An Integrated Femtosecond Timing Distribution System for XFELs

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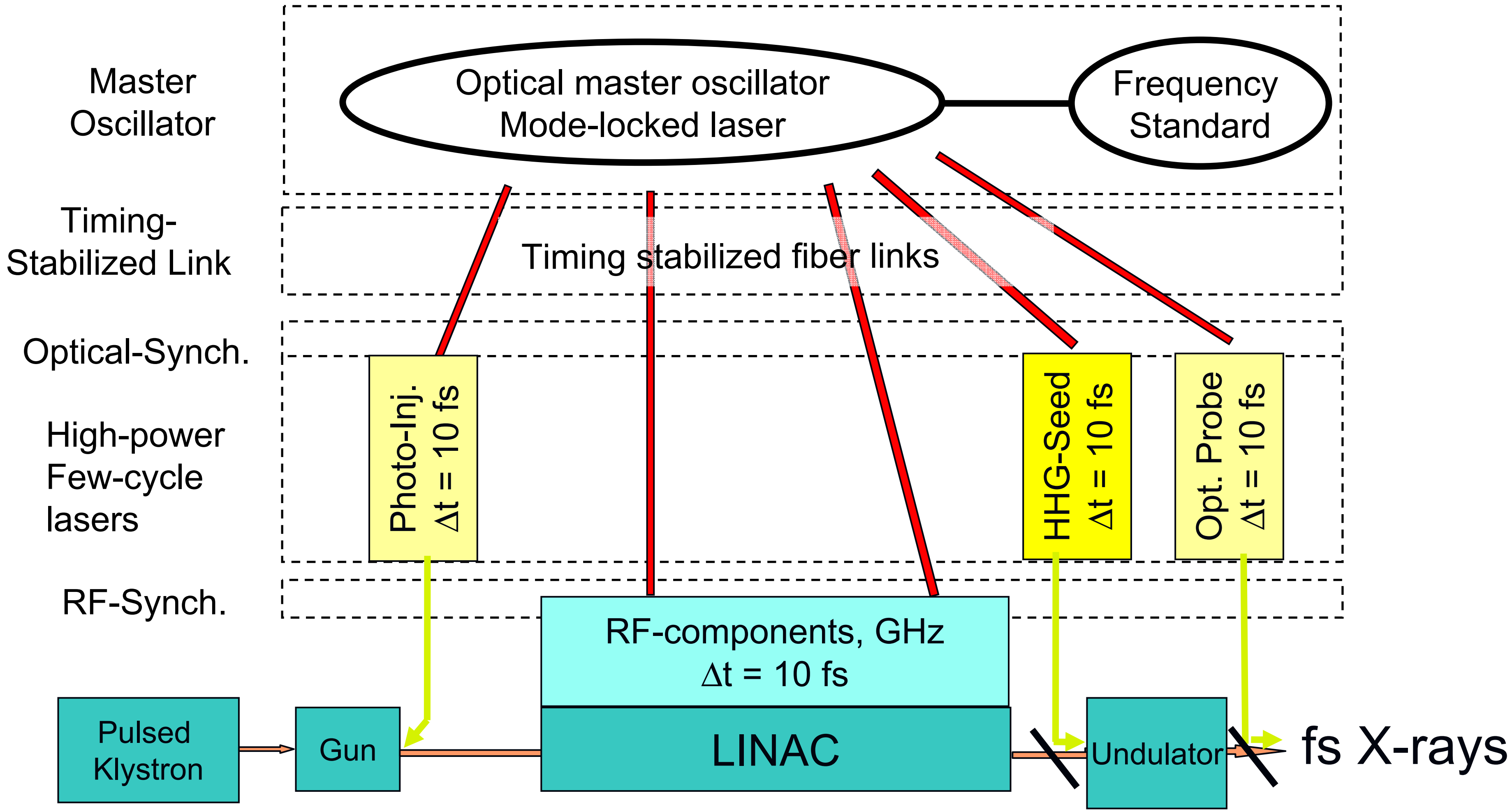
Supported by DESY, FERMI-Trieste, MIT-Bates Laboratory & ONR

4th Generation Light Sources: XFEL



Max timing jitter in each section Δt: 10 fs ~ 3μm

Demands on Optical Timing Distribution

- 4-th Generation Light Sources demand increasingly precise timing

  today << 100 fs, in 3 years: < 10fs , in 6 years: < 1fs?

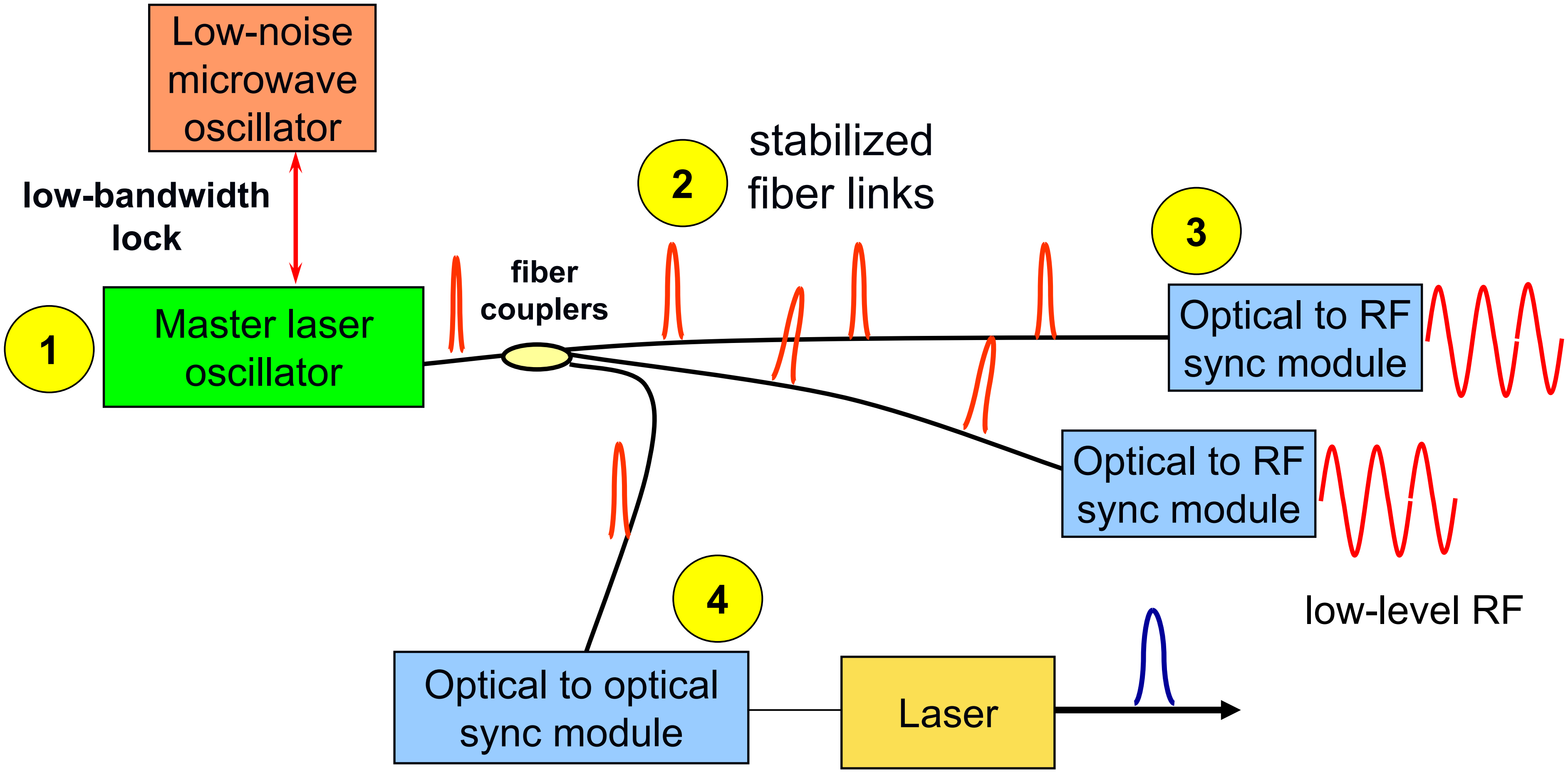
  → Scalability to these levels should be possible!

- Must serve multiple locations separated by up to 1-5 km distances.

- This is beyond what a direct RF-distribution (coaxial cables) can handle.
  - thermal drifts of coaxial cables
  - drifts of microwave mixers
  - etc.

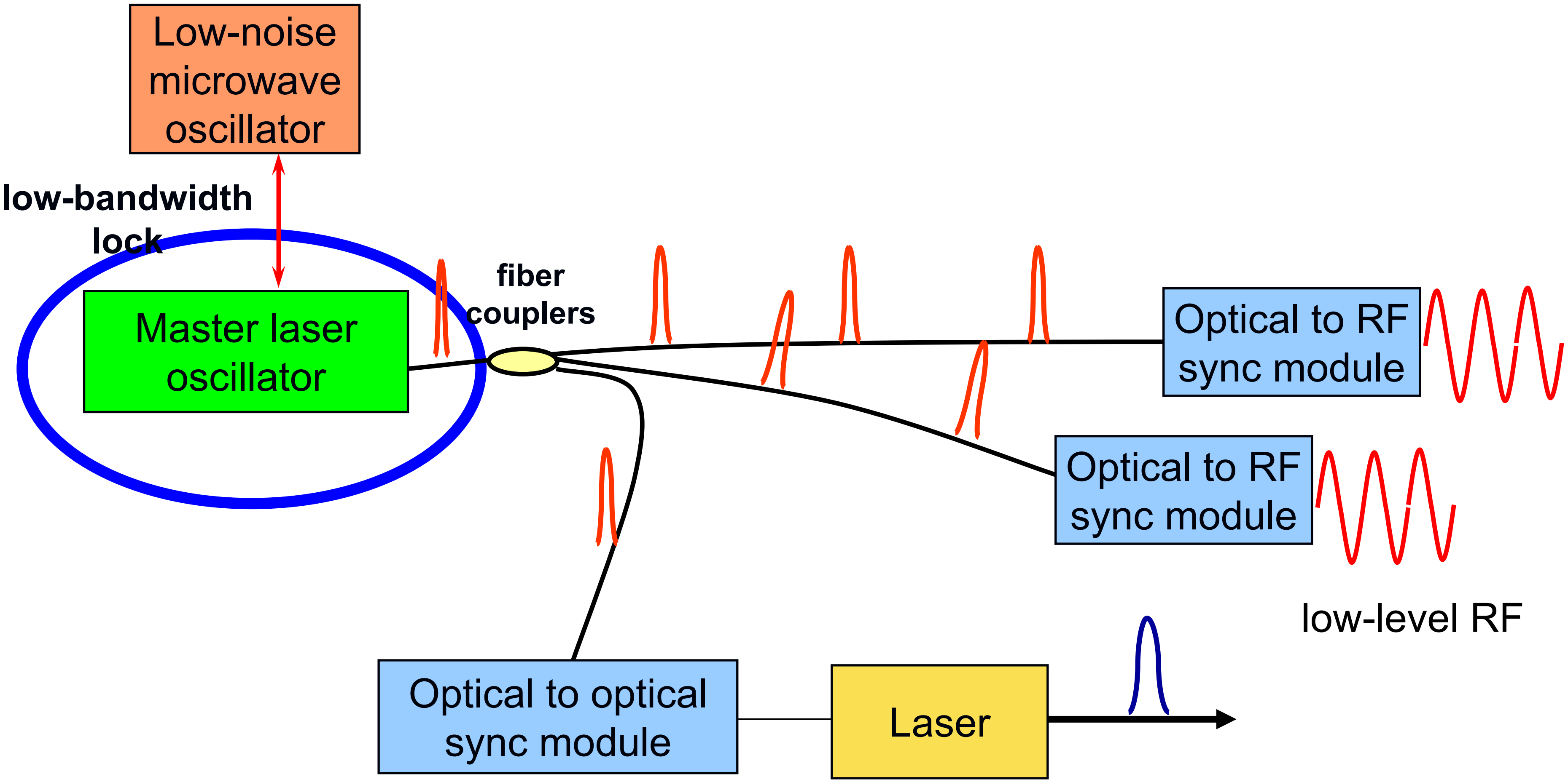
- It will lead to a considerable reduction in cost and space!

