INTEGRATED PHOTONICS TO THE RESCUE OF FEMTOSECOND BEAM DIAGNOSTICS

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Department of Physics and The Hamburg Center for Ultrafast Imaging,
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and
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IBIC 2017 - Grand Rapids, Michigan, USA

Acknowledgement

Femtosecond Timing:

M. Xin
A. Kalaydzhyan
M. Peng (JPL)
K. Safak, (Cycle GmbH)
A. Nejadmalayeri (Samsung)
J. Kim (KAIST)
J. Cox (Sandia National Laboratory)

Collaborators:
AdvR: P. Battle, T. Roberts
DESY: H. Schlarb, F. Ludwig,
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Integrated Photonics - ADC:

P. Callahan
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F. Gan (SIMIT)
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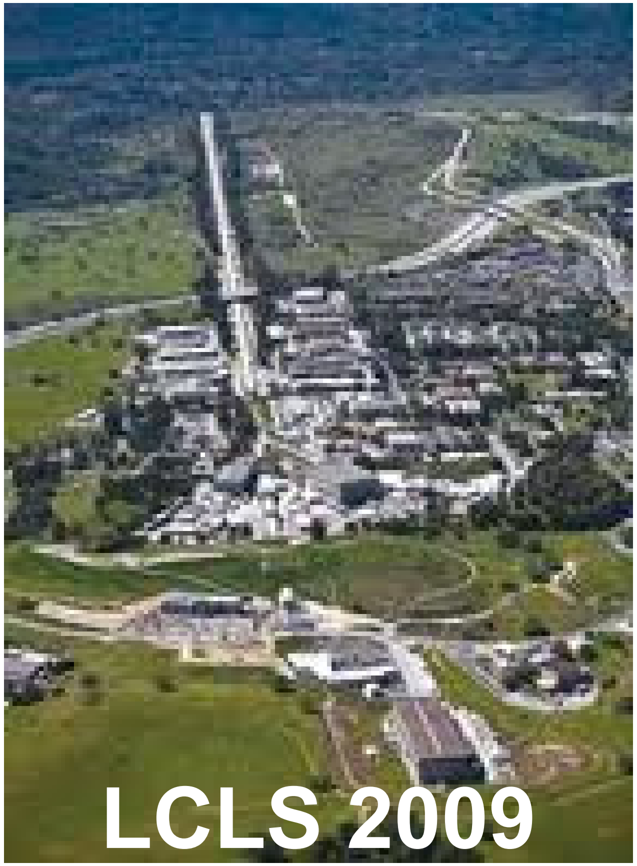
O. O. Olubuyide
M. Park
M. A. Popovic (Boston University)
M. Y. Sander (Boston University)

Collaborators:
MIT: E. Ippen, M. Watts, M. Perrott
MIT-LL: T. Lyszczarz, M. Geis,
M. Grein, S. Spector, J. Wang,
J. Yoon

X-Ray FELs: Combined Accelerator and Laser Facilities


LCLS 2009

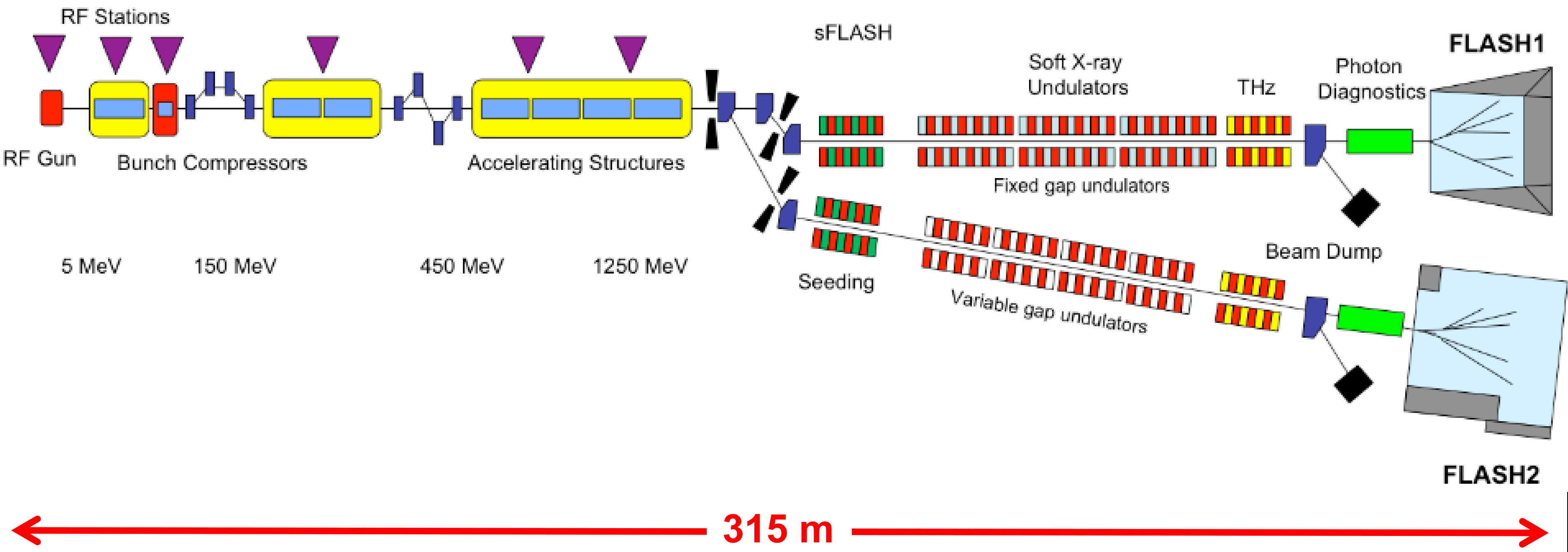

FLASH 2005


FERMI 2010


First Light May 4th, 2017

European XFEL

Lasers in FLASH



Courtesy FLASH Facility

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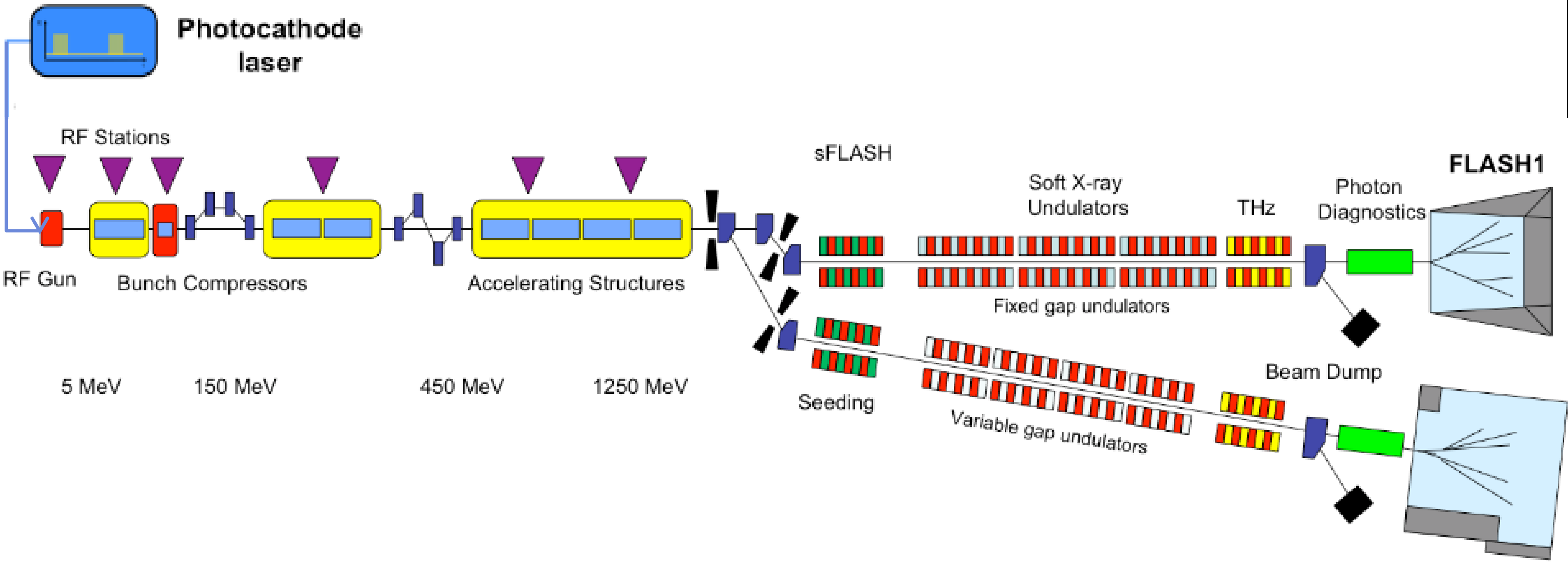
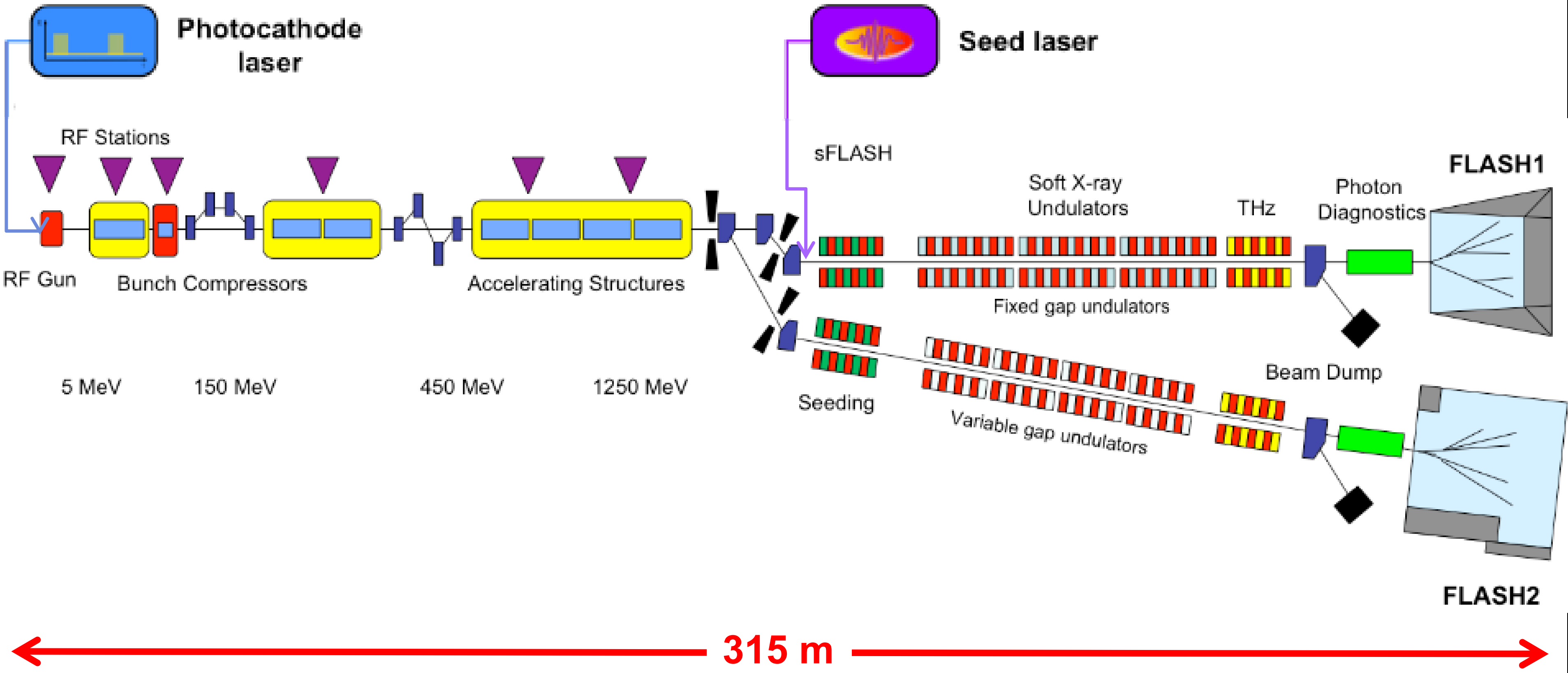


FLASH2

315 m

Courtesy FLASH Facility

Lasers in FLASH



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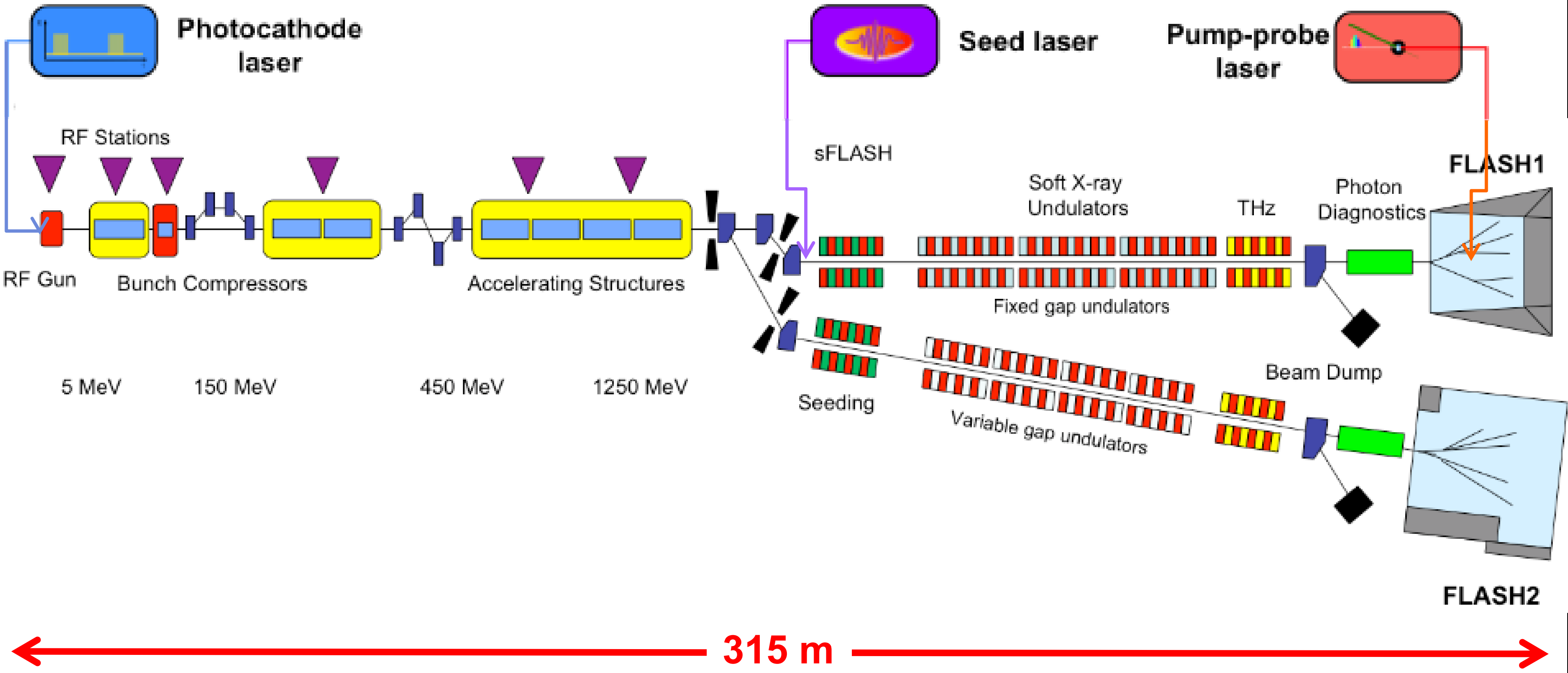

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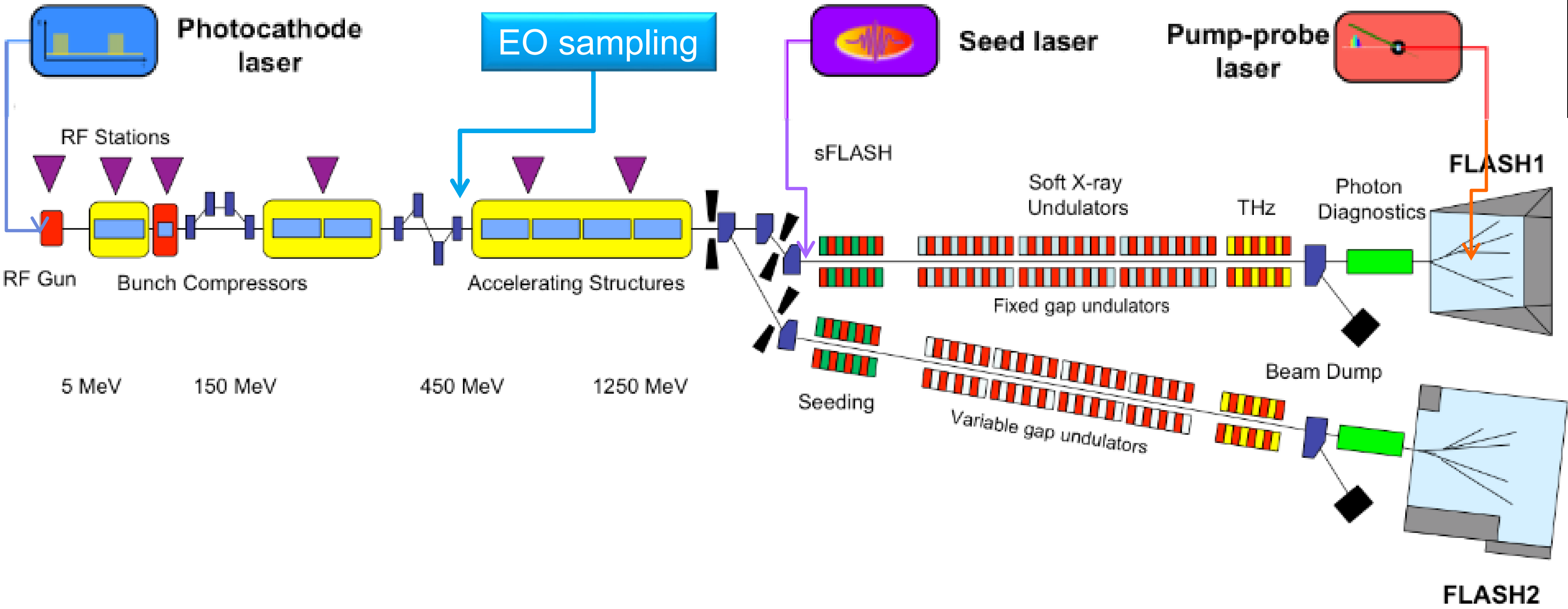
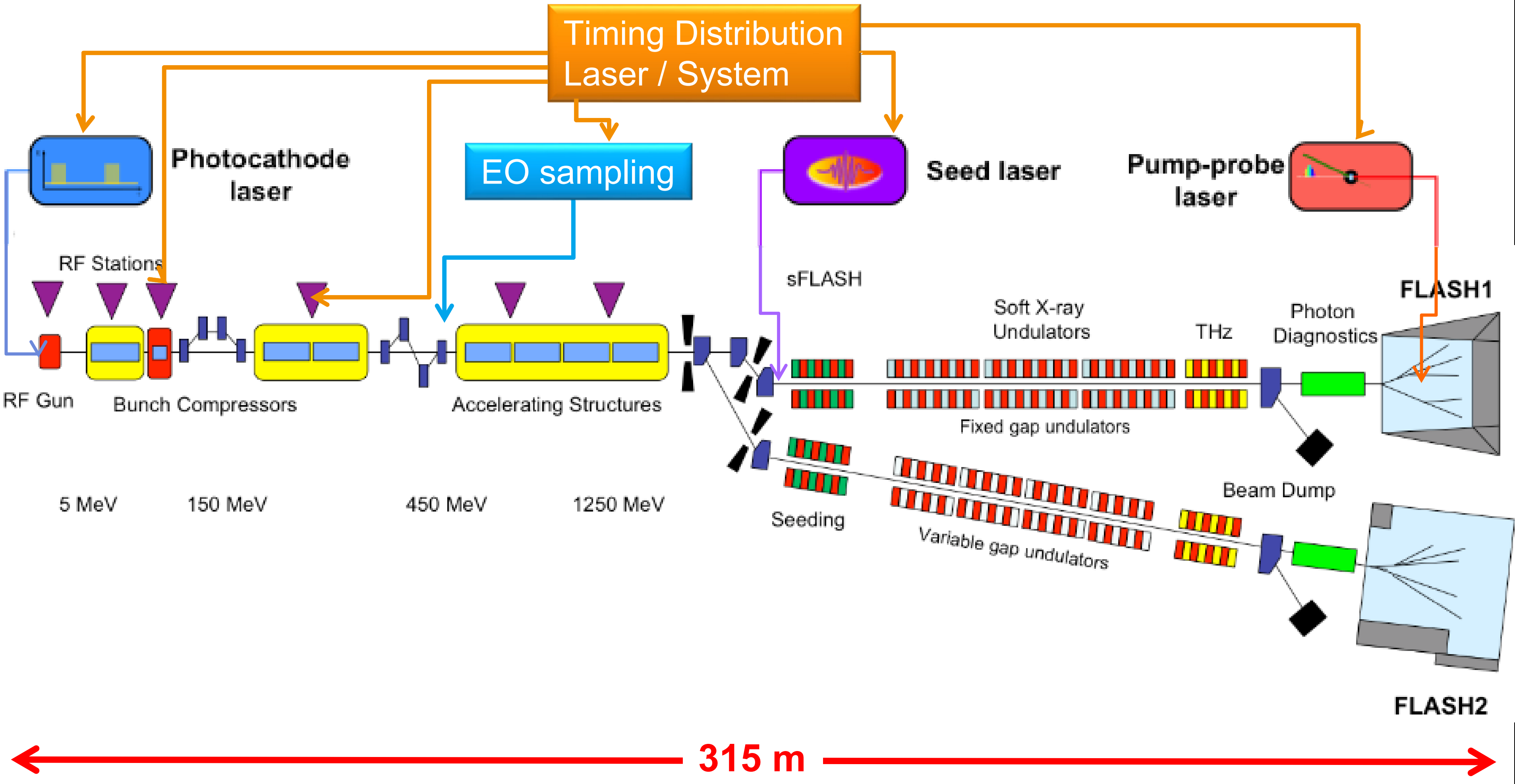


315 m

Courtesy FLASH Facility

Lasers in FLASH



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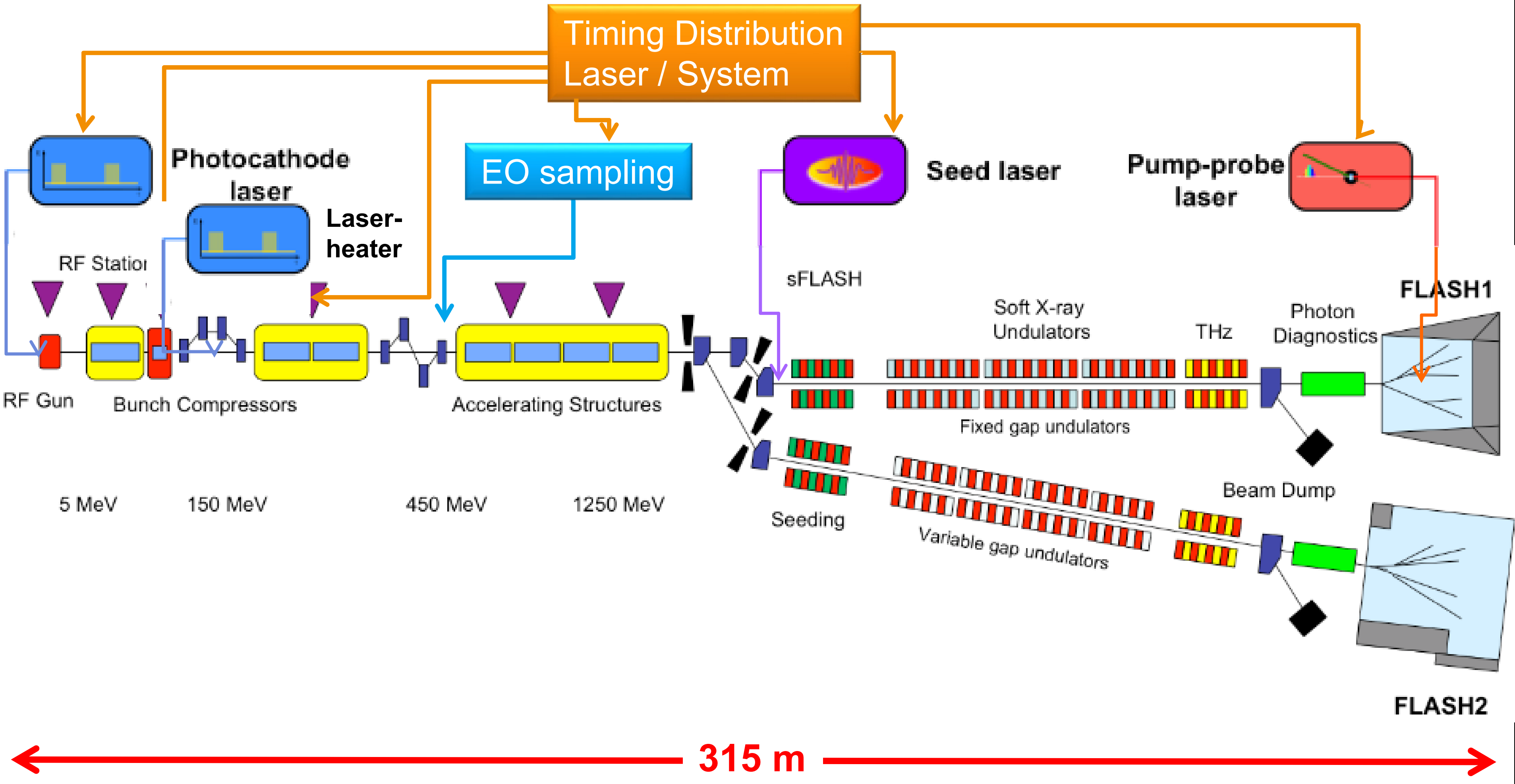
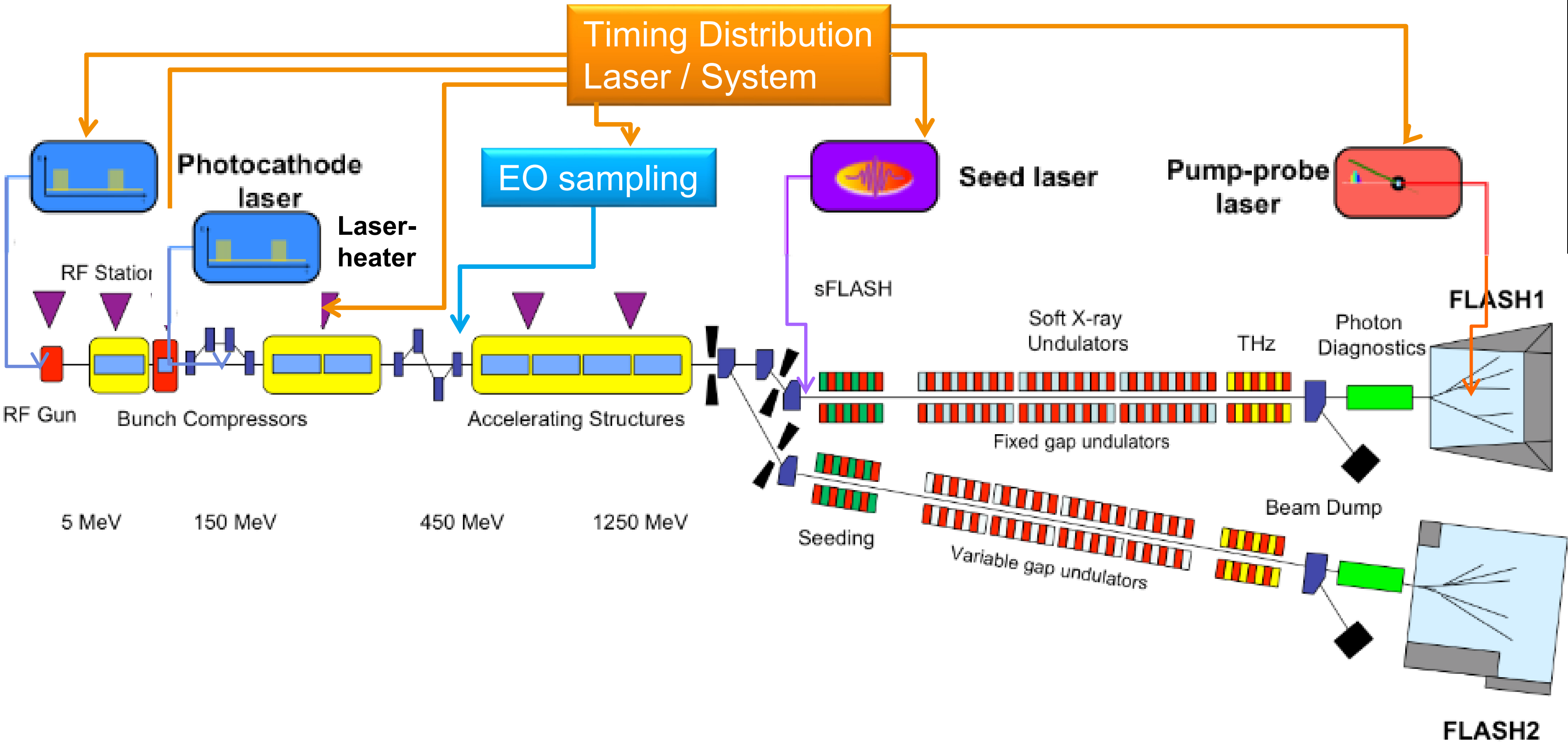


Courtesy FLASH Facility

Lasers in FLASH

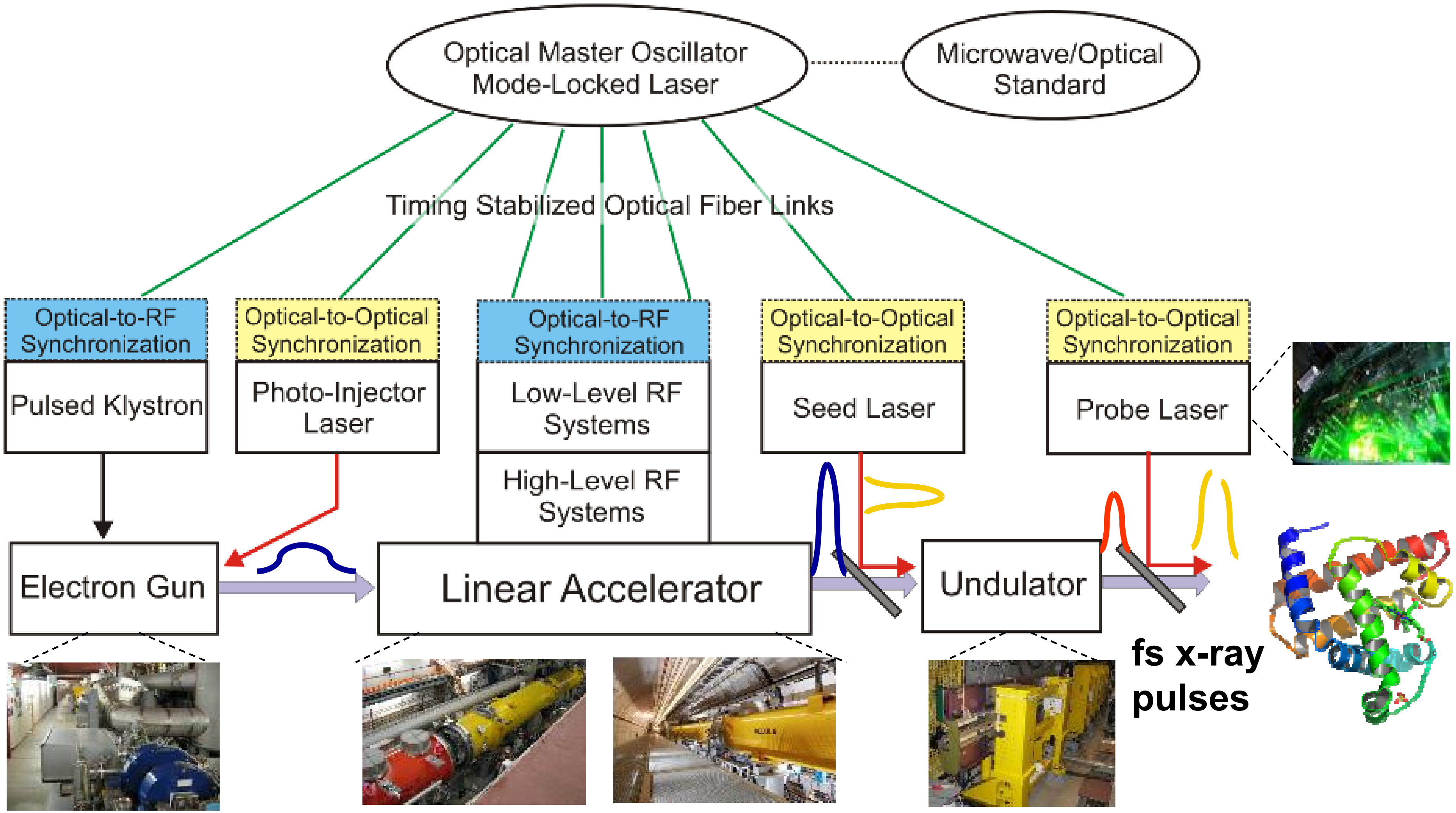
Ultralow loss femtosecond laser



315 m

Courtesy FLASH Facility

Pulsed femtosecond timing distribution



Optical Master Oscillator Mode-Locked Laser

Microwave/Optical Standard

Timing Stabilized Optical Fiber Links

Optical-to-RF Synchronization

Pulsed Klystron

Optical-to-Optical Synchronization

Photo-Injector Laser

Optical-to-RF Synchronization

Low-Level RF Systems

High-Level RF Systems

Optical-to-Optical Synchronization

Seed Laser

Optical-to-Optical Synchronization

Probe Laser

Electron Gun

Linear Accelerator

Undulator

fs x-ray pulses

J. Kim, FXK, FEL 2004

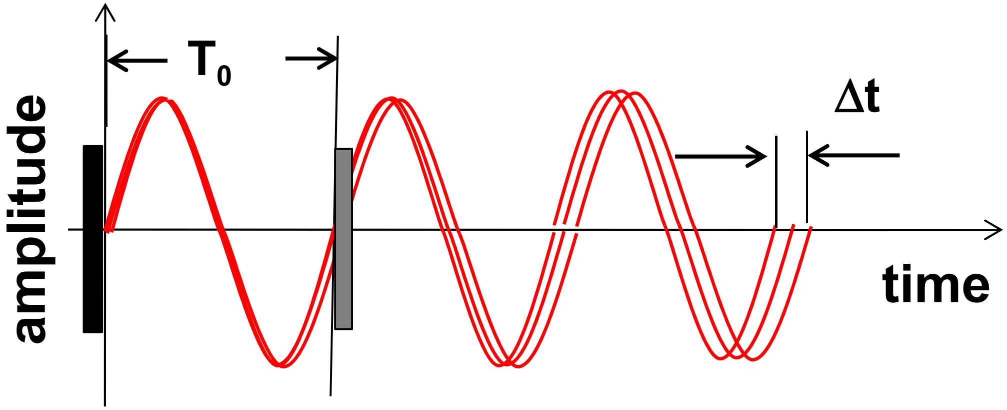
What more can optics, especially integrated optics, do for diagnostics and control?

Outline

- Ultralow Noise Properties of Femtosecond Lasers
  - Inherently lower timing jitter than microwave sources
  - Short pulses, large bandwith → sharp markers in time
  - (fs, …. as)
- Integrated cross-correlators for improved timing
- Analog to Digital Conversion (ADCs)
  - Potential for > 10^3 improvement in Bandwidth x Resolution
  - Silicon Photonics a path to broadband p-ADCs
  - Experimental results
  - Narrowband down-conversion for RF-phase measurement
- MIT Silicon Photonics Platform (Prof. M. Watts)
  - Modulators, Detectors, Filters, cw- and mode-locked Lasers

Timing Jitter of Femtosecond Lasers

Electronic Oscillator



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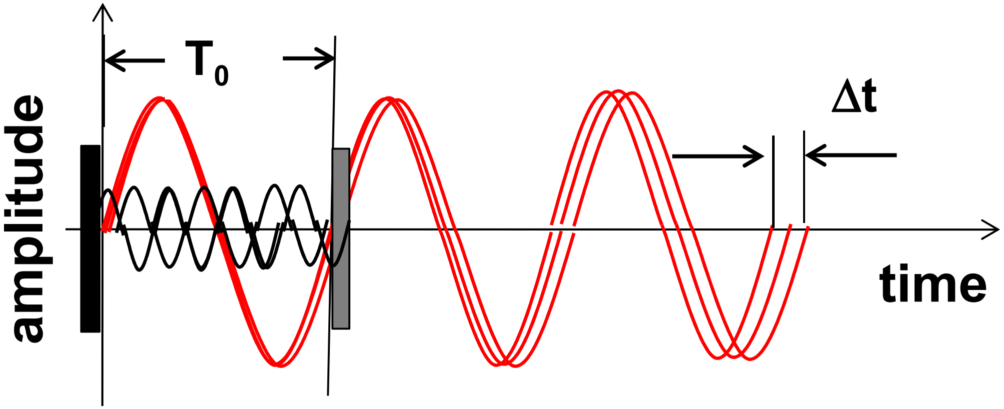

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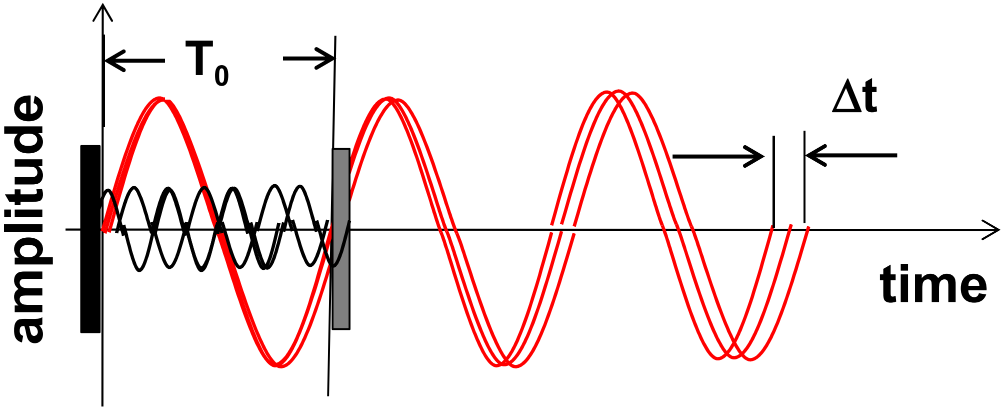

Dissipation-Fluctuation Theorem

$$\frac{d}{dt} < \Delta t_{RF}^2 > \approx T_0^2 \cdot \frac{1}{W_{\mathrm{mode}}} \cdot \frac{kT}{\tau_{cav}}$$

period ~100ps

cavity lifetime

kT = thermal energy

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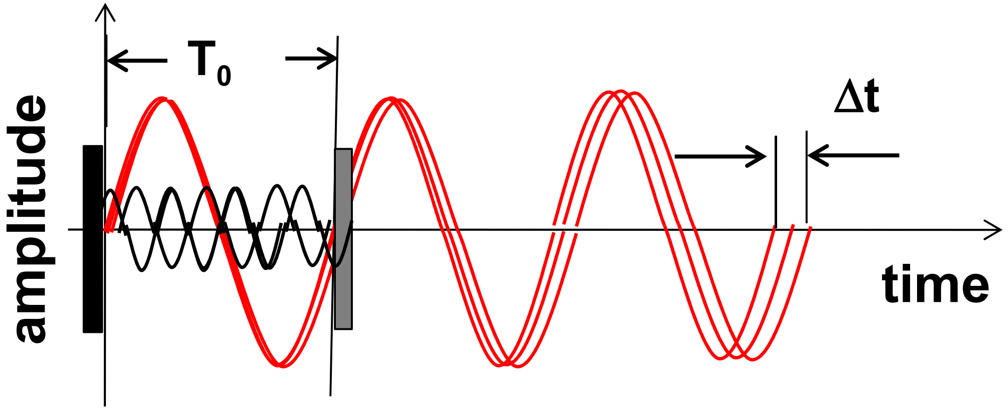
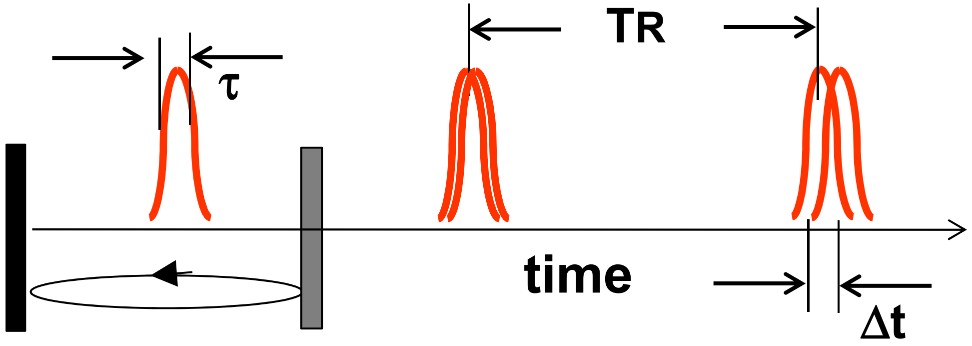


Femtosecond Laser



Optical Cavity

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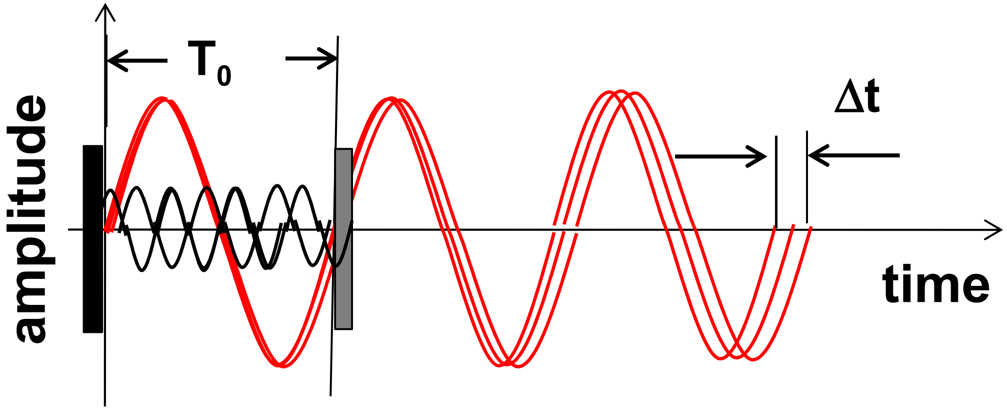

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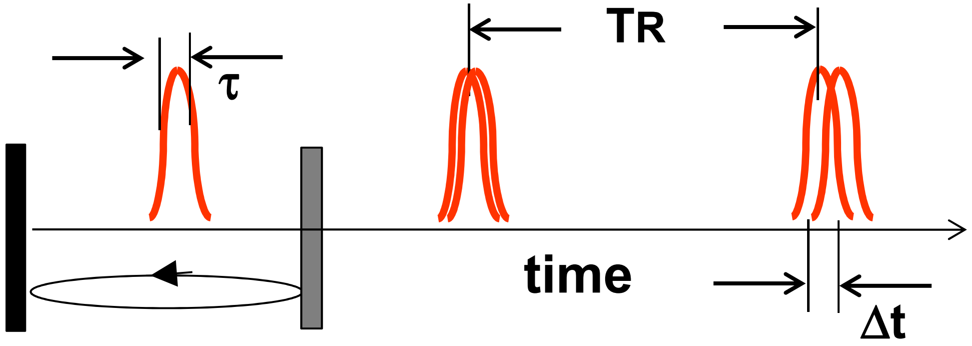

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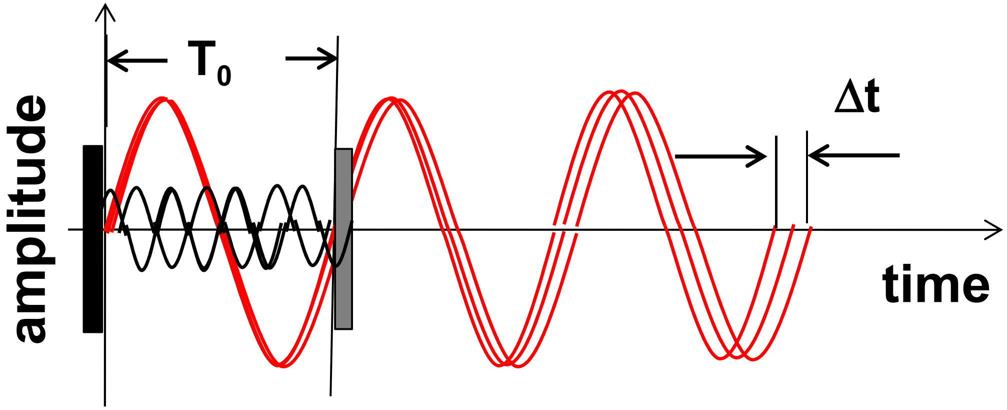

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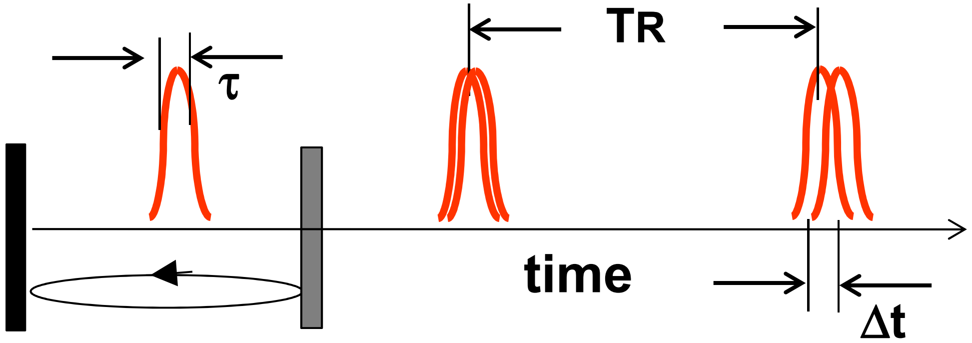

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period ~100ps

cavity lifetime

10^{-6}

pulse width ~100fs

$$\frac{d}{dt} < \Delta t_{ML}^2 > \approx \tau^2 \cdot \frac{1}{W_{pulse}} \cdot \frac{\hbar\omega_c}{\tau_{cav}}$$

$$\hbar\omega_c \sim 50kT$$

kT = thermal energy

$\hbar\omega_c$ = photon energy

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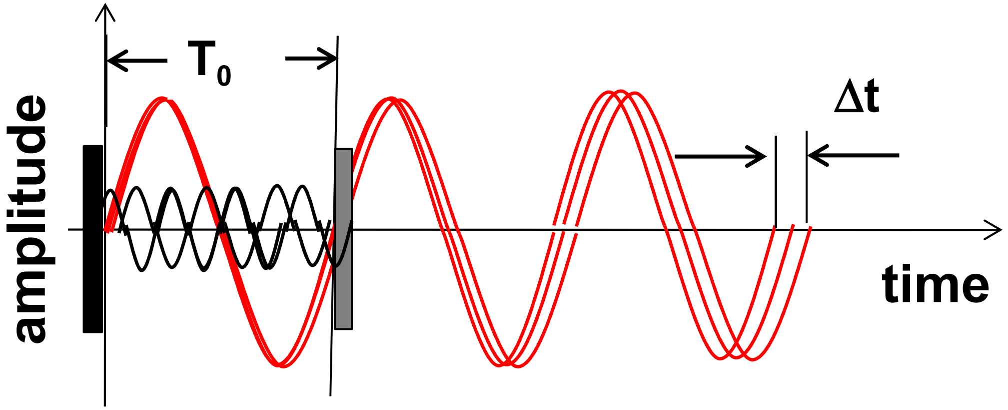

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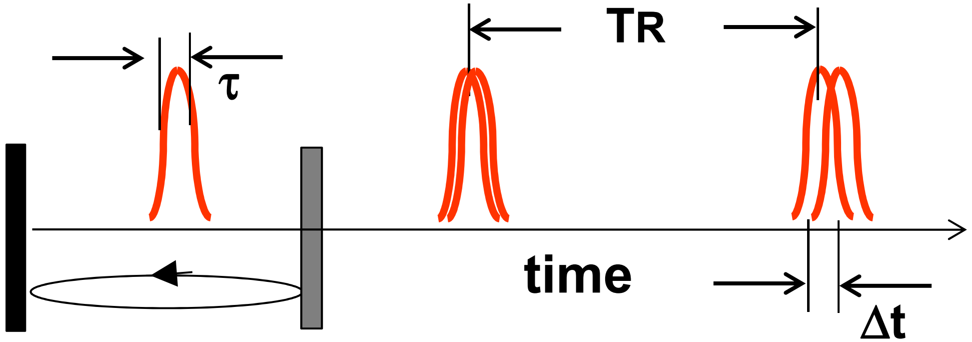

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Timing, Synchronization and Sampling

Femtosecond lasers are very low jitter:

- High intracavity pulse energy
- High Q Cavity
- 10 - 100 fs pulses, good time markers (e.g. EOS)

→ sub-femtosecond jitter for f > 1kHz

Balanced optical cross correlation:

- High timing sensitivity (zeptoseconds)
- low drift (only dielectrics involved)
- attosecond laser to laser locks

→ attosecond laser-to-laser locks and fiber links

Balanced optical microwave phase detection:

- sub-femtosecond jitter microwaves

J. Kim, et al. Nat. Photonics 2, 733 (2008).

How Do We Measure Low Jitter?

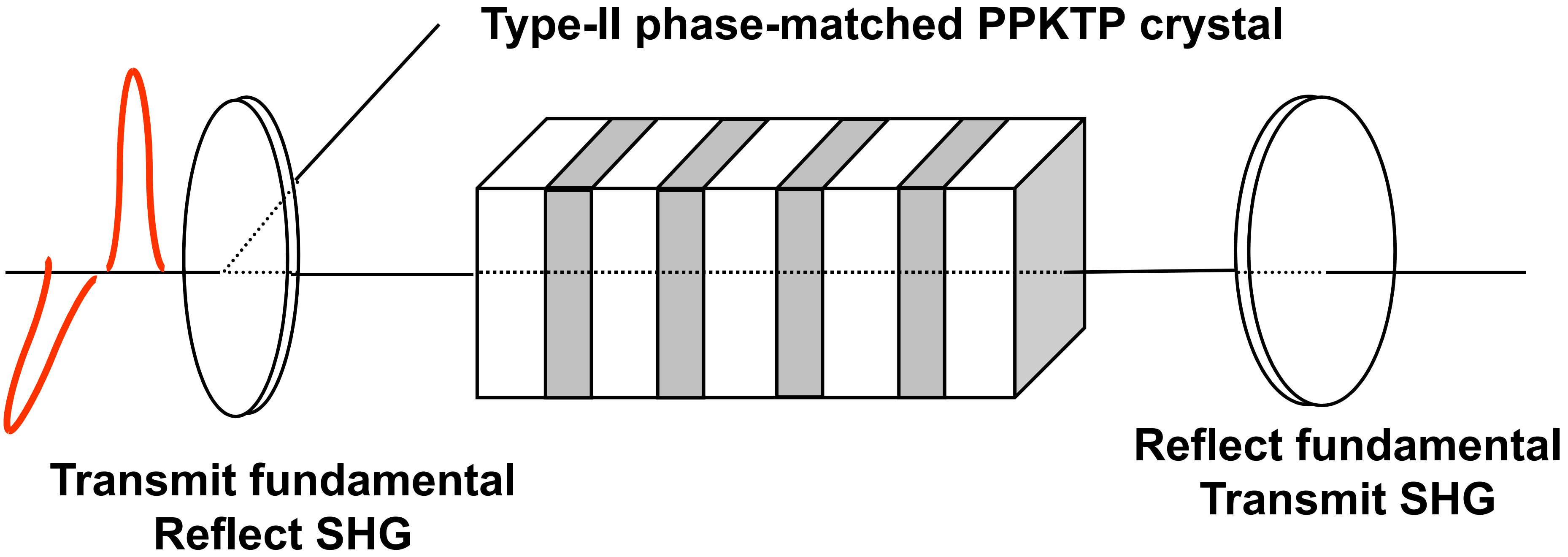
Sensitive Time Delay Measurements

by

Balanced Optical Cross Correlation

Single-crystal balanced cross-correlator

T. Schibli et al, OL 28, 947 (2003)



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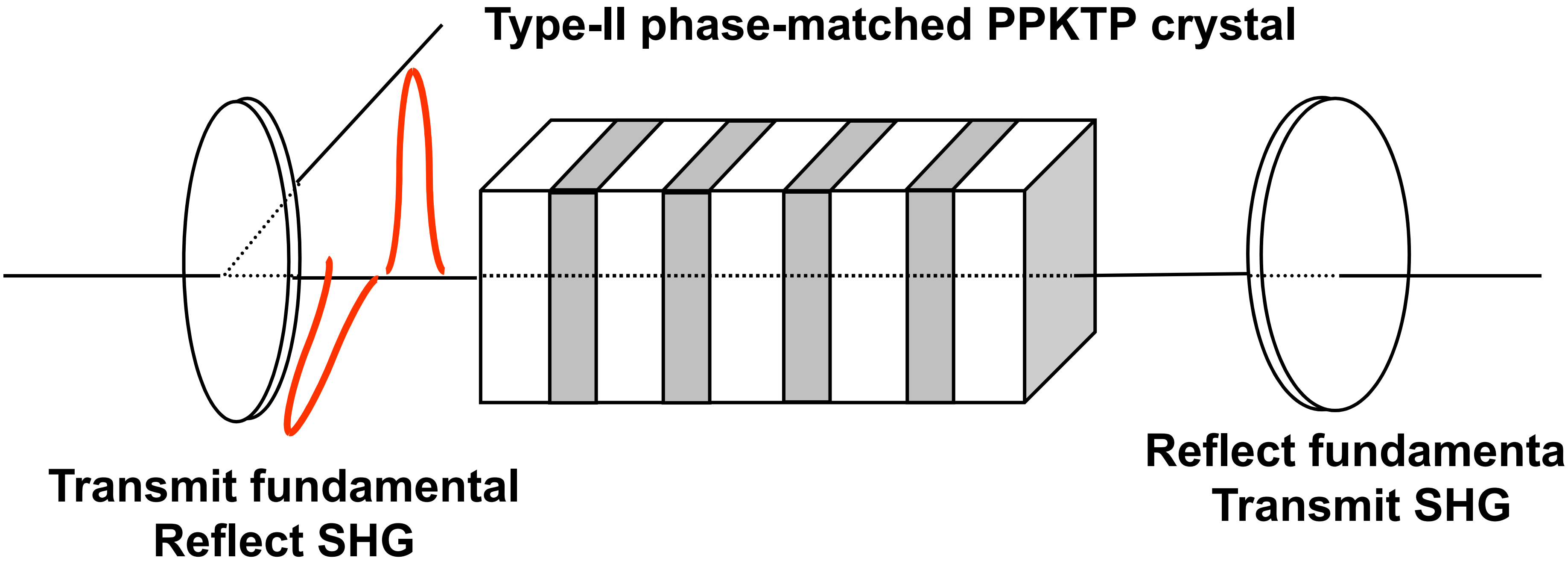
Type-II phase-matched PPKTP crystal

Transmit fundamental
Reflect SHG

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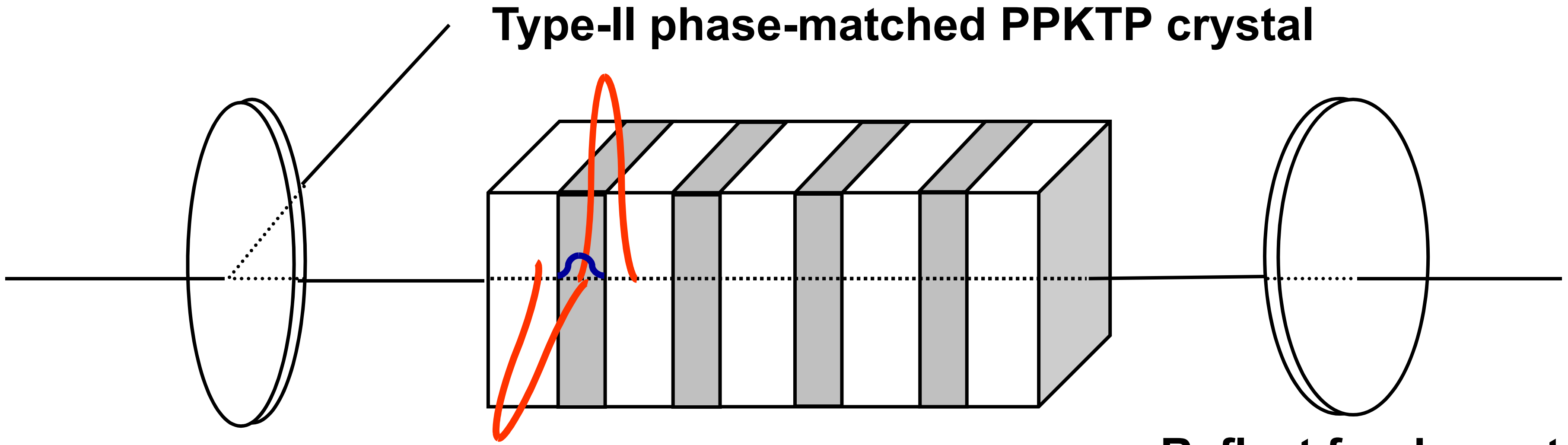

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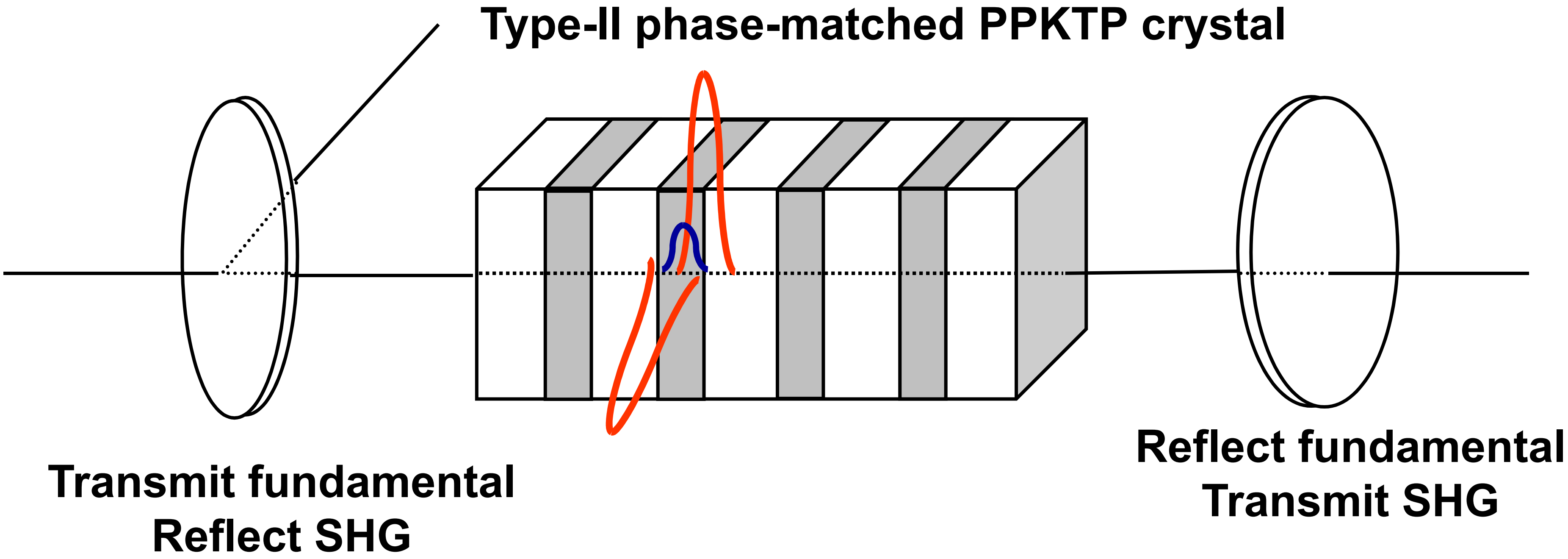

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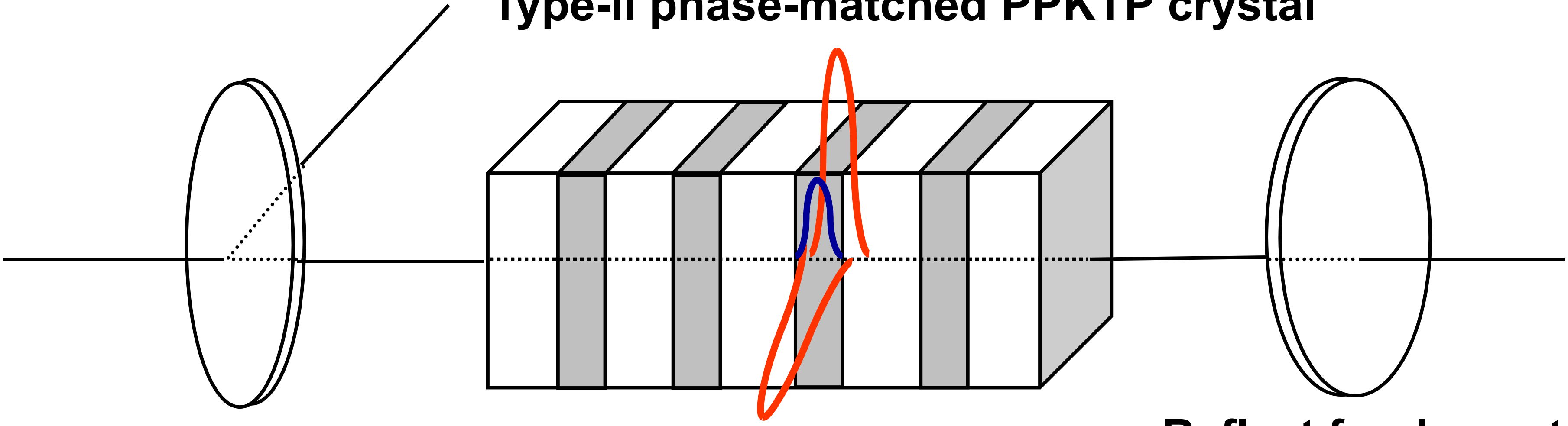

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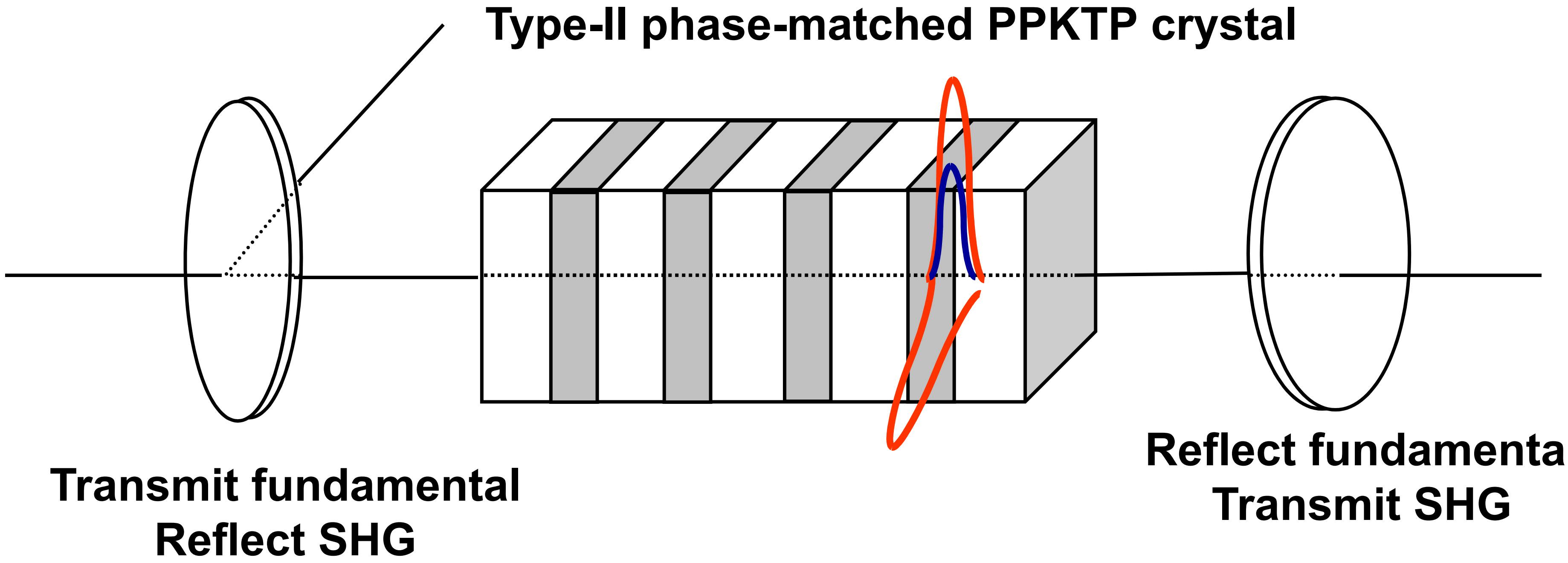

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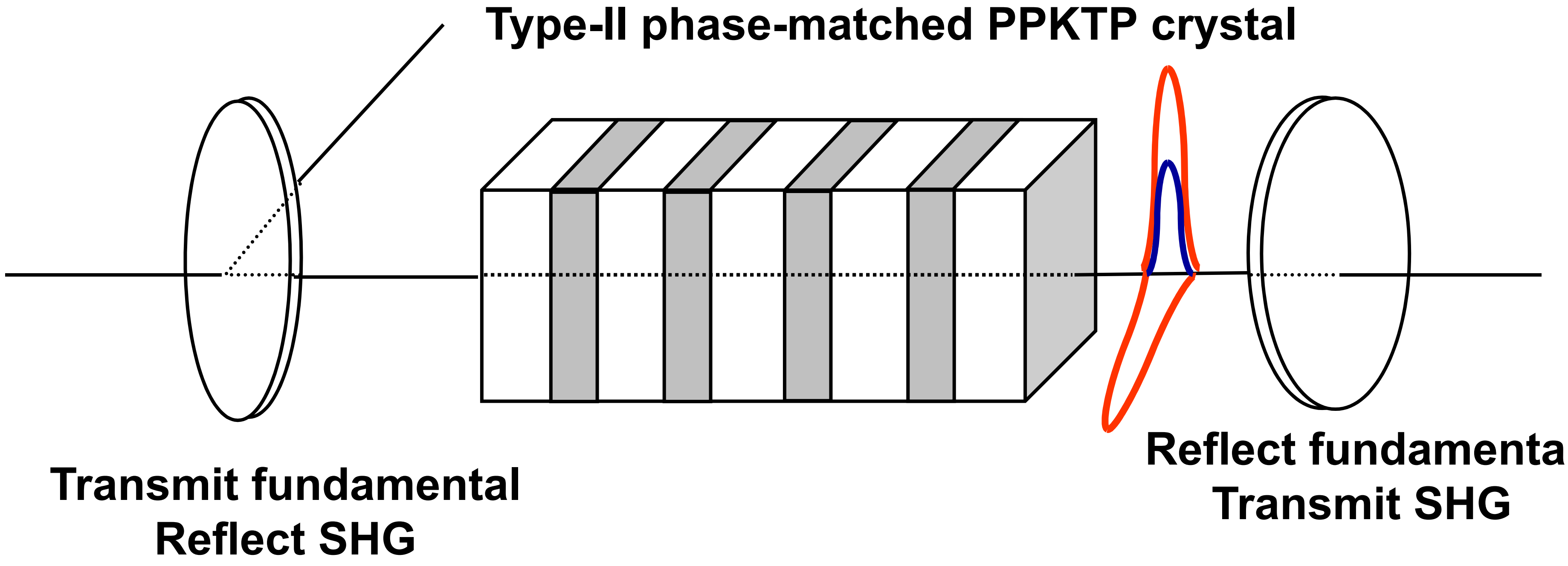

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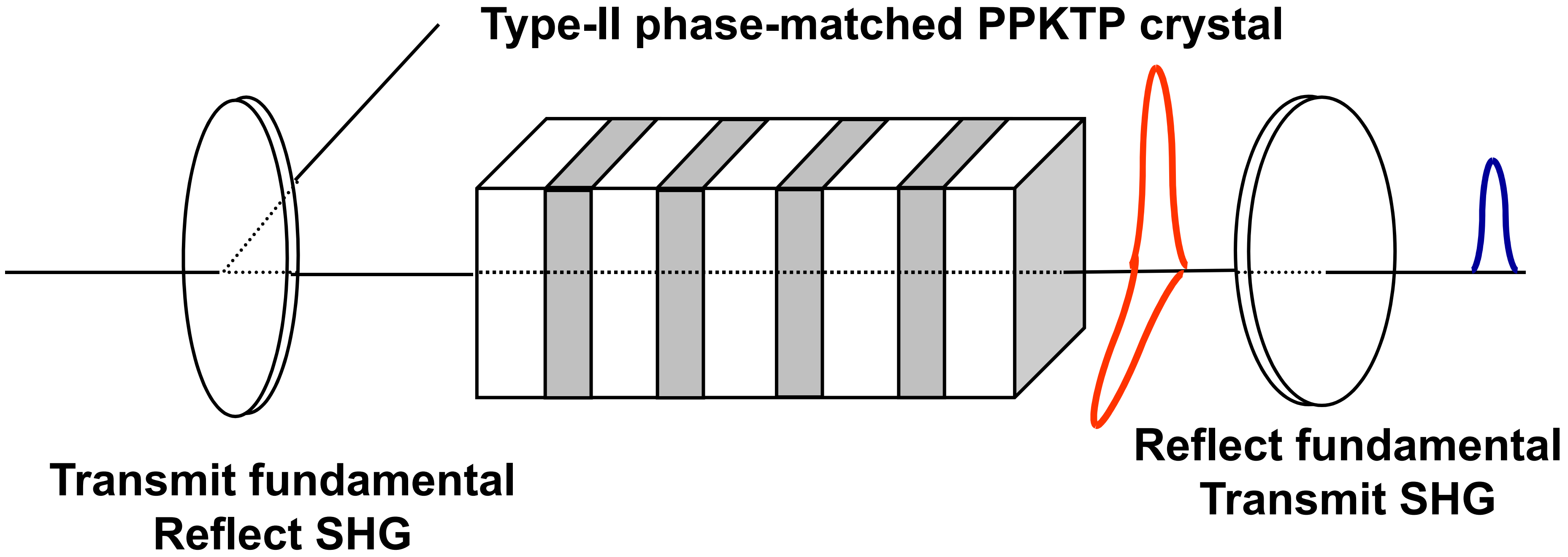

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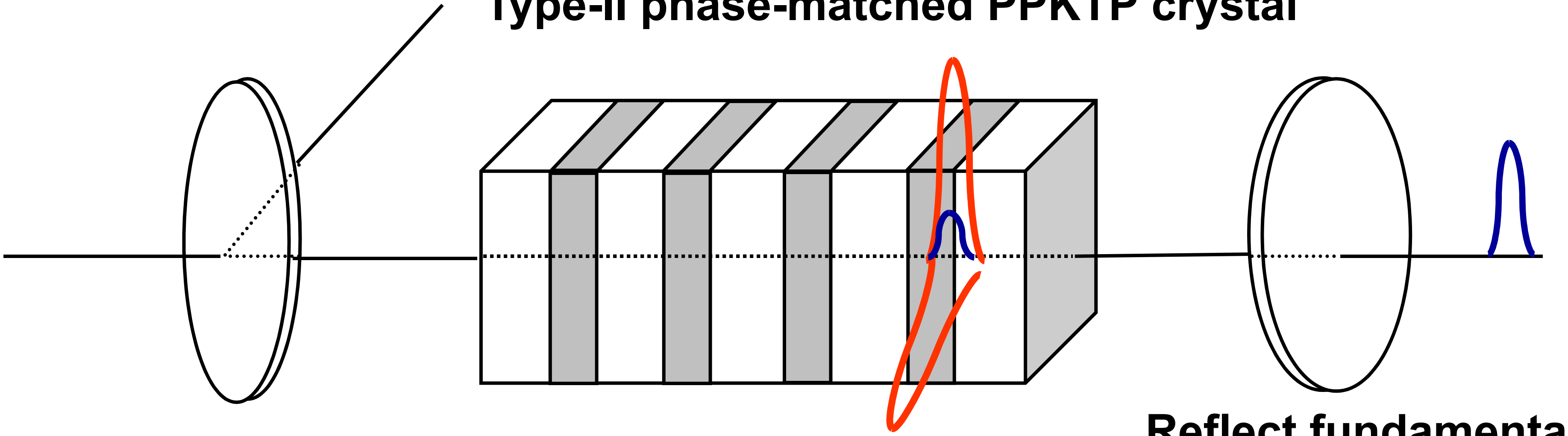

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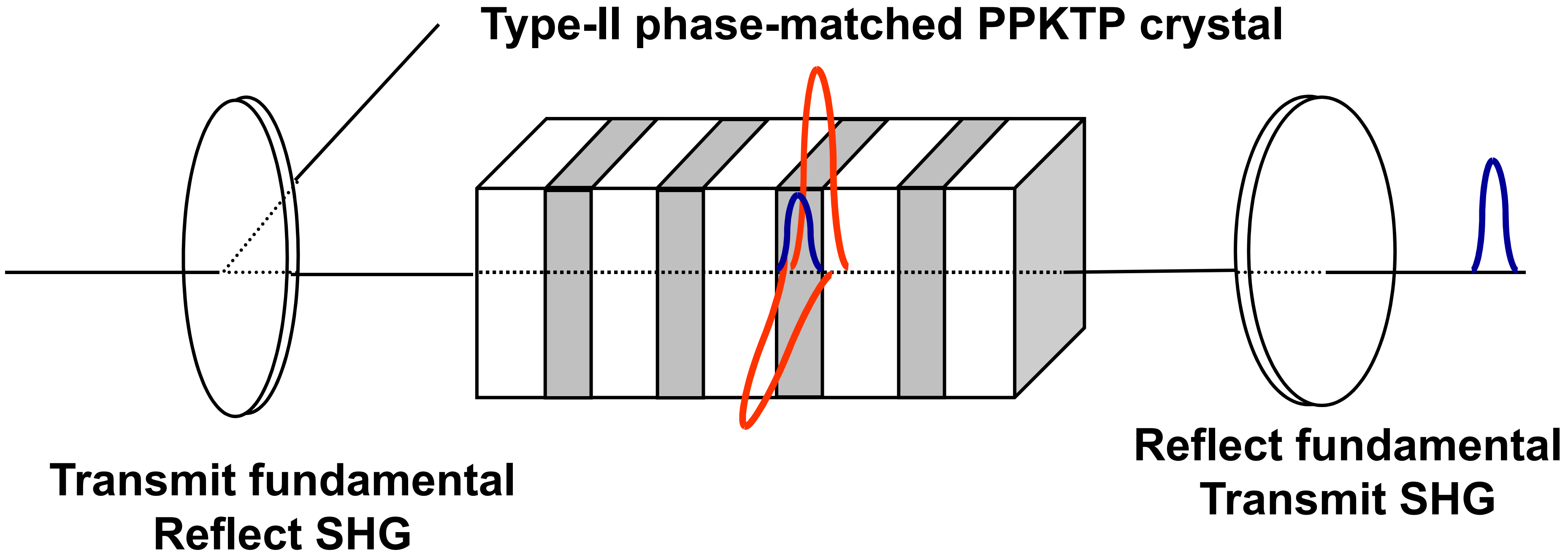

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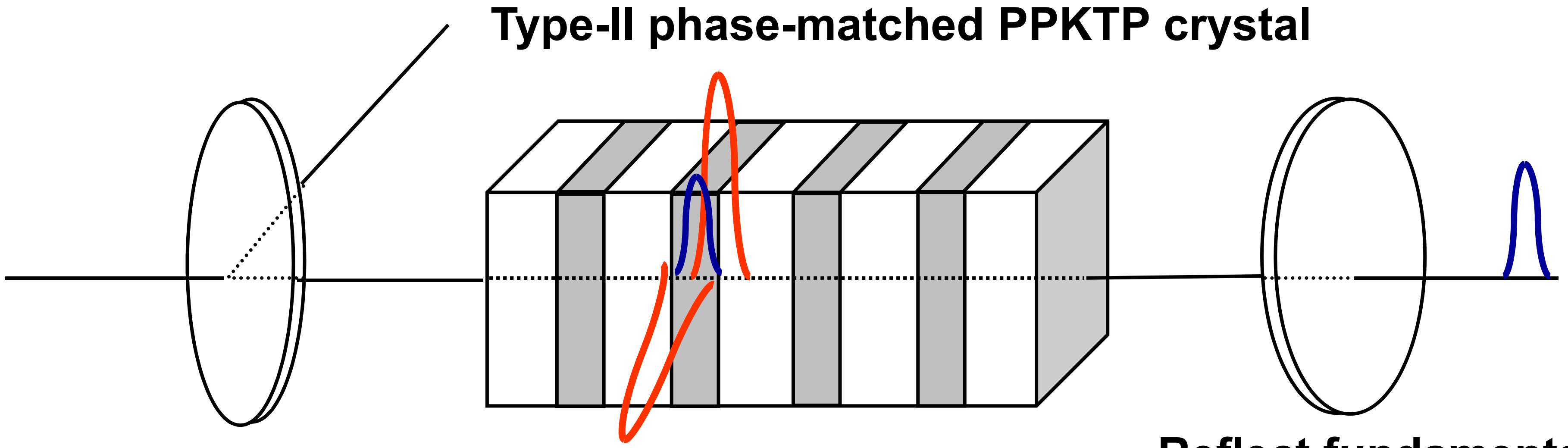

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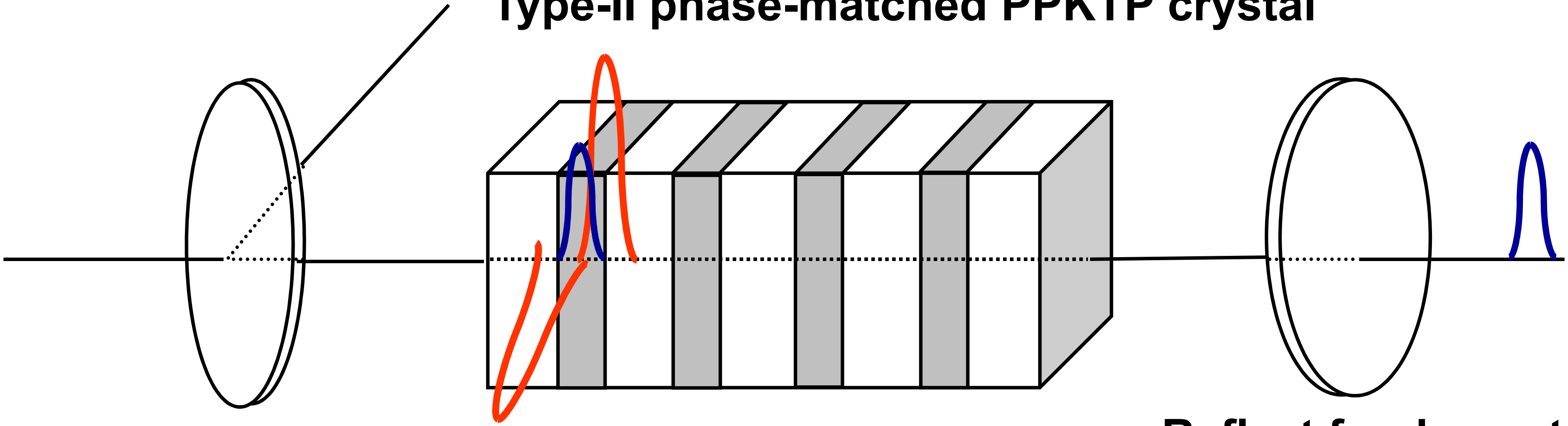

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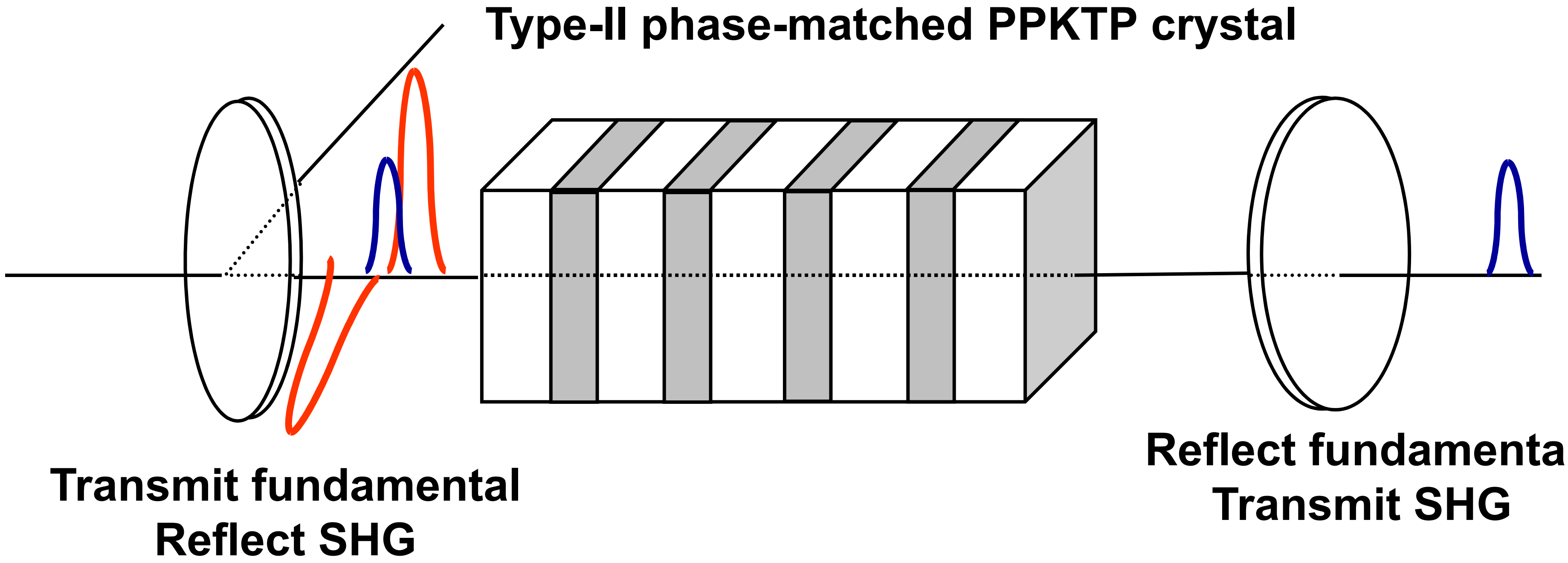

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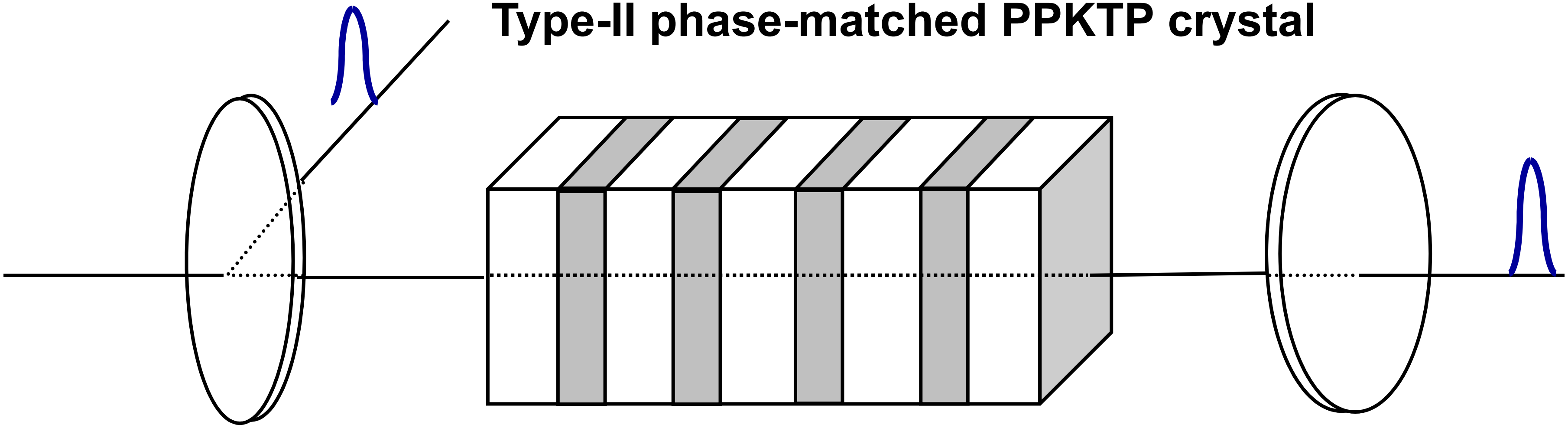

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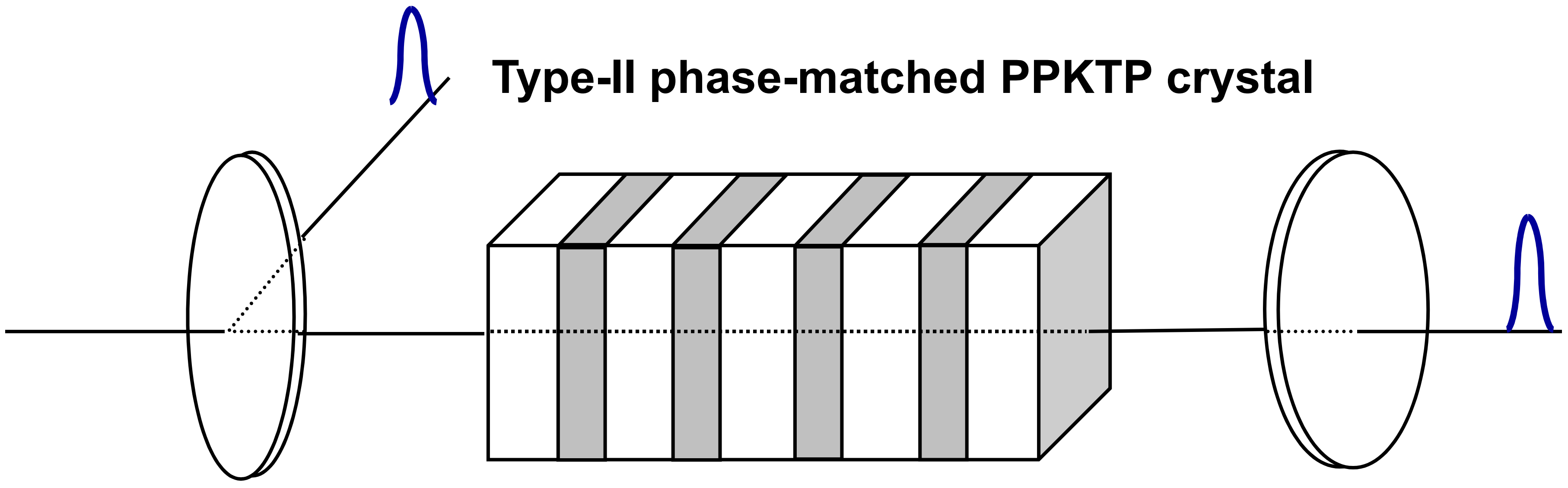

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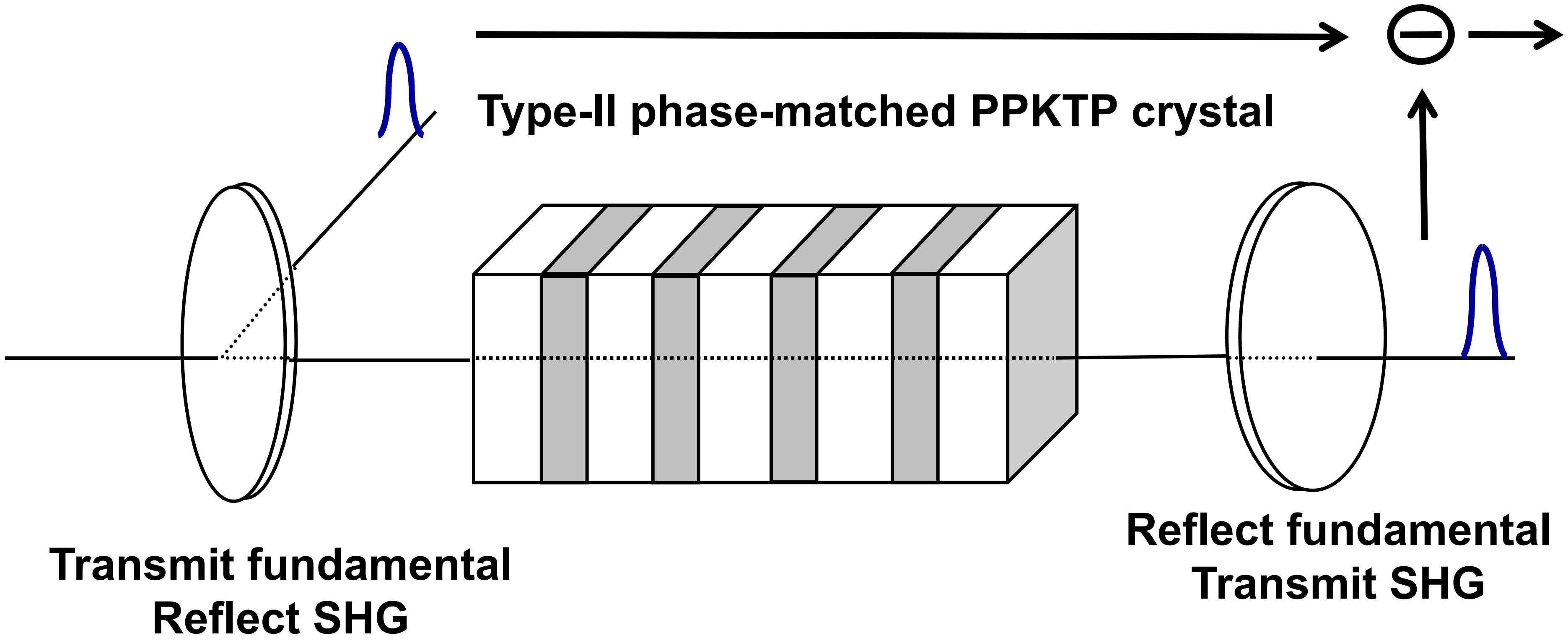

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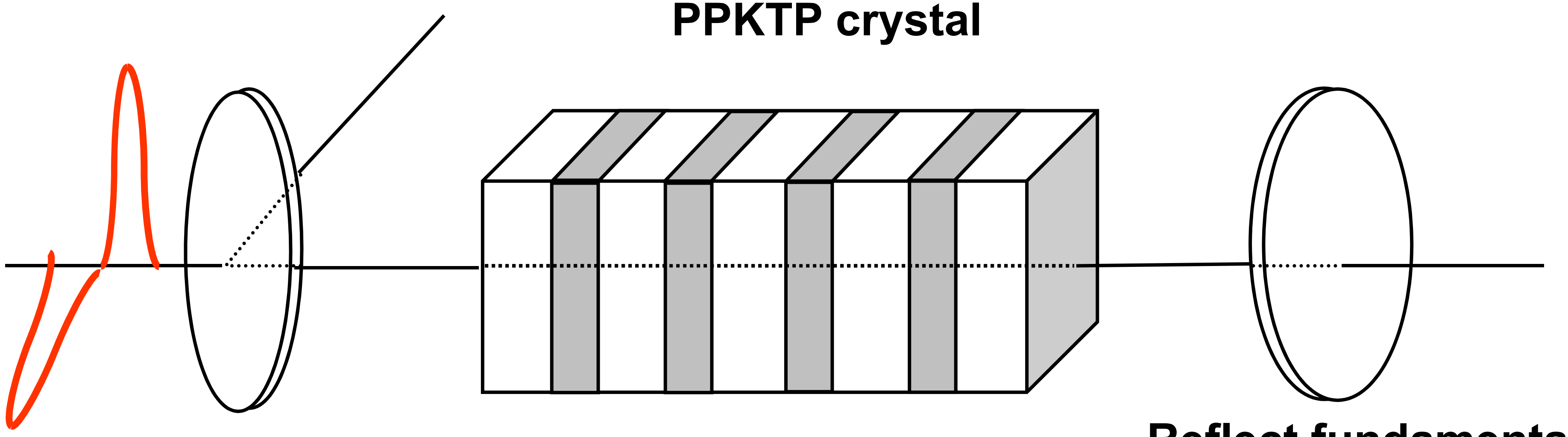

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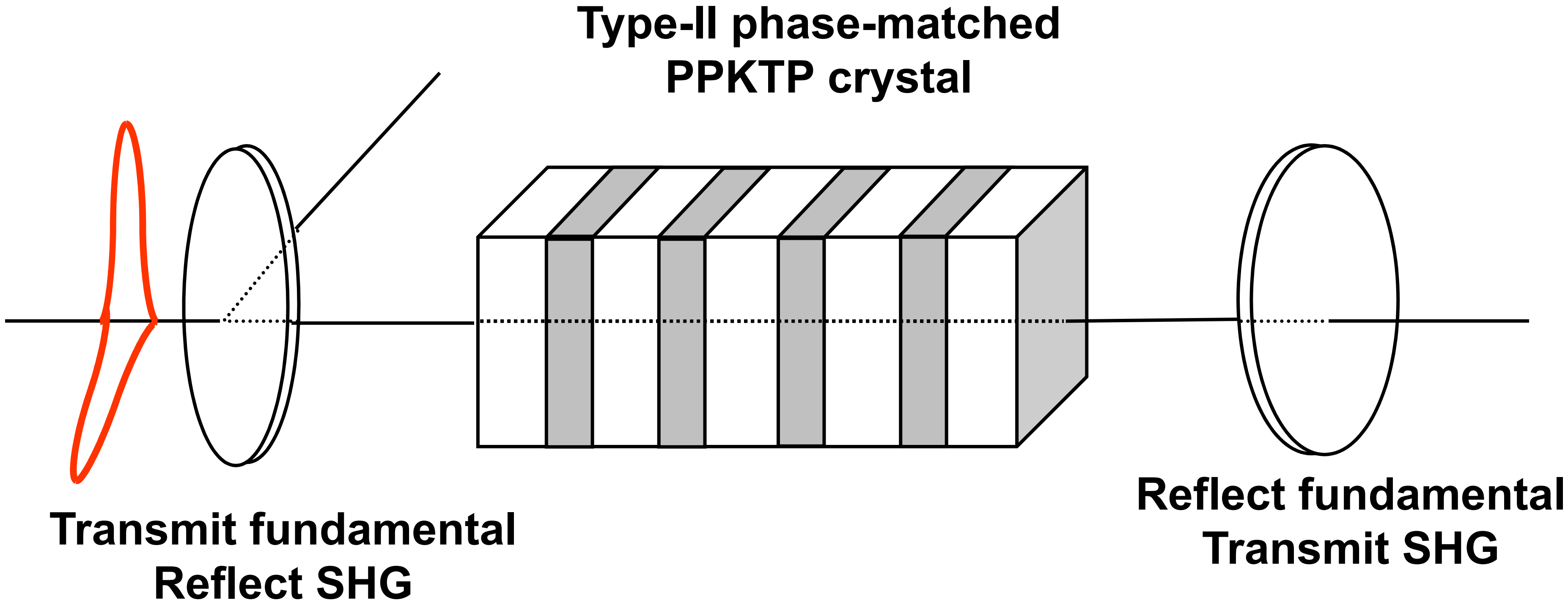

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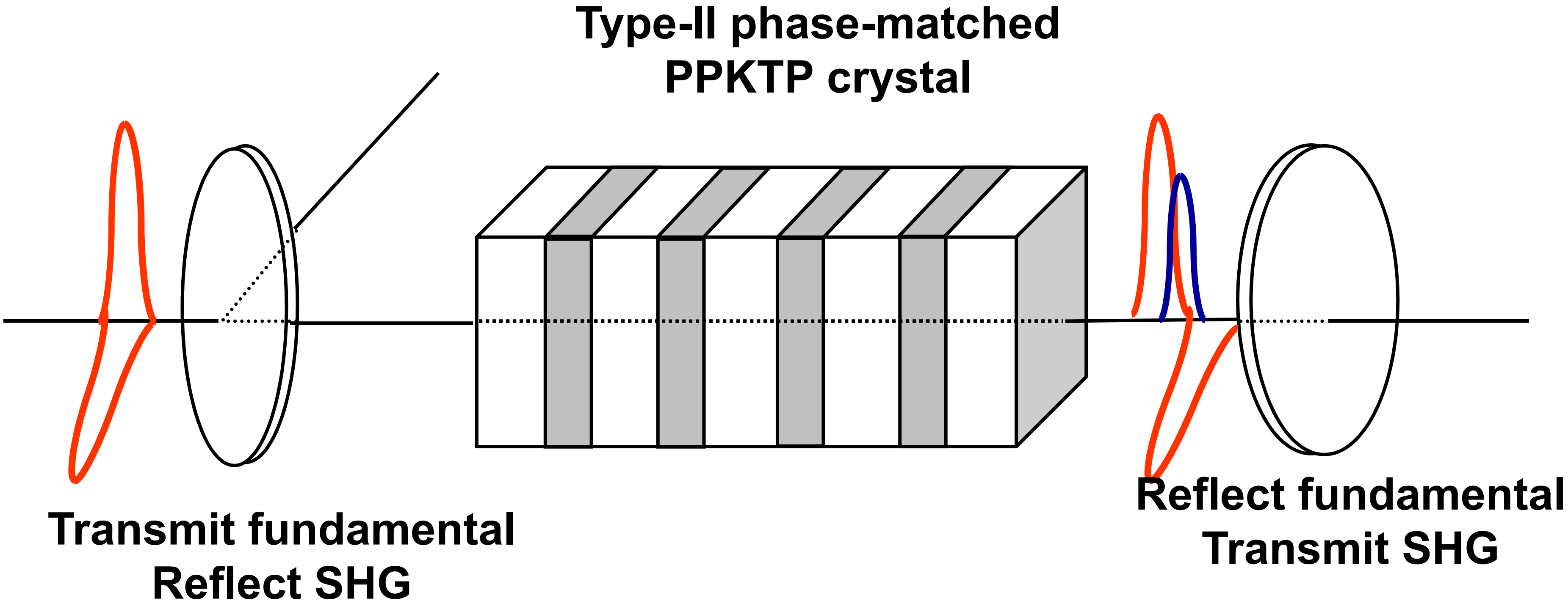

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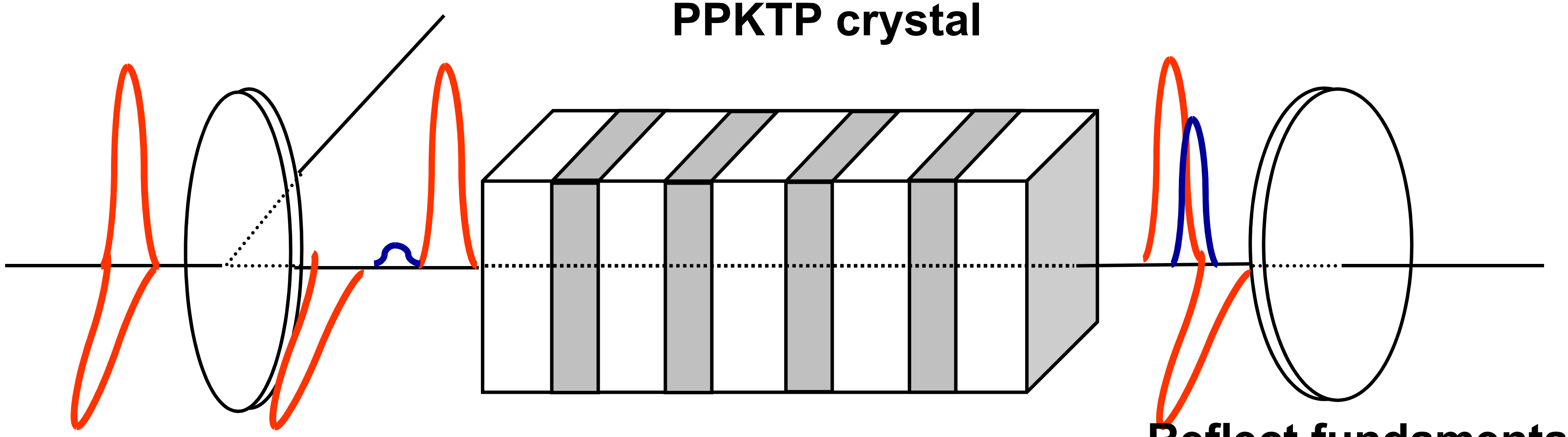

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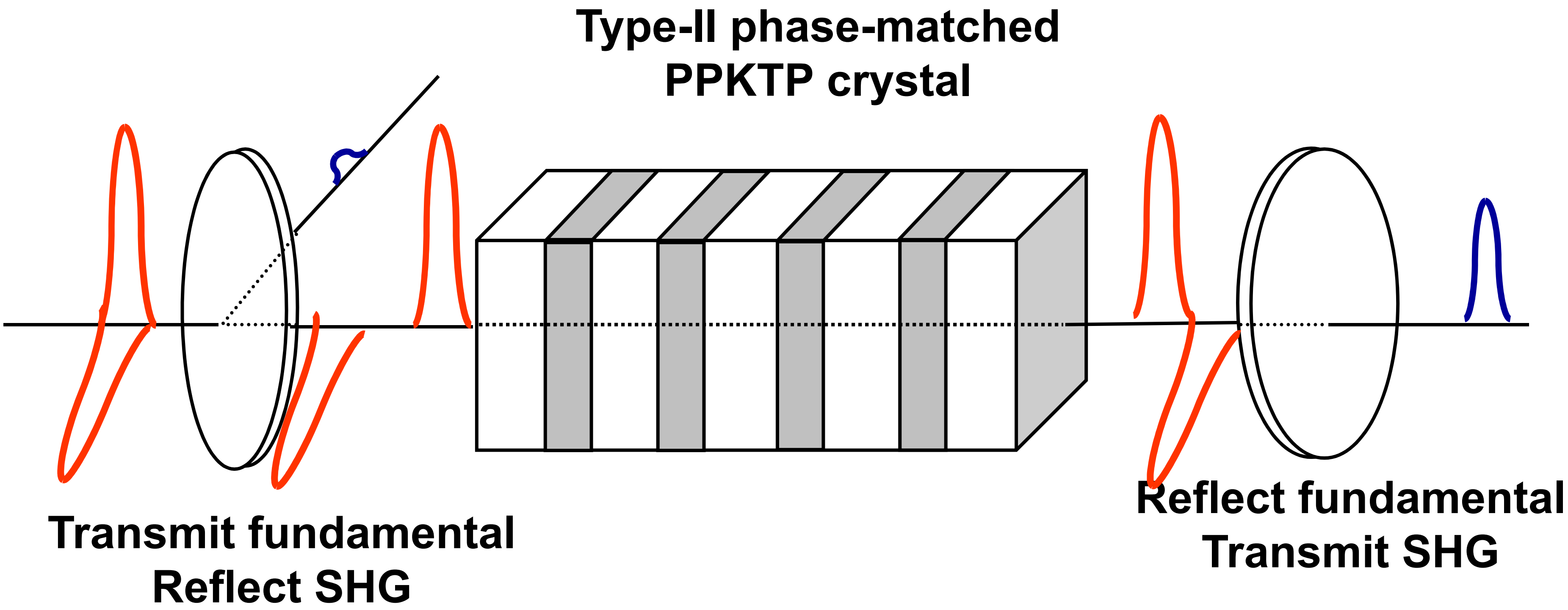
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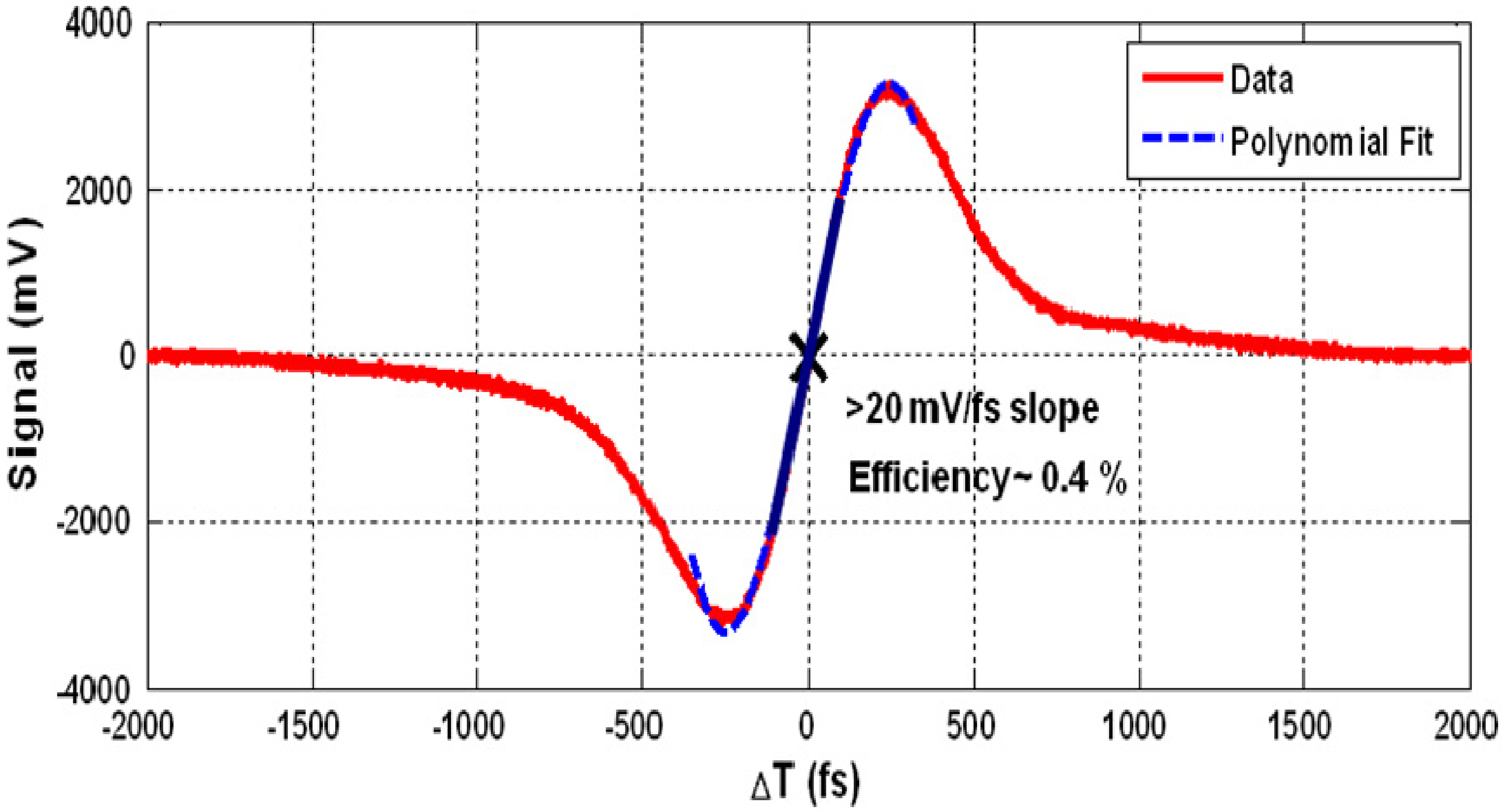
Transmit SHG

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

Single-crystal balanced cross-correlator

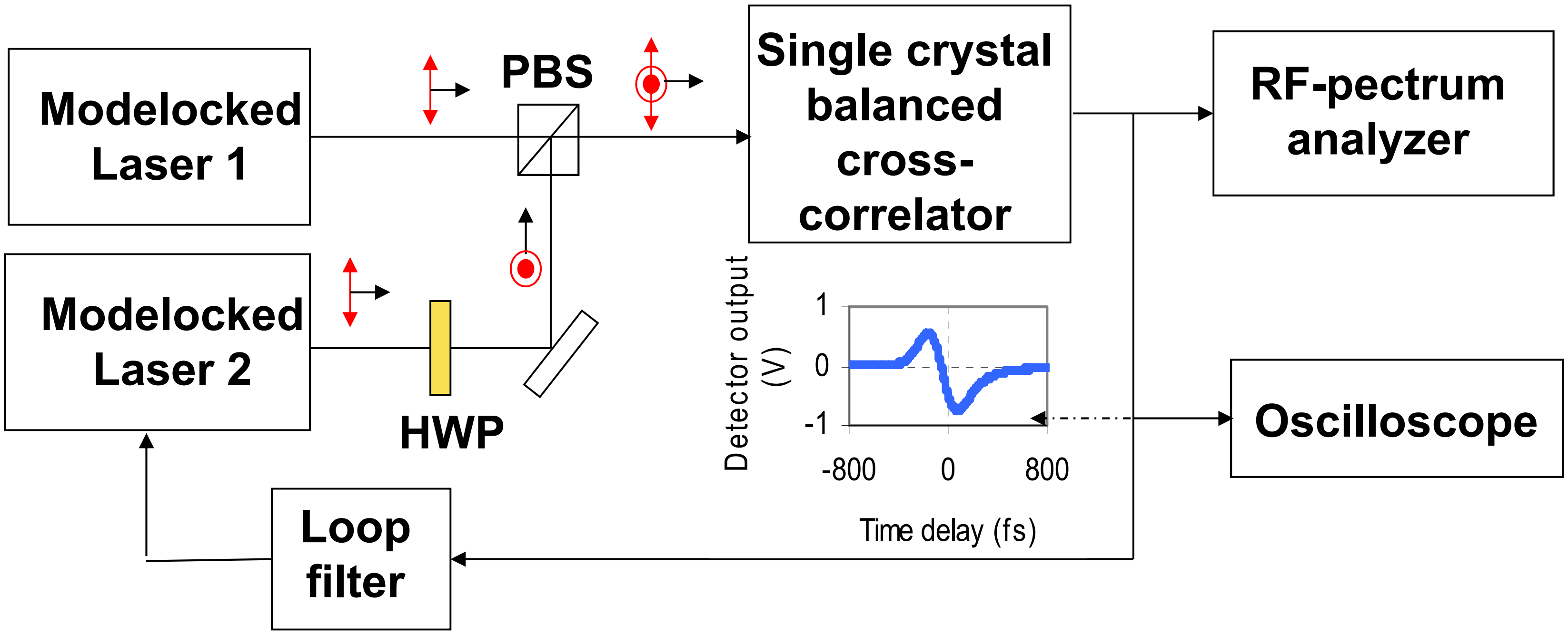


80 pJ, 200 fs
1550nm input pulses
at 200 MHz rep. rate

In comparison:
Typical microwave mixer
Slope ~1 μV/fs @ 10 GHz
Greatly reduced thermal drifts!

Timing jitter of lasers

Phase detector method → Timing Detector method



Modelocked Laser 1

Modelocked Laser 2

PBS

HWP

Single crystal balanced cross-correlator

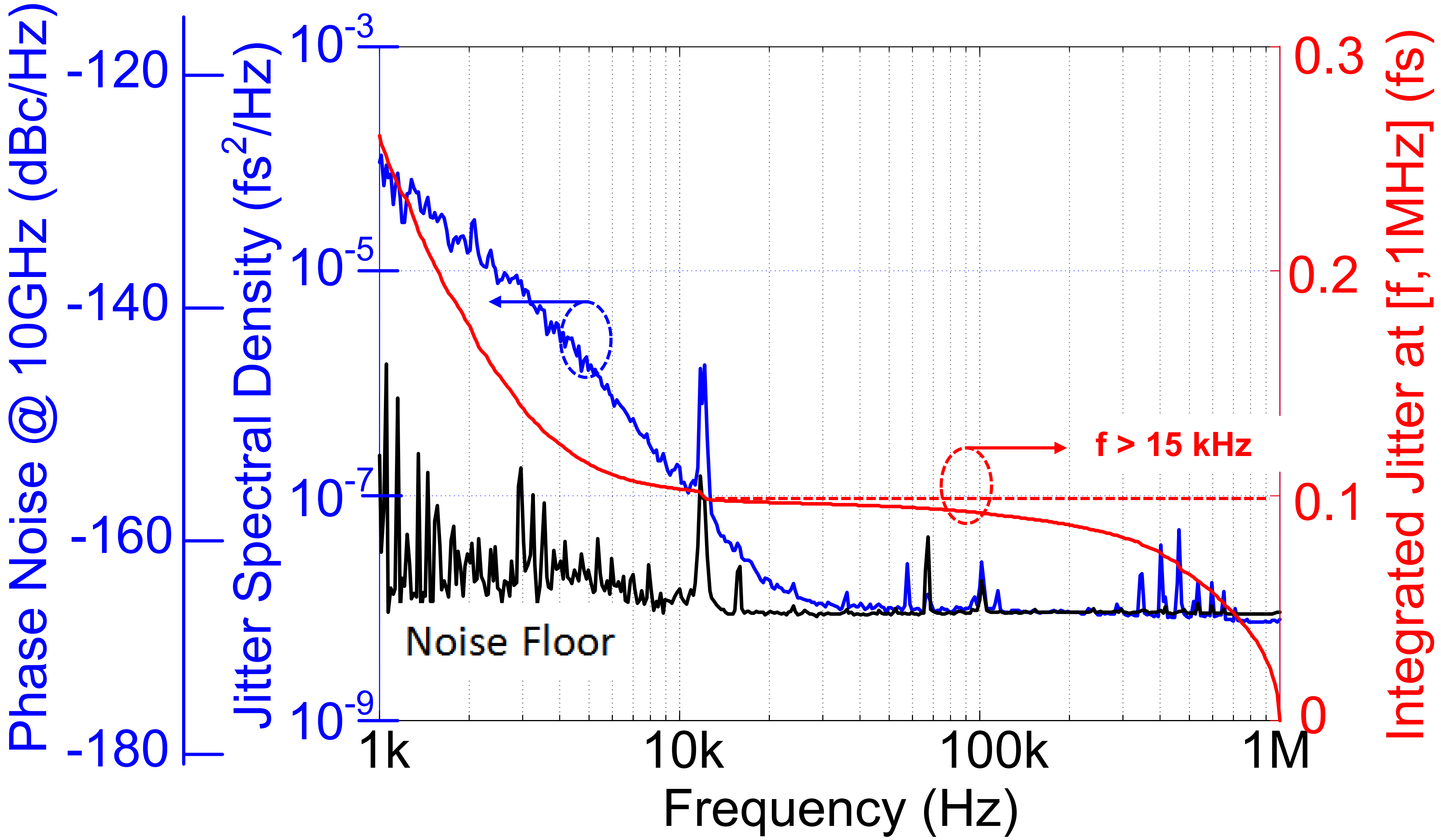
RF-pectrum analyzer

Oscilloscope

Loop filter

J. Kim, et al. , Opt. Lett. 32, 3519 (2007).

Timing jitter of OneFive:Origami Laser



K. Safak et al., Int. J. Structural Dynamics 2:(4) 041715 (2015).

Attosecond Timing ?

How do we get to Attosecond Jitter Lasers?

$$\frac{d}{dt} < \Delta t_{ML}^2 > \approx \boxed{\tau^2} \cdot \boxed{\frac{1}{W_{pulse}}} \cdot \frac{\hbar\omega_c}{\boxed{\tau_{cav}}}$$

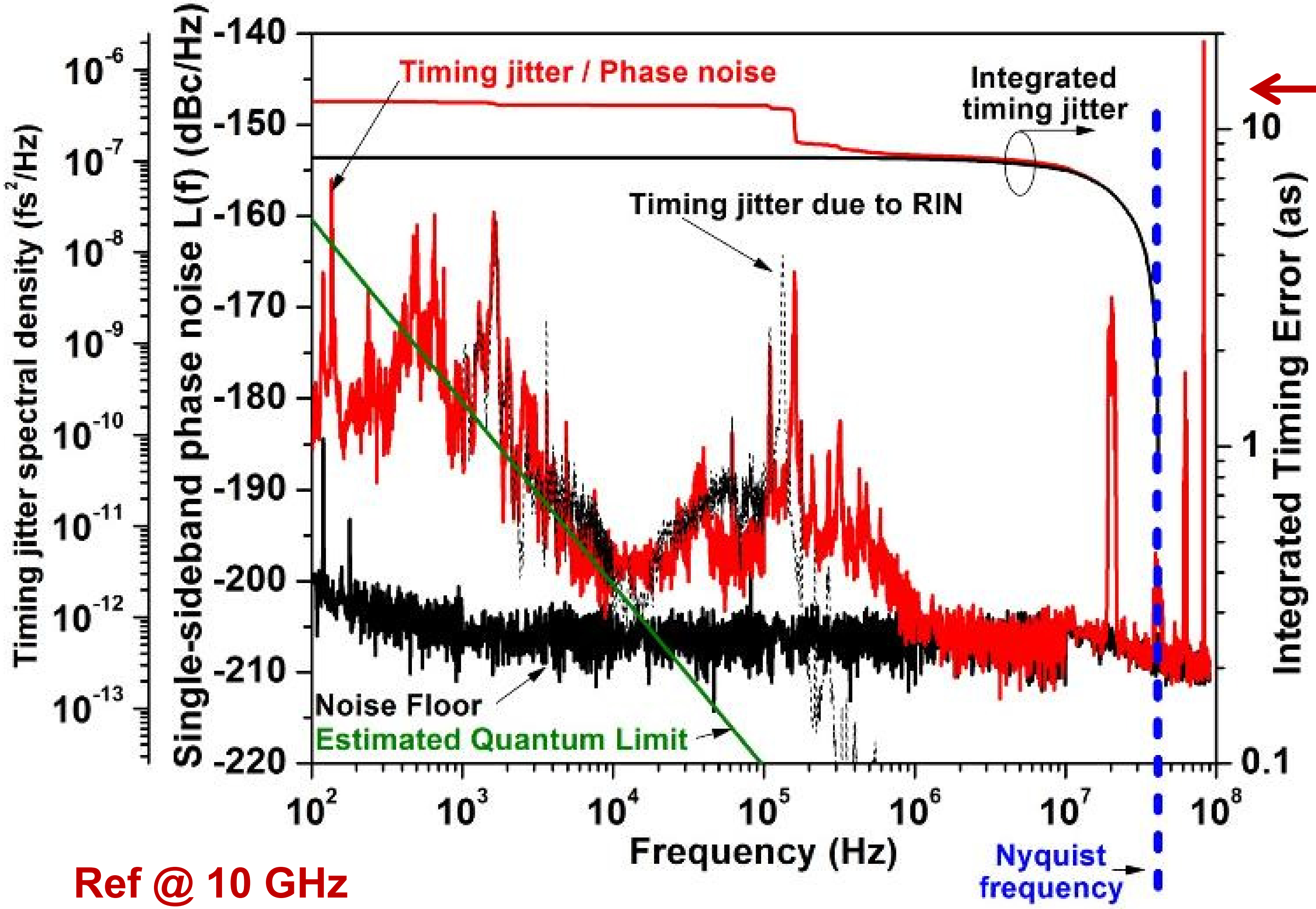
Intracavity losses down (Factor of 50)

Intracavity energy up (Factor of 50)

10-fs pulses (Factor of 100)

~ 10^6 Is it true?

Two 10-fs Ti:Sapphire Lasers Synchronized within 13 as



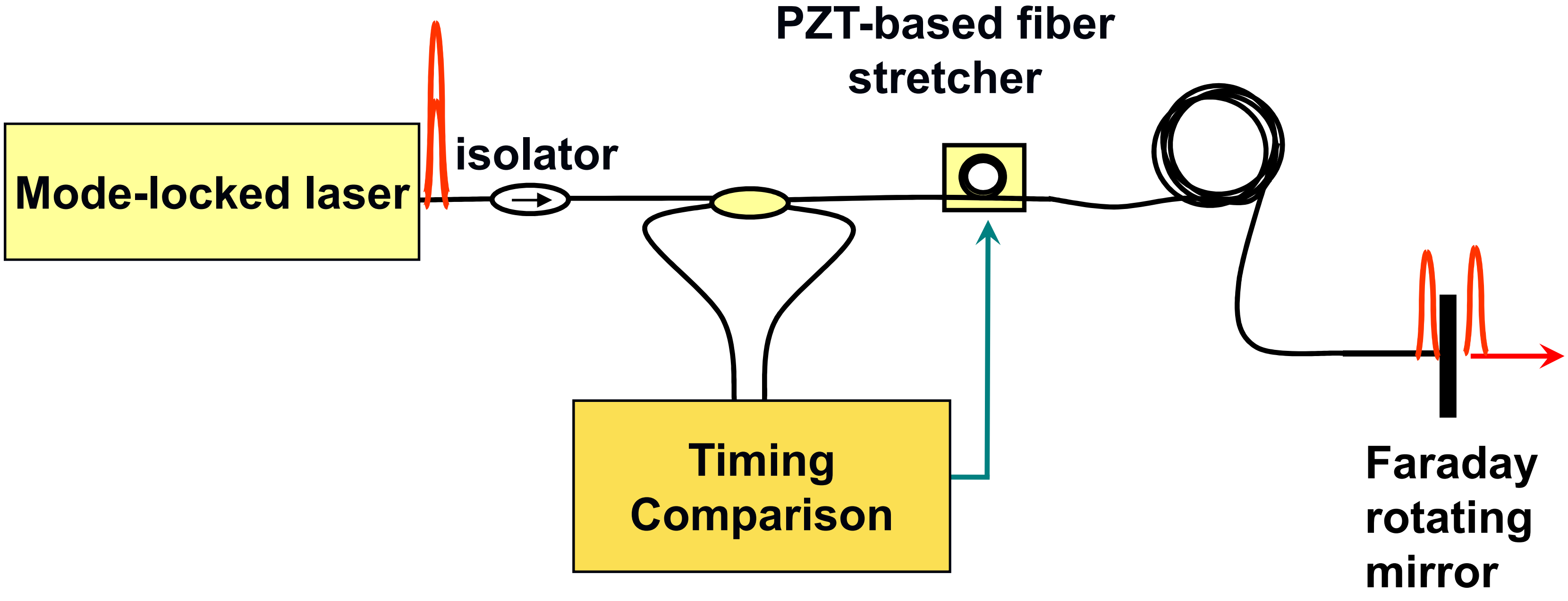
13 as

Ref @ 10 GHz

A. Benedick, et al. Nat. Phot. 6, 97-100, 2012

Timing-stabilized fiber links

Fiber link ~ 100m - 5km
SMF/DCF or PM/PMDCF

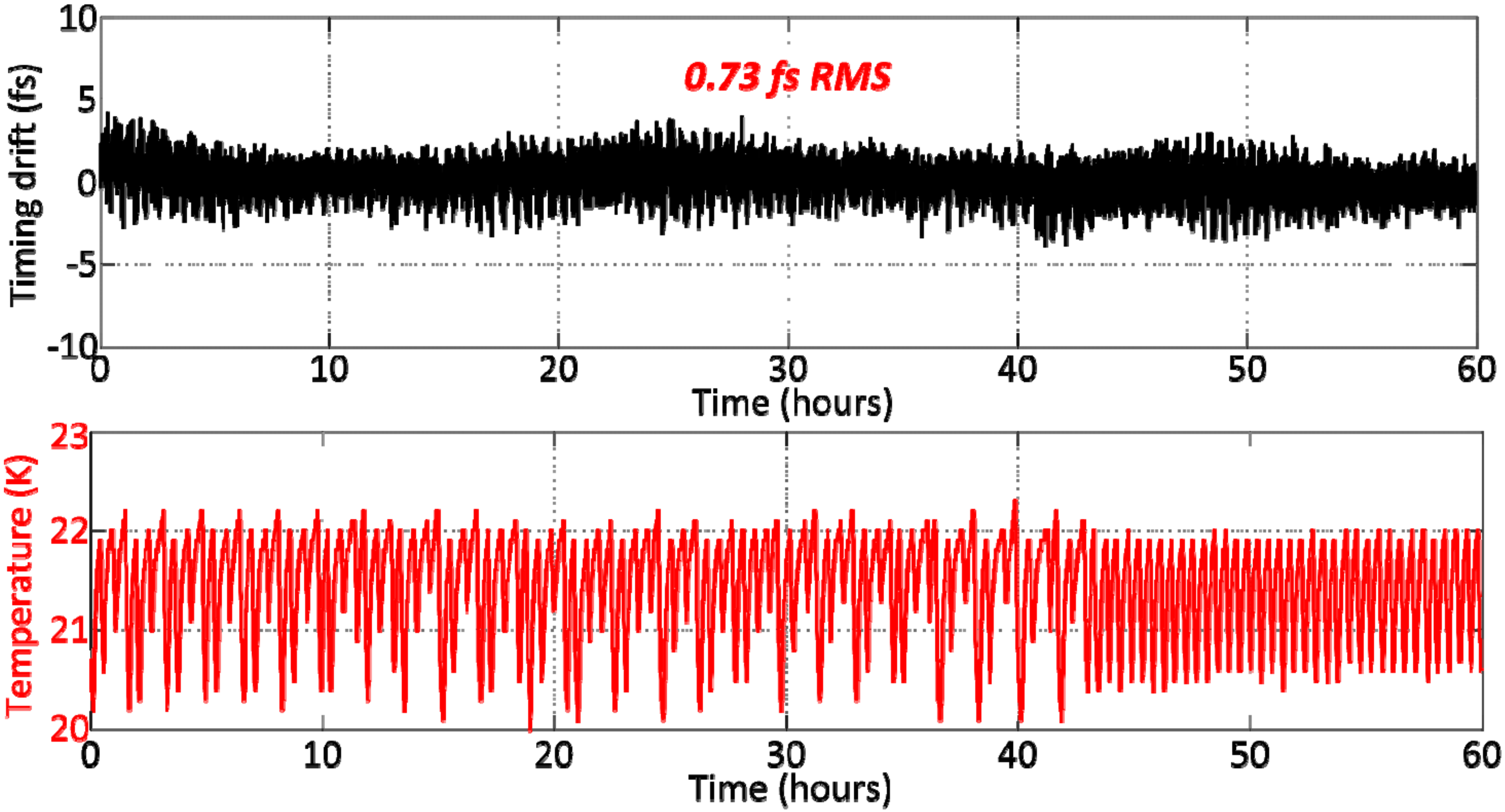


Cancel fiber length fluctuations slower than the pulse travel time (2nL/c).

1 km fiber: travel time = 10 μs → ~100 kHz BW

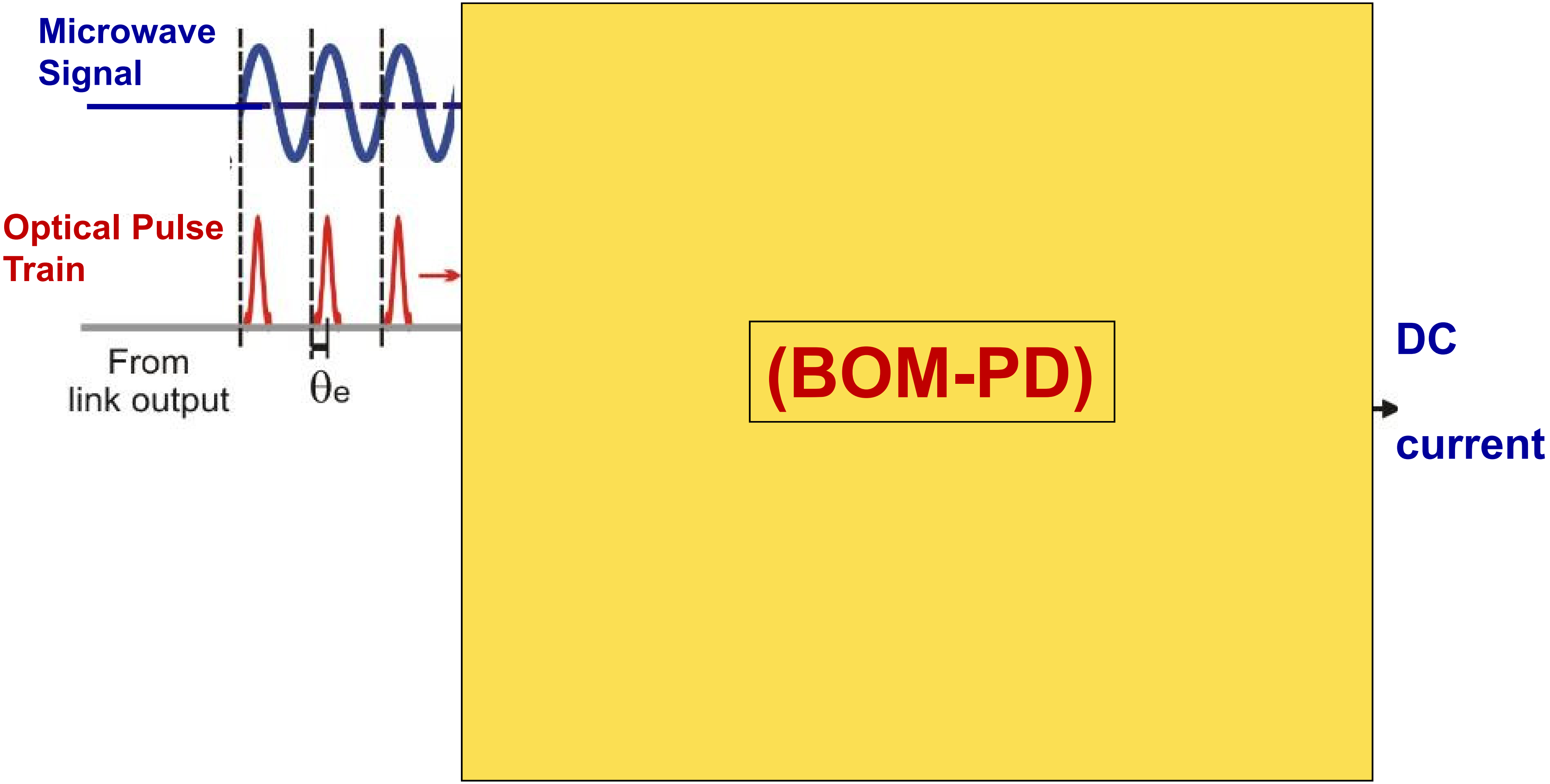
60 hours operation in commercial system

Out-off loop timing titter between two 150 m PM-links in a 16-link system



Courtesy Cycle GmbH

Balanced Optical-Microwave Phase Detector



Microwave Signal

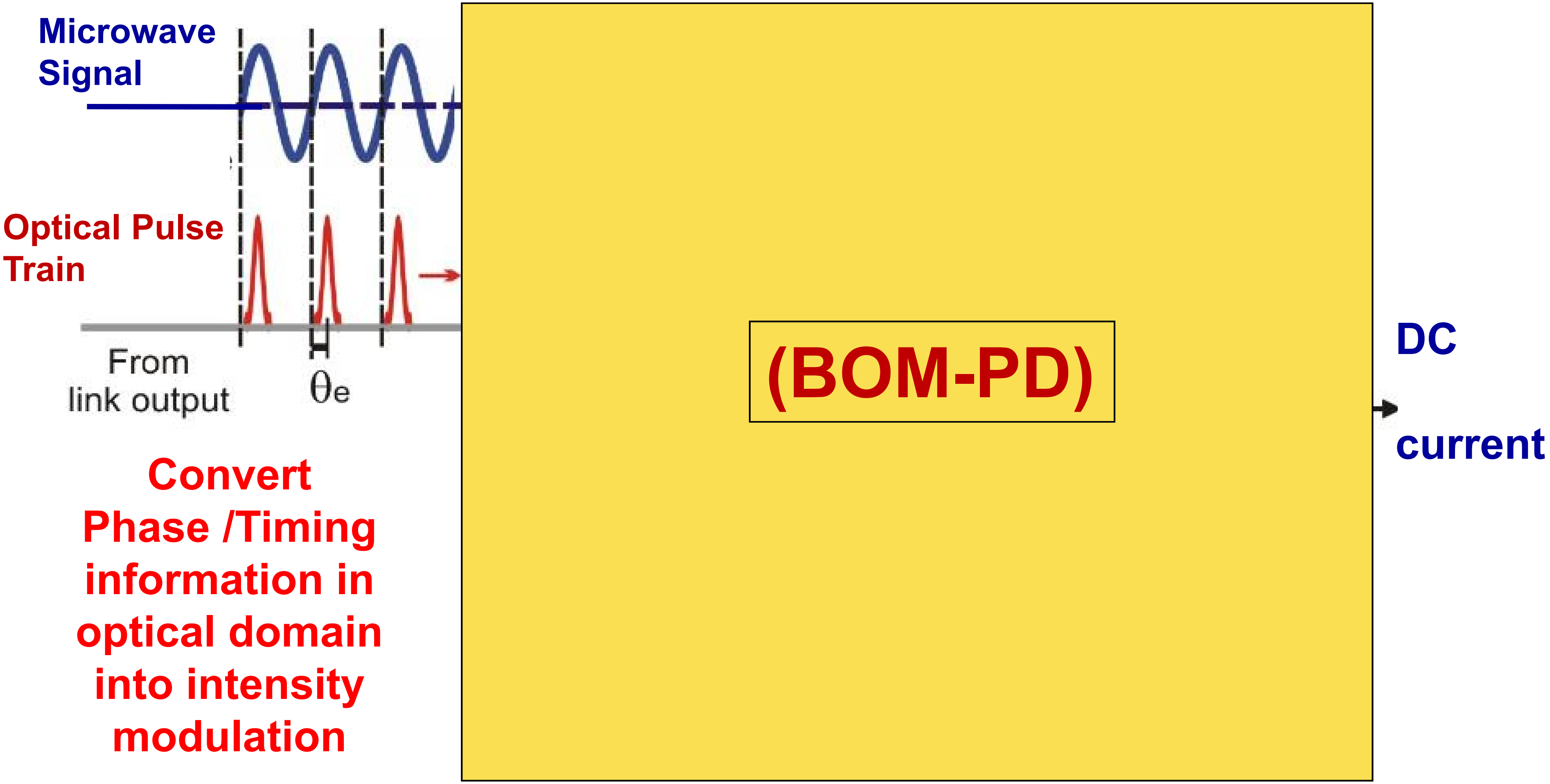
Optical Pulse Train

(BOM-PD)

DC current

J. Kim et al., Opt. Lett. **29**, 2076 (2004), **31**, 3659 (2006).

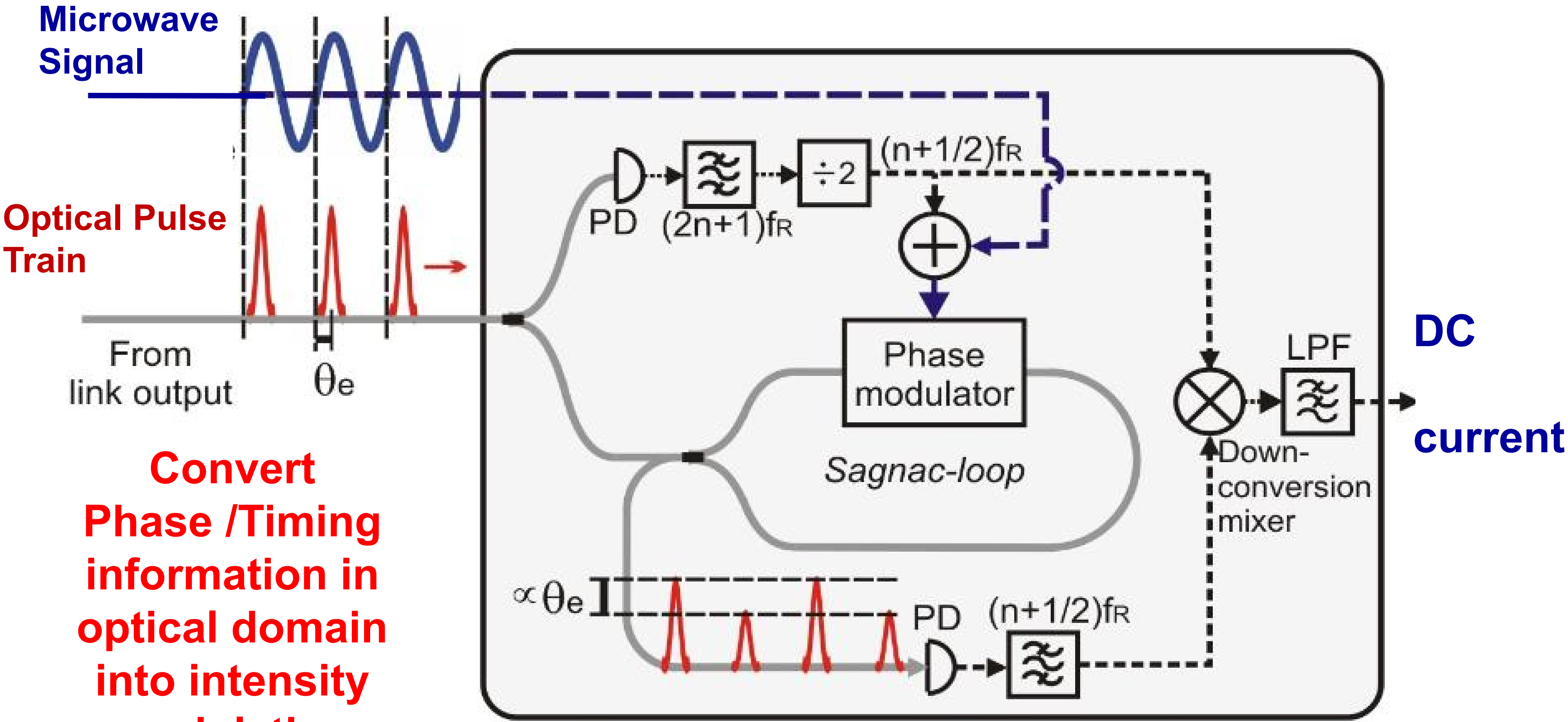
Balanced Optical-Microwave Phase Detector



Convert Phase /Timing information in optical domain into intensity modulation

J. Kim et al., Opt. Lett. **29**, 2076 (2004), **31**, 3659 (2006).

Balanced Optical-Microwave Phase Detector

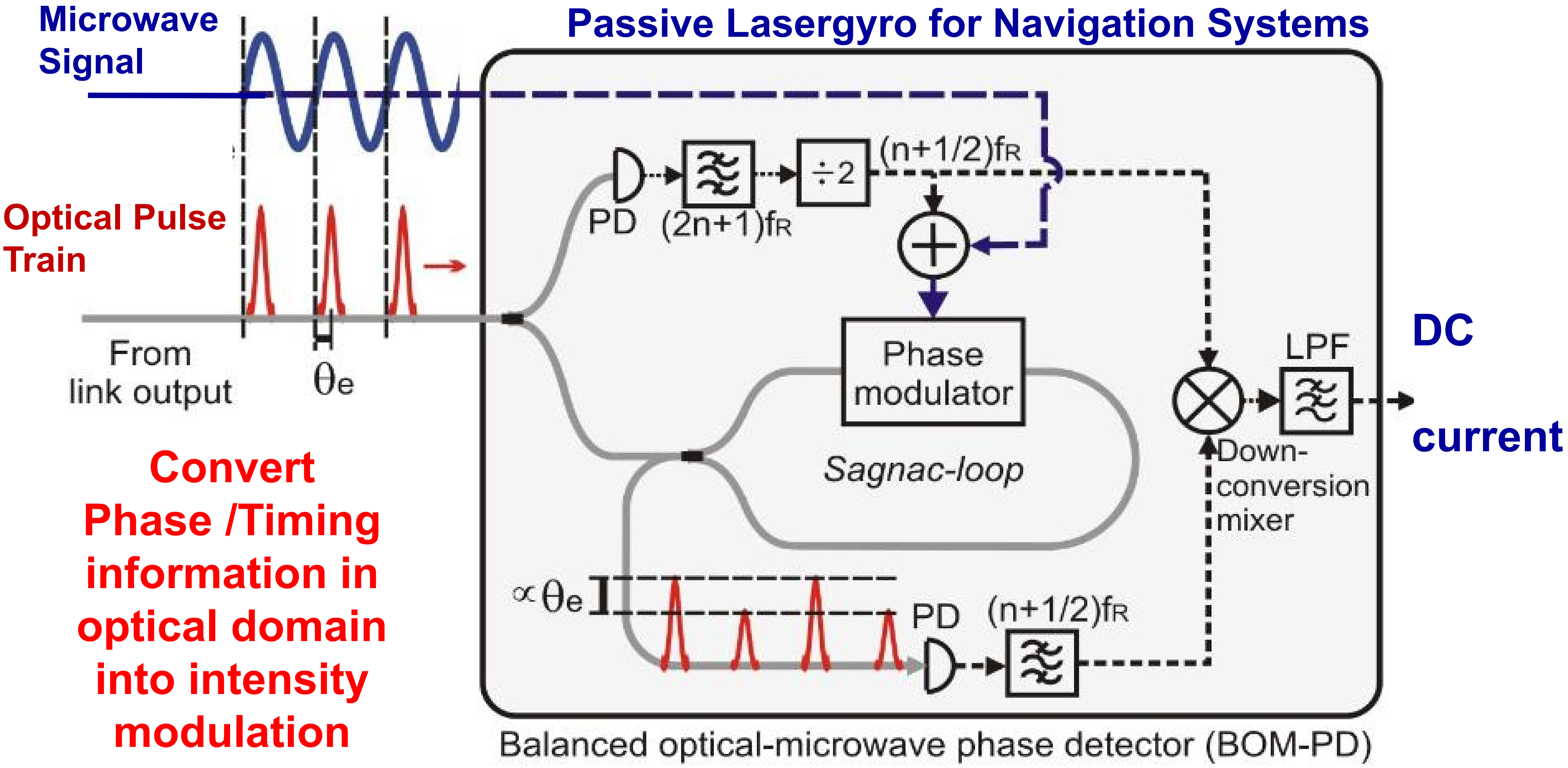


Balanced optical-microwave phase detector (BOM-PD)

Convert Phase /Timing information in optical domain into intensity modulation

J. Kim et al., Opt. Lett. **29**, 2076 (2004), **31**, 3659 (2006).

Balanced Optical-Microwave Phase Detector



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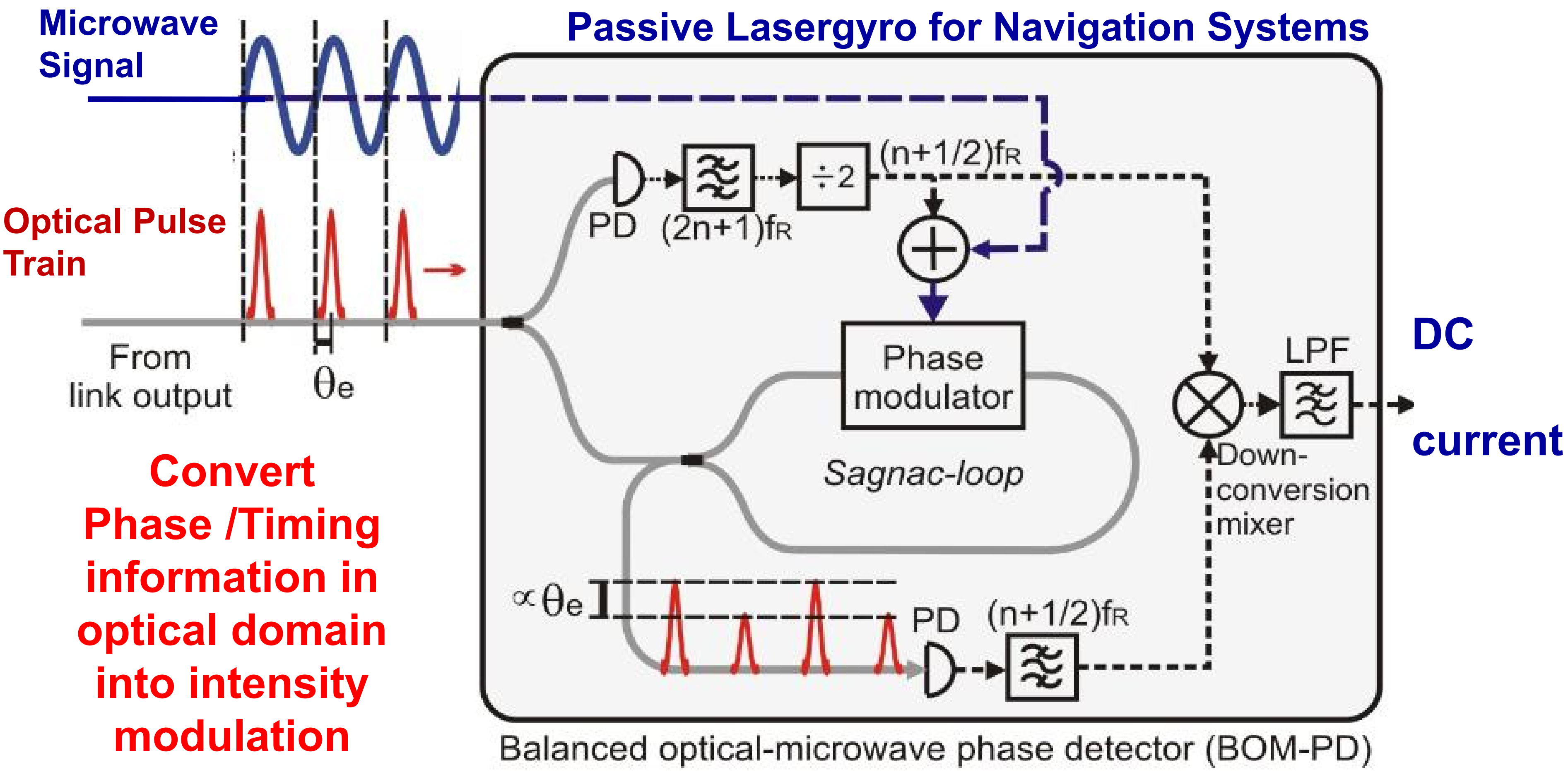
Balanced Optical-Microwave Phase Detector



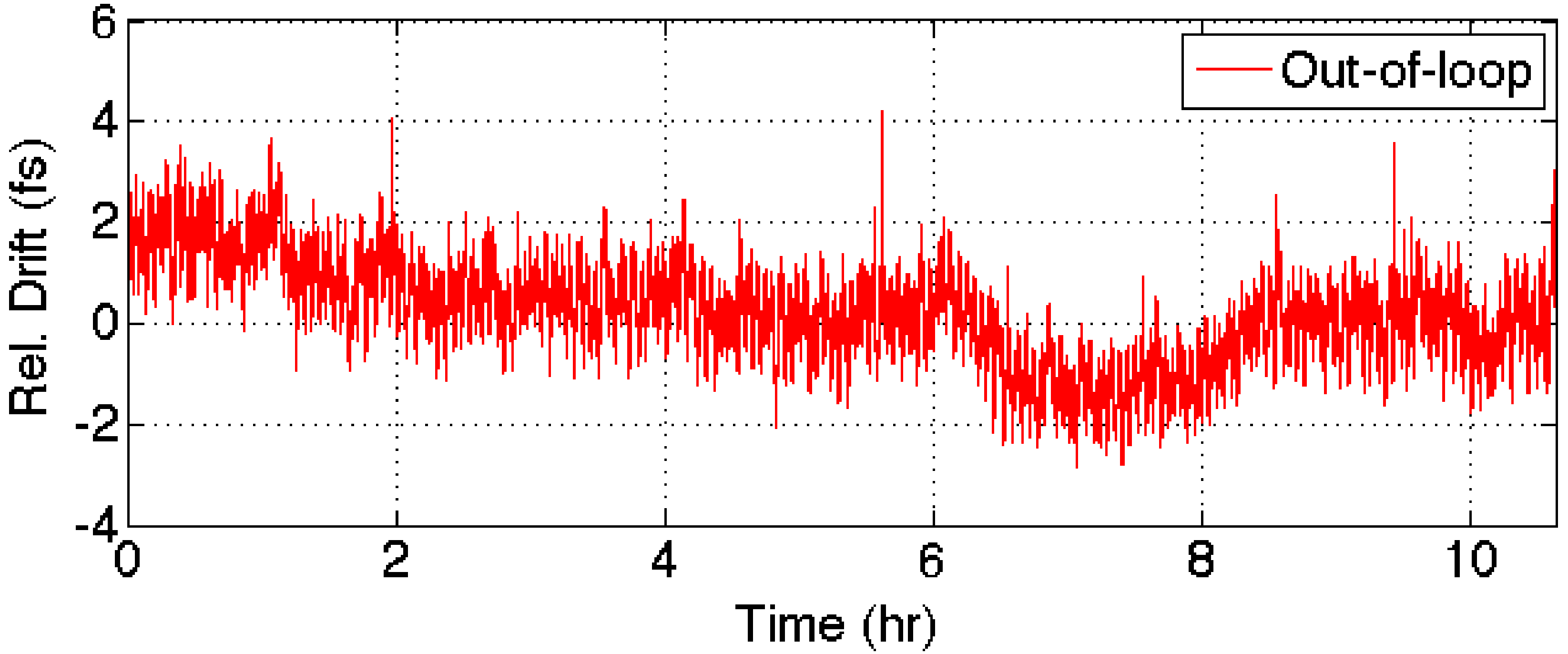
Balanced optical-microwave phase detector (BOM-PD)

Convert Phase /Timing information in optical domain into intensity modulation

Electro-optic sampling of microwave signal with optical pulse train

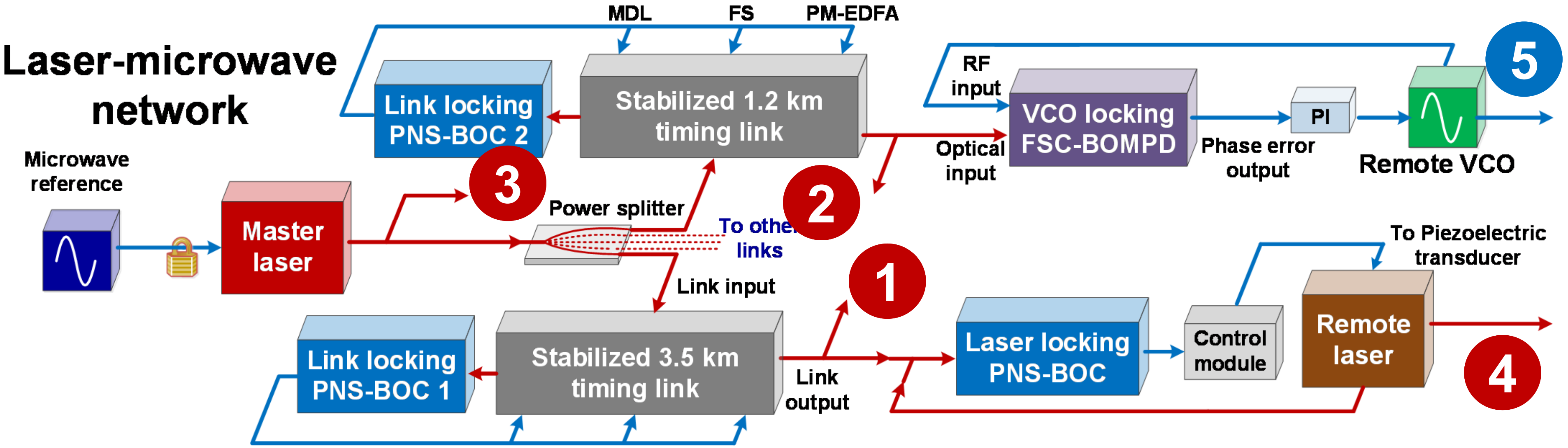
J. Kim et al., Opt. Lett. **29**, 2076 (2004), **31**, 3659 (2006).

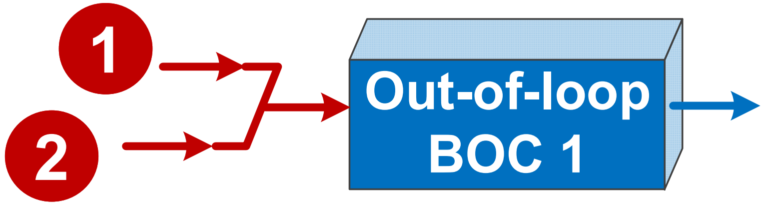
Long-term stability: < 1 fs rms drift over 10 hours



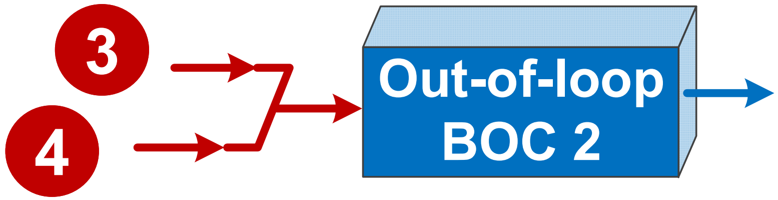
M. Y. Peng, A. Kalaydzhyan, F. X. Kärtner, Opt. Express, 22:(22) pp.27102 (2014).

4.7 - km laser-microwave network

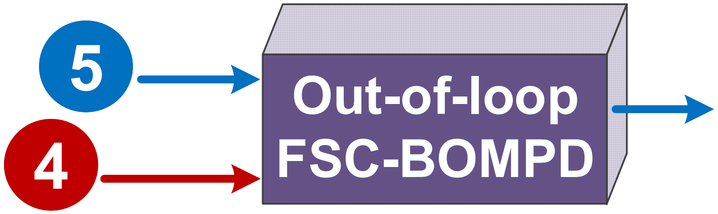




Link network

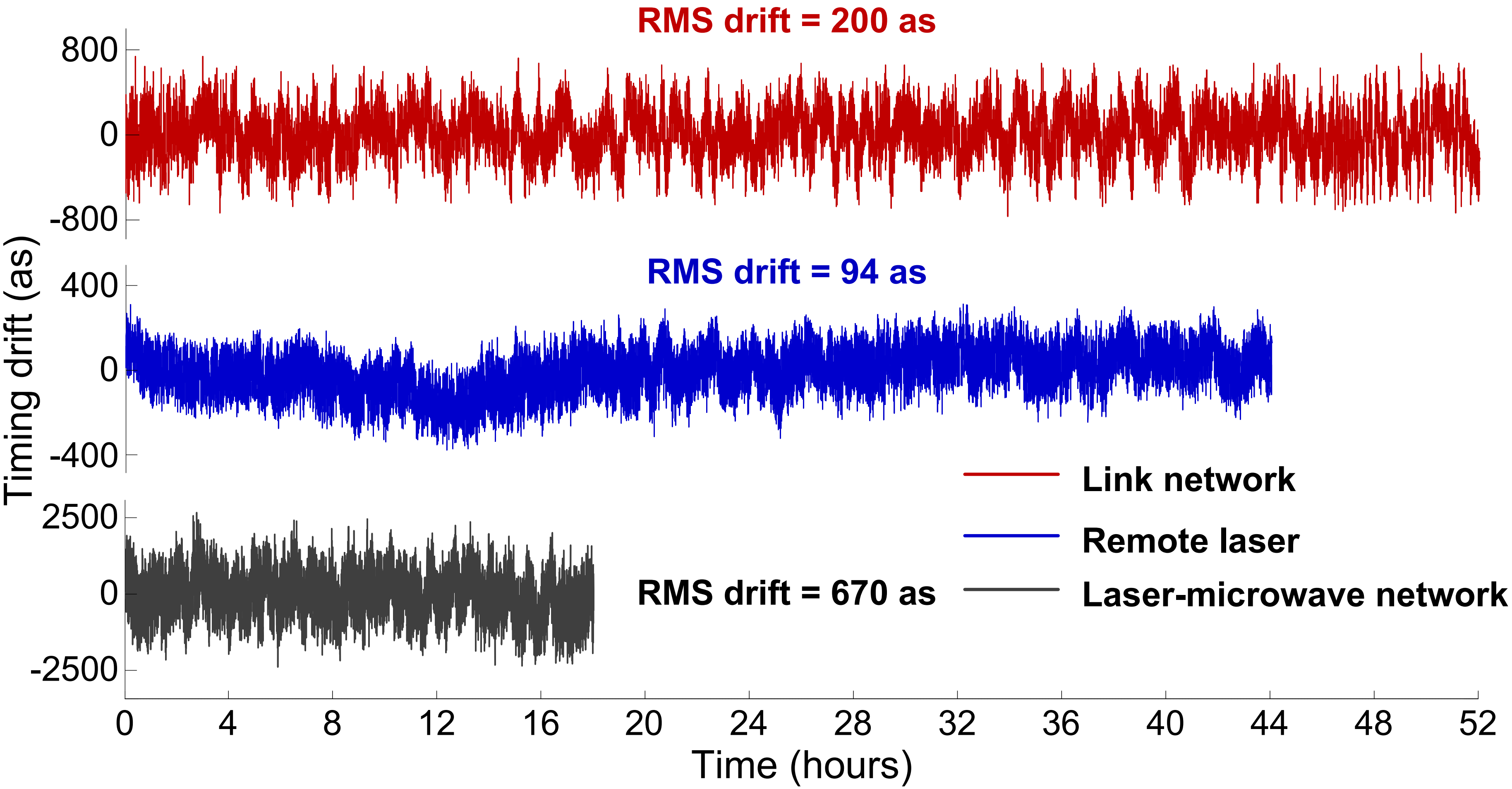


Remote laser



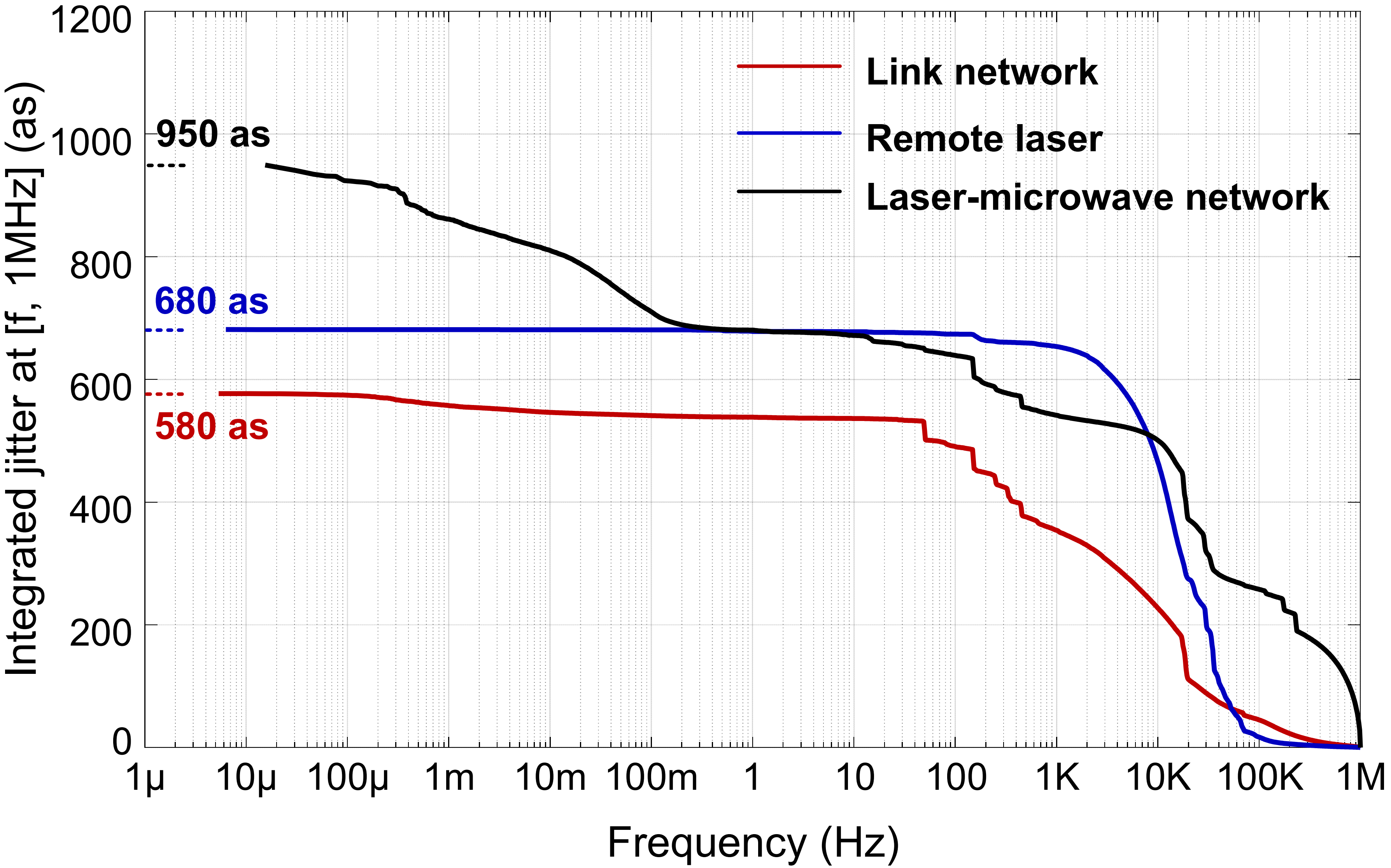
Laser-microwave network

Results—long-term timing drift



Light: Science & Applications, doi: 10.1038/lsa.2016.187.

Results—Integrated timing jitter

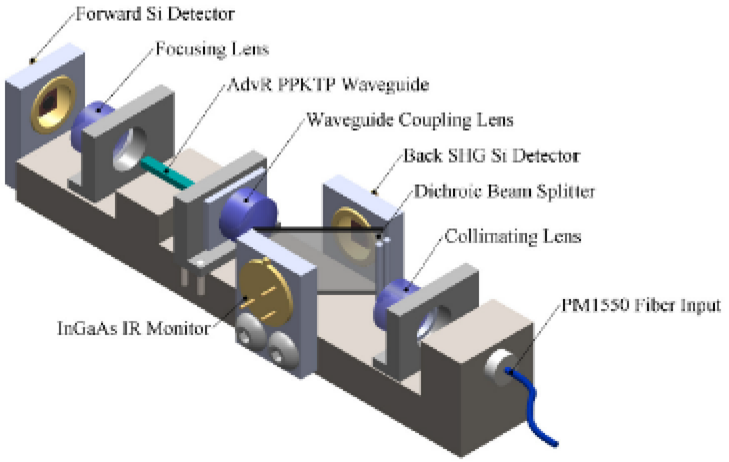


Light: