TUOANO02
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Long-term Stable, Large-Scale, Optical Timing Distribution Systems with Sub-Femtosecond Timing Stability

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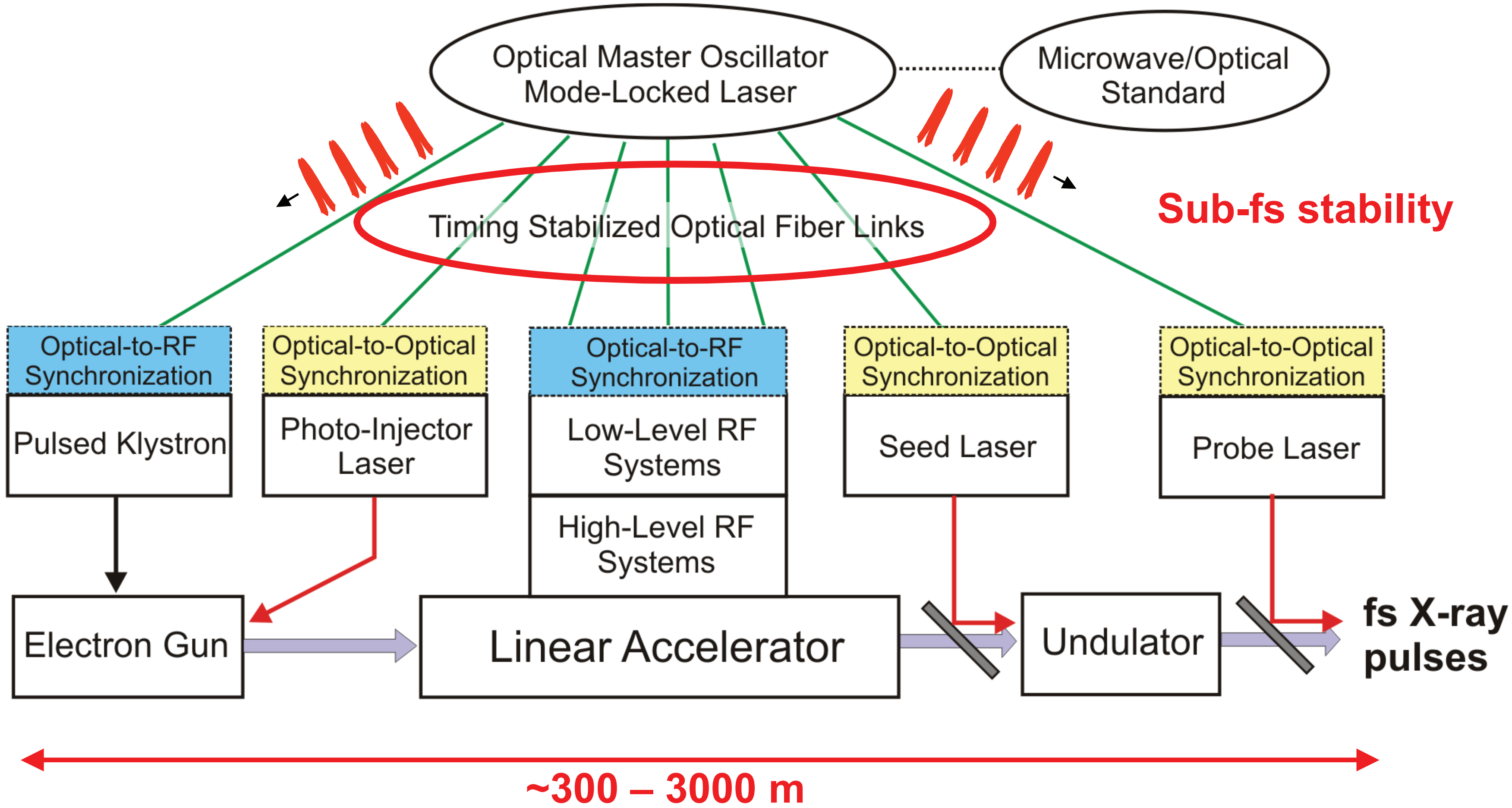
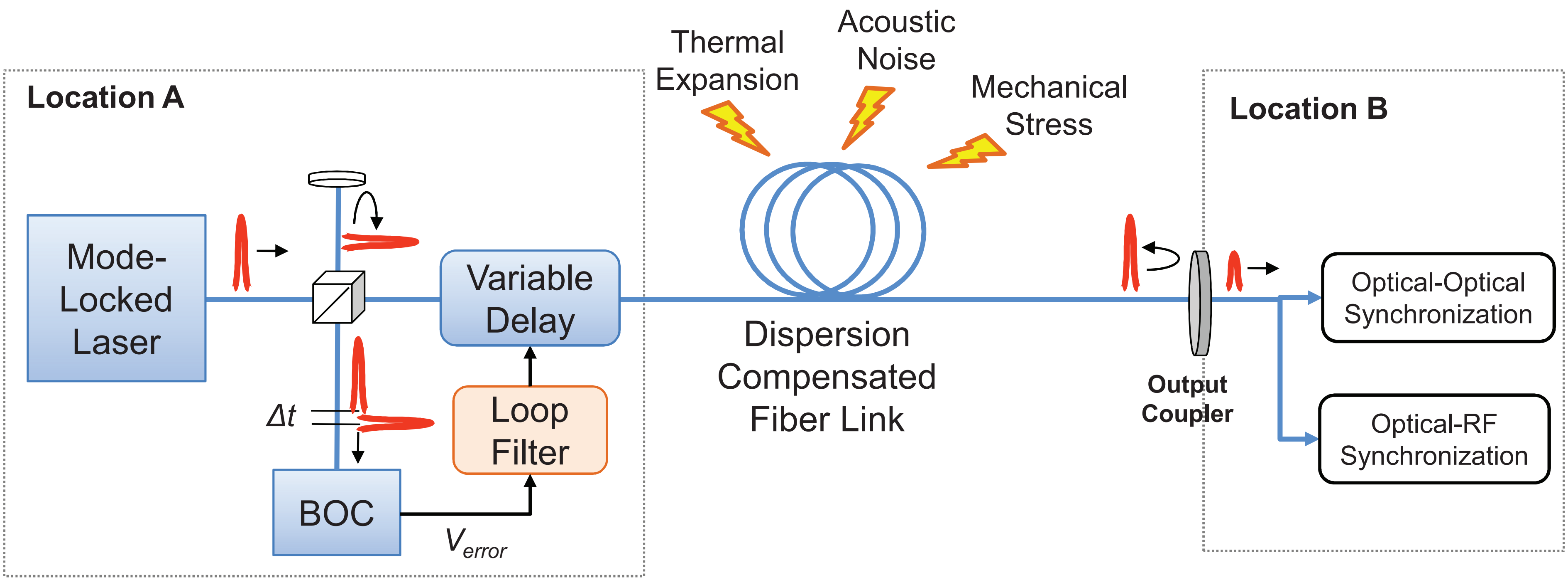
Timing Distribution for X-ray Free Electron Laser