Synchronization System Layout

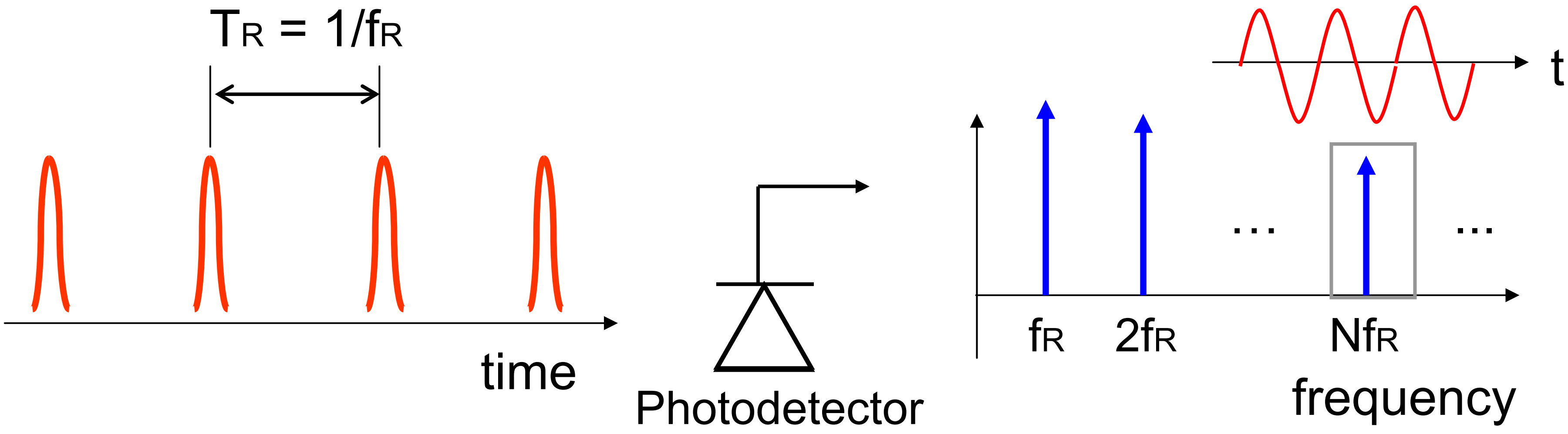


1. Optical Master Oscillator

A master mode-locked laser producing a very stable pulse train
(can be locked to a microwave oscillator for long-term stability)



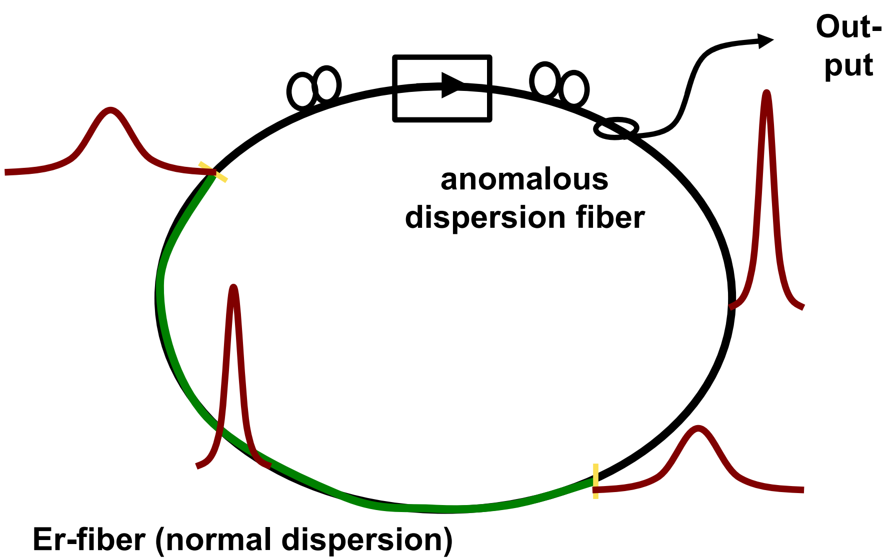
Why Optical Pulses (Mode-locked Lasers)?

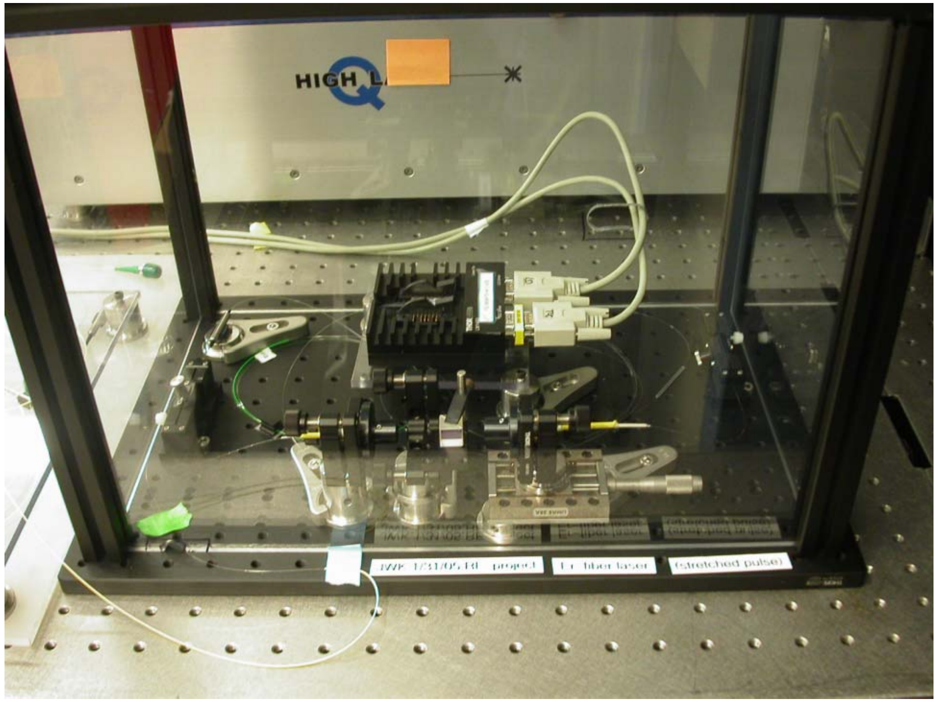


- RF signal is encoded in the pulse repetition rate.
  → Every harmonic can be extracted.
- Suppress Brillouin scattering and undesired reflections.
- Optical cross-correlation can be used for timing stabilization.
- Pulses can directly seed amplifiers.
- Group delay is directly stabilized.

Er-Fiber Laser

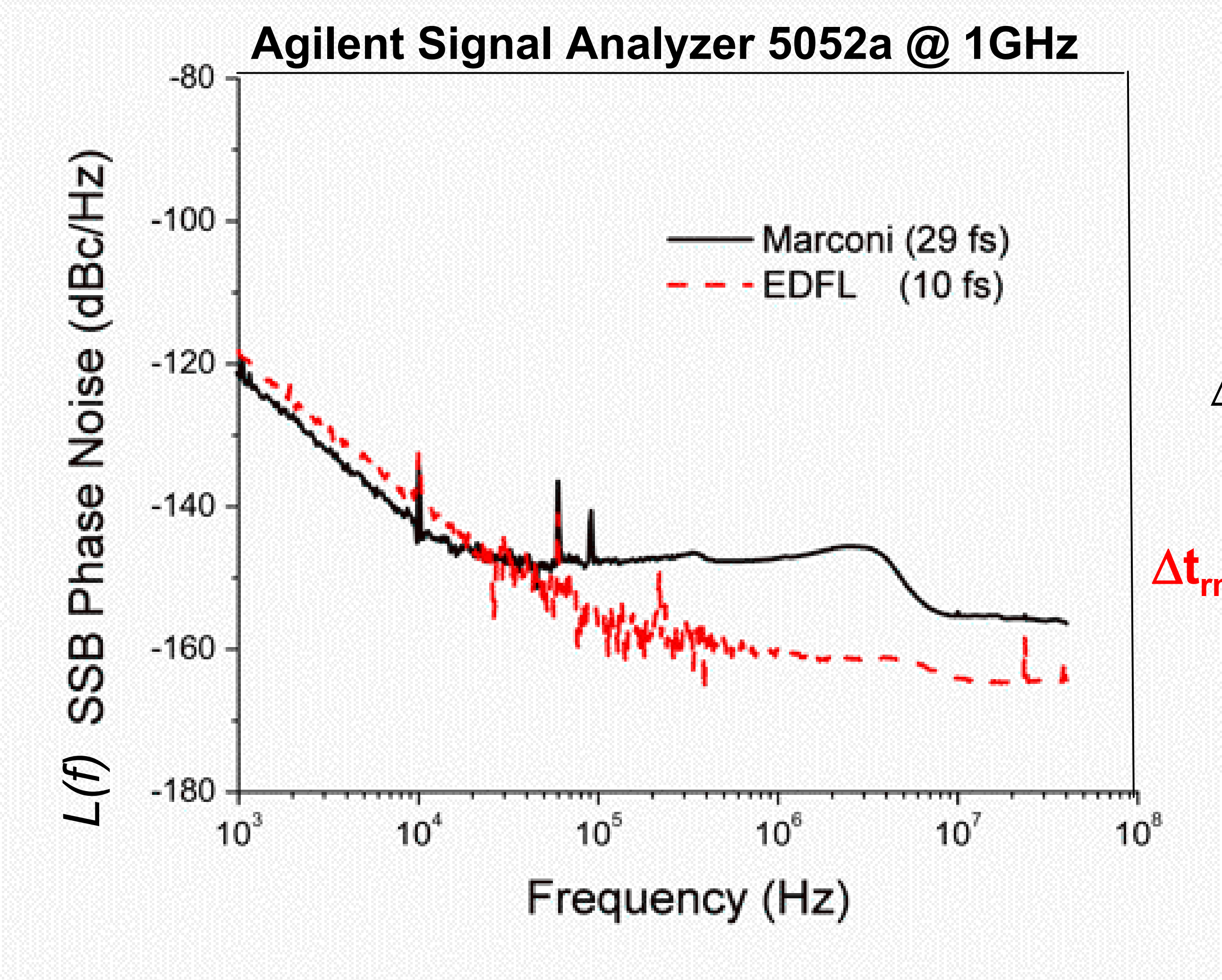
Stretched-pulse Er-fiber Laser: Tamura et al. OL **18**, 1080 (1993).





Footprint can fit into Letter-size

Phase Noise (Timing Jitter) Measurements



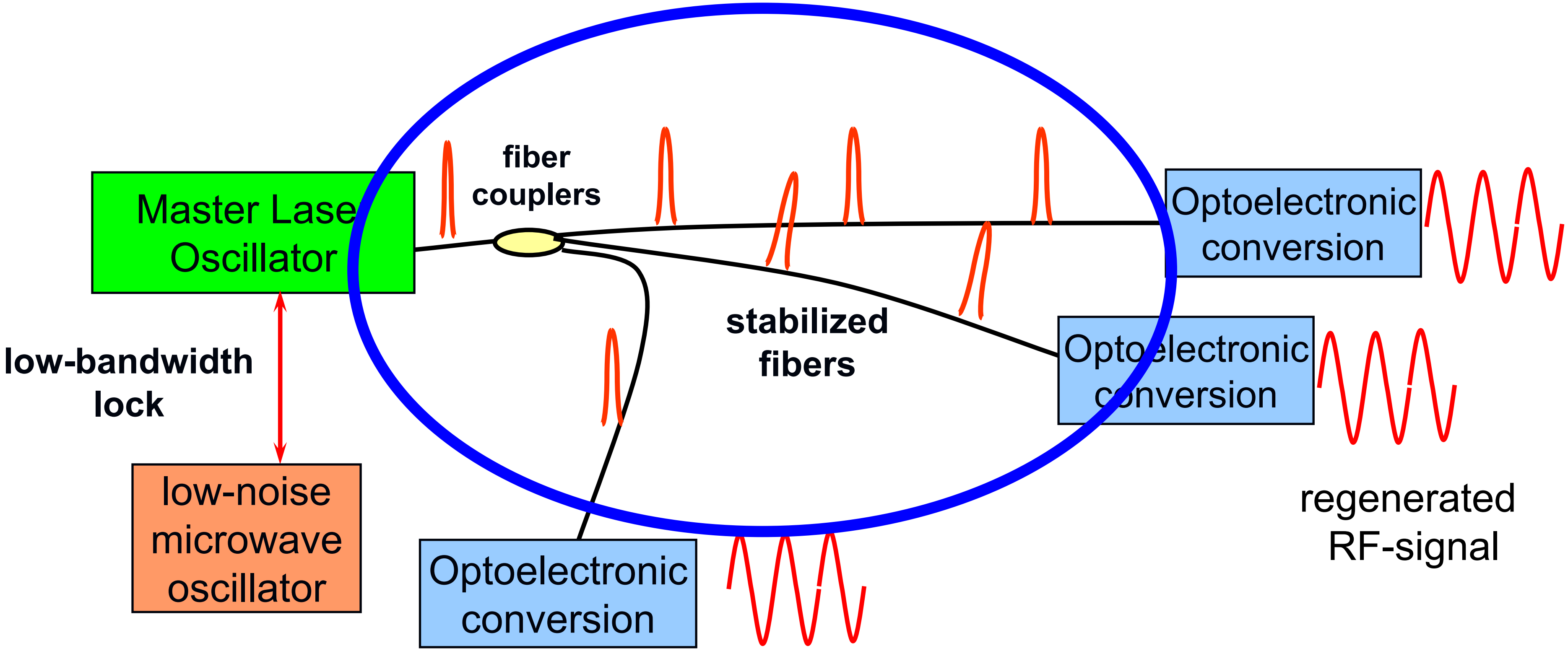
$$\Delta t_{rms} = \frac{\sqrt{2\int_{f_1}^{f_2} L(f)df}}{2\pi f_0}$$

