Femtosecond Synchronization and Stabilization Techniques

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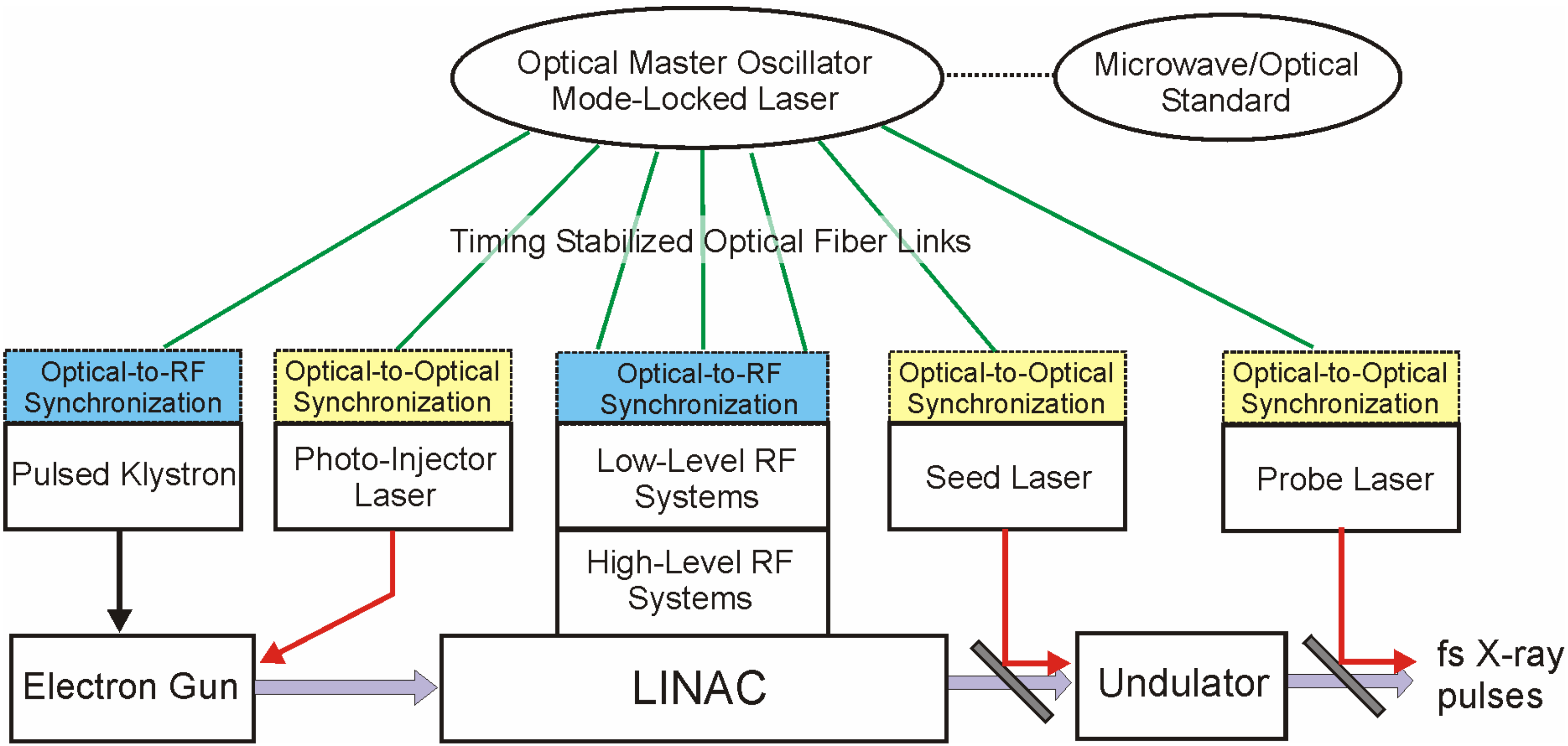
4th Generation Light Sources: XFEL



J. Kim et al., FEL 2004.

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.

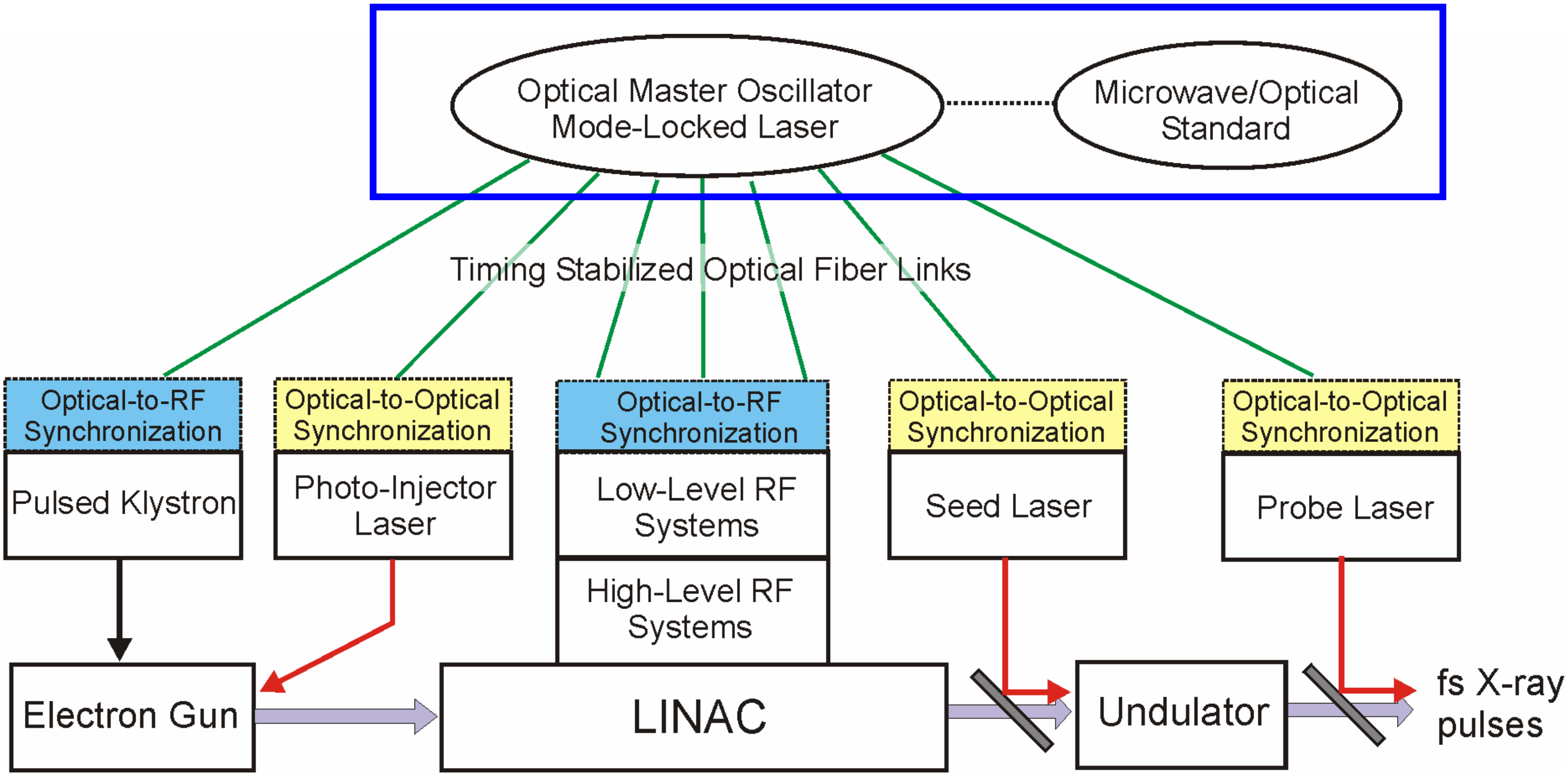
- Must serve multiple locations separated by up to 1-5 km distances.

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

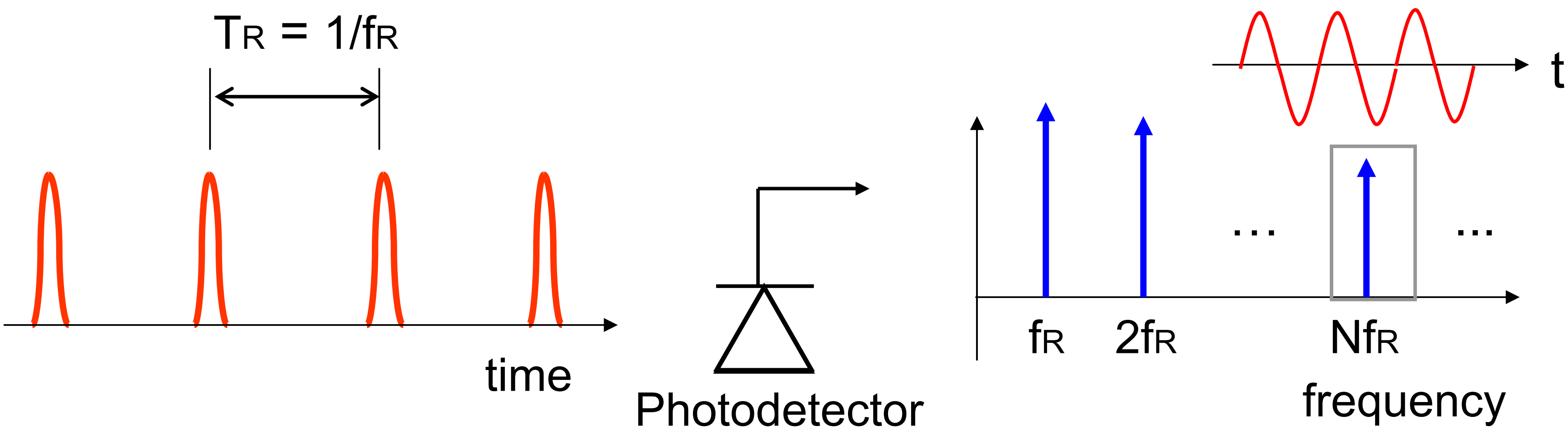
- It will lead to a considerable reduction in cost and space.