J. Kim et al., Opt. Lett. 32, 9 (2007)
R. Wilcox et al., Opt. Lett. 34, 20 (2009)

Timing Link Stabilization Scheme



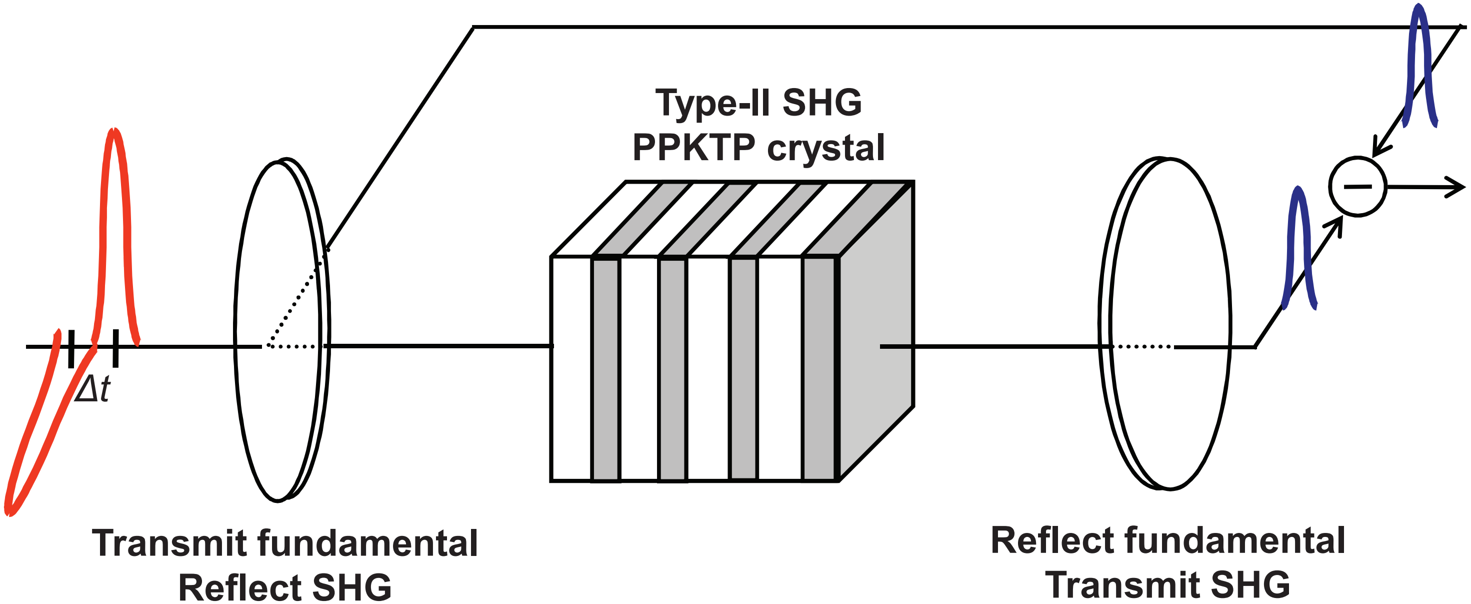
1. Detect timing error at link input

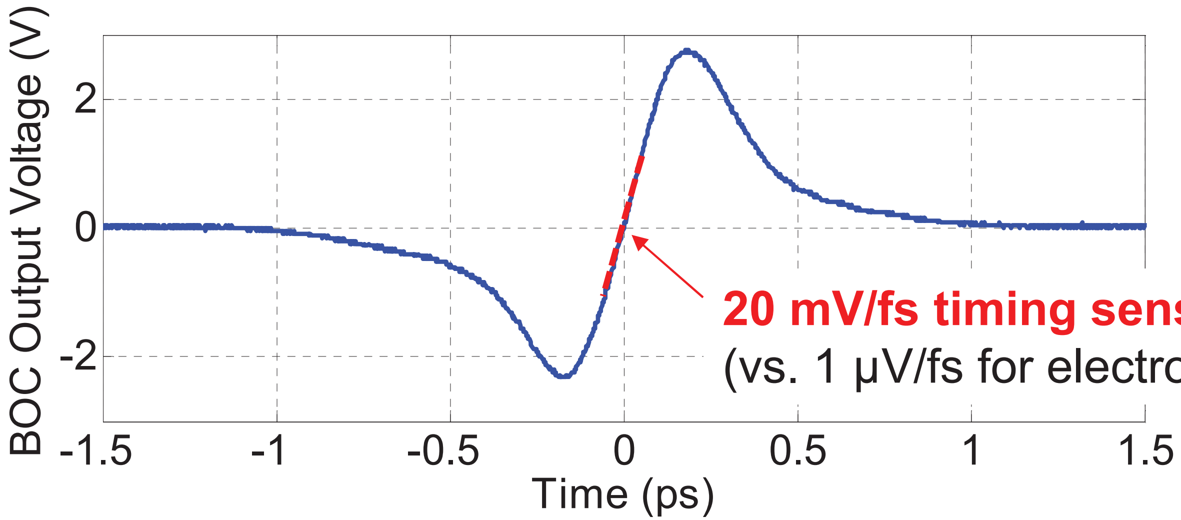
   via Balanced Optical Cross-correlator (BOC)

2. Compensate error with negative feedback

   via Variable Delay

Balanced Optical Cross-Correlator (BOC)

