Femtosecond precision optical frequency and timing distribution systems

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Workshop on Synchronization and Timing Systems (WSTS)

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Synchronized femtosecond lasers reveal the unknown properties of the DNA mutation.

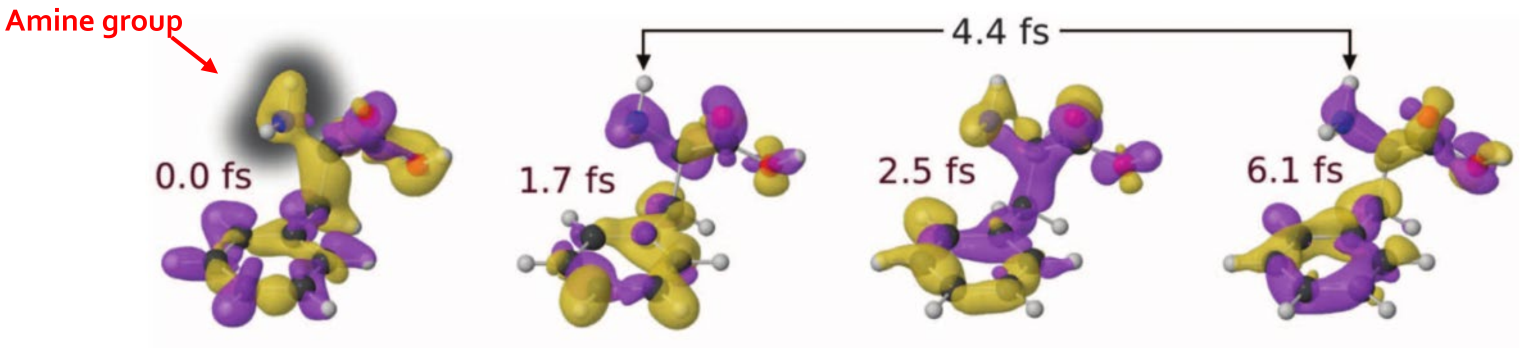
Ultrafast photography

Synchronized flash and shutter within few milliseconds

1964, photograph by Dr. Harold Edgerton, MIT.

Ultrafast charge migration in amino acids[2]

DNA mutation in response to X-ray radiation



F. Calegari et al., Science, vol. 346, pp. 336-339, 2014.

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X-ray free electron lasers have the most challenging timing distribution and synchronization requirements.

Large laser interferometers: LIGO
Area: Gravitational-wave detection
Required precision: < 1µs

B. P. Abbott et al., Rep. Prog. Phys, vol. 72, no. 076901, pp. 1-25, 2009.

Radio telescope networks: ALMA
Area: Sensitive imaging of dark regions in the universe
Required precision: <1 ps

A. Wootten and A. R. Thompson, Proceedings of the IEEE, vol. 97, no. 8, 2009.

X-ray free-electron lasers: European XFEL
Area: Ultrafast molecular imaging
Required precision: <1 fs

T. Sato et al., Optica, vol. 7, no. 6, pp. 716-717, 2020.

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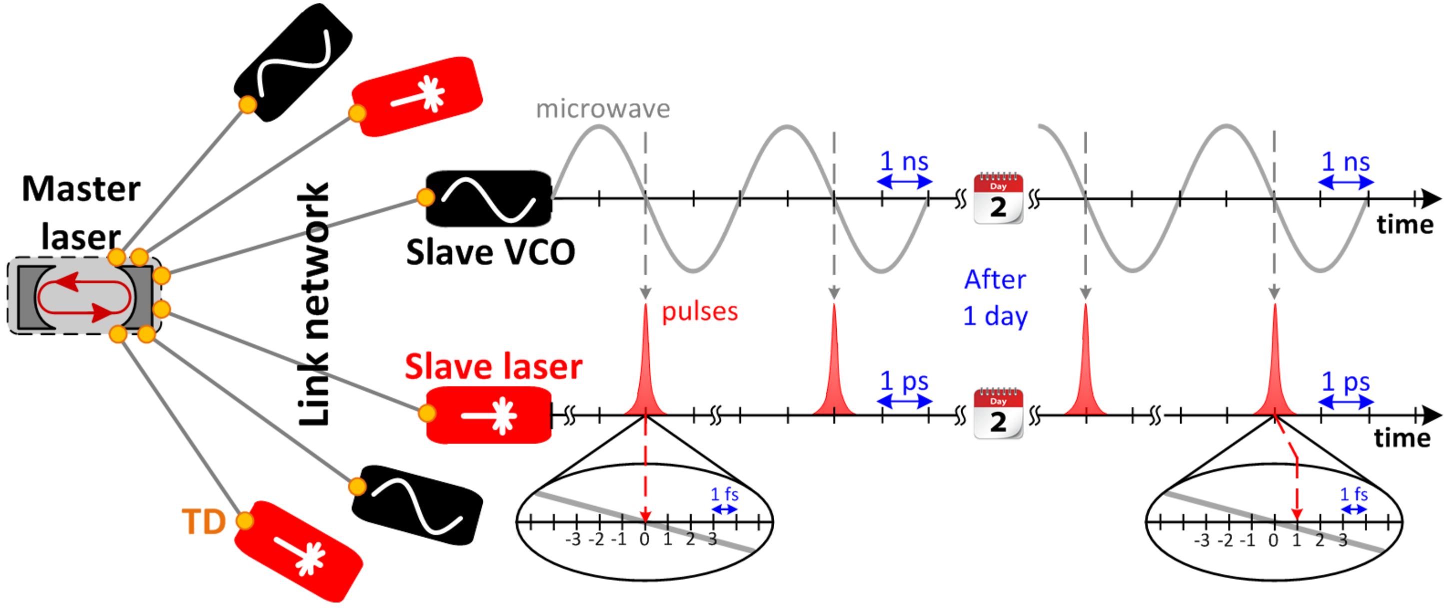
The solution is to devise a pulsed timing distribution network with sub-femtosecond precision.



