FLS Workshop 2012
March 7, 2012

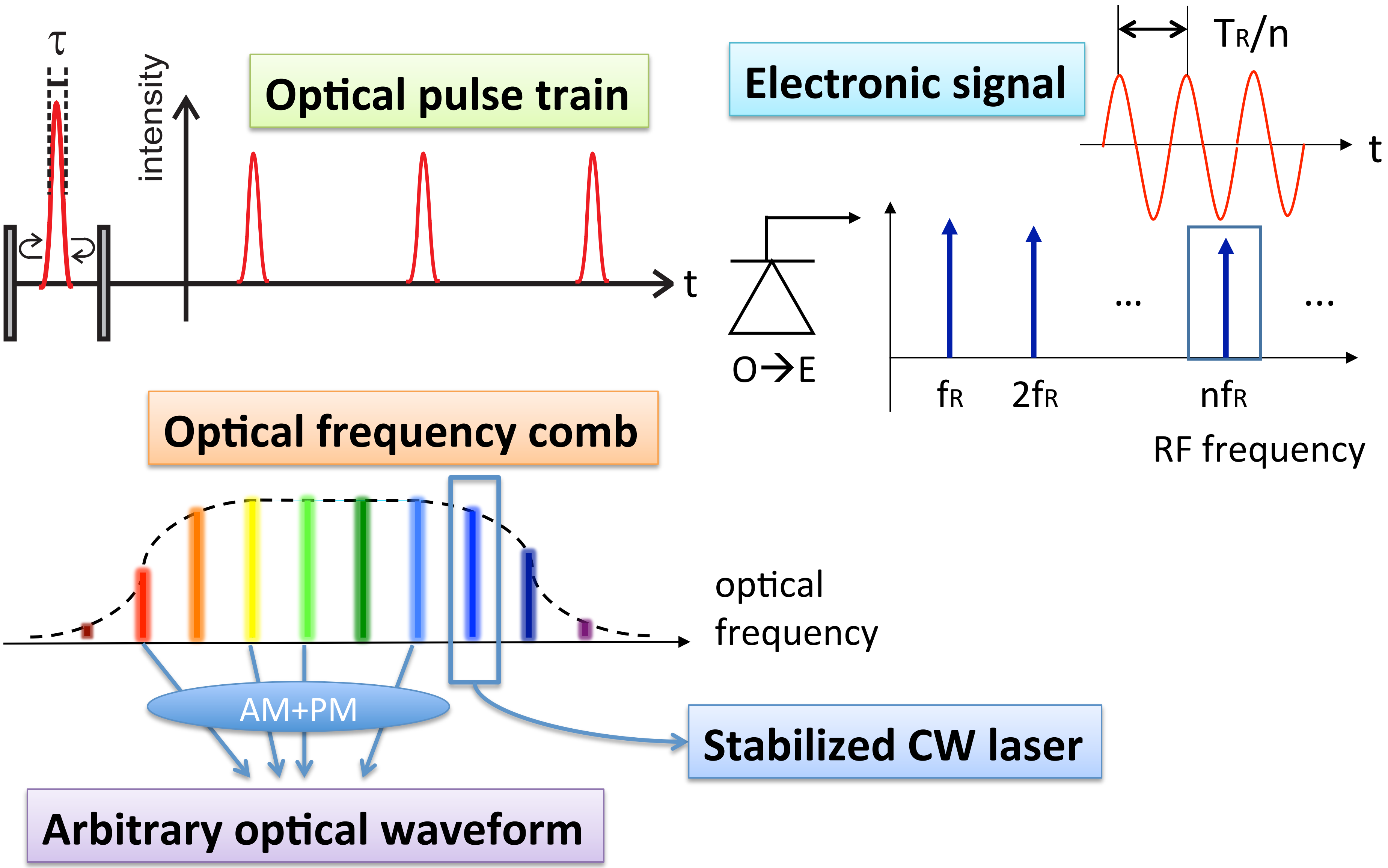
Toward Optical and Microwave Signals with Attosecond Timing Jitter and Drift for Future Light Sources

Jungwon Kim, Kwangyun Jung, Chur Kim, Taekeun Kim, Youjian Song

Korea Advanced Institute of Science and Technology (KAIST)
jungwon.kim@kaist.ac.kr
http://upcam.kaist.ac.kr/

Funding: *National Research Foundation of Korea (2010-0003974), Technology Innovation Program of MKE Korea, Pohang Accelerator Laboratory*

Ultrafast lasers as ***ultralow-noise*** optical and electronic signal generators



Optical pulse train

Electronic signal

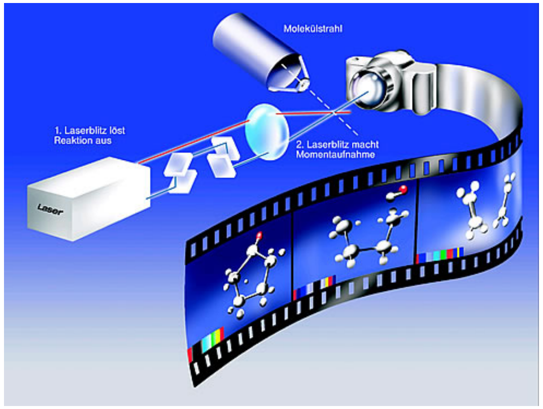
Optical frequency comb

Stabilized CW laser

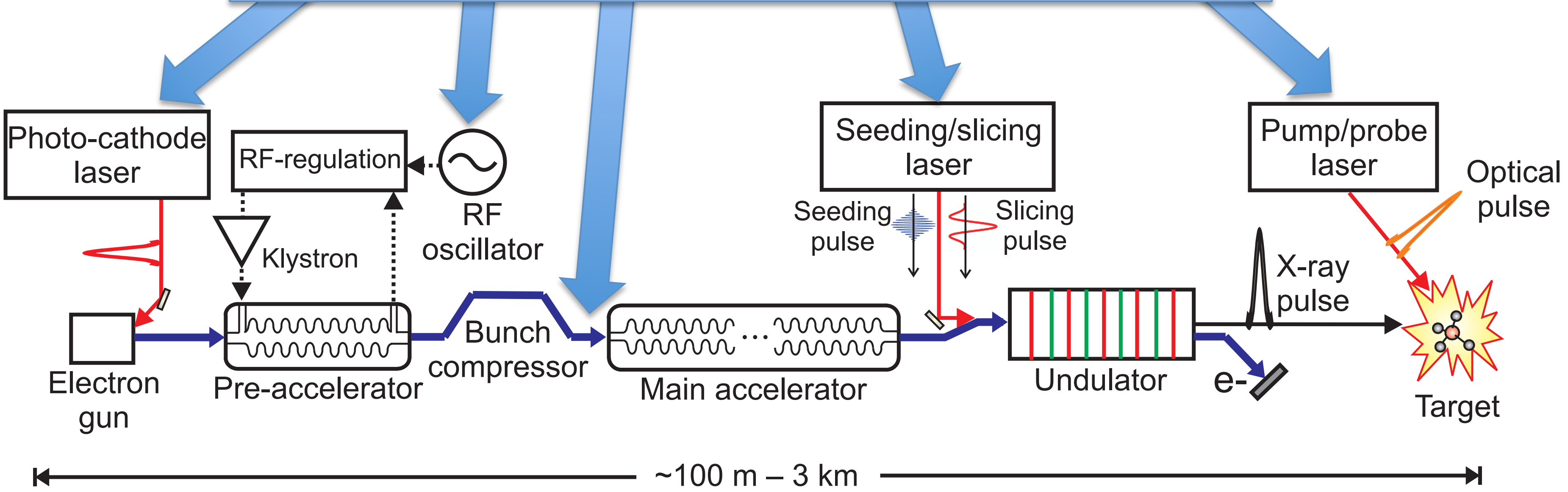
Arbitrary optical waveform

Motivation for ultra-low timing jitter signal sources – Clocking large-scale X-ray free-electron lasers (XFELs)

Future X-ray FELs will enable **super-fine temporal (fs) and spatial (Å) resolutions** with ultra-high peak brilliance that could not be achieved before.



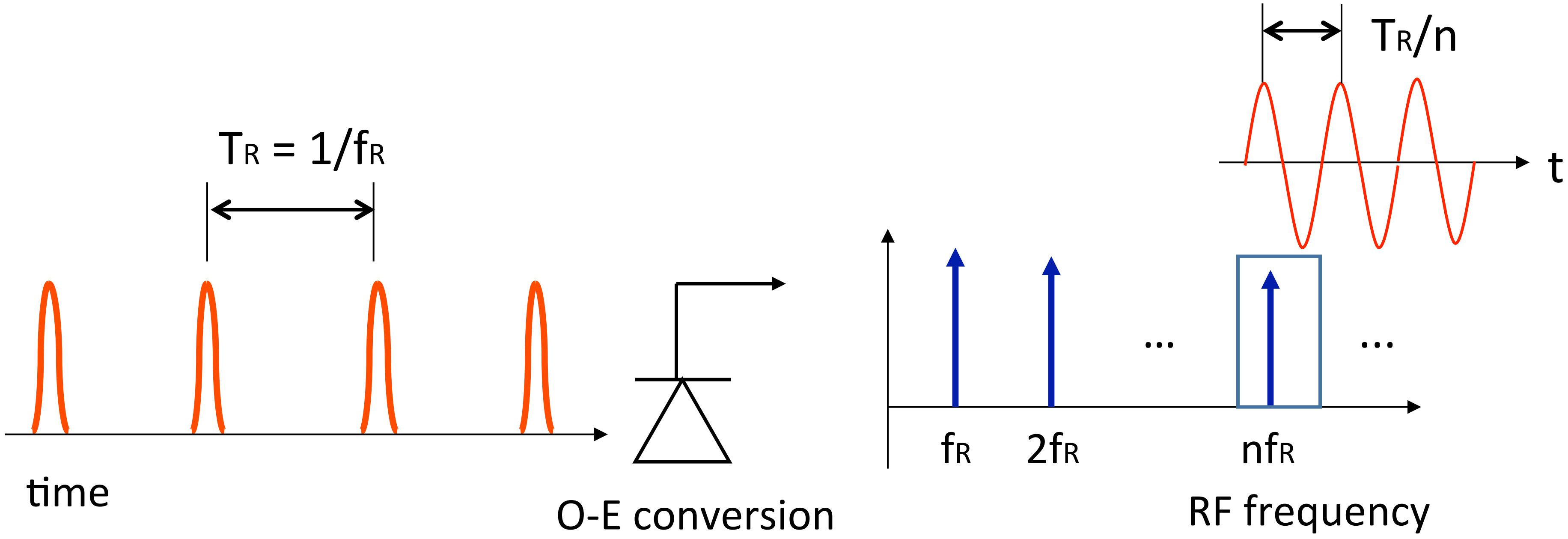
Requires drift-free, sub-10-fs timing precision over the entire FEL facility



Overview of Pulsed Optical Synchronization System

Principle 1: Ultralow-jitter RF/microwave is encoded in the repetition rate and the harmonics.

→ Can provide **ultra-low phase noise RF signals** to accelerators

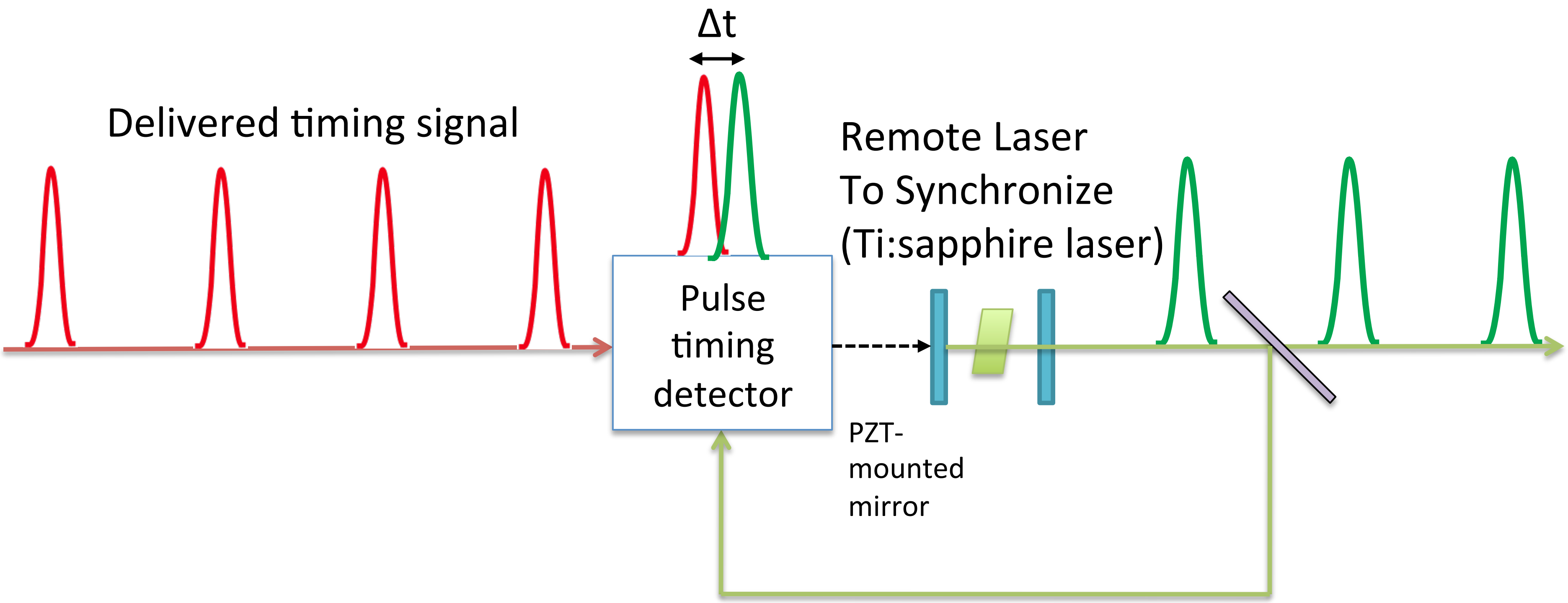


If f_{rep} = 79.3 MHz, one can extract
2.856 GHz (36th harmonic), 5.712 GHz (72nd harmonic),
and 11.4 GHz (144th harmonic) simultaneously at any location!