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)



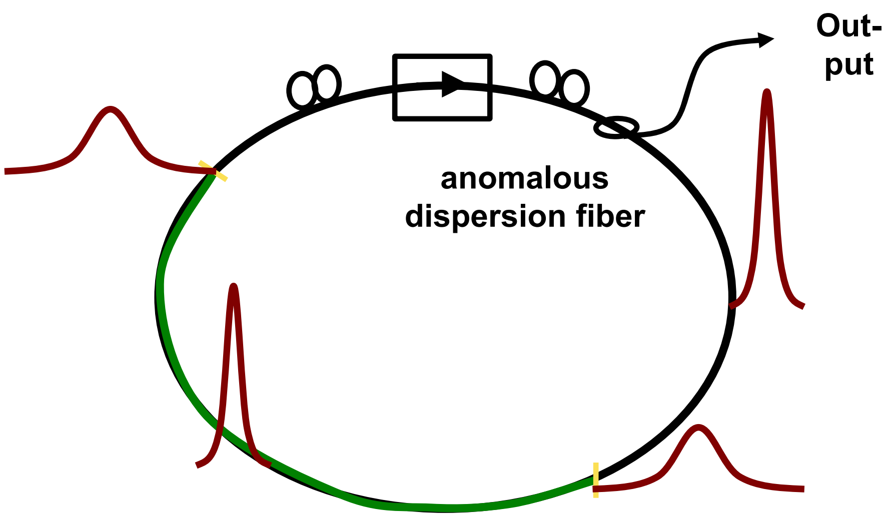
Why Optical Pulses (Mode-locked Lasers)?



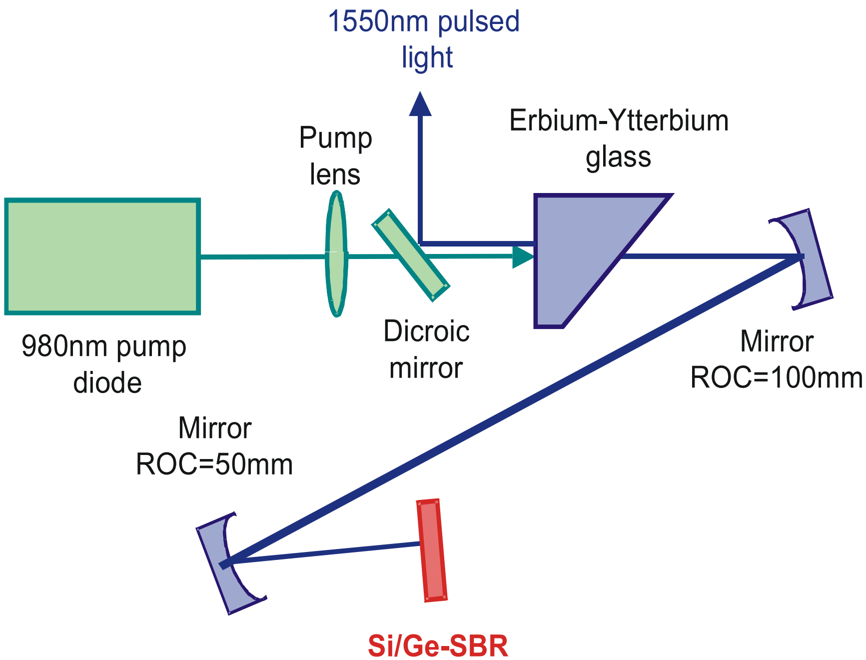
- RF signal is encoded in the pulse repetition rate.
  → Every harmonic can be extracted.
- Suppress Brillouin scattering and undesired reflections.
- Optical cross-correlation can be used for timing stabilization.
- Pulses can directly seed amplifiers.
- Group delay is directly stabilized.

Low-Jitter Mode-locked Lasers

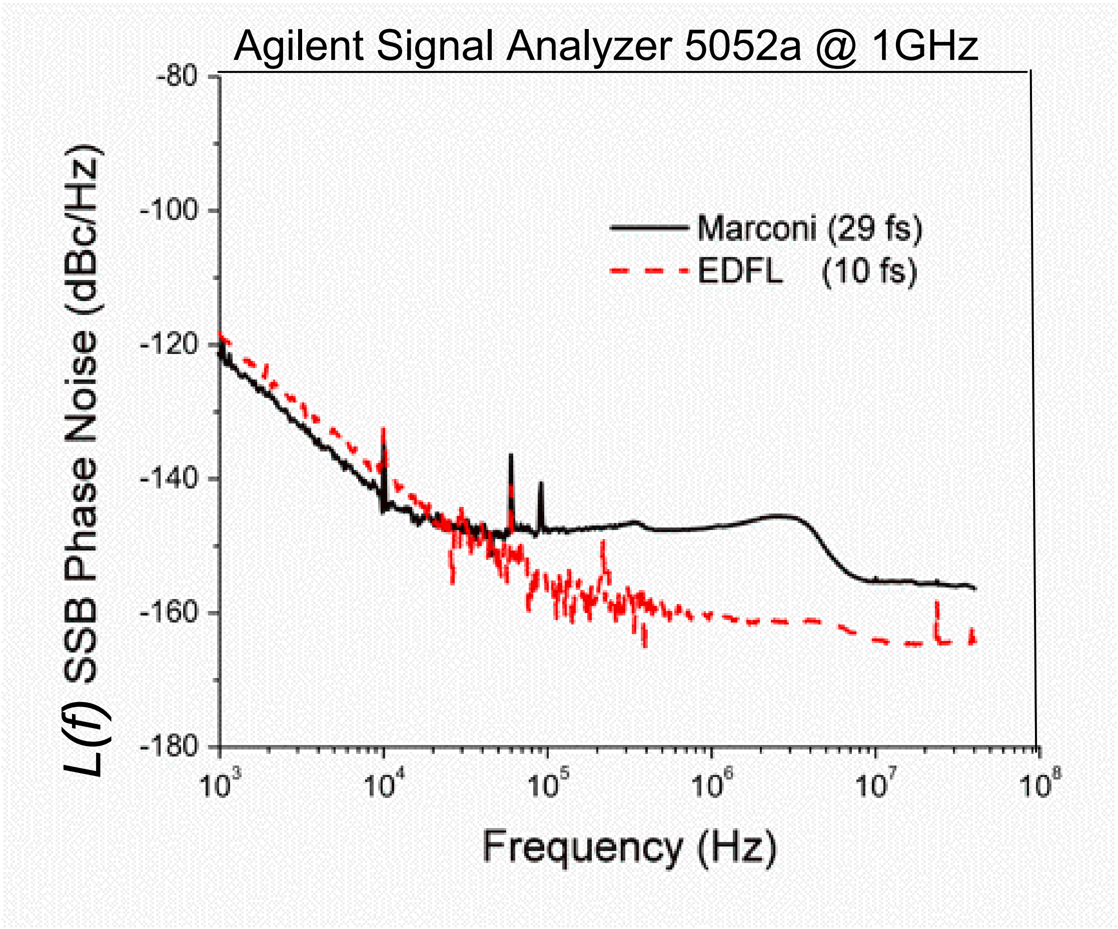
Stretched-pulse Er-fiber laser
Tamura et al. OL **18**, 1080 (1993)



Semiconductor saturable absorber based Er/Yb-glass laser
Schlager et al. OL **28**, 2411 (2003).
Zeller et al, EL **40**, 875 (2004).



Phase Noise (Timing Jitter) Measurements



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

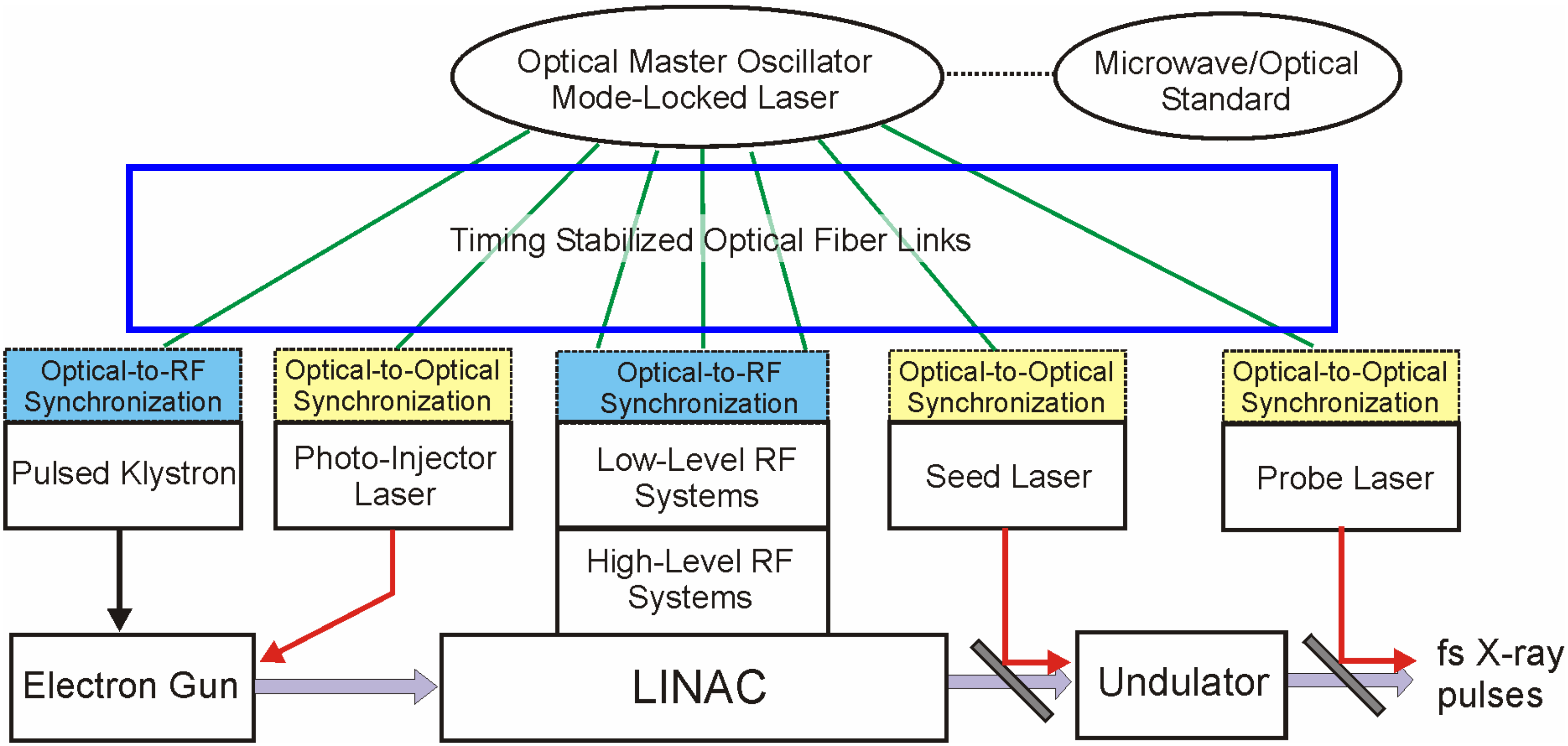
Δt_{rms}[10kHz,22MHz] = 10 fs

Kaertner et al, PAC 2005.
Winter et al, FEL 2005.