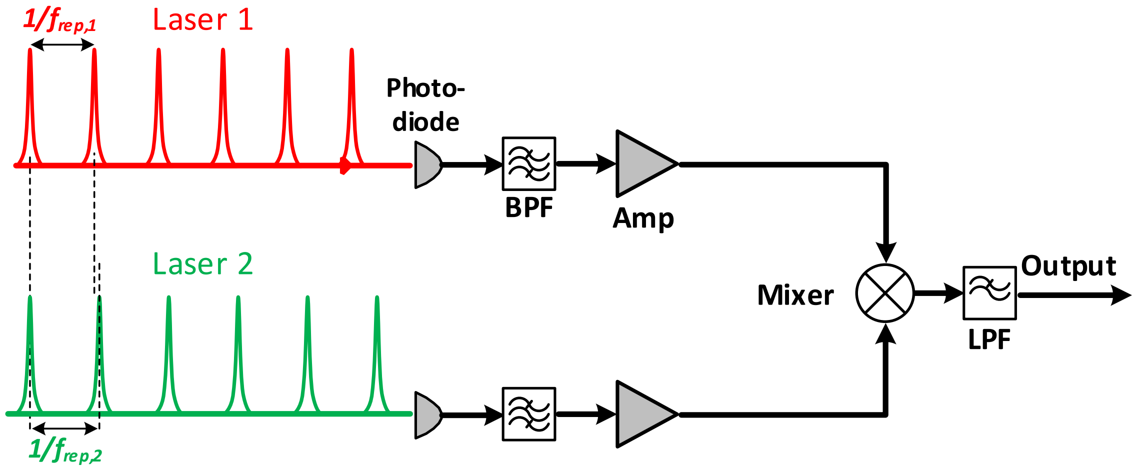
Outline:

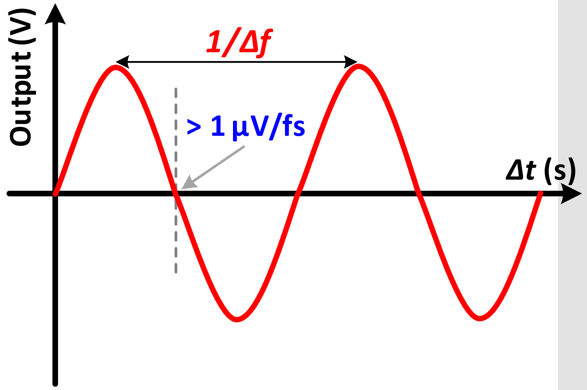
1. High precision timing detectors
2. Lower noise photonic oscillators
3. Highly stable timing distribution via fibers

1. Timing detectors:

Electronic phase detection.

Electronics cannot detect femtosecond fluctuations.