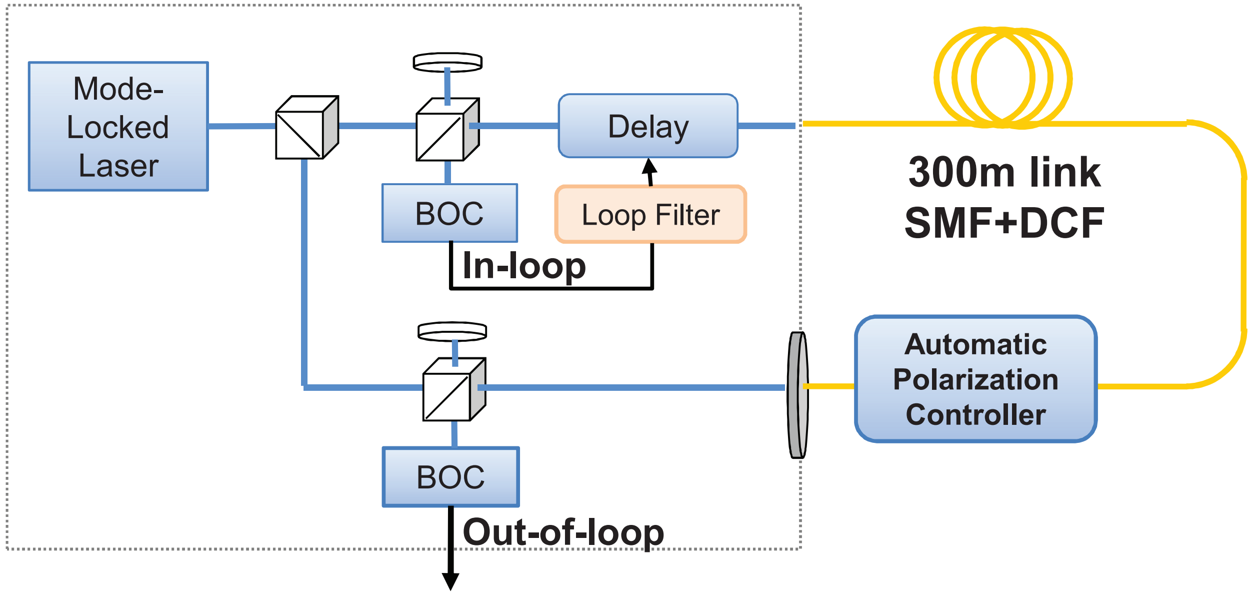


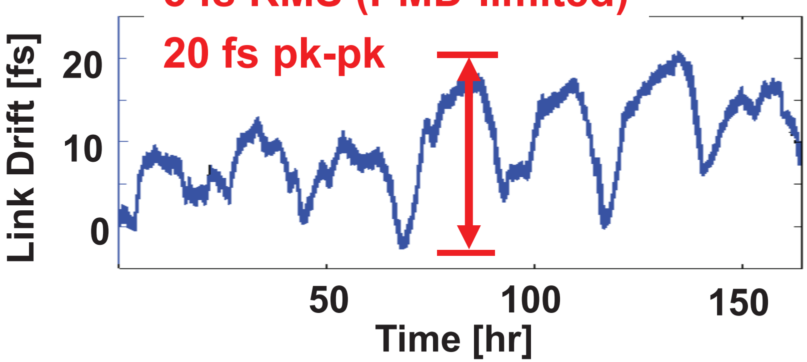


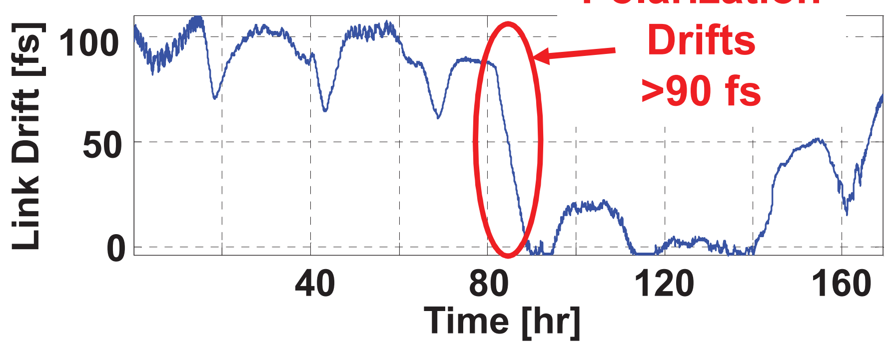
20 mV/fs timing sensitivity
(vs. 1 μV/fs for electronic mixers)