Overview of Pulsed Optical Synchronization System

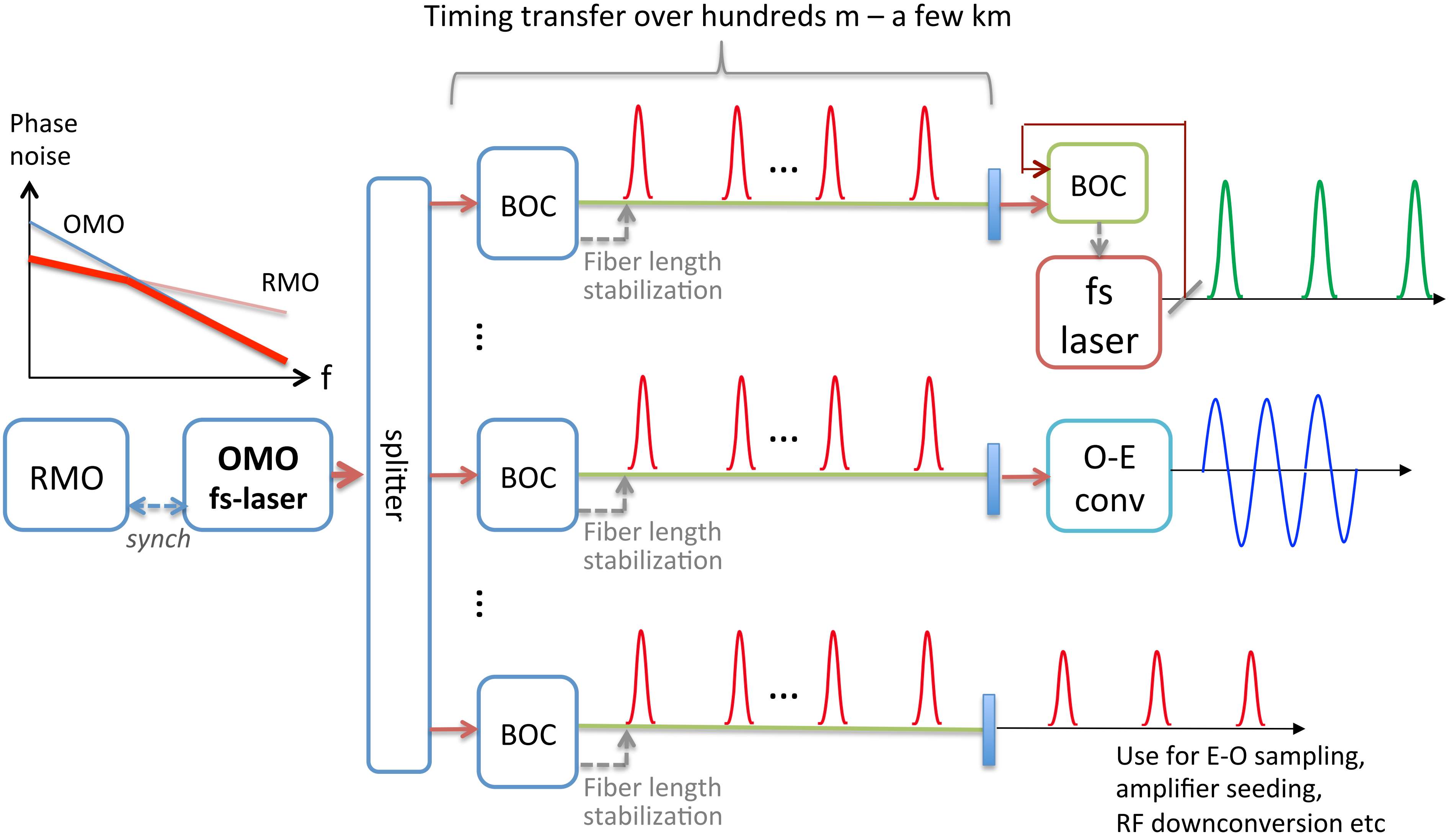
Principle 2: Timing pulse trains can be synchronized with other femtosecond lasers (Ti:sapphire lasers) using optical cross-correlator

→ Can provide **attosecond-precision synchronization** of lasers



Overview of Pulsed Optical Synchronization System

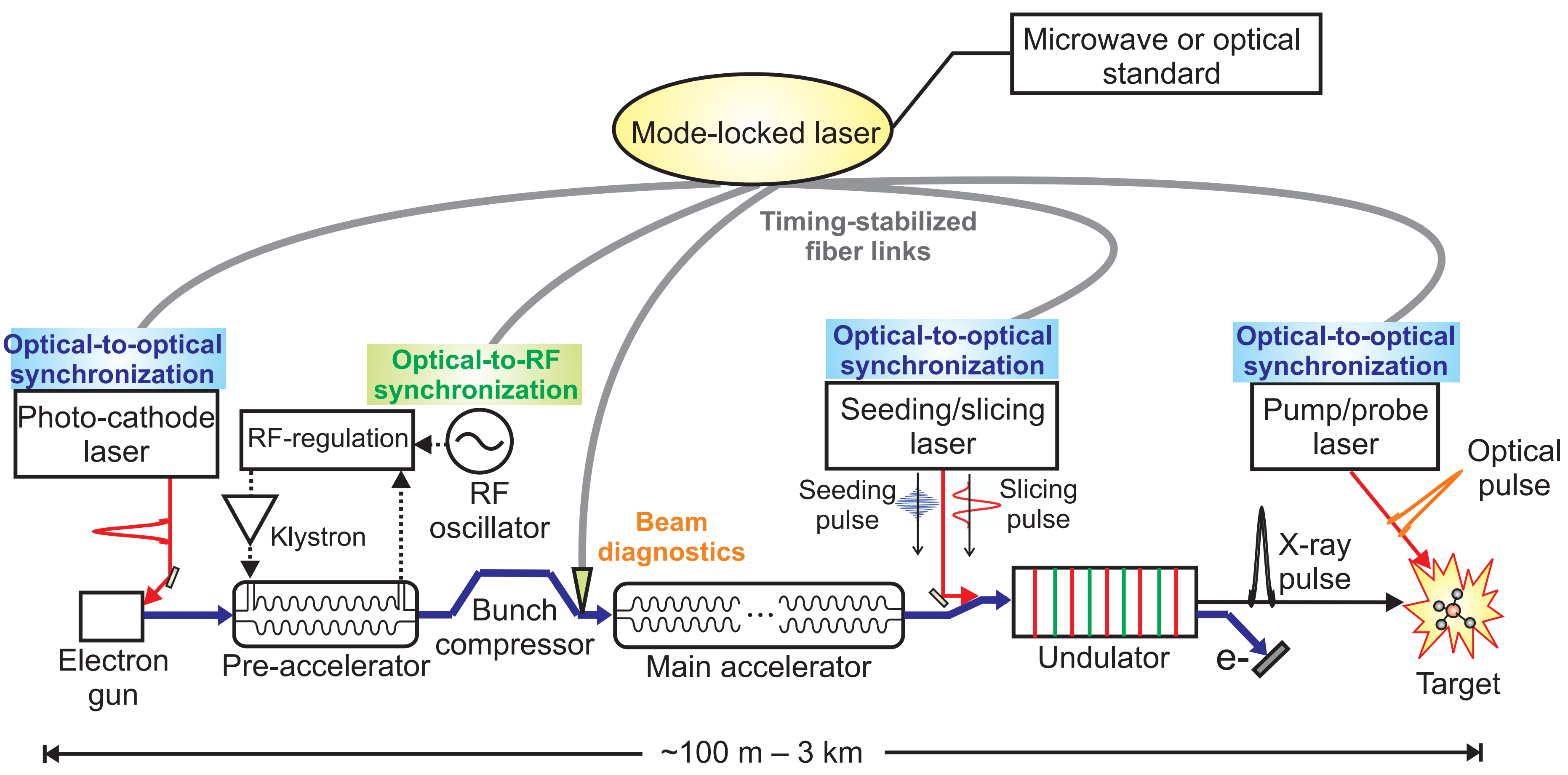
Schematic of a pulsed optical timing and synchronization system



Use for E-O sampling, amplifier seeding, RF downconversion etc

Large-scale timing synchronization for X-ray FELs

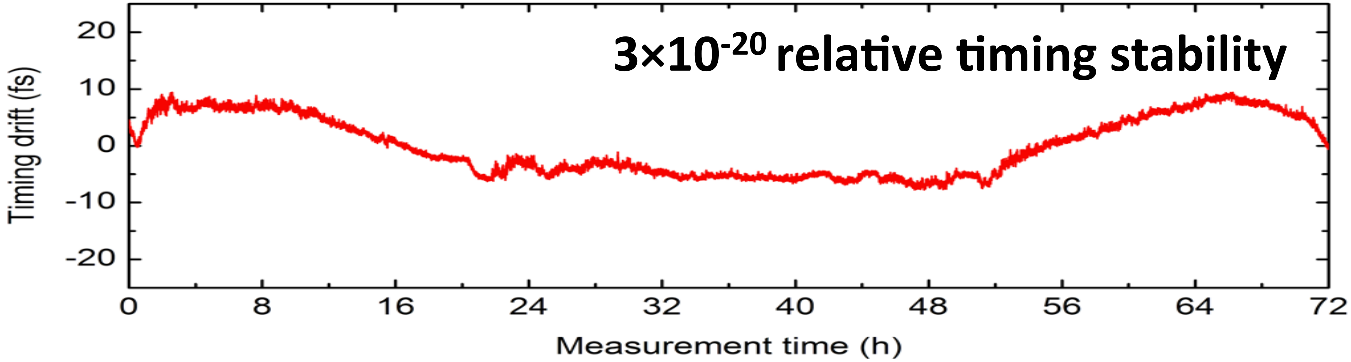
- Solution: Pervasive synchronization of an FEL with an optical master oscillator



J. Kim *et al*, Nature Photonics **2**, 733 (2008).

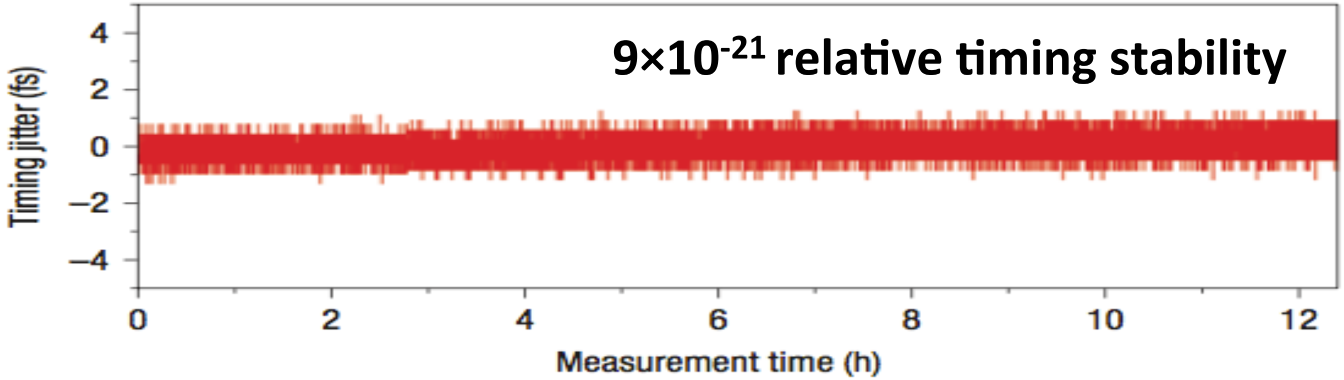
Using ultrafast fiber laser-based technology, long-term stable sub-10 fs remote timing synchronization is possible.