Parameter	Electronic detection
Sensitivity	> 1 µV / fs
Jitter above 1 Hz	> 100 fs RMS
Drift below 1 Hz	> 500 fs RMS

J. M. Glownia et al., Opt. Express, vol. 18, pp. 17620–17630, 2010.

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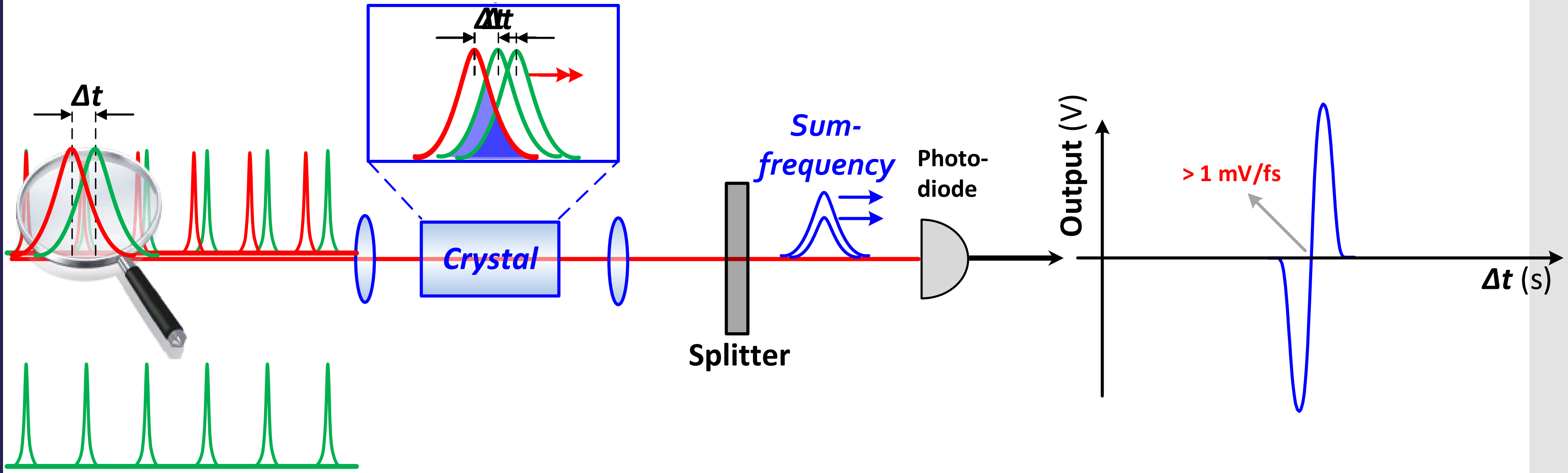
1. Timing detectors:

Optical cross-correlation.

Pulsed optical timing detection enables sub-femtosecond synchronization.



Parameter	Electronic detection	Pulsed-optical detection
Sensitivity	> 1 µV / fs	**> 1000 µV / fs**
Jitter above 1 Hz	> 100 fs RMS	**< 1 fs RMS**
Drift below 1 Hz	> 500 fs RMS	**< 1 fs RMS**

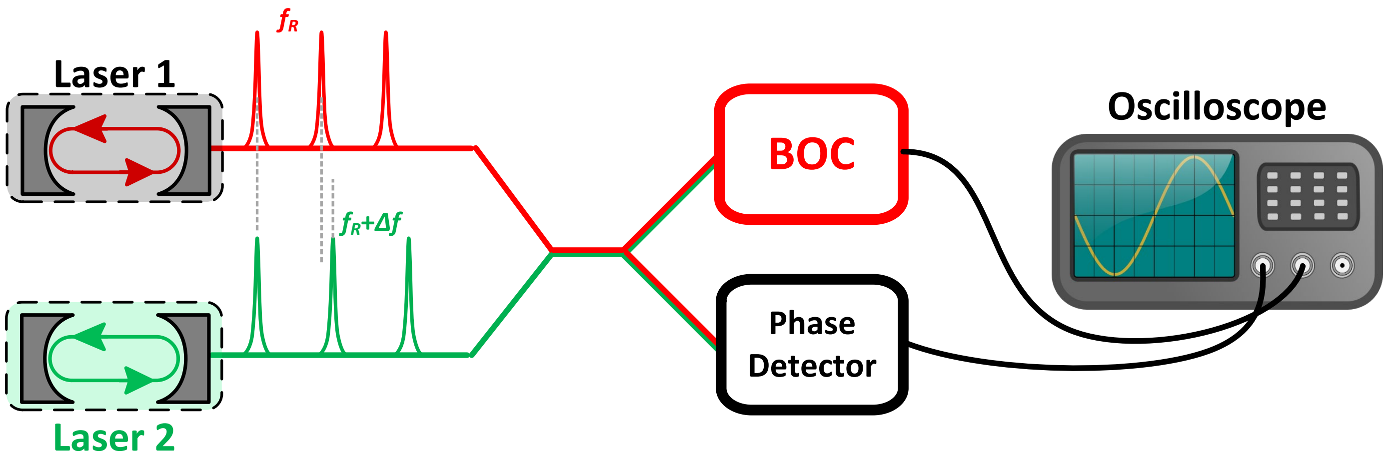
T. R. Schibli et al., *Opt. Lett.*, vol. 28, no. 11, pp. 947-949, 2003.