J. Kim et al, Opt. Lett. 32, 9 (2007)
Schibli et al, Opt. Lett. 28, 11 (2003)

Previous Results

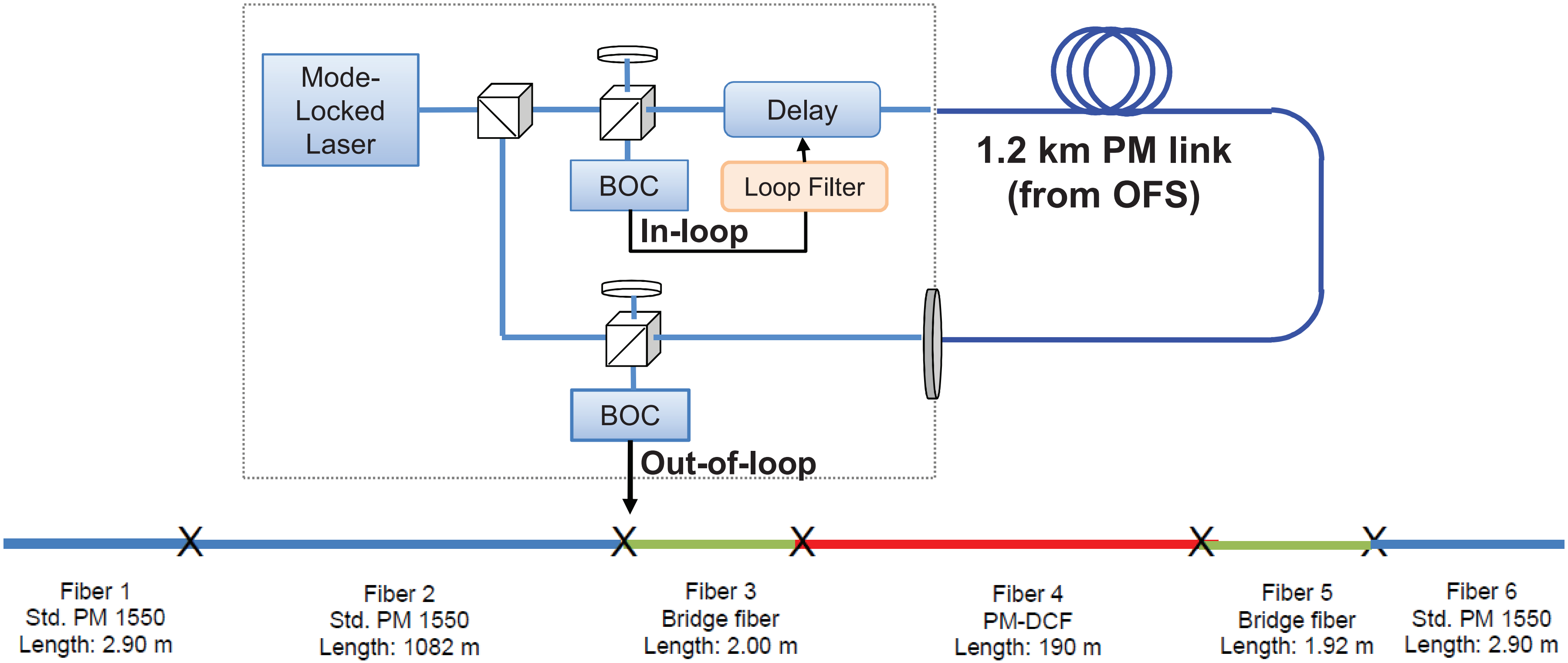






Need to eliminate PMD for sub-fs stability

Eliminating Polarization-Mode Dispersion

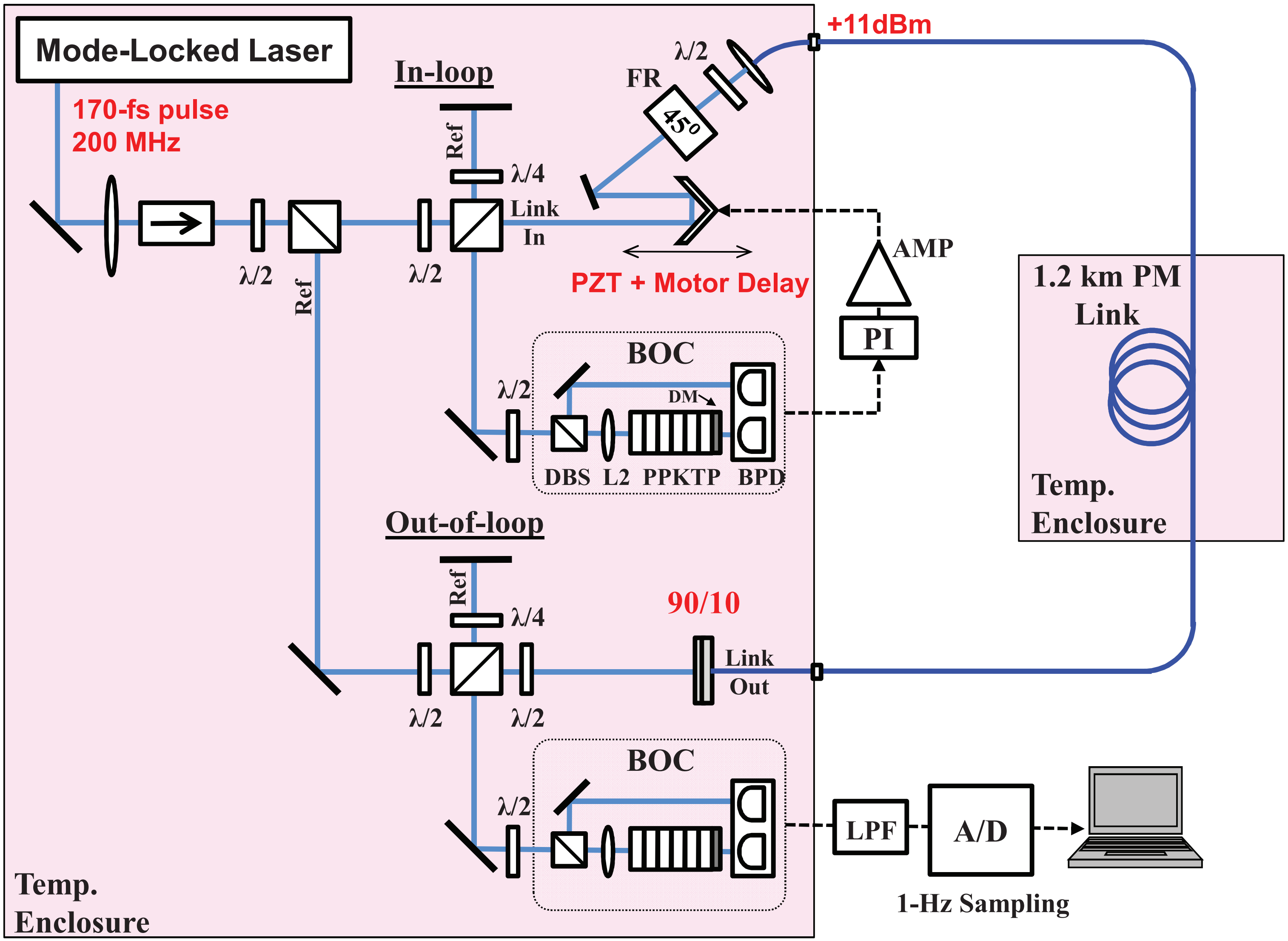