Timing-stabilized fiber link



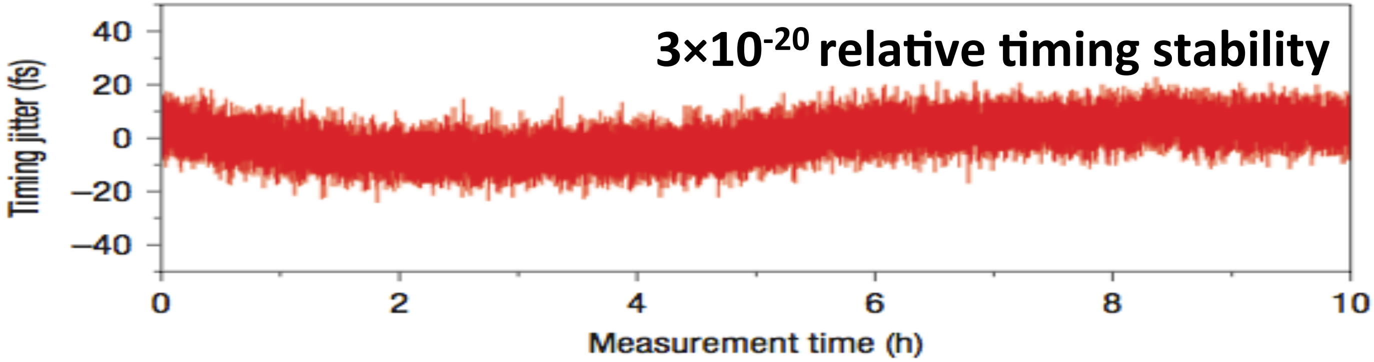
3×10^{-20} relative timing stability

Optical-optical synchronization



9×10^{-21} relative timing stability

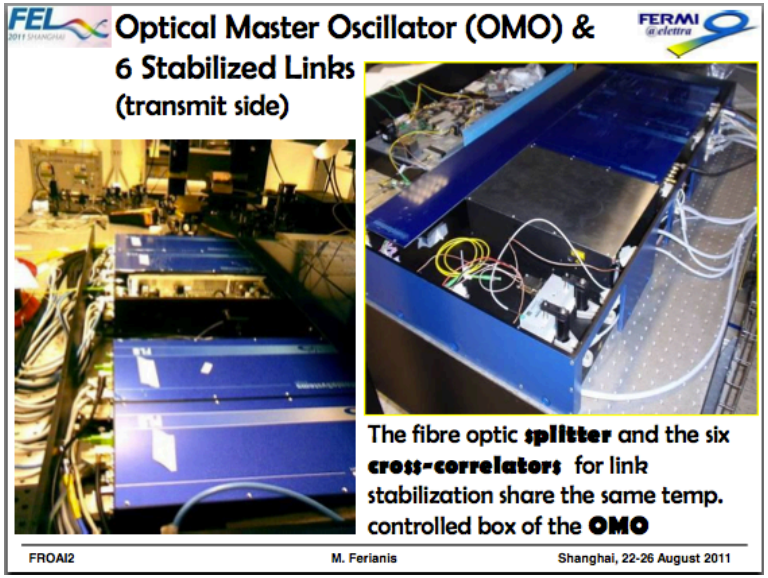
Optical-RF synchronization



3×10^{-20} relative timing stability

J. Kim *et al*, Nature Photonics **2**, 733 (2008).

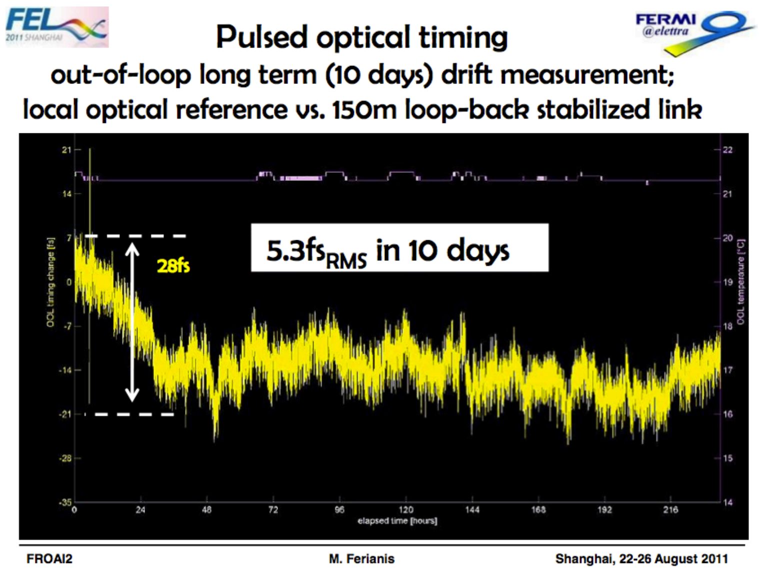
Through technology transfer, ultrafast fiber laser-based sub-10-fs-precision timing systems are now being actively installed



Optical Master Oscillator (OMO) & 6 Stabilized Links
(transmit side)

The fibre optic **splitter** and the six **cross-correlators** for link stabilization share the same temp. controlled box of the **OMO**

FROAI2 M. Ferianis Shanghai, 22-26 August 2011



Pulsed optical timing

out-of-loop long term (10 days) drift measurement;
local optical reference vs. 150m loop-back stabilized link

5.3fs$_{RMS}$ in 10 days

FROAI2 M. Ferianis Shanghai, 22-26 August 2011

M. Ferianis, FEL 2011

FERMI (at Trieste, Italy) results show that robust 10-fs timing and synchronization is possible in the accelerator environment.

We are in charge of fs-precision timing system entirely based on ultrafast fiber lasers and technology at PAL-XFEL (under construction)

PAL-XFEL Project

0.1-nm Hard X-ray 10-GeV XFEL

- **Project Period: 2011 ~ 2014**
- **Total Budget: 400 M$**

◆ Wavelength

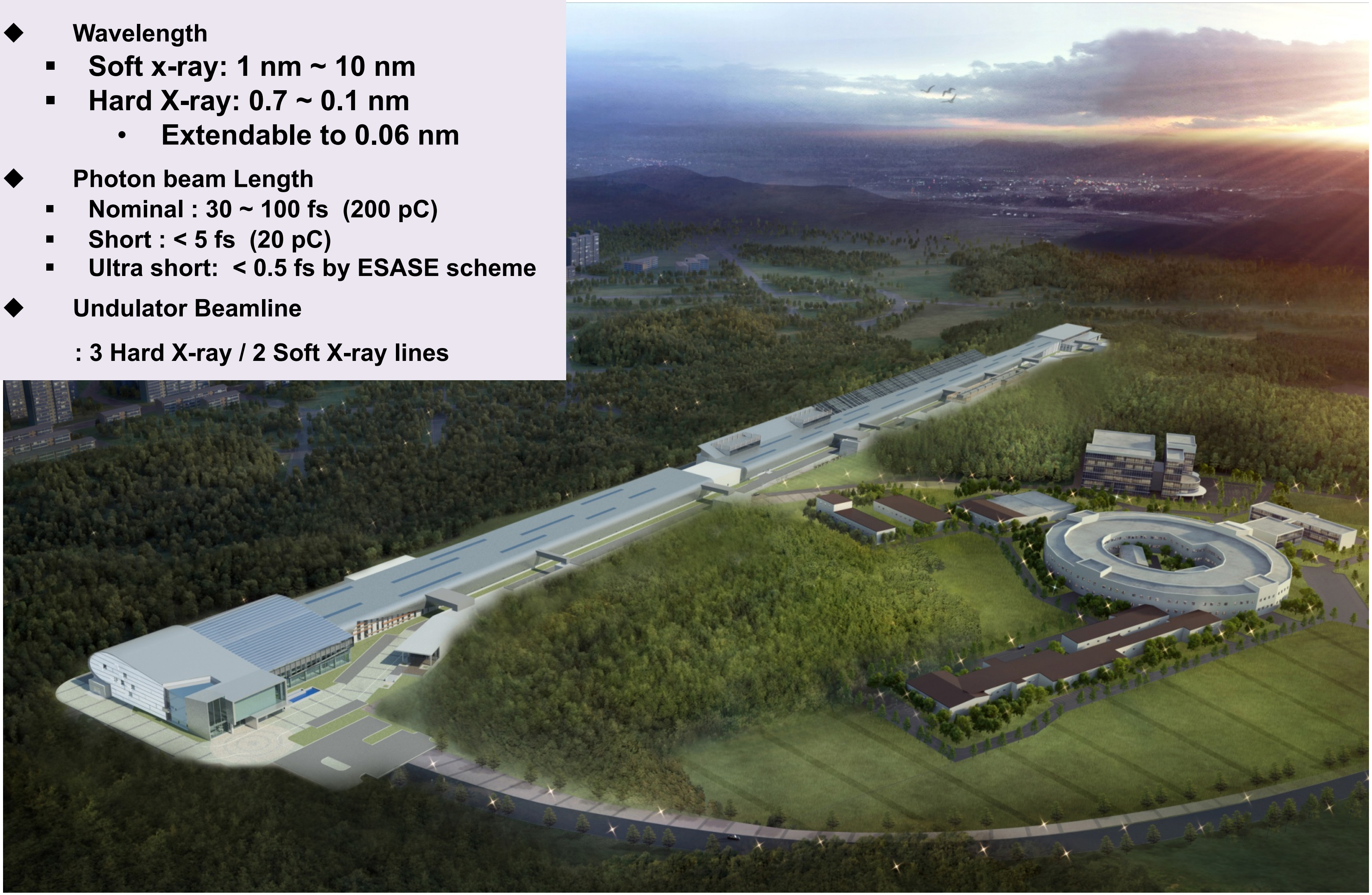
- Soft x-ray: 1 nm ~ 10 nm
- Hard X-ray: 0.7 ~ 0.1 nm
    - Extendable to 0.06 nm

◆ Photon beam Length

- Nominal : 30 ~ 100 fs (200 pC)
- Short : < 5 fs (20 pC)
- Ultra short: < 0.5 fs by ESASE scheme

◆ Undulator Beamline

: 3 Hard X-ray / 2 Soft X-ray lines

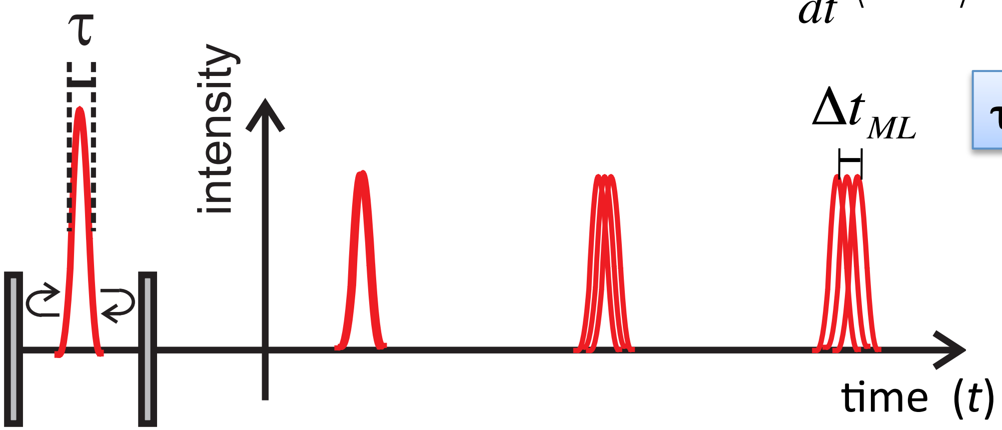


Now using ultrafast fiber lasers, 10-fs level timing precision can be (rather routinely) obtained.

Is this the ultimate limit?

Scaling of timing jitter into the attosecond (10^{-18} s) regime

Mode-locked laser



$$\frac{d}{dt}\left\langle \Delta t_{ML}^2 \right\rangle = \frac{\pi^2}{6}\boxed{\cdot\,\tau^2\cdot}\frac{1}{[\text{pulse energy}]}\cdot\frac{\boxed{\hbar\omega_c}}{[\text{cavity decay time}]}$$

τ = 100 fs and below

$\hbar\omega_c = 0.8\text{eV}$

$$\tau^2 < \frac{1}{10^6}T_0^2$$

$\hbar\omega_C \approx 30kT$

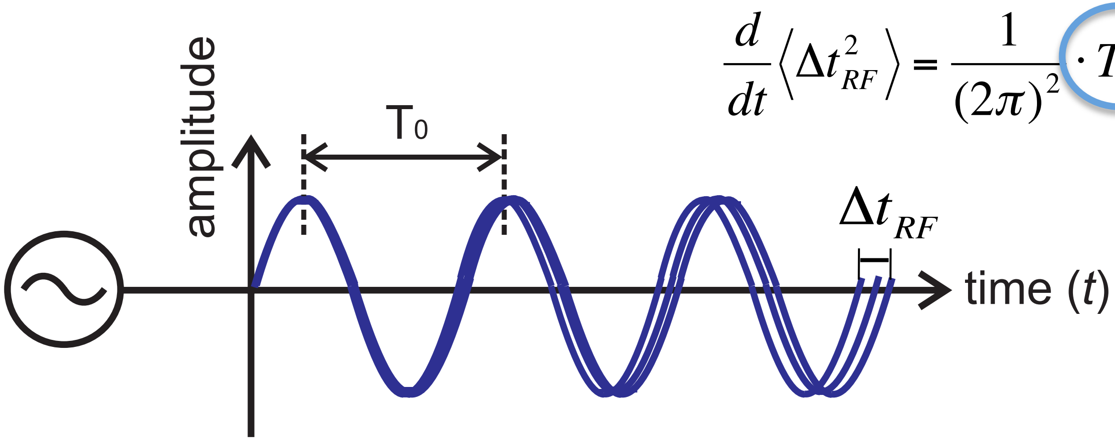
at 1550 nm, 300 K

T_0 = 100 ps for 10 GHz

kT = 0.025 eV

Electronic oscillator

$$\frac{d}{dt}\left\langle \Delta t_{RF}^2 \right\rangle = \frac{1}{(2\pi)^2}\boxed{\cdot\,T_0^2\cdot}\frac{1}{[\text{mode energy}]}\cdot\frac{\boxed{kT}}{[\text{cavity decay time}]}$$

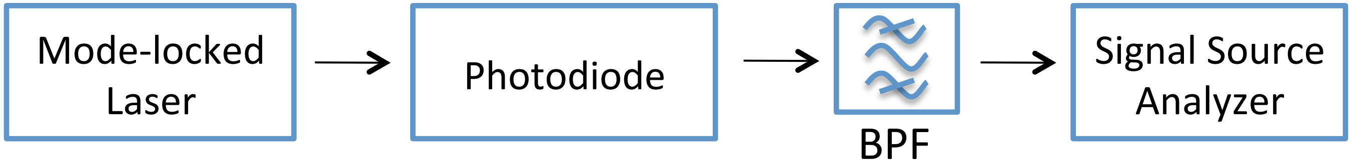


(Haus, IEEE JQE 1995;
Kim and Kärtner, LPR 2009)

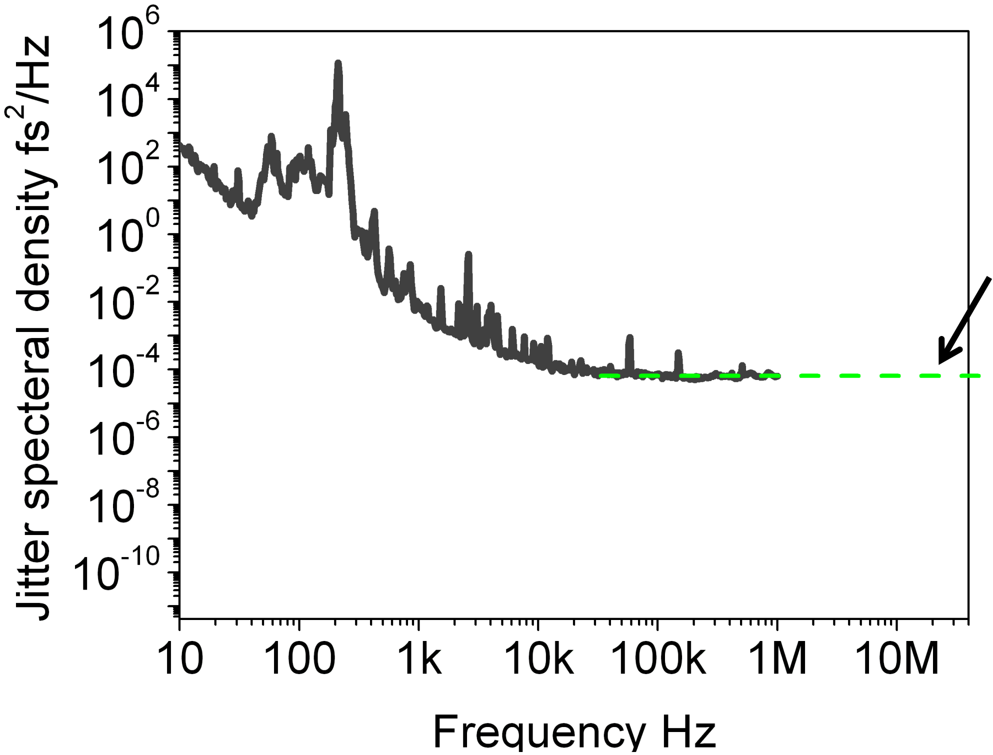
For the optimization of timing jitter of ultrafast lasers, sub-femtosecond-resolution characterization is first required.

