Laser Technology for X-ray FELs: Femtosecond Synchronization and High-Power Seed Generation

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Optical Timing Synchronization

- Next generation accelerators demand increasingly precise timing sync (<< 100 fs)
- Must sync multiple locations separated by ~ 1 km distances.

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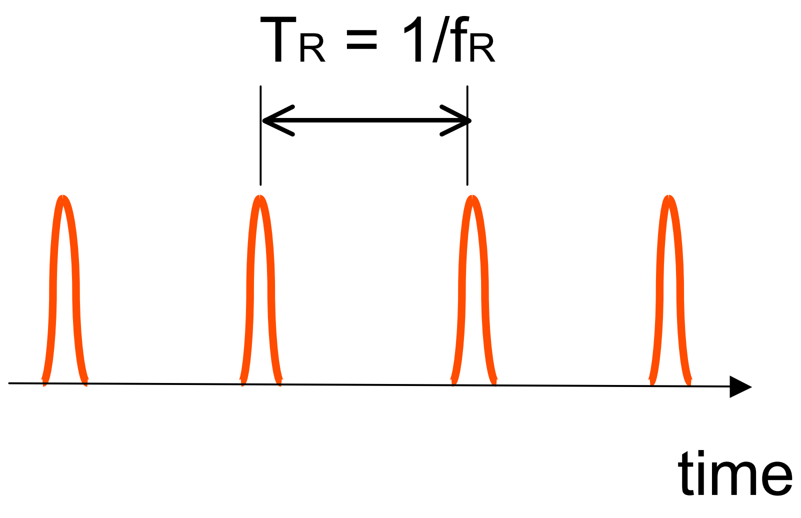
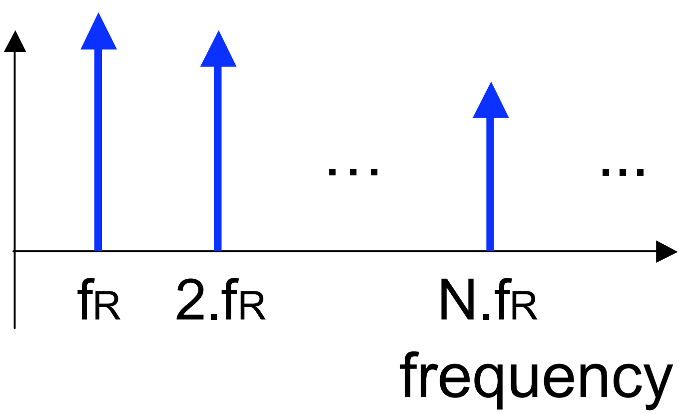
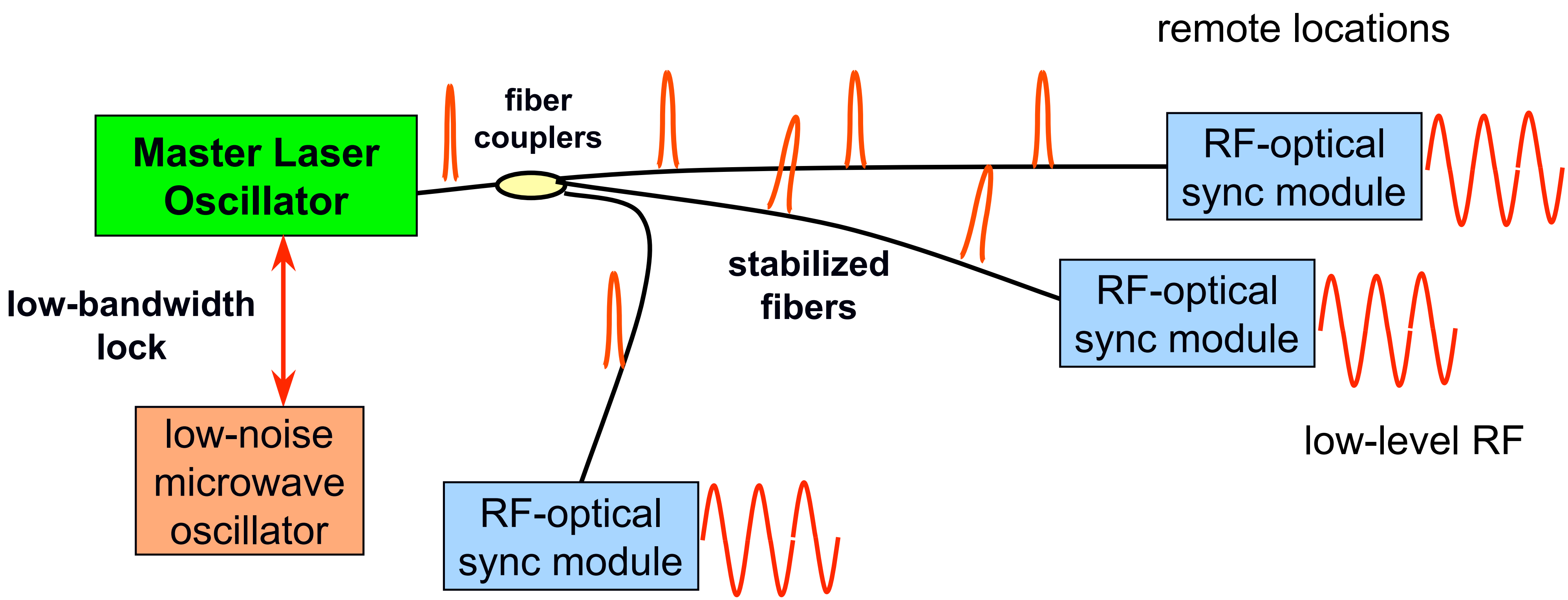
- Must sync multiple locations separated by ~ 1 km distances.
- One way is to distribute timing information via **short optical pulses** of a **definite repetition rate**.