<u>Custom dispersion-compensating PM Fiber</u>

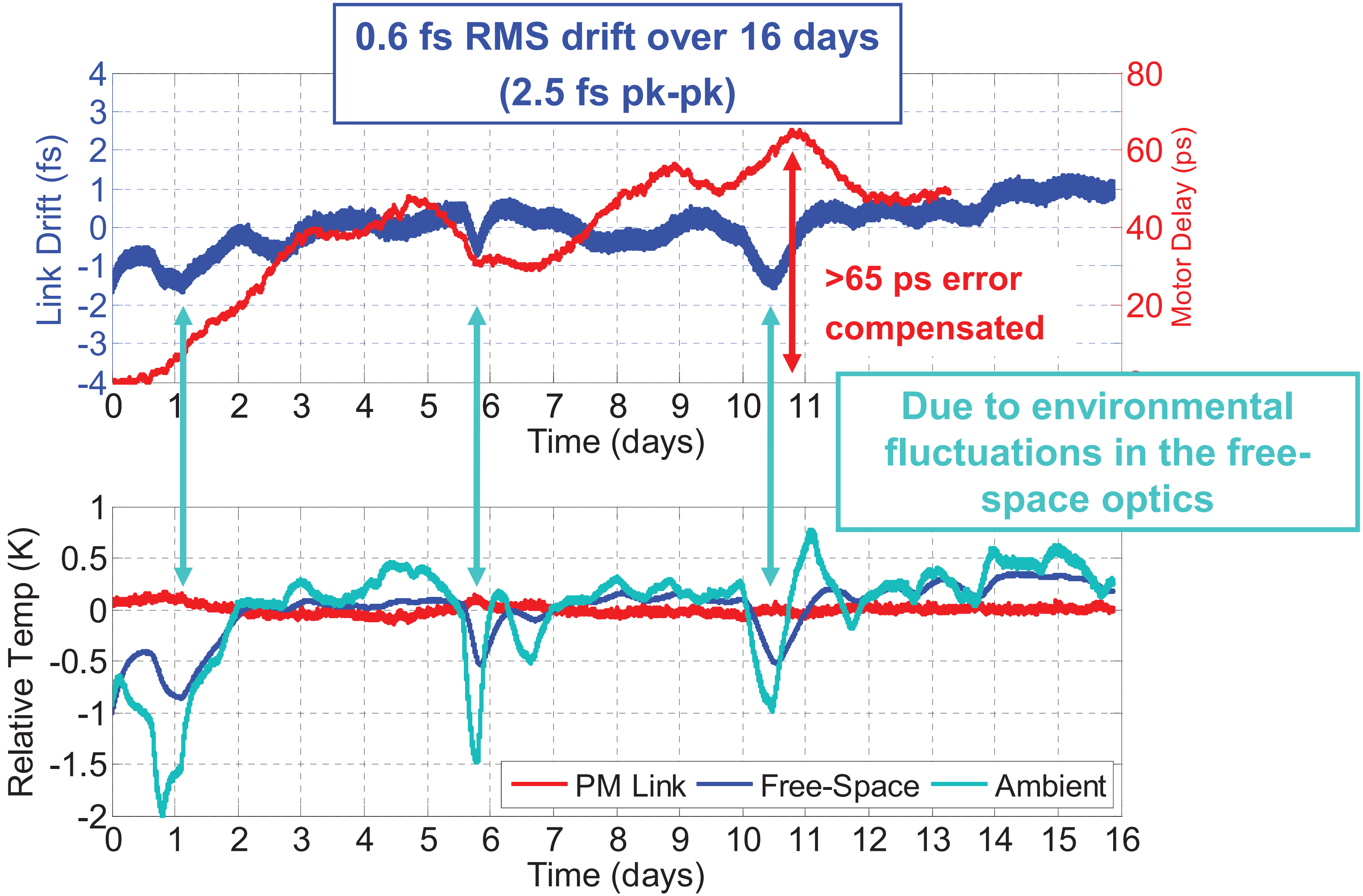
- PANDA-like geometry
- conventional core index profile

D = -104.1 ps/nm·km @1550nm, slow
D’ = -0.34 ps/nm^2·km

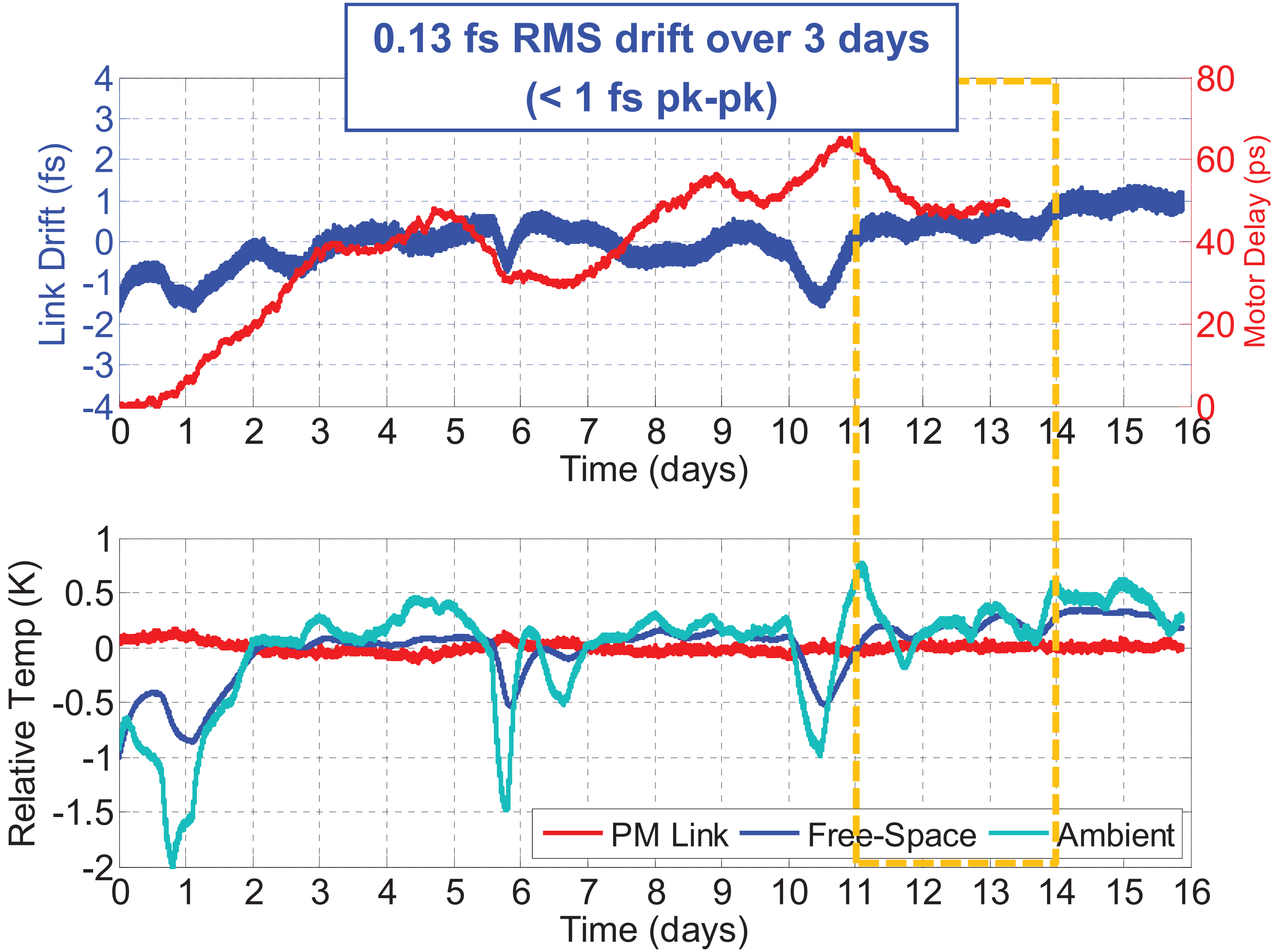
PM Link Testbed with Temperature Stabilization