- Conventional direct photodetection:

Resolution limit: ~10 fs

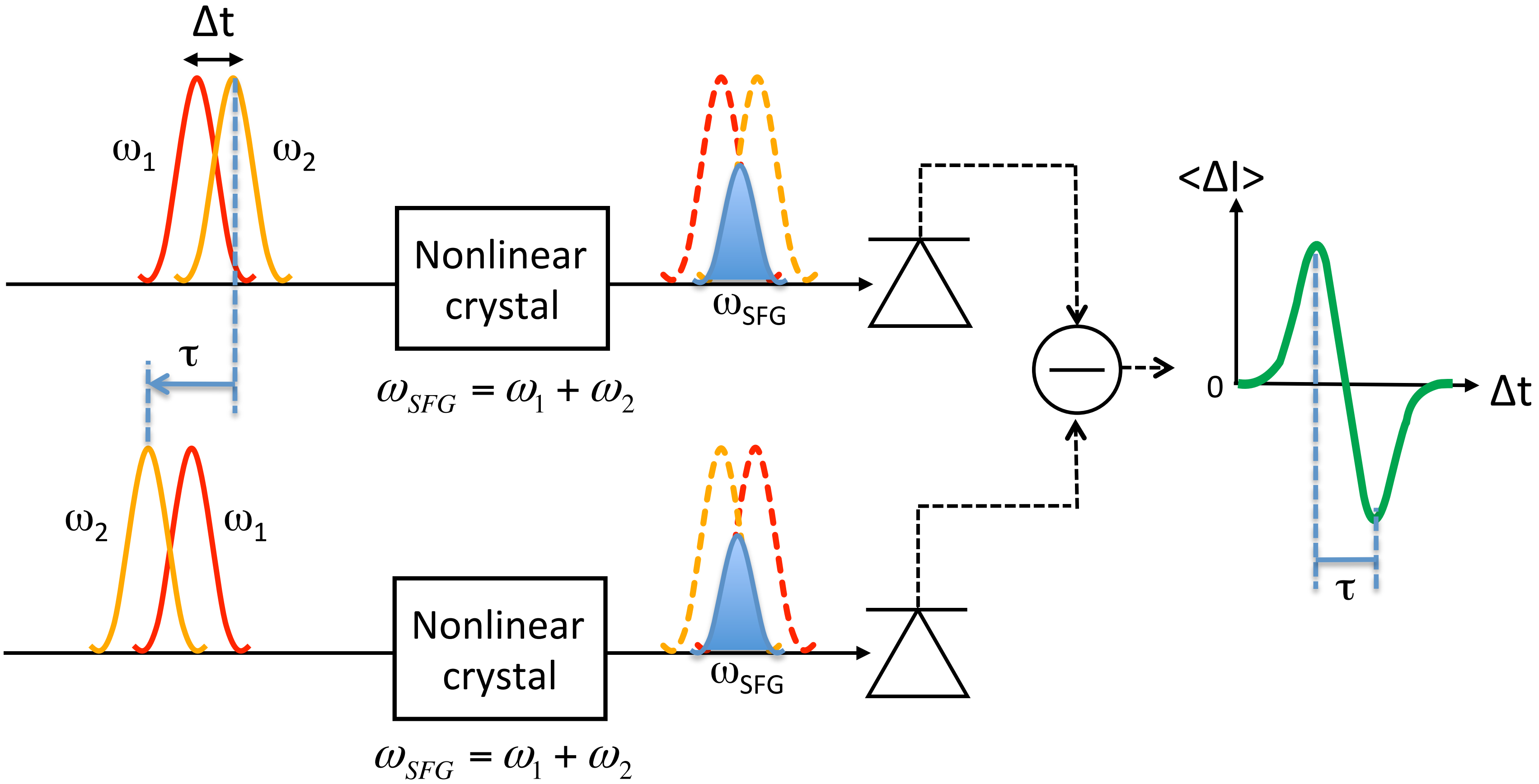


Mode-locked Laser → Photodiode → BPF → Signal Source Analyzer

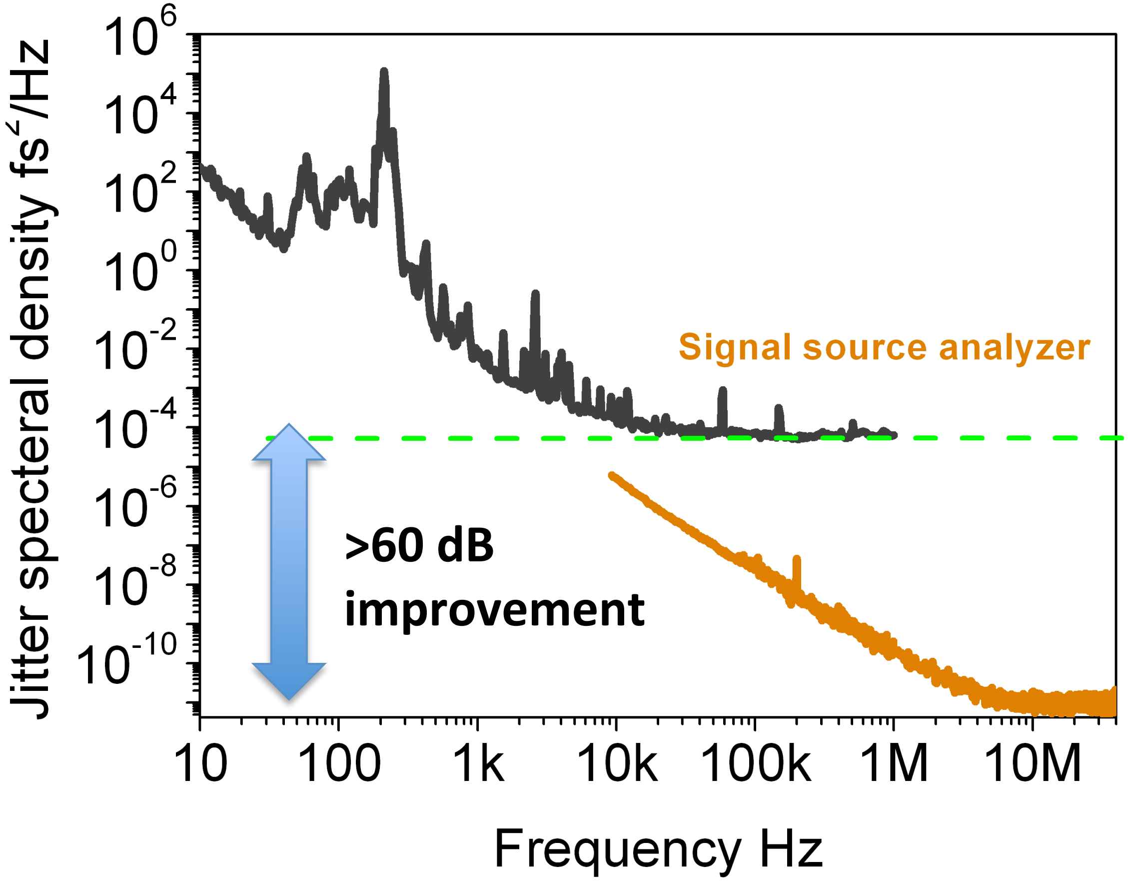


Measurement noise floor

The use of balanced optical cross-correlation (BOC) provides both very high timing detection sensitivity and amplitude-noise-free operation



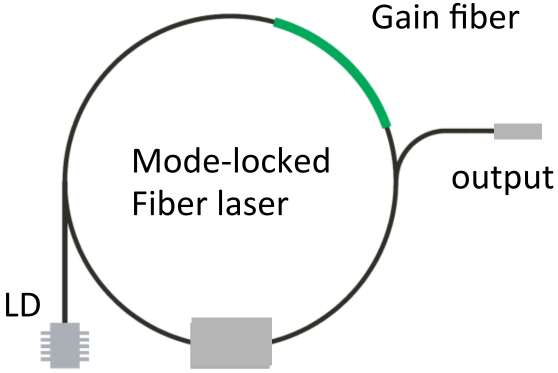
The use of BOC enables attosecond-resolution timing jitter characterization of femtosecond mode-locked lasers



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

Advantages of fiber lasers

Simple and reliable operation



Gain fiber

Mode-locked
Fiber laser

output

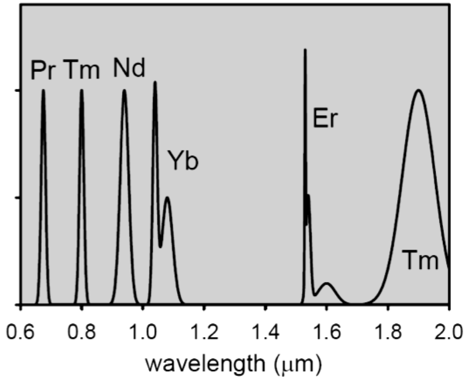
LD

Saturable absorber

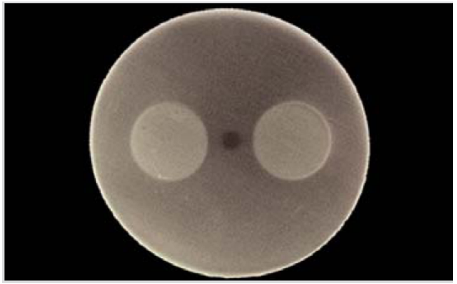
Compact and alignment-free

(IMRA)

Various wavelength due to rare-earth doping technology

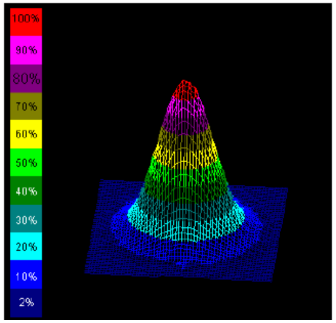


Enhanced environmental stability with PM technology



Large gain due to long fiber propagation

Diffraction-limited beam quality



With balanced optical cross-correlator (BOC) in hand, we pursued sub-20 as resolution timing jitter measurement over the full Nyquist frequency.