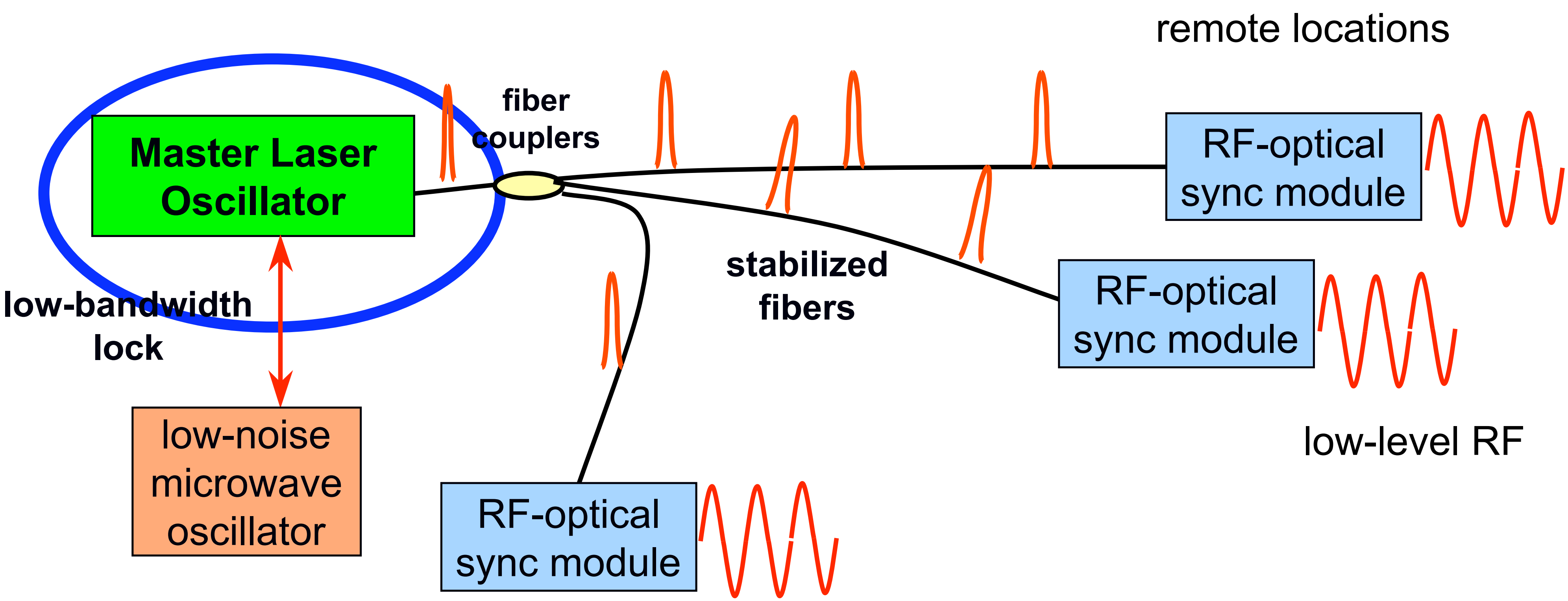


Synchronization System Layout



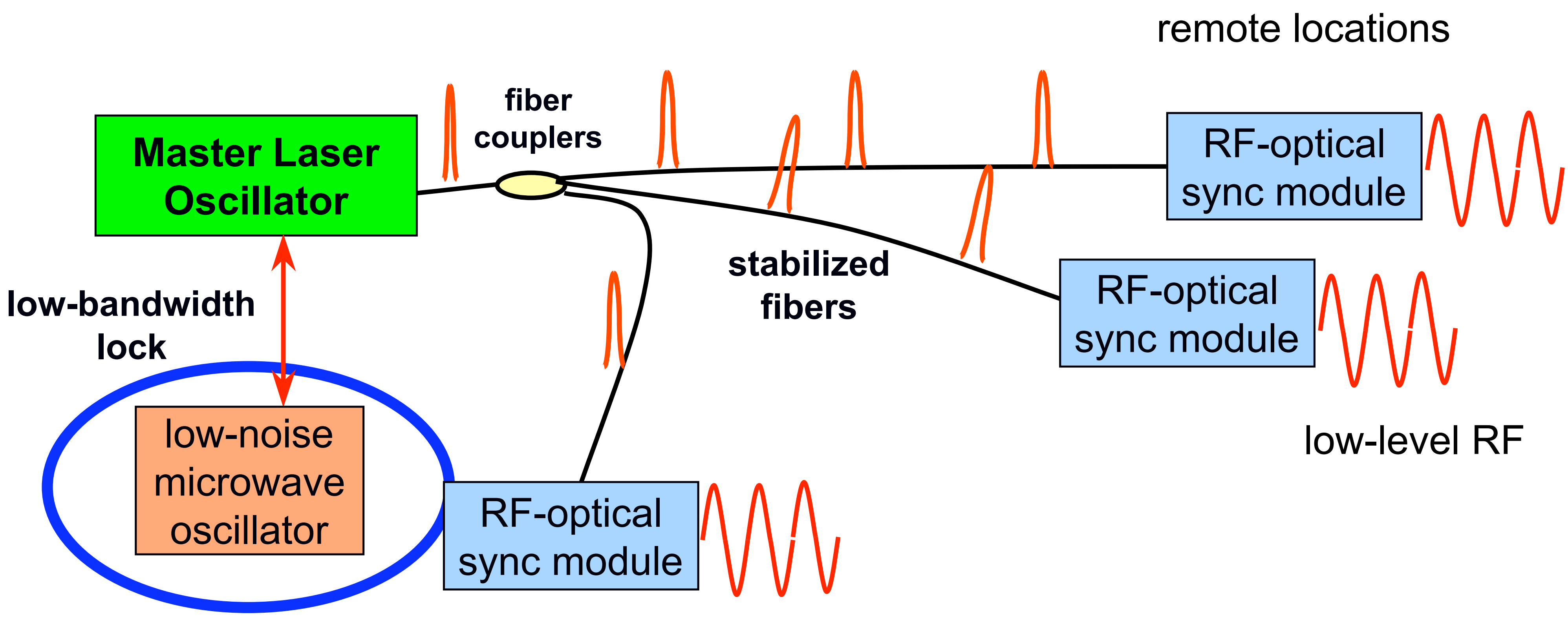
Synchronization System Layout

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



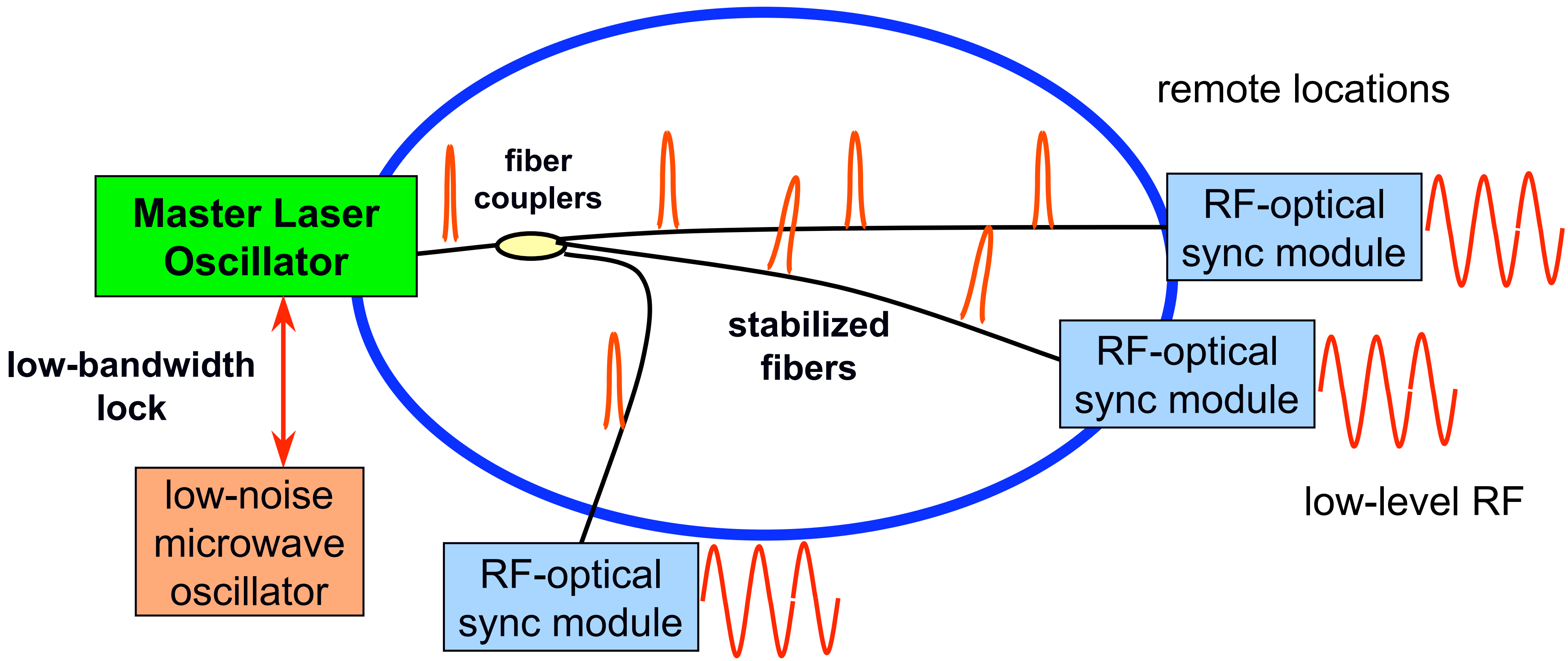
Synchronization System Layout

The master laser is locked to a microwave oscillator for long-term stability



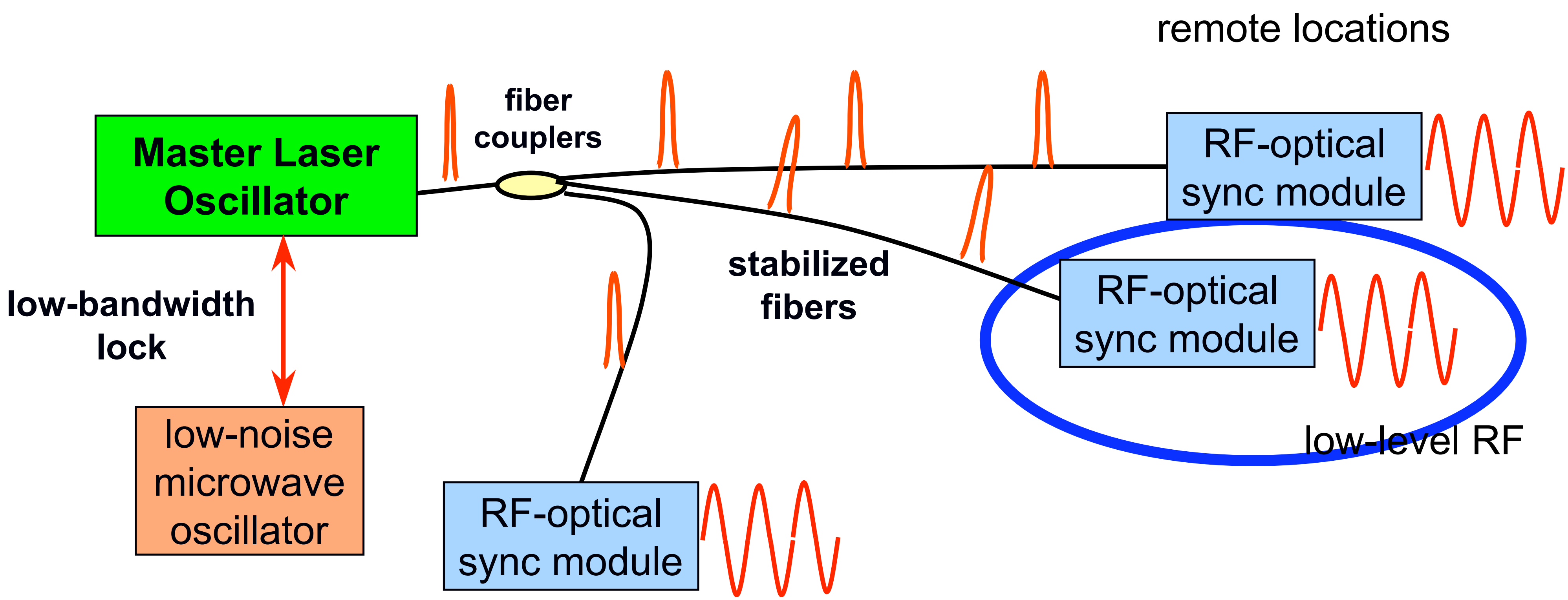
Synchronization System Layout

Stabilized fiber links that transport the pulse train to multiple locations



Synchronization System Layout

Other lasers can be locked to this train or can generate an RF signal locally



Optical Timing Synchronization

We envision that

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

ii. The master laser locked to a microwave source for long-term stability,

iii. Stabilized fiber links that transport the pulse train to multiple locations,

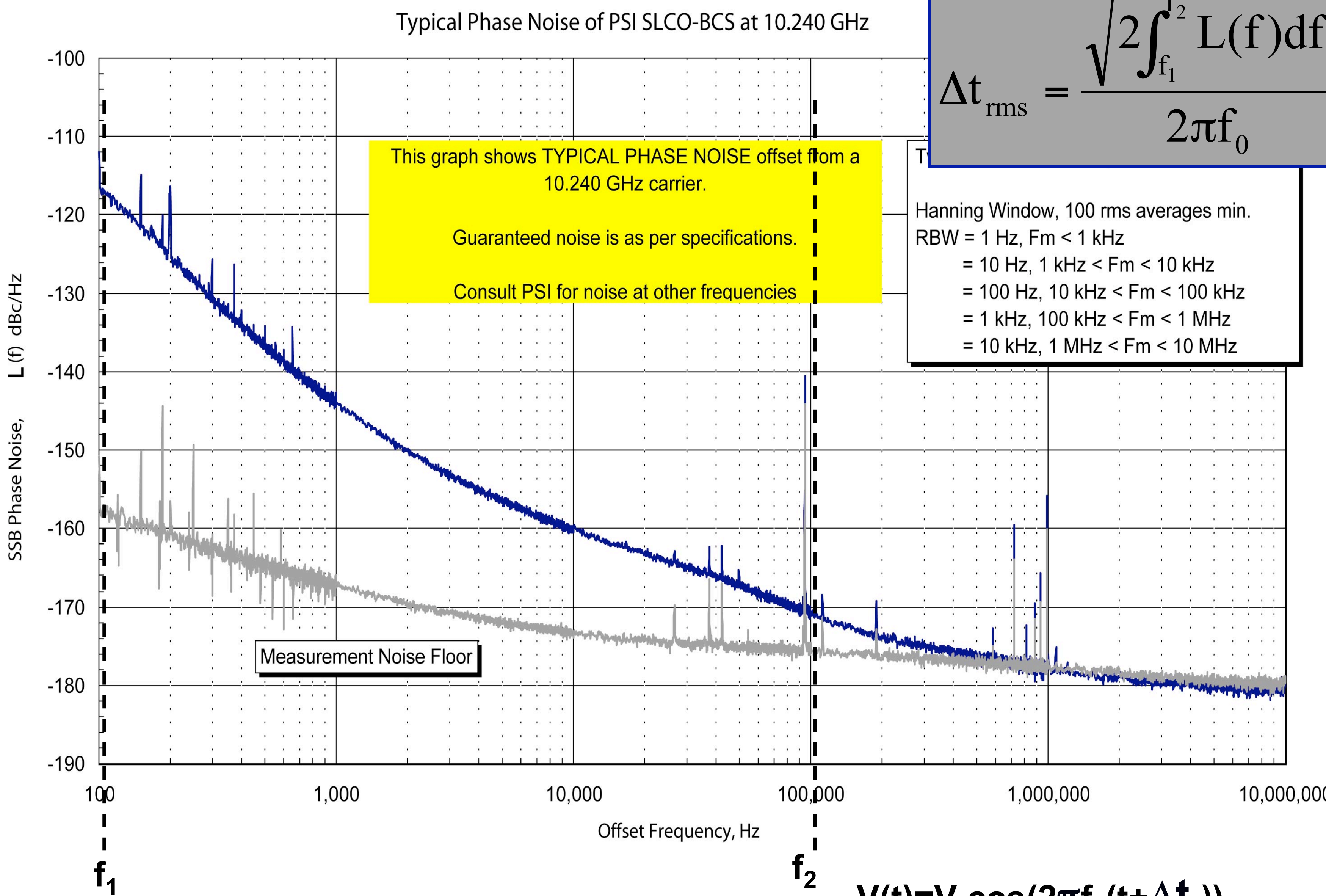
iv. Other lasers locked to this train or generation of an RF signal locally,

form a complete scheme with < 100 fs, eventually few fs precision.

