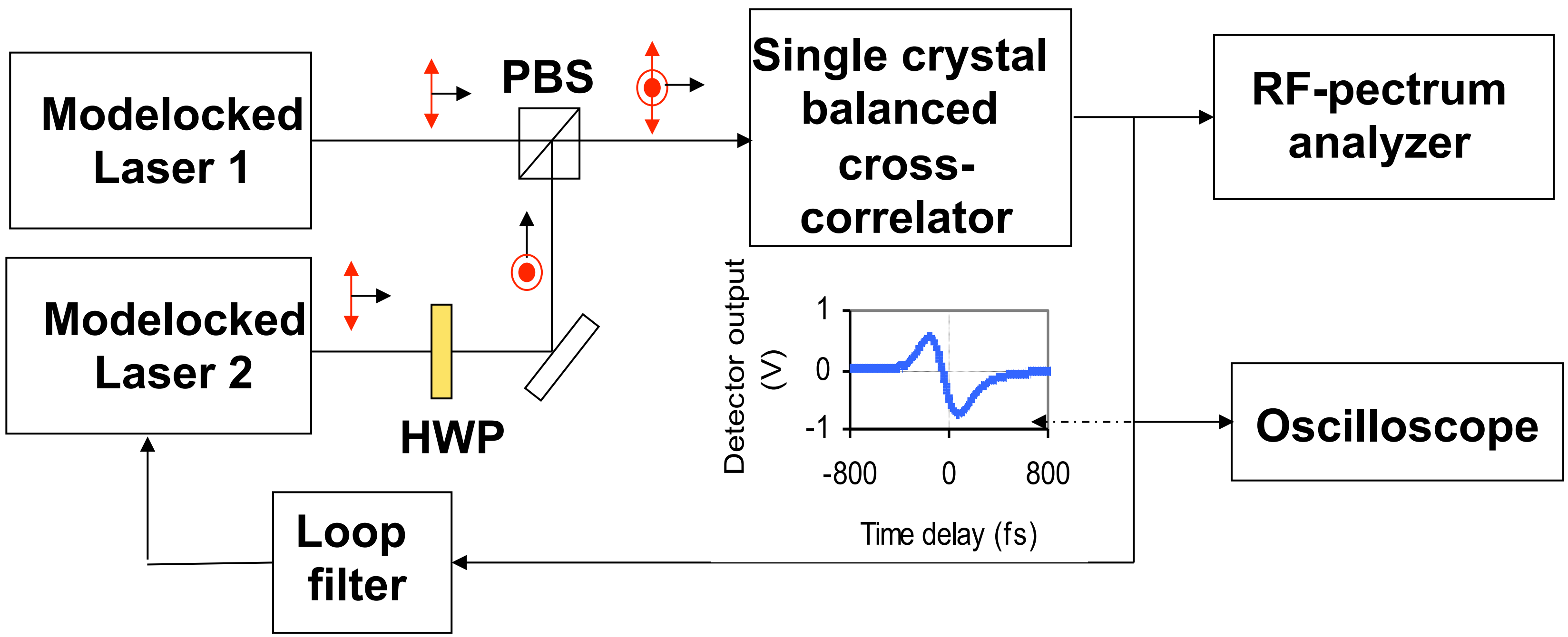


80 pJ, 200 fs
1550nm input pulses
at 200 MHz rep. rate

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

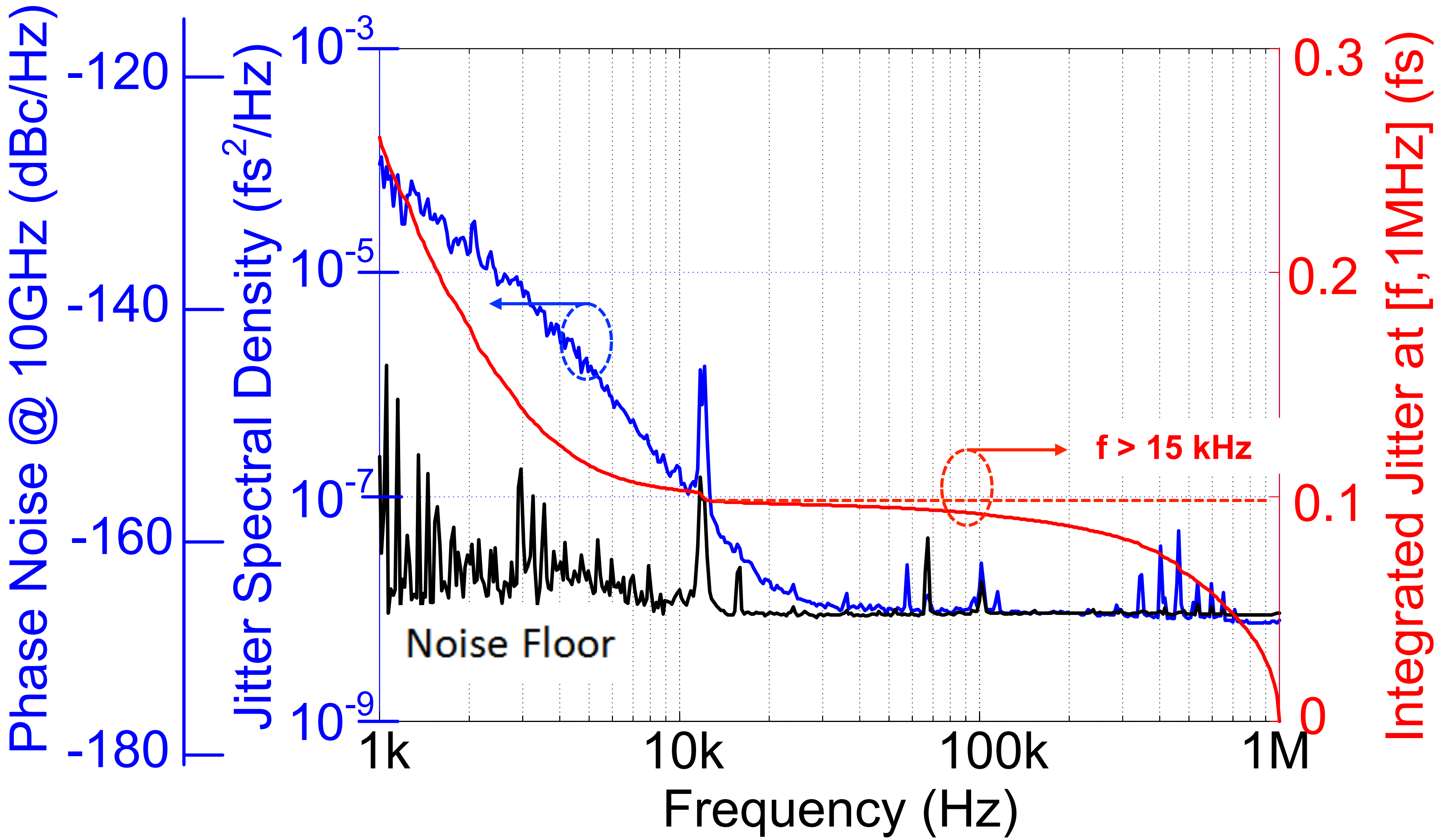
Timing jitter of lasers

Phase detector method → Timing Detector method