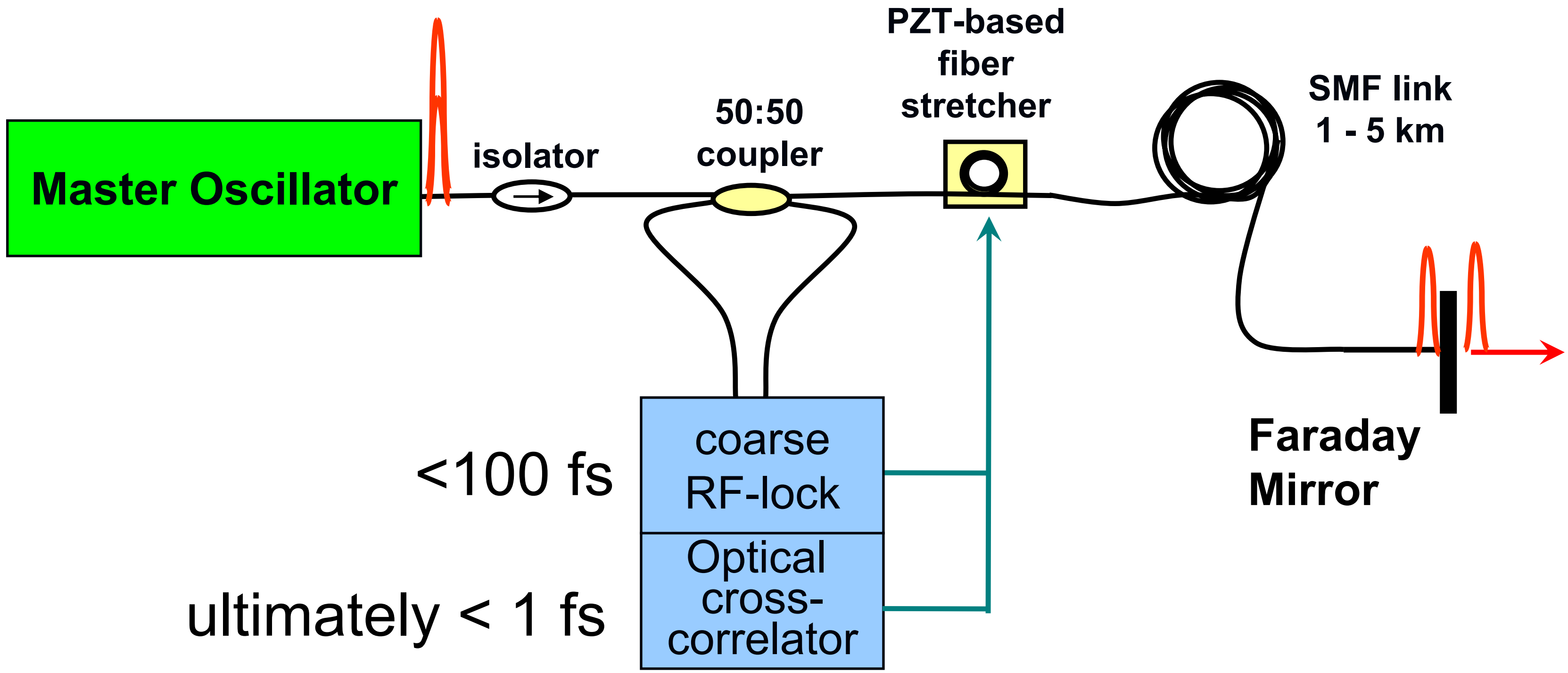
- Noise floor limited by photo detection
- Theoretical noise limit <1 fs

Timing-Stabilized Fiber Links

Stabilized fiber links delivering the pulse train to multiple remote locations



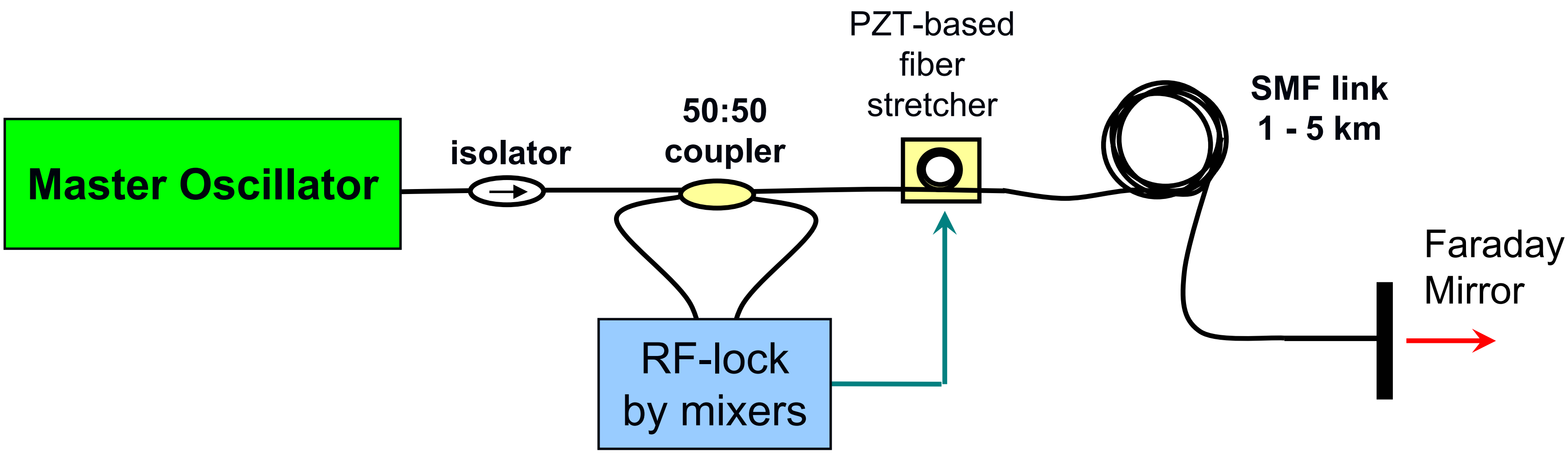
Timing Stabilization



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

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

Short-term Stabilization using RF-mixers



- Test done at accelerator environment (MIT Bates Laboratory)
  - Locked EDFL to Bates master oscillator
  - Transmitted pulses through 400 meters fiber link
  - Close loop on fiber length feedback (12-fs in-loop jitter [0.1Hz,5kHz])

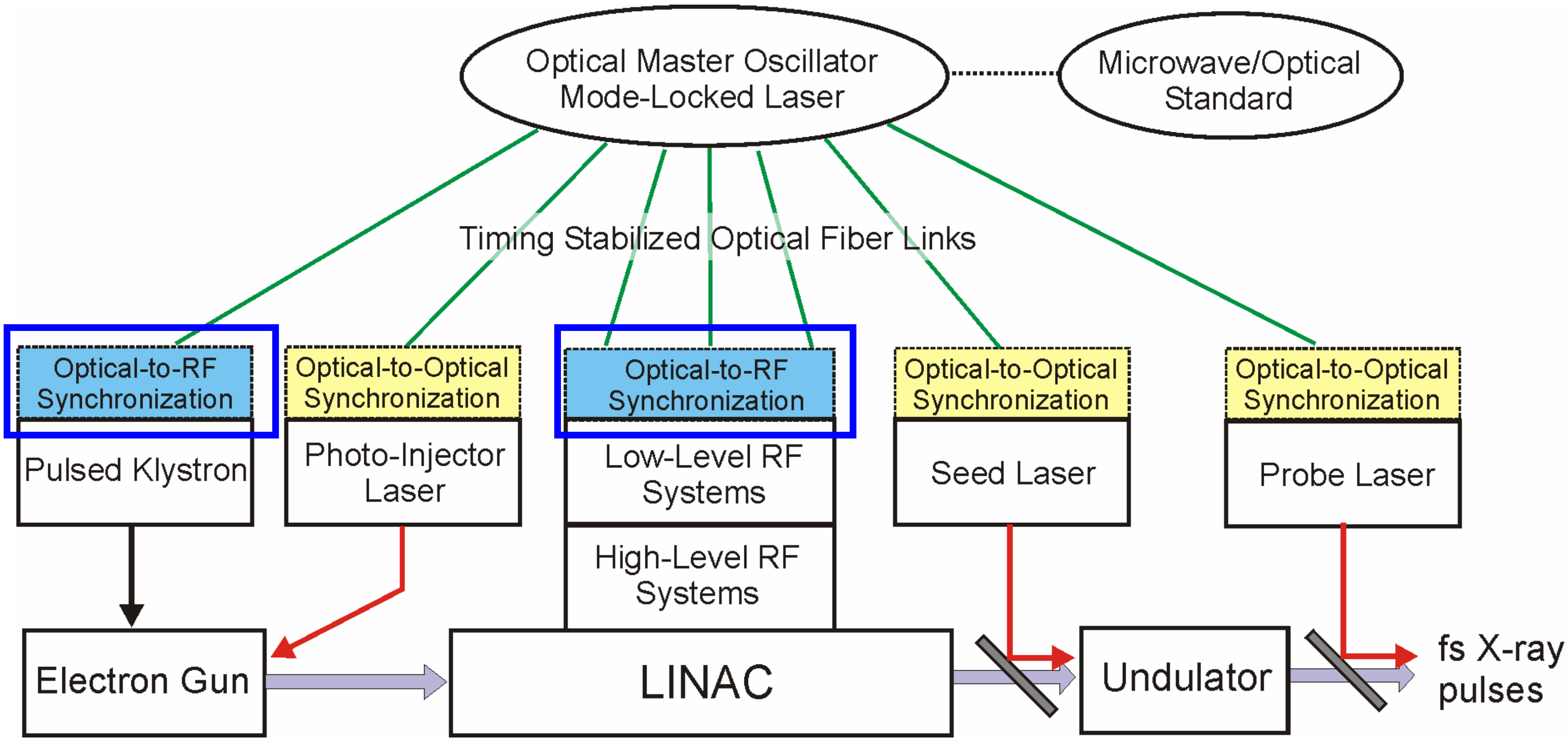
A. Winter et al., Paper FROA002, FEL 2005.