Frequency standard or highly stable microwave oscillator

Commercial Low-Noise Microwave Oscillators

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

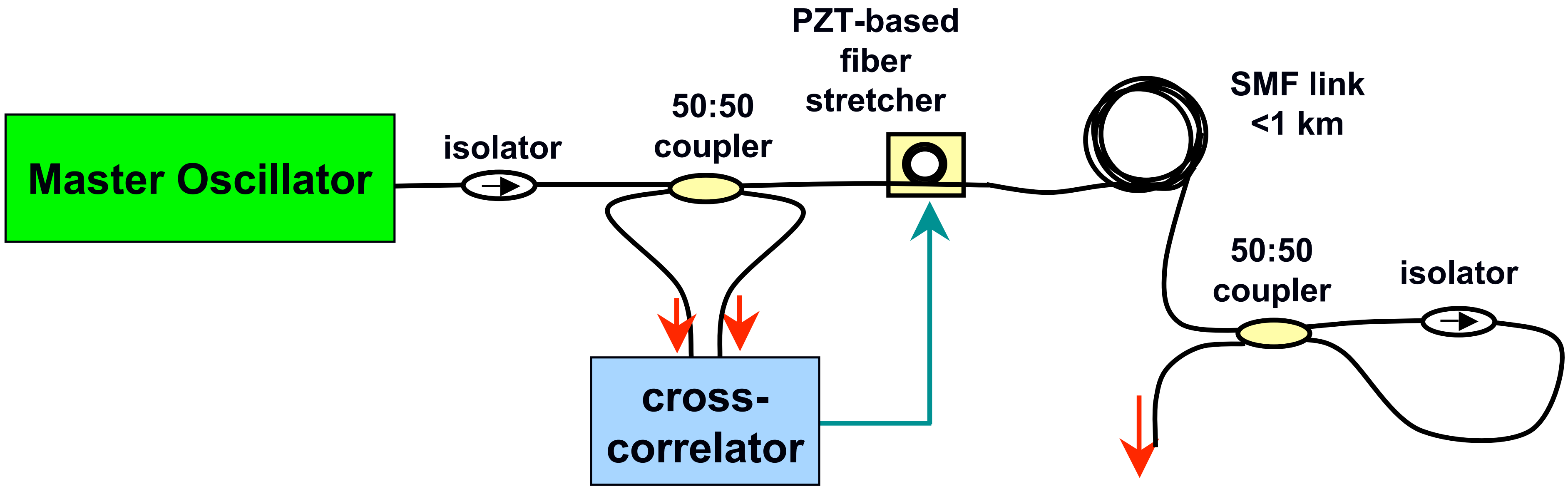


$$V(t)=V\cos(2\pi f_0(t+\Delta t))$$

$$\Delta\varphi = 2\pi f_0 \Delta t$$

Timing stabilized fiber links

Timing-Stabilized Fiber Links

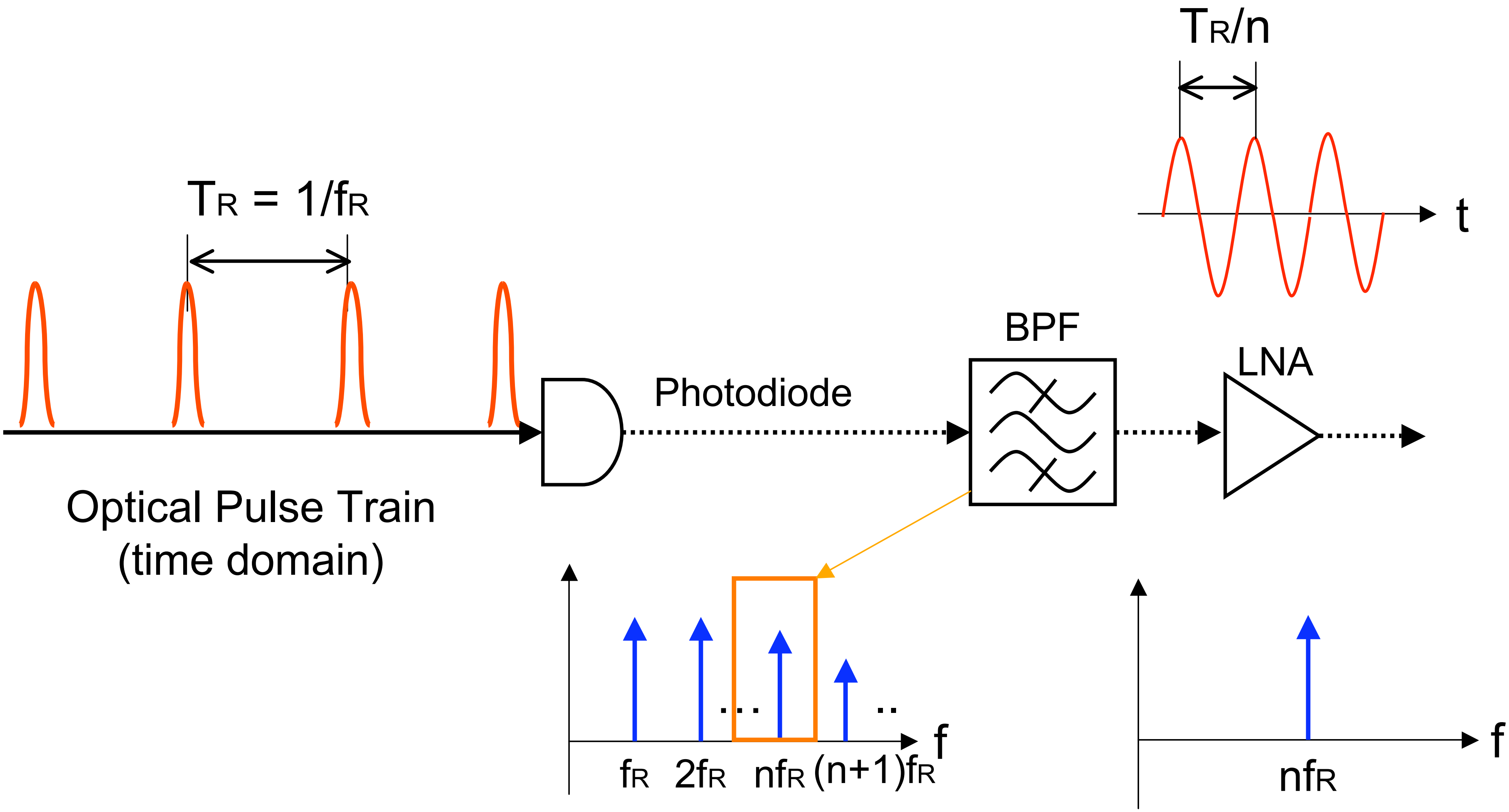


Assuming no fiber length fluctuations faster than T=2nL/c.

L = 1 km, n = 1.5 => T=1 μs, f_{max} = 1 MHz

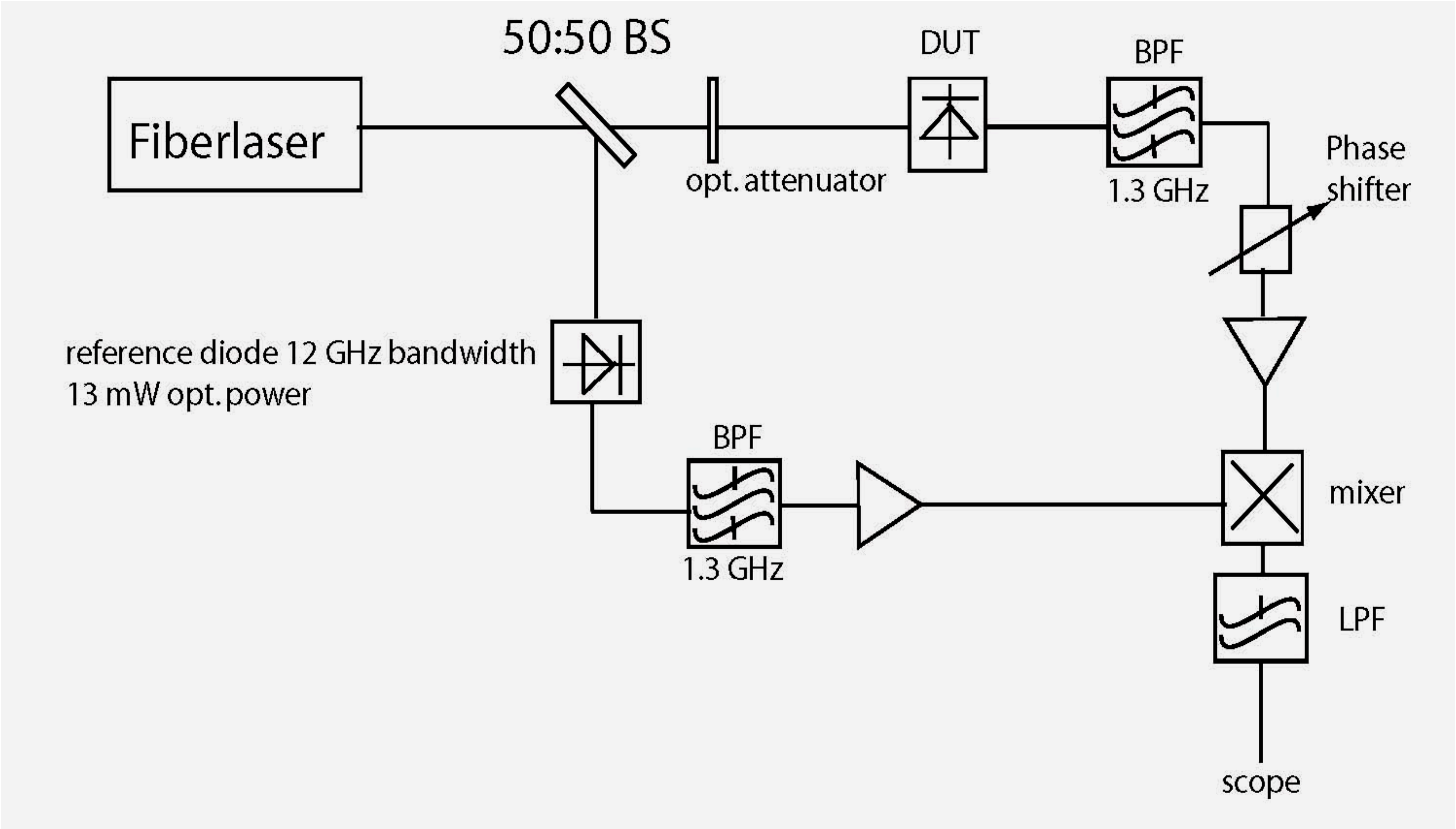
RF-synchronization module for RF-optical & optical-optical

Direct Detection to Extract RF from the Pulse Train



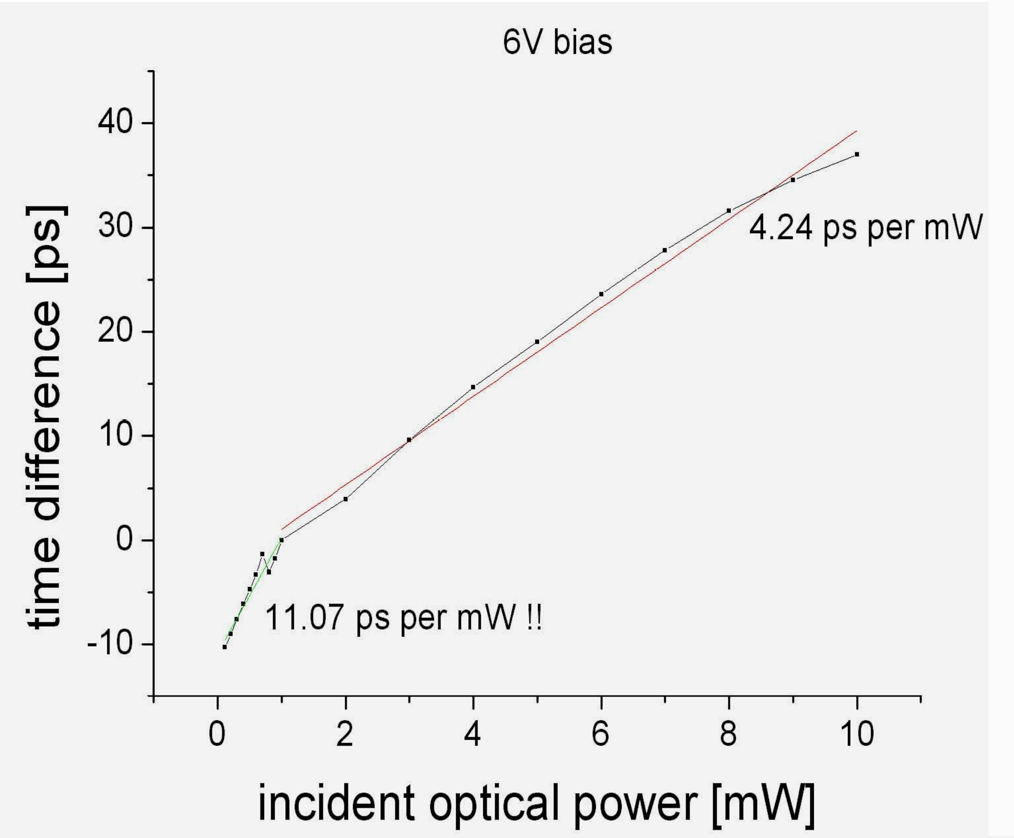
Amplitude-to-phase conversion introduces excess timing jitter

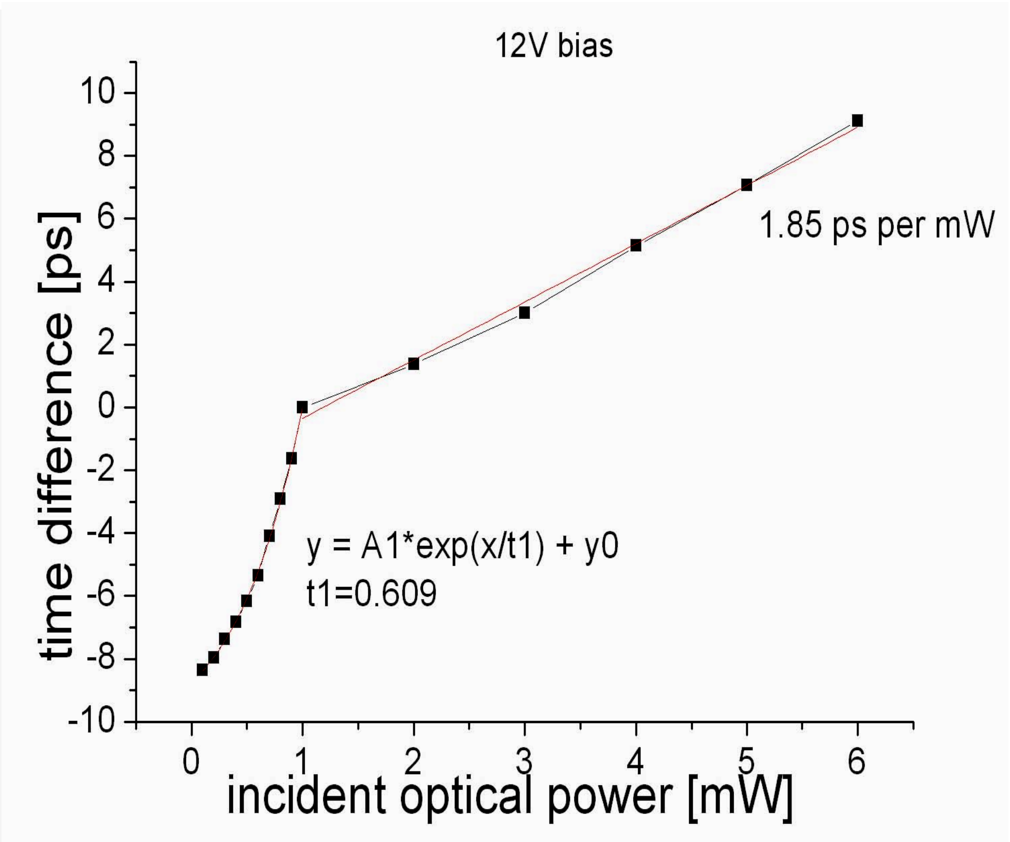
Amplitude to Phase Conversion: Experimental Setup



