Attosecond Precision Multi-km Laser-Microwave Network

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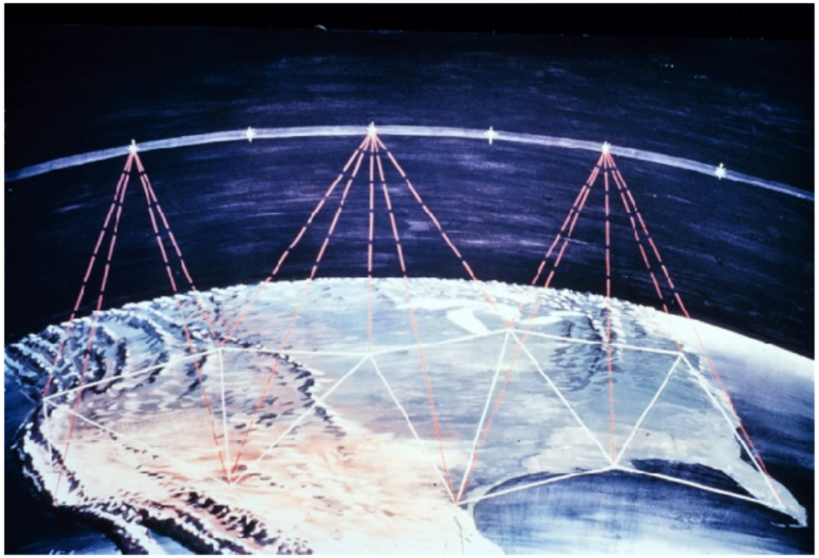
IBIC 2016 Barcelona, Spain

Session: Time Resolved Diagnostics and Synchronization

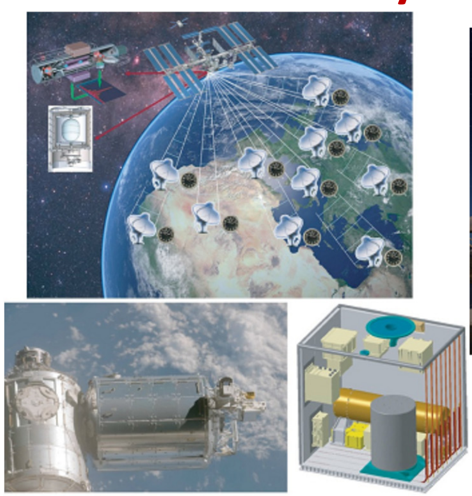
Sept. 13, 2016

Synchronous laser-microwave networks

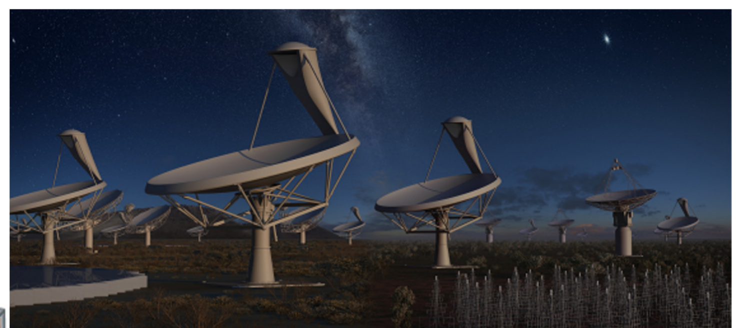


Geodesy studies

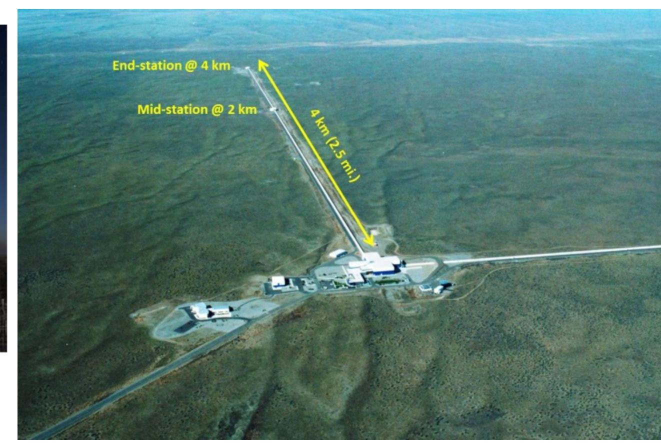
Radio telescope arrays



High-precision navigation

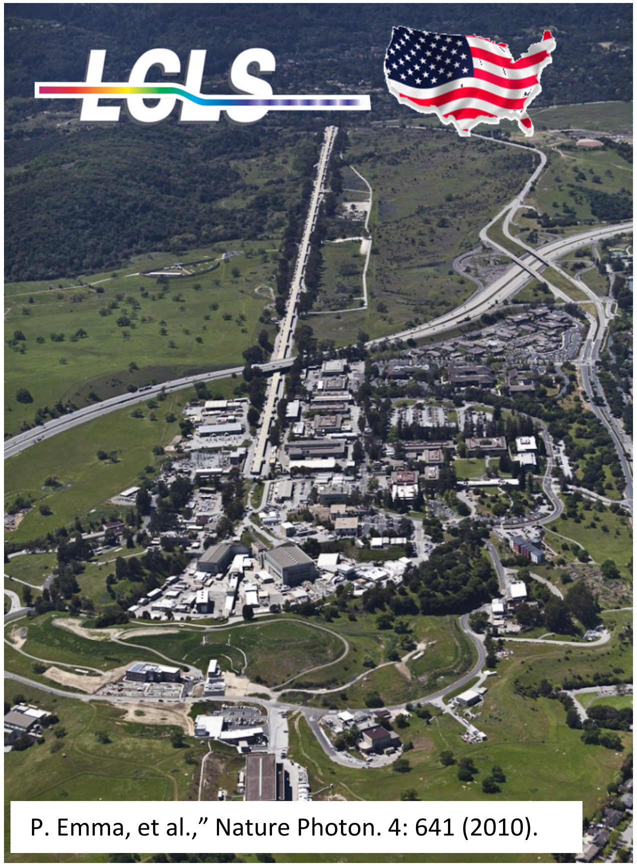


Very-long-baseline interferometry



Gravitational-wave detection

New generation free-electron lasers:



P. Emma, et al.," Nature Photon. 4: 641 (2010).

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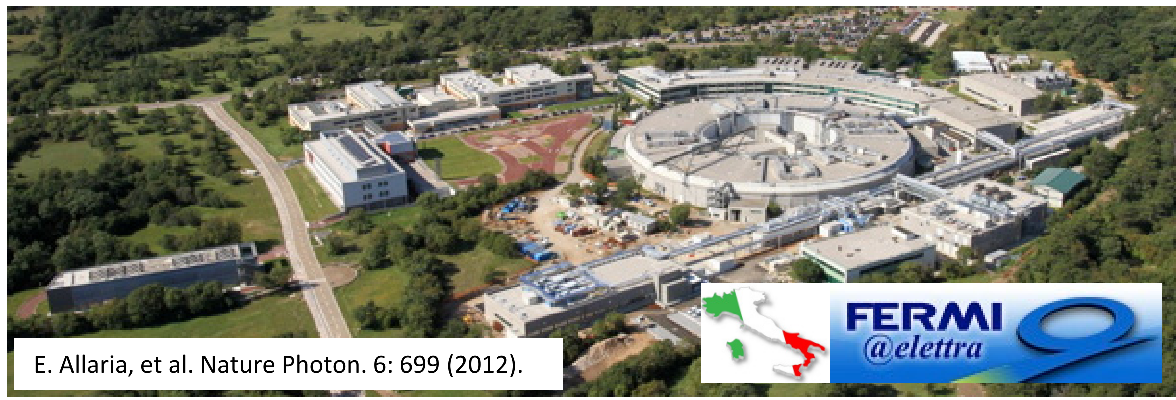

E. Allaria, et al. Nature Photon. 6: 699 (2012).

M. Altarelli, et al., Technical Design Report, DESY 97 (2006).

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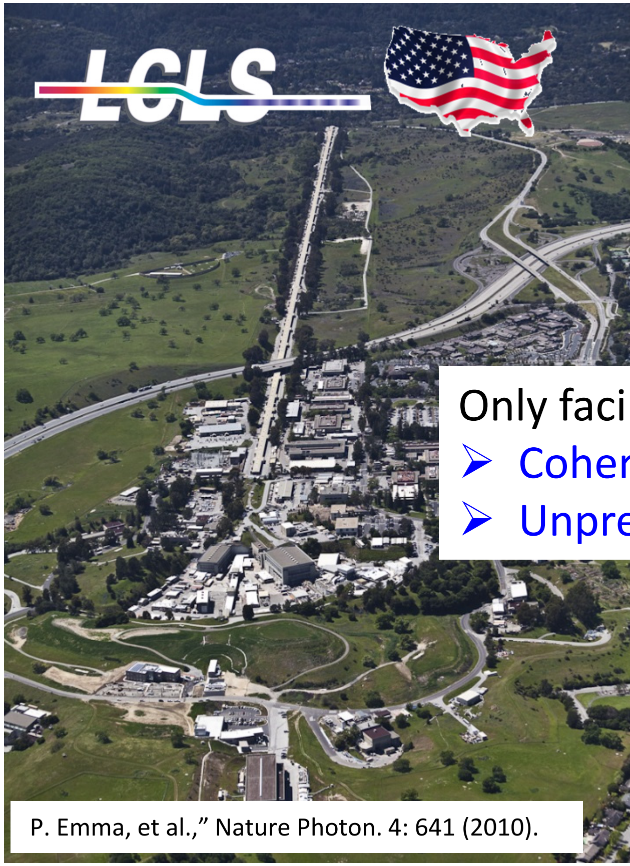
New generation free-electron lasers:

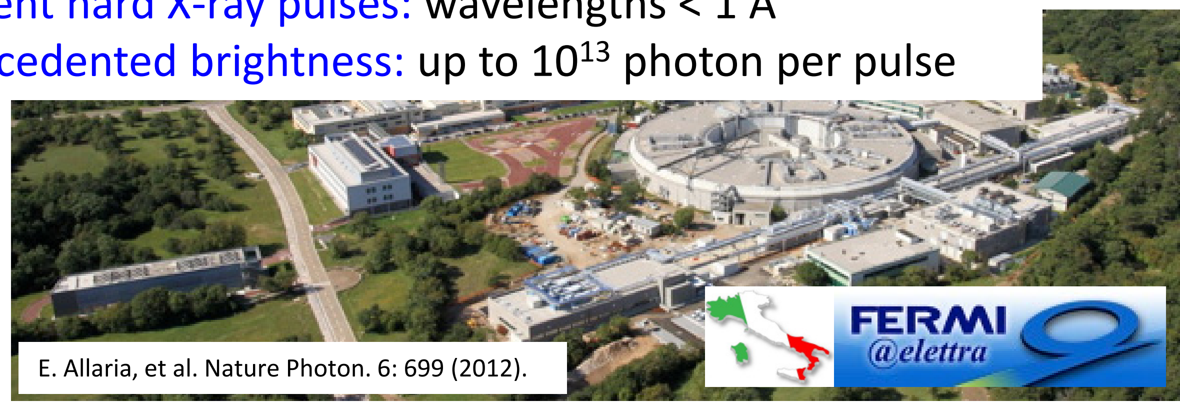


P. Emma, et al.," Nature Photon. 4: 641 (2010).

T. Ishikawa, et al., Nature Photon. 6: 540 (2012).

Only facilities generating:

- Coherent hard X-ray pulses: wavelengths < 1 Å
- Unprecedented brightness: up to 10^{13} photon per pulse



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M. Altarelli, et al., Technical Design Report, DESY 97 (2006).

Timing distribution for next generation FELs

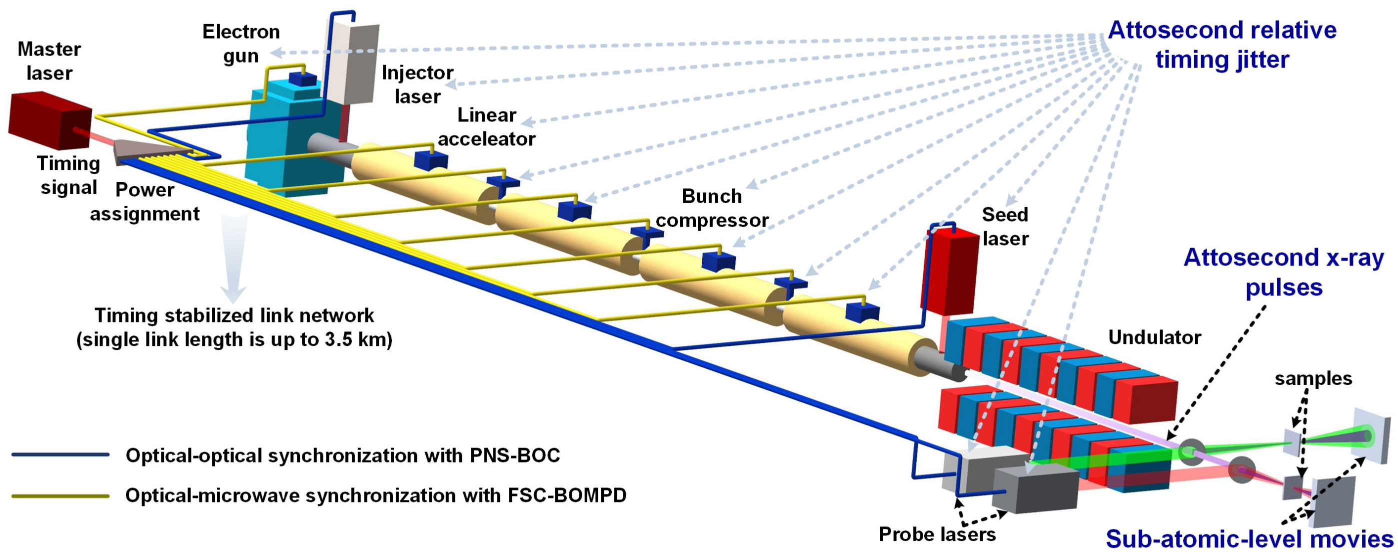
Quest for isolated ultrashort hard X-ray pulses:

Ultrafast Auger processes in X-ray imaging: S. Hau-Riege et al., *PRL*, **108**, 238101 (2012).

Intramolecular charge transfer: F. Calegari et al., *Science*, **346**, 336-339 (2014).

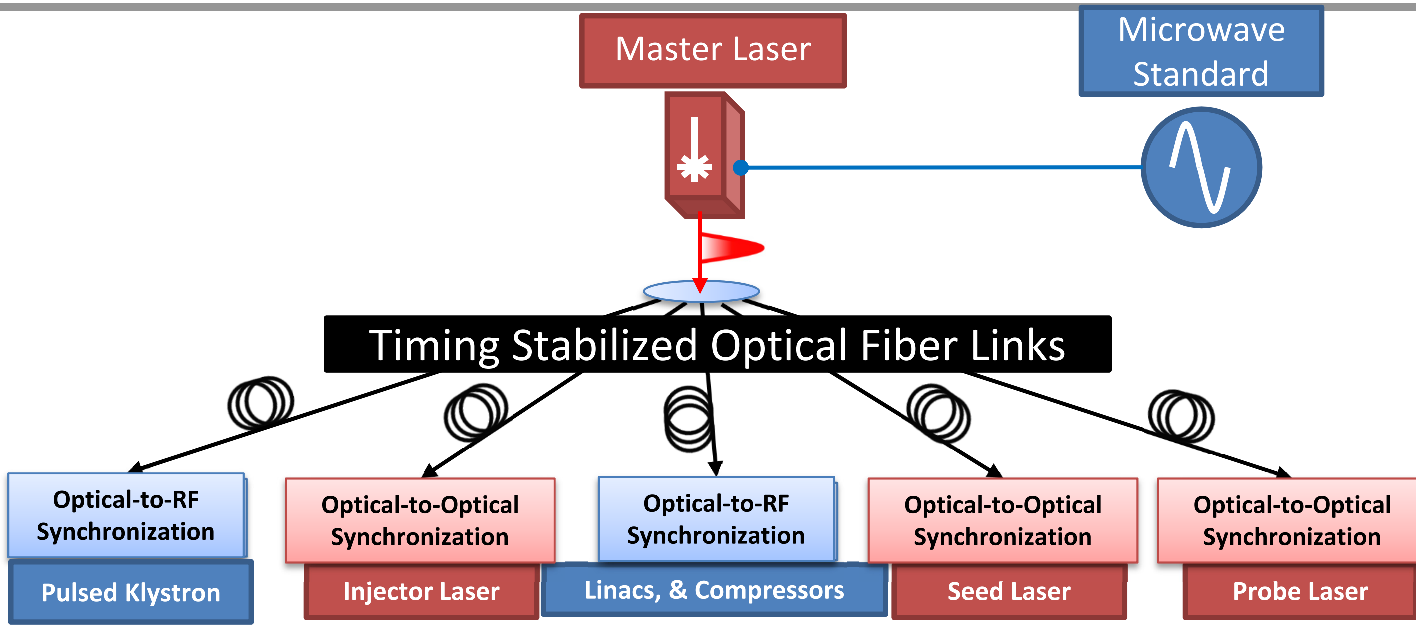
altering the chemistry of matter on an attosecond timescale!

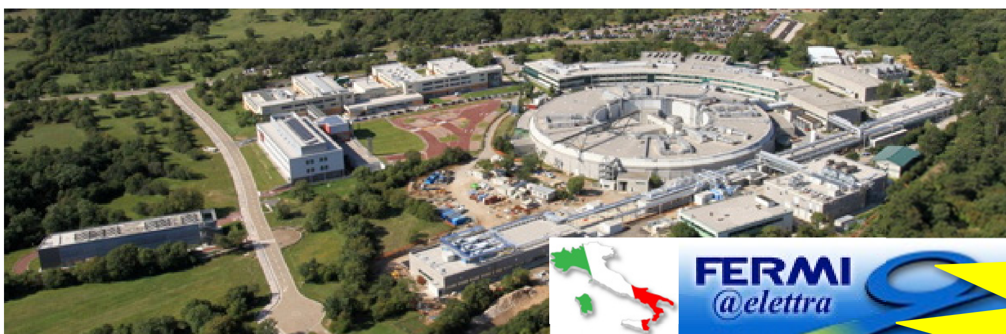
High precision synchronization remains to be a major obstacle!