- Test done at the installed fiber underground (NIST/JILA)
  - Transmitted pulse train via a 7-km fiber link between NIST and JILA
  - 19-fs relative jitter between two locations [1 Hz, 46.5MHz]

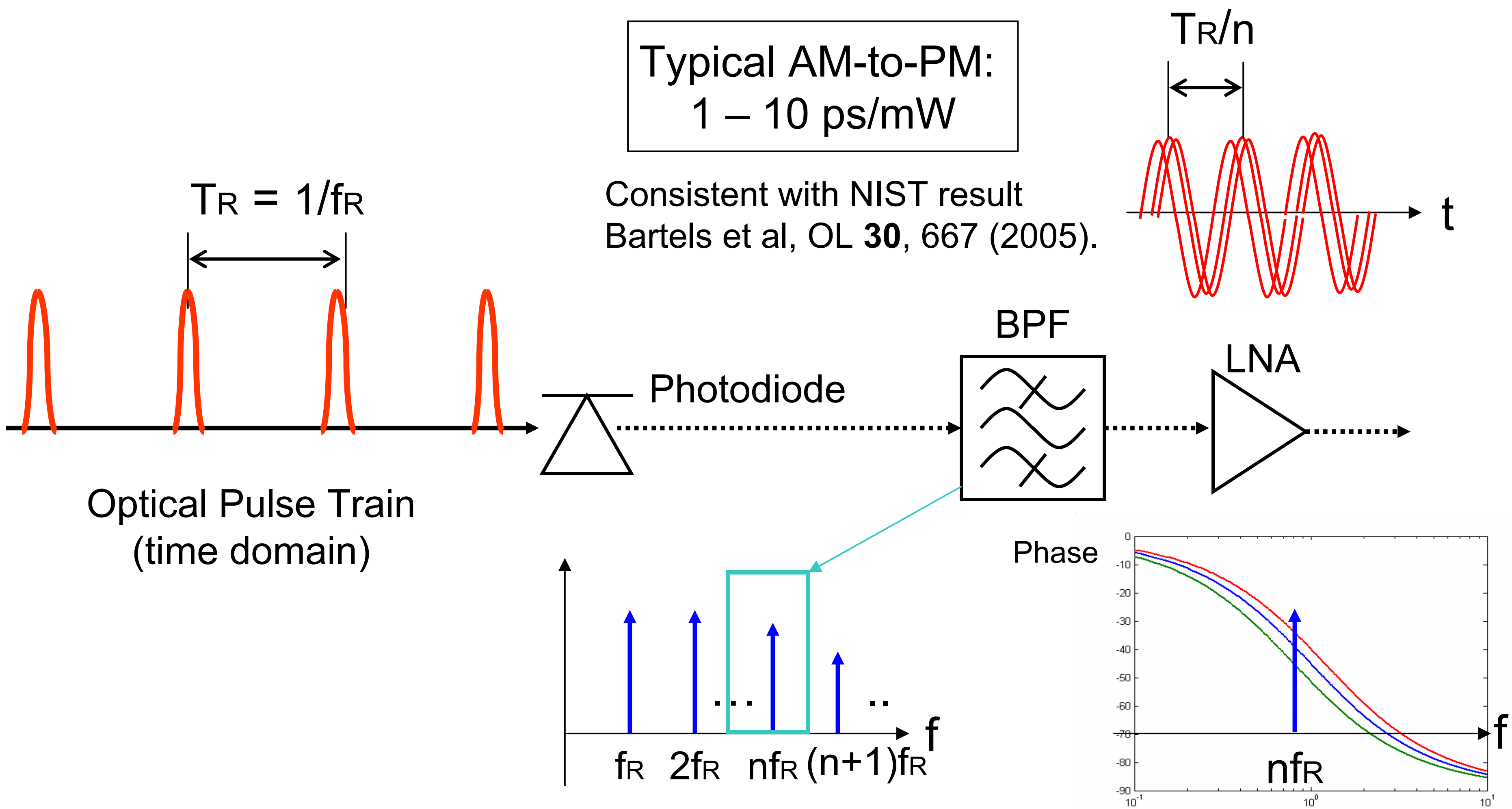
D. Hudson et al, OL **31**, 1951 (2006).

Optical-to-RF Synchronization

Converting optical pulse train to RF-signal at remote locations



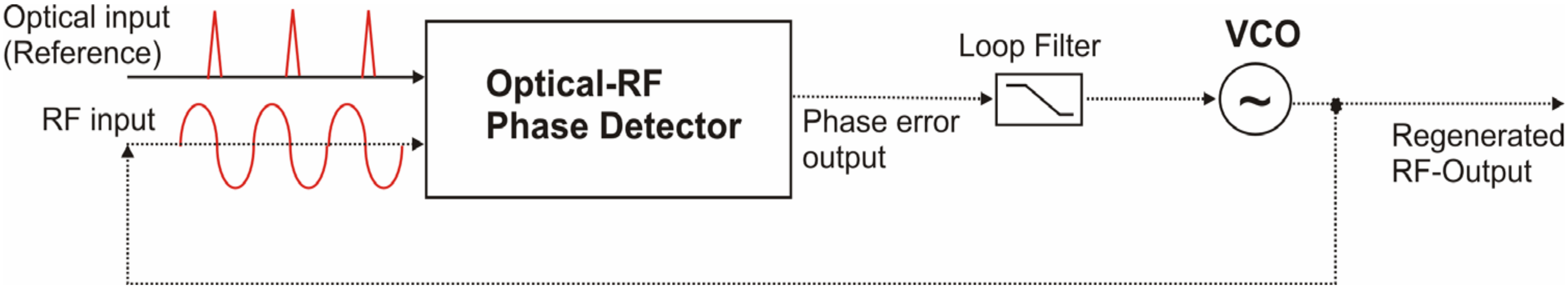
Direct Extraction of RF from Pulse Train



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

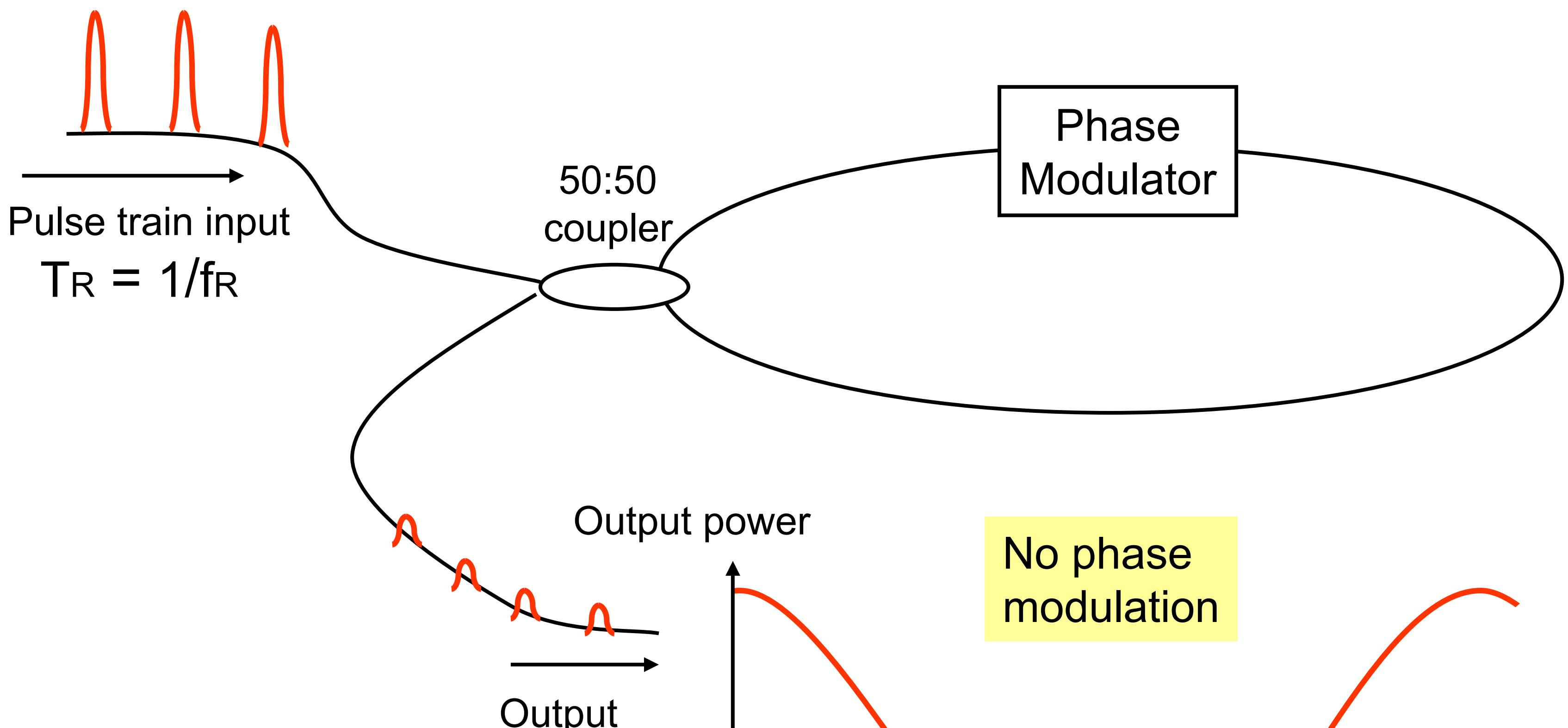
Optoelectronic Phase-Locked Loop (PLL)