- determine timing jitter due to power fluctuations
- mix 1.3 GHz component of laser signal to baseband and vary optical power

Amplitude to Phase Conversion in the PD





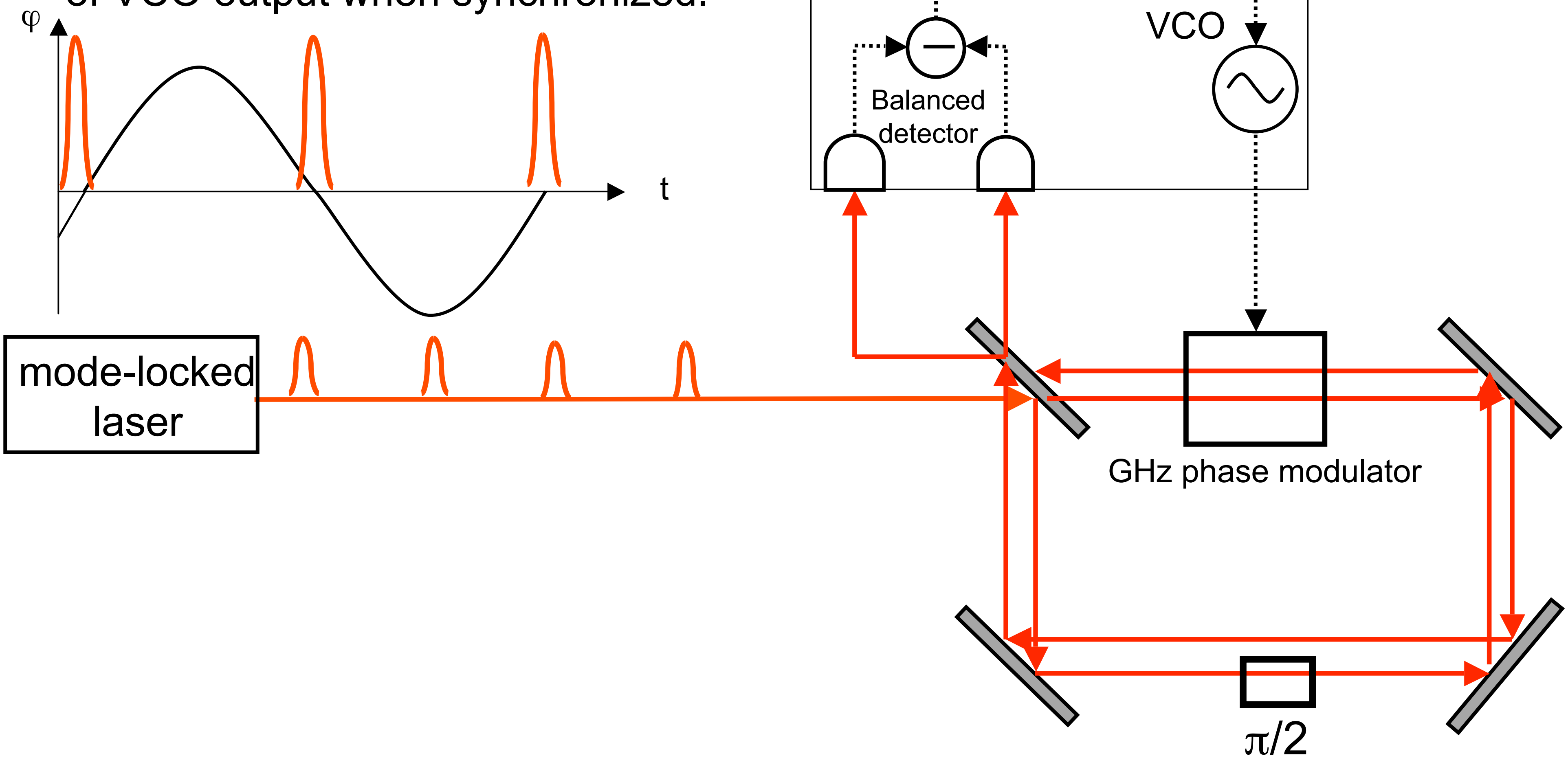
To minimize timing error at photodetection:

- increase bias
- use higher bandwidth detector

RF-Synchronization Module

Transfer timing information into intensity imbalance

The pulses sit on the zero-crossings of VCO output when synchronized.



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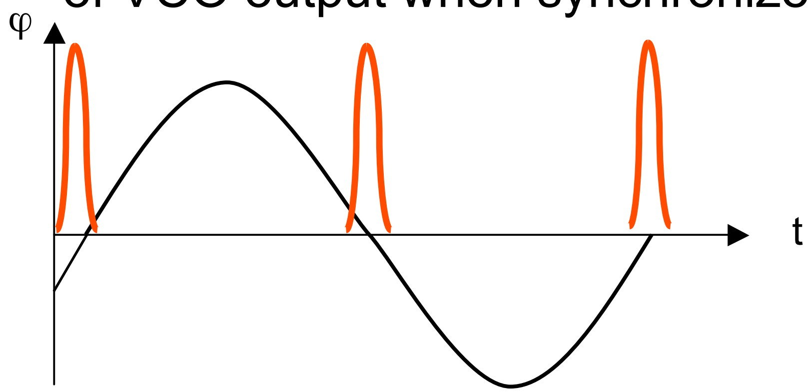
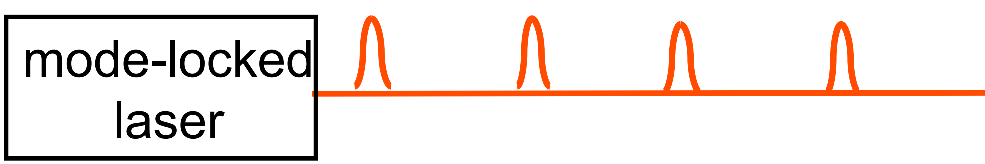
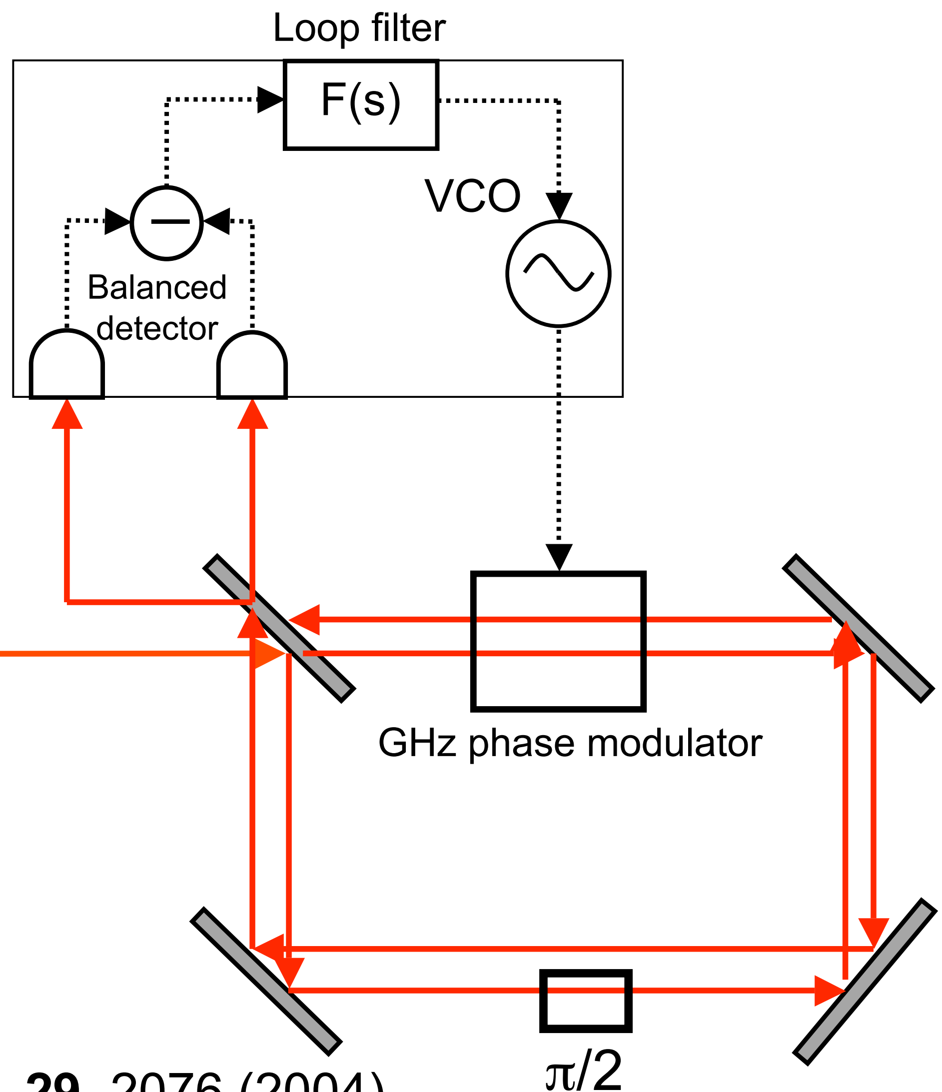


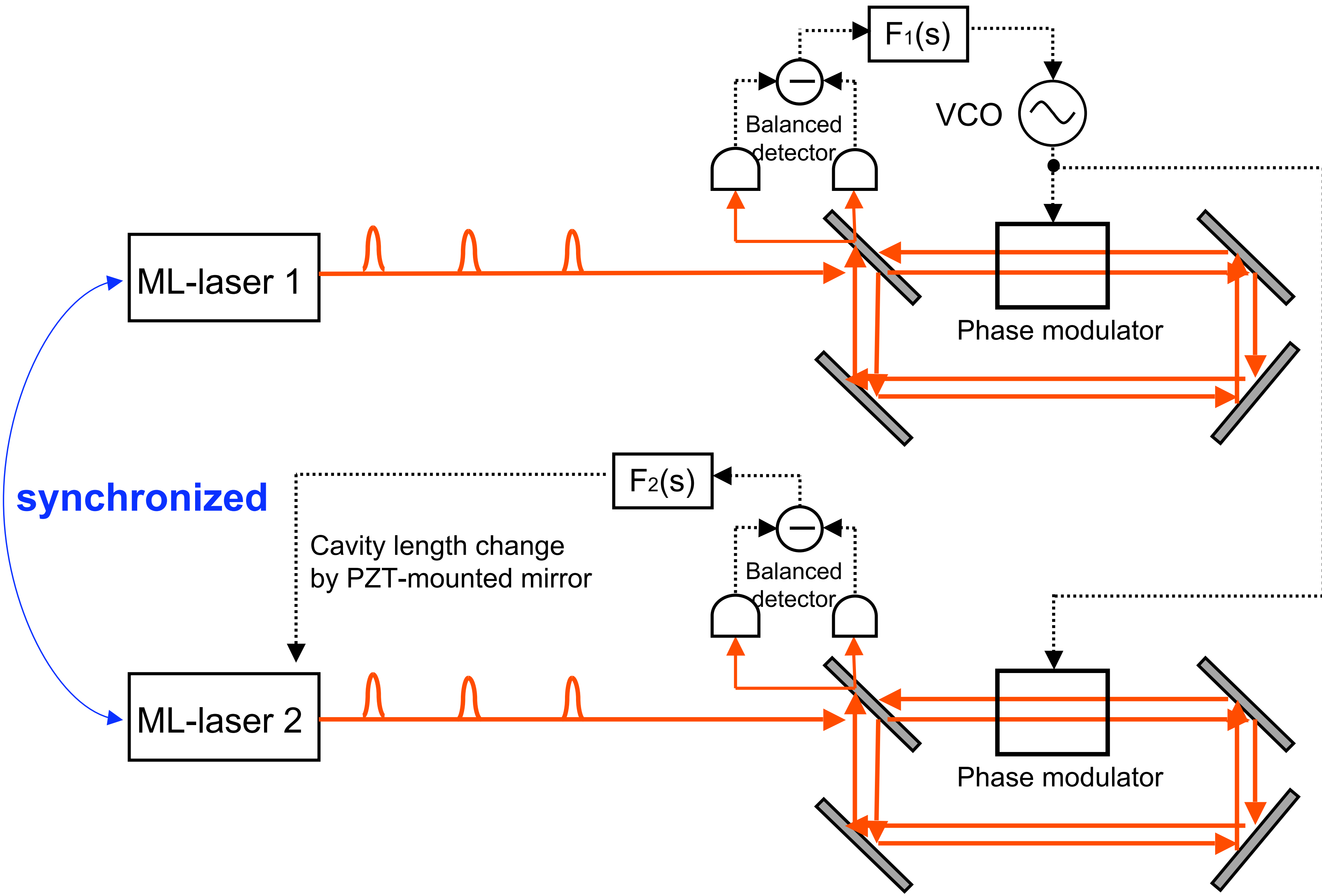




60 fs (100 Hz-10 MHz) demonstrated
<10 fs possible on the long run

J. W. Kim, F. X. Kärtner, M. Perrot, Opt. Lett. **29**, 2076 (2004)

Optical-to-Optical Synchronization



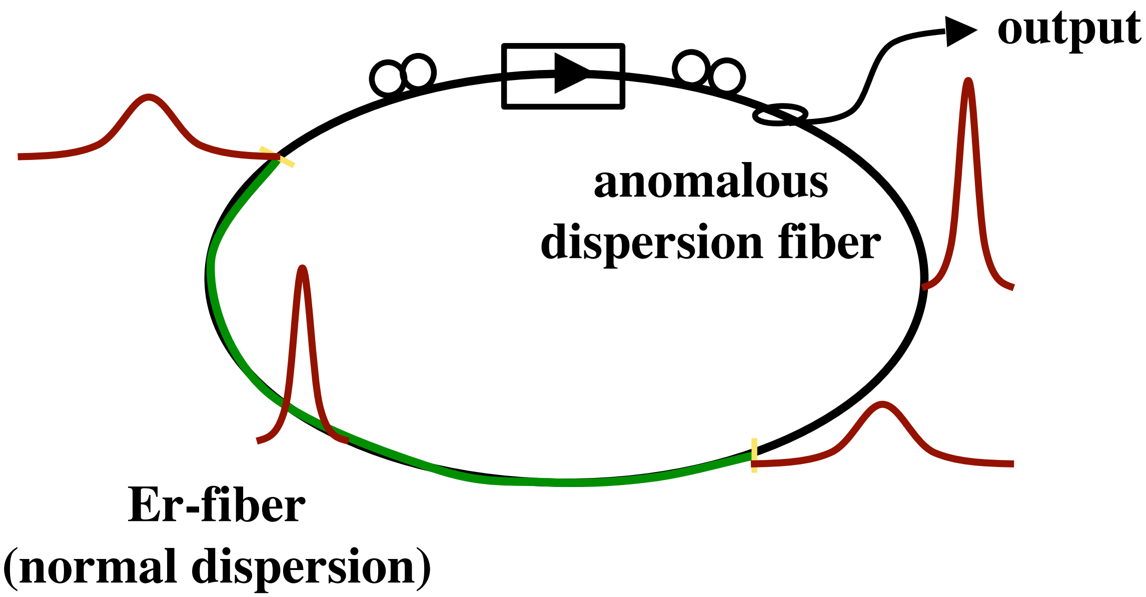
Low-Noise Master Laser Oscillator

Robust, Low-Noise Laser Oscillator Development

- Passively modelocked lasers, superior high-frequency noise.
- Er-fiber lasers:
  - sub-100 fs to ps pulse duration
  - 1550 nm (telecom) wavelength for fiber-optic component availability
  - repetition rate 50-100 MHz
- Reliable, long-term operation without interruption:
  - weeks of uninterrupted operation, with minimal environmental protection (just a box around)
  - use multiple lasers for redundancy

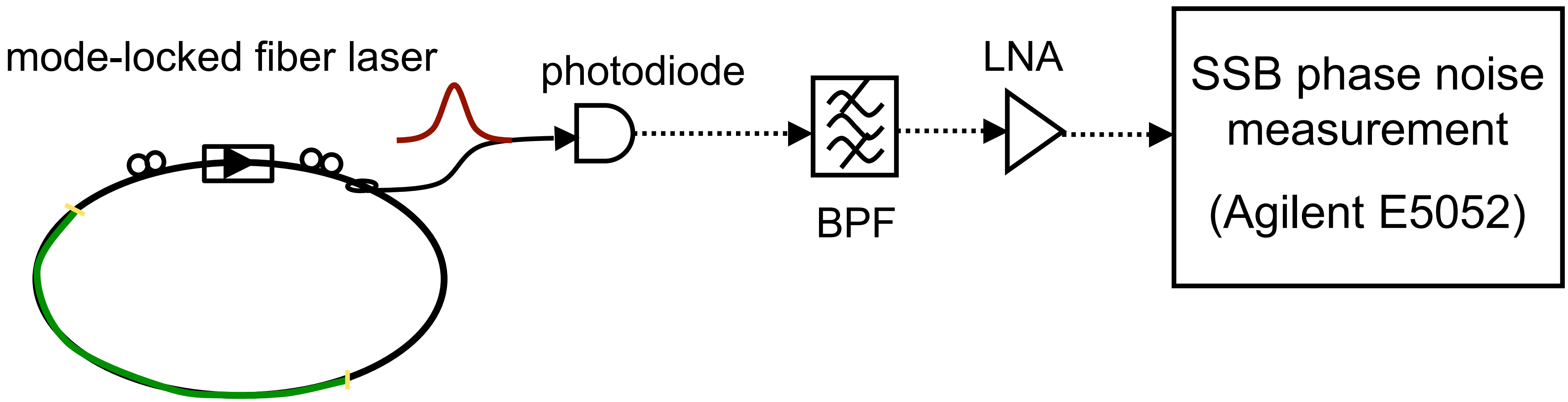
Passively Mode-locked Fiber Lasers

- Pulse builds up by itself from noise (ns-ps domain)
  - A saturable absorber ensures higher intensity <=> higher gain
  - Given constant intra-cavity energy, the stable solution is a localized solution (a single pulse).



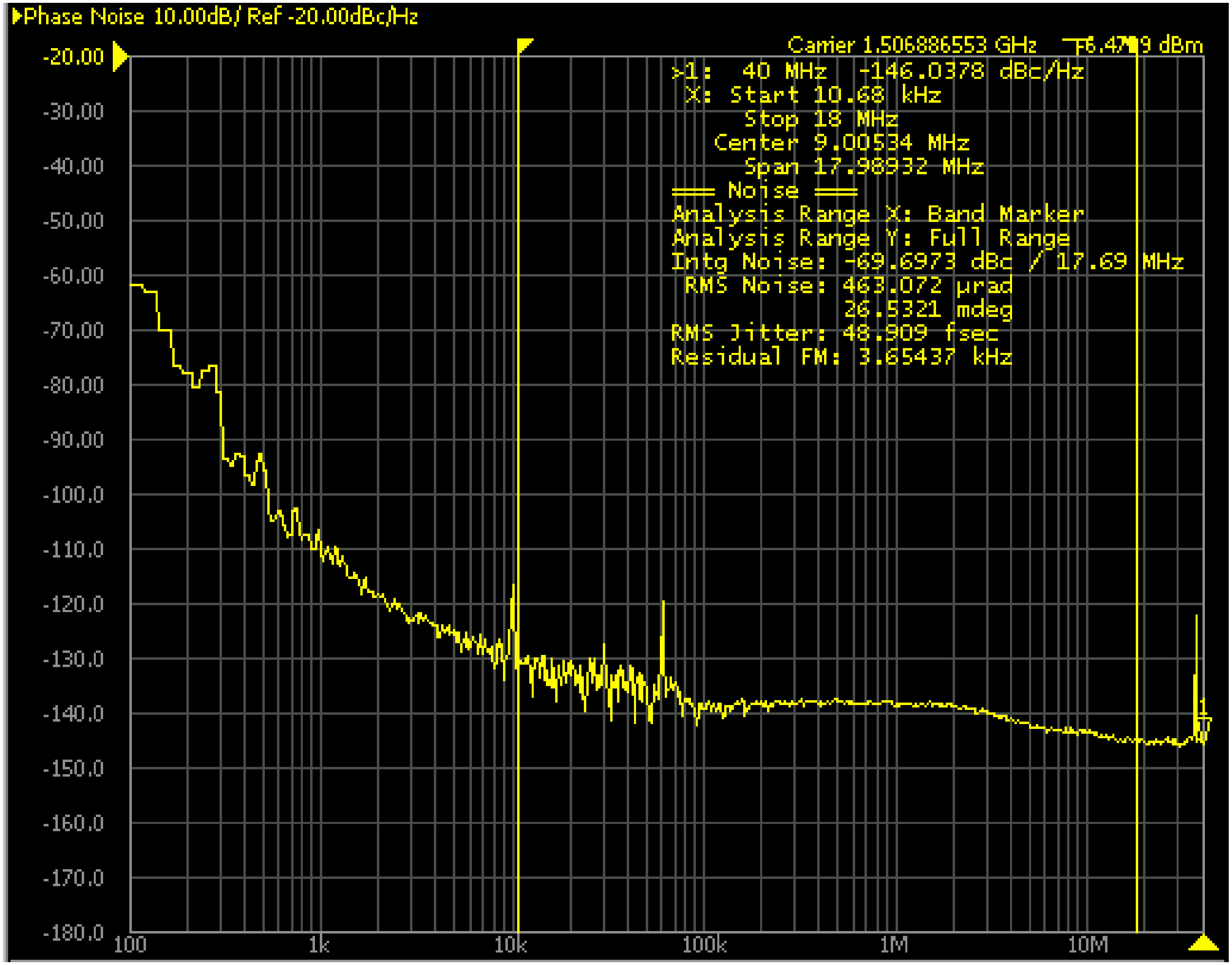
- Picture is different in the femtosecond domain:
  - Dispersion and nonlinear dominate pulse shaping.
  - Soliton-like pulses balance these effects => very short pulses

Phase Noise (Timing Jitter) Measurements



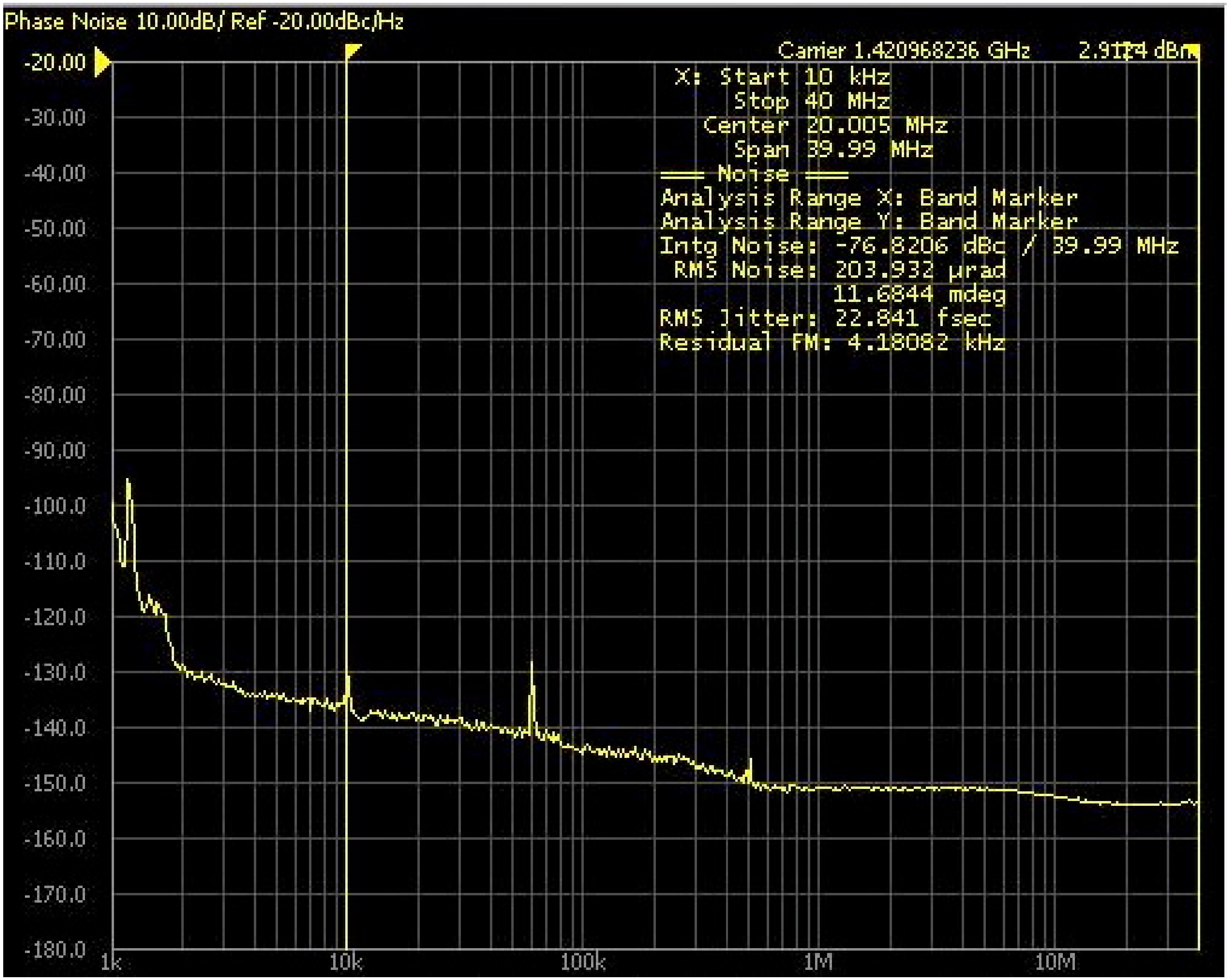
Phase Noise (Timing Jitter) Results

Er-fiber laser at normal dispersion: ~50 fs (10 kHz - Nyquist)



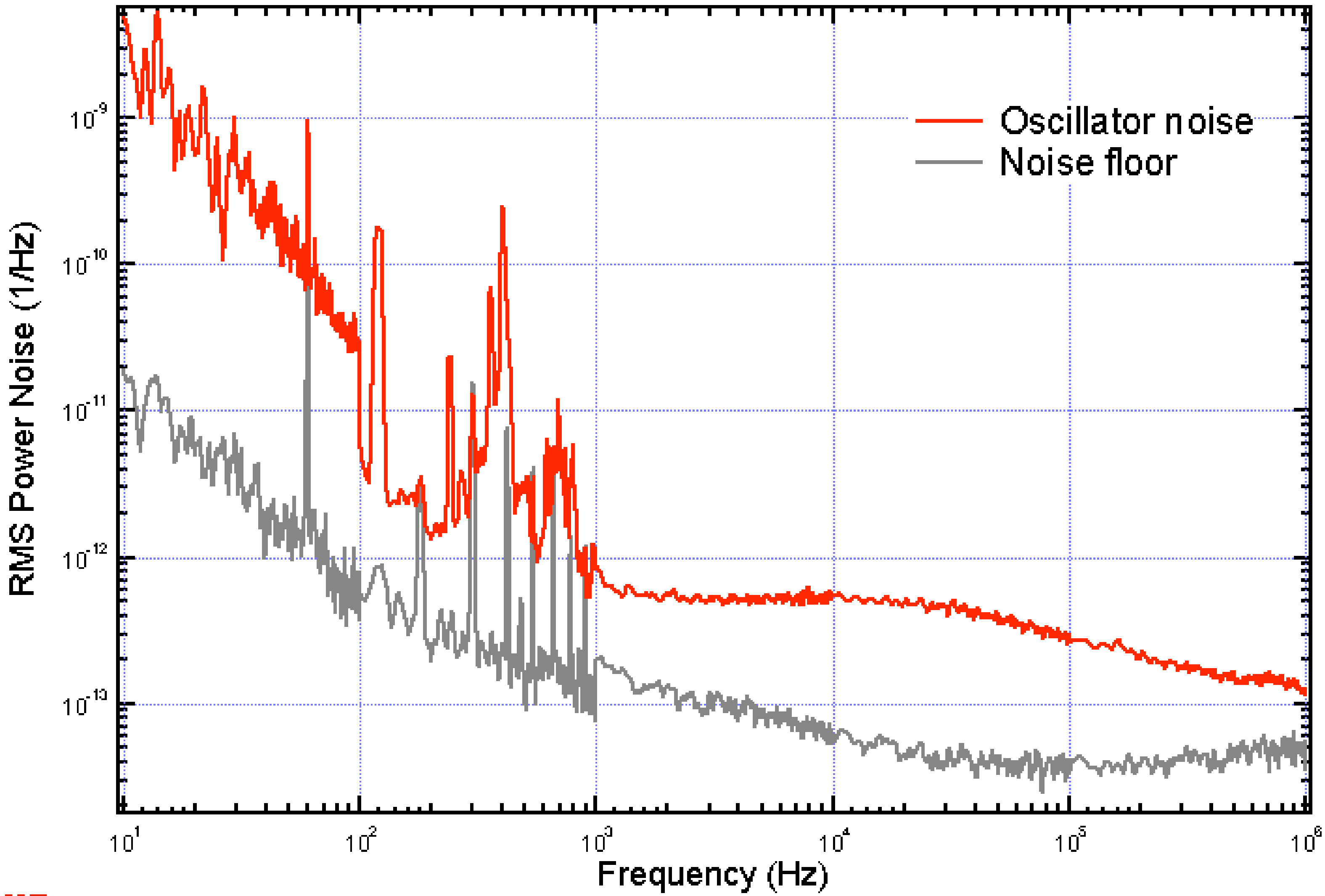
Phase Noise (Timing Jitter) Results

Yb-fiber laser near zero dispersion: ~23 fs (10 kHz - Nyquist)

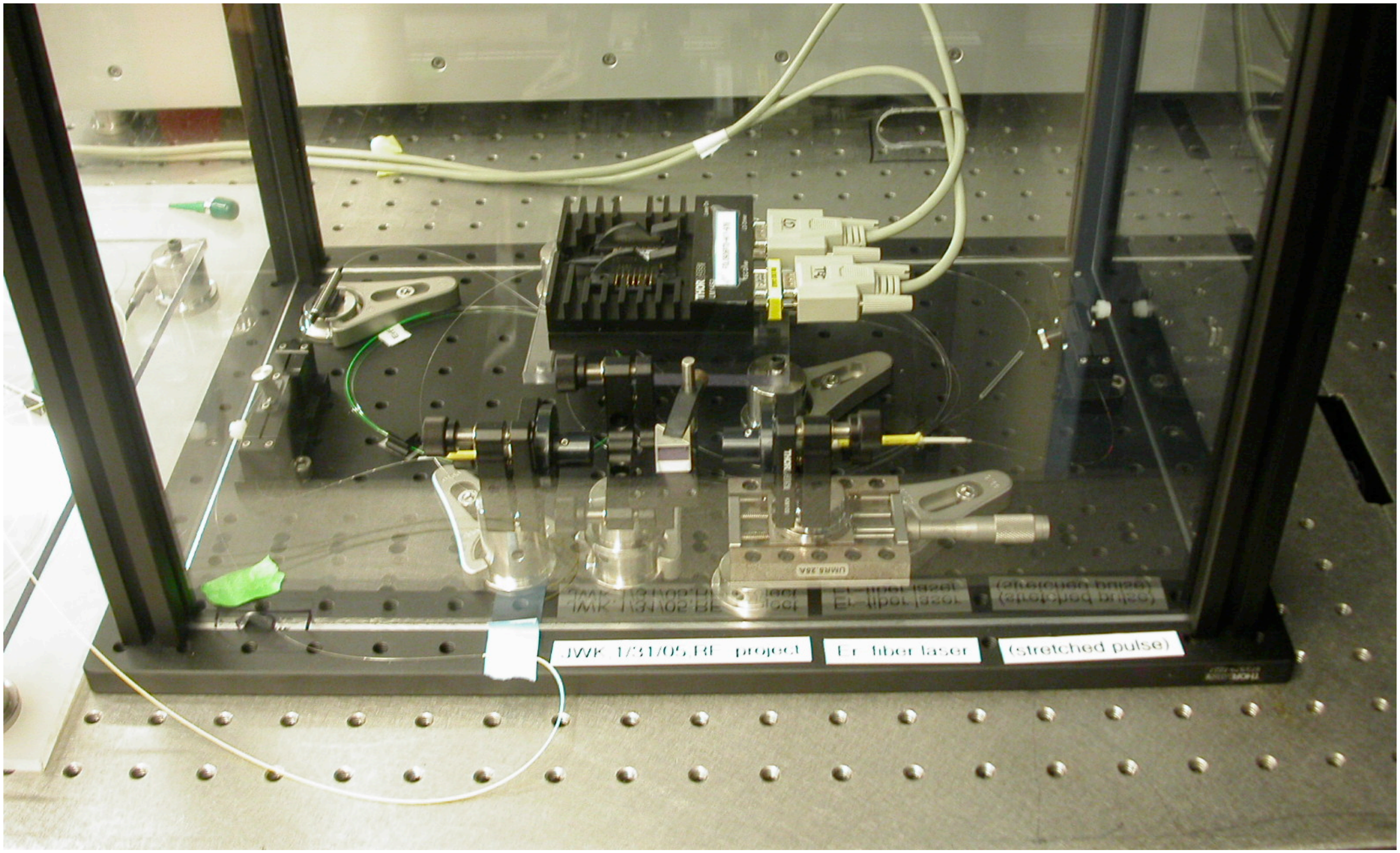


Amplitude Noise

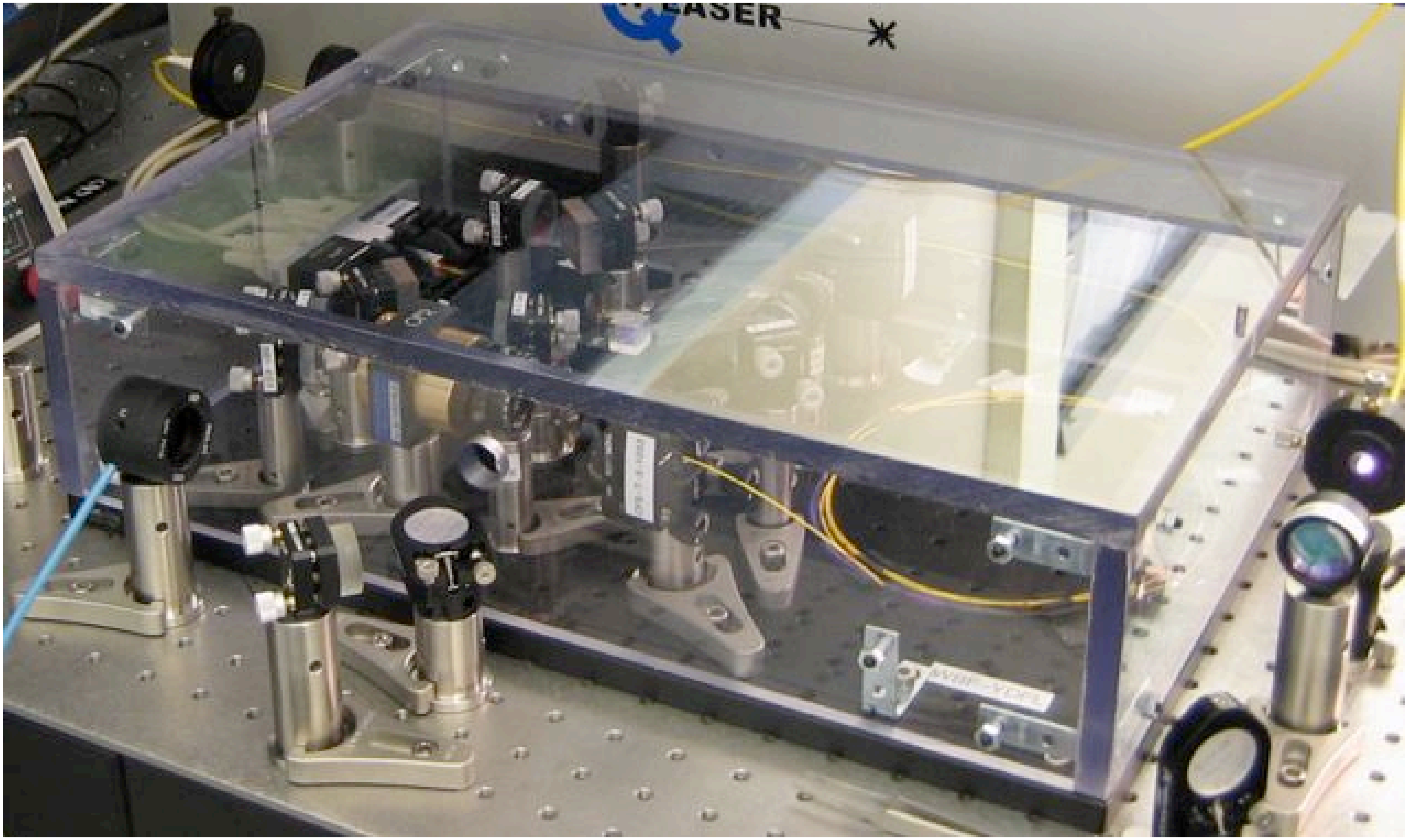
Recall that amplitude noise is converted to phase noise at the photodetector.
Preliminary data indicate this contribution is substantial -- under investigation



One of our Er-fiber lasers

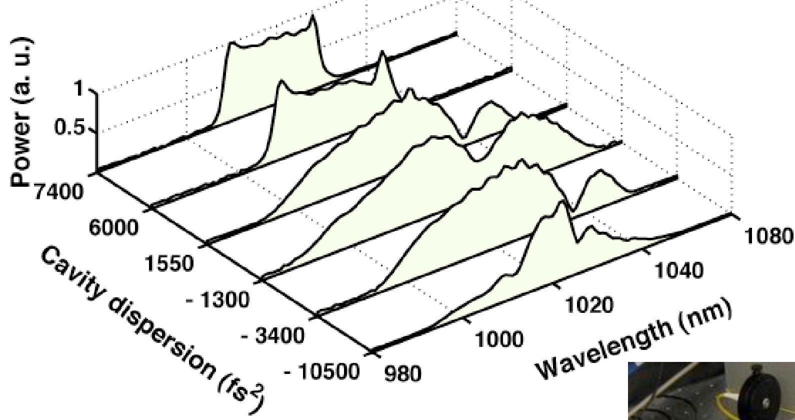


One of our Yb-fiber lasers



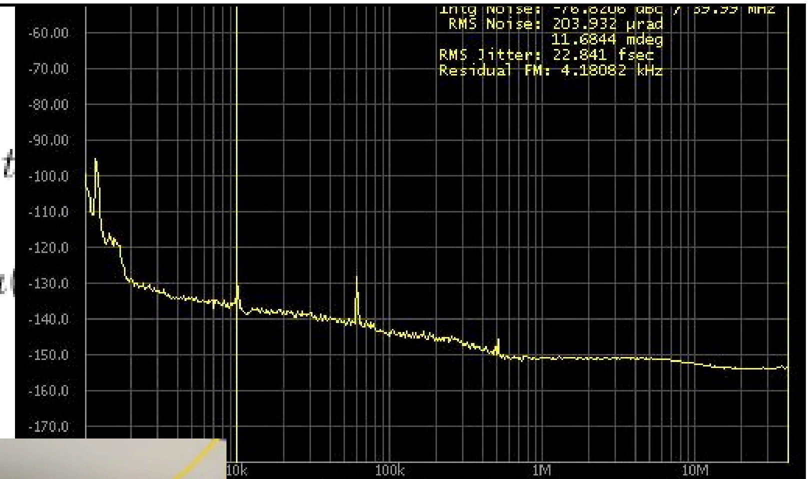
Conclusions

- Optical timing synchronization based on:
  - Ultra-low noise, long-term stabilized mode-locked fiber lasers,
  - Stabilized fiber links to distribute to remote locations,
  - A scheme to extract low-level RF from optical pulse train locally.
- Most critical component is the **master laser**:
  - Laser dynamics important (dispersion, nonlinear effects).
  - Ultimate limit set by quantum fluctuations in the photon number.
  - Currently noise < 30 fs possible, may be lower.
- Currently < 100 fs seems achievable.
- Following a few years of development, < 10 fs may be reached.



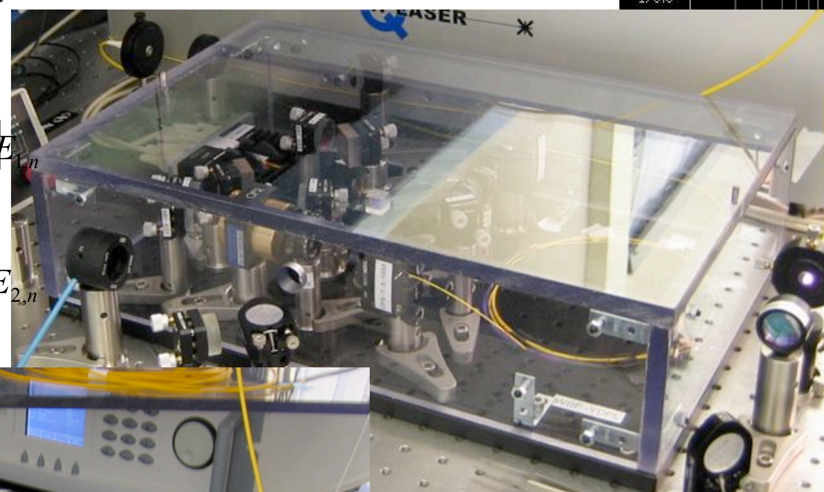
$$\frac{\ldots z,t)}{2} - i\gamma|a(z,t)|^2 a(z,t\ldots$$

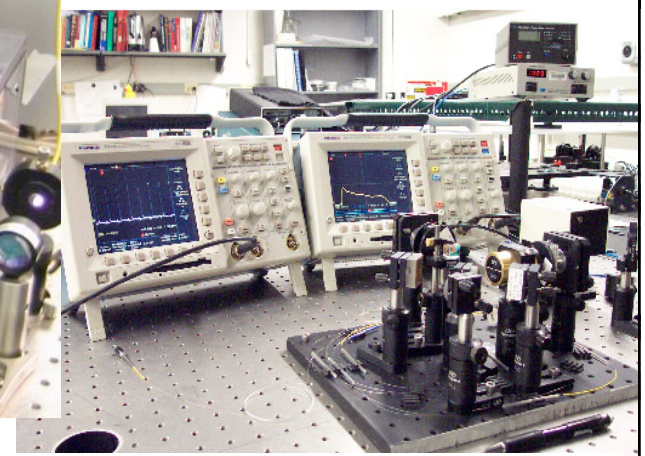
$$a(z,t) = -q(a(z,t))a\ldots$$

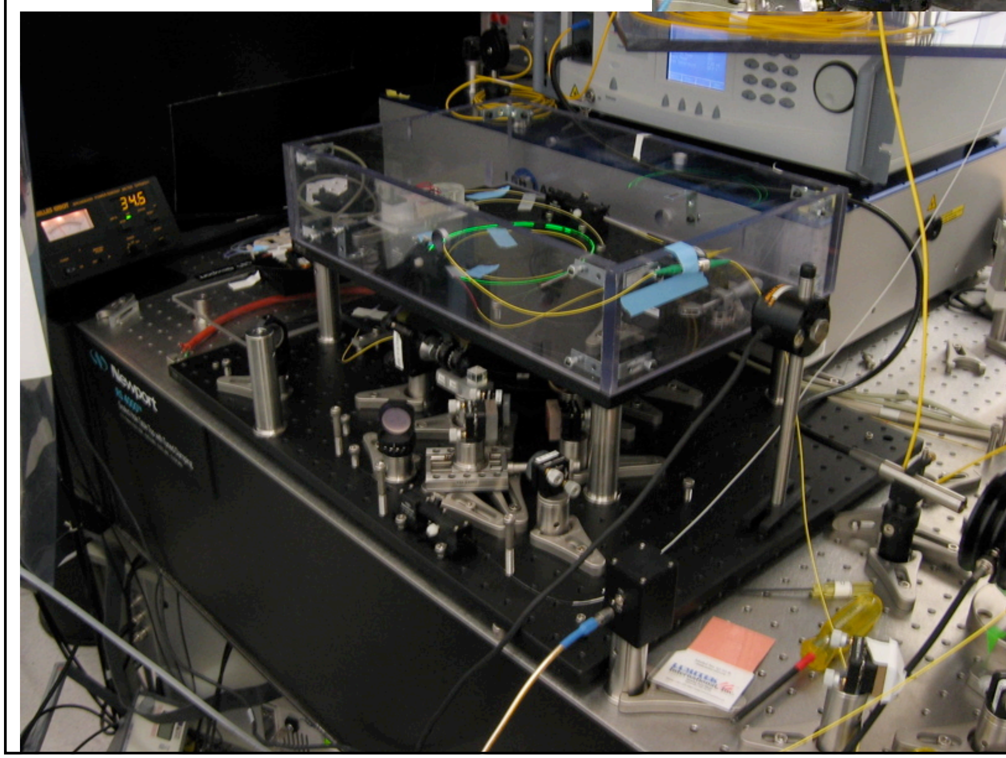


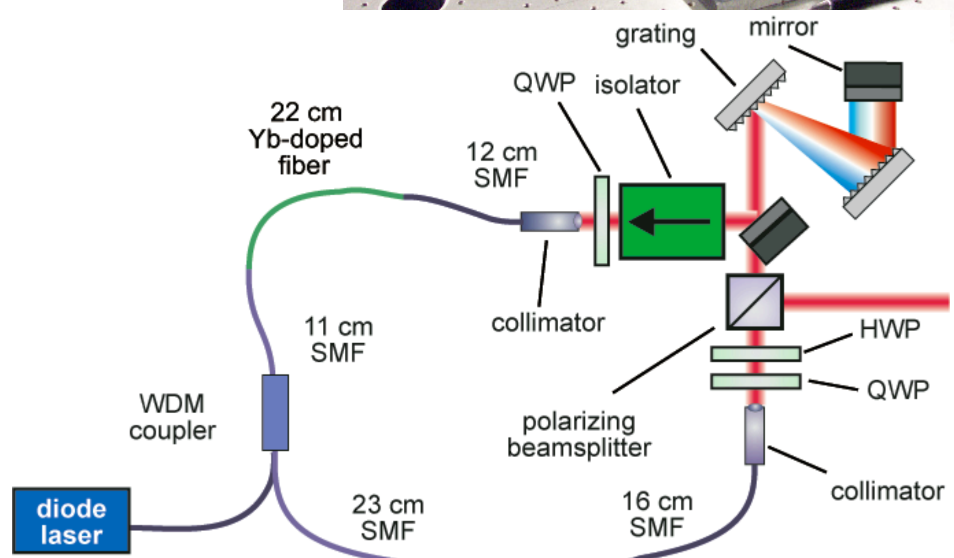
$$E_{1,n+1} = \frac{g_{net,0}/2}{1+\left(E_{1,n}+E_{2,n}\right)/E_{sat}}\left[1-q\cos\left(\pi E_{1,n}\right)\right]E_{1,n}$$

$$E_{2,n+1} = \frac{g_{net,0}/2}{1+\left(E_{1,n}+E_{2,n}\right)/E_{sat}}\left[1-q\cos\left(\pi E_{2,n}\right)\right]E_{2,n}$$

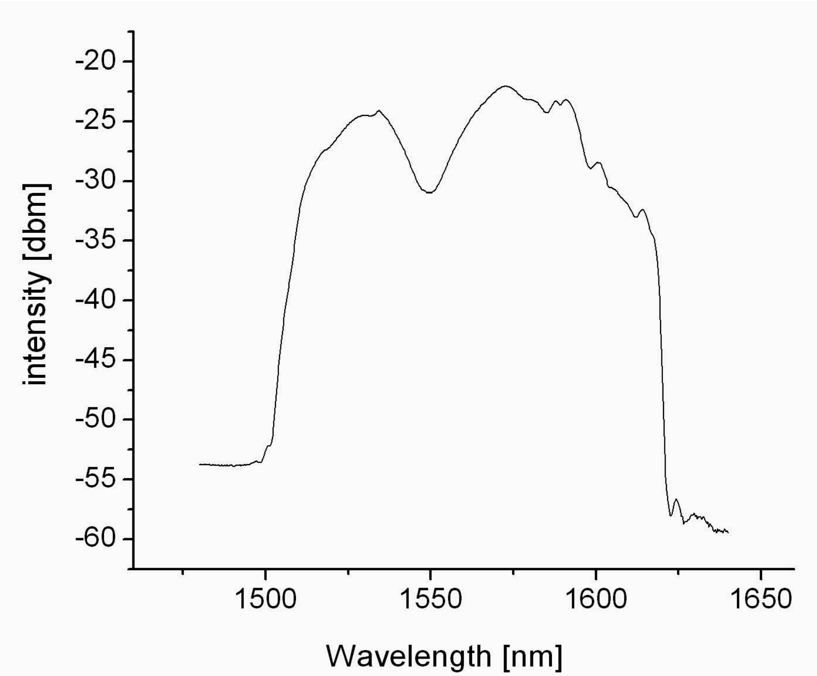


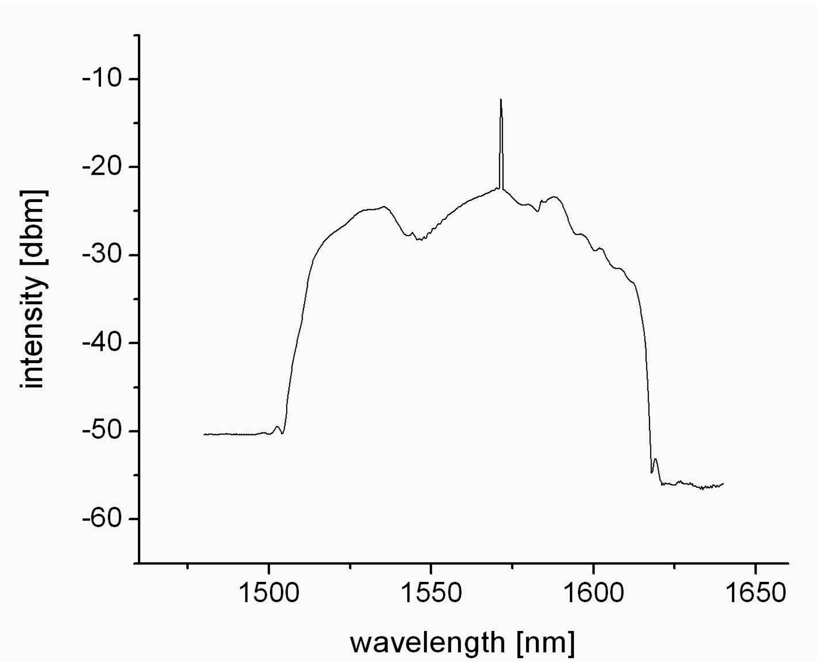




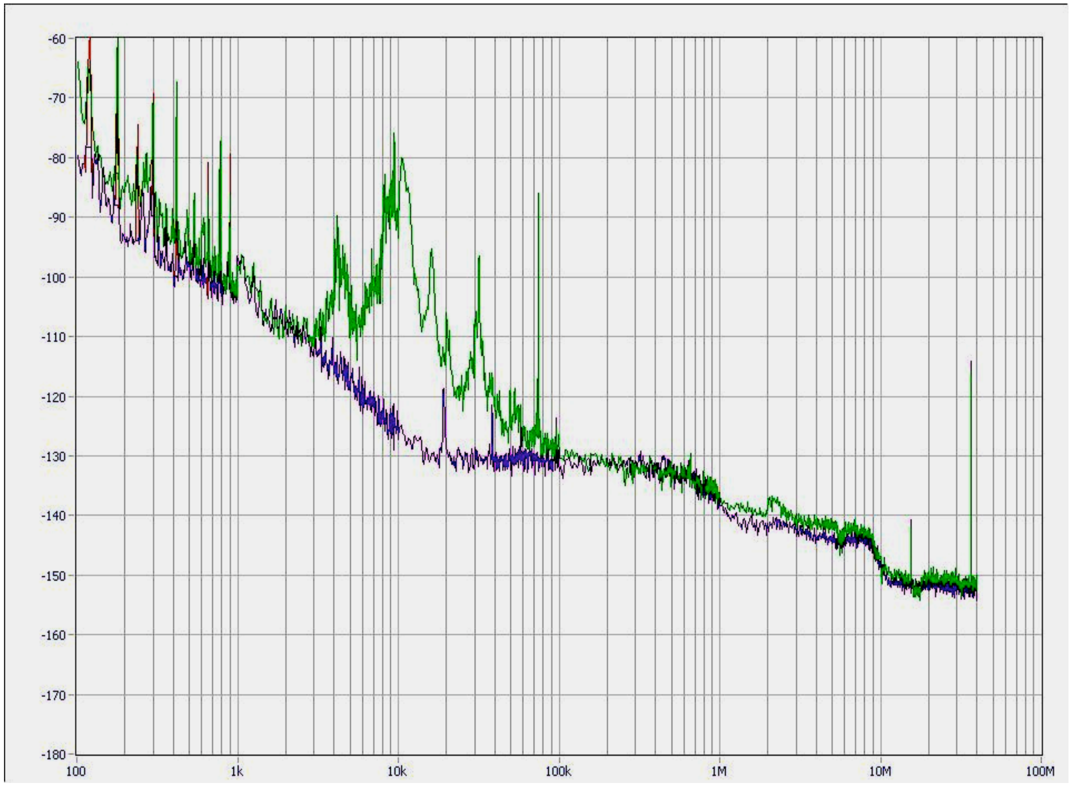


Timing jitter measurement with stretched pulse fiber laser





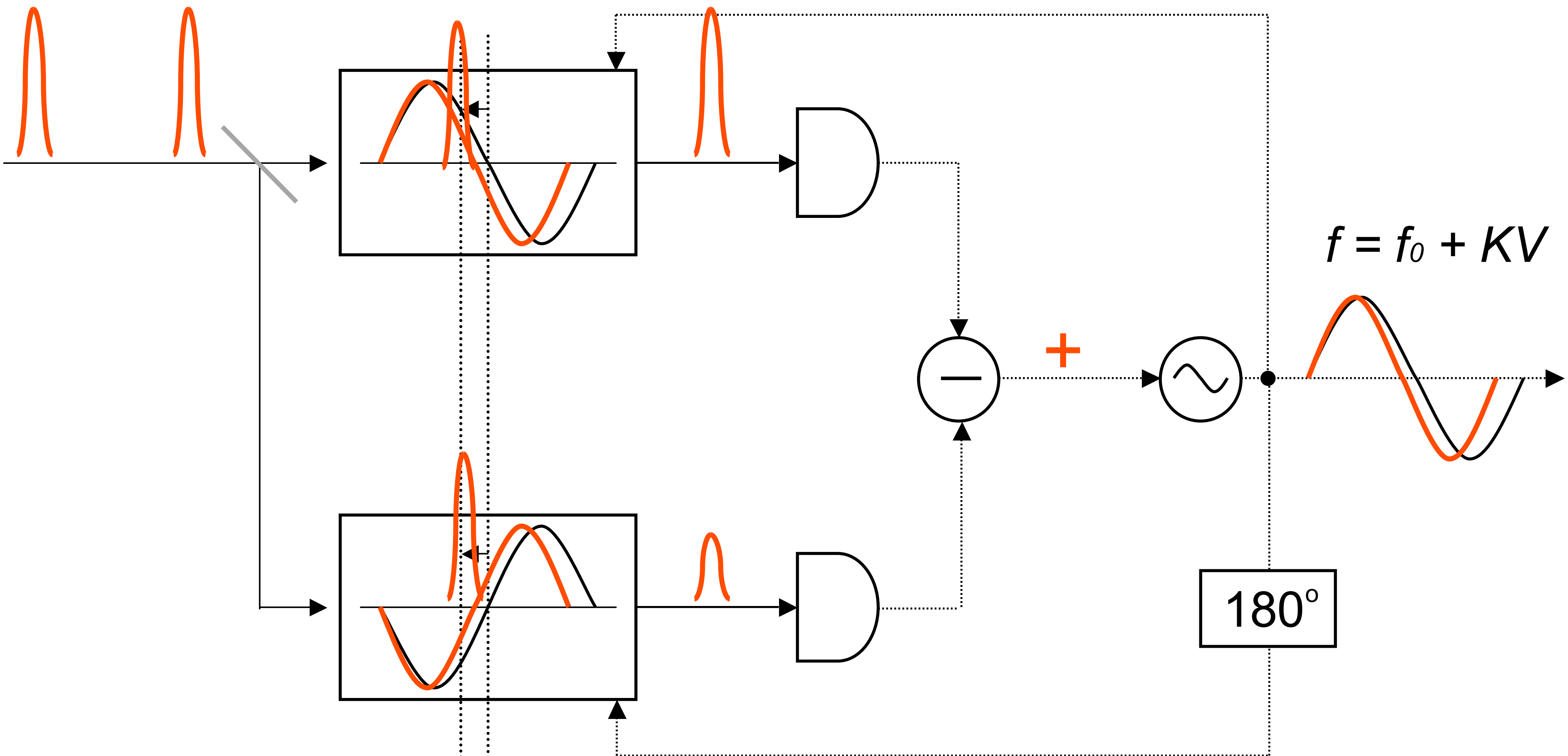
@ 2 GHz



cw spike results in significant increase in phase noise around 10 kHz

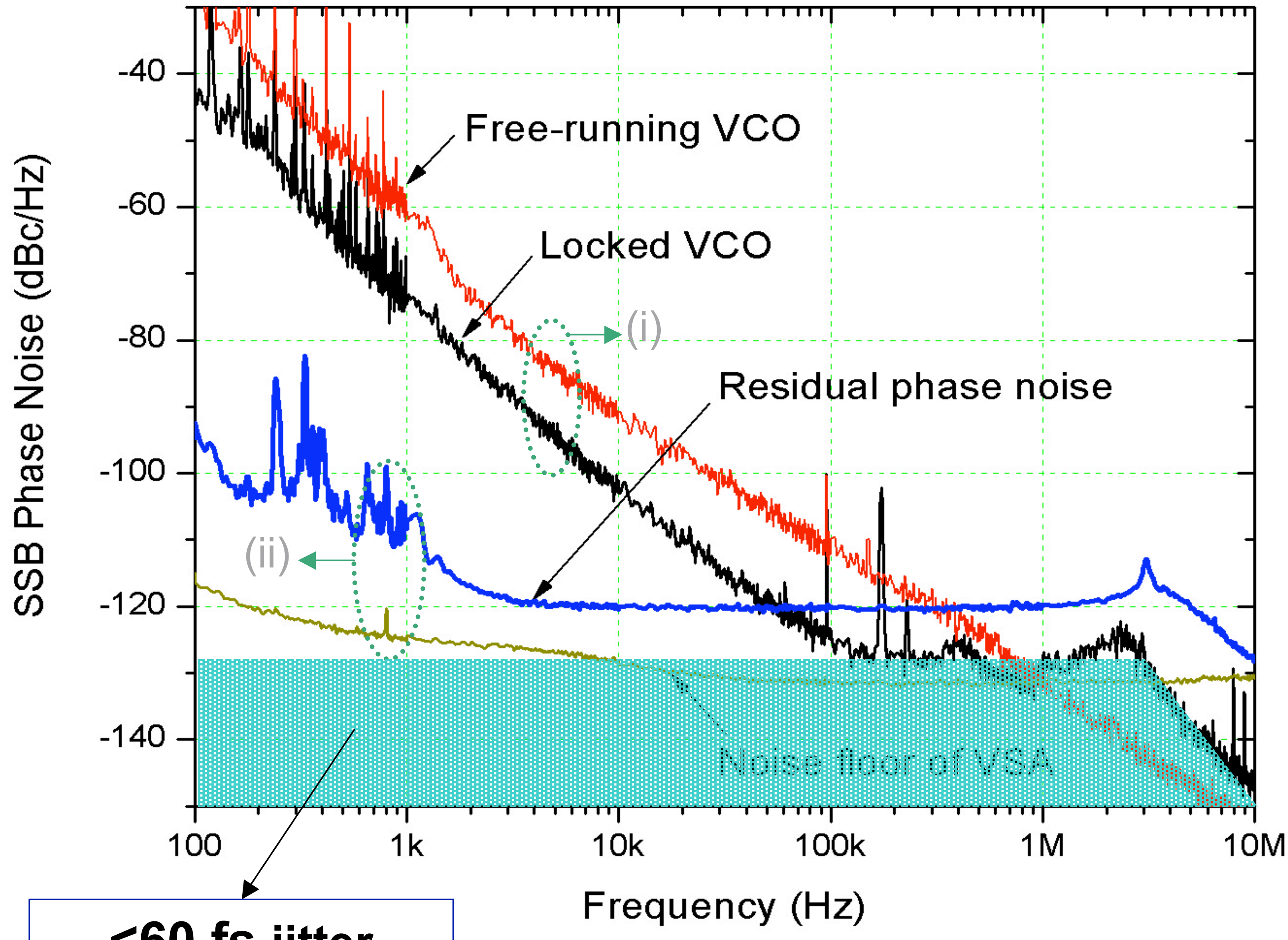
RF-Synchronization Module

It is difficult to accurately measure very small timing variations.



Transfer of timing information into intensity imbalance in optical domain --- easier to measure

Phase Noise Measurement



<60 fs jitter
(100Hz-10MHz)

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