# Large Scale Femtosecond Timing Distribution and RF-Synchronization

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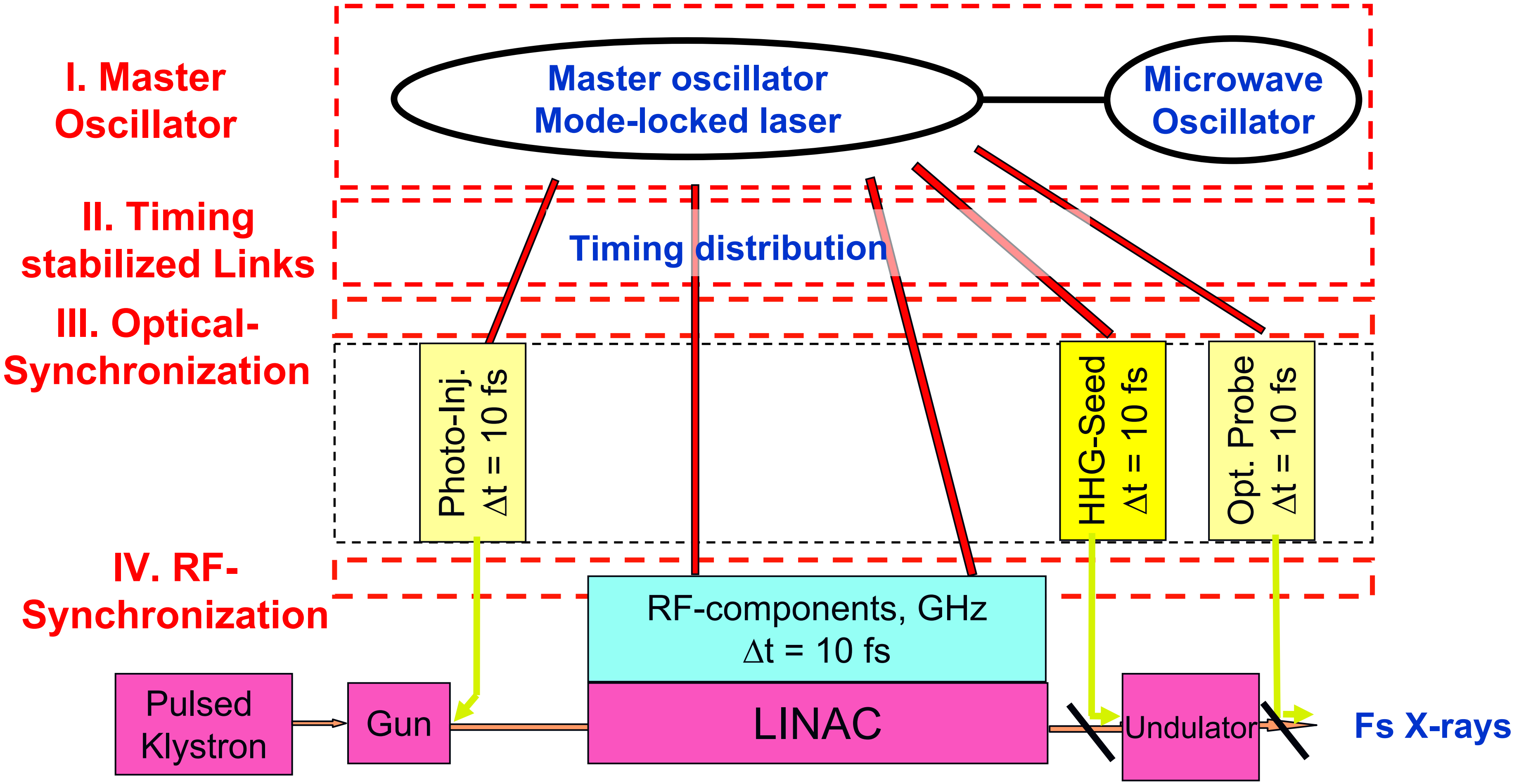
Supported by DESY, FERMI-Trieste, MIT-Bates Laboratory & ONR

# 4th Gen. 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, ?

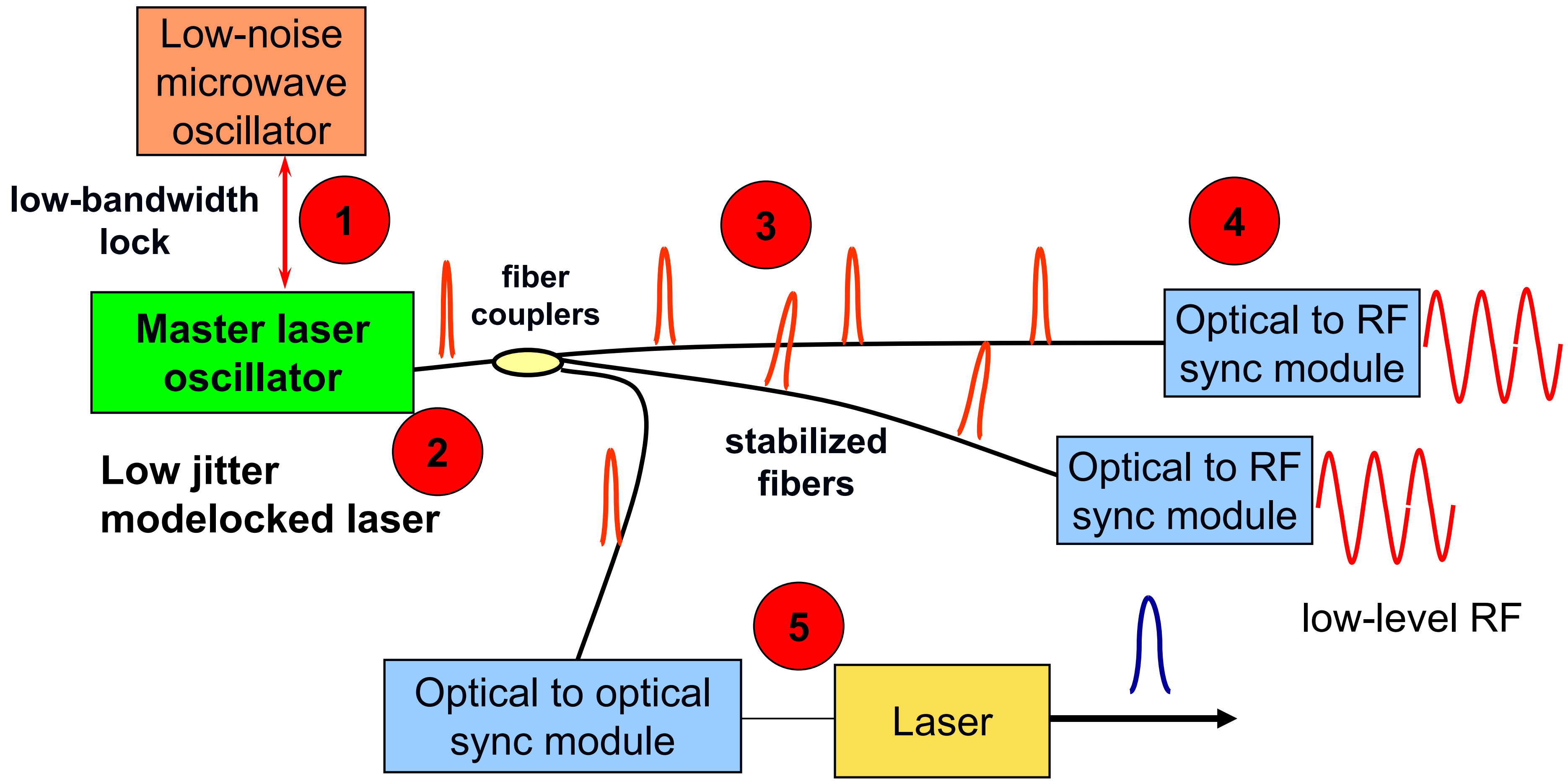
  → Scalability to these levels should be possible!

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

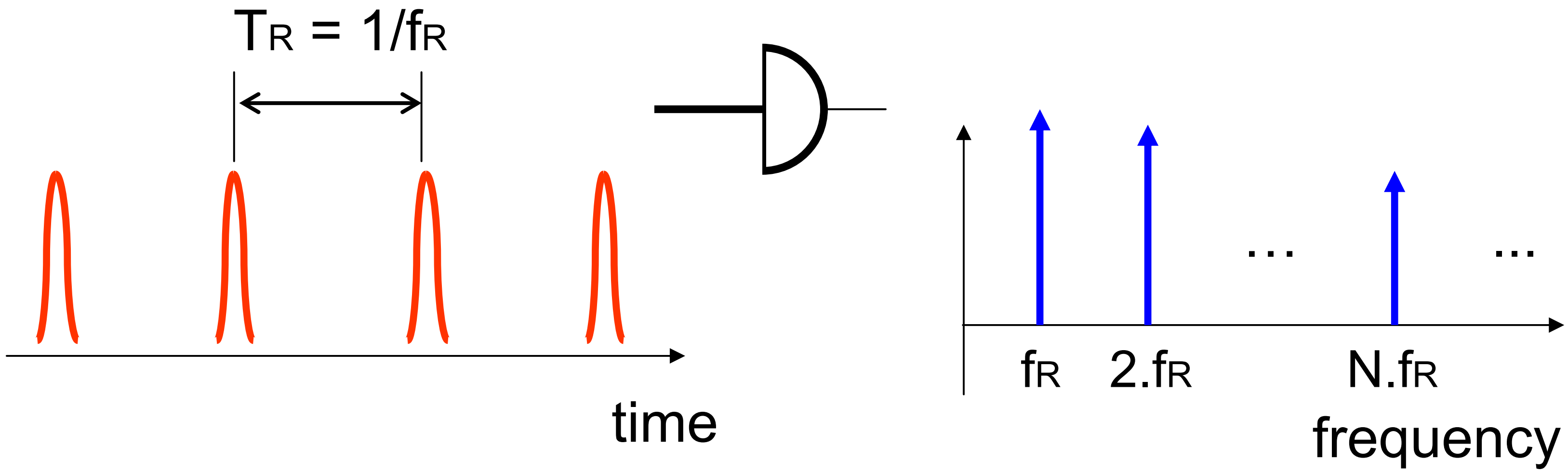
- This is beyond what a direct RF-distribution system (coaxial cables) can handle
  - thermal drifts of coaxial cables
  - drifts of microwave mixers
  - etc.