Task: **Synchronize the complete facility from e-gun to probe laser with sub-fs stability**

Optical timing distribution system





~10 fs timing precision

Attosecond precision

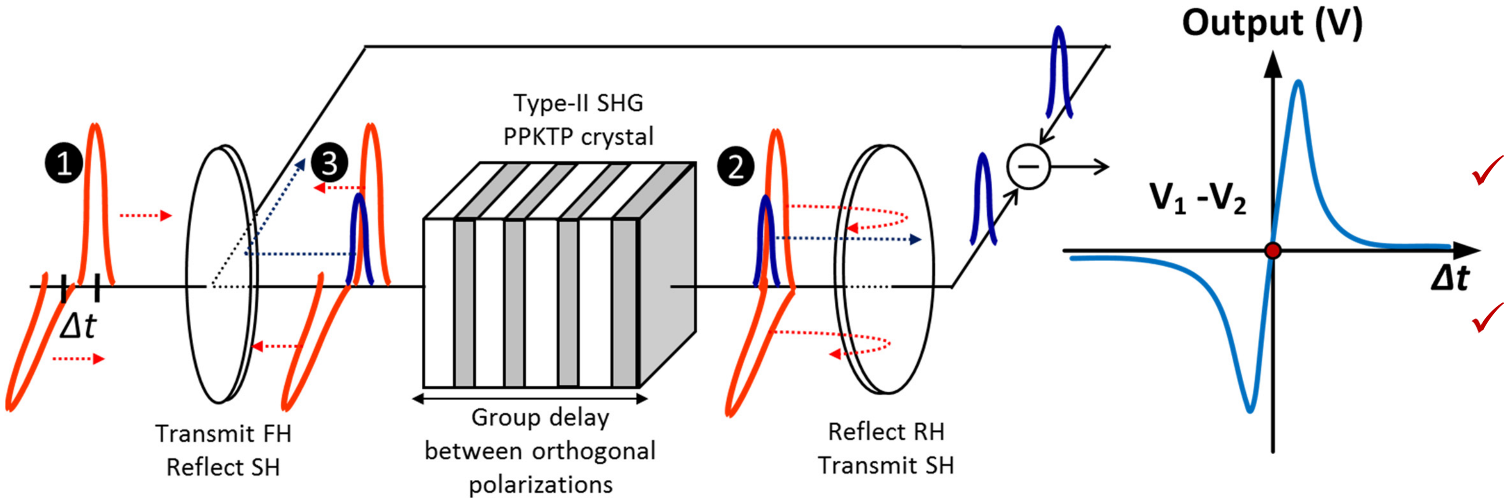
Optical-to-optical detector

Optical-to-microwave detector

Fundamental noise sources in fiber transmission

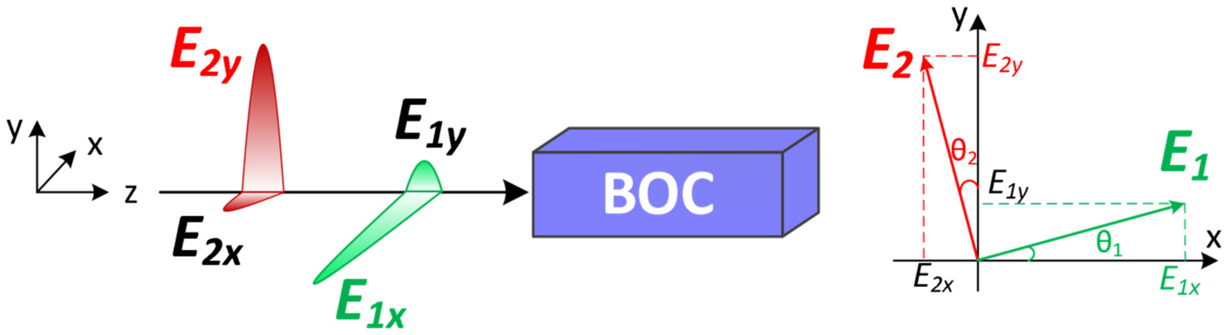
J. Kim et al, *Nat. Photonics* **5,** (2008).

Optical-to-optical: *balanced optical cross-correlator*



- ✓ **AM-to-PM noise free**
- ✓ **Environmentally robust**

➢ **Polarization-noise-supressed BOC:**



Schibli et al, *Opt. Lett.* **28**, 11 (2003).
J. Kim et al, *Opt. Lett.* **32**, 24 (2007).

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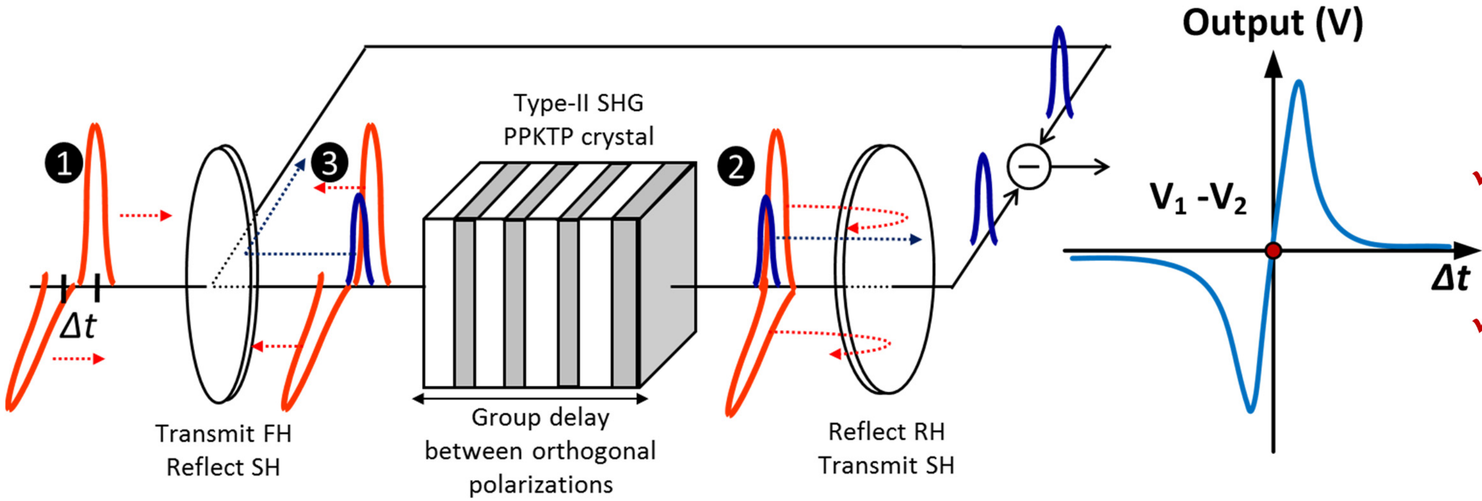

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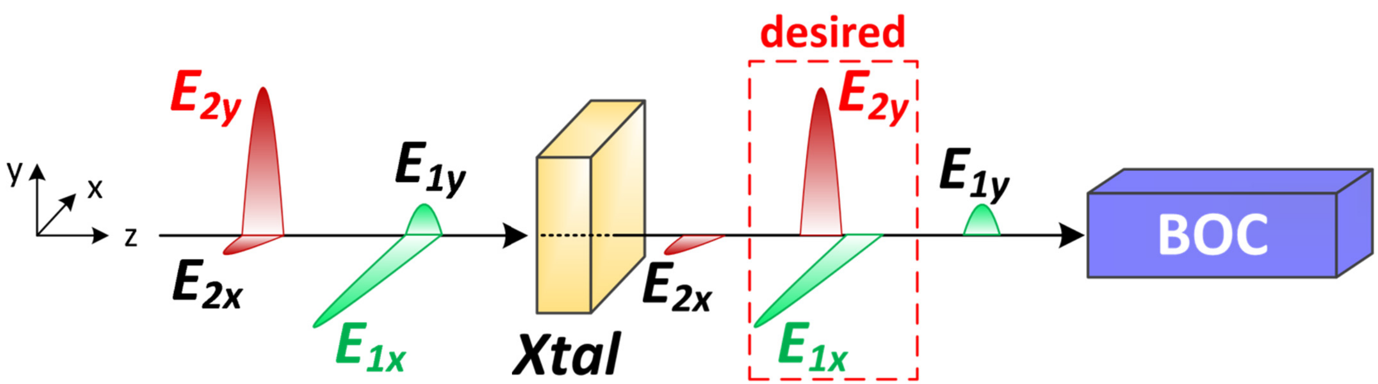