Δt_{rms}[10kHz,22MHz] = 10 fs

- Noise floor limited by photo detection
- Theoretical noise limit <1 fs

2. Timing-Stabilized Fiber Links

Stabilized fiber links delivering the pulse train to multiple remote locations

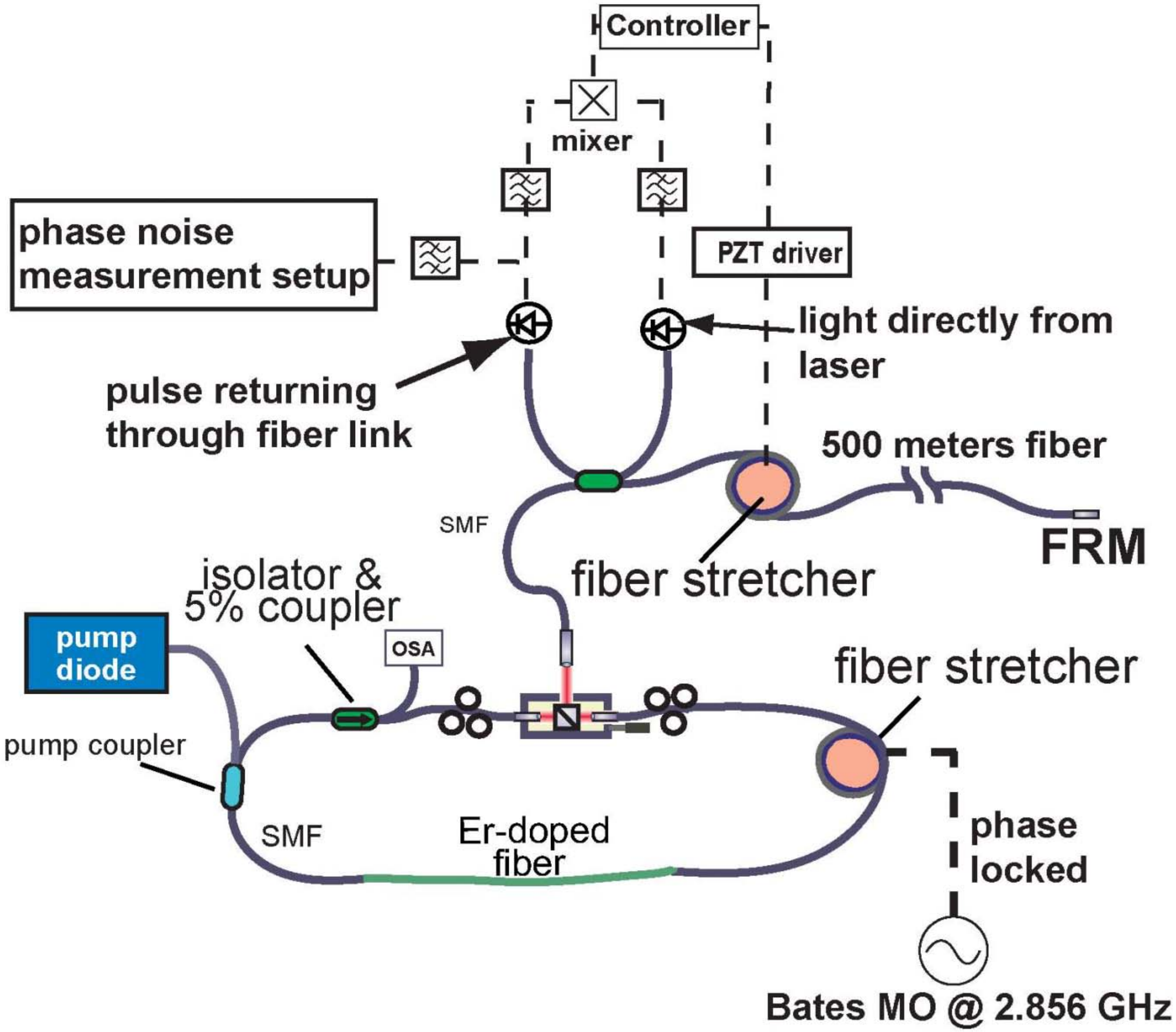


System Test in Accelerator Environment

- Test done at MIT Bates Laboratory:
  - Locked EDFL to Bates master oscillator
  - Transmitted pulses through 400 meters partially temperature stabilized fiber link
  - Close loop on fiber length feedback

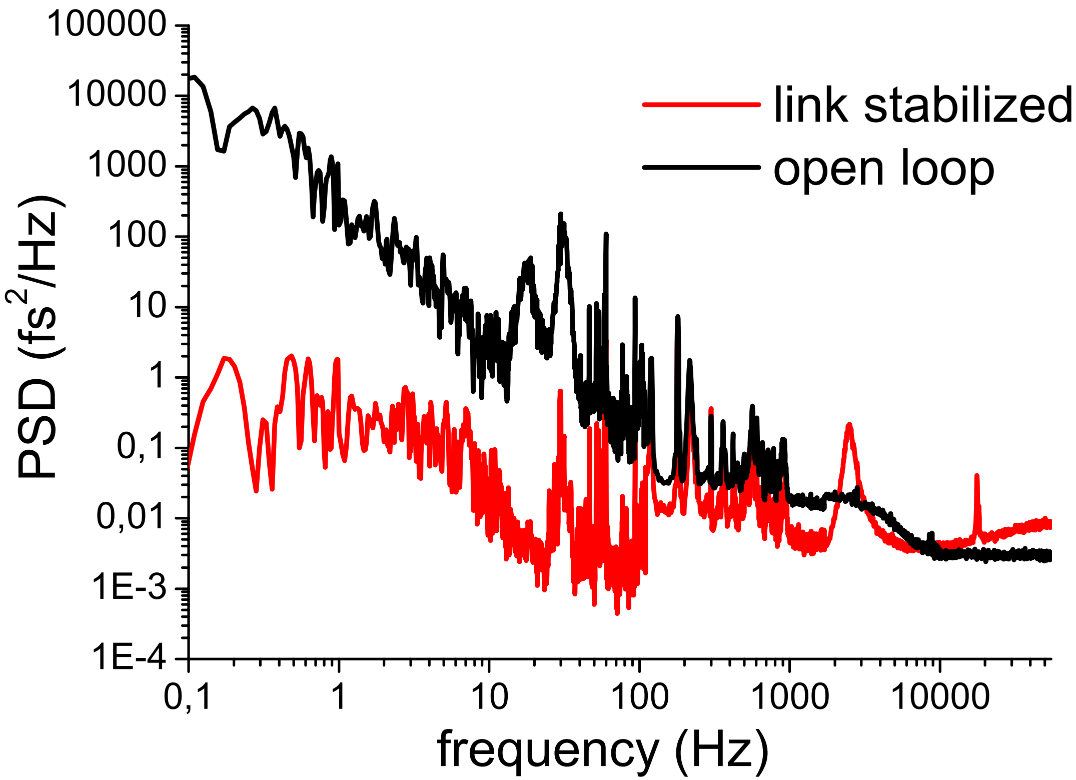
For more info: A. Winter et al, FEL 2005
F. Ö. Ilday et al, CLEO 2006

RF-Transmission over Stabilized Fiber Link



- Passive temperature stabilization of 500 m
- RF feedback for fiber link
- EDFL locked to 2.856 GHz Bates master oscillator

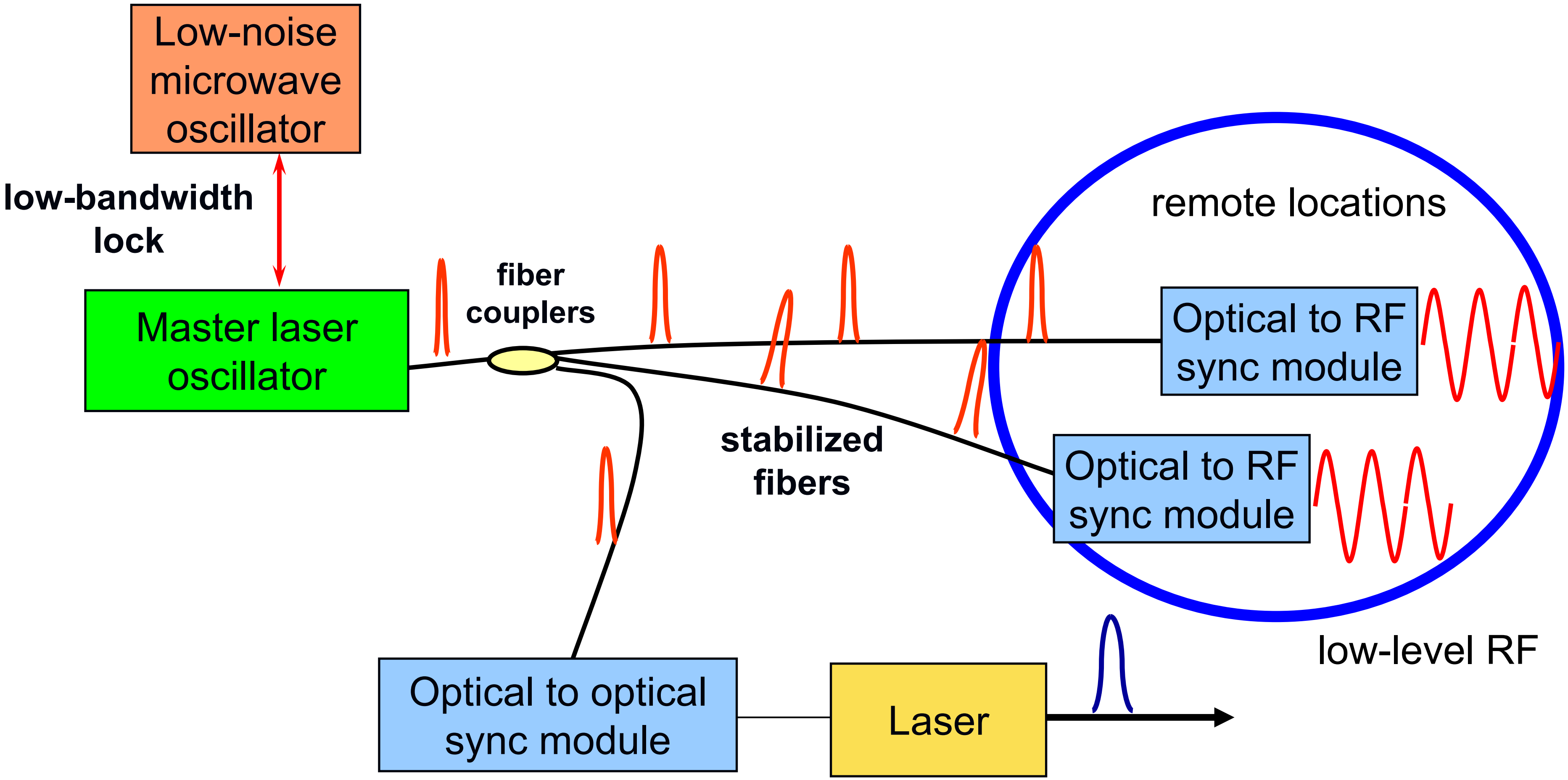
Jitter: Timing Stabilized Fiber Link



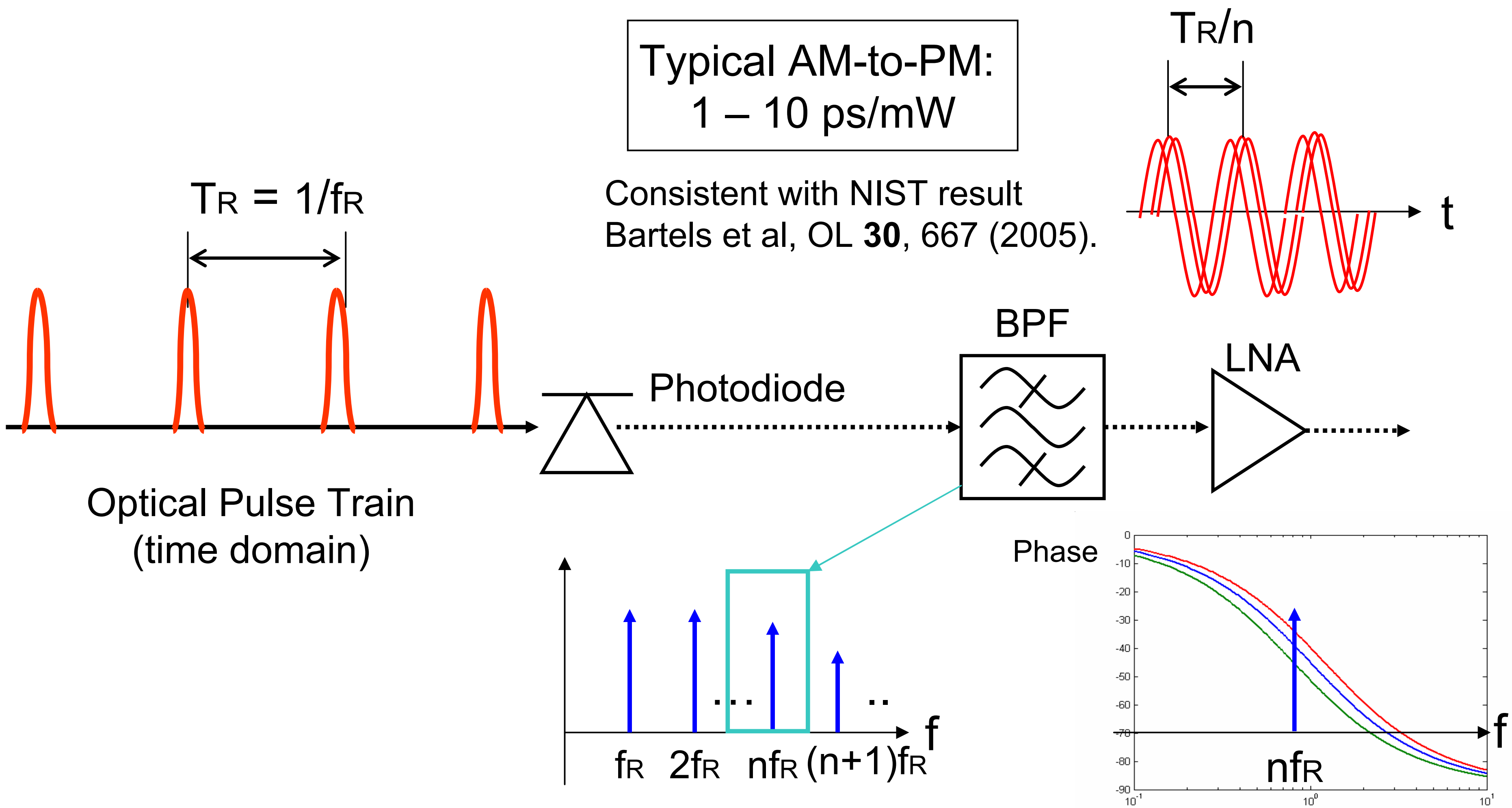
- Fiber link extremely stable even for open loop (60 fs for 0.1 Hz-5 kHz)
- Closing feedback loop reduces noise (**12 fs for 0.1 Hz-5kHz**)
- No significant noise added at higher frequencies

3. Optical-to-RF Synchronization

Converting optical pulse train to RF-signal at remote locations



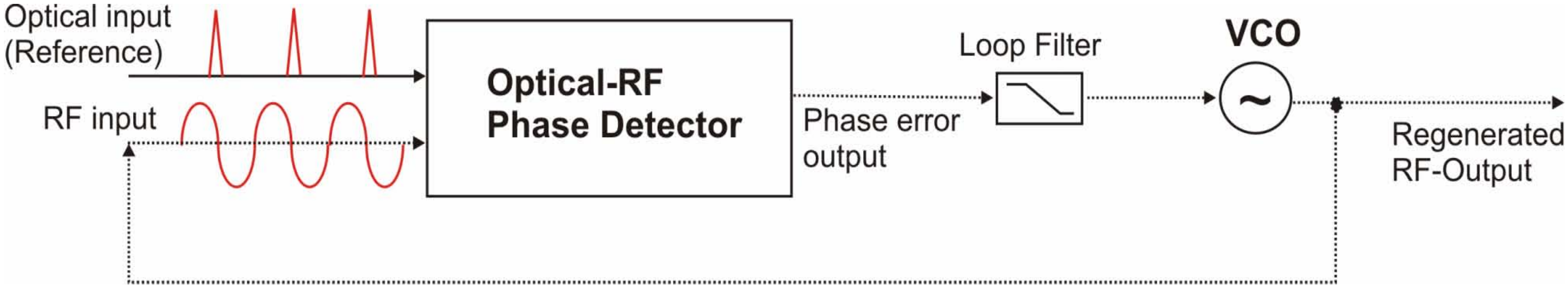
Direct Extraction of RF from Pulse Train



Conversion of optical signal into electronic signal is the major bottleneck in signal properties (noise, stability, and power).

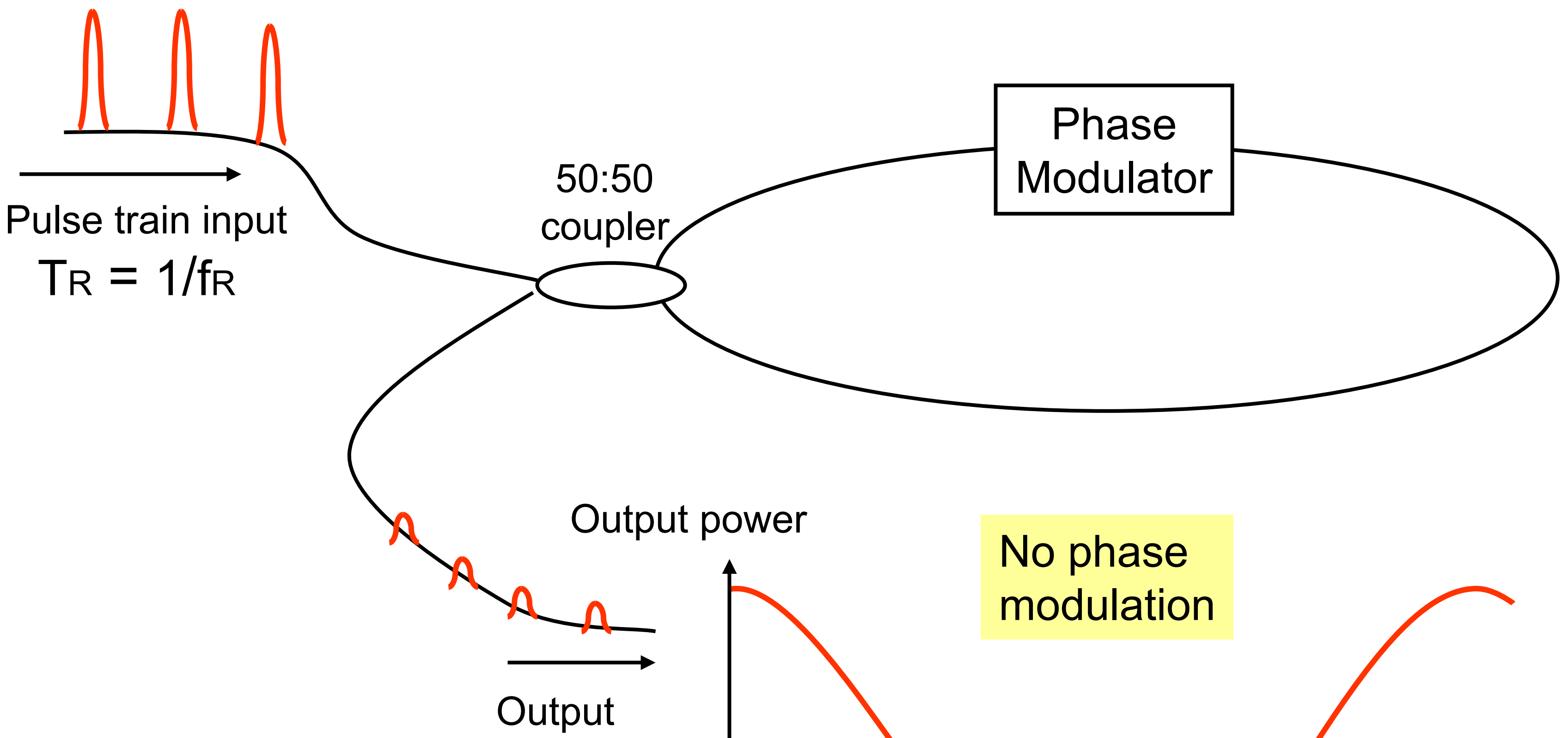
Optoelectronic Phase-Locked Loop (PLL)

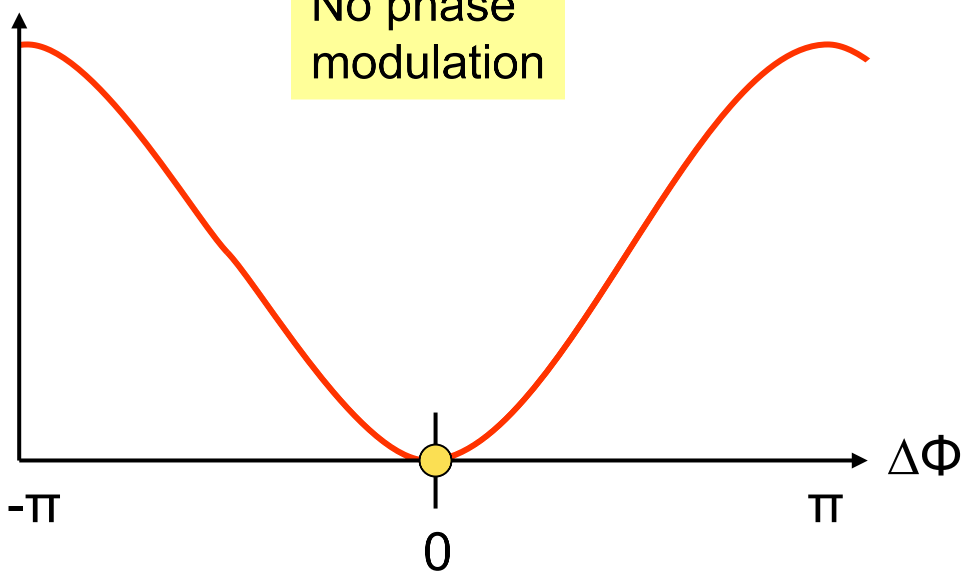
Can we regenerate a high-power, low-jitter and drift-free RF-signal whose phase is locked to the optical pulse train?



Implementation of optical-RF phase detectors
for high-power, low-jitter and drift-free RF-signal regeneration

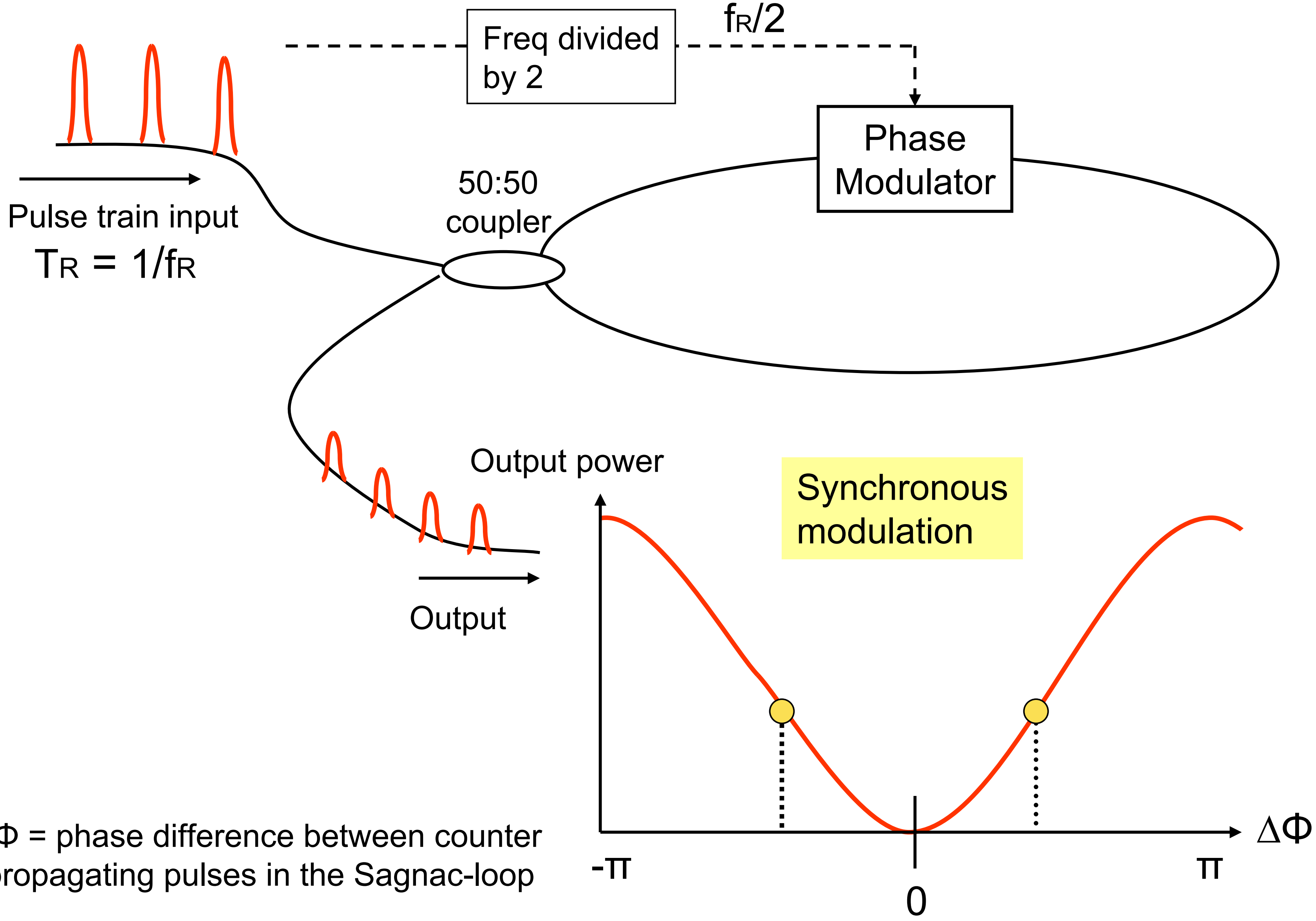
Sagnac-Loop for Electro-Optic Sampling





$\Delta\Phi$ = phase difference between counter -propagating pulses in the Sagnac-loop

Sagnac-Loop for Electro-Optic Sampling



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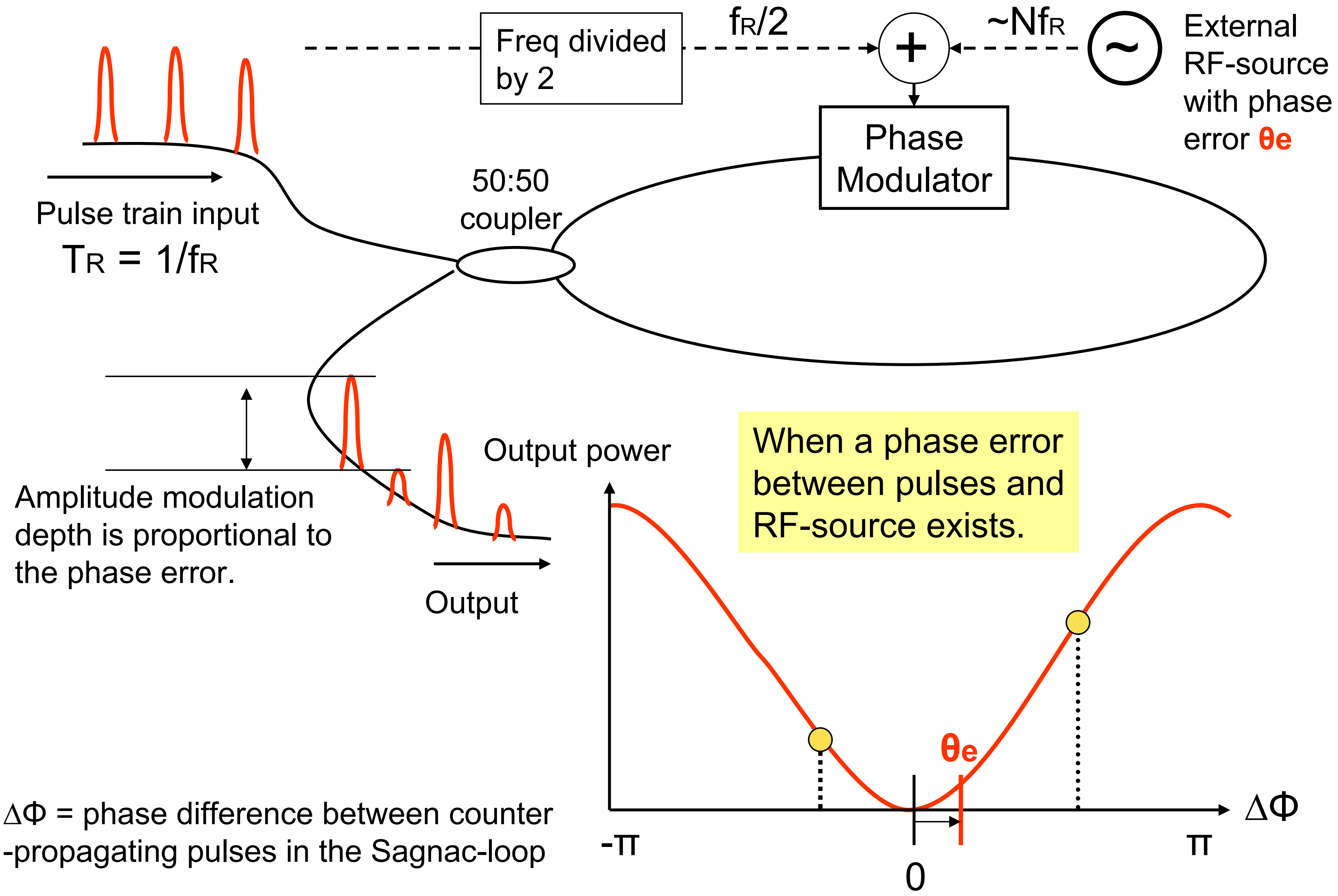

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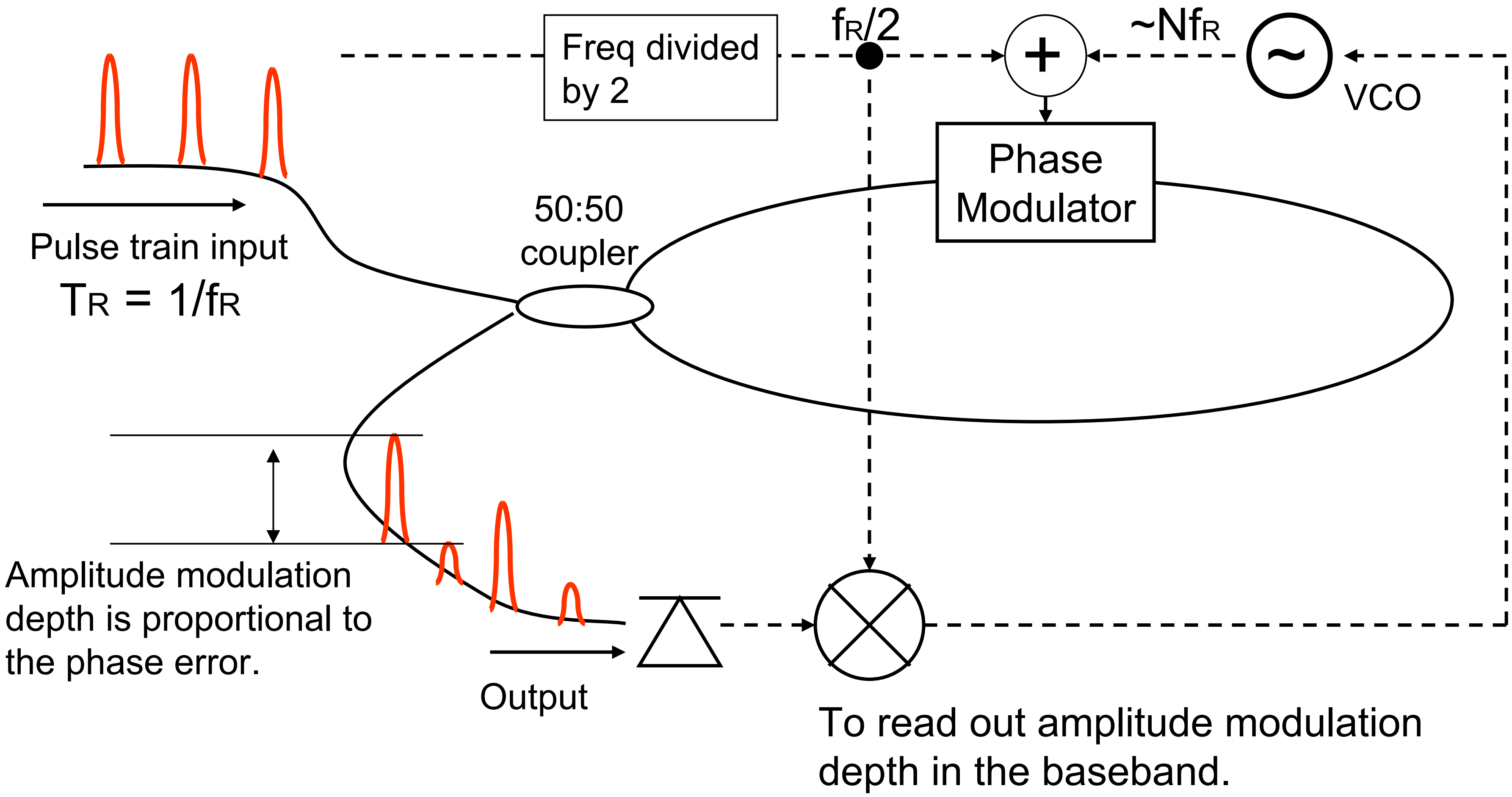

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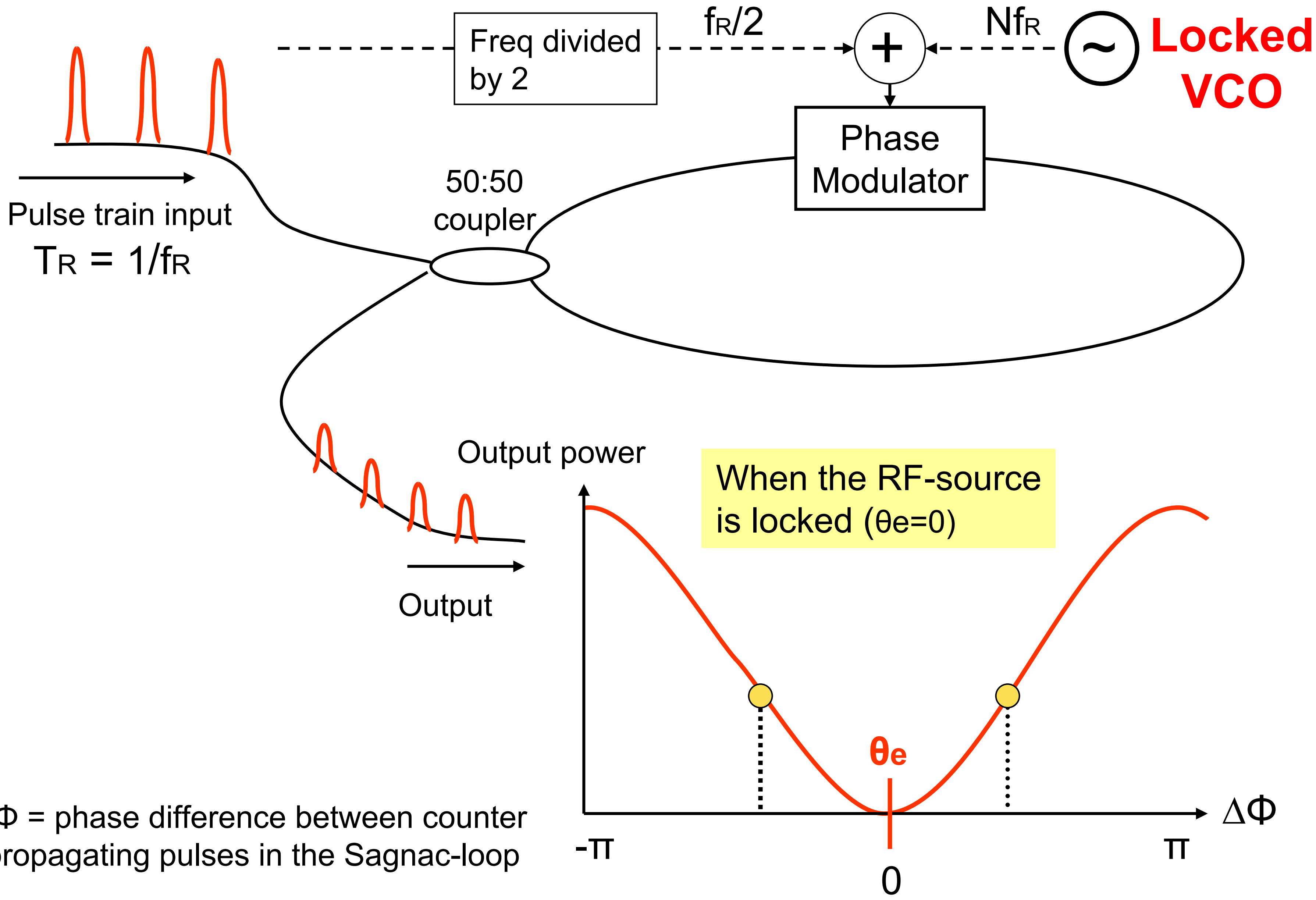
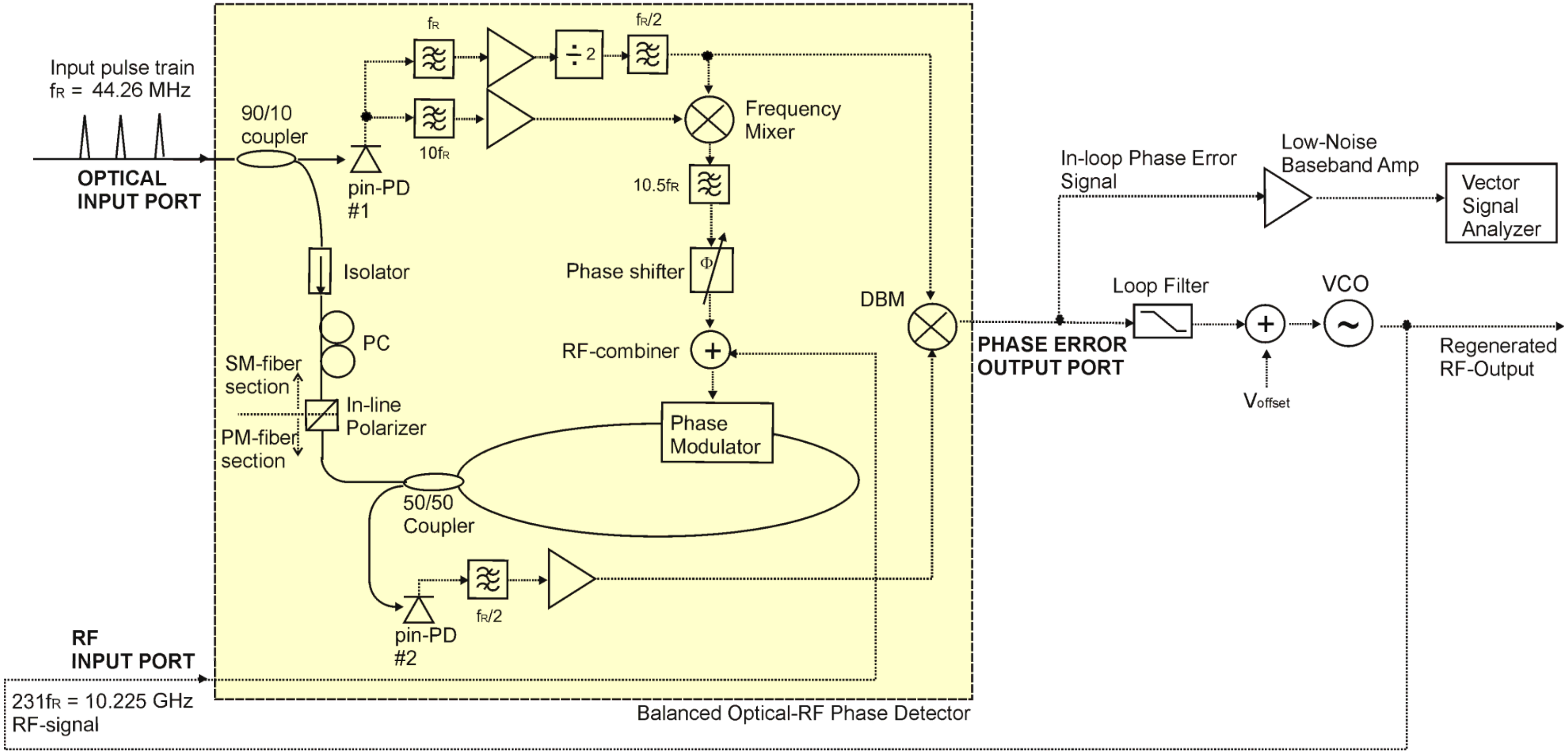
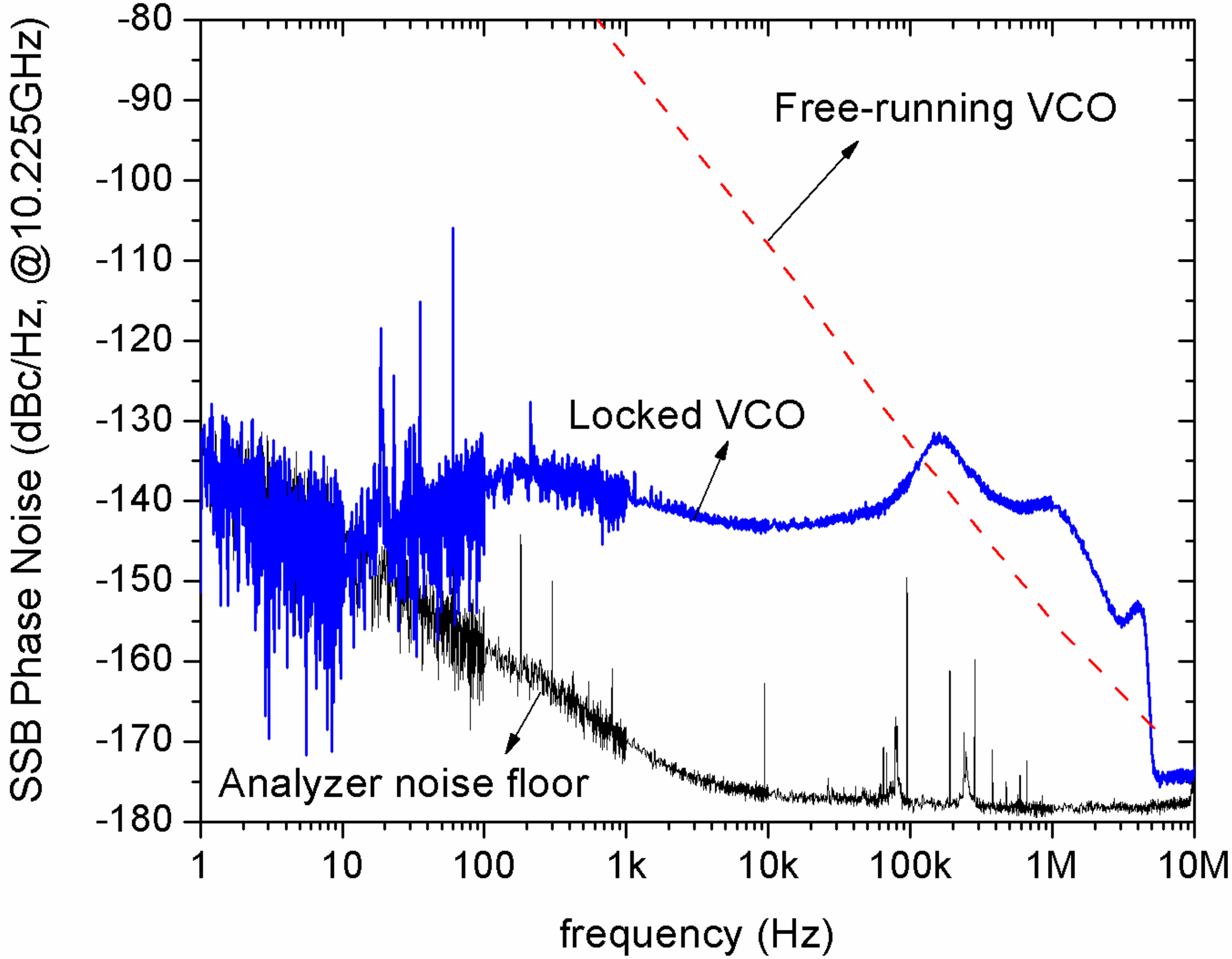


ΔΦ = phase difference between counter -propagating pulses in the Sagnac-loop

Demonstration Experiment

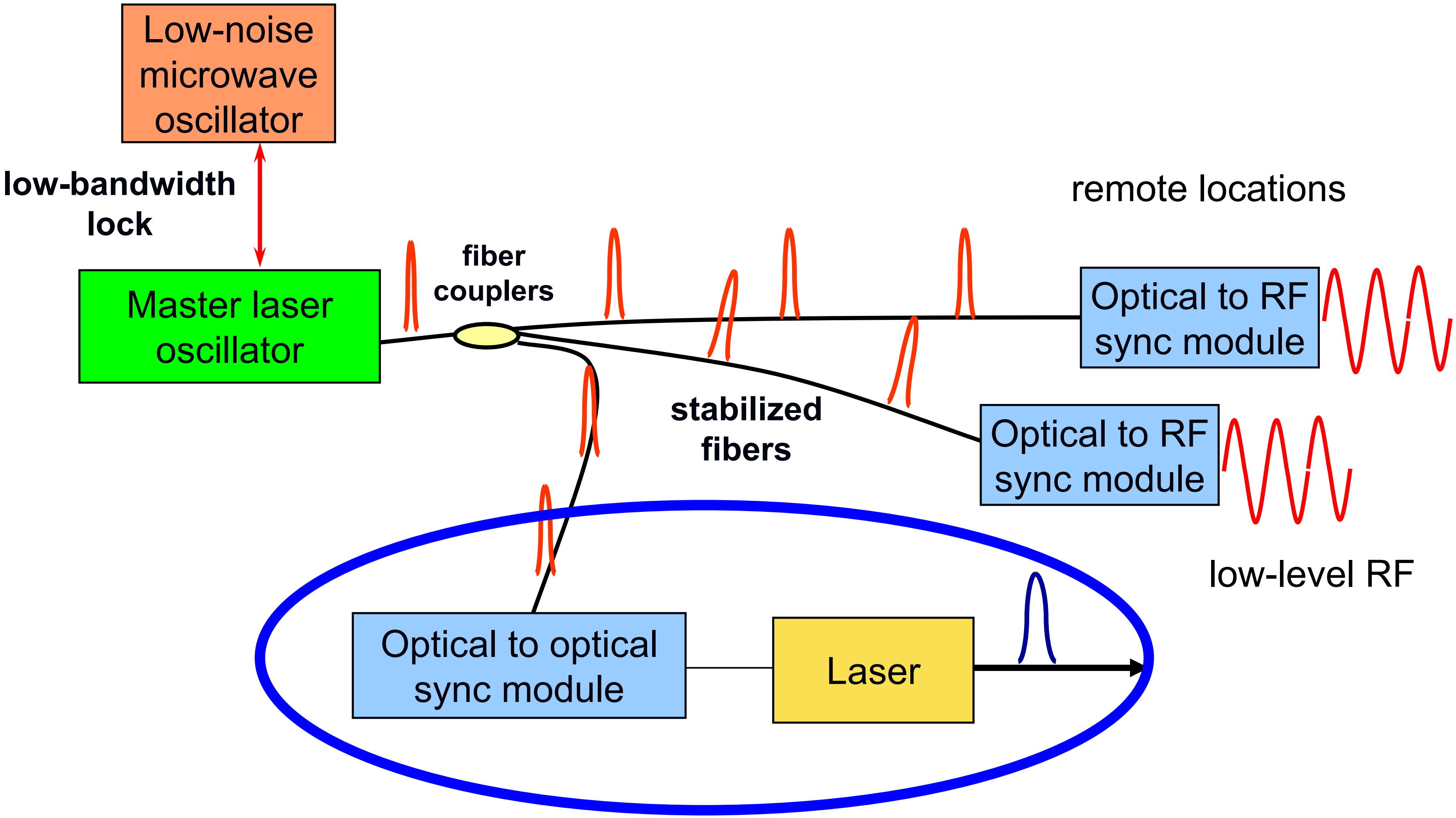


In-Loop Phase Noise Measurement

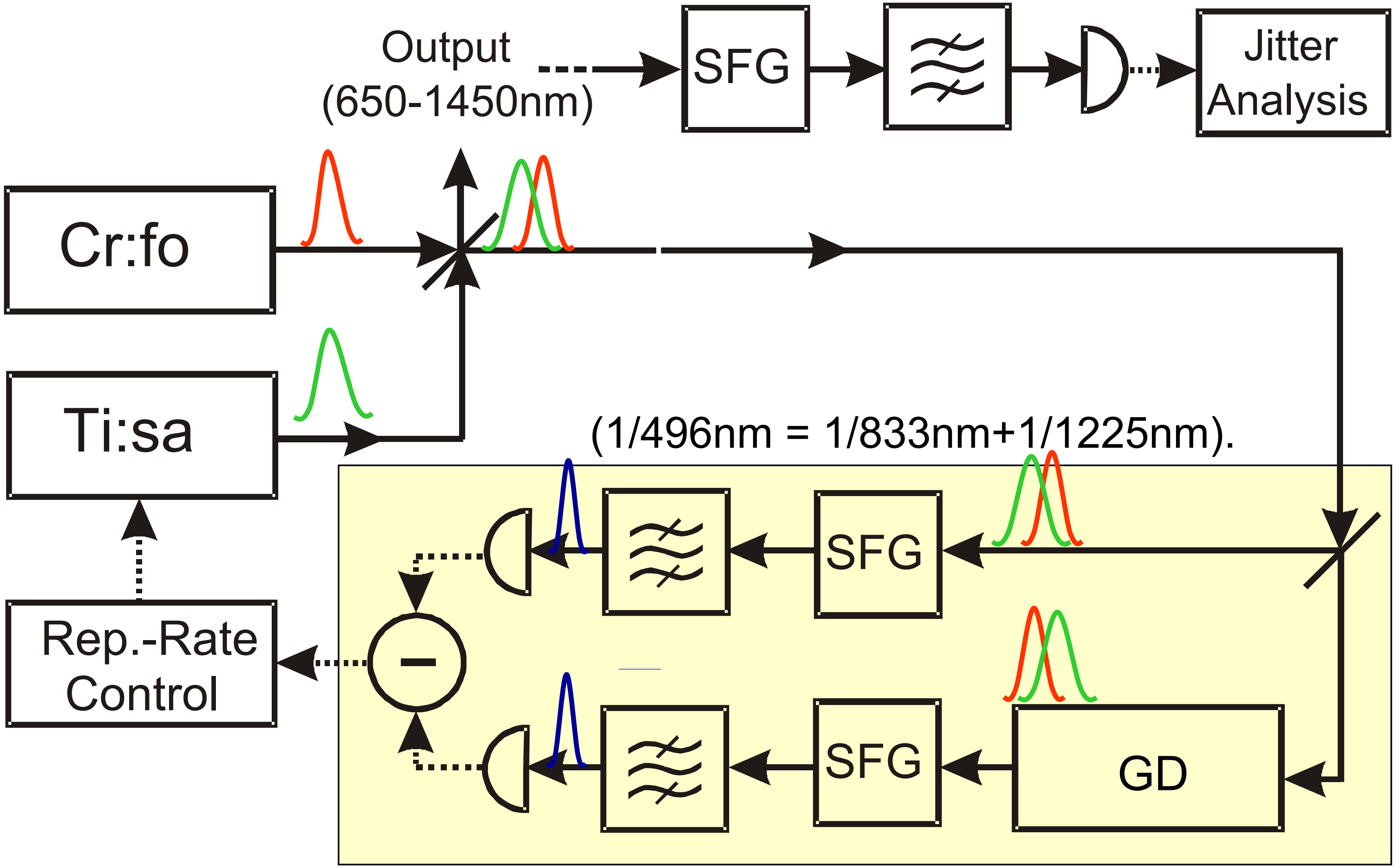


Residual timing jitter = 3 fs ± 0.2 fs (1Hz-10MHz)