Long-term Stabilization



Long-term Stabilization

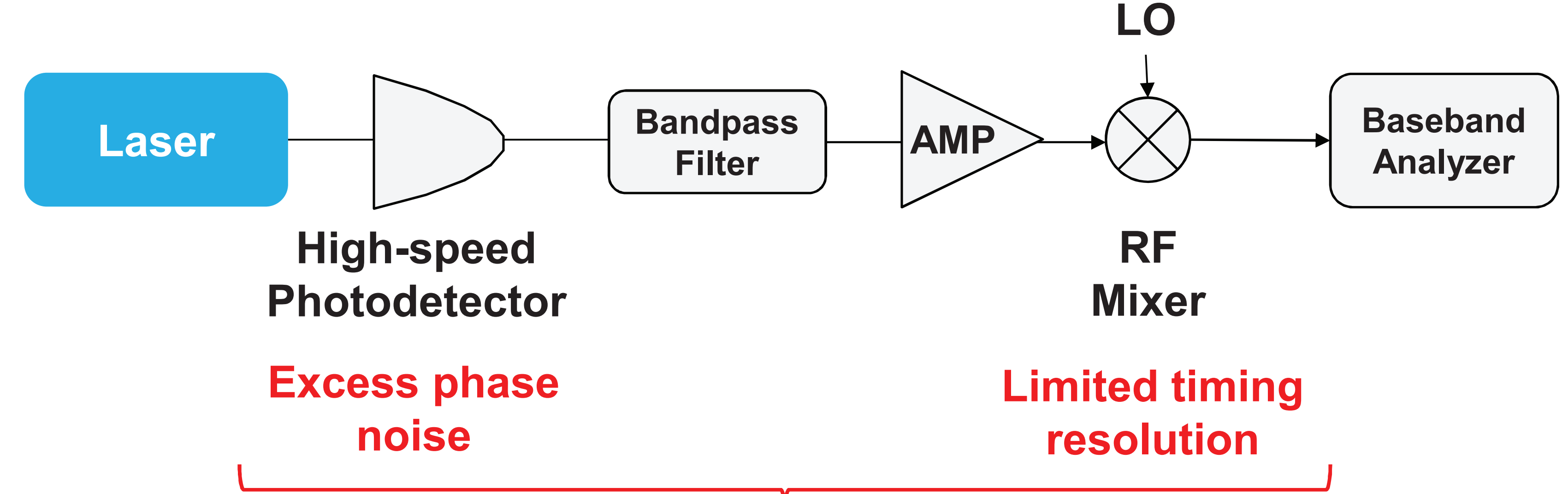


Laser Timing Jitter Measurement

Ultralow-noise femtosecond lasers

- Sub-femtosecond timing jitter
- Commercially available

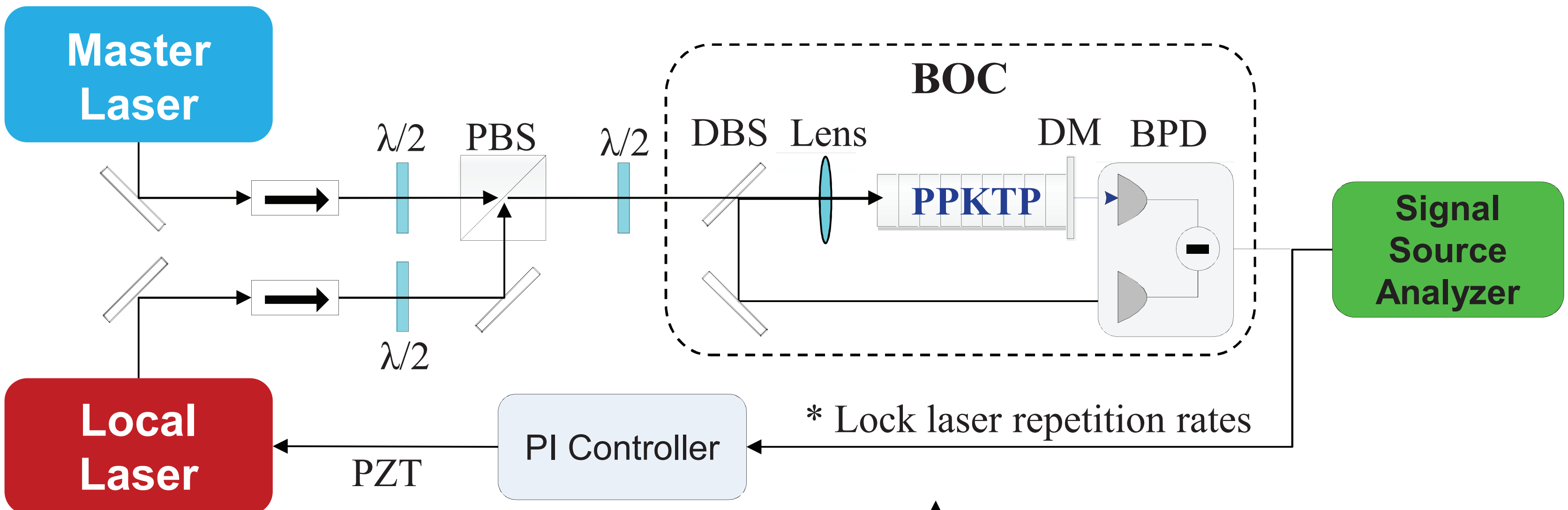
➢ Conventional method



Limited to ~ 1 fs

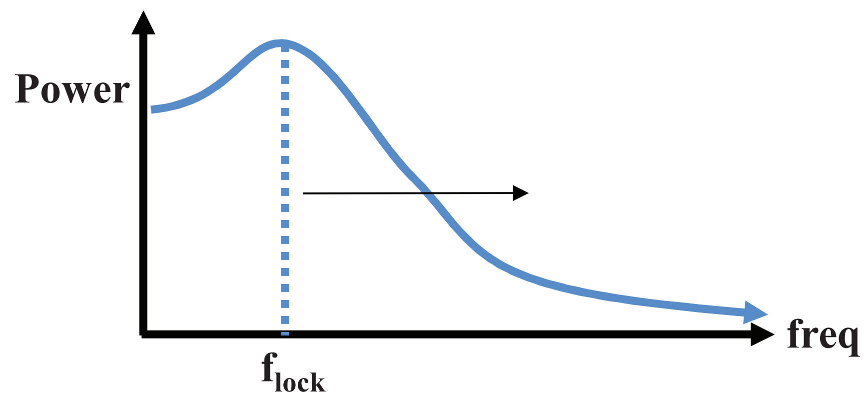
Laser Timing Jitter Measurement

➢ **BOC Method (requires locking laser's repetition rate)**



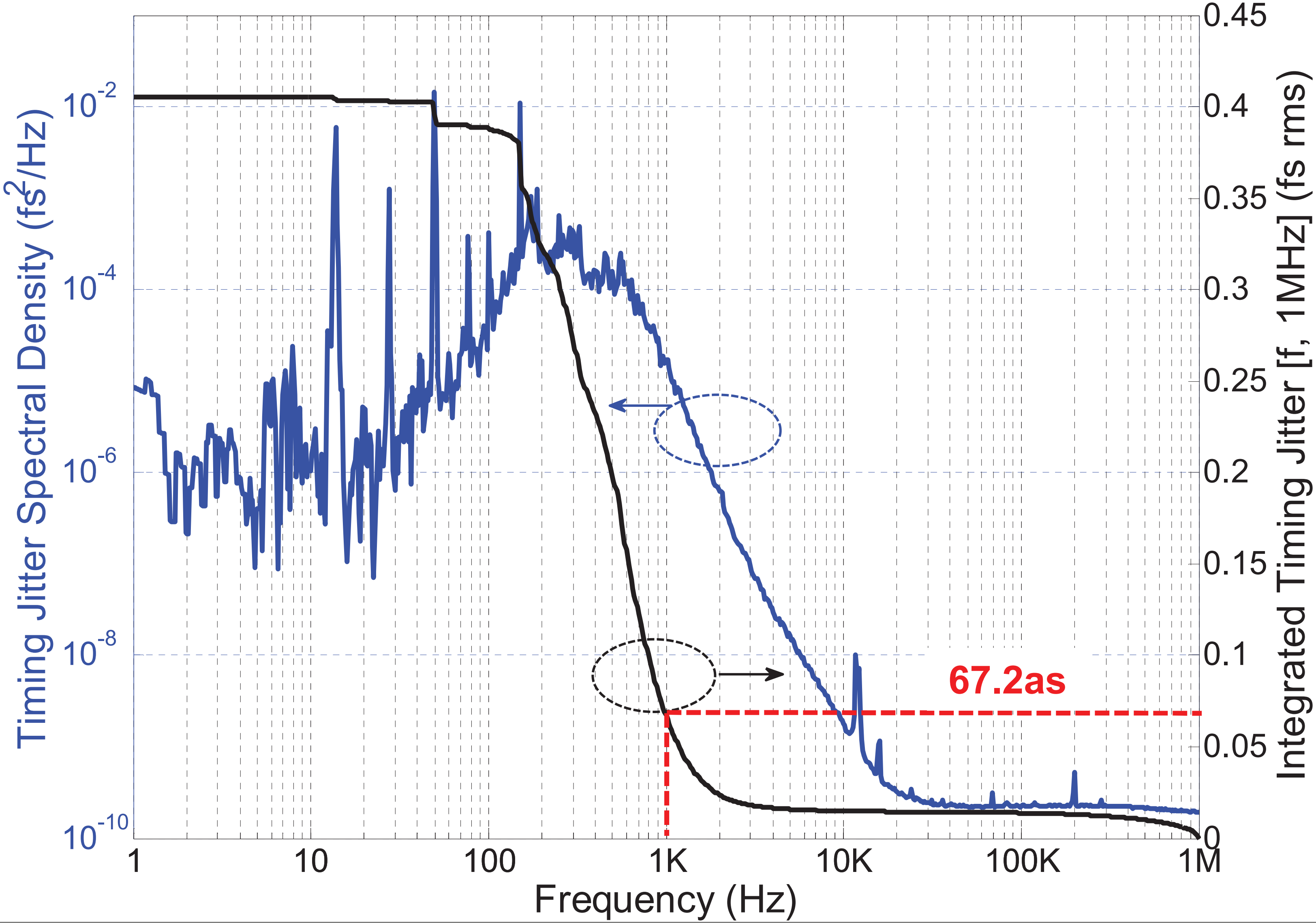
ORIGAMI-15 (Onefive)

170 mW
170 fs
1554 nm



✓ **Timing jitter outside the locking bandwidth measured by SSA**

Timing Jitter measurement results

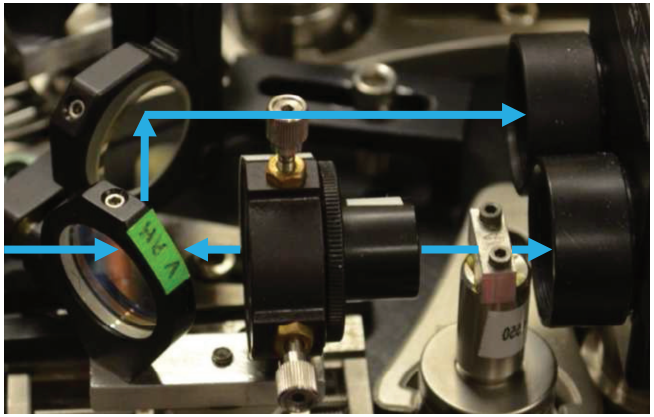


Bulk-Optic vs Waveguide BOC

- Need to improve BOC accuracy…

Bulk-Optic Crystal

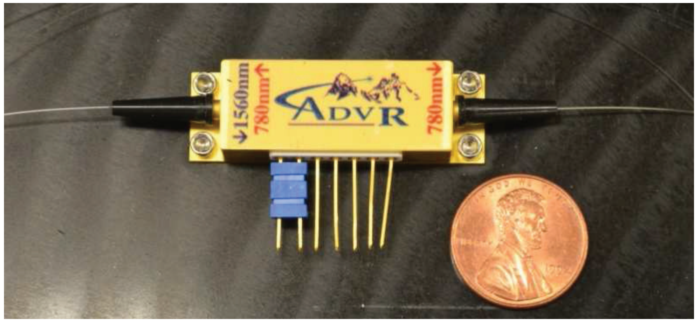
- Poor Environmental Isolation
  - Thermal
  - Acoustic
  - Vibration
- Limited SHG power
  - Fiber nonlinearity



OR

Integrated Waveguides

- Fiber-coupled packaging
  - Ease of implementation
  - Eliminates free-space misalignment and drift
- Higher SHG power
  - Tightly-confined mode
  - Longer interaction length
  - x10–100 SHG efficiency



Comparison of Measured SHG Efficiency

- **Bulk-optic crystal BOC:**

  τ = 200 fs
  f_r = 200 MHz
  $P_{avg,FH}$ = 15 mW
  $P_{avg,SH}$ = 60 μW

  $\Rightarrow \eta$ = 0.4 %*

- **Waveguide BOC:**

  η_0 = 1.76 % / [W-cm^2]
  L ≈ 1.72 mm
  (same input pulses)

  $\Rightarrow \eta$ = 19.5 %
  x 50 increase

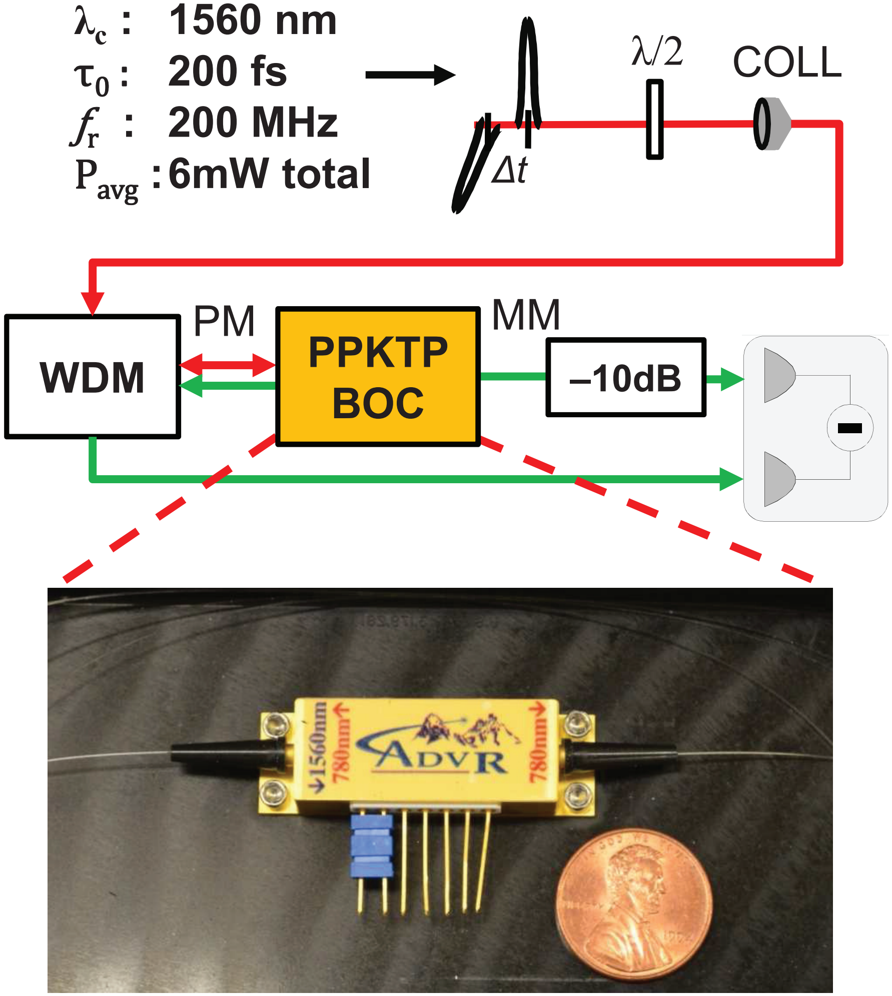
➢ **Lower operating power**
- Reduce nonlinearity-induced timing errors
- Increase number of links

*J. Kim et al., Opt. Lett. 32, 1044 (2007)

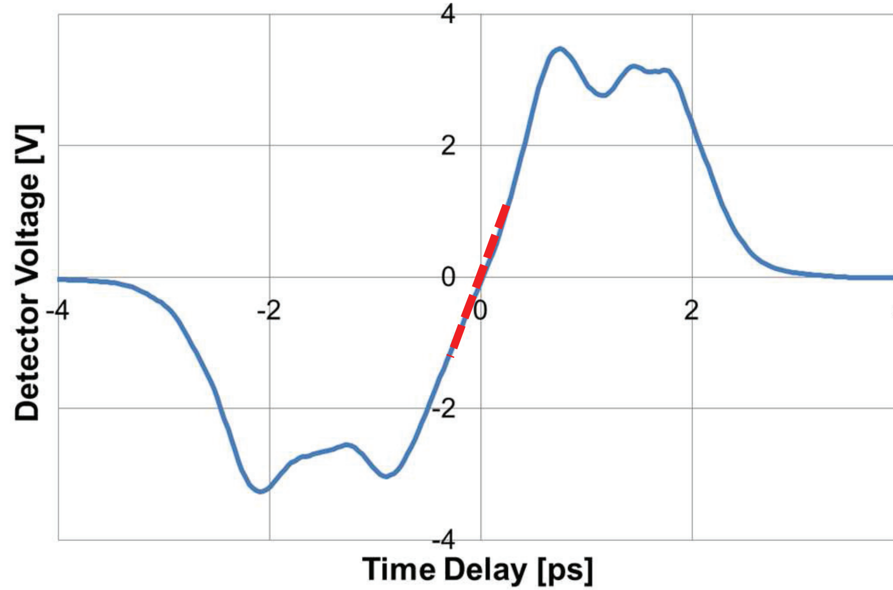
Fiber-Coupled Waveguide Device

Input pulses

λ_c : **1560 nm**
τ_0 : **200 fs**
f_r : **200 MHz**
P_{avg} : **6mW total**



- **Preliminary Device Operation**



4 mV/fs timing sensitivity

Further improvements

- **Coupling loss**
- **Dispersion-compensation**

Conclusion

1.2-km PM Link Stabilization

- PM fiber reduced PMD effects (sub-10fs limited)
  - 0.6 fs RMS drift over 16 days → limited by temperature drifts
  - 0.13 fs RMS drift over 3 days

Laser Timing Jitter

- Low jitter fs lasers commercially available (Onefive-ORIGAMI-15)
  - <70 as integrated jitter for f = [1 kHz, 1 MHz]

Integrated BOC

- Increased SHG conversion efficiency (vs bulk-optic crystals)
  - 50x expected improvement
  - 4 mV/fs measured – can be further improved