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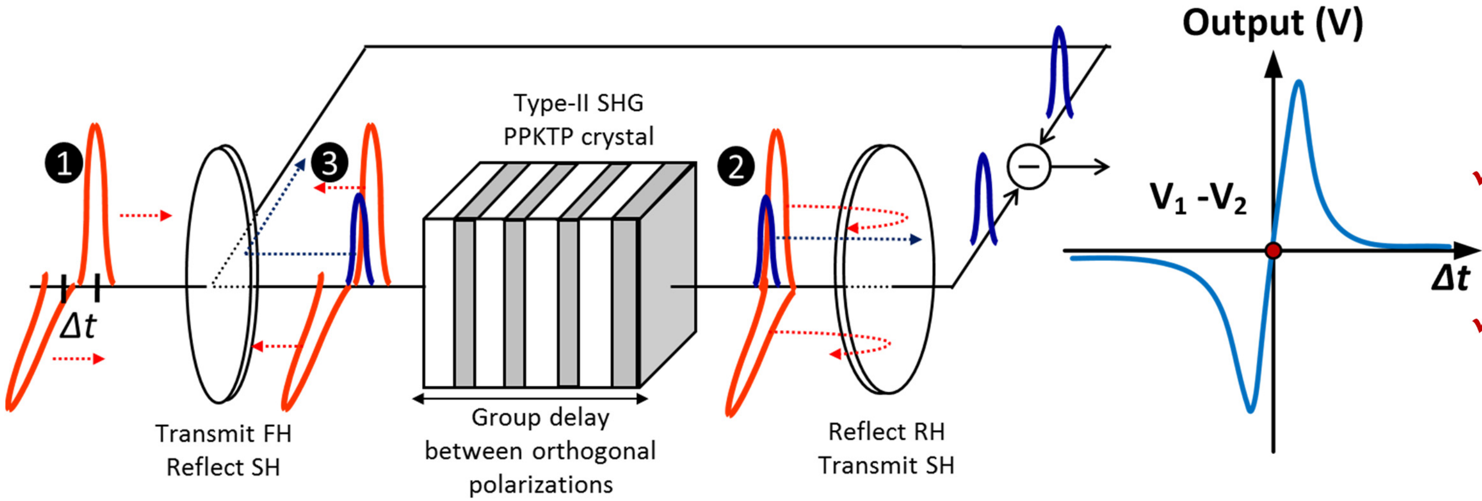

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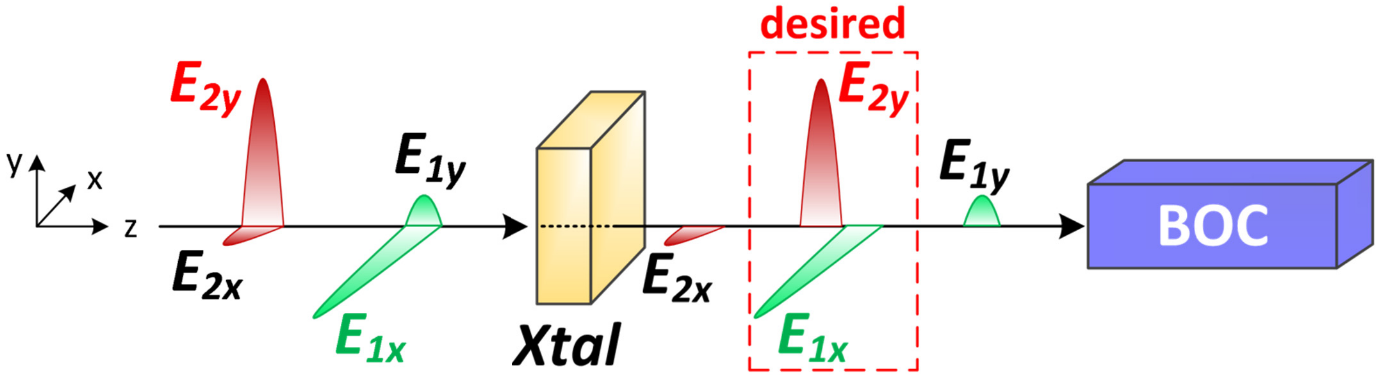
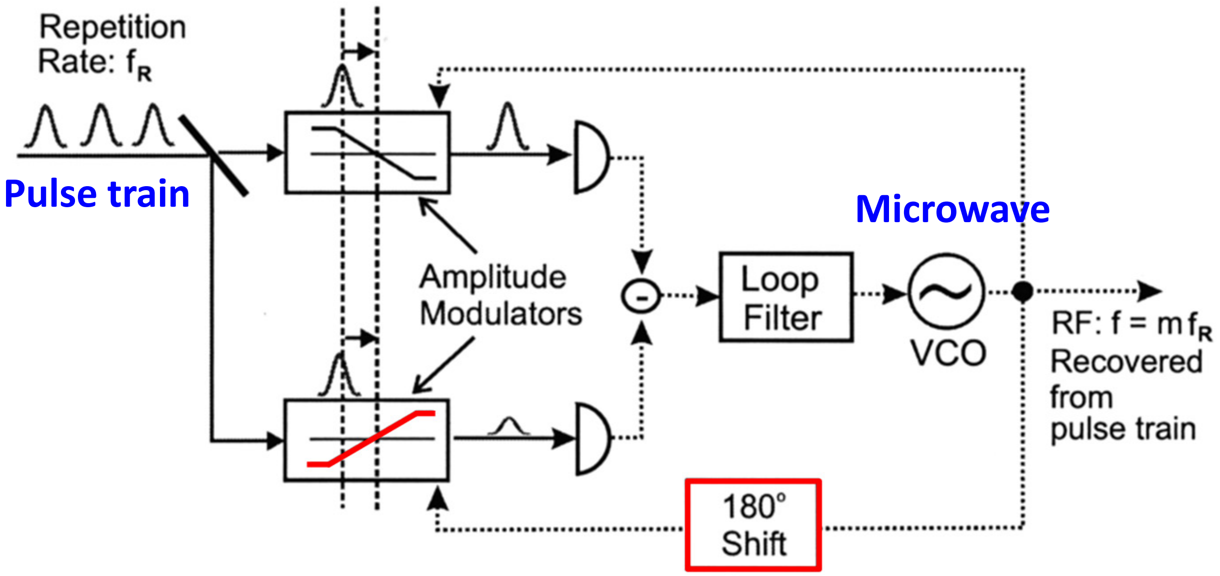


- ✓ **Background noise free**
- ✓ **Polarization noise free**

Schibli et al, *Opt. Lett.* **28**, 11 (2003).
J. Kim et al, *Opt. Lett.* **32**, 24 (2007).

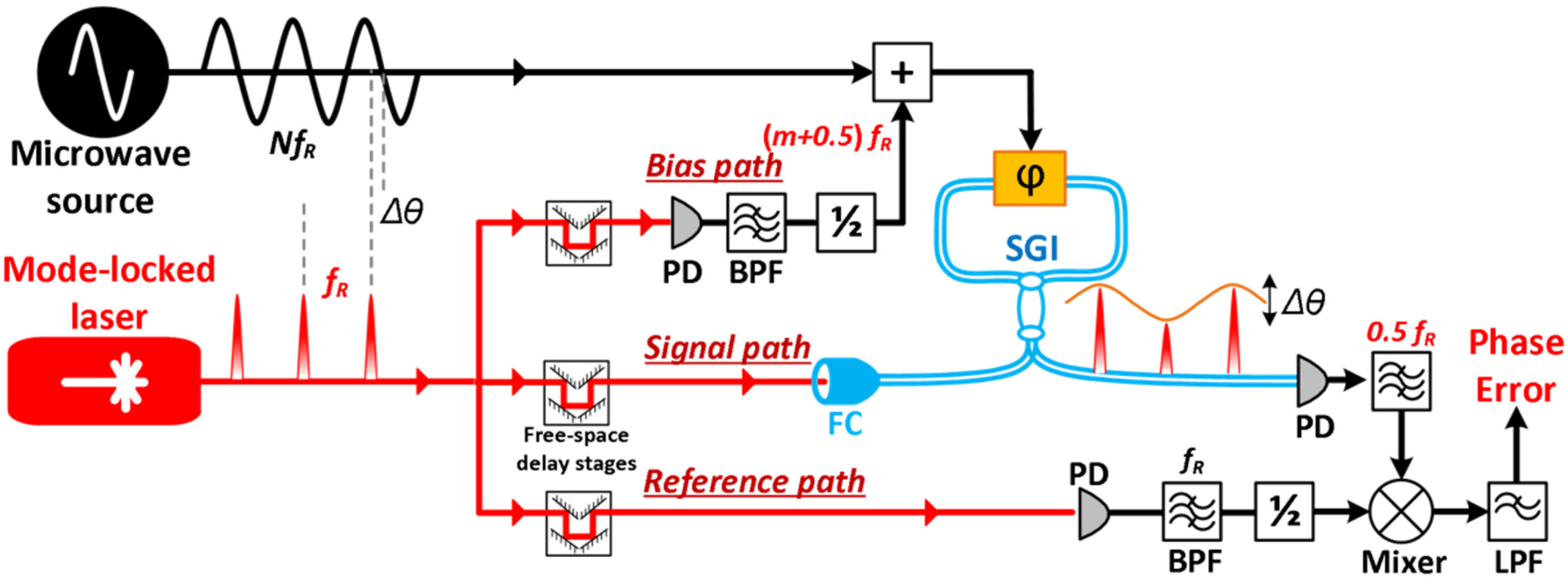
Optical-to-microwave: *balanced optical microwave phase detector*

<u>BOMPD detection scheme:</u>



1. 180˚ out-of-phase amplitude modulation: Sagnac interferometer
2. Synchronous optical pulses and microwave: zero error output
3. Timing deviation: intensity imbalance of the split optical pulses

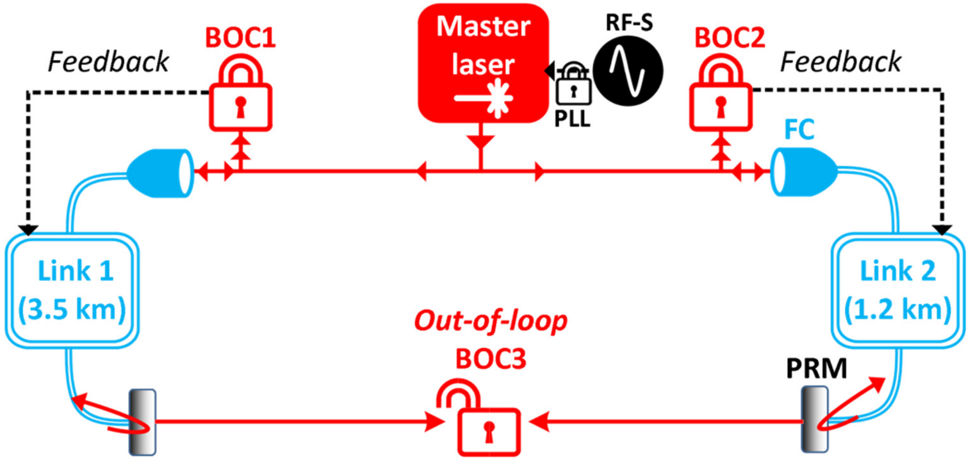
Free-space coupled balanced optical microwave phase detector:



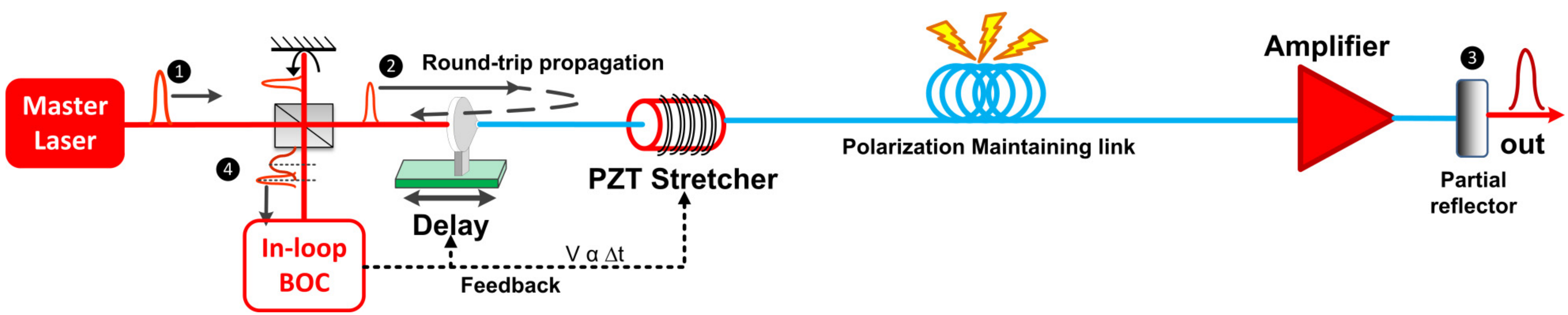
1. Free-space optics for optical beam distribution:
   - ✓ Reduced long-term drifts caused by the environment
2. High-frequency signal (13 GHz) to bias the phase modulator in the SGI:
   - ✓ unidirectional phase modulation, insensitive to unequal SGI arms & environmental robustness
3. Low-frequency (108 MHz) down-mixing at the reference arm
   - ✓ Higher signal-to-noise ratio at photodetection

Abbreviations: PD: photodetector; BPF: bandpass filter; ½: frequency divider; +: voltage summer; LPF: lowpass filter; ϕ: phase modulator; SGI: Sagnac-interferometer; FC: fiber collimator.

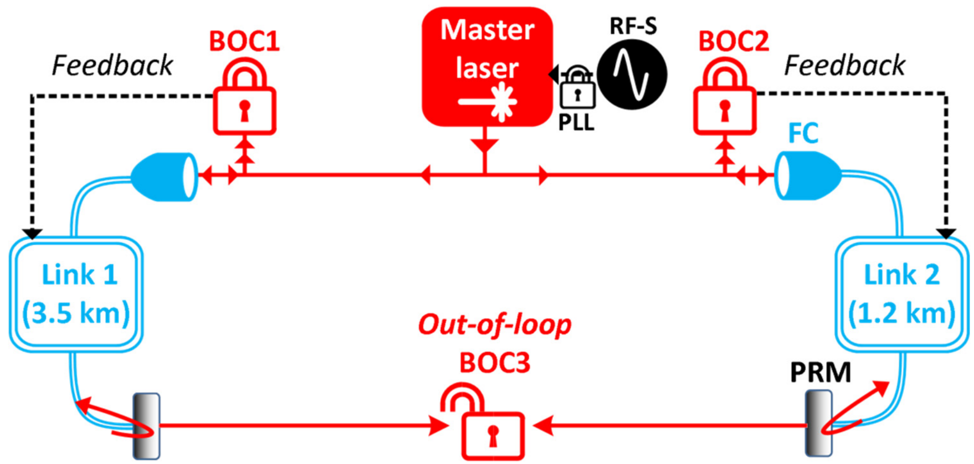
Fundamental noise limitations in fiber transmission



- **RF-S:** RF synthesizer
- **PLL:** phase-locked loop
- **BOC:** balanced optical cross-correlator
- **FC:** fiber collimator
- **PRM:** partially reflecting mirror



3. Fundamental noise limitations in fiber transmission



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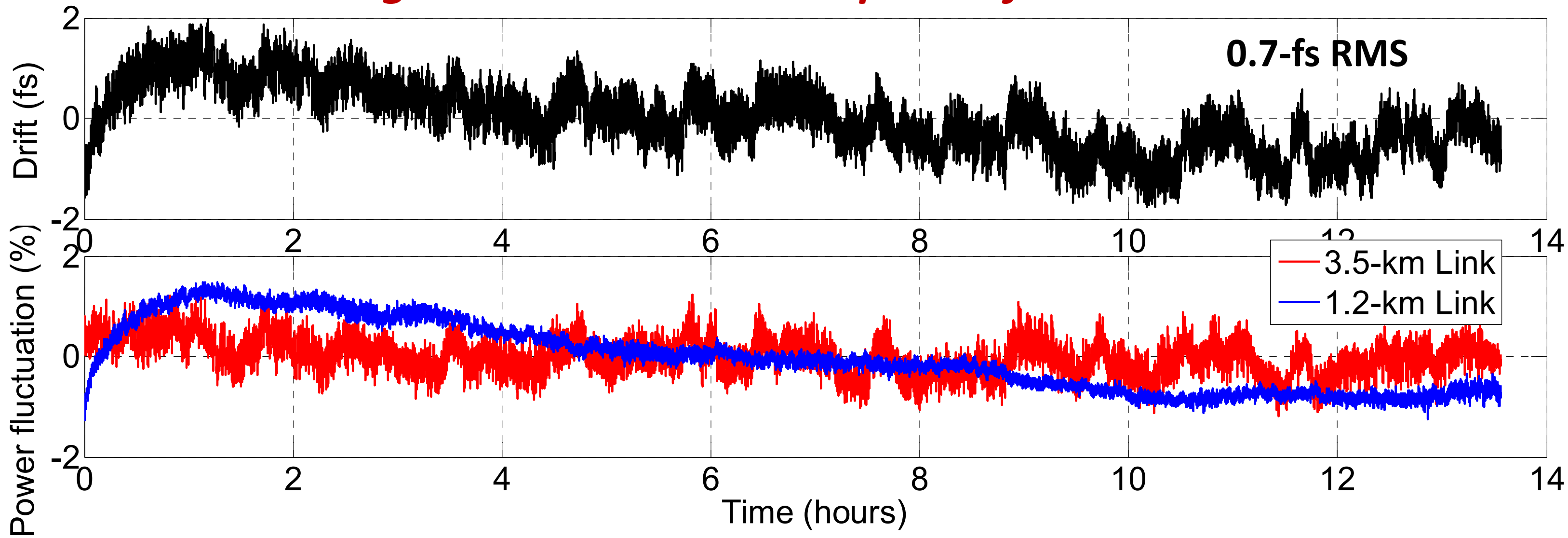
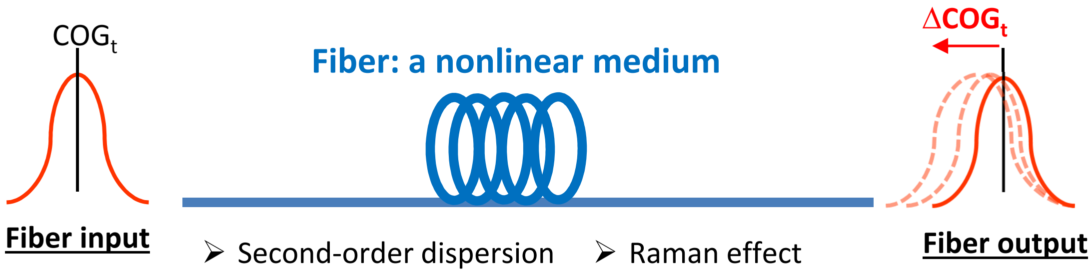
Strong correlation with link power fluctuations!

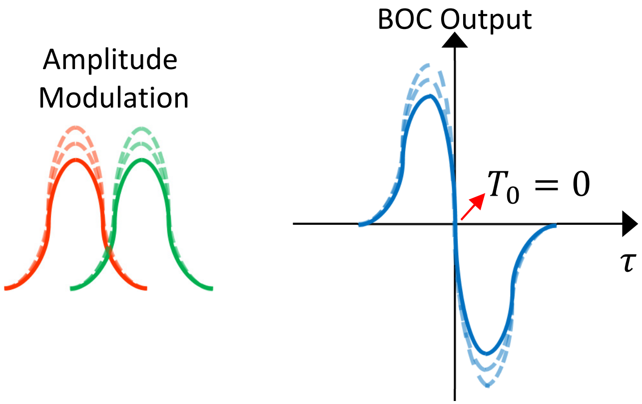


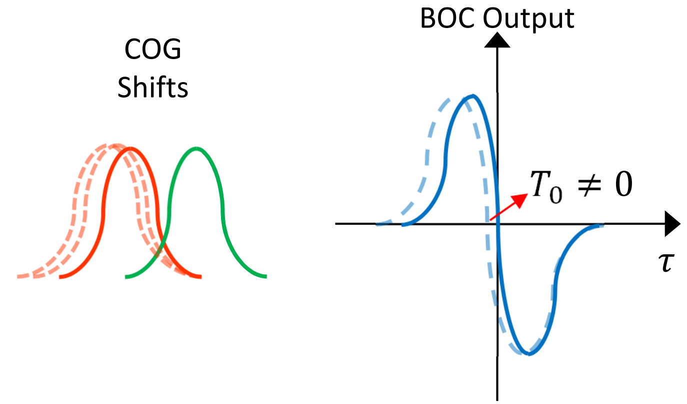
Nonlinear pulse propagation in fibers



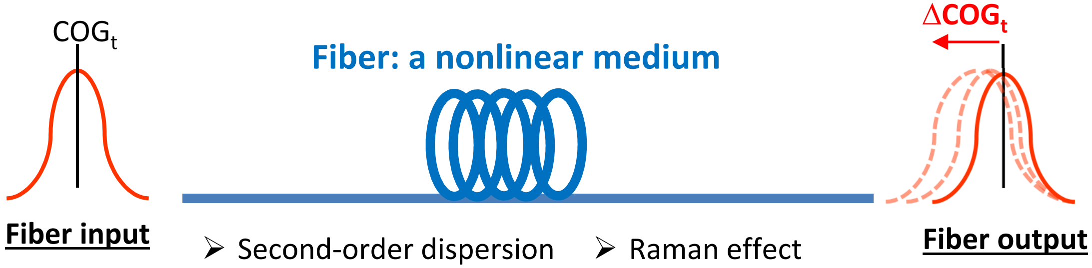
- Second-order dispersion
- Third-order dispersion
- Self-phase modulation
- Raman effect
- Self steepening

$$\Delta COG_t \propto \Delta P_{peak} \times nonlinearities$$





Nonlinear pulse propagation in fibers



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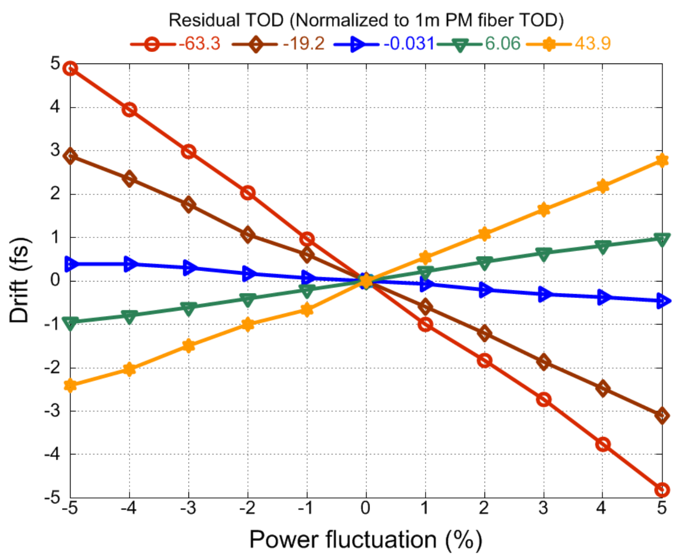
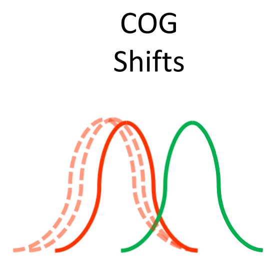
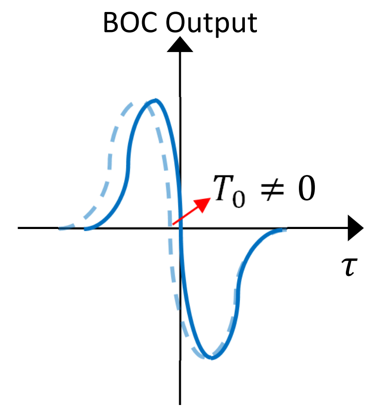




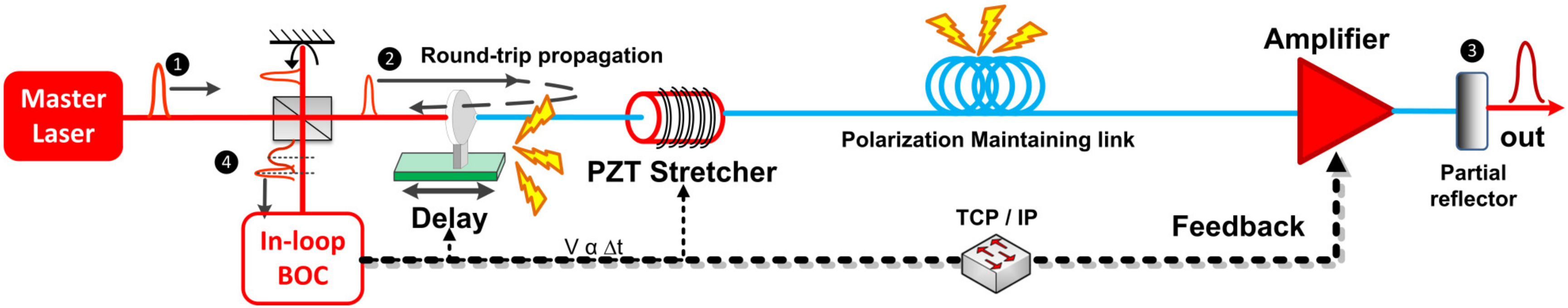


- up to 3-fs drift for 5% fluctuation with 20-m residual third order dispersion

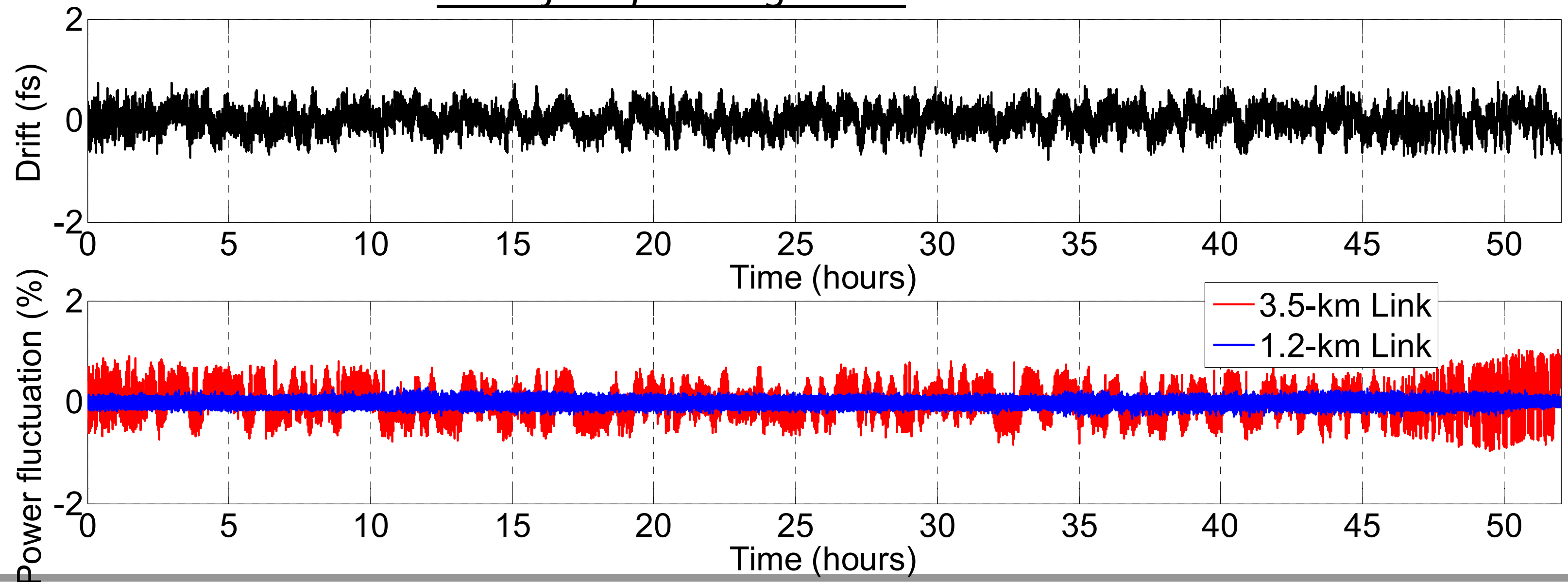
M. Xin et al., *Light Sci. App., 6, e16187* (2016).

Nonlinear pulse propagation in fibers

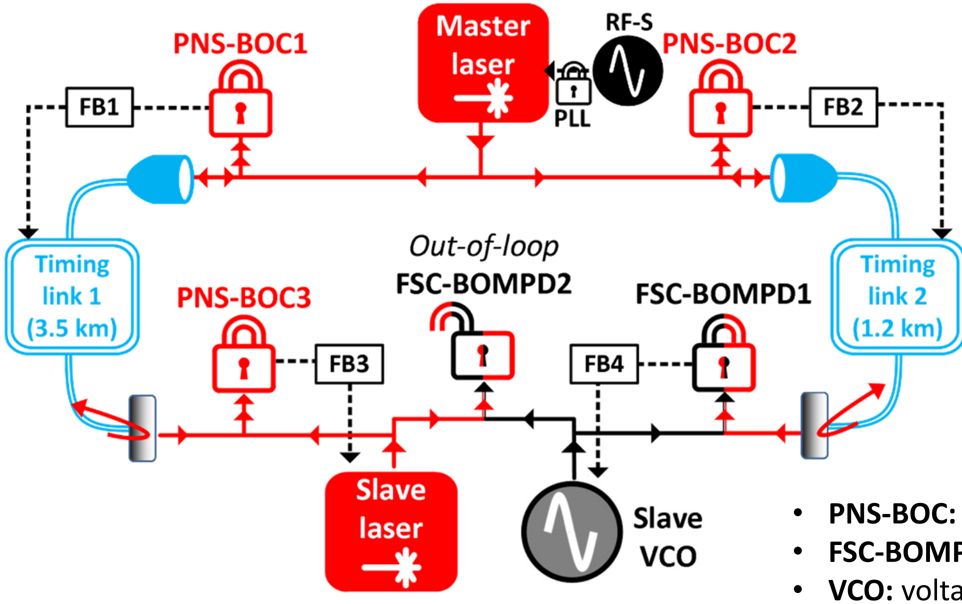
$$\Delta COG_t \propto \Delta P_{peak} \times nonlinearities$$



Out-of-loop timing error: 200 as RMS

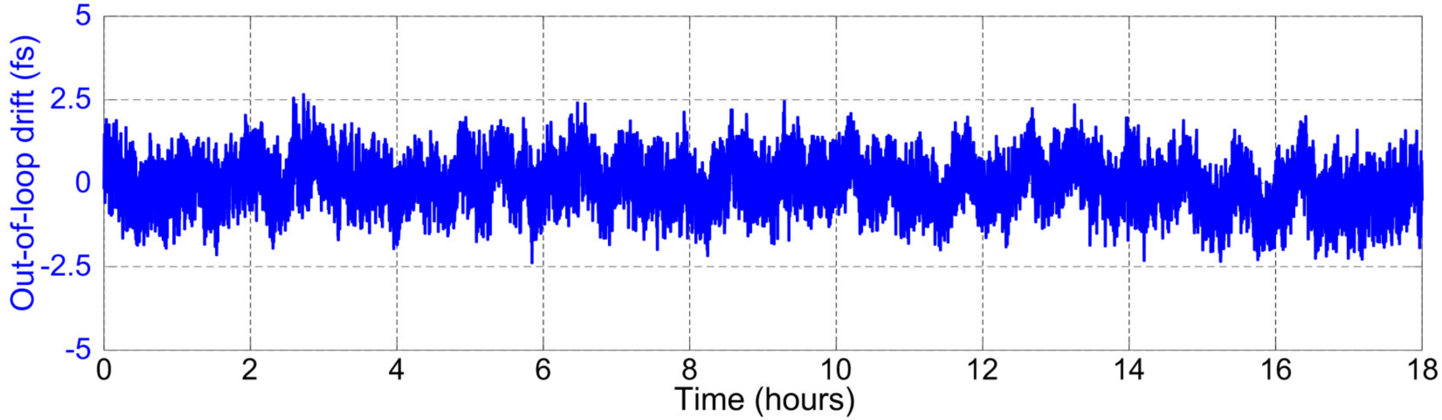


Synchronous laser-microwave network

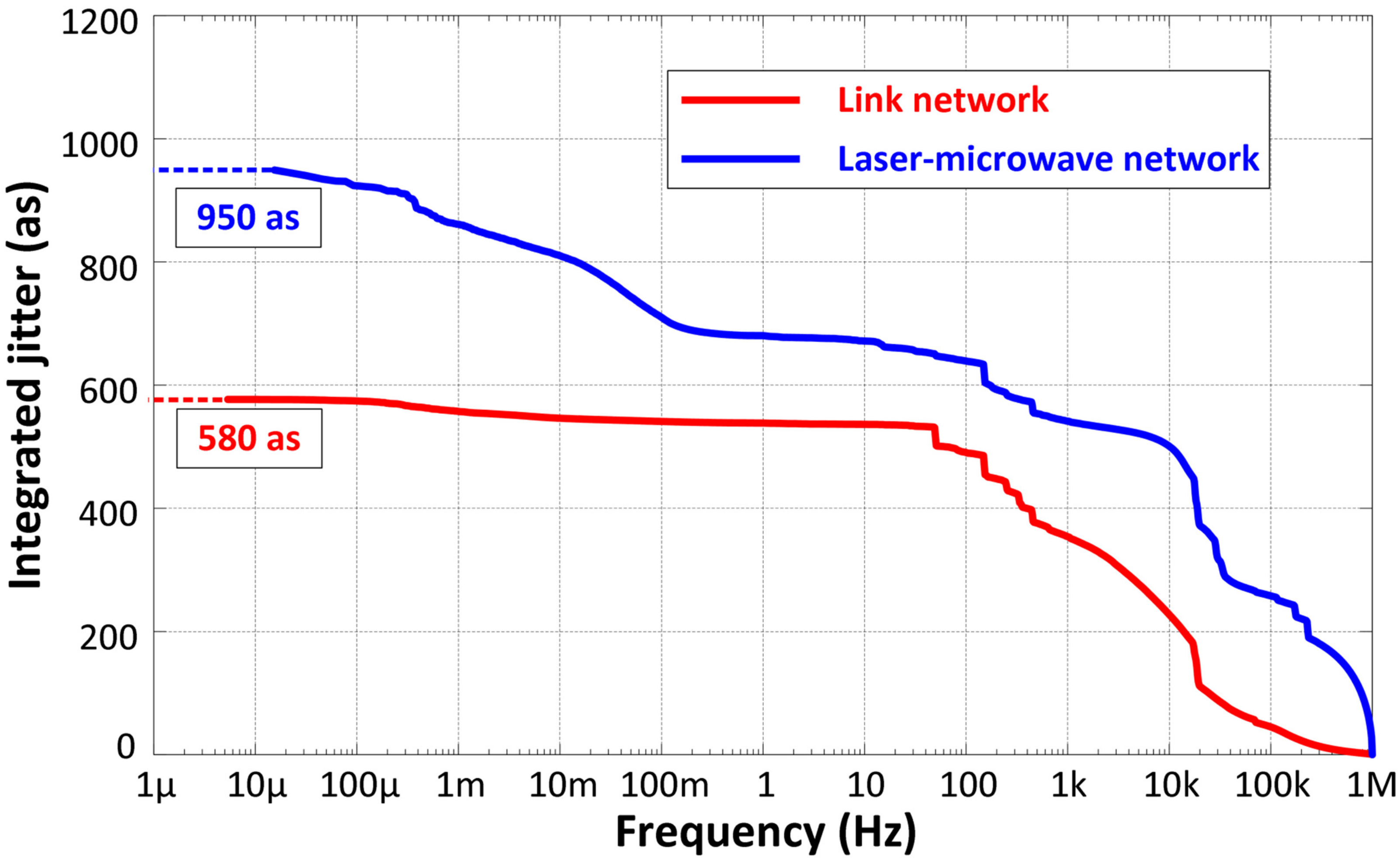


- **PNS-BOC:** polarization-noise-suppressed BOC
- **FSC-BOMPD:** free-space-coupled BOMPD
- **VCO:** voltage-controlled-oscillator
- **FB:** improved feedback scheme

Out-of-loop timing error: 670 as RMS



Integrated timing jitter



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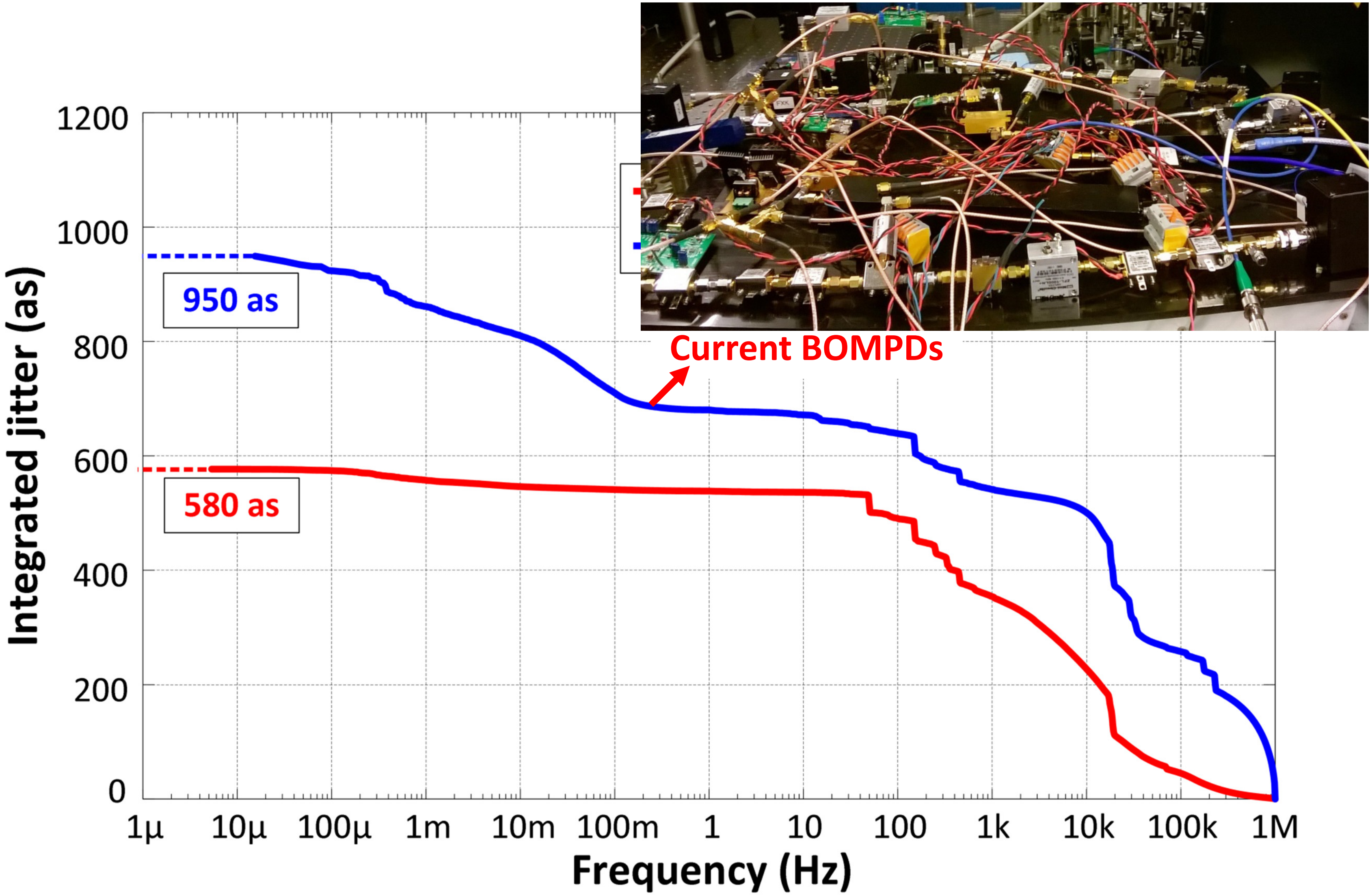
Integrated timing jitter



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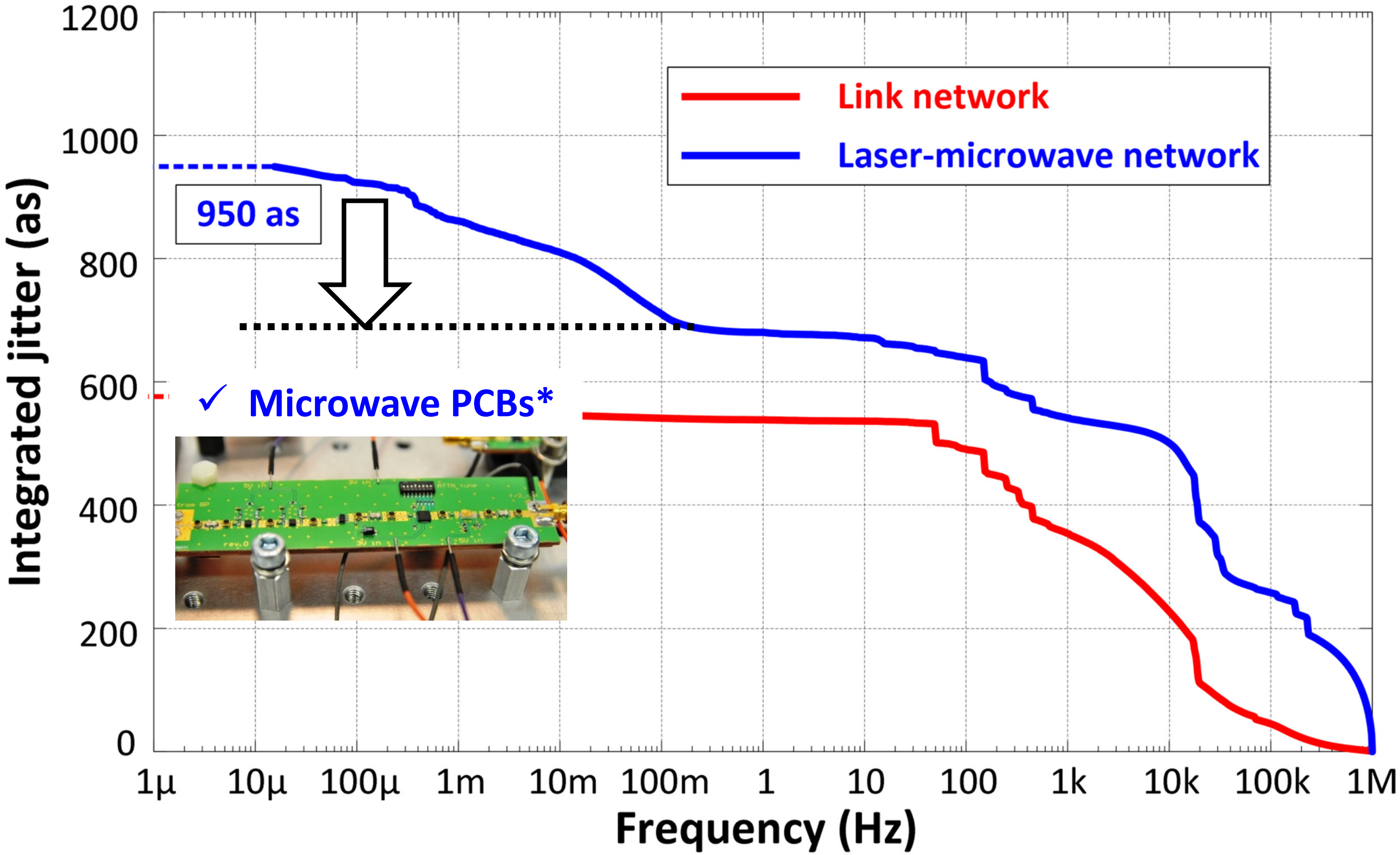
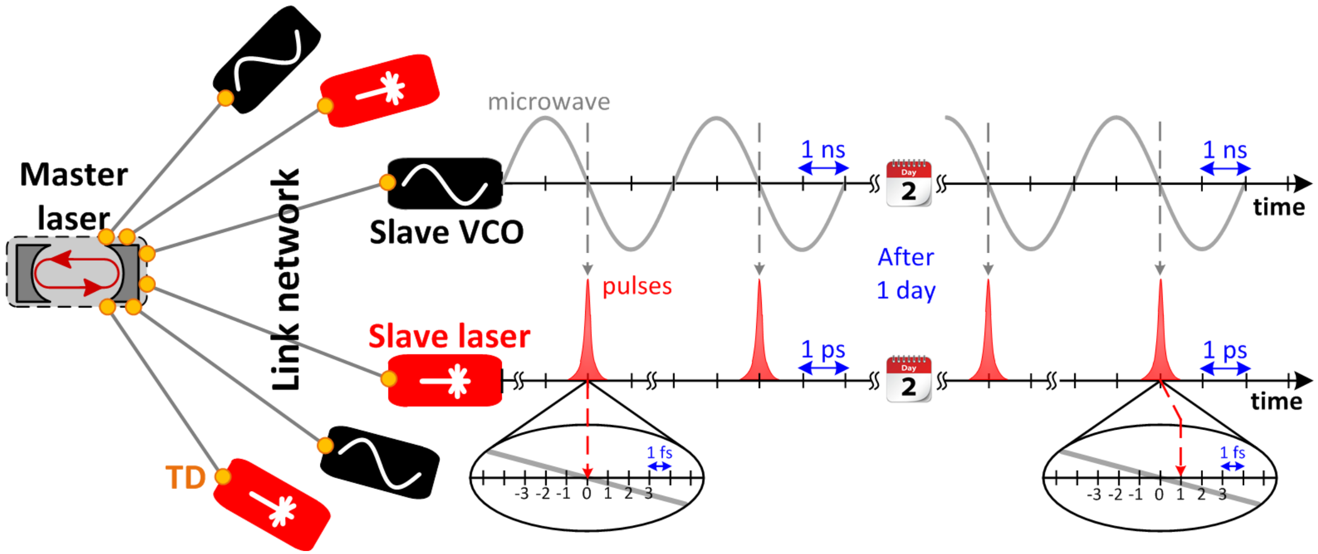


*Johann Derksen @ Cycle

Conclusion & outlook



- Improved sensitivity and robustness in BOCs and BOMPDs
- Observation of sub-fs time delays due to fiber nonlinearities
- Correction via link power modulation
- **Link network:** 200 as RMS drift (< 1Hz) over 2 days
- **Laser-microwave network:** 670 as RMS drift (<1Hz) over 18 hours

- **Established a spinoff company commercializing our detectors and timing systems**

Cycle

Visit us in booth 3!


ANY
QUESTIONS
?