1. Timing detectors:

Electronic phase detector

vs.

Balanced optical cross-correlator (BOC)



1. Timing detectors:

Electronic phase detector

vs.

Balanced optical cross-correlator (BOC)

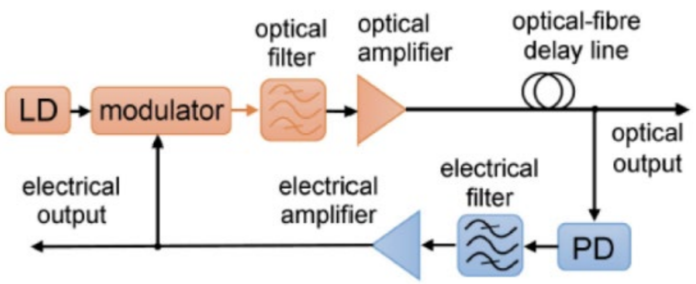
2. Photonic oscillators:

State-of-the-art photonic oscillators:

- Opto-electronic oscillator (CW laser)

- Comb-based photonic microwave oscillator

Opto-electronic oscillator



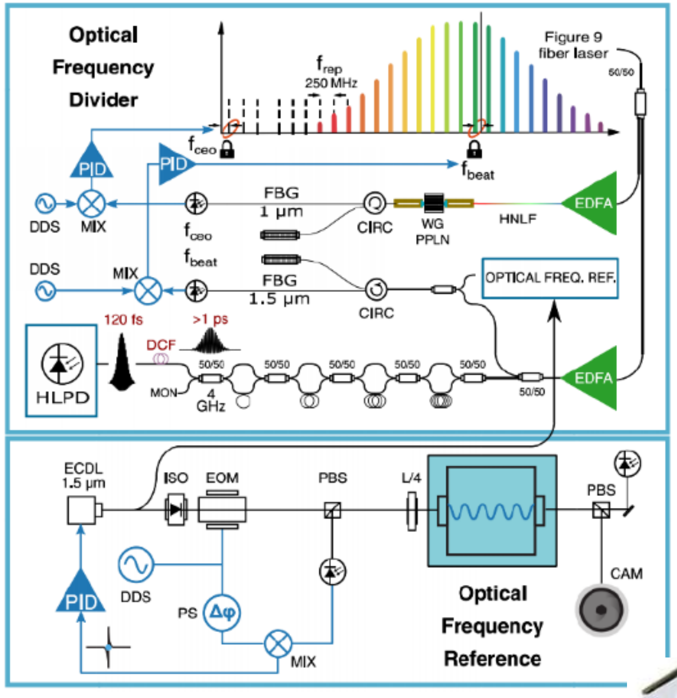
Quelle: https://en.wikipedia.org/wiki/Opto-electronic_oscillator

OEwaves INVENT • DEVELOP • DELIVER | HI-Q™ COMPACT OPTO-ELECTRONIC OSCILLATOR

https://www.high-tech.co.jp/list/wp-content/uploads/HI-Q-Compact-OEO.pdf

- Based on a stabilized monochromatic laser.
- Long fiber path serves as the reference for stabilizing the oscillator.
- Handbook size

Comb-based photonic oscillator



Optics Letters, Vol. 45, No. 5 / 1 March 2020.

- Based on optical frequency division with a stabilized femtosecond laser
- An "ultra-stable" vacuum based cavity serves as the reference fo[r] stabilizing the oscillator.
- Half 19" rack size