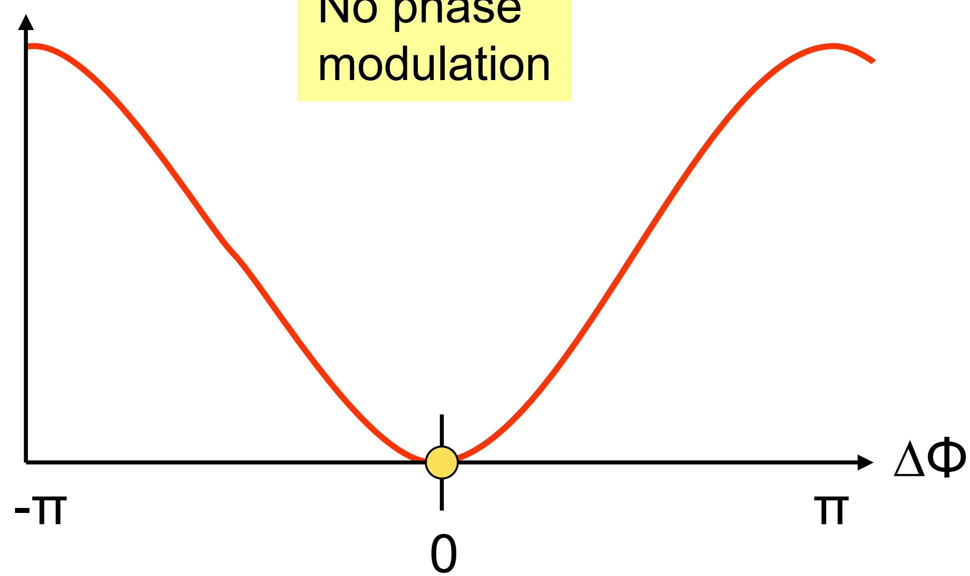
Can we regenerate a high-power, low-jitter and drift-free RF-signal whose phase is locked to the optical pulse train?



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

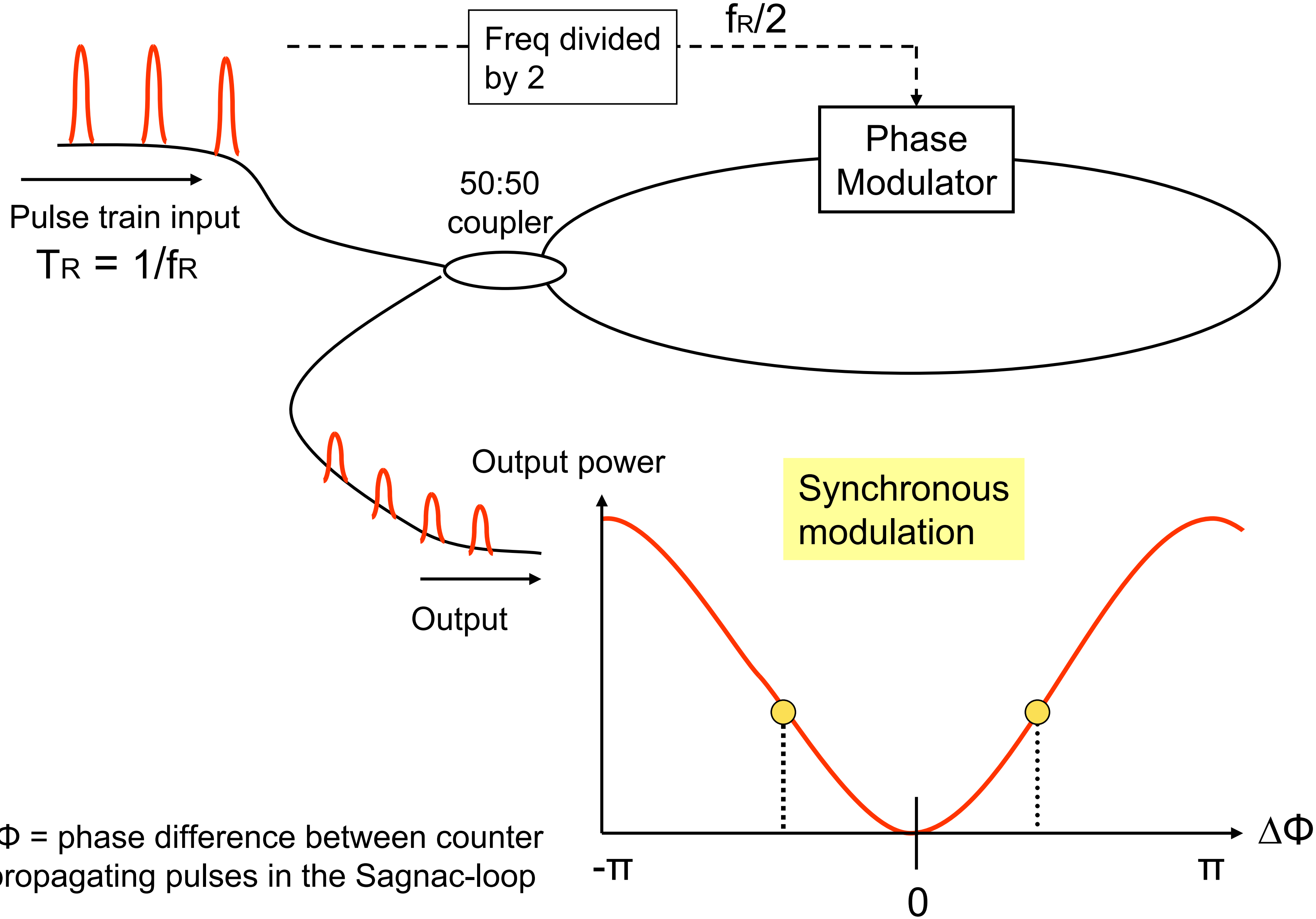
Sagnac-Loop for Electro-Optic Sampling





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

Sagnac-Loop for Electro-Optic Sampling



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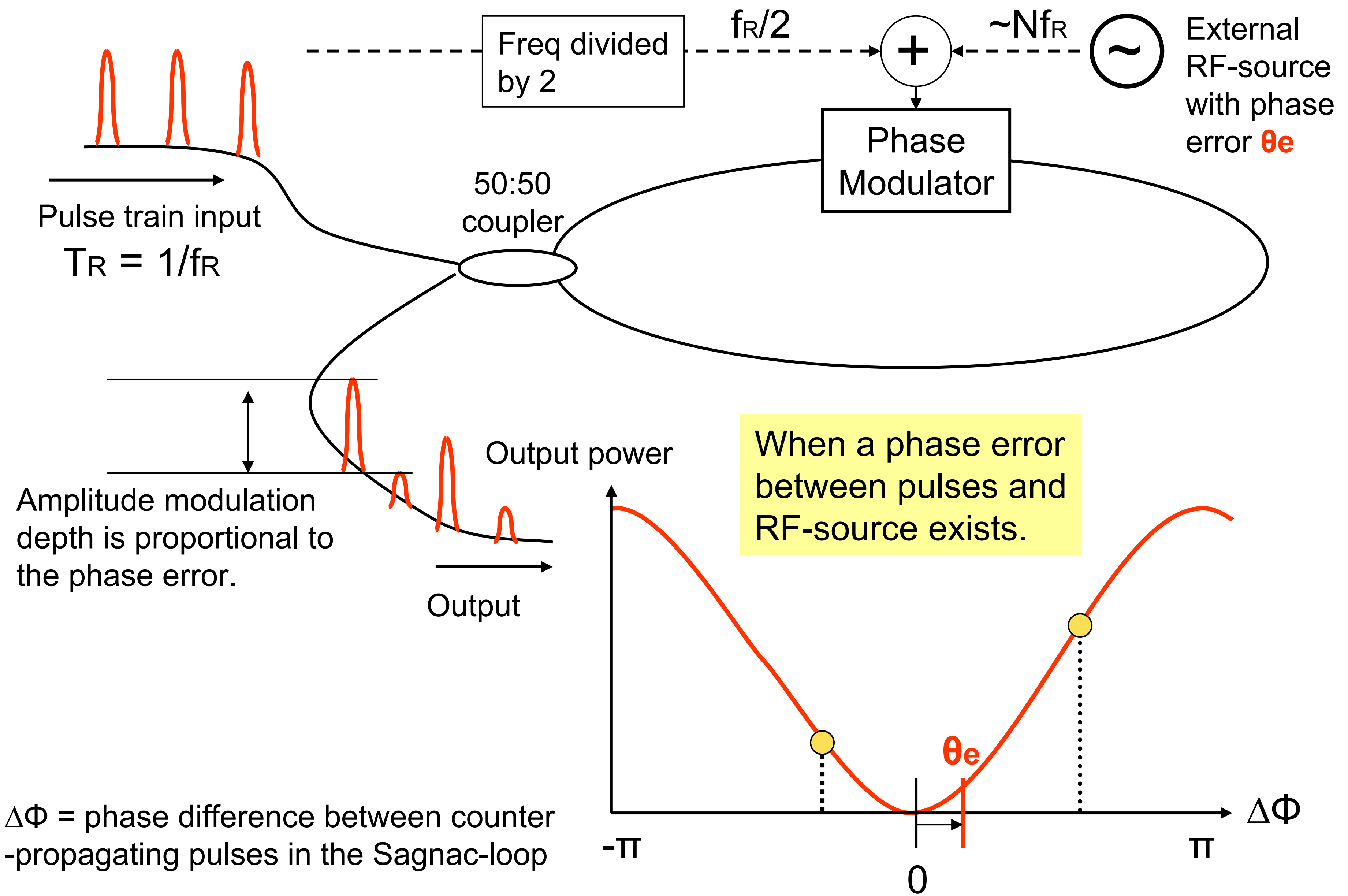

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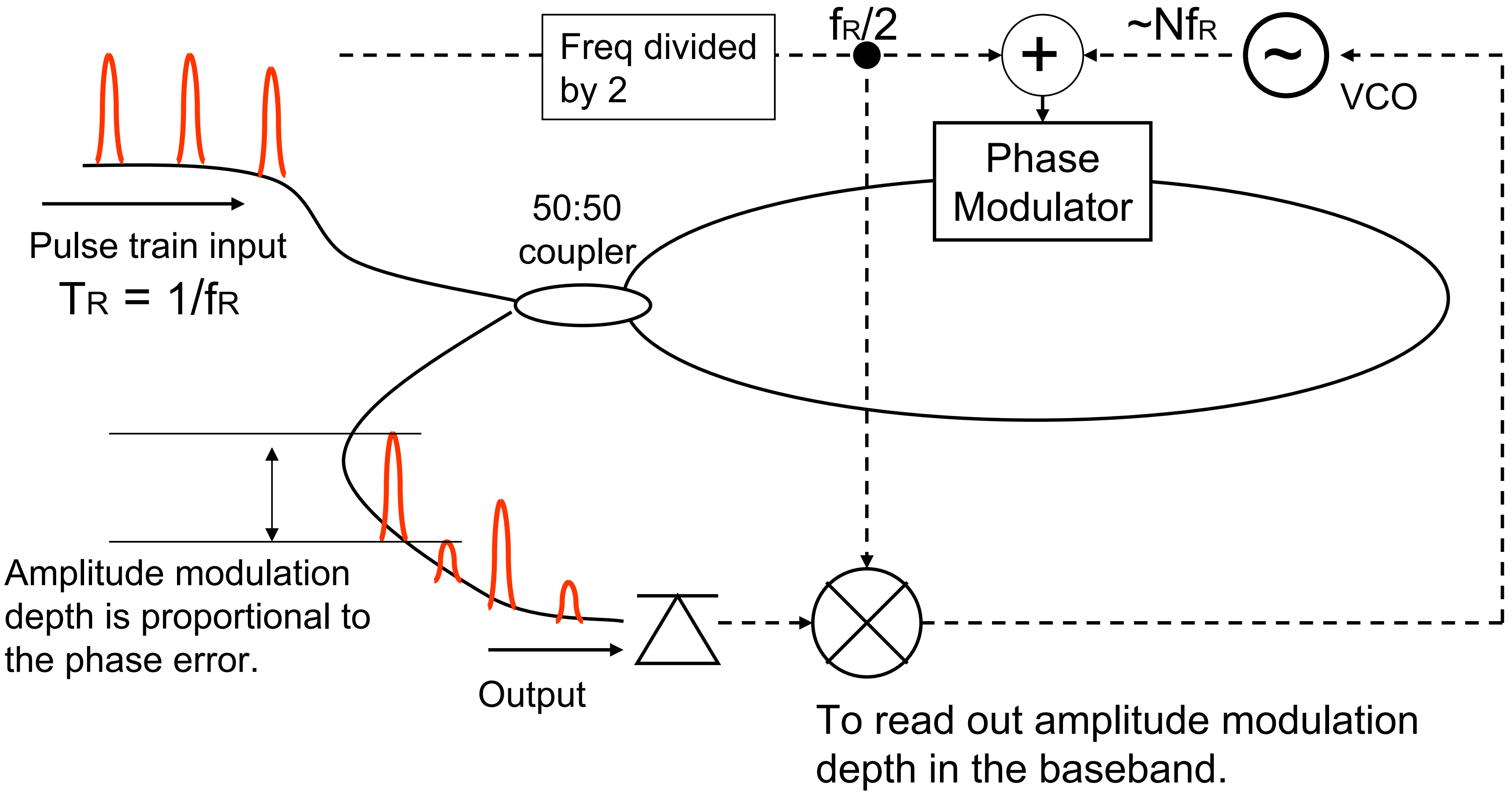
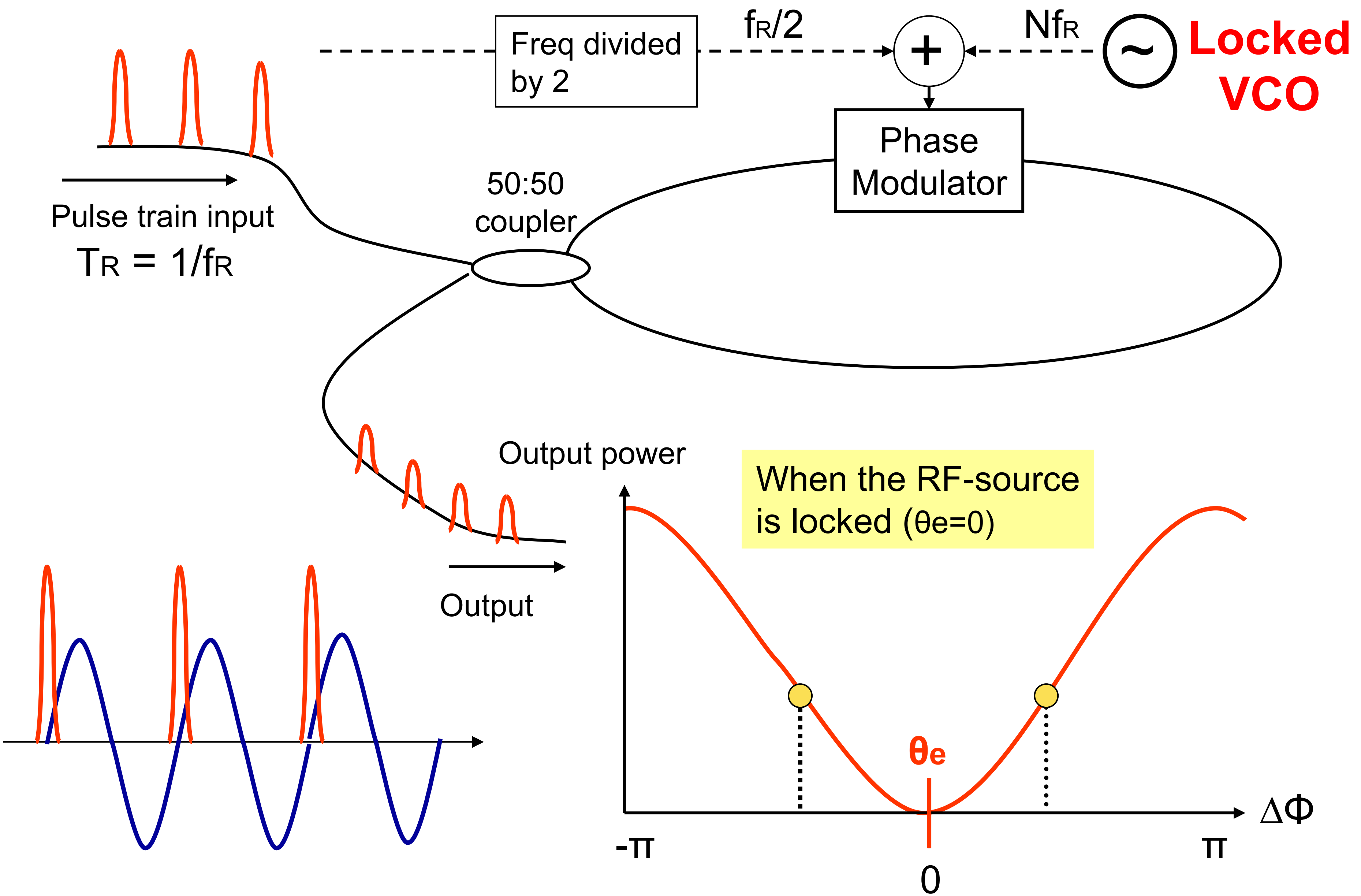
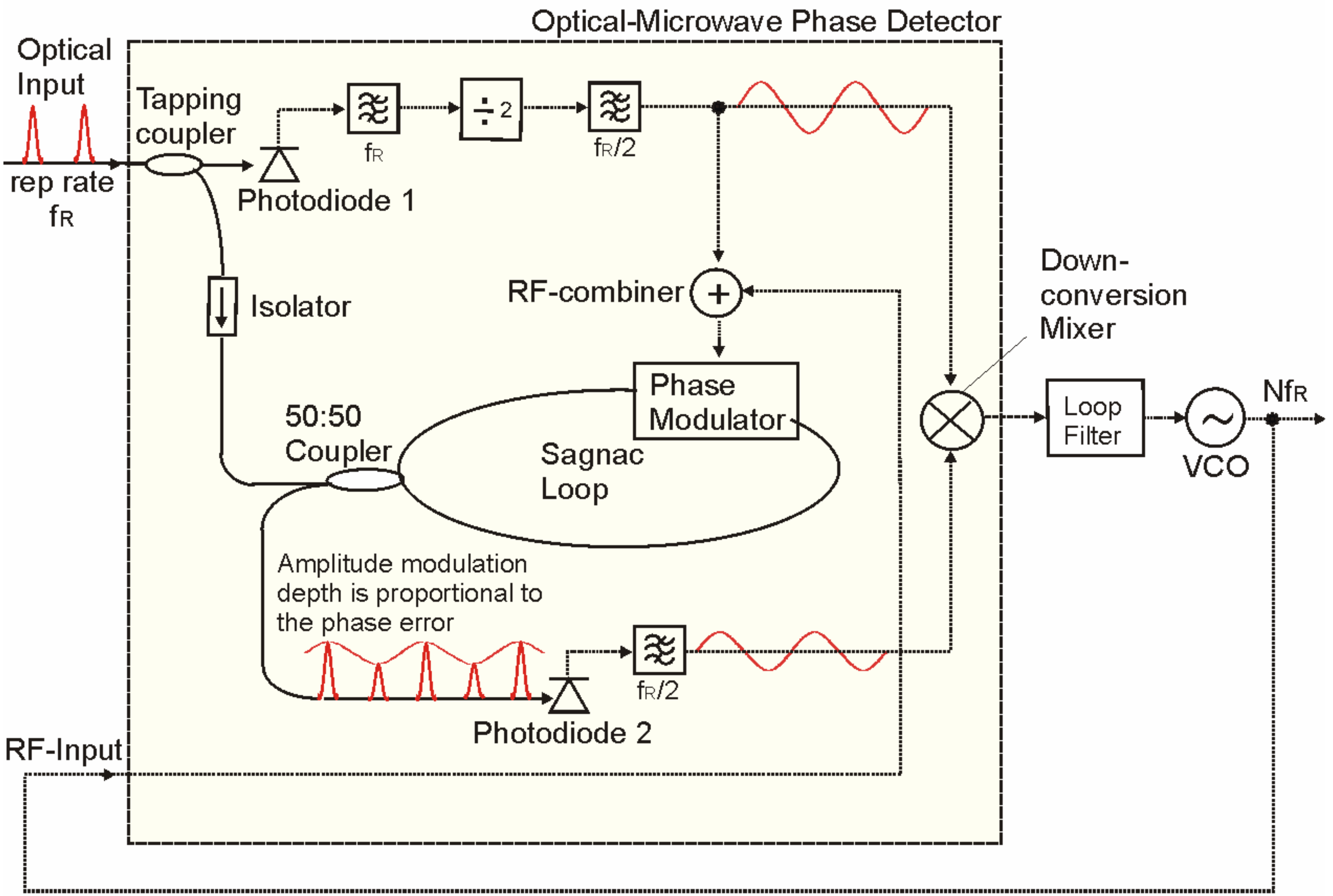


Sagnac-Loop for Electro-Optic Sampling

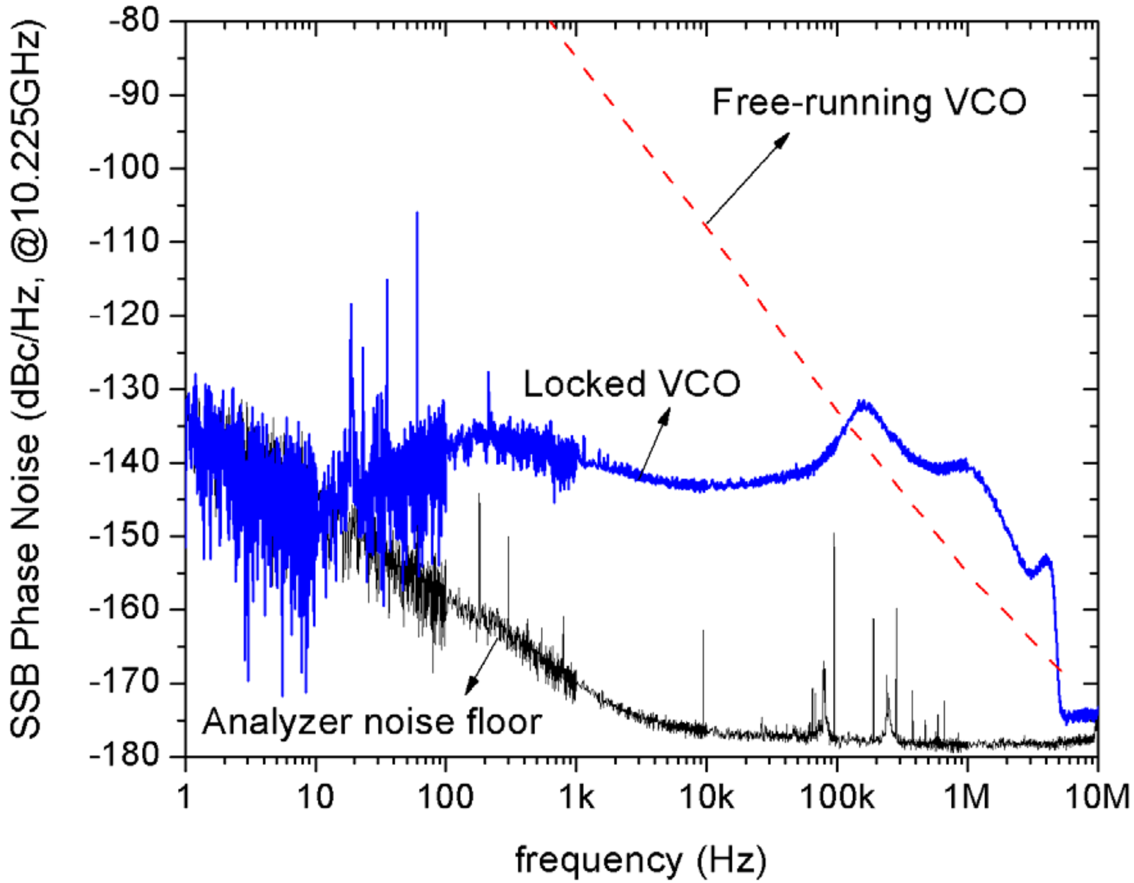


Demonstration Experiment



- 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

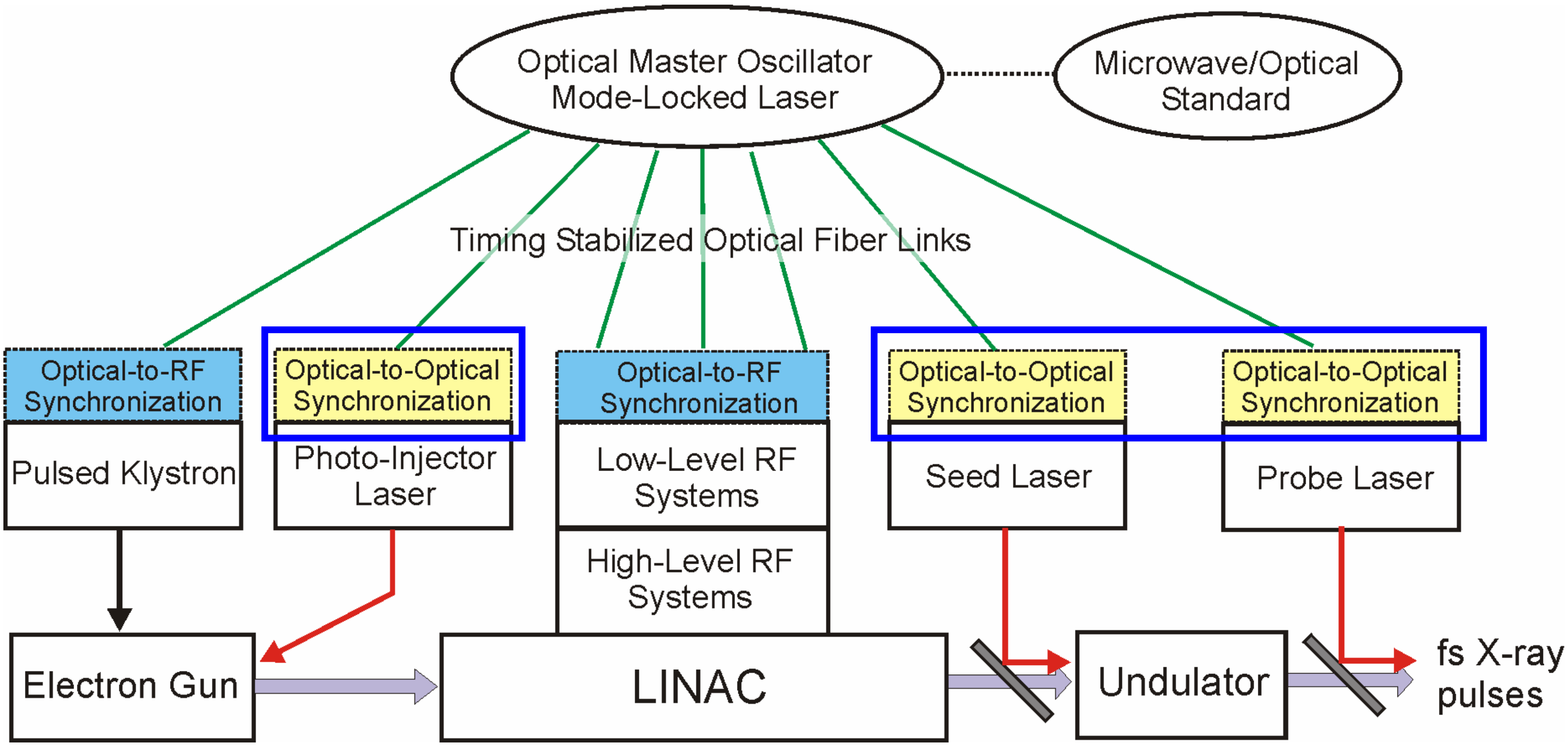
In-Loop Phase Noise Measurement



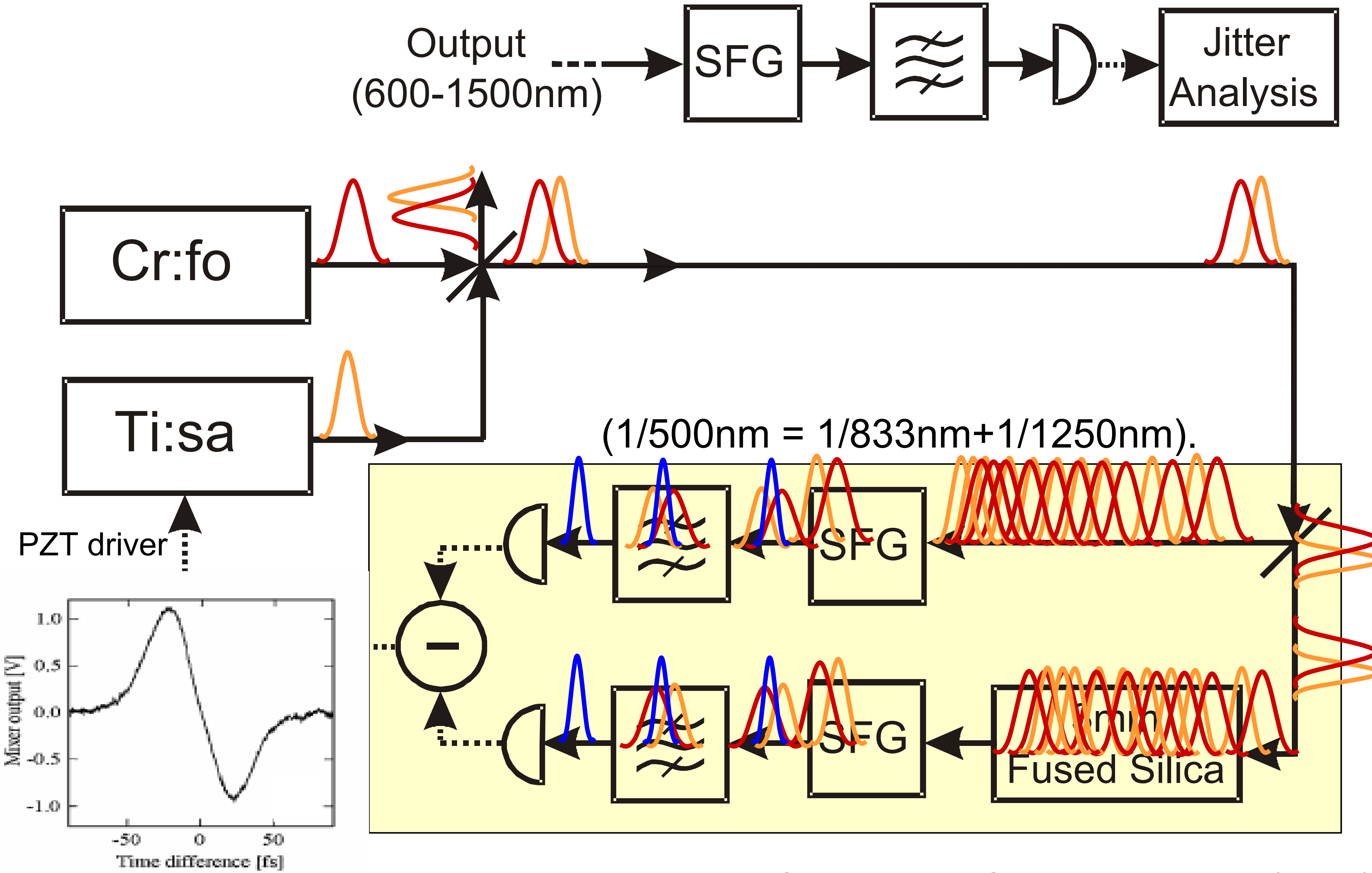
Residual timing jitter = 3 fs ± 0.2 fs (1Hz-10MHz)

Long-term (>several hours) locking is possible.
Out-of-loop measurement is in progress.

Optical-to-Optical Synchronization



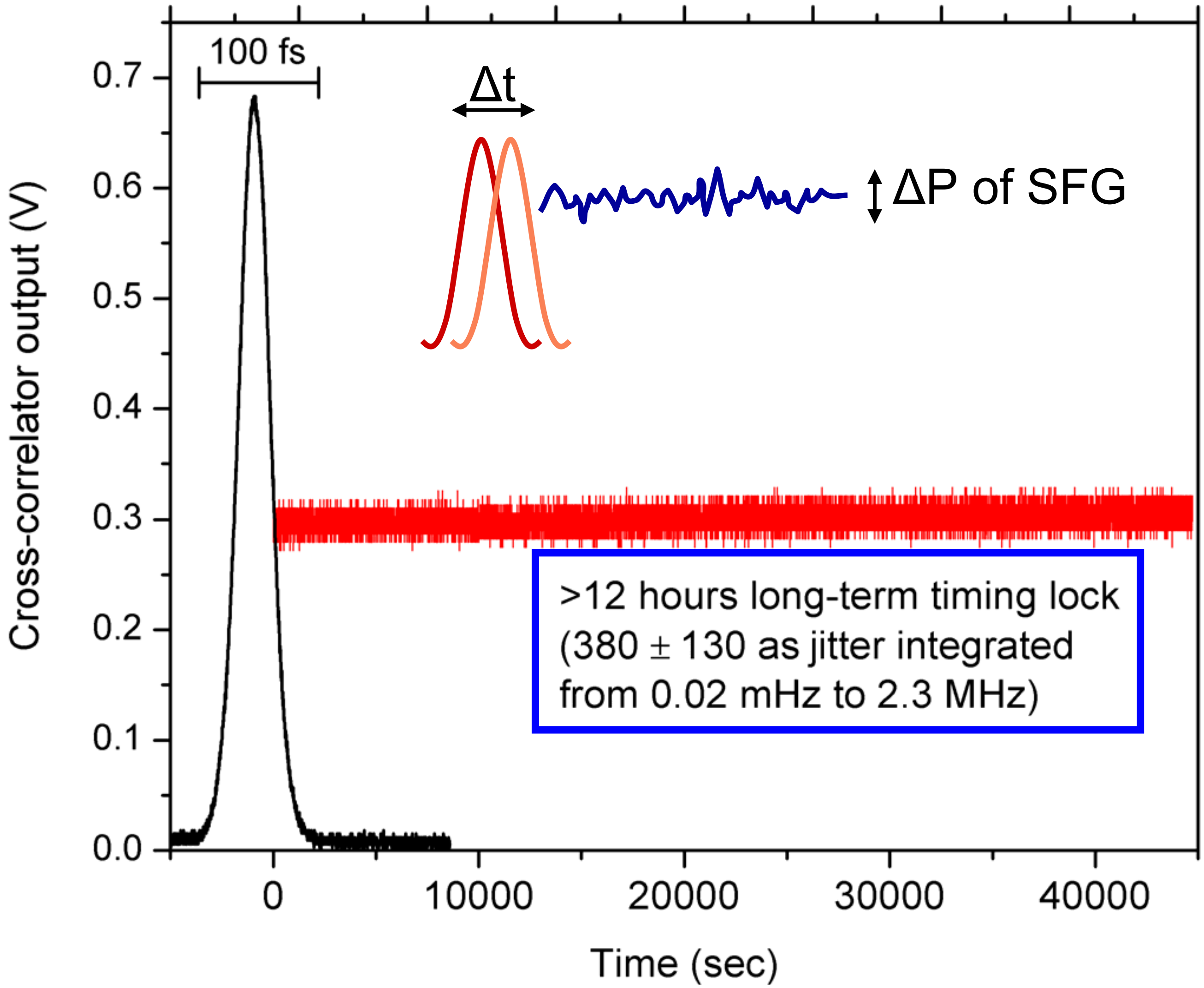
Balanced Optical Cross-Correlation



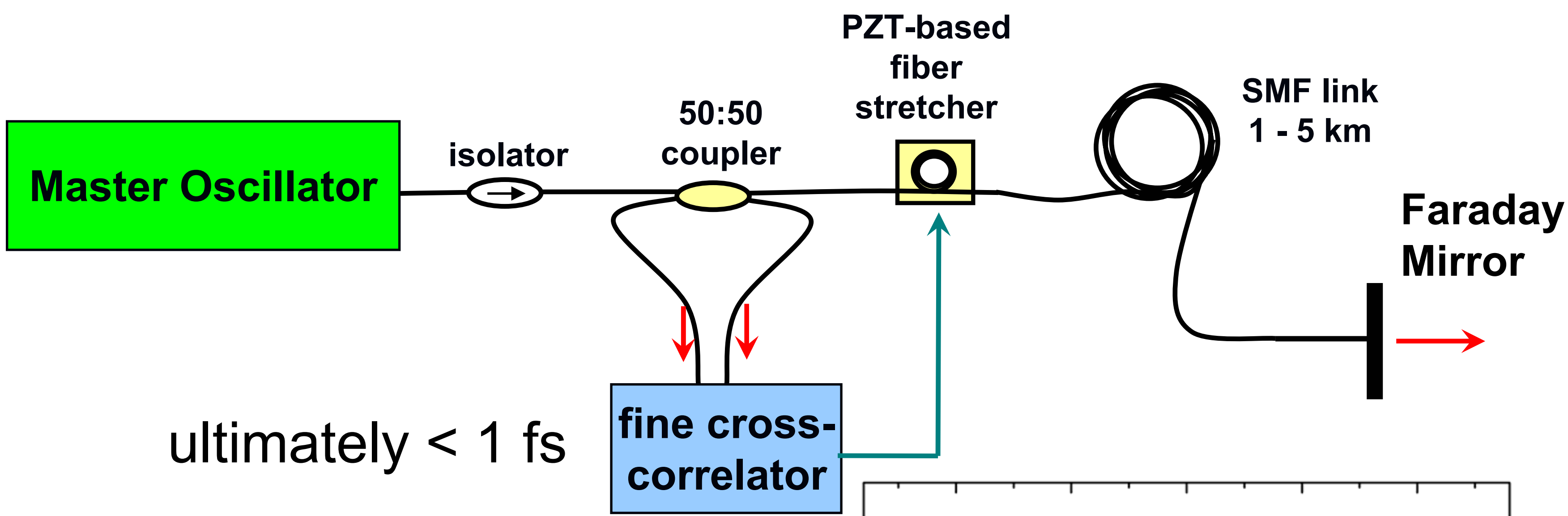
T. Schibli et al, Opt. Lett. **28**, 947 (2003).

Long-Term Locking Between Two Lasers

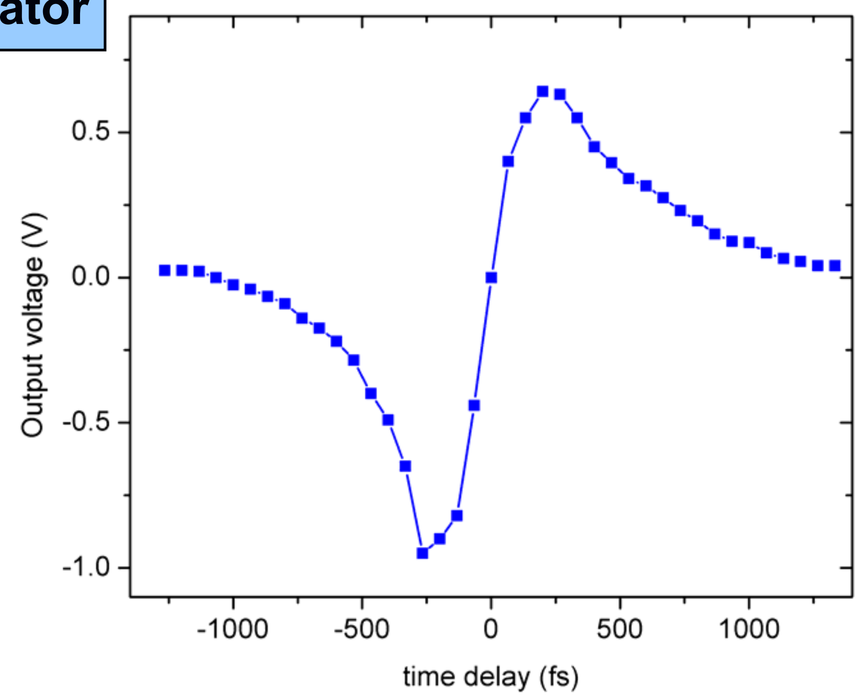
(Out-of-Loop Measurements)



Timing Stabilization with Cross-Correlators



ultimately < 1 fs



Currently working on a simplified and self-aligned cross-correlator

Long-term (> several hours) stabilization will be possible.

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. (short-term ~10 fs → long-term <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 → long-term <1 fs)
- **Optical-to-optical synchronization**: Balanced optical cross-correlation. Long term stable sub-femtosecond precision is already achieved. (<1 fs)

(Sub-)femtosecond timing synchronization and stabilization for 4th generation light sources can be accomplished.