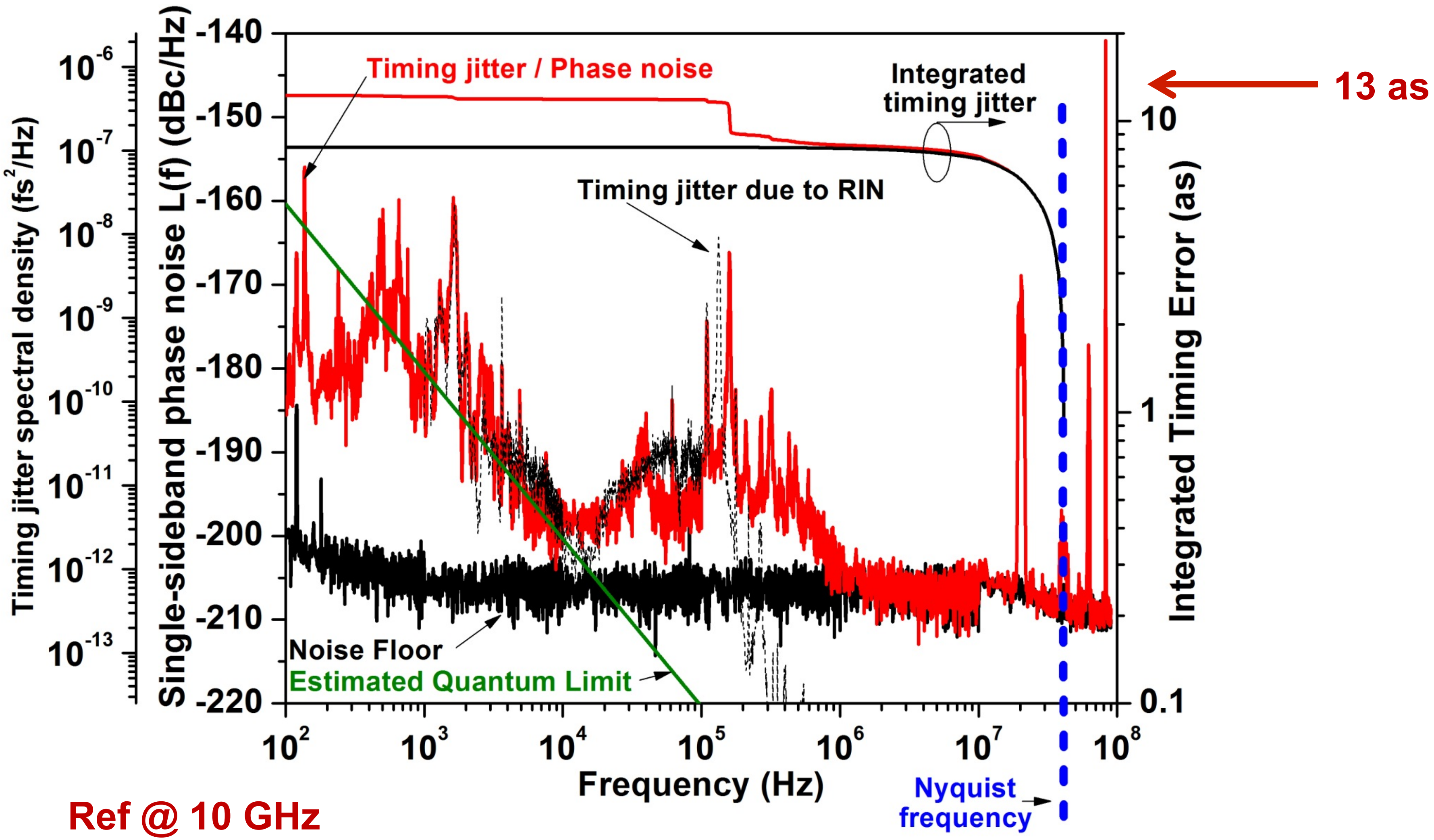


J. Kim, et al. , Opt. Lett. 32, 3519 (2007).

Timing jitter of OneFive:Origami Laser



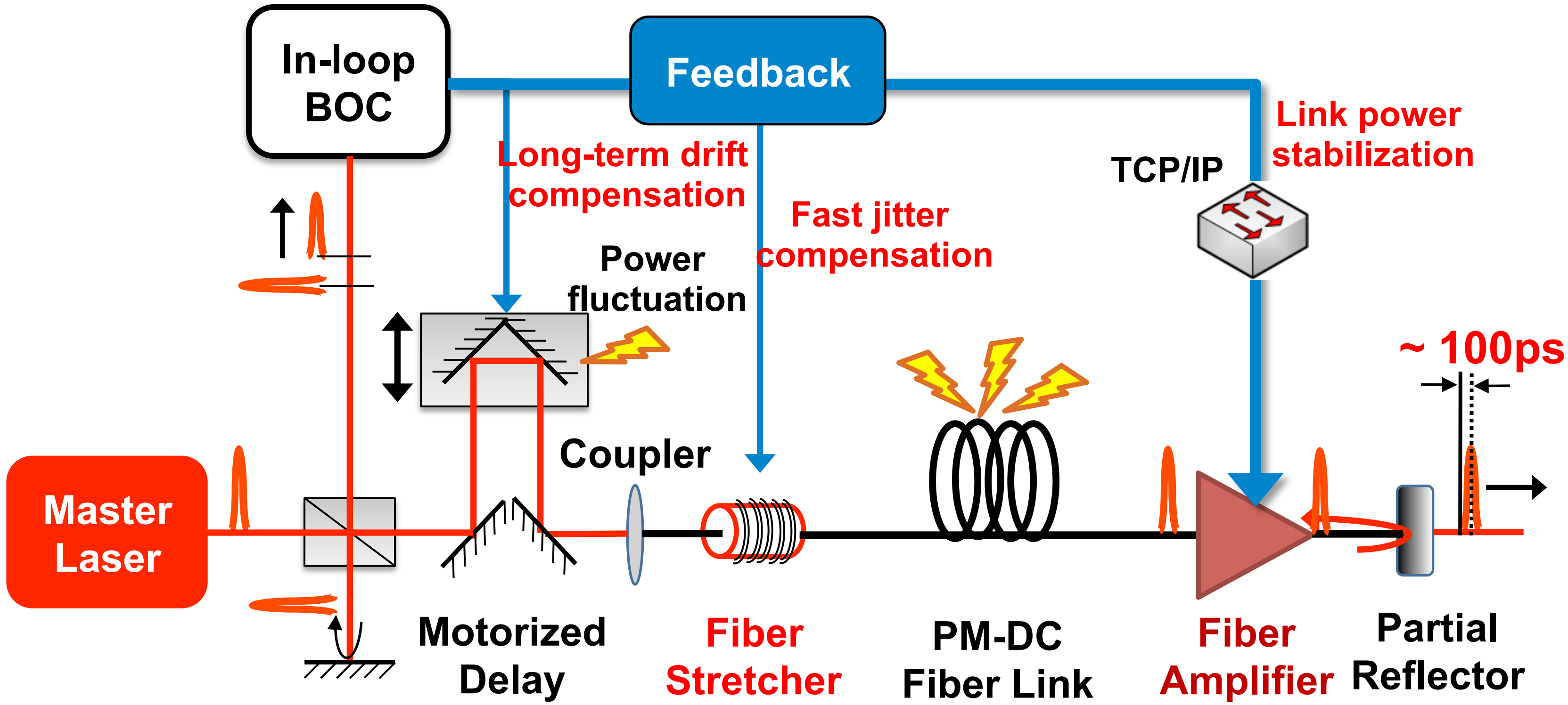
Two 10-fs Ti:Sapphire Lasers Synchronized within 13 as