4. Optical-to-Optical Synchronization



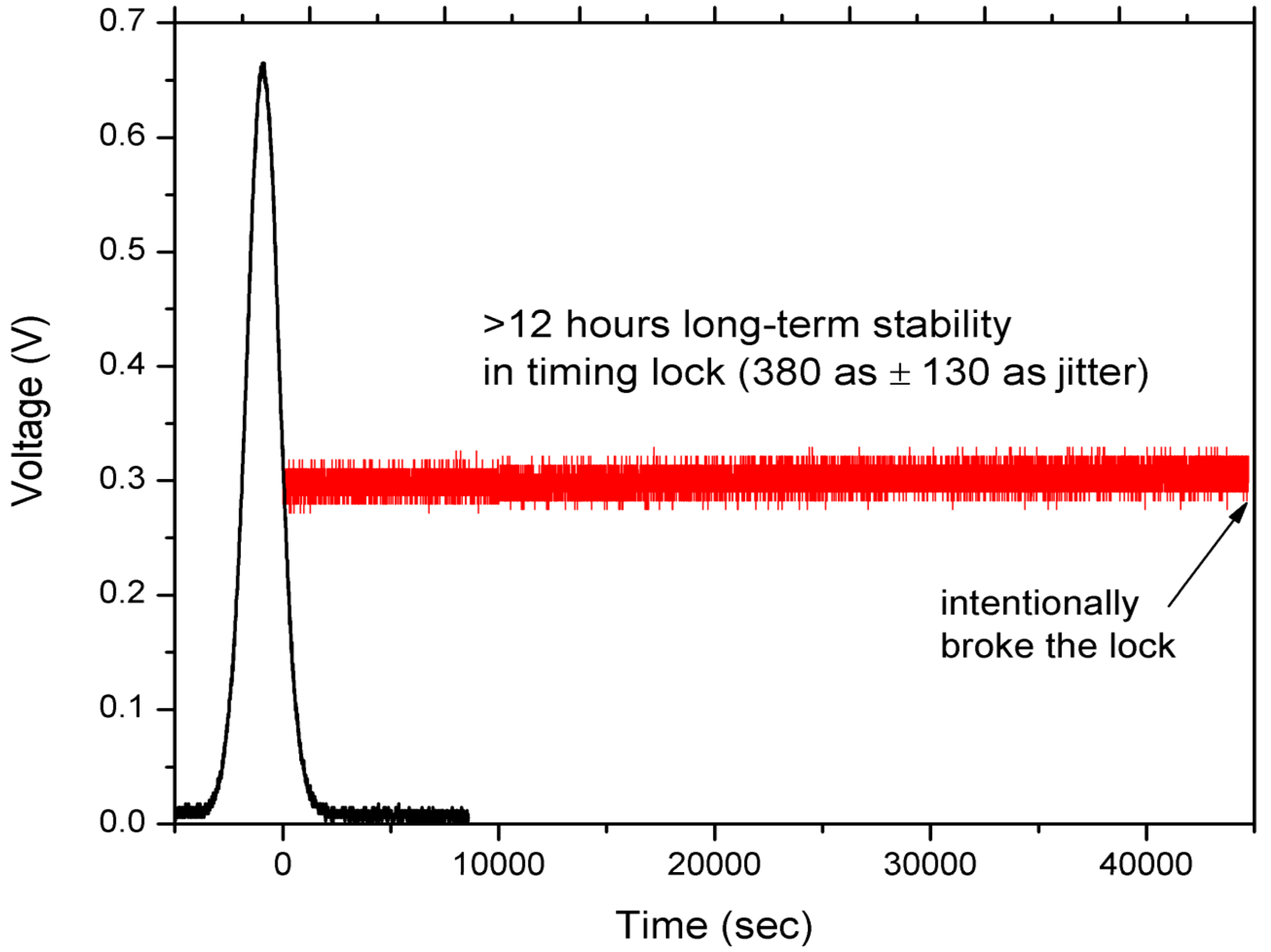
Balanced Optical Cross-Correlation



Measured 0.3 fs jitter from 10mHz to 2.3 MHz
T. Schibli et al, Opt. Lett. **28**, 947 (2003).

Long-Term Locking Between Two Lasers

(Out-of-Loop Measurements)

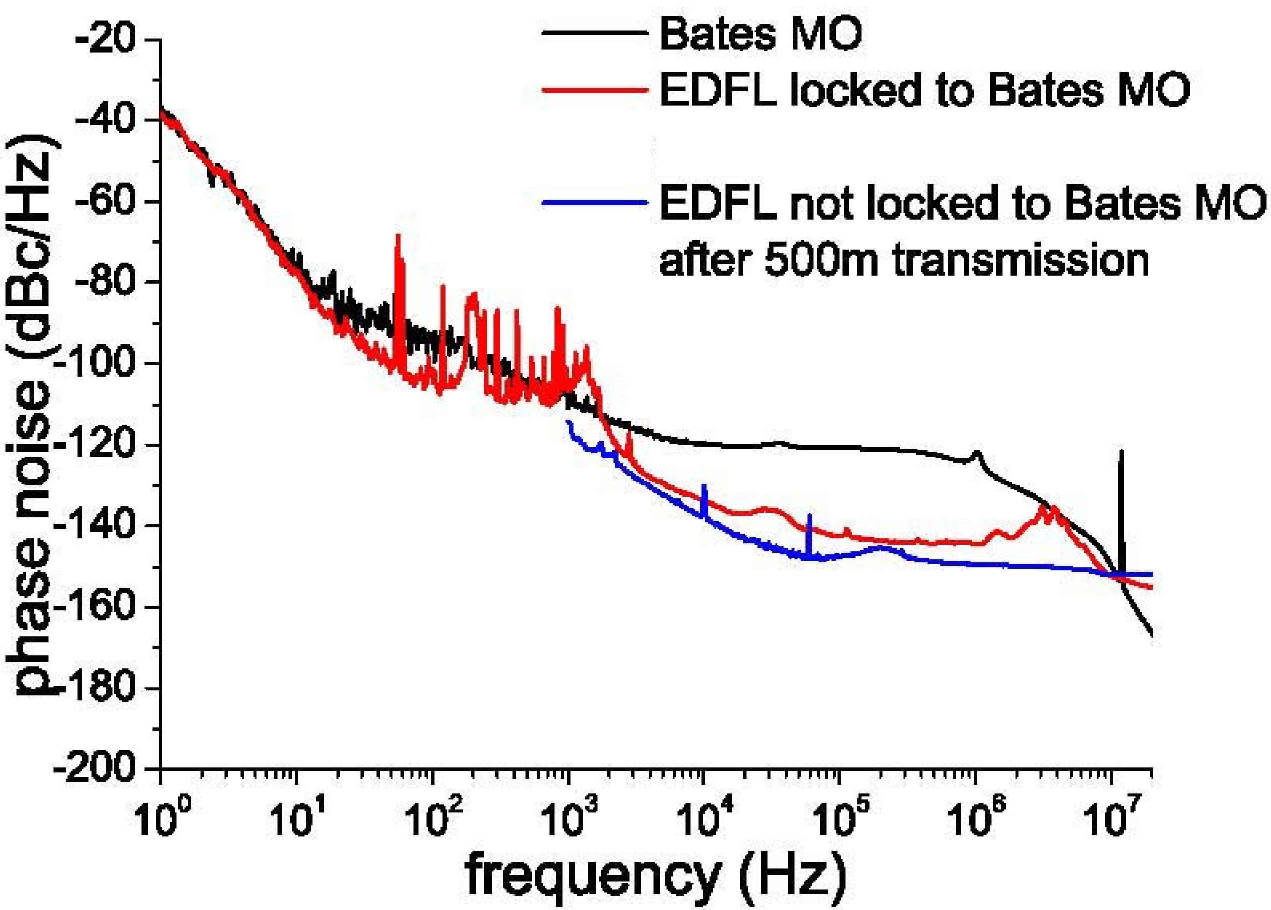


Summary and Outlook

- **Optical master oscillator**: Ultrashort pulse trains from mode-locked lasers have excellent phase/timing noise properties. (~10 fs → <1 fs)
- **Timing-stabilized fiber links**: initial demonstration in the accelerator environment. Optical cross-correlation system in progress for low-jitter, drift-free operation. (~10 fs → <1 fs)
- **Optical-to-RF synchronization**: Balanced optical-RF phase detectors are proposed for femtosecond and potentially sub-femtosecond optical-to-RF synchronization. (~3 fs → <1 fs)
- **Optical-to-optical synchronization**: Balanced optical cross-correlation. Long term stable sub-femtosecond precision is already achieved. (<1 fs)

A (sub-)femtosecond timing distribution and synchronization system for 4th generation light sources can be accomplished.

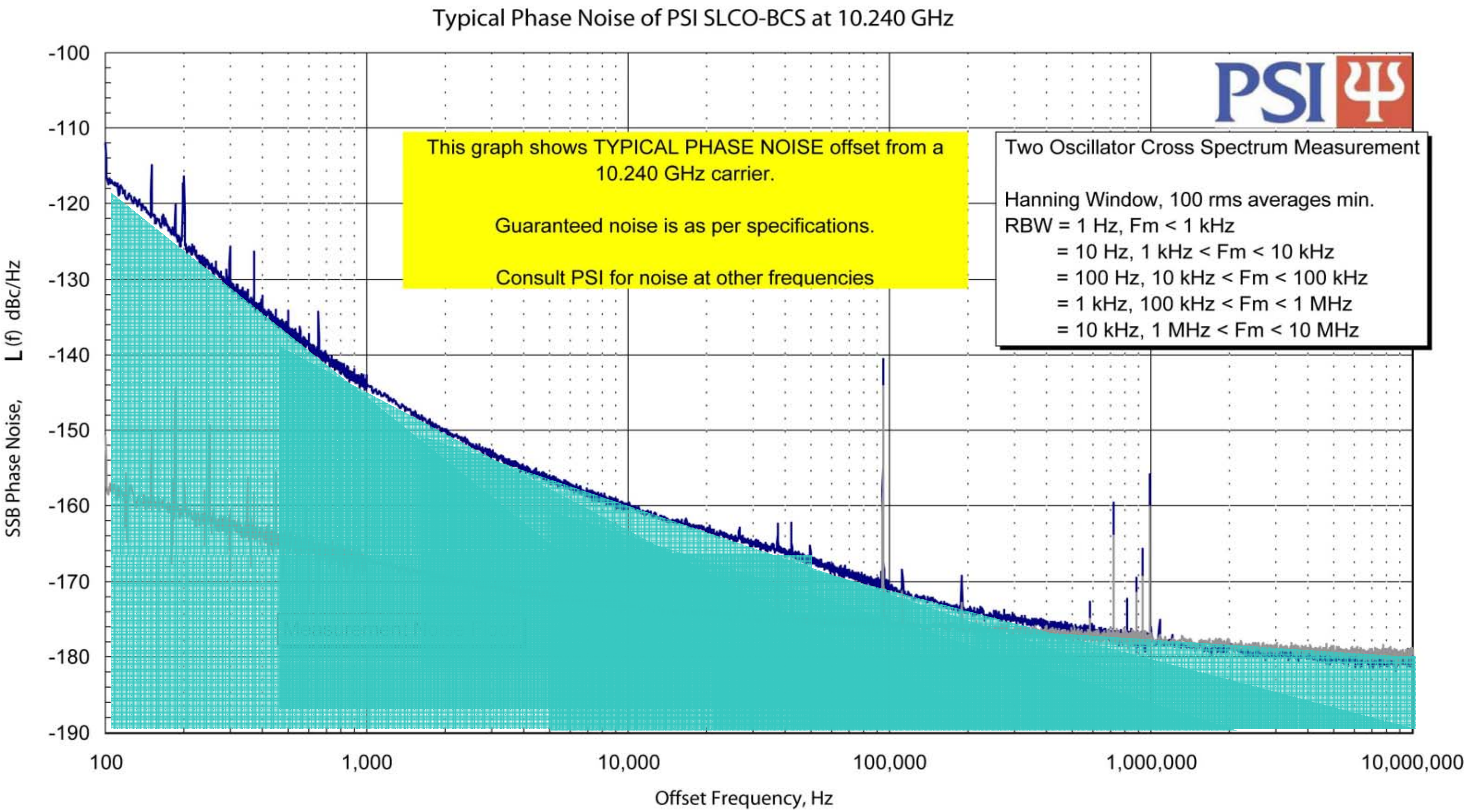
Phase Noise (Jitter) of Transmitted Signal



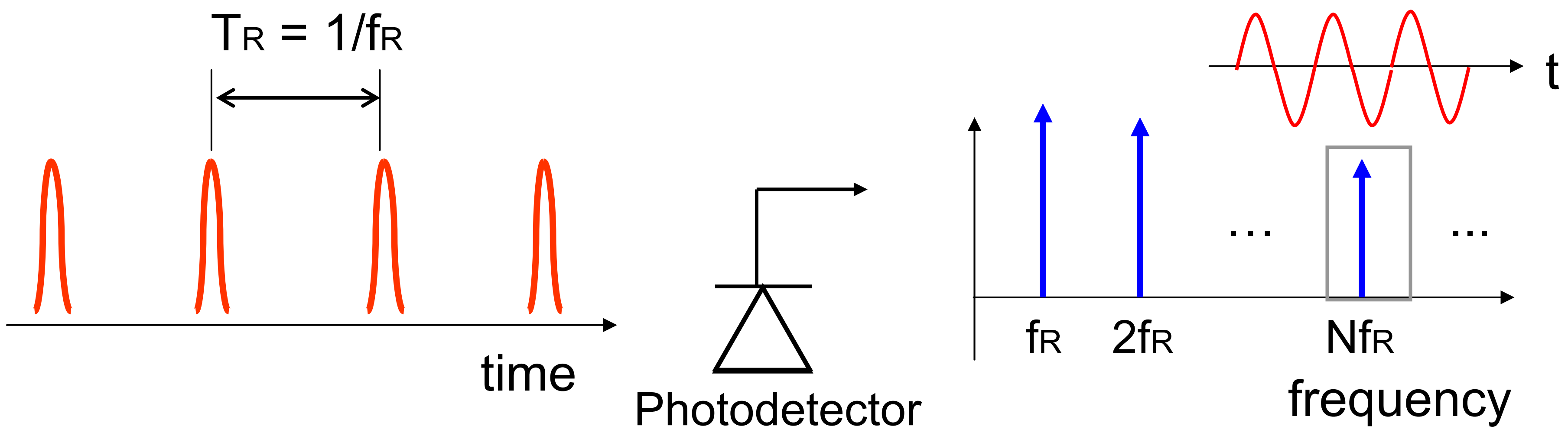
- Jitter between Bates MO and optical master laser ~30 fs (10 Hz..2 kHz)
- Jitter added by Link < 22fs
- Total jitter added (1- 4) < 52 fs

Commercial Low-Noise Microwave Oscillators

- Very good microwave oscillators are commercially available for low phase noise in the low frequency range (< 1 kHz).
- Eventually can lock to an optical standard for μHz-level stability.

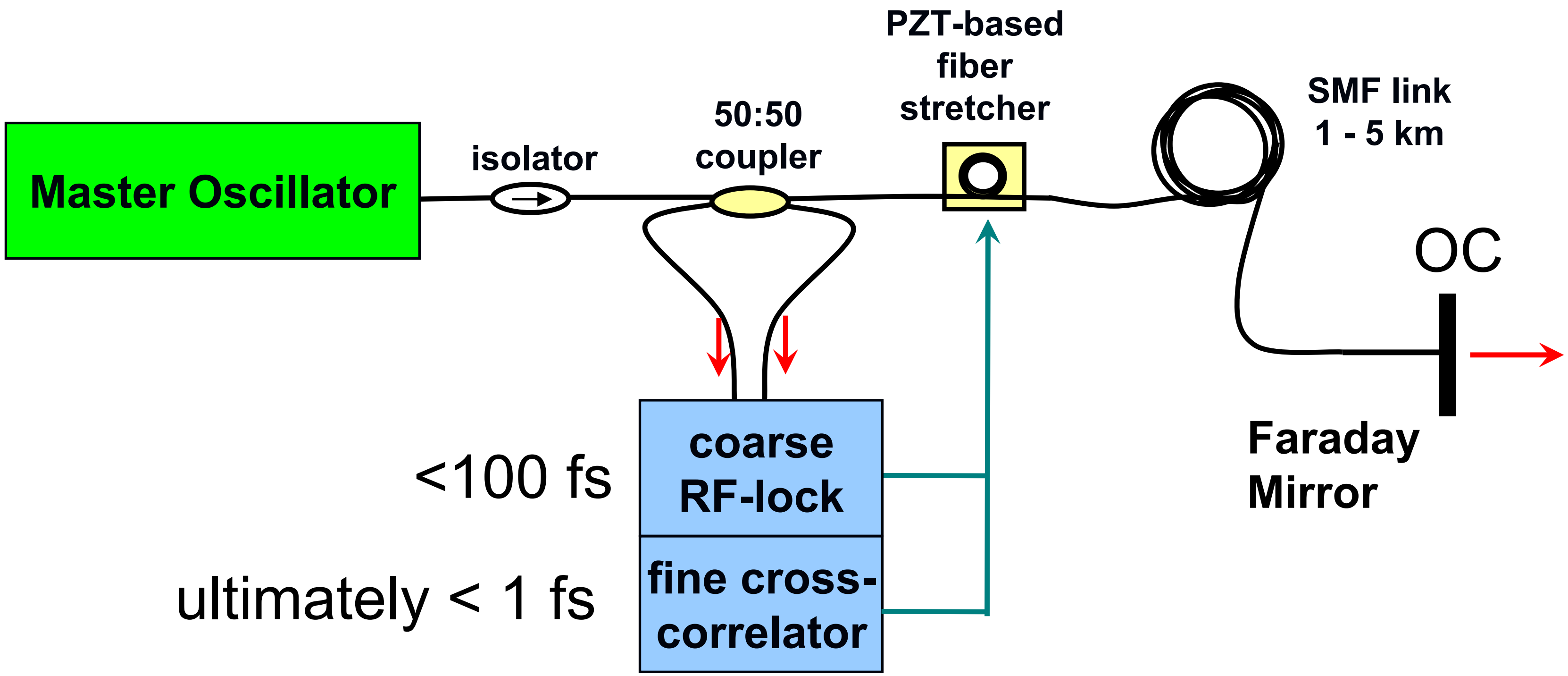


Why Optical Pulses (Mode-locked Lasers)?



- RF encoded in pulse repetition rate, every harmonic can be extracted.
- Suppress Brillouin scattering and undesired reflections.
- Optical cross correlation can be used for link stabilization or for optical-to-optical synchronization with other lasers
- Pulses can be directly used to seed amplifiers at end stations.
- Group delay is directly stabilized, not phase delay as would be the case in an interferometric link stabilization. (For L=1km and 1^0C, τ_{phase}-τ_{group}> 10fs, Polarization Mode Dispersion: 0.01-0.1ps/√km)

Timing-Stabilized Fiber Links



<100 fs

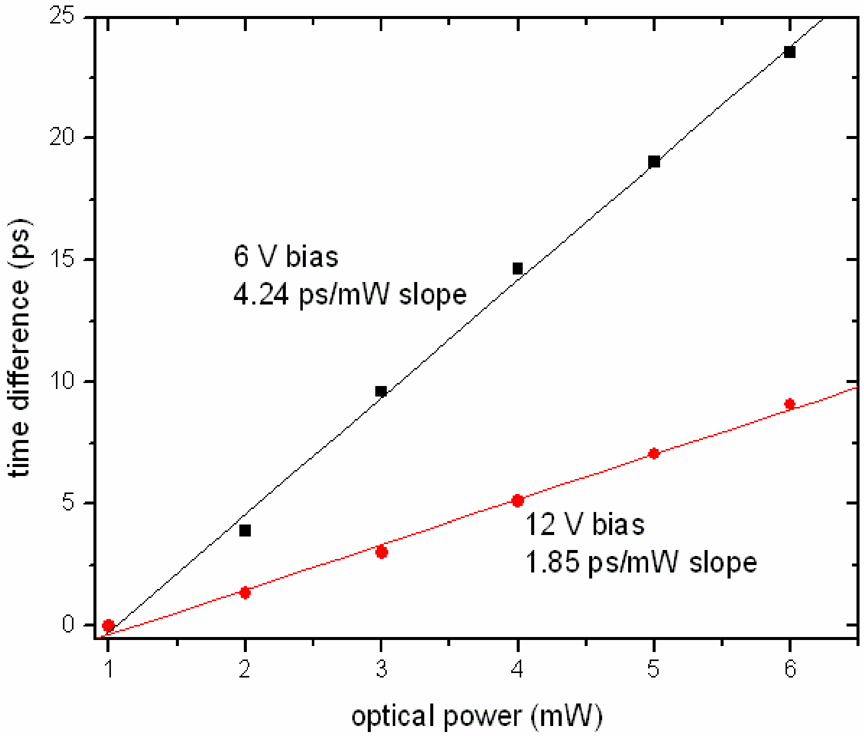
ultimately < 1 fs

Assuming no fiber length fluctuations faster than T=2nL/c.

L = 1 km, n = 1.5 => T=1 μs, f_{max} ~ 100 kHz

K. Holman, et al. Opt. Lett. 30, 1225 (2005); < 40 fs in 1Hz-100kHz

Amplitude-to-Phase Conversion Measurement



Typical AM-to-PM:
1 – 10 ps/mW

Consistent with NIST result
Bartels et al, OL **30**, 667 (2005).

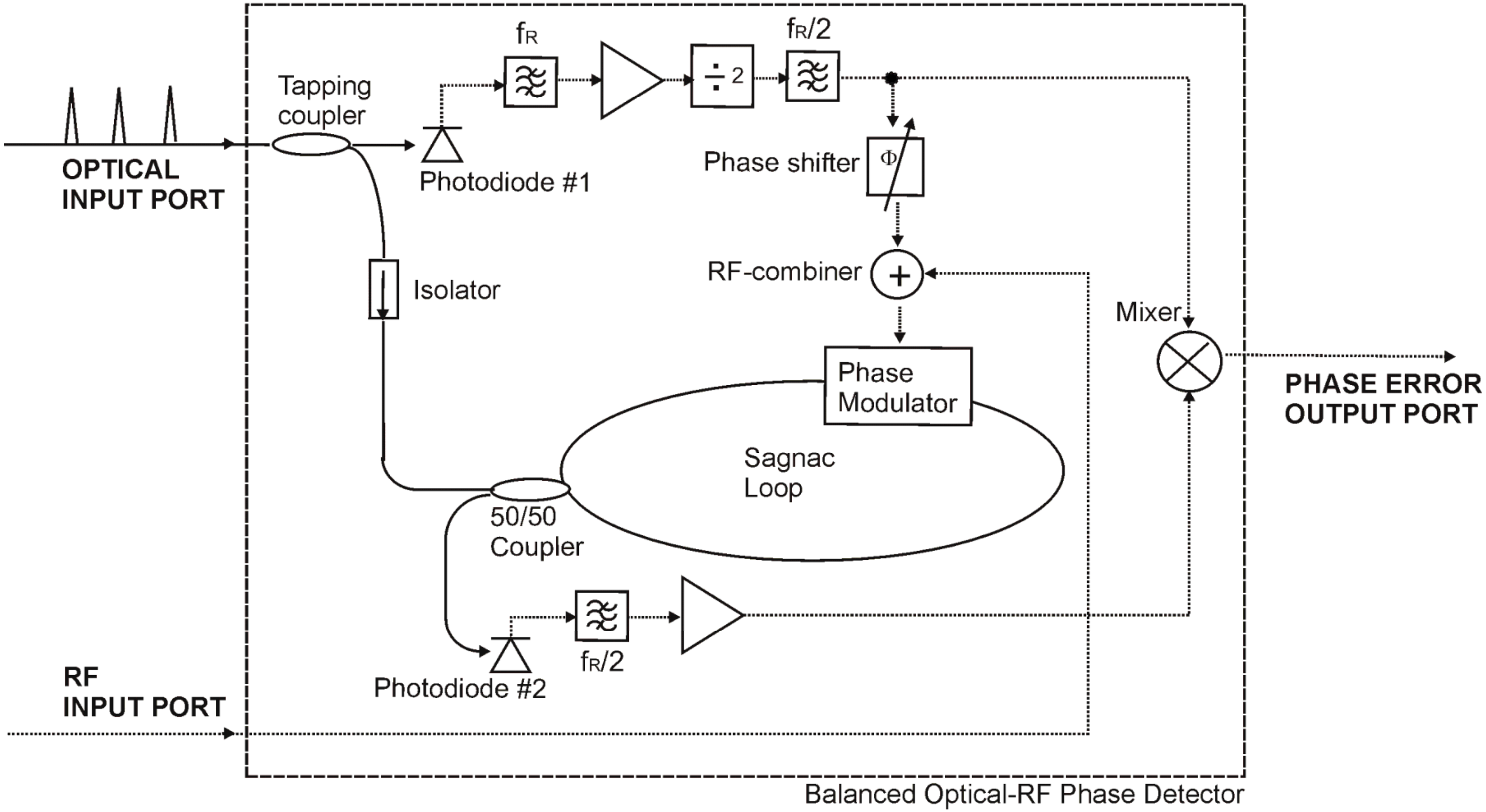
RIN~0.04% (10kHz-22MHz)
→ Δt_{excess}~ 5-20 fs

Limitations in direct photodetection

1. Amplitude-to-phase conversion
2. Limited SNR by small-area high speed detector
3. High temperature sensitivity of photodiode

Conversion of optical signal into electronic signal is the major bottleneck in signal properties (noise, stability, and power).

Balanced Optical-RF Phase Detector



- Capable of driving high-power VCO → High-power regenerated RF-signal
- Scalable phase detection sensitivity → Low-jitter synchronization
- Fiber-based “balanced” scheme → Long-term drift-free operation

Scalability in Phase Detection Sensitivity

Scalable Phase Detection Sensitivity

$$K_d = \frac{V_d}{\theta_e} \propto P_{avg}\Phi_0\Phi_m$$

Shot Noise Floor Scalability

$$S_{\varphi,shot} = \frac{< \overline{V}^2_{shot,mix} >}{K_d^2 / N^2} = \frac{8q}{RP_{avg}\Phi_0^2}$$

P_{avg}	Optical power circulating Sagnac-loop	10 mW
Φ_0	Phase modulation depth from VCO signal	0.4 rad
Φ_m	Phase modulation depth from synchronous signal	0.2 rad
R	Photodetector responsivity	0.9 A/W
q	Electron charge	1.6×10^{-19} C
Shot noise limited jitter = 0.5 fs (currently limited by other noise sources) → Scalable by increasing optical power and RF modulation depth		

Balanced Cross-Correlator