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

# Synchronization System Layout



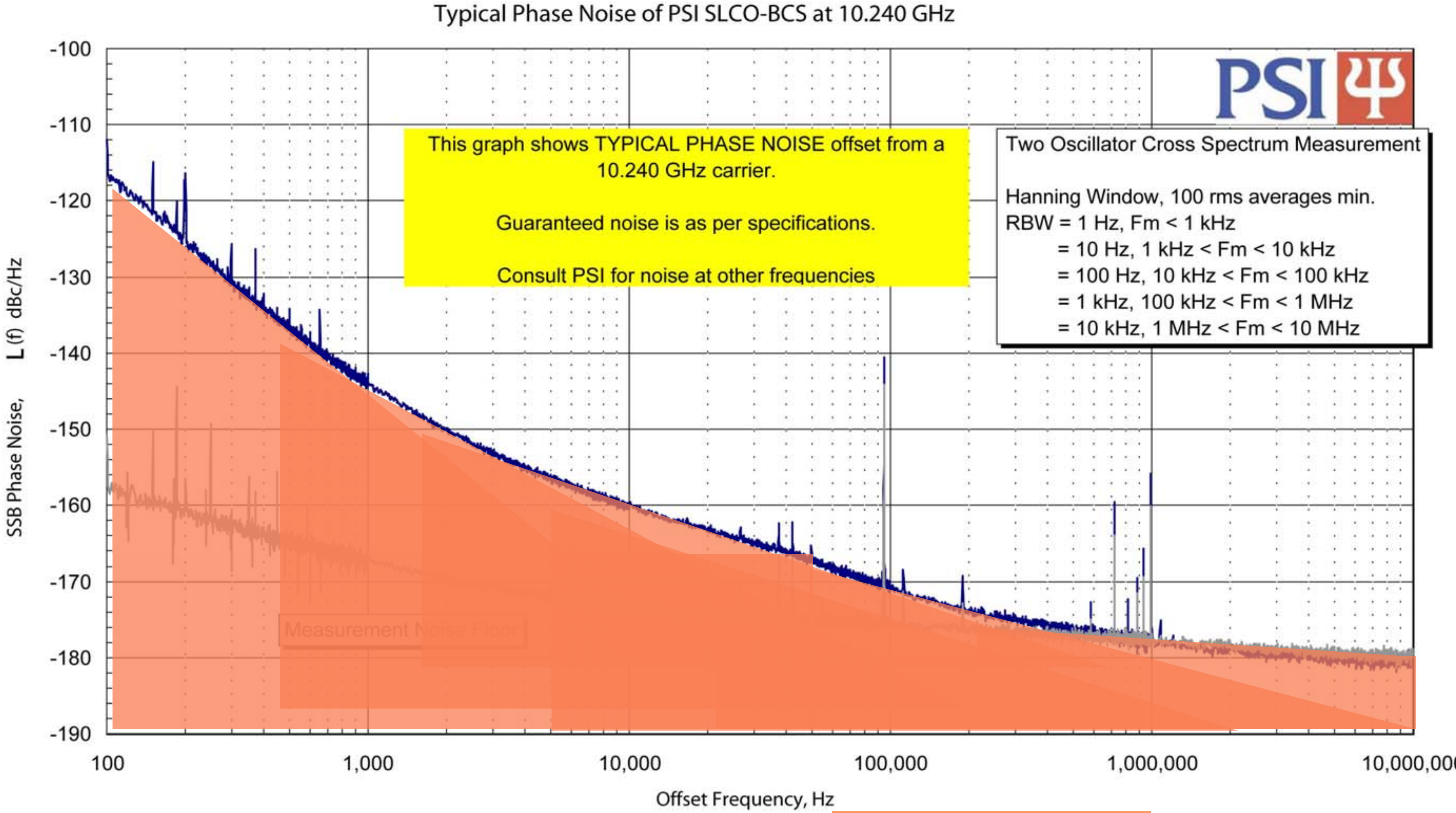
# Why Optical Pulses (Mode-locked Lasers)?




- RF is encoded in pulse repetition rate, every harmonic can be extracted at the end station.
- Suppress Brillouin scattering and undesired reflections.
- Optical cross correlation can be used for link stabilization or for optical-to-optical synchronization of 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 $1^0$C, $\tau_{phase}$-$\tau_{group}$> 10fs, Polarization Mode Dispersion: 0.01-0.1ps/Sqrt[km])

# Highly Stable Microwave Oscillator

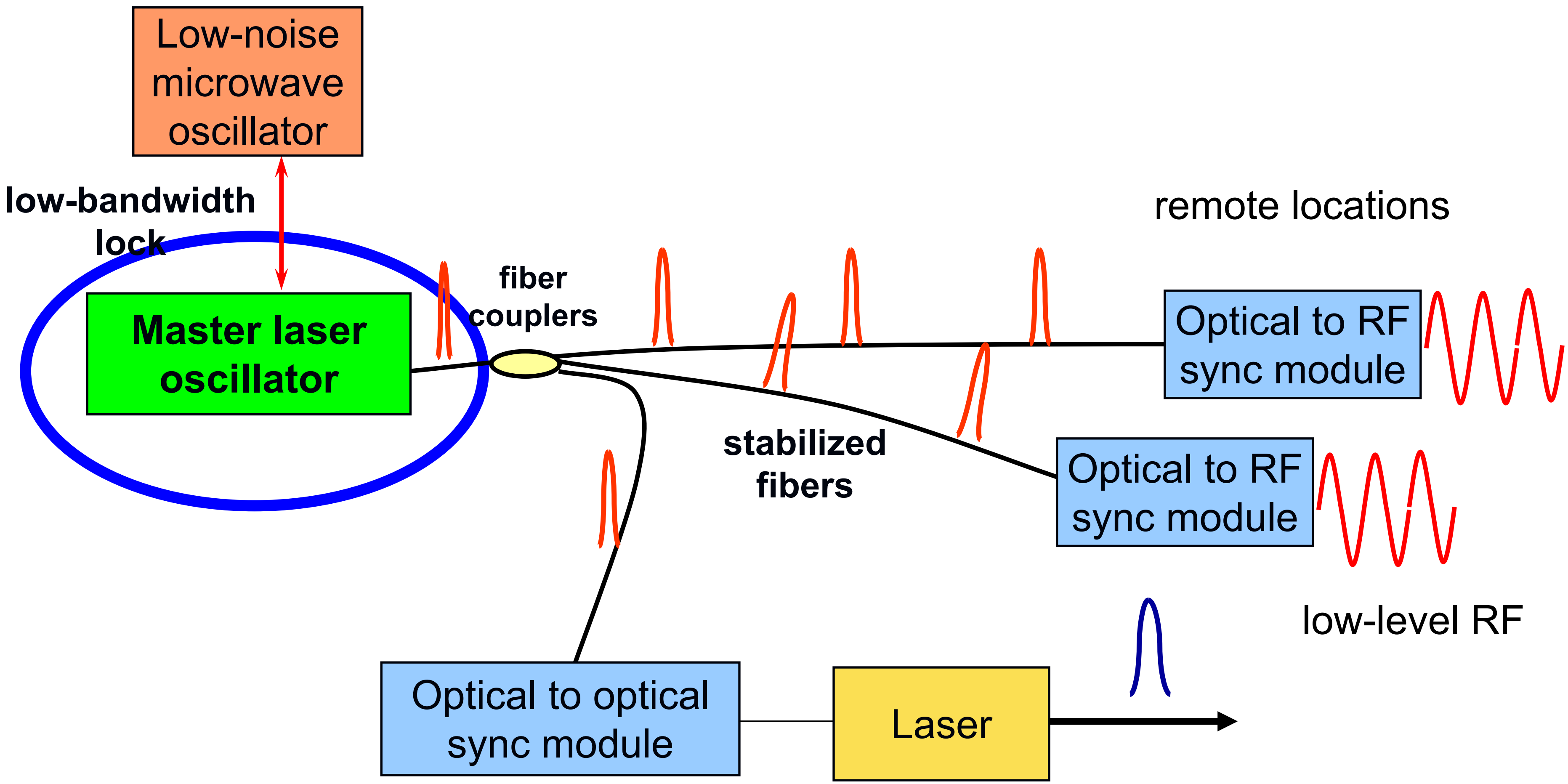
# Microwave Master Clocks




Timing jitter: $$\Delta t_{rms} = \frac{\sqrt{2\int_{f_1}^{f_2} L(f)df}}{2\pi f_0}$$ < 1fs