Ref @ 10 GHz

A. Benedick, et al. Nat. Phot. 6, 97-100, 2012

Timing-stabilized fiber links



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

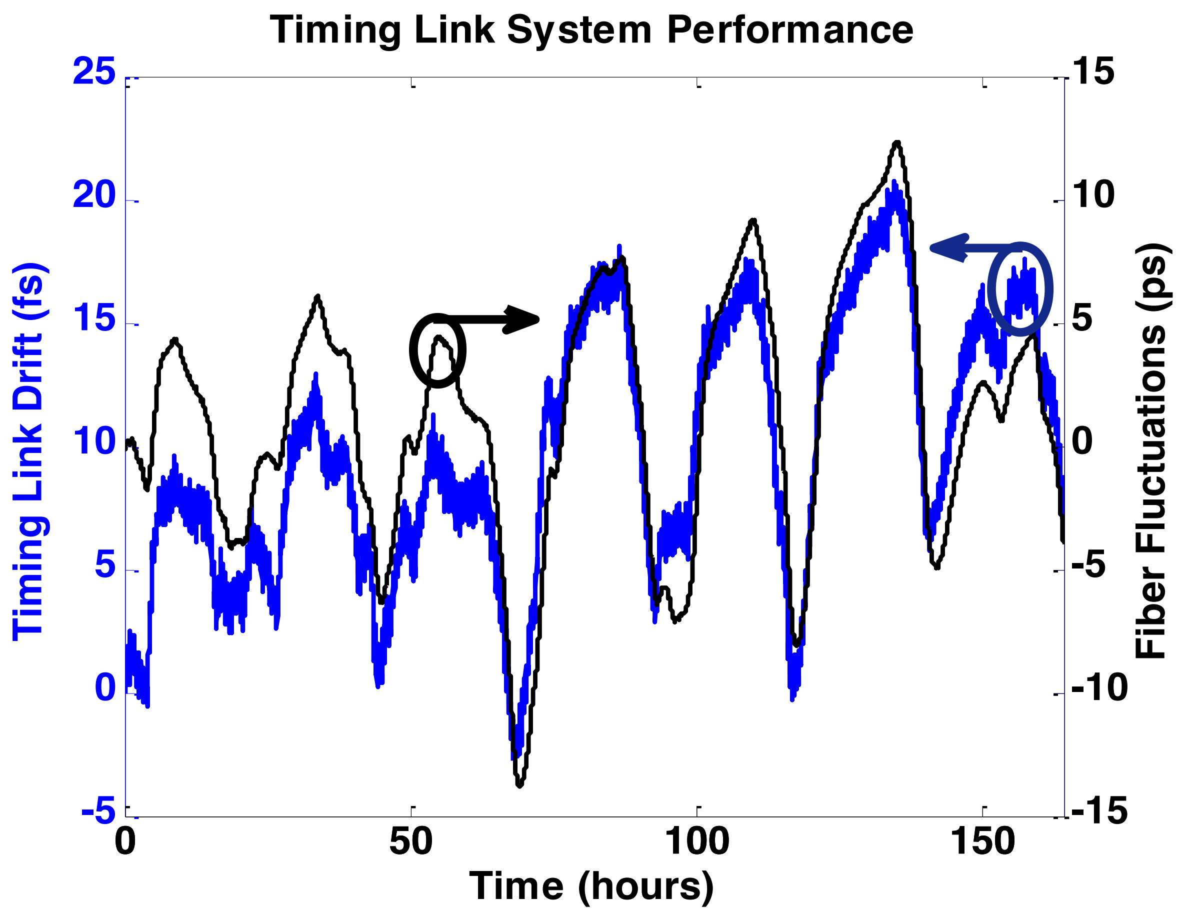
1 km fiber: travel time = 10 μs → ~100 kHz BW

Free Space
Fiber
Electrical Path

PM-DC: Polarization-maintaining dispersion-compensated

J. Kim et al., Nat. Phot., 2, 12 (2008).

1-week operation with SMF/DCF

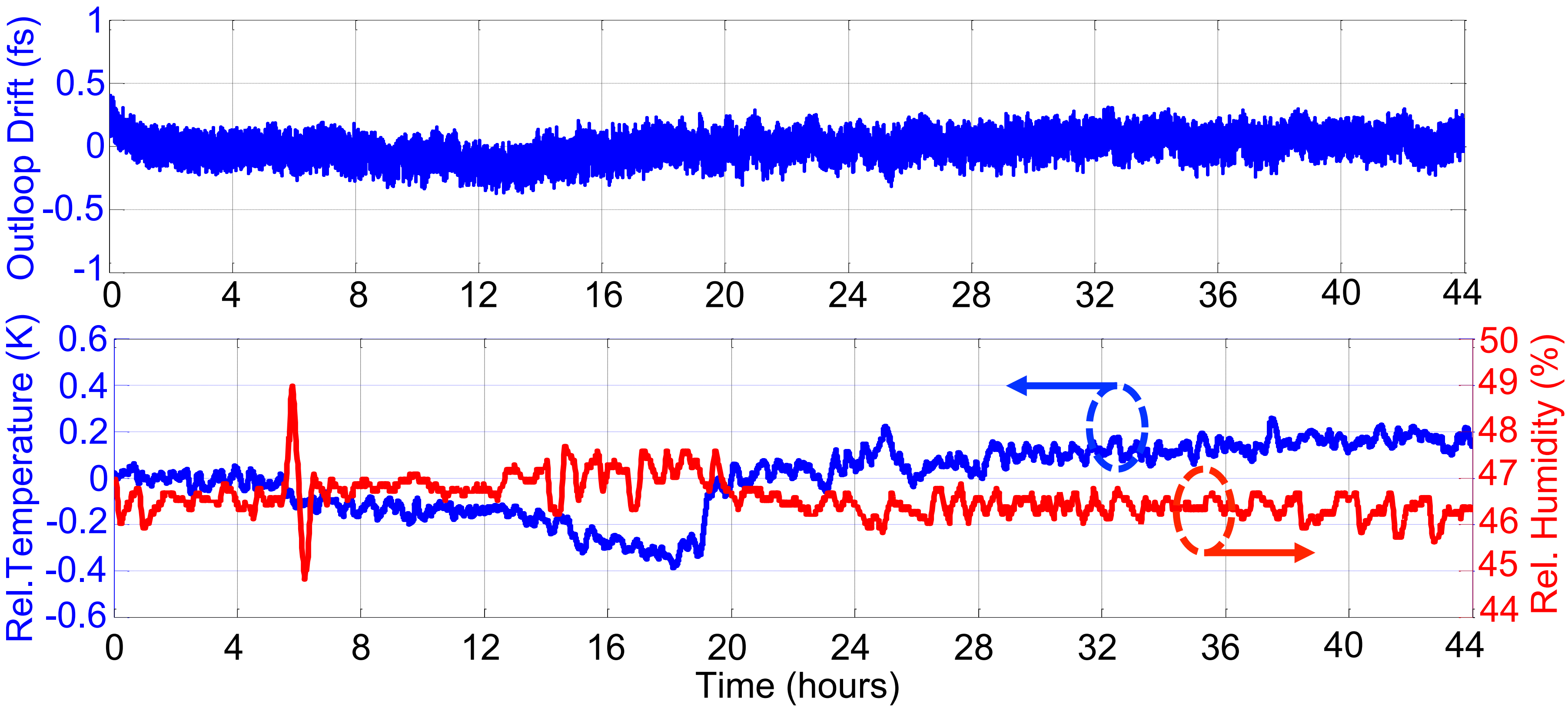


5 fs (rms) drifts over one week of operation

FLASH, FERMI, and tests at PAL and LCLS (2008-2014)