https://www.menlosystems.com/products/ultrastable-microwaves/pmwg-1500/

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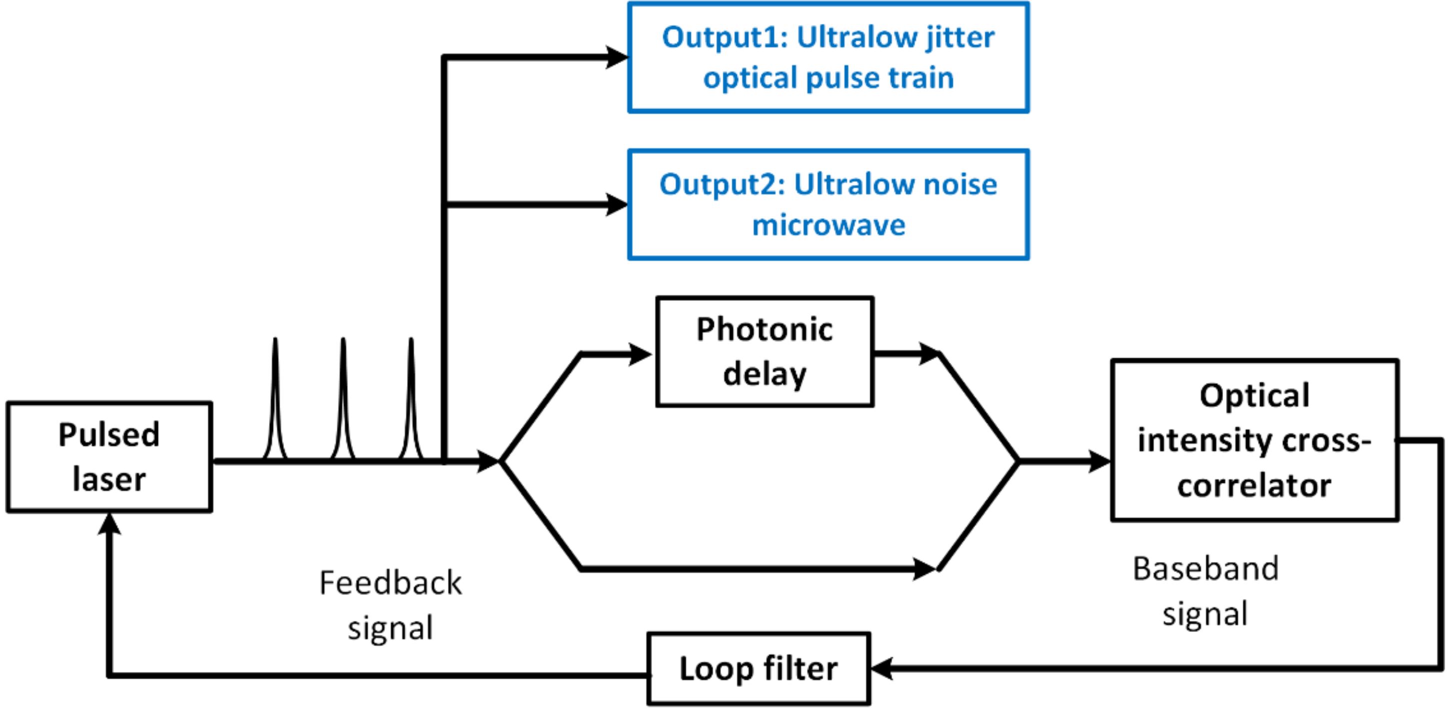
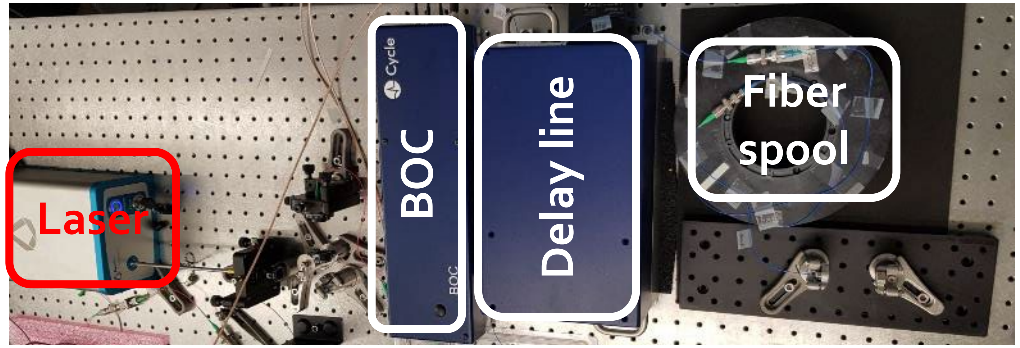
2. Photonic oscillators:

PRESTO:

Photonically
Reference
Extremely
STable
Oscillator



- Pulse repetition rate is locked to the delayed optical pulse train.
- The long fiber delay serves as the reference for the stabilization.
- The timing jitter is measured with highly sensitive BOCs
- First demonstration experiment:



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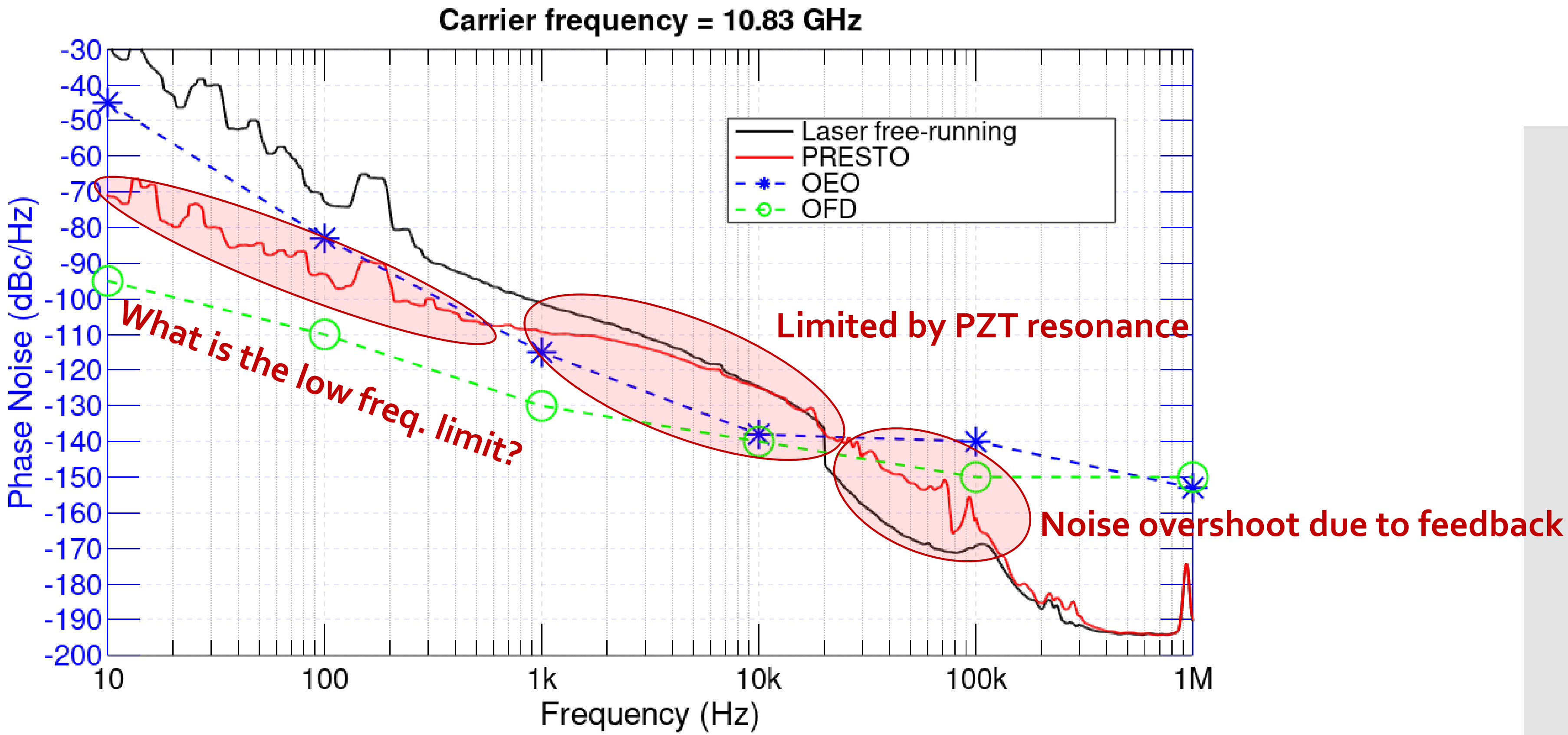
Patent pending: EP 21 17 1191 & US 17/731 233

2. Photonic oscillators:

Timing jitter of the laser is highly suppressed within the lock bandwidth (~10 kHz) from 2 ps down to 20 fs RMS.
Noise from 1 kHz to 20 kHz can be improved with better intracavity PZT of the laser.