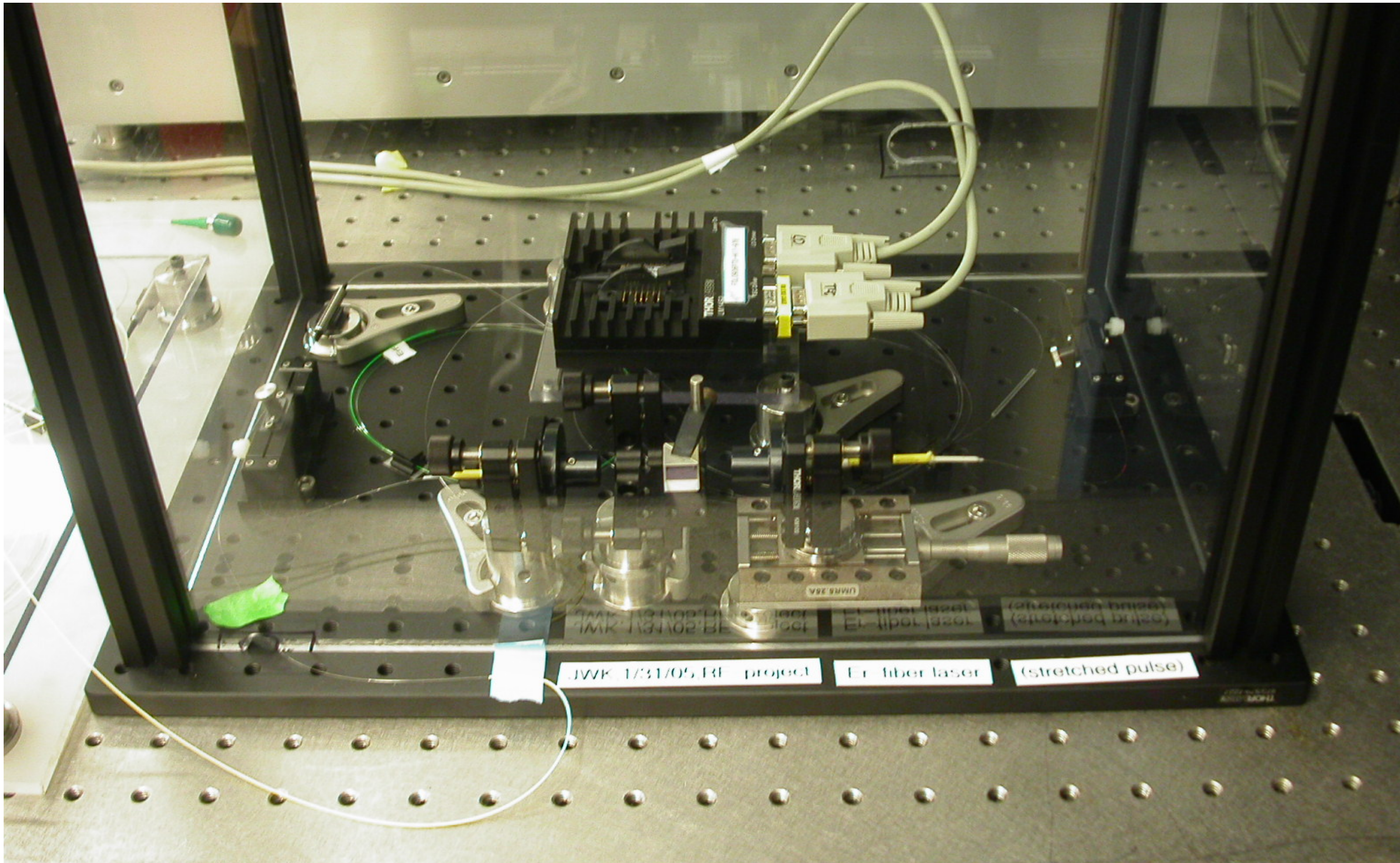
# Optical Master Oscillator

A master mode-locked laser producing a very stable pulse train

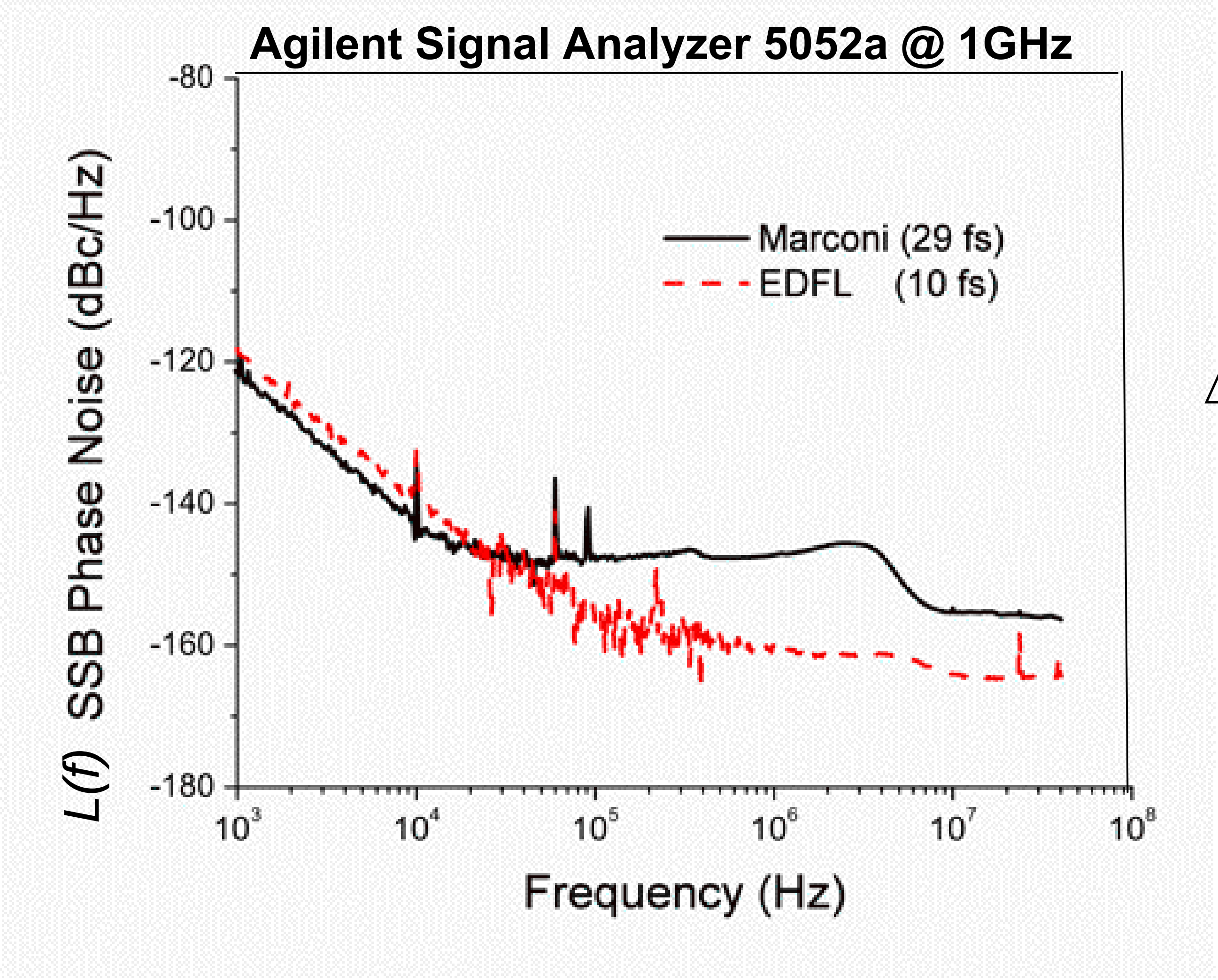


# Er-Fiber Laser

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



# Phase Noise (Timing Jitter) Measurements




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

$\Delta t_{rms}[10kHz,22MHz] = 10fs$

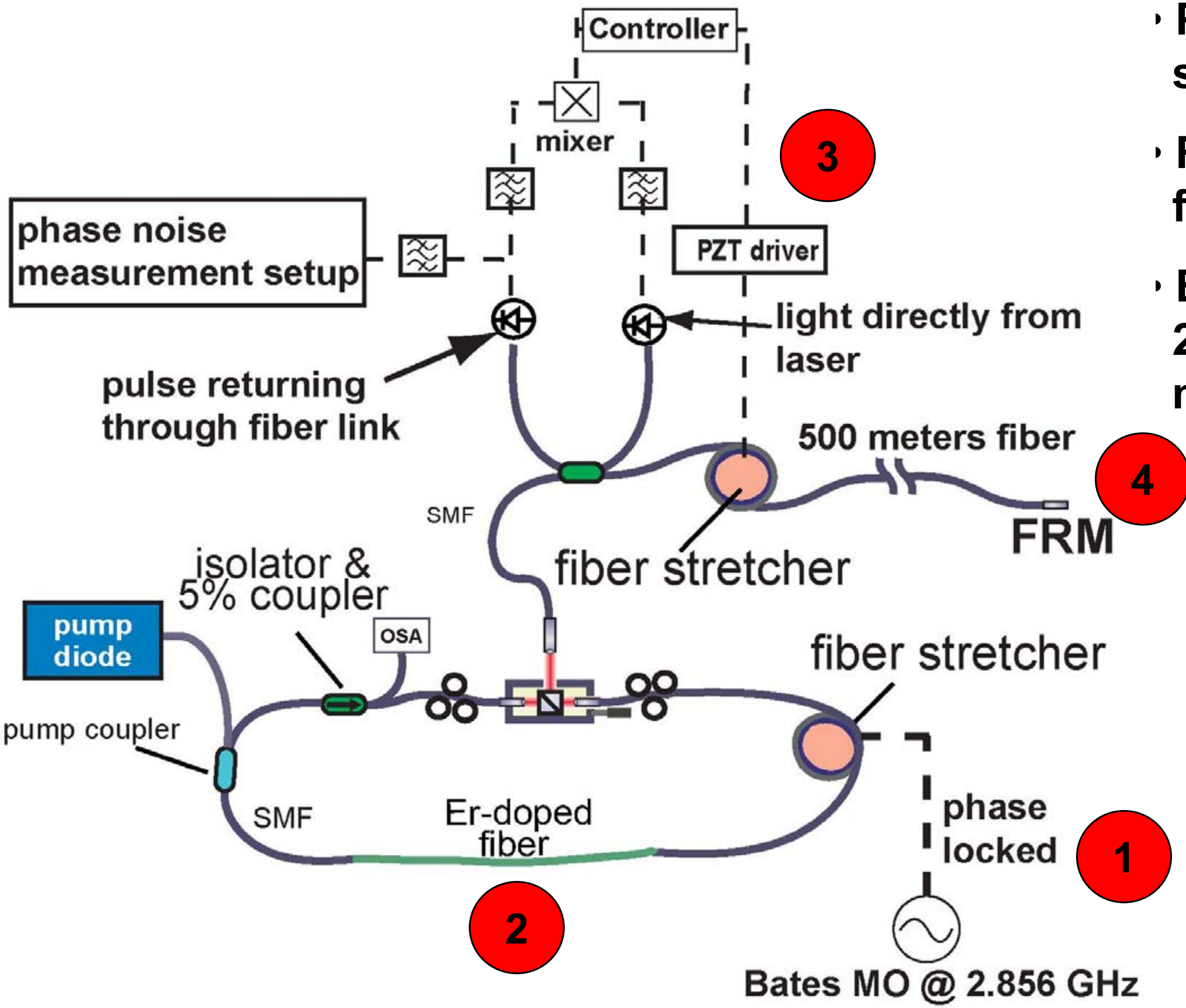
$f_0 = 1.3GHz$

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

# System Test in Accelerator Environment

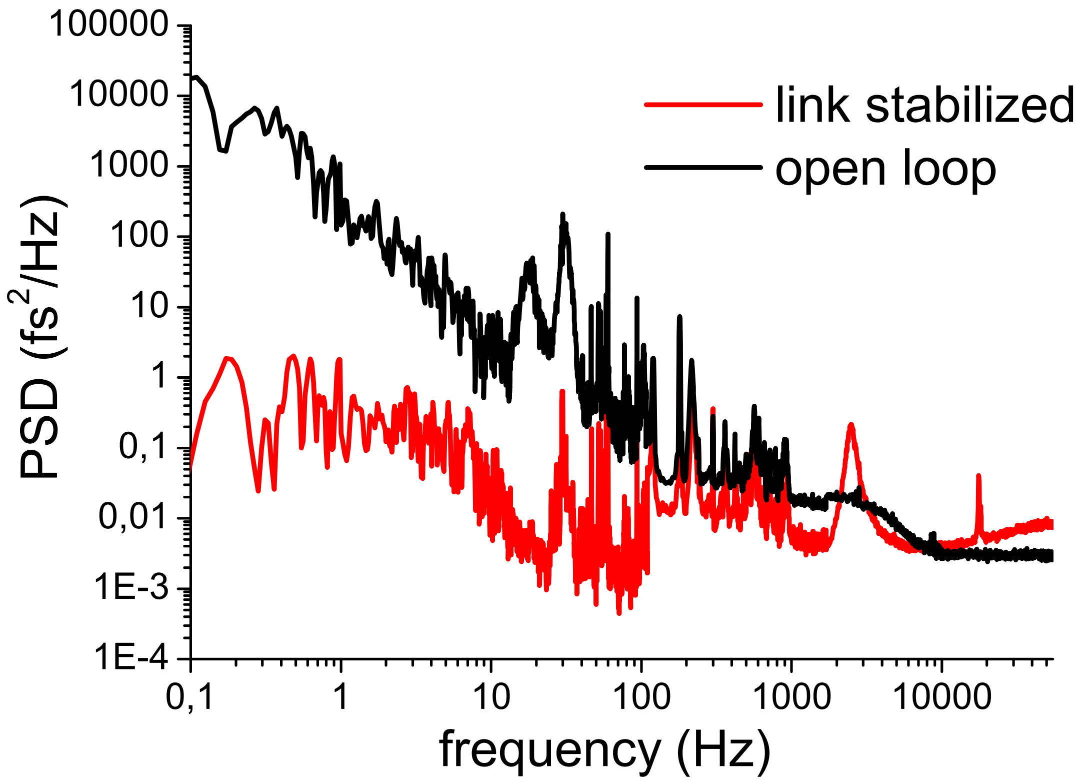
- Test done at MIT Bates Laboratory:
  - Locked EDFL to Bates master oscillator
  - Transmitted pulses through 400 meter partially temperature stab. fiber link
  - Close loop on fiber length feedback

# 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

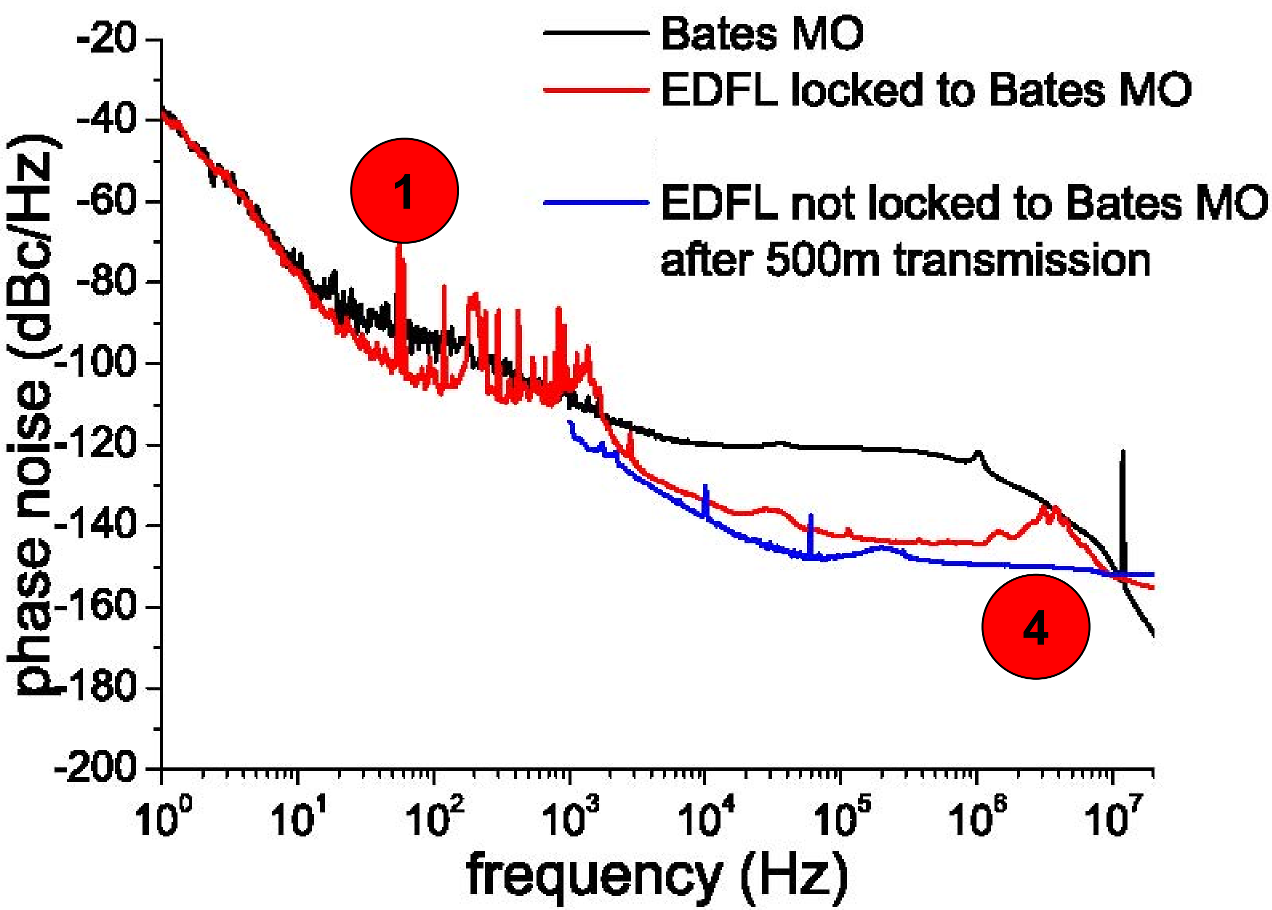
# Jitter: Timing Stabilized Fiber Link




- Fiber link extremely stable without closing 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

**(2-4) jitter: < 22 fs**

# Phase Noise (Jitter) of Transmitted Signal

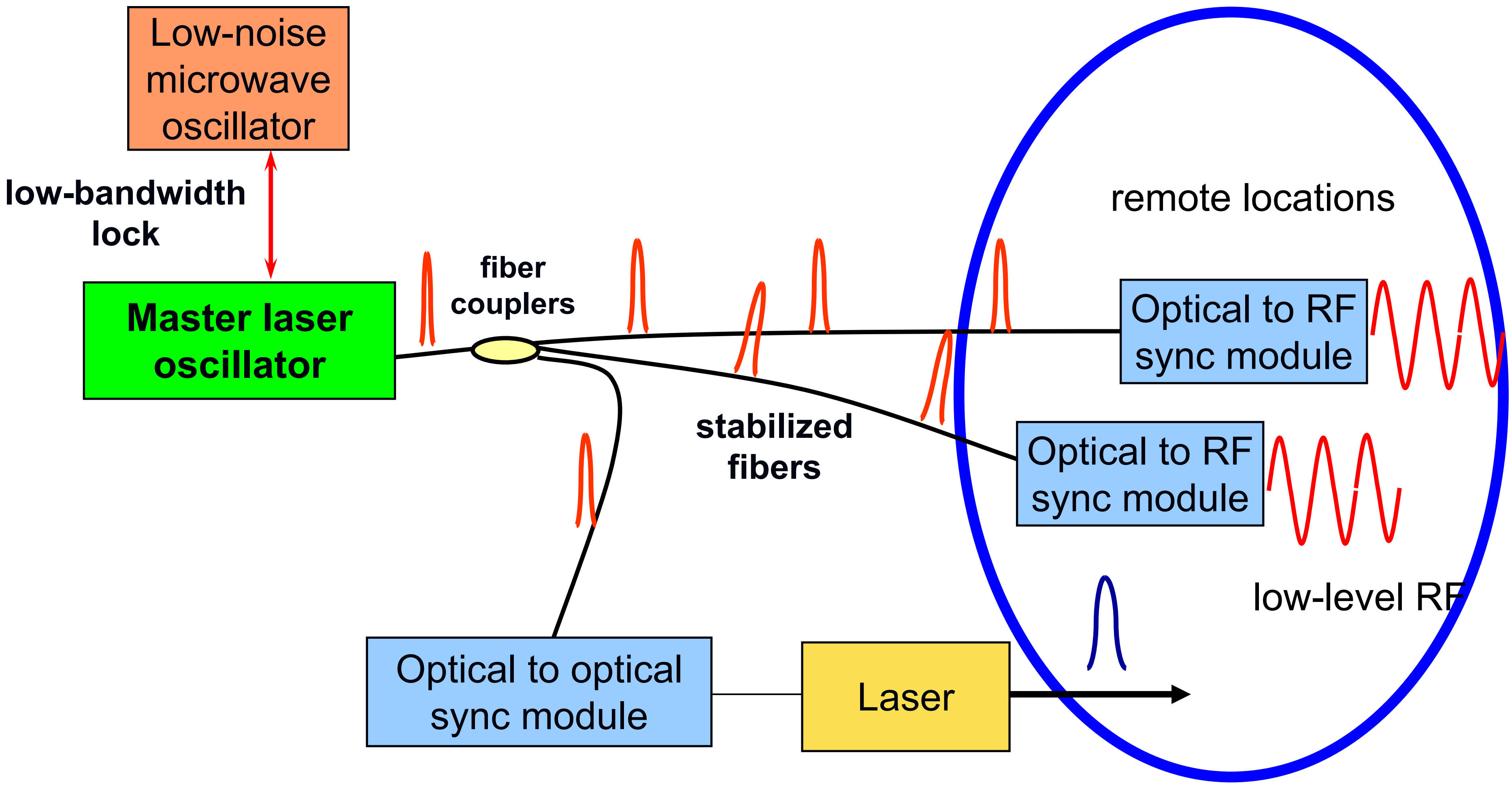



- Jitter between Bates MO and optical master laser ~30 fs (10 Hz..2 kHz)
- Jitter added by Link < 22fs
- Total jitter added (1- 4 ) < 52 fs

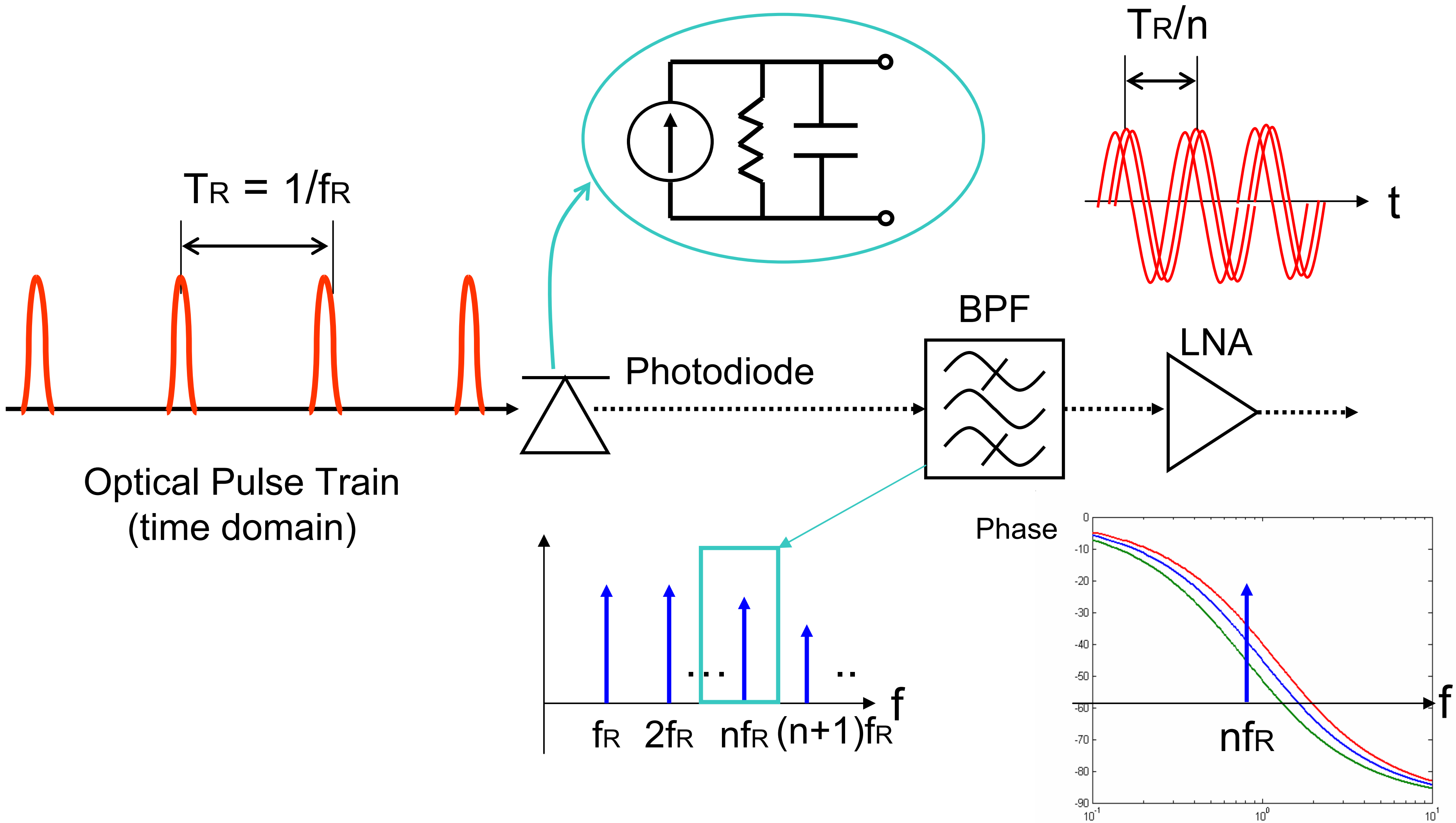
## How to improve on these results and make it long term stable?

## Transition from microwave to optical techniques

# Optical to RF-Conversion



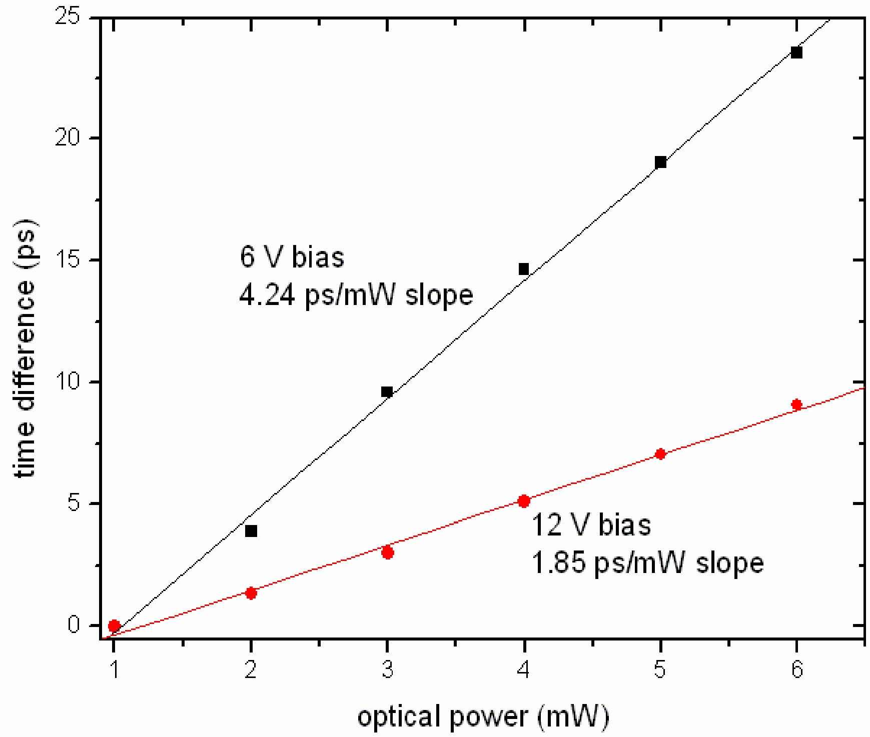
# Direct Extraction of RF from Pulse Train




Amplitude-to-phase conversion introduces excess timing jitter.

E.N. Ivanov et al., IEEE JSTQE **9**, 1059 (2003)

# 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)
→ $\Delta t_{excess}$~ 5-20 fs

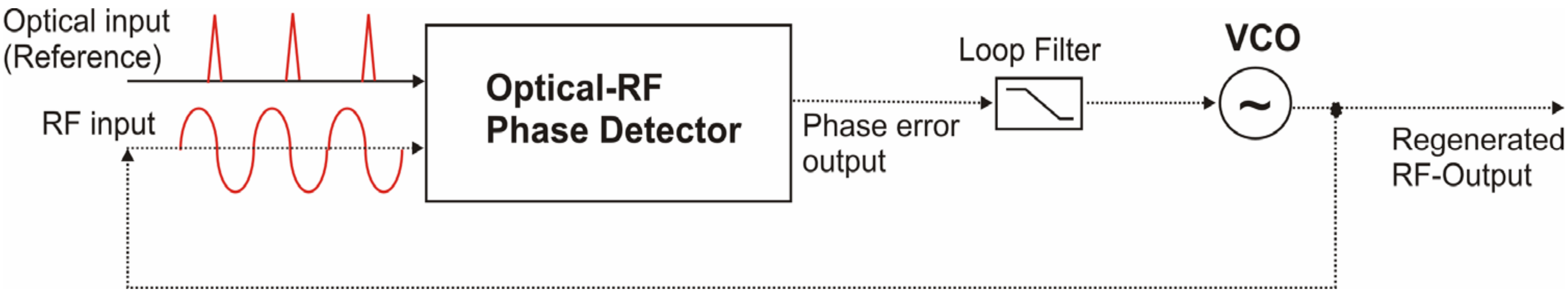
<u>Limitations in direct photodetection</u>

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).

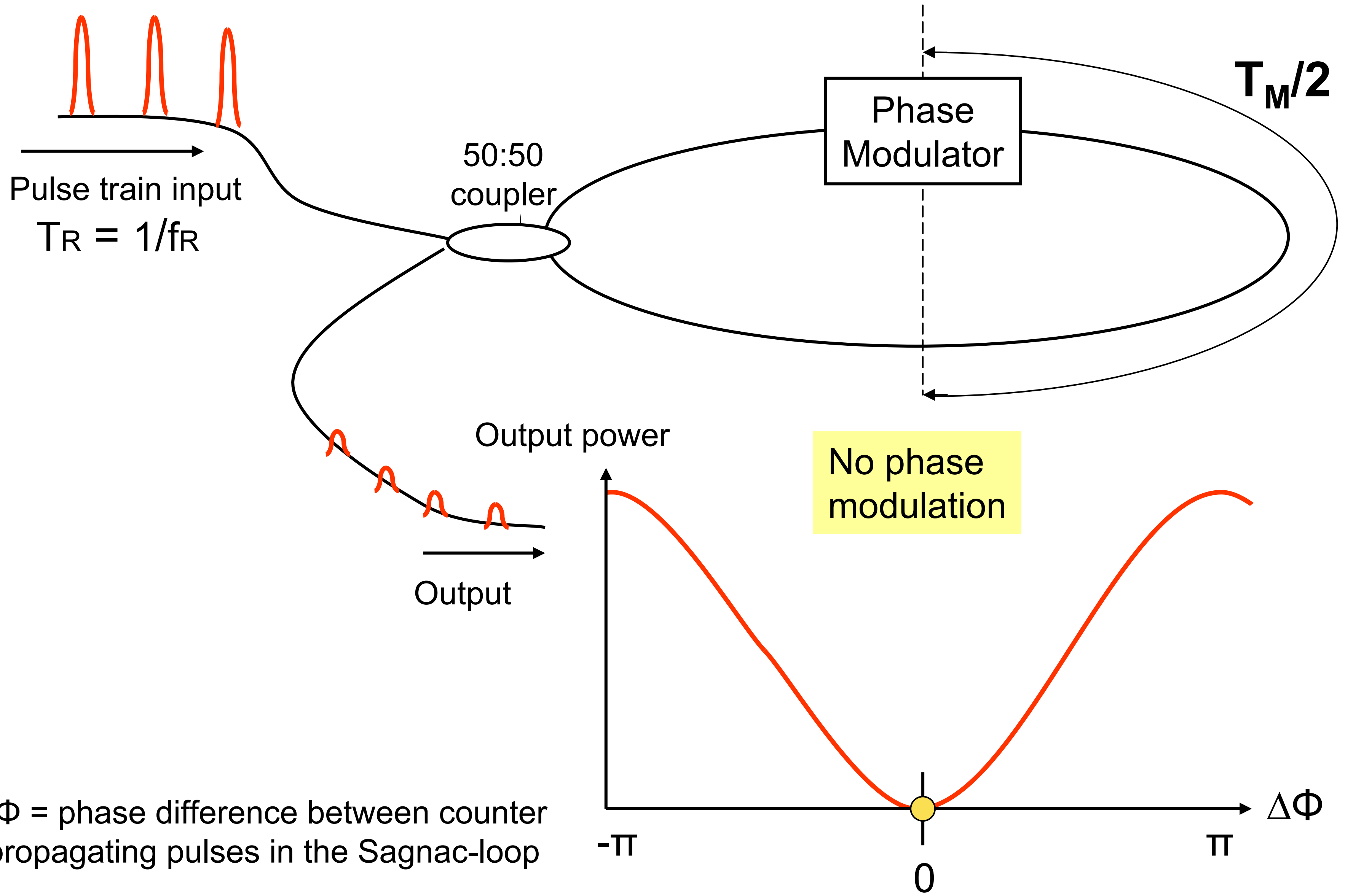
# Optical/Electrical Phase-Locked Loop (PLL)

Can we regenerate a high-power, low-jitter RF-signal
whose phase is locked long term stable 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

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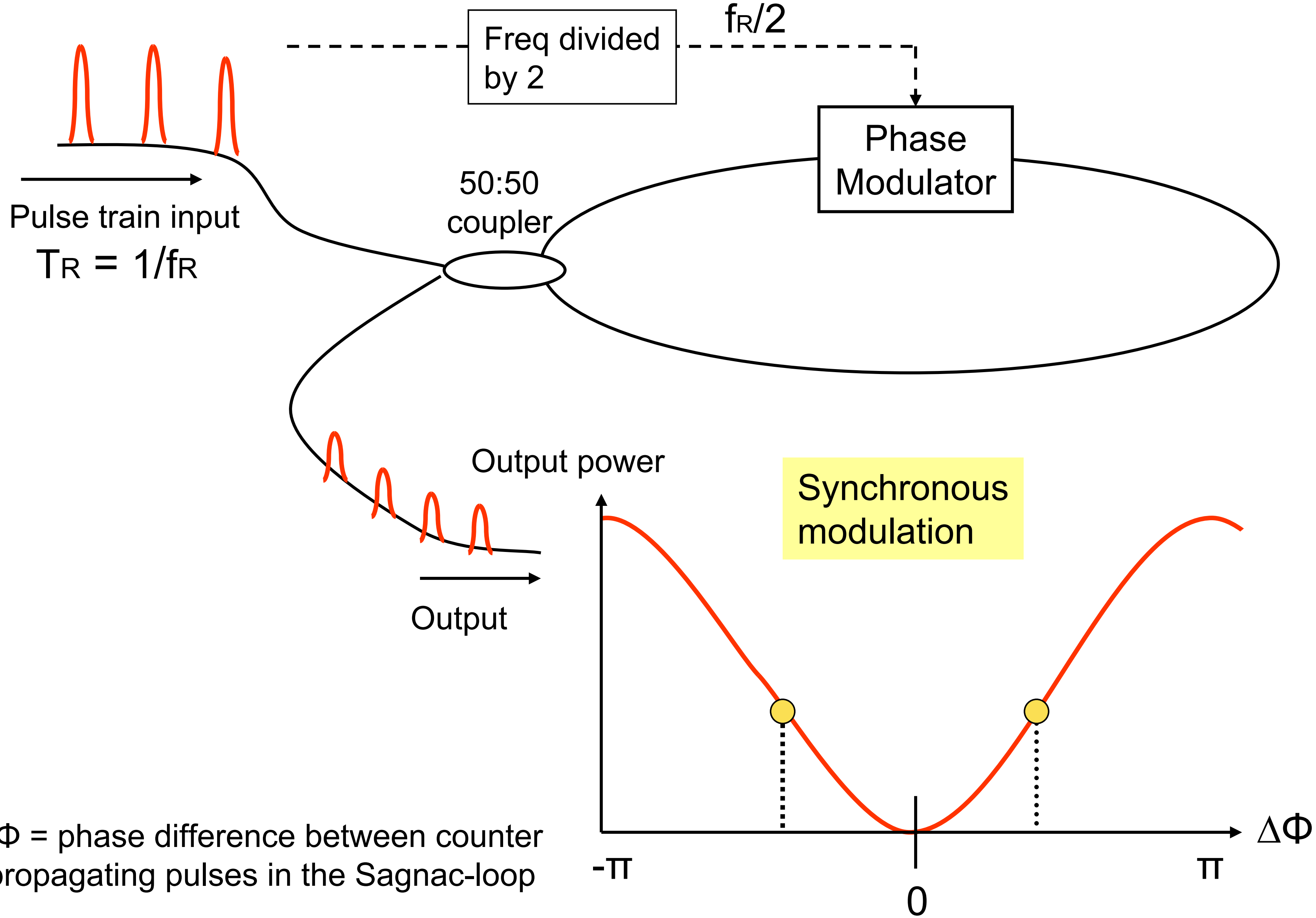


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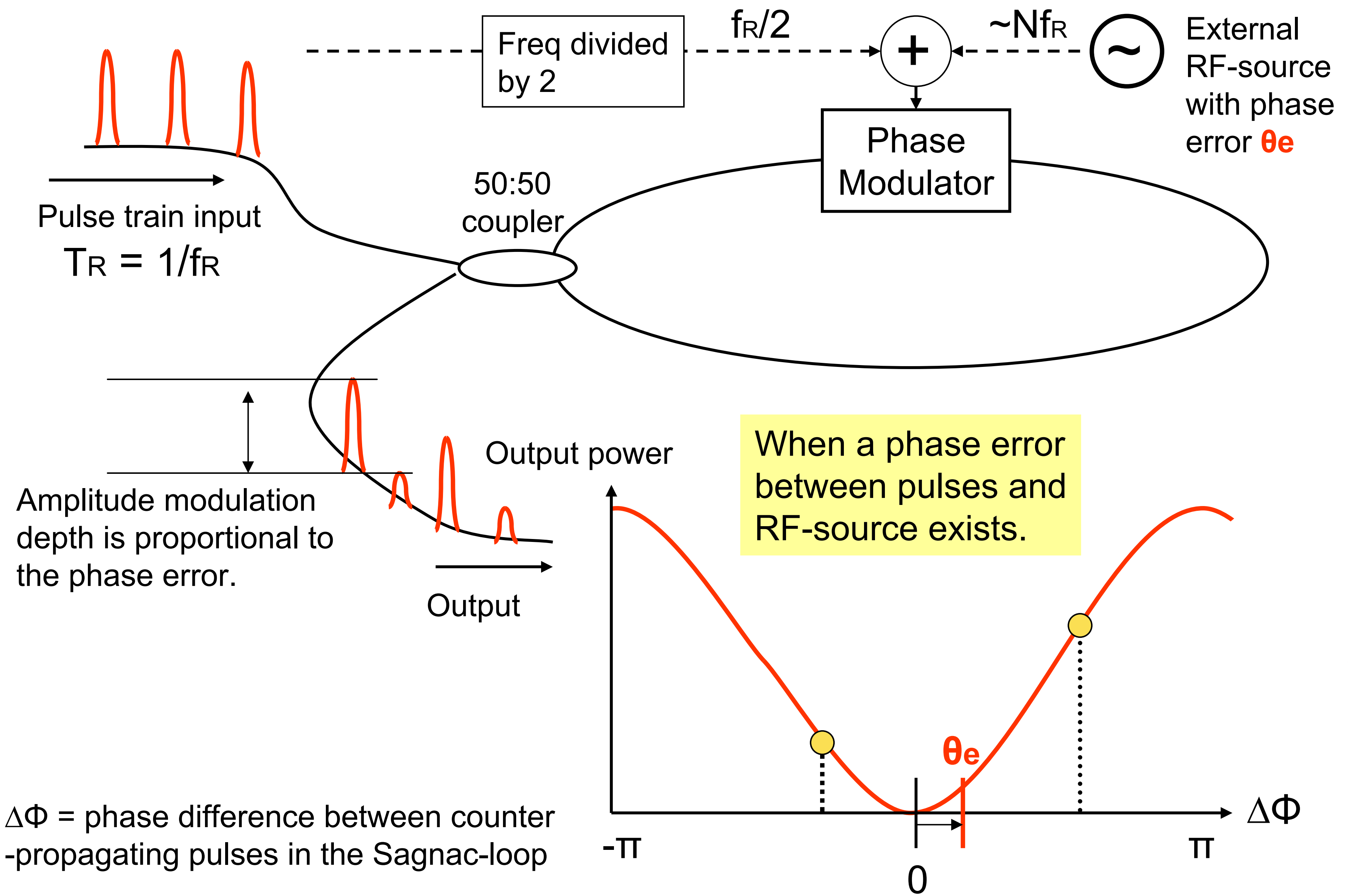

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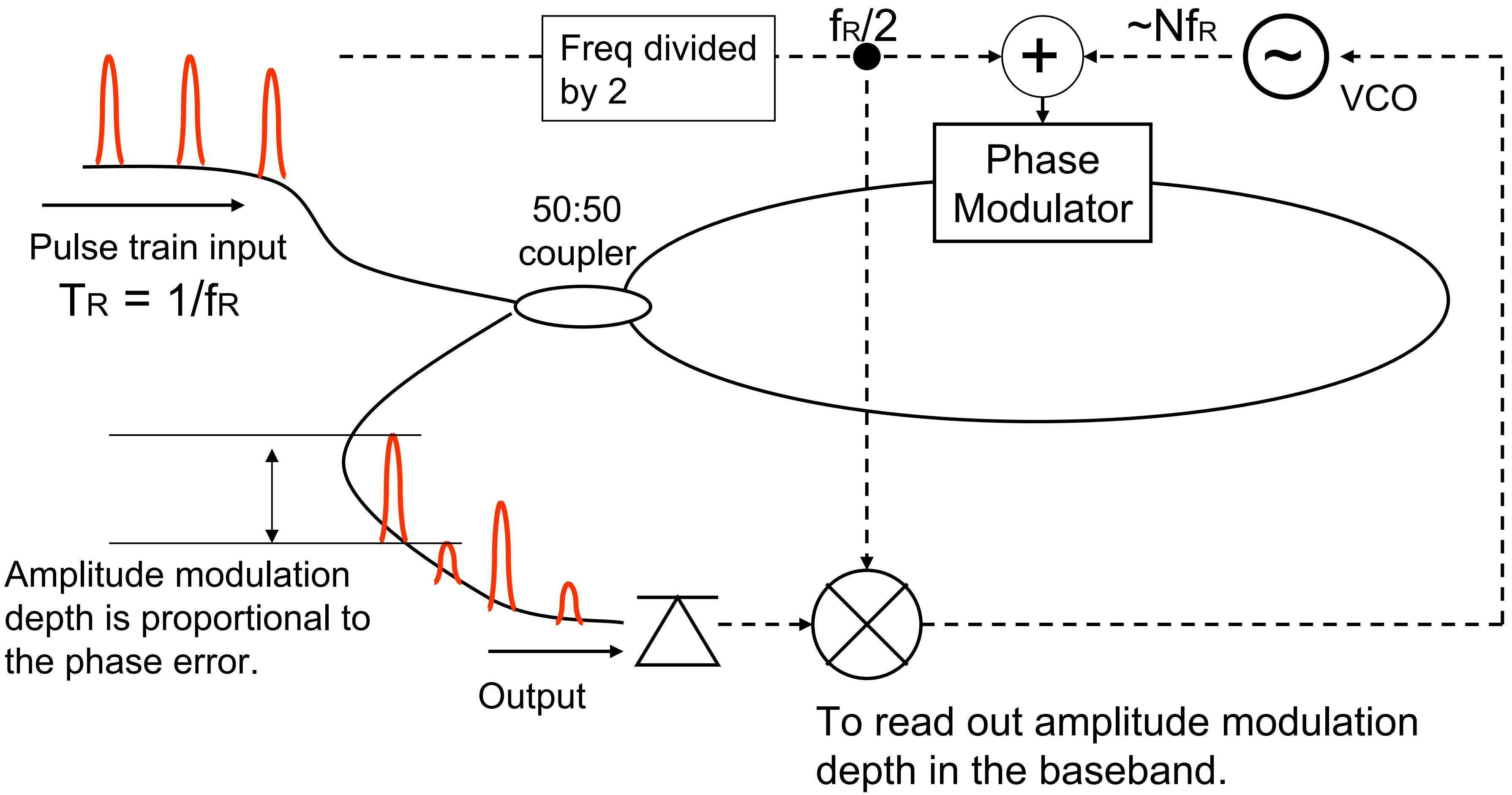

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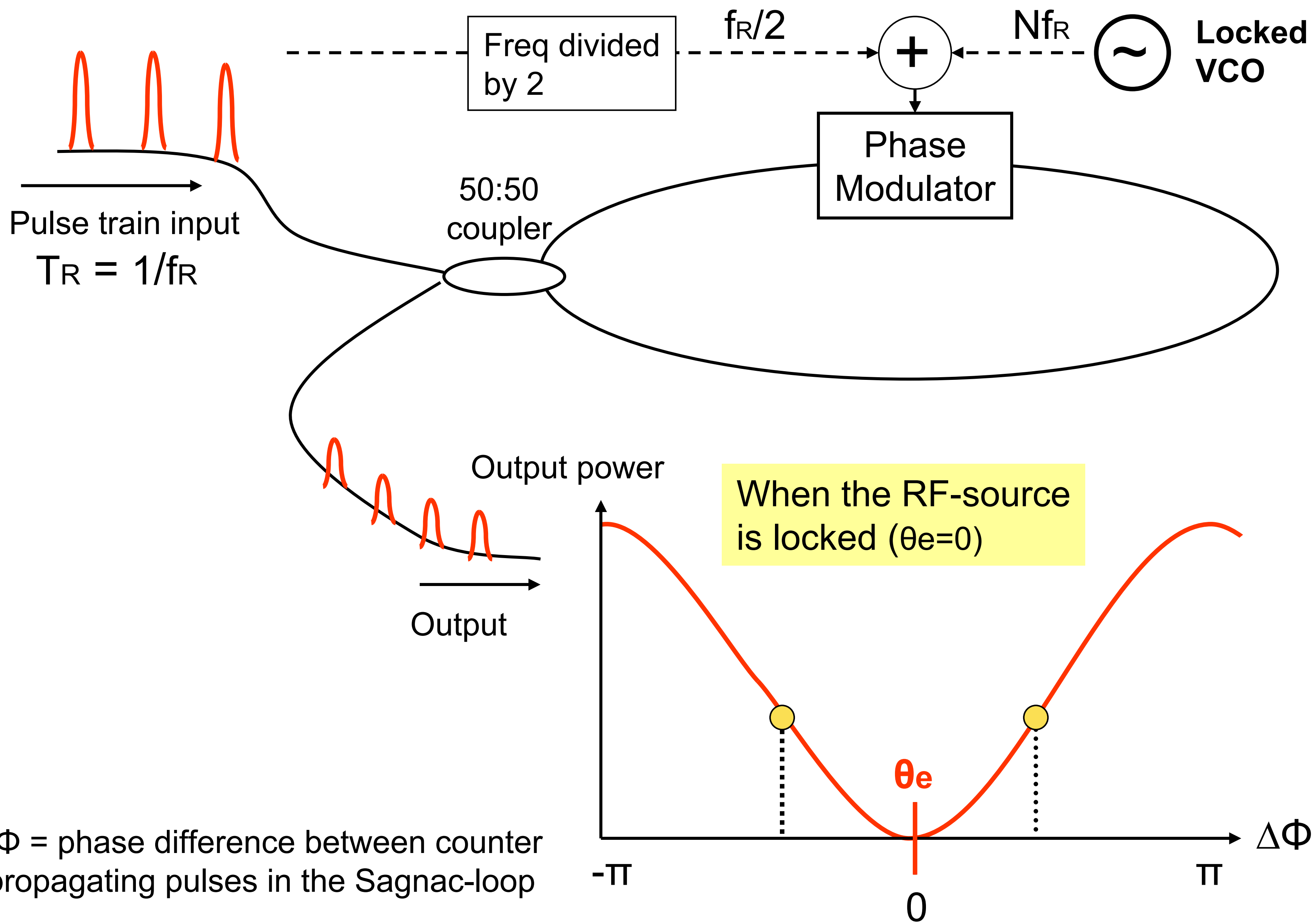
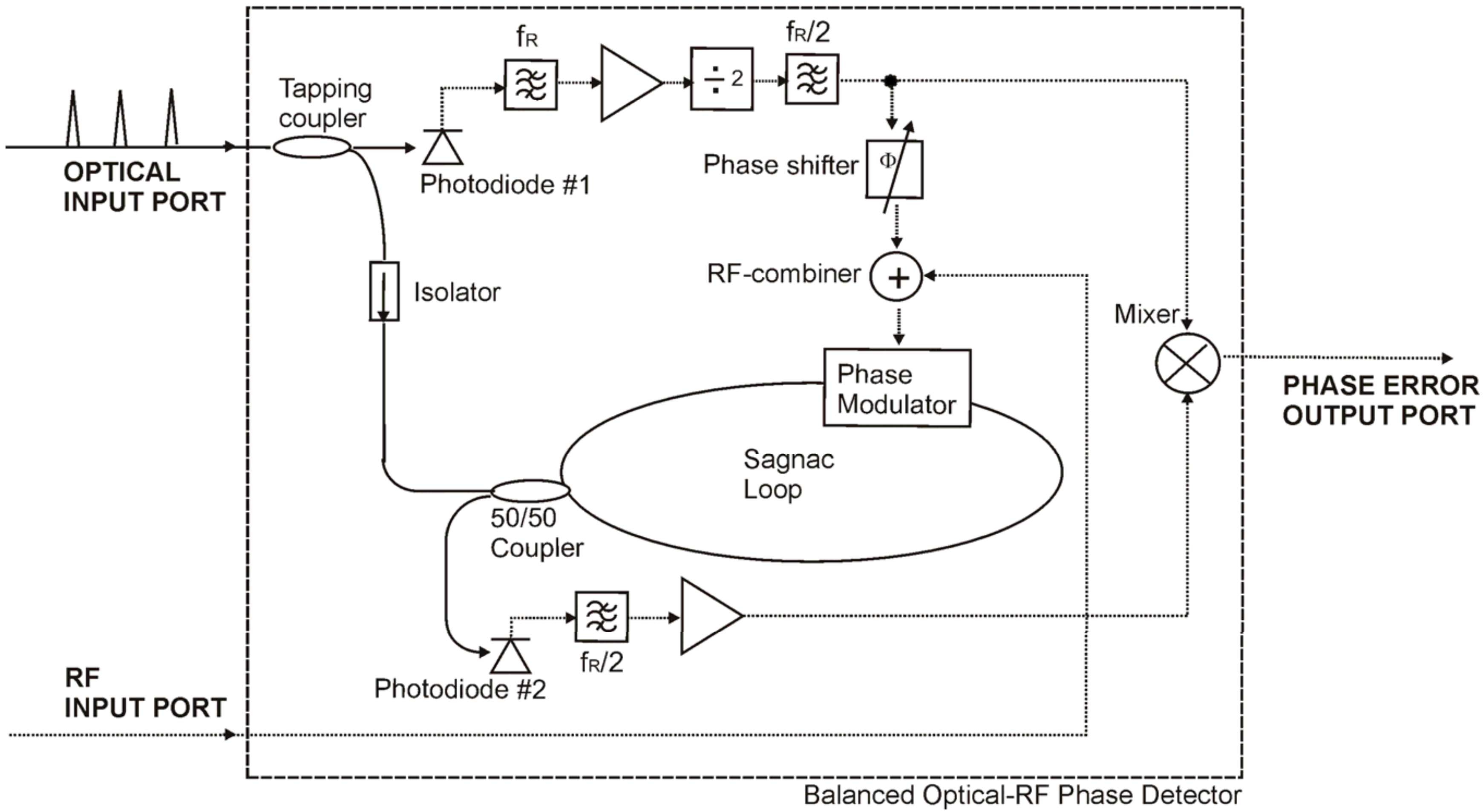


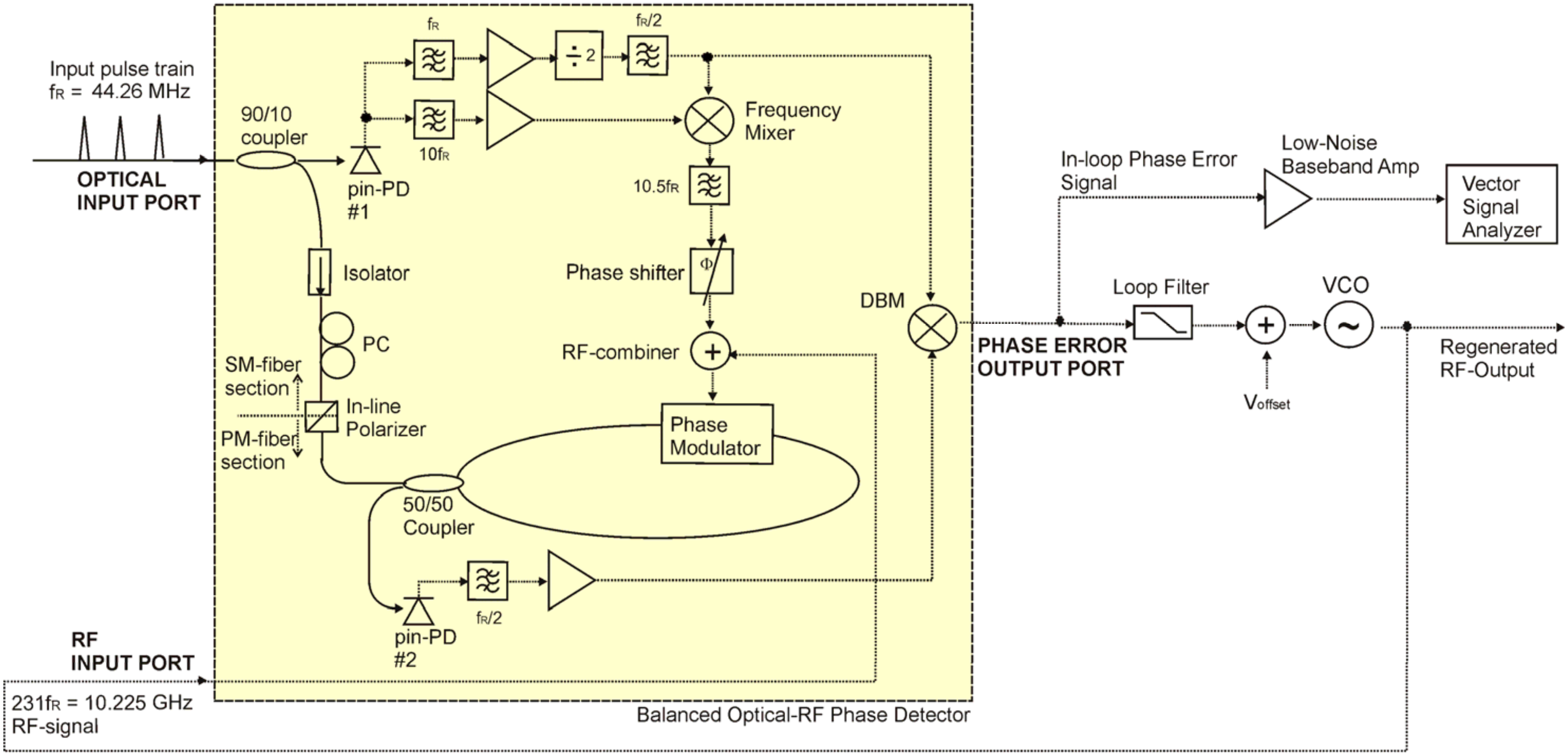

ΔΦ = phase difference between counter -propagating pulses in the Sagnac-loop

# Balanced Optical-RF Phase Detector

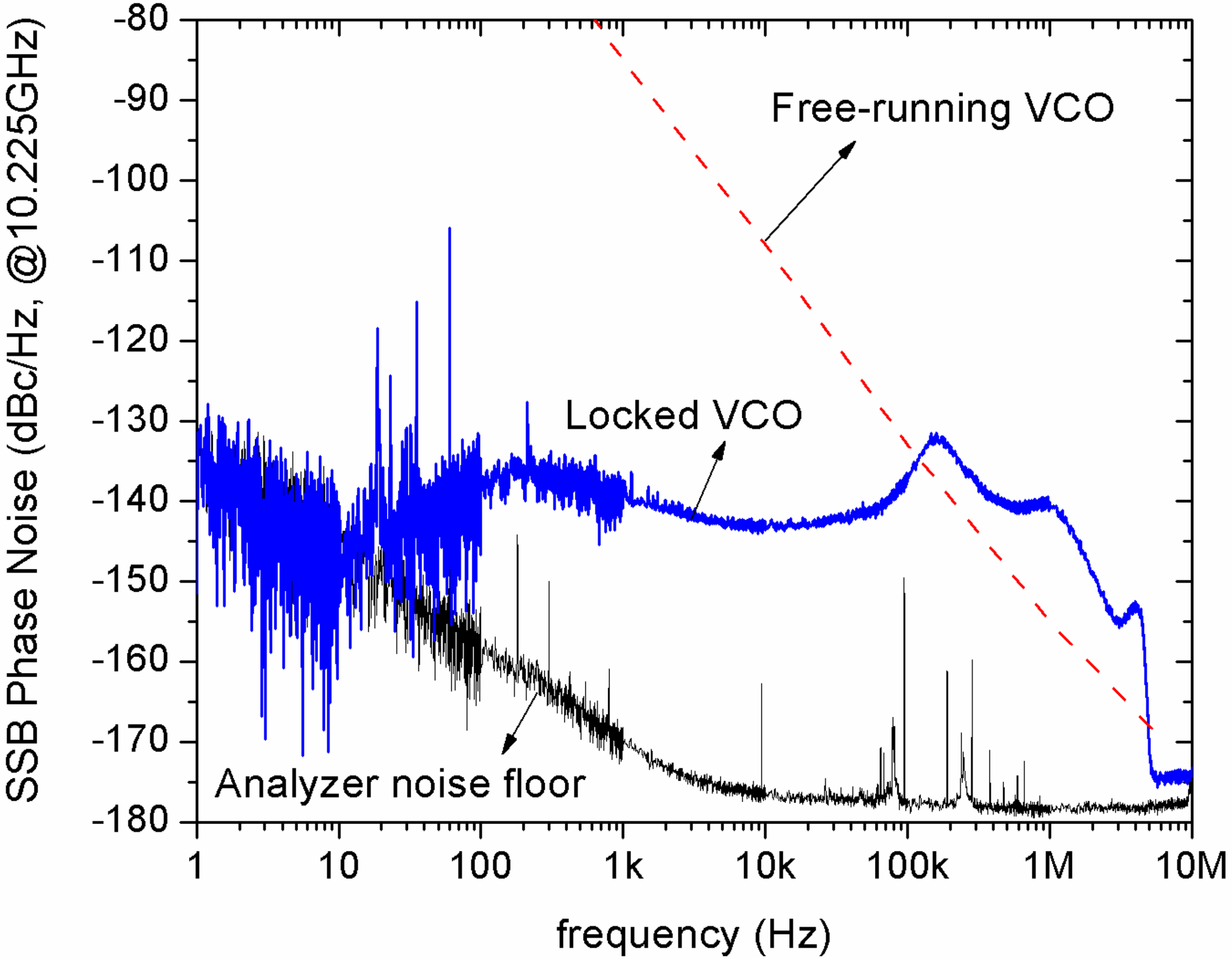



- Capable of driving high-power VCO → High-power regenerated RF-signal
- Scalable phase detection sensitivity → Low-jitter synchronization
- Fiber-based “balanced” scheme → Long-term drift-free operation

# Demonstration Experiment



# In-Loop Phase Noise Measurement




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

# Scalability in Phase Detection Sensitivity

Scalable Phase Detection Sensitivity

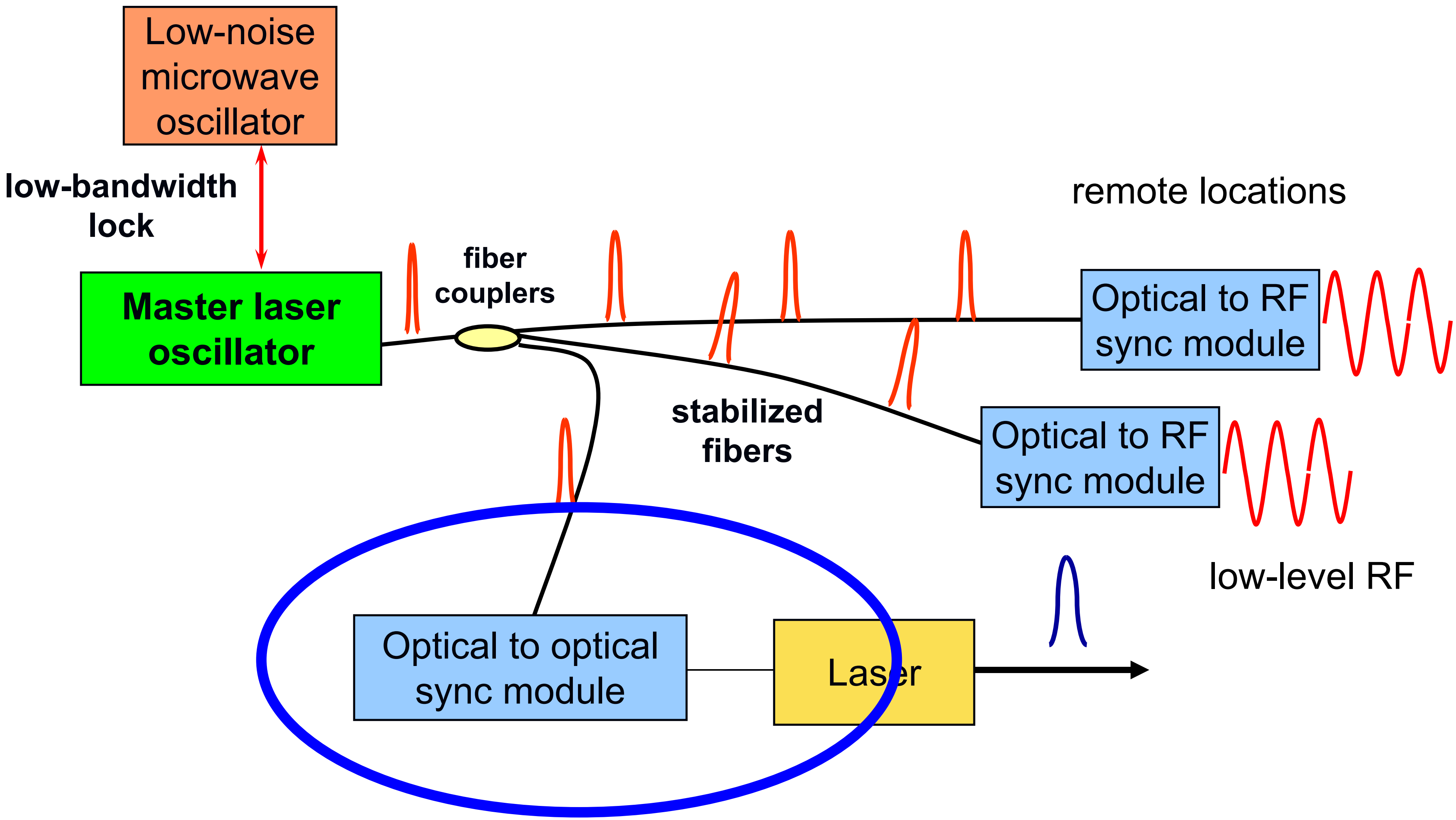
$$K_d = \frac{V_d}{\theta_e} \propto P_{avg} \Phi_0 \Phi_m$$

Shot Noise Floor Scalability

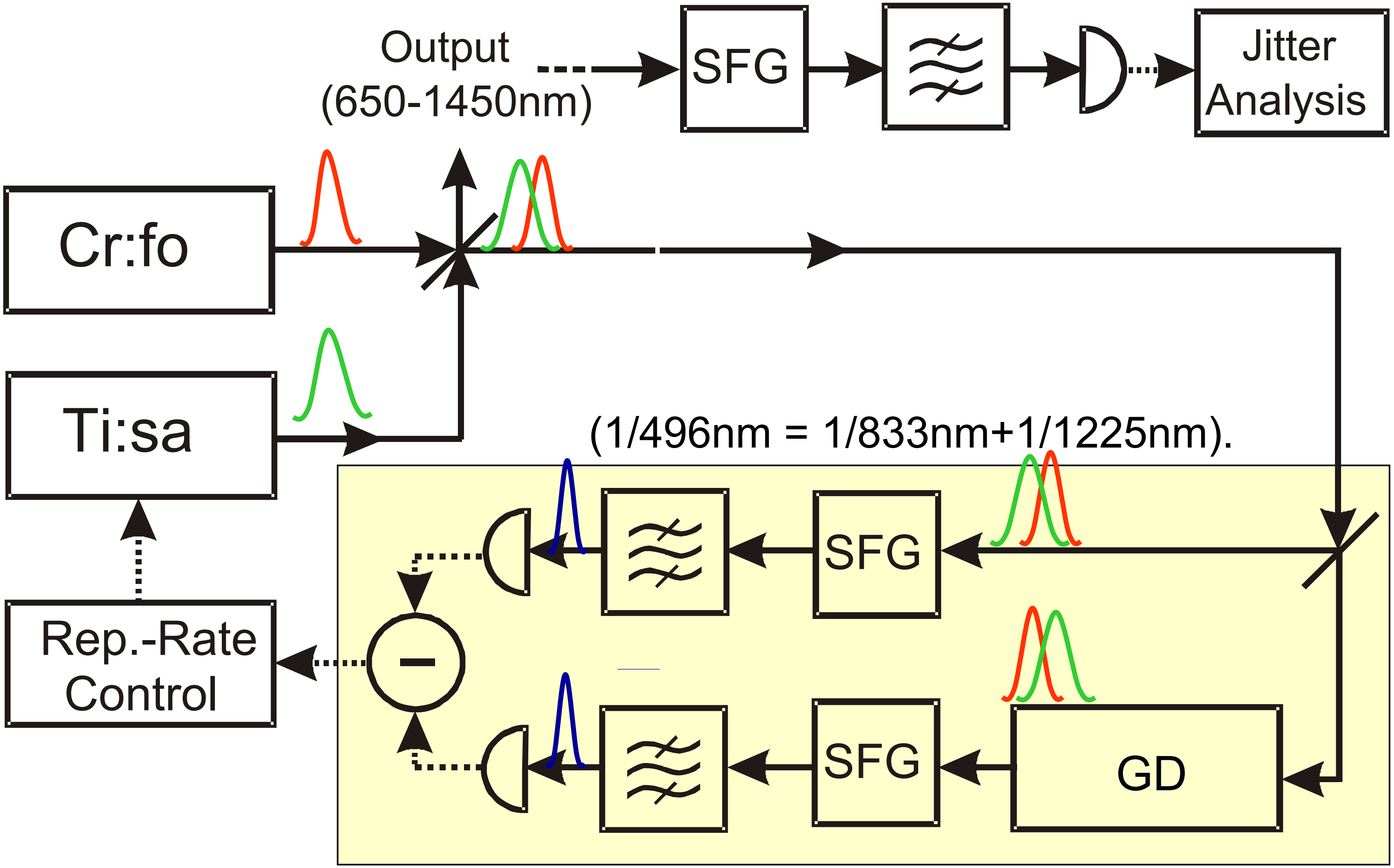
$$S_{\varphi,shot} = \frac{< \overline{V}^2_{shot,mix} >}{K_d^2 / N^2} = \frac{8q}{R P_{avg} \Phi_0^2}$$

| | | |
|---|---|---|
| $P_{avg}$ | Optical power circulating Sagnac-loop | 10 mW |
| $\Phi_0$ | Phase modulation depth from VCO signal | 0.4 rad |
| $\Phi_m$ | Phase modulation depth from synchronous signal | 0.2 rad |
| R | Photodetector responsivity | 0.9 A/W |
| q | Electron charge | $1.6 \times 10^{-19}$ C |
| Shot noise limited jitter = 0.5 fs (currently limited by other noise sources)<br>→ Scalable by increasing optical power and RF modulation depth | | |

# Optical to Optical Synchronization



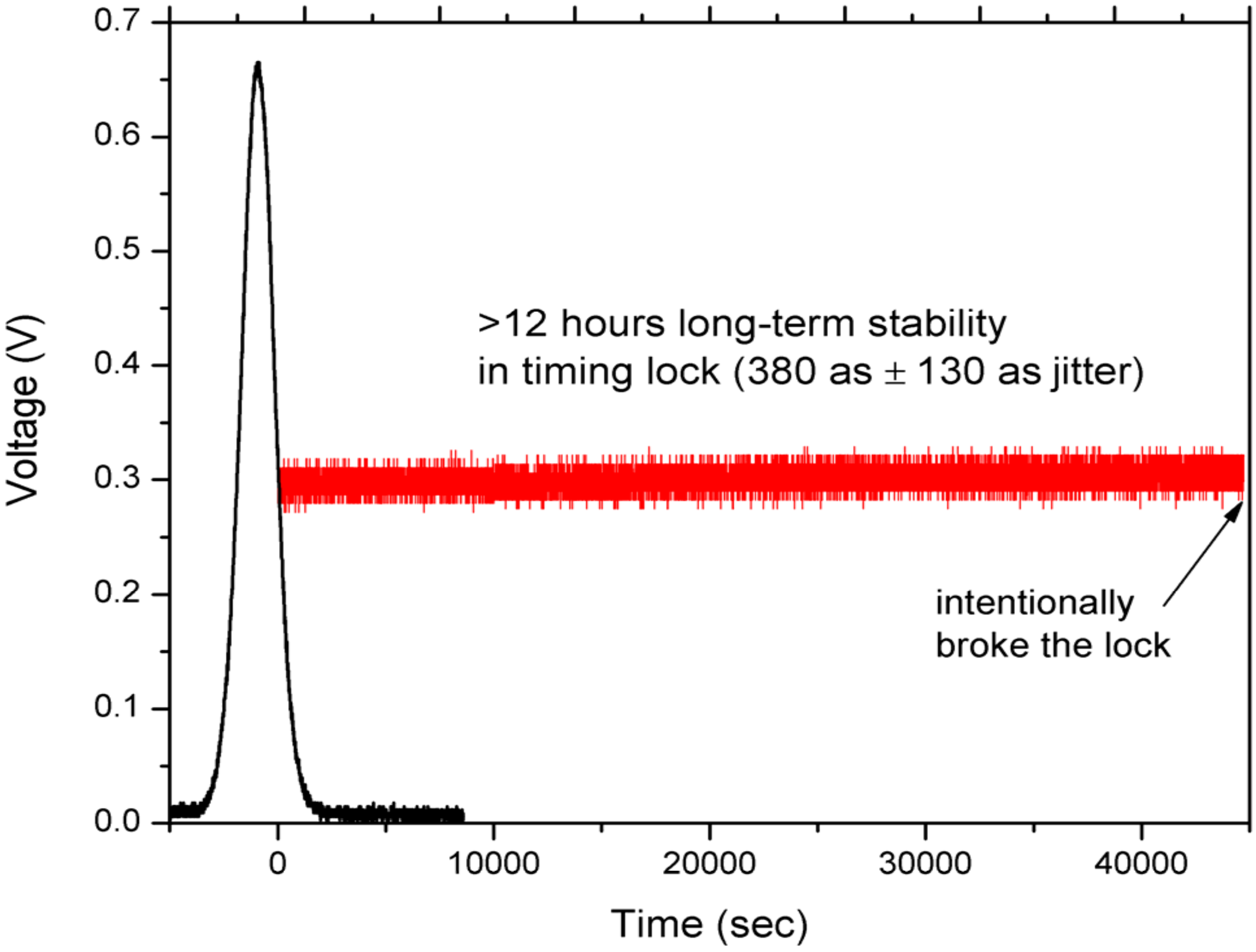
# Balanced Optical Cross-Correlation




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

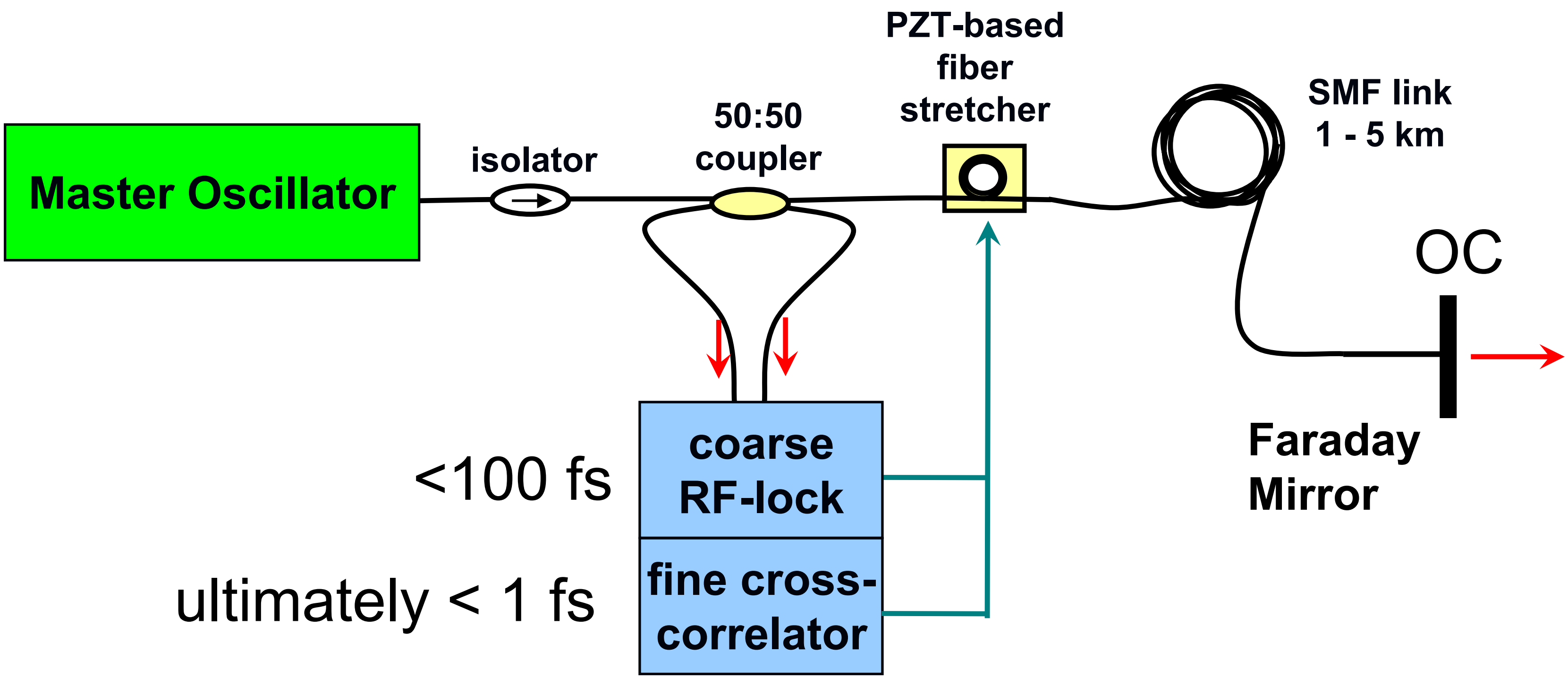
# Long-Term Locking Between Two Lasers

## (Out of Loop Measurements)



# Timing stabilized fiber links

# Timing-Stabilized Fiber Links




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

# Summary

- Ultrashort pulse trains from mode-locked lasers have excellent phase/timing noise properties.
- They can be used as optical master oscillators
- Optical/Electrical PLLs: Balanced optical-RF phase detectors are proposed for femtosecond and potentially sub-femtosecond optical to RF-synchronization.
- Optical/Optical Synchronization: Based on balanced optical cross-correlation. Long term stable sub-femtosecond precision is already achieved.
- Together with timing stabilized fiber links a (sub-) femtosecond timing distribution and synchronization system for $4^{th}$ generation light sources can be accomplished.