High precision PM-link results (OFS)

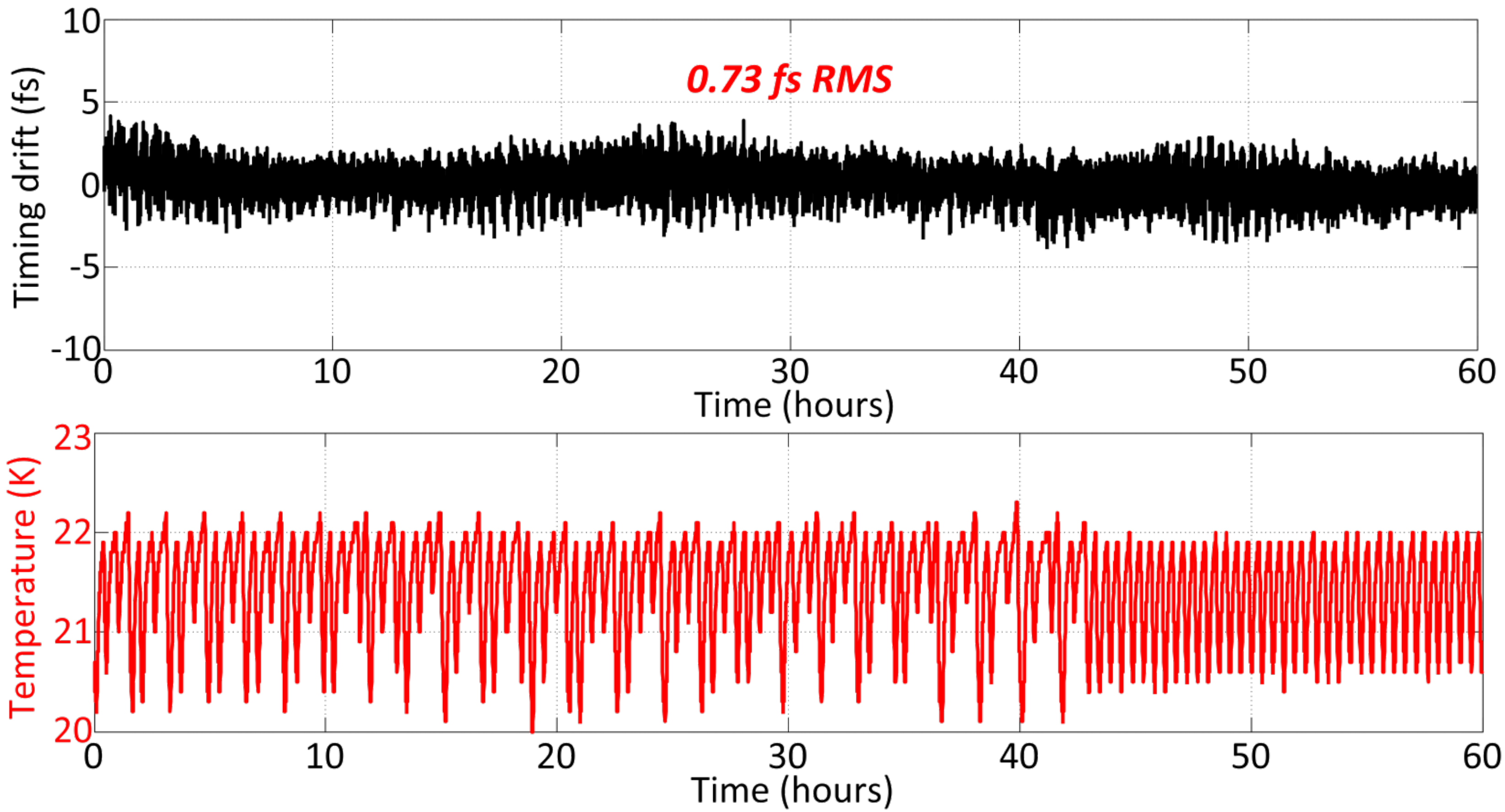
Laser-to-Laser Remote Synch.: 100 as RMS & 0.6 fs Pk-Pk drift (< 1Hz) over 44 h



M. Y. Peng et al. Opt. Exp. 21, 19982 (2013)
M. Xi et al. Opt. Exp. 22, 14904 (2014)

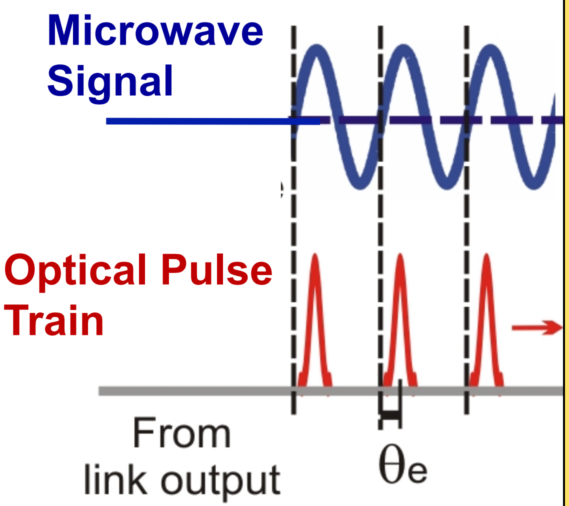
60 hours operation in commercial system

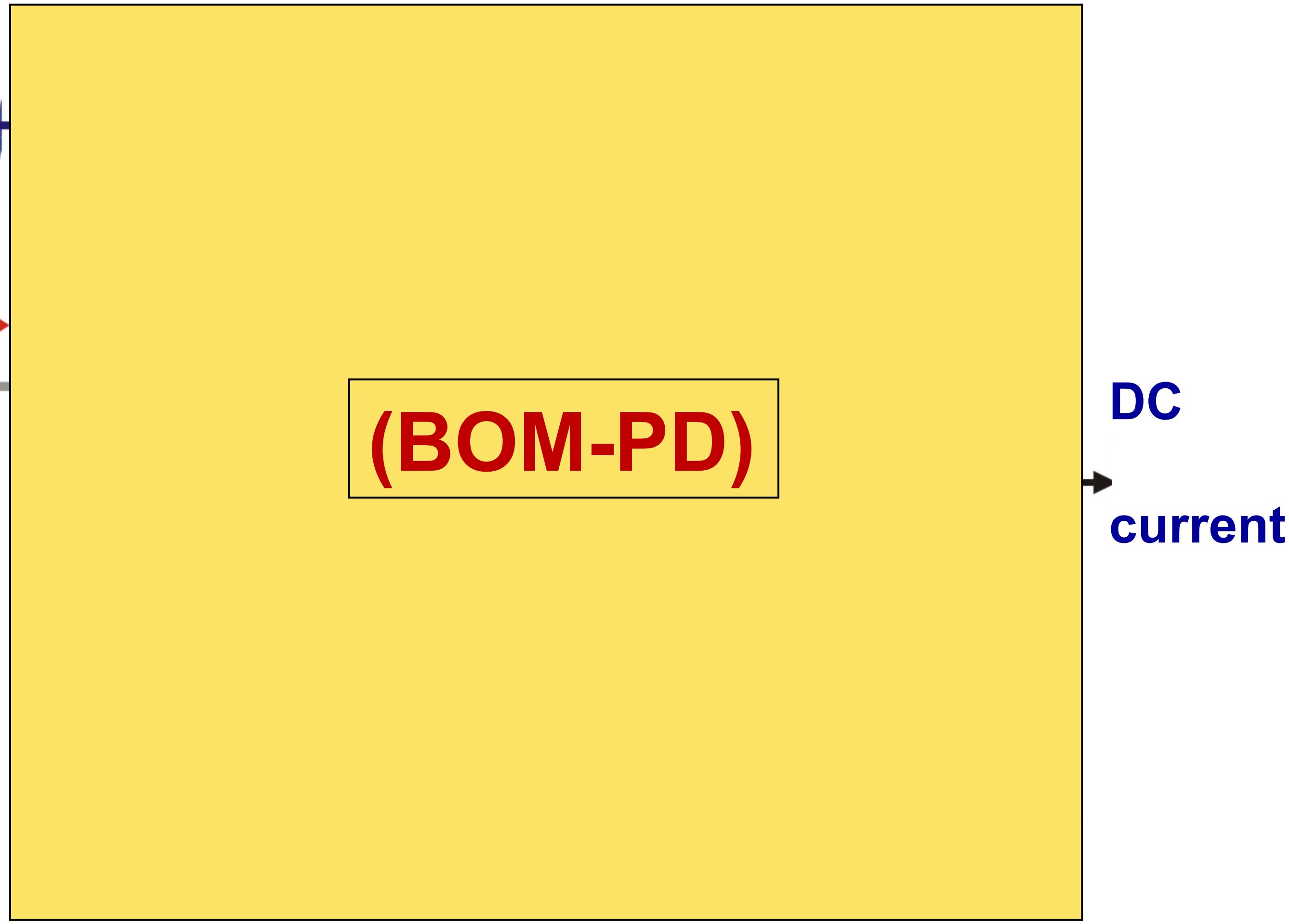
Out-off loop timing titter between two 150 m PM-links in a 16-link system



Courtesy Cycle GmbH

Balanced Optical-Microwave Phase Detector



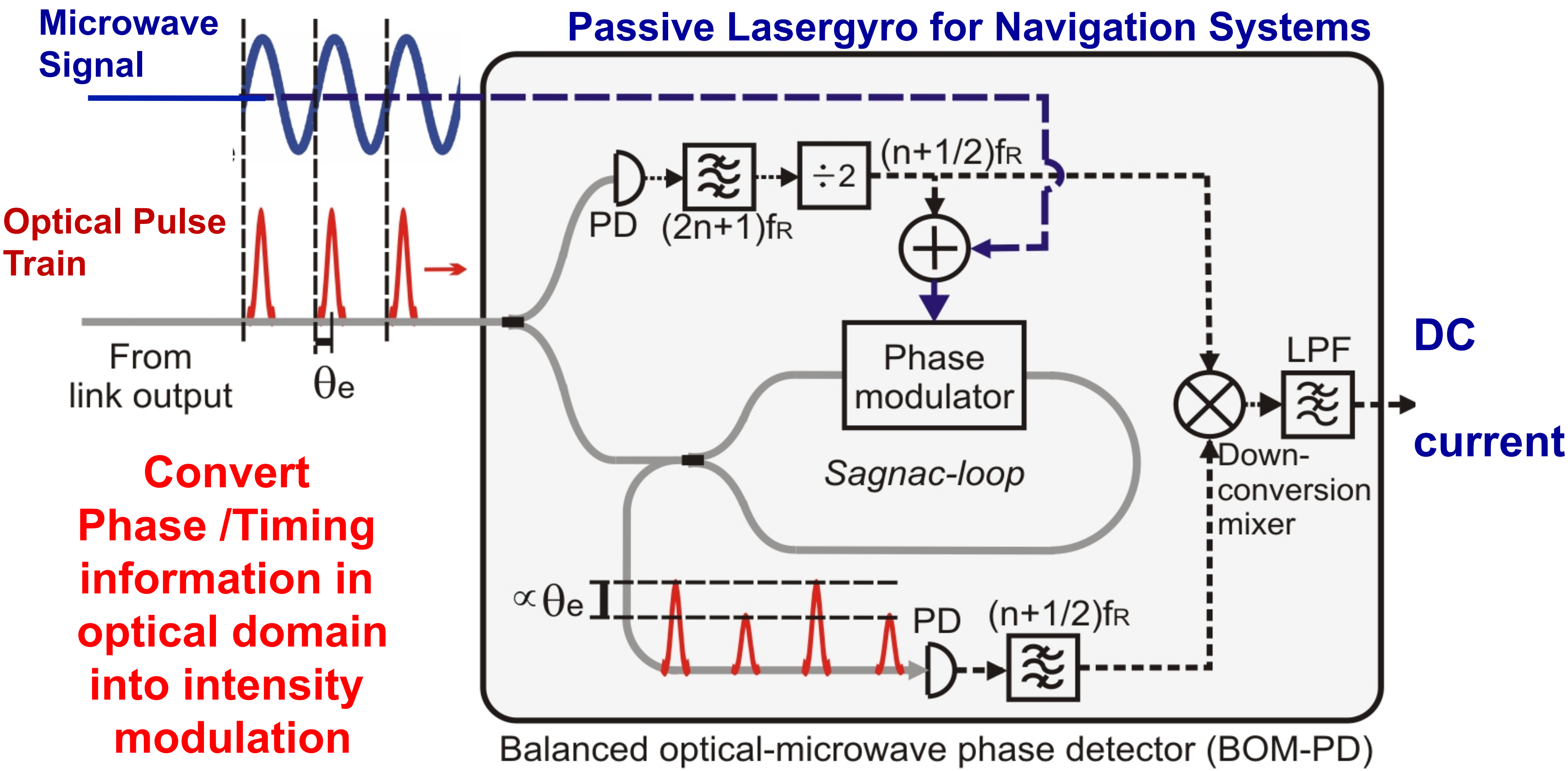


Convert Phase /Timing information in optical domain into intensity modulation

Electro-optic sampling of microwave signal with optical pulse train

J. Kim et al., Opt. Lett. **29**, 2076 (2004), **31**, 3659 (2006).

Balanced Optical-Microwave Phase Detector

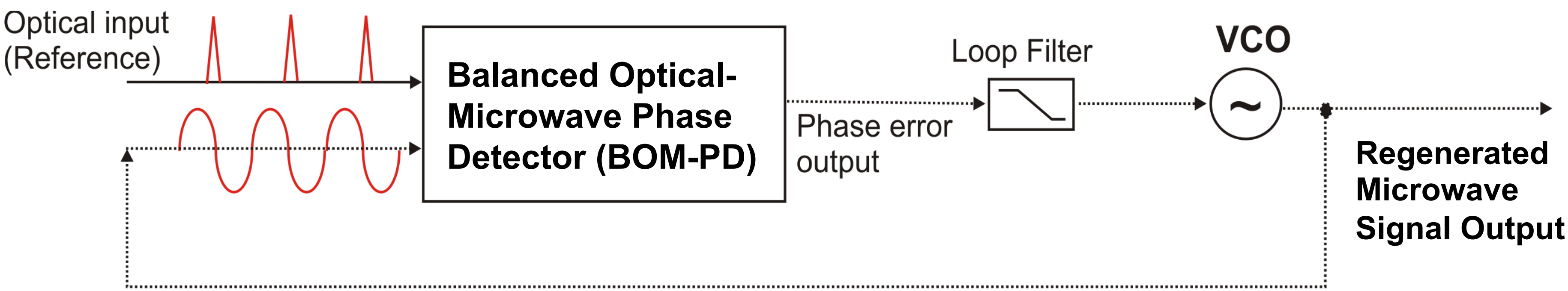


Convert Phase /Timing information in optical domain into intensity modulation

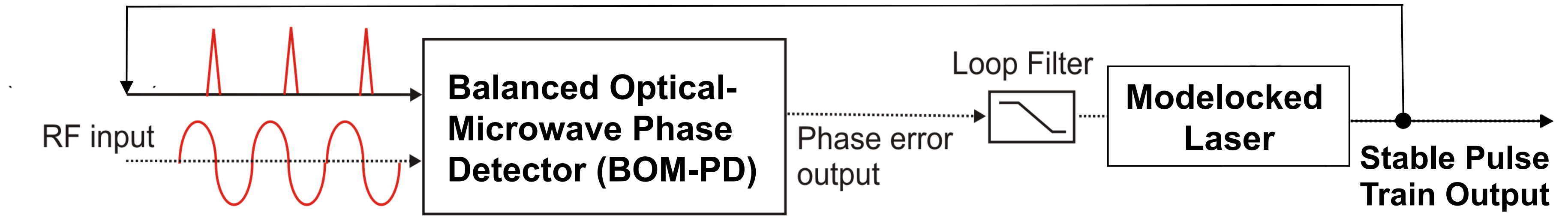
Electro-optic sampling of microwave signal with optical pulse train

Optoelectronic Phase-Locked Loop (PLL)

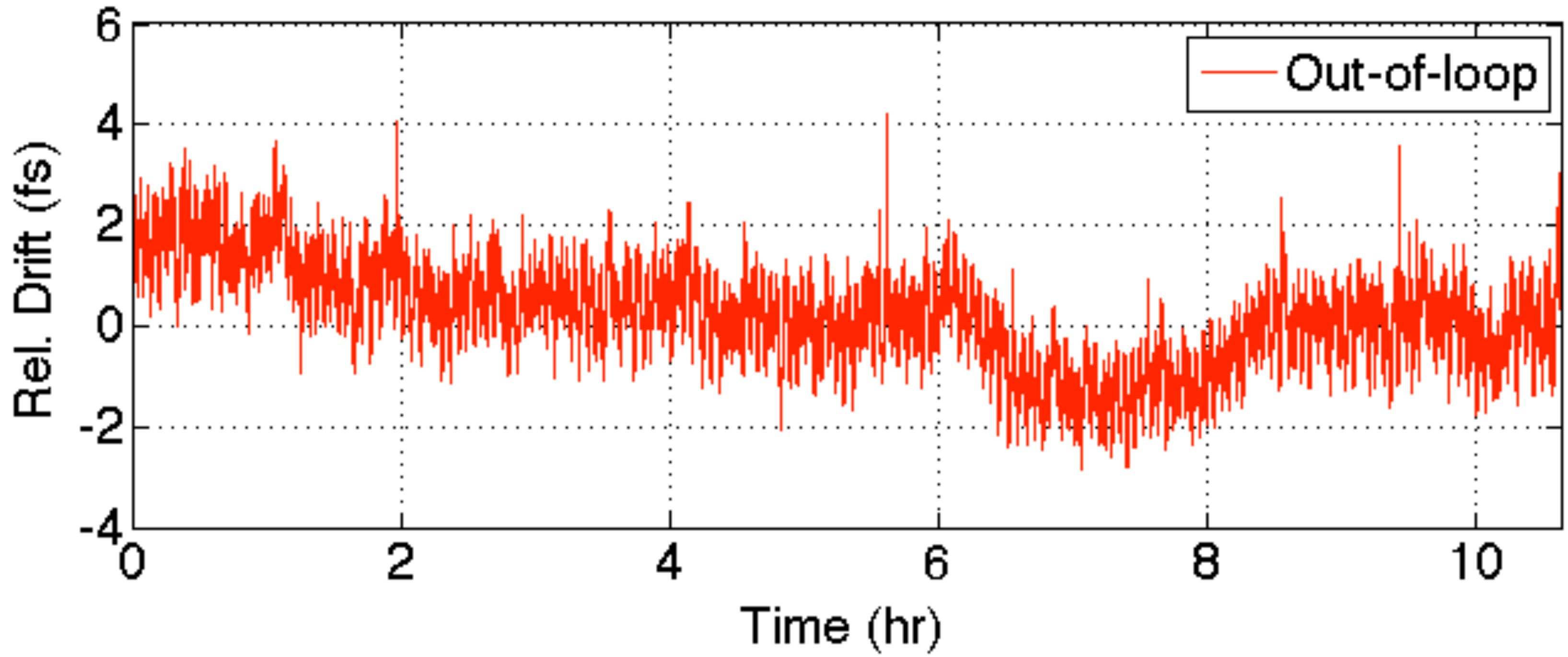
Regeneration of a high-power, low-jitter and drift-free microwave signal whose phase is locked to the optical pulse train.



Tight locking of modelocked laser to microwave reference

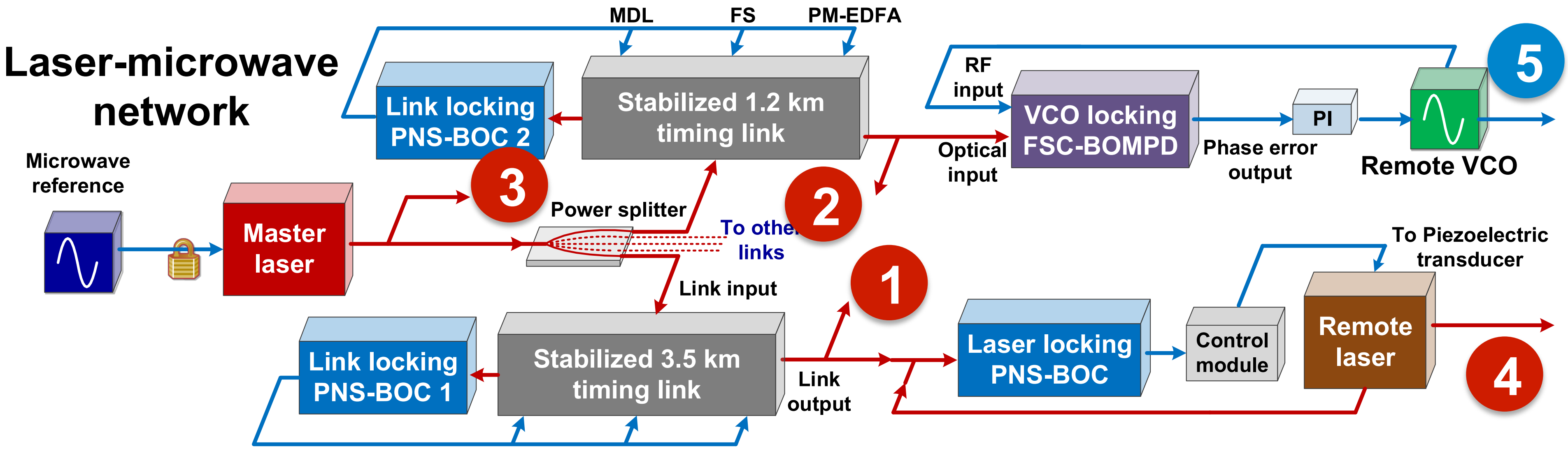


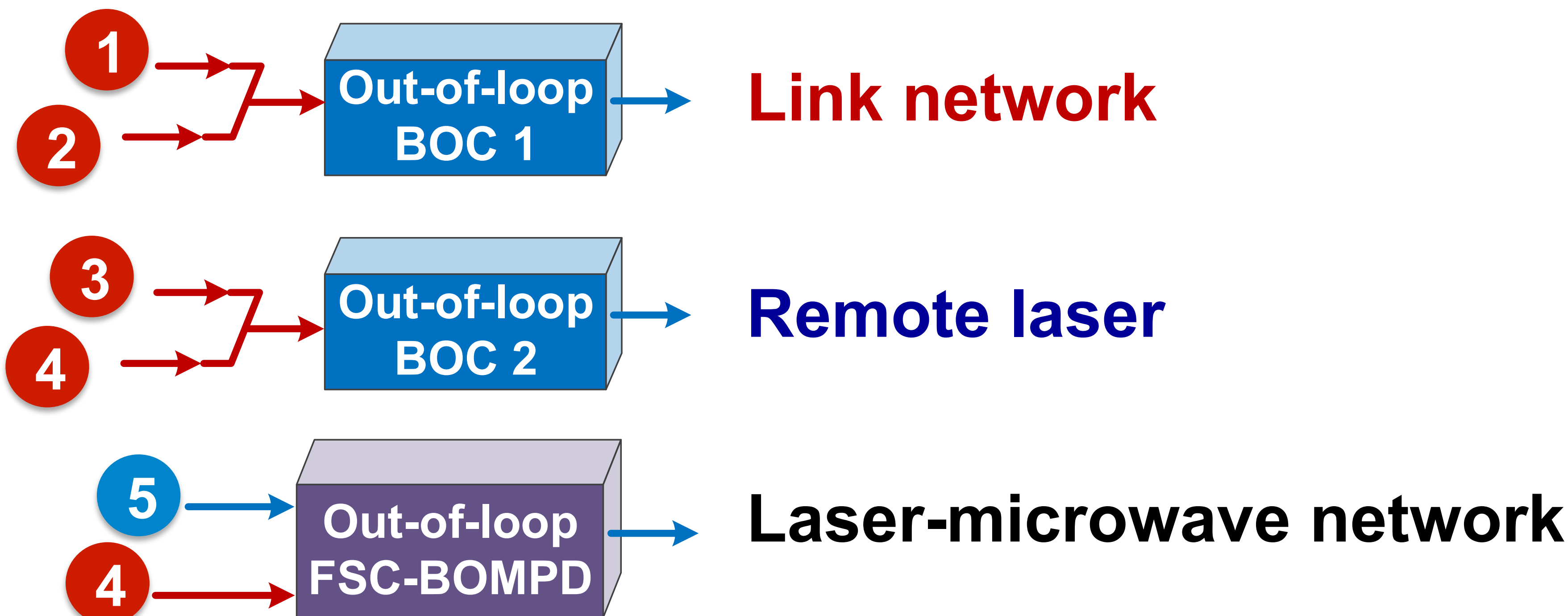
Long-term stability: < 1 fs rms drift over 10 hours



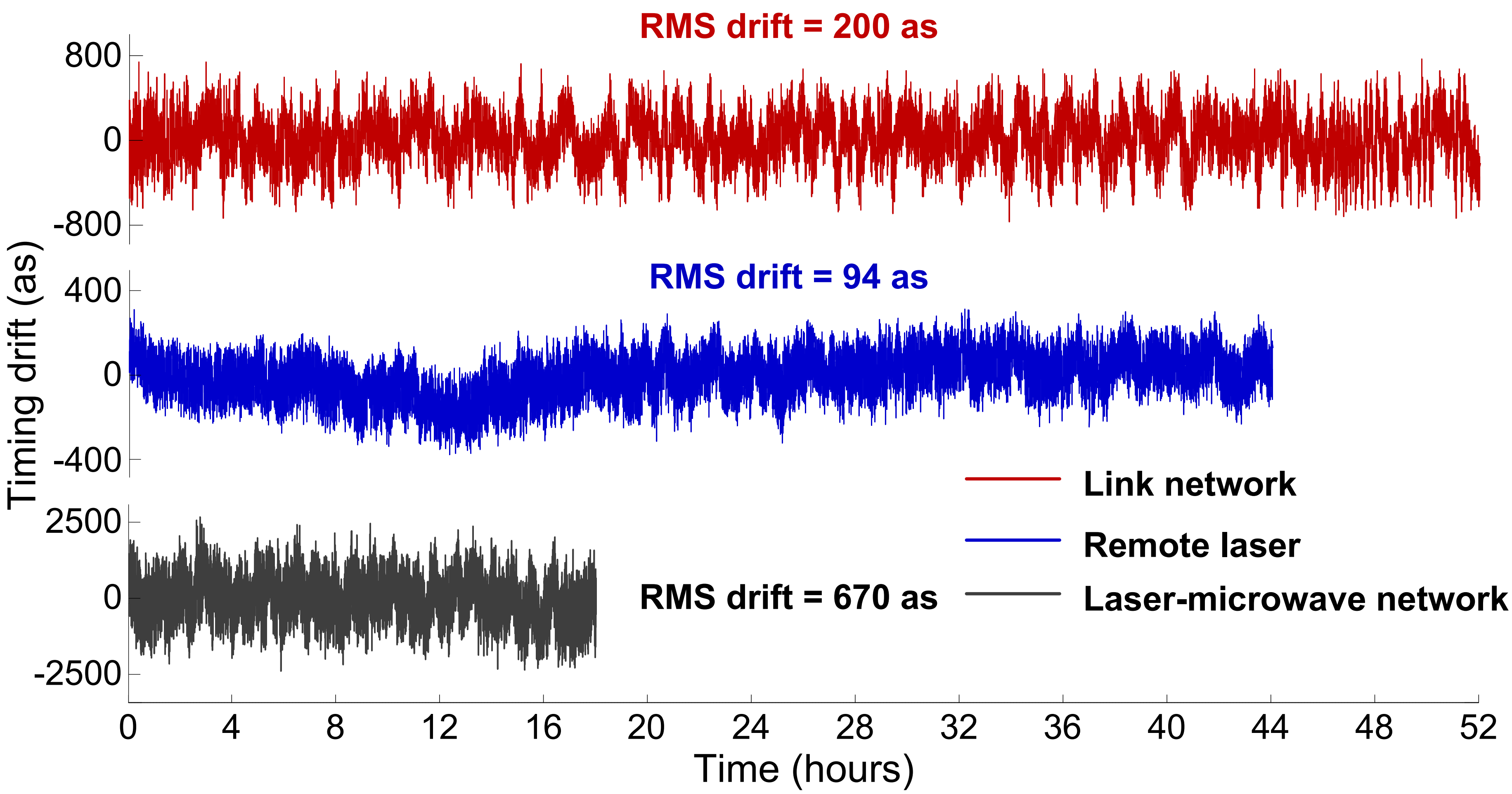
M. Y. Peng, A. Kalaydzhyan, F. X. Kärtner, Opt. Express, 22:(22) pp.27102 (2014).

4.7 - km laser-microwave network



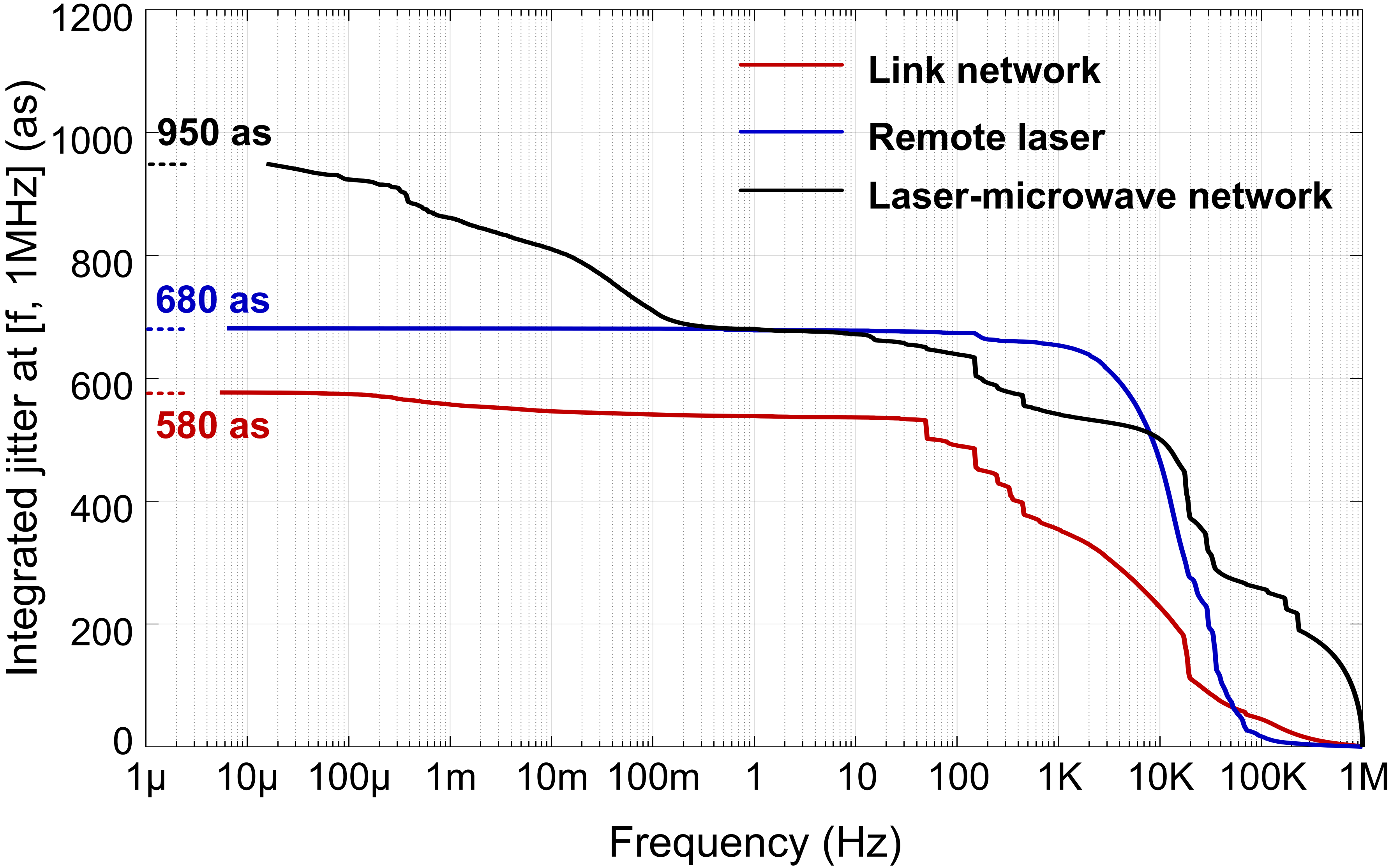


Results—long-term timing drift



Light: Science & Applications, doi: 10.1038/lsa.2016.187.

Results—Integrated timing jitter



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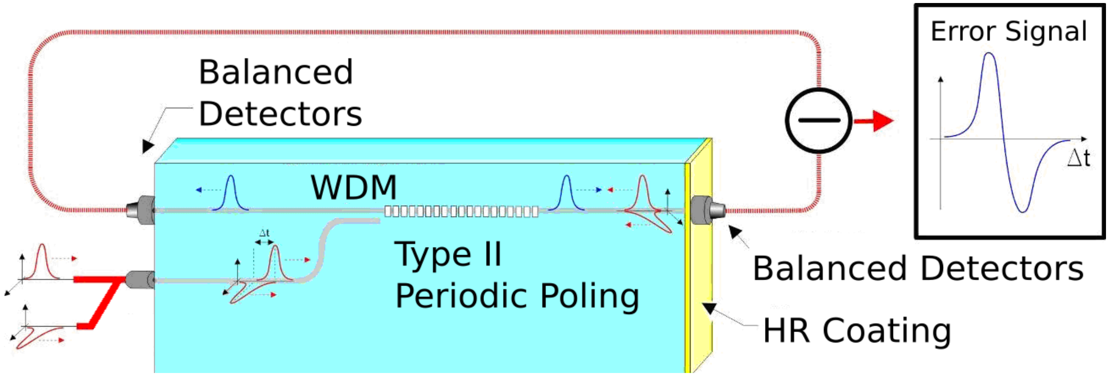
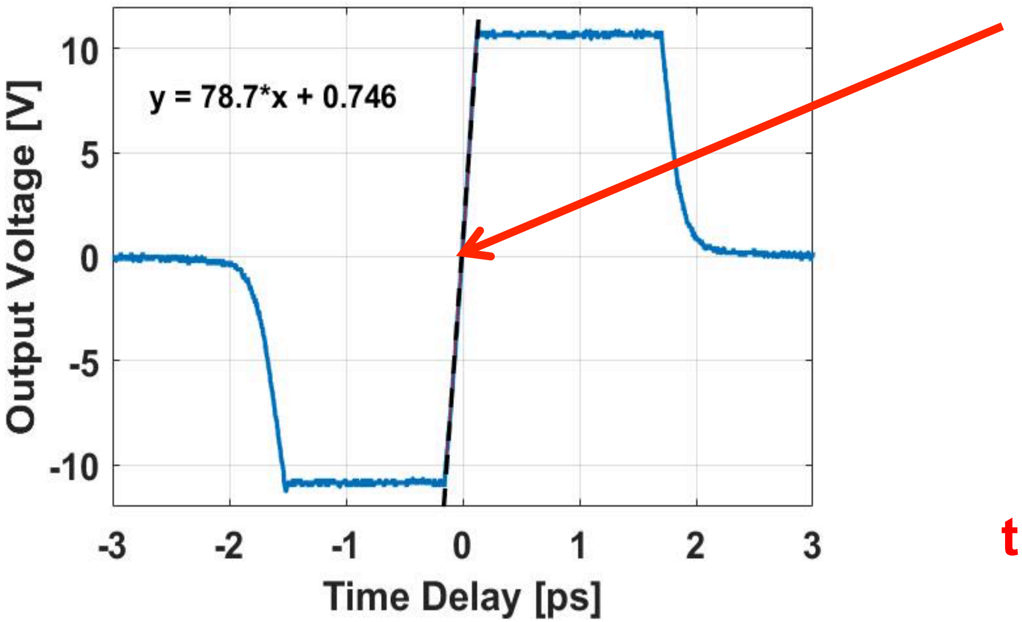
Integrated Waveguide BOCs

Packaged KTP waveguides with integrated WDM coupler





79 mV / fs

10 mW avg. power
100 fs, 200 MHz

2 mW enough for single link

Up to 5 x more link for the same optical system power

Conclusions

- **Sub-femtosecond timing distribution using fs-pulse trains developed for over a decade is reality.**
- **Clocking of femtosecond and attosecond FELs possible**
- **Both for optical and microwave signals over km-distances**
- **Unique markers in time and frequency domain, that can be reused at each end station**
- **Ongoing improvements using integrated devices**
- **Commercial systems via Spin-off** Cycle