Phase noise at 10.83 GHz

Freq. (Hz)	Laser free running (dBc/Hz)	OEO (dBc/Hz)	PRESTO (dBc/Hz)	OFD (dBc/Hz)
10	-27	-45	-71	-95
100	-73	-83	-93	-110
1k	-101	-115	**-109**	-130
10 k	-125	-138	**-125**	-140
100 k	-170	-140	-161	-150
1 M	-190	-153	-190	-150

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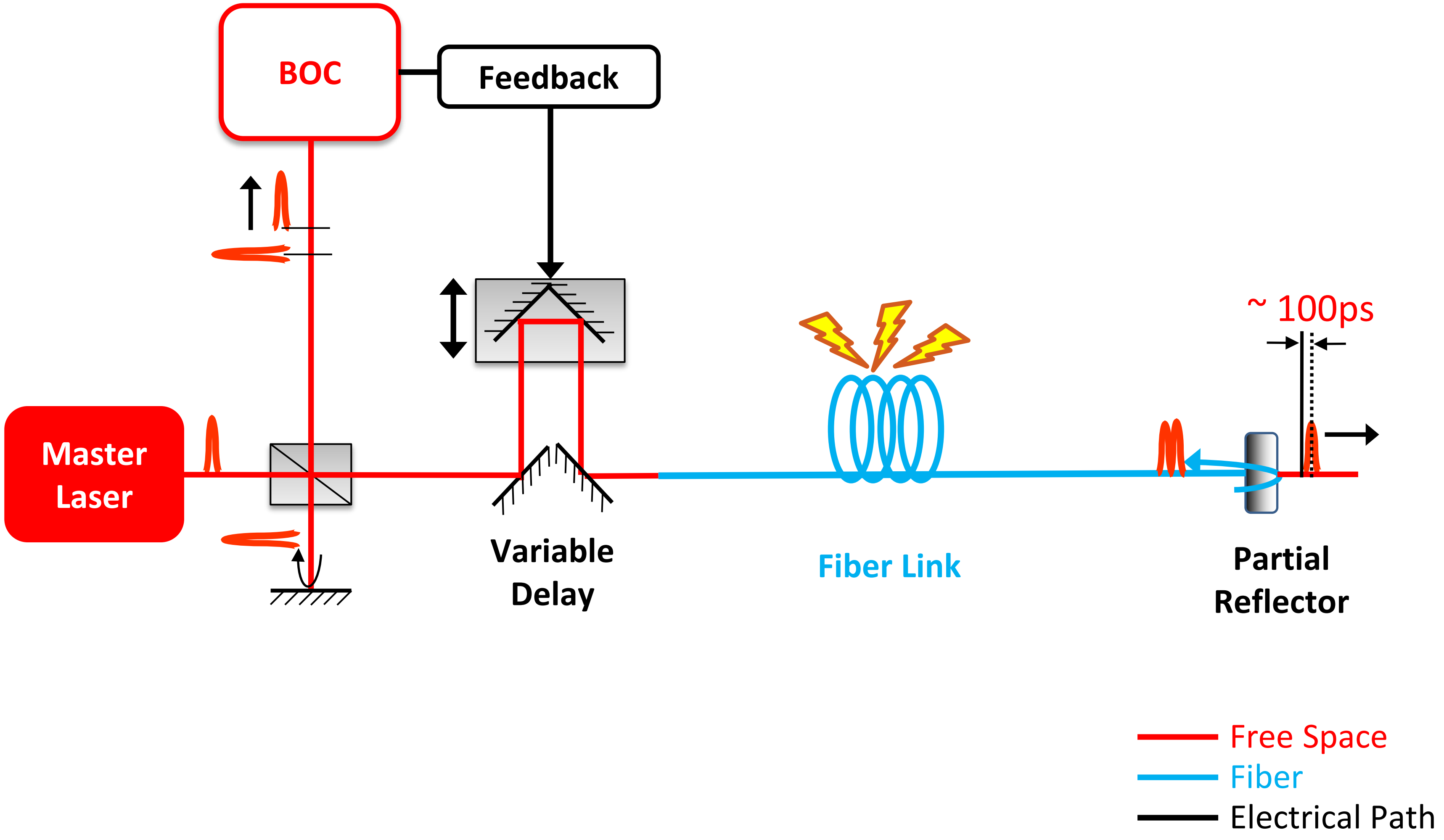
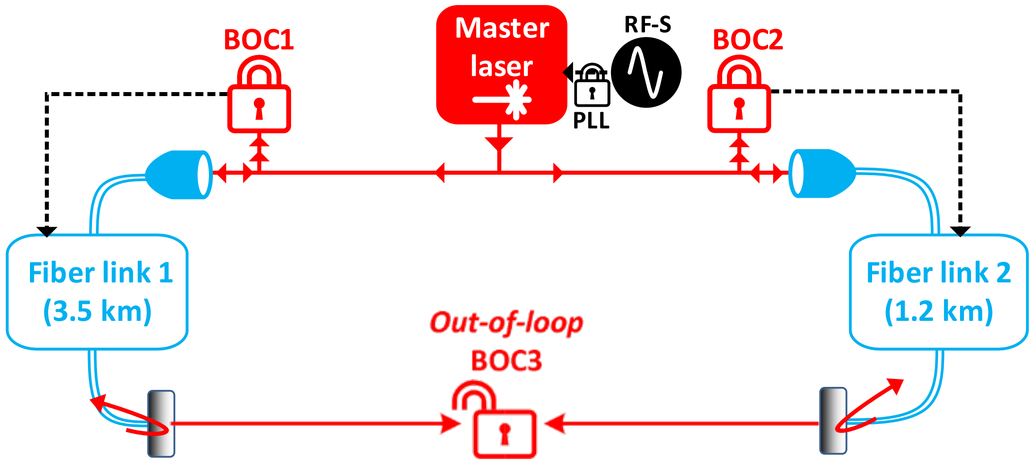
3. Timing distribution:

We detect the round-trip fiber noise and build a feedback loop on an optical variable delay element in the link.

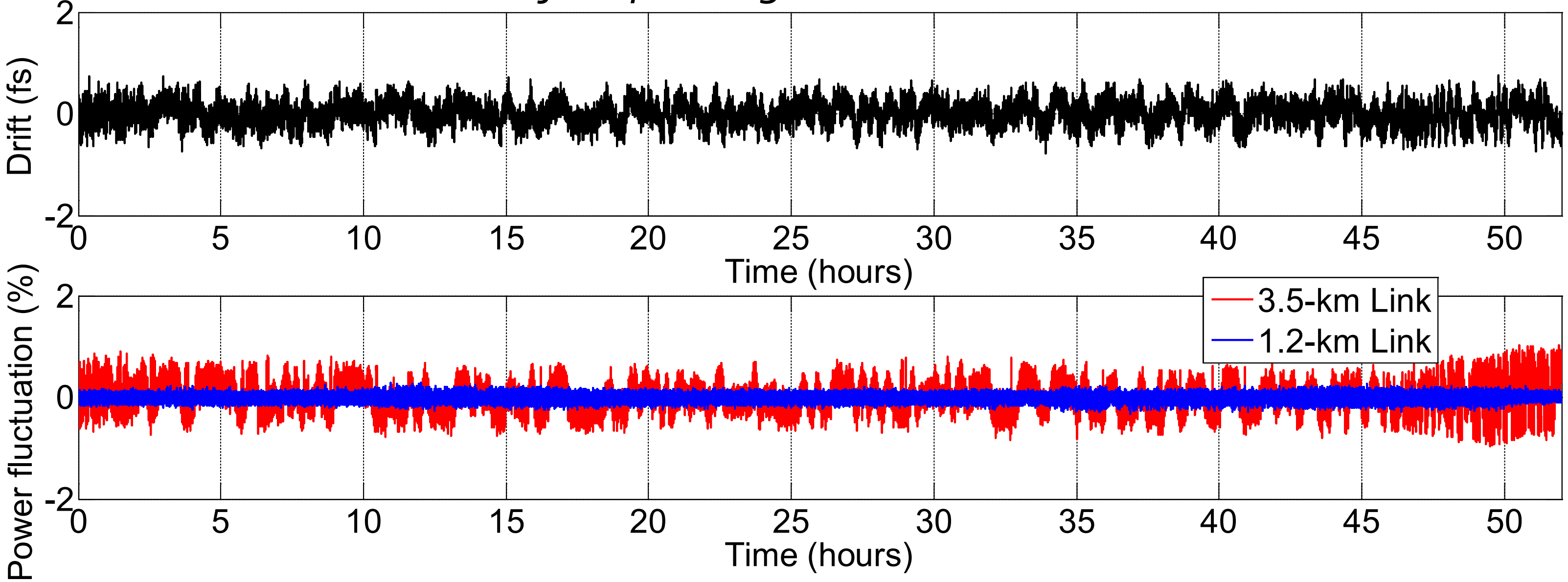


3. Timing distribution:

Due to high timing sensitivity and robustness against environmental fluctuations of the optical cross-correlation, we can achieve timing distribution with daily sub-femtosecond precision.



Out-of-loop timing error: 200 as RMS



M. Xin et al., *Light Sci. Appl.*, vol. 6, no. e16187, 2017.

Achieved milestones:

2017: first system installed

2019: Delivery of a timing system for an X-ray laser

2022: Delivery of an optical timing system for a deep space antenna

Dalian China, 2017

Stanford USA, 2019

ESTRACK ESA, 2020 – 2025

IN COLLABORATION WITH

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The view expressed herein can in no way be taken to reflect the official opinion of the European Space Agency.

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Thank you!

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