- Yb-fiber laser (1030 nm) & Er-fiber laser (1550 nm)
- Impact of pulse formation mechanisms (soliton, stretched-pulse, and self-similar) and intra-cavity dispersion on timing jitter
- Demonstration of the lowest-jitter performance from fiber lasers

Yb-doped fiber laser

New physical Phenomena at 1 µm

Higher energy, shorter pulses

Excellent source for frequency comb generation

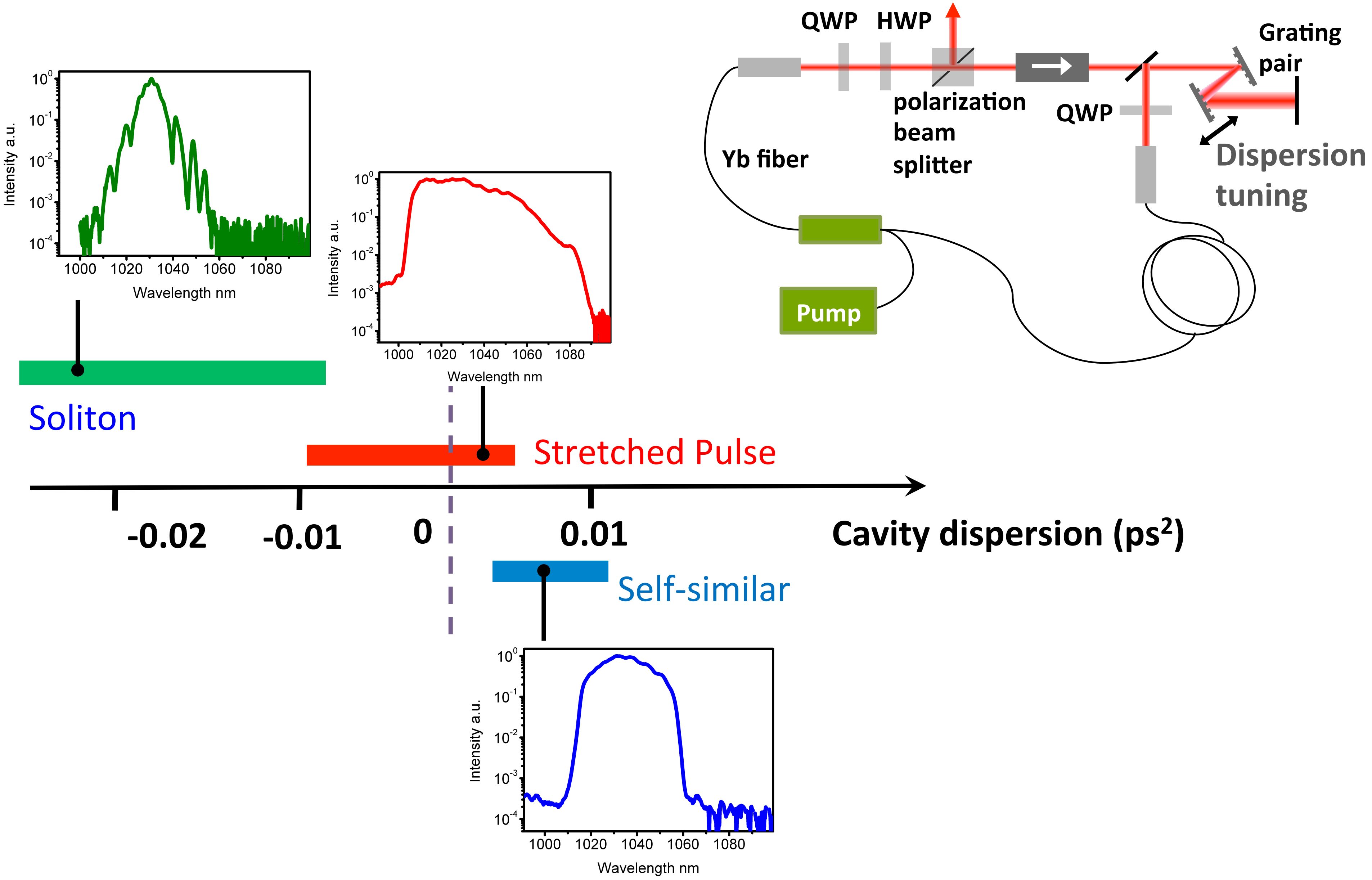
Er-doped fiber laser

Telecomm wavelength
→ suitable for photonic signal processing

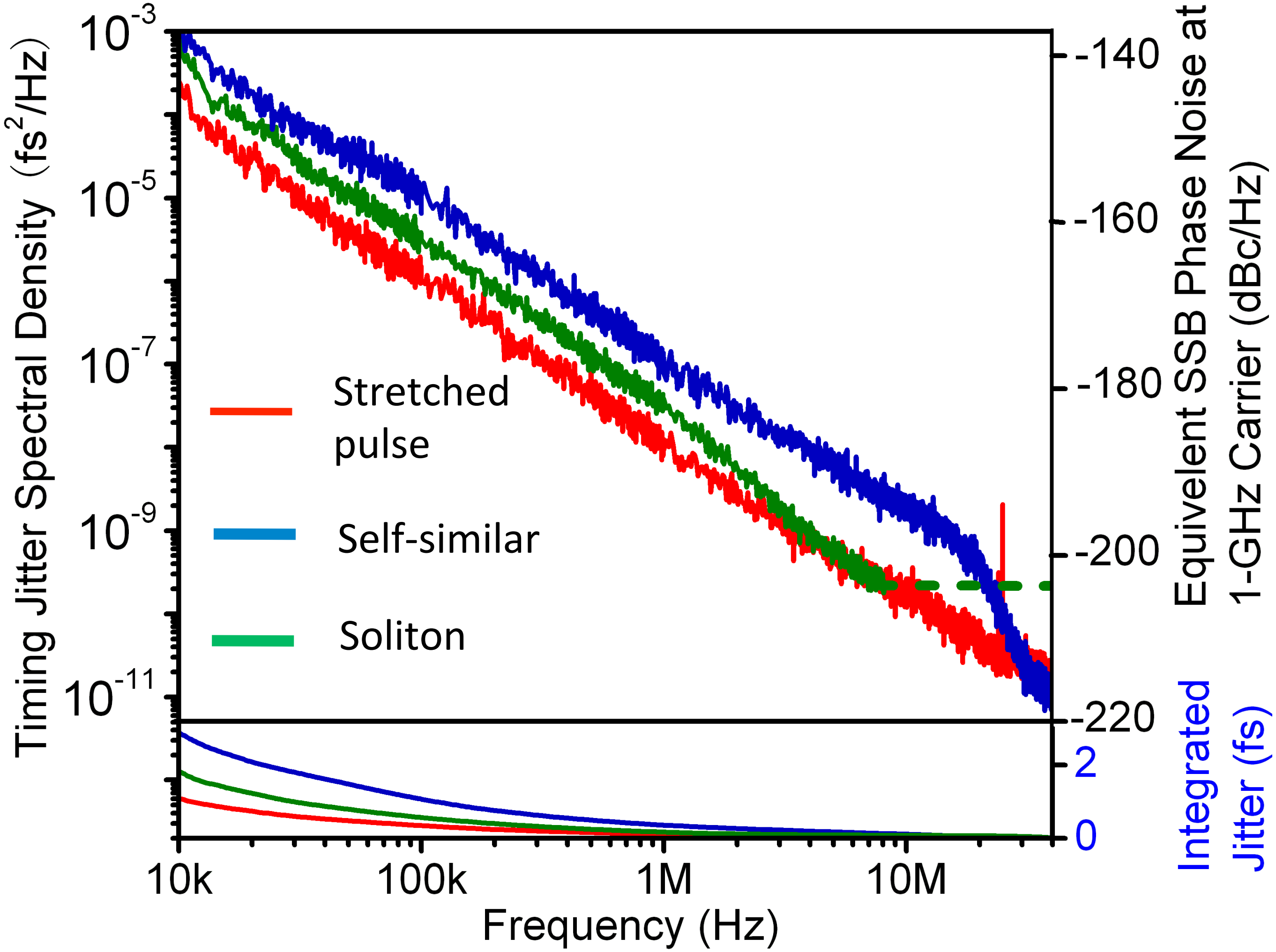
Reliable and low-cost component

Easy dispersion control (SMF-28 has negative dispersion)

Mode-locking conditions used for the timing jitter characterization

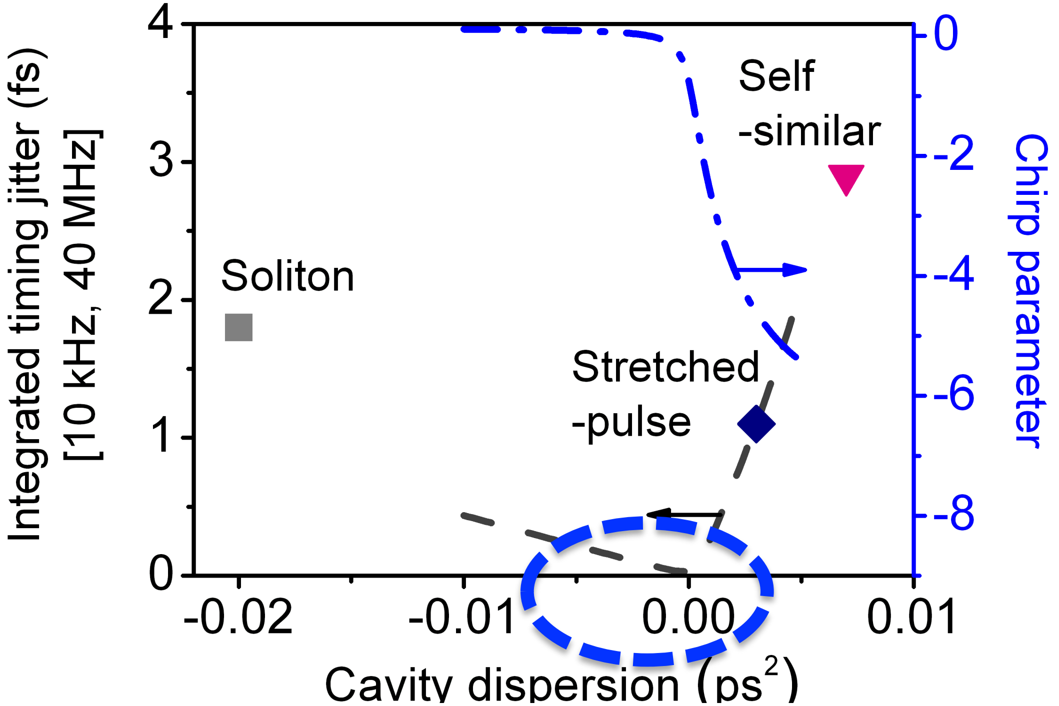


Measured jitter spectral density of Yb-fiber lasers with different mode-locking regimes



Y. Song et al, Opt. Lett. **36**, 1761 (2011)

Optimization of timing jitter at close-to-zero dispersion



Directly-coupled jitter from ASE

$$\Delta t_{direct} \propto (1+\beta^2)^{3/4} \frac{\tau}{\sqrt{E_p}}$$

- Higher pulse energy E_p
- Shorter pulse width τ
- Lower chirp parameter β

→ Leading to lower direct jitter

Indirectly-coupled jitter from center frequency fluctuations

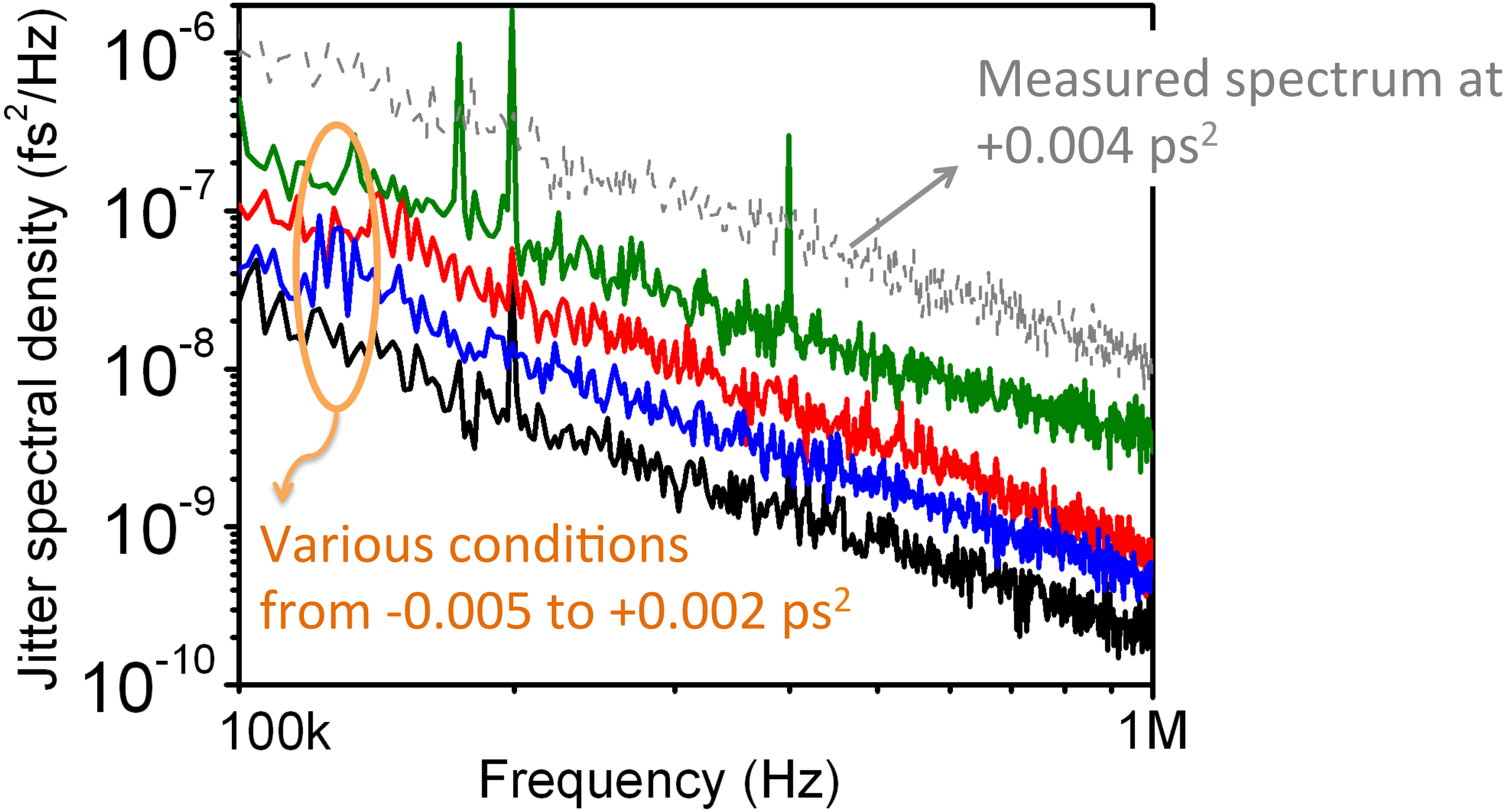
$$\Delta t_{indirect} \propto |D| \cdot BW$$

Close-to-zero dispersion (D) may lead to lower indirect jitter

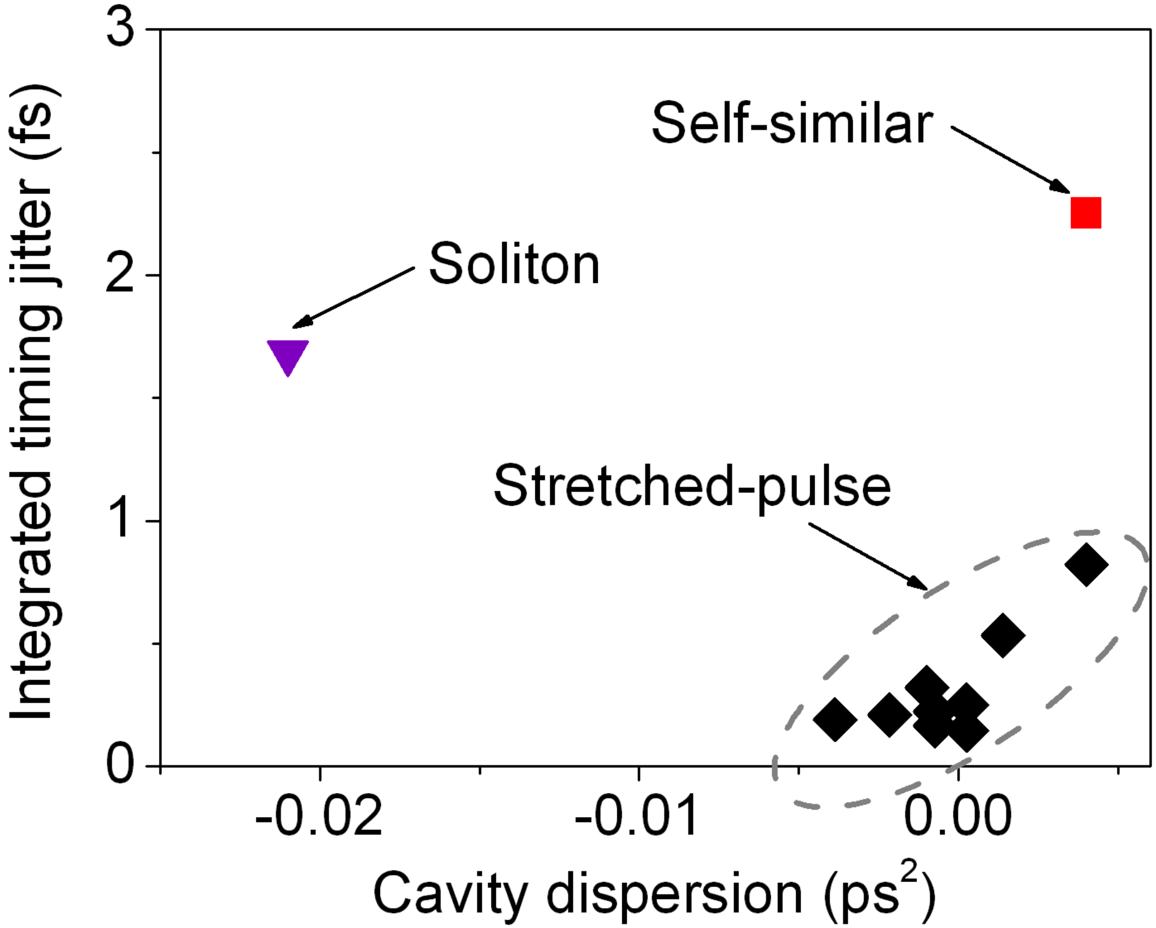
Stretched-pulse operation at close-to-zero dispersion may lead to the lowest timing jitter in fiber lasers.

Namiki and Haus, IEEE JQE **33**, 649 (1997)

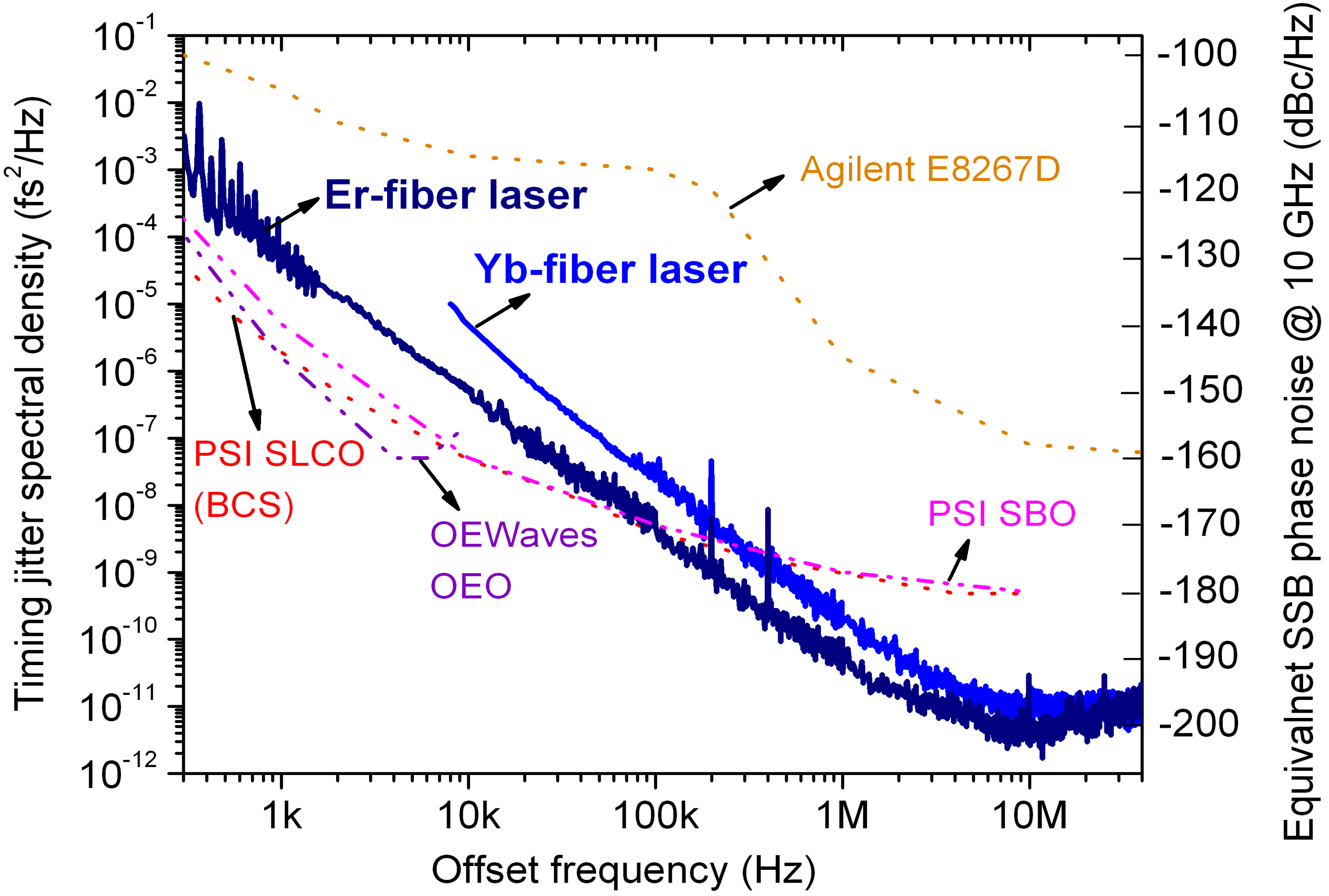
Measured jitter spectral densities of Yb-fiber lasers at close-to-zero dispersion (-0.005 ps^2 to +0.002 ps^2)



Integrated timing jitter of Yb fiber lasers [10 kHz – 40 MHz] vs intra-cavity dispersion and mode-locked regimes



Measured lowest timing jitter spectral density of ultrafast fiber lasers → *Sub-100-attosecond timing jitter is demonstrated*



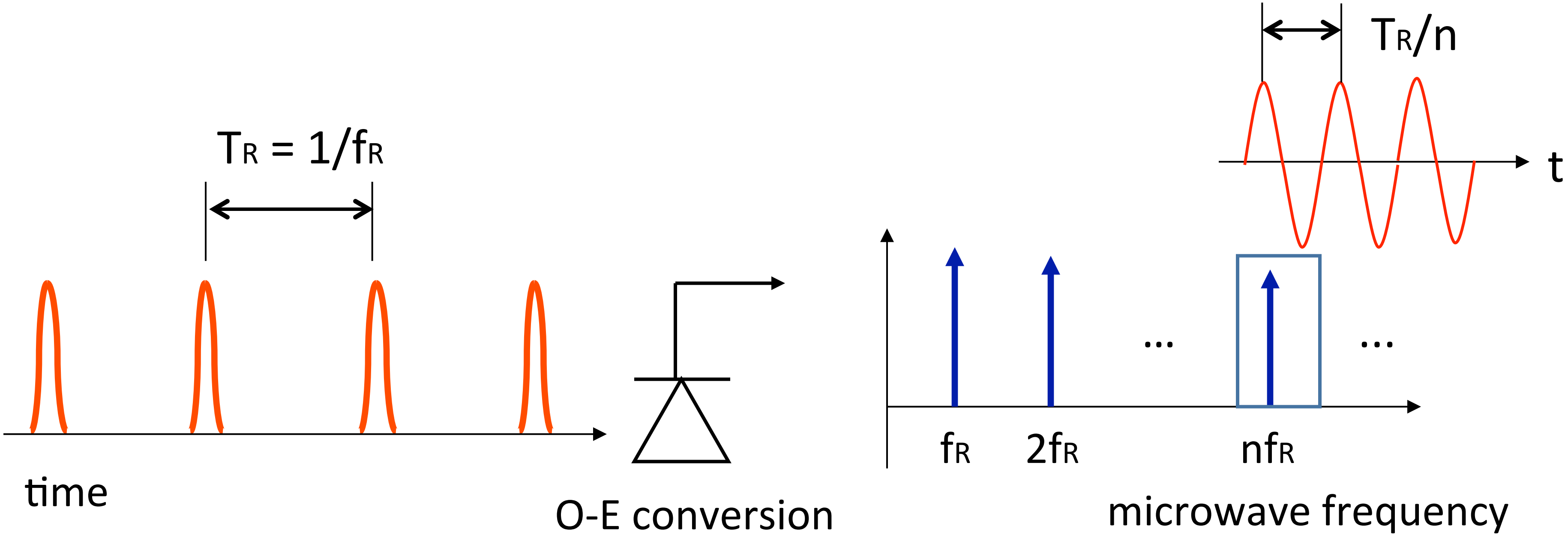
Pulse dynamics vs noise study: Y. Song et al, Opt. Lett. **36**, 1761 (2011)

175-as jitter from Yb-fiber lasers: Y. Song et al, Opt. Express **19**, 14518 (2011)

70-as jitter from Er-fiber lasers: T. K. Kim et al, Opt. Lett. **36**, 4443 (2011)

Ultralow-jitter microwave signals are encoded in the repetition-rate and its harmonics of optical pulse trains

→ Can generate **ultra-low phase noise microwave signals** from ultrafast lasers



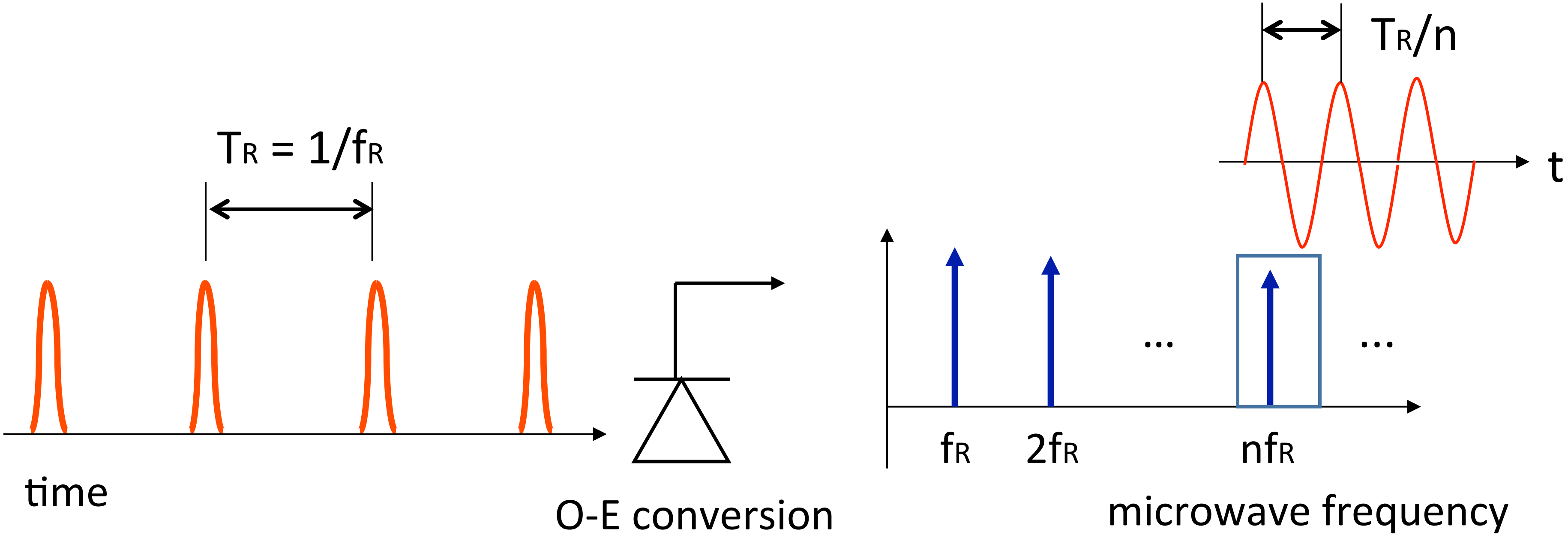
Ultralow-jitter microwave signals are encoded in the repetition-rate and its harmonics of optical pulse trains

→ Can generate **ultra-low phase noise microwave signals** from ultrafast lasers

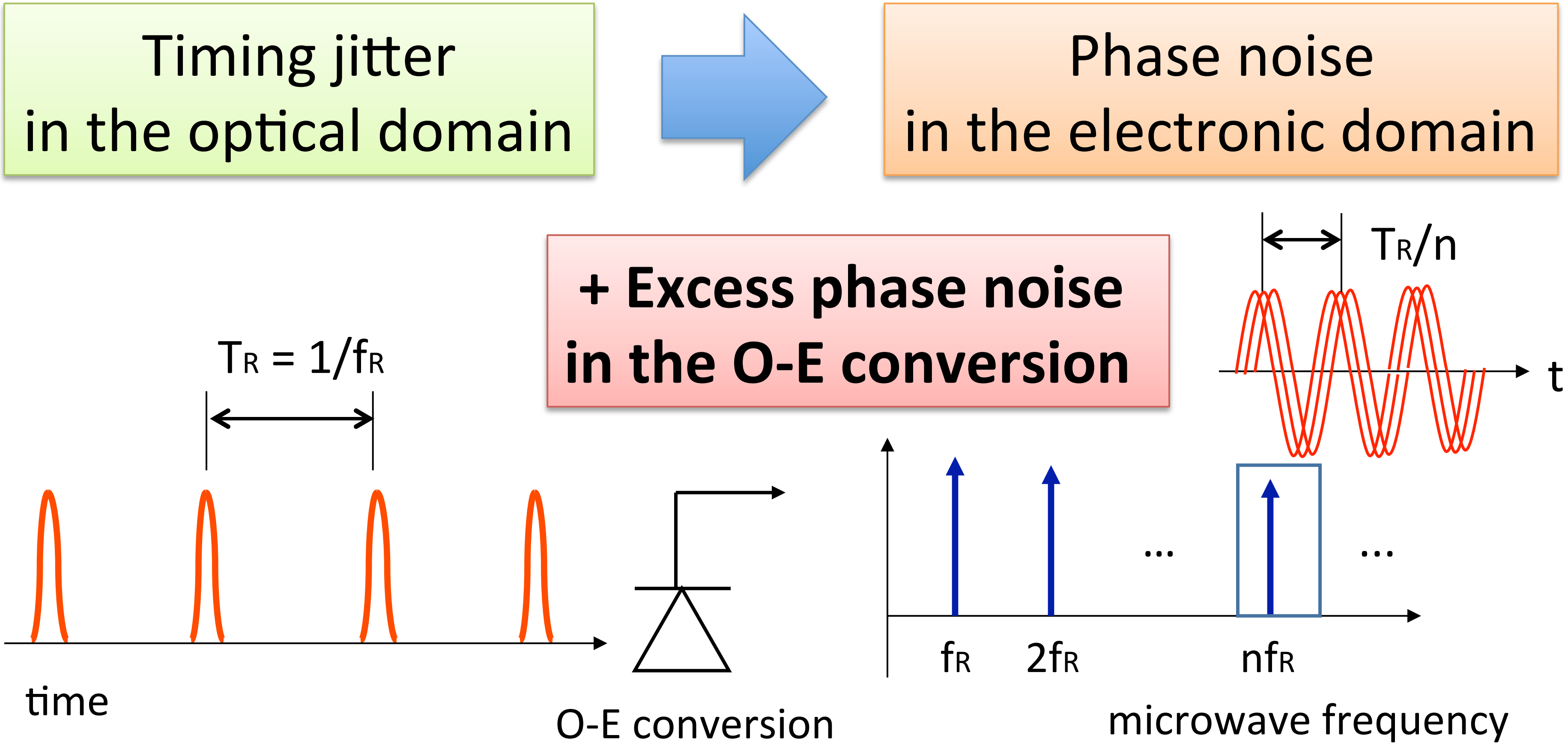
Timing jitter
in the optical domain

→

Phase noise
in the electronic domain



However, excess phase noise in the optical-to-electronic conversion process limits the achievable phase noise of extracted microwave signals



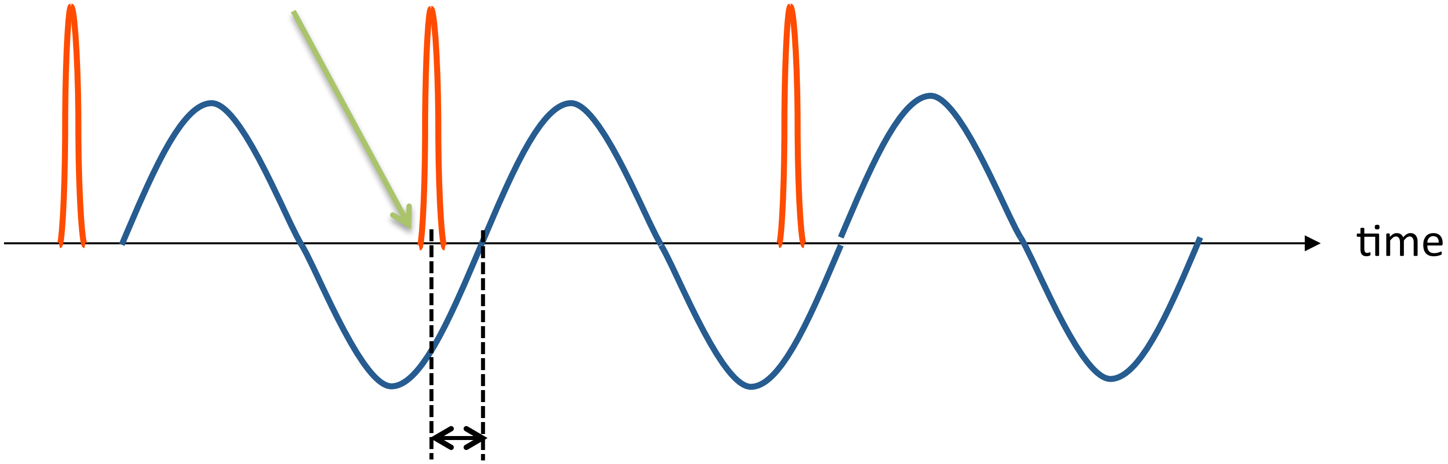
Timing jitter in the optical domain

Phase noise in the electronic domain

+ Excess phase noise in the O-E conversion

Can we regenerate an **ultralow-jitter & drift** microwave signal, the phase of which is locked to the optical pulse train?

<-150 dBc/Hz residual noise floor & <1 fs long-term drift

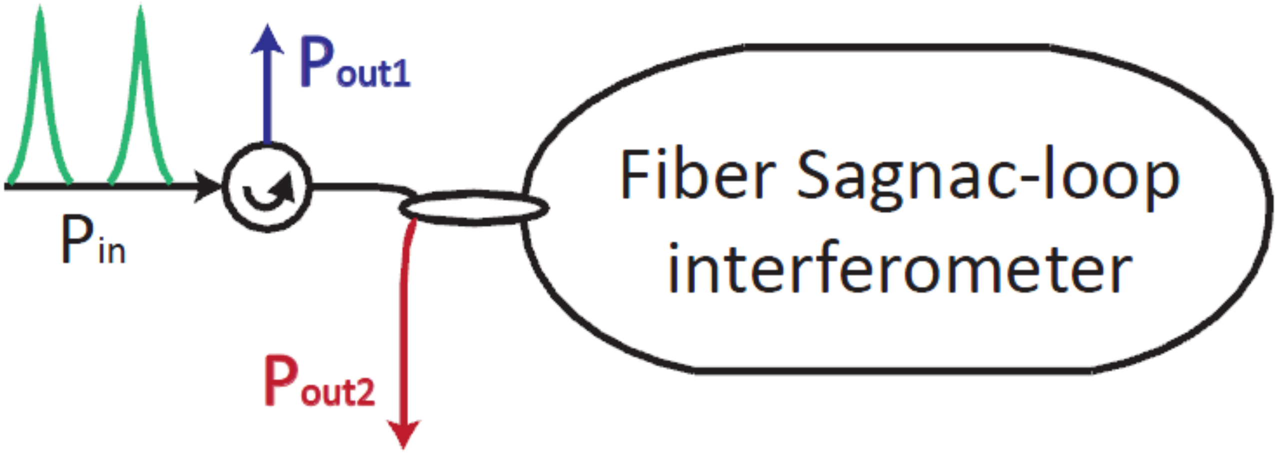


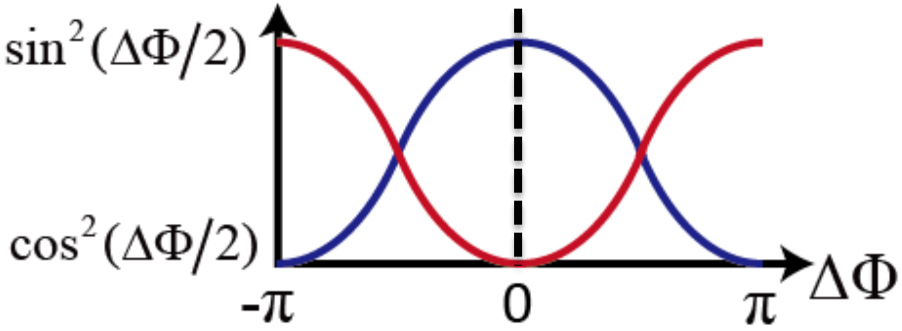
(2) Lock the zero crossings of microwave signal to the optical pulse train by **feedback control**

(1) Detect the phase error between optical pulse train and microwave signal

Operation of the optical phase detector

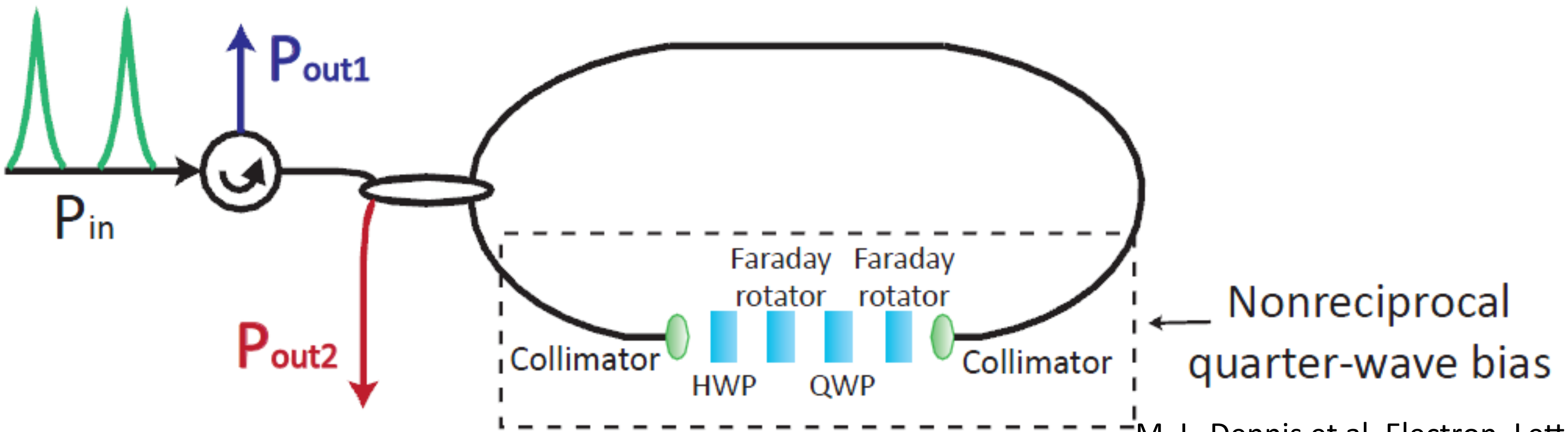
Phase error converted to optical intensity imbalance based on fiber Sagnac-loop



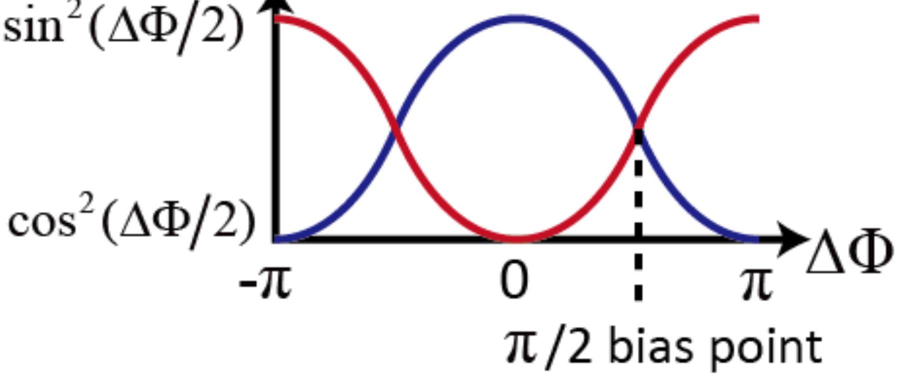


$\Delta\Phi$: Phase difference between counter-propagating pulses

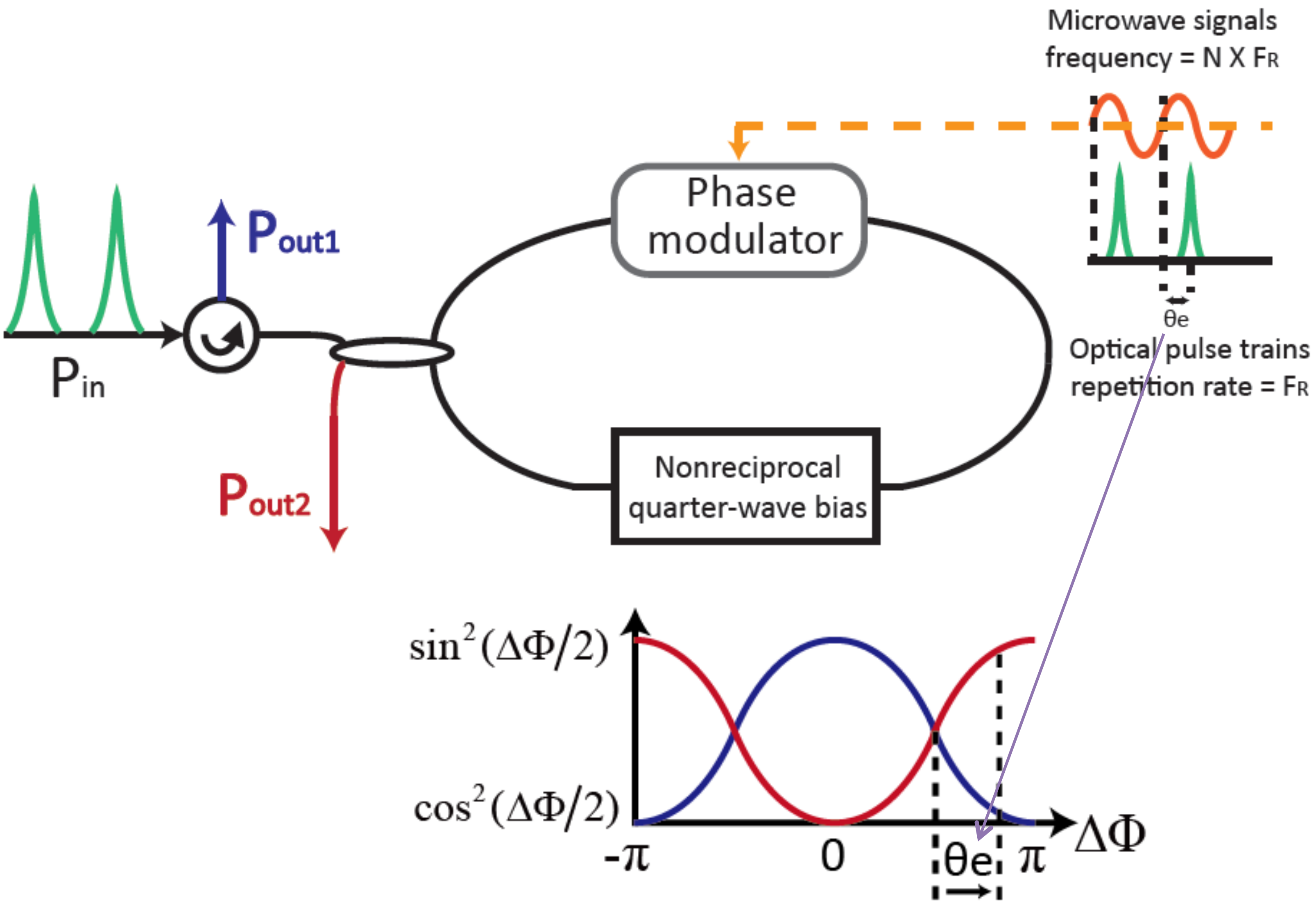
Operation of the optical phase detector



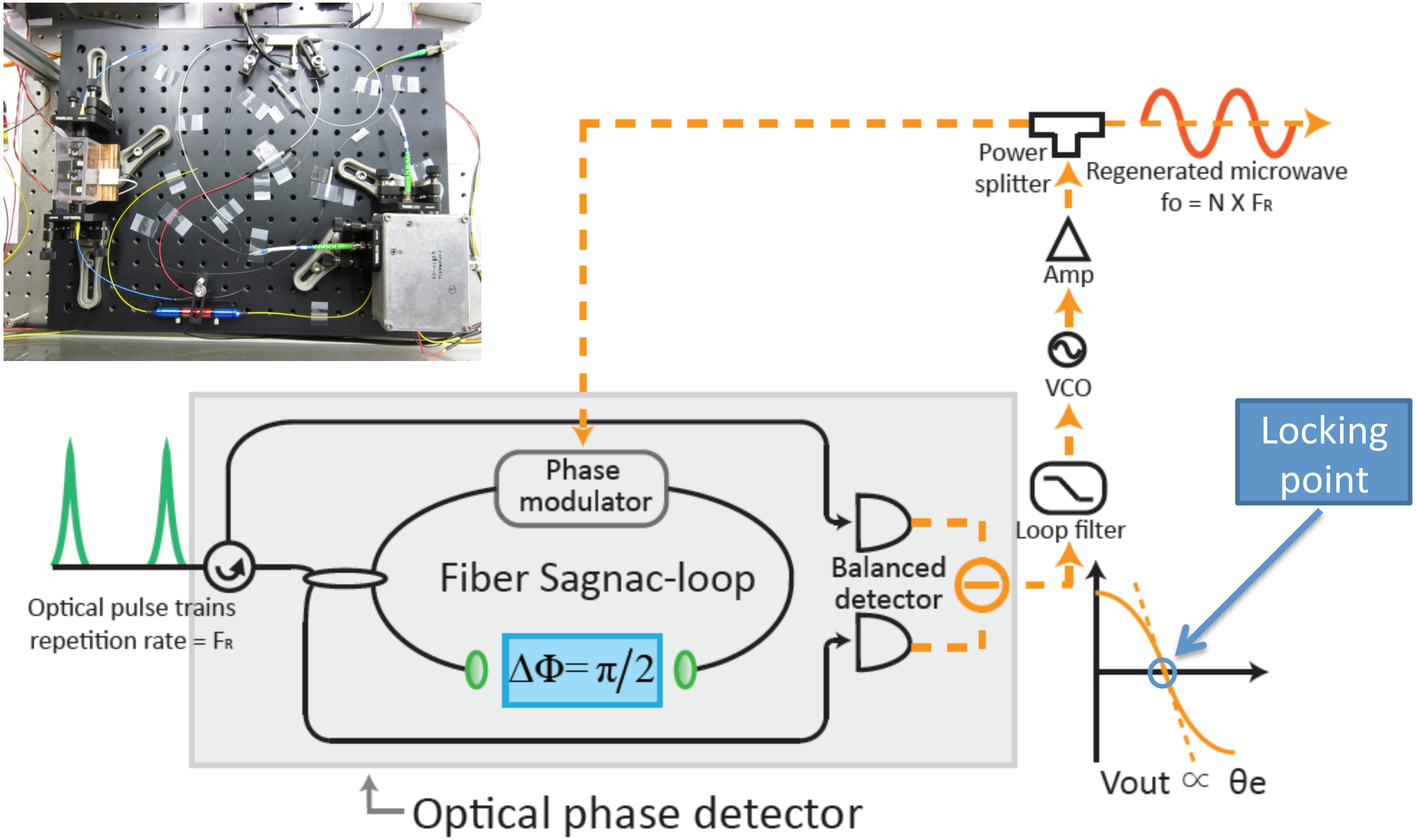
M. L. Dennis et al. Electron. Lett. **32**, 547-548 (1996)



Operation of the optical phase detector



Synchronization using phase-locked loop



Power splitter

Regenerated microwave

fo = N X FR

Amp

VCO

Loop filter

Locking point

Phase modulator

Fiber Sagnac-loop

$\Delta\Phi = \pi/2$

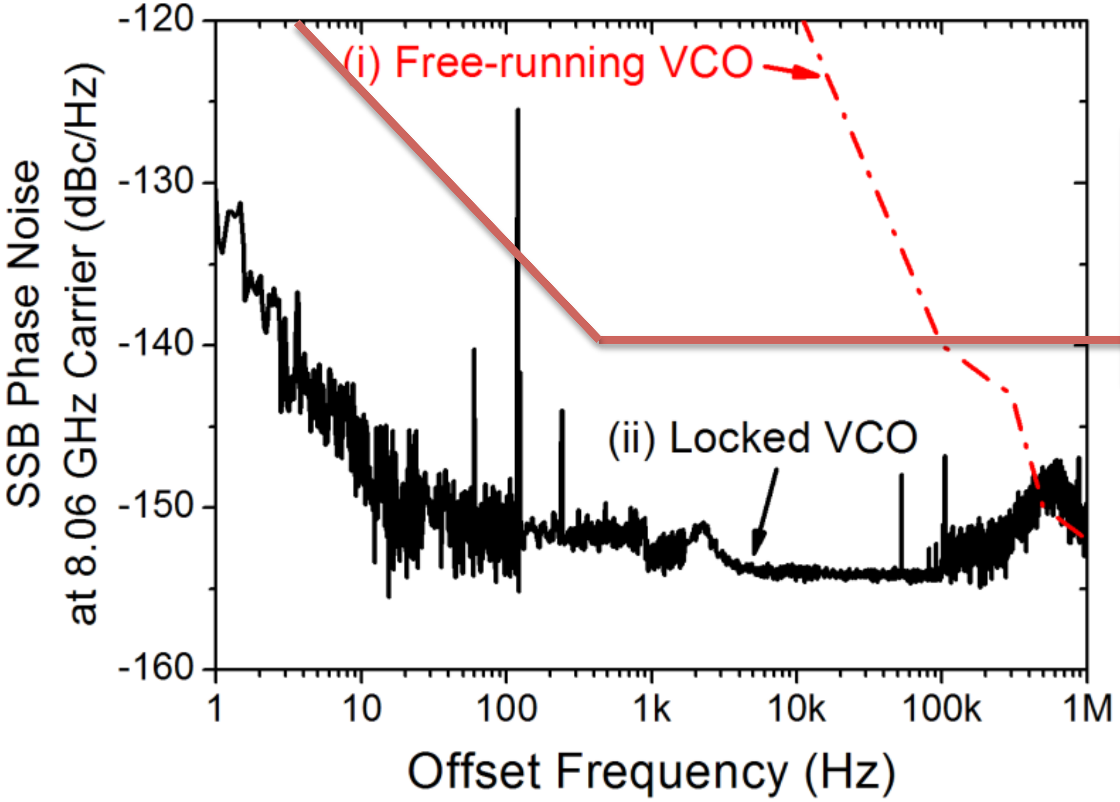
Balanced detector

Optical pulse trains repetition rate = FR

Vout ∝ θe

Optical phase detector

Residual phase noise of 8.06 GHz microwave synchronized with 77.5 MHz Er-fiber laser

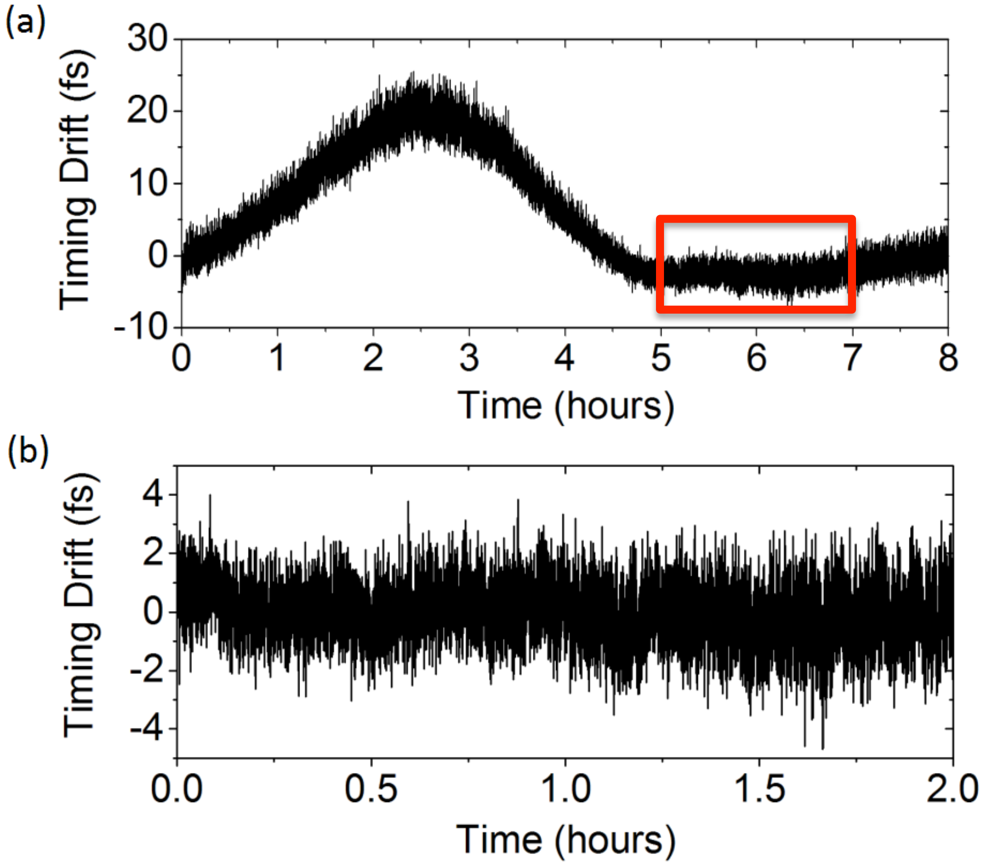


Typical limitation by direct extraction from conventional fiber lasers and photodiodes

This result is the best short-term synchronization performance.

-133 dBc/Hz at 1 Hz offset, -154 dBc/Hz at 5 kHz offset
Integrated rms timing jitter: **838 as** [1 Hz–1 MHz]

Relative timing drift between optical pulse trains and regenerated 8.06 GHz microwaves



8.0 fs rms timing drift for 8 hours – (a)
0.99 fs rms timing drift for 2 hours – (b)

Summary

- Demonstrated the **record-low timing jitter from ultrafast fiber lasers: 70 attoseconds jitter** [10 kHz – 40 MHz offset frequency], which is comparable with the best microwave signal sources with much reduced cost and engineering complexity.

- Demonstrated the microwave signal extraction technique with 840-as residual jitter to **generate the microwave signals from ultrafast fiber lasers with the ultra-low phase noise and high phase stability.**

- **Ultrafast fiber lasers have great potentials for generating ultralow-noise optical and electronic signals** and various applications that need higher timing/phase/frequency precision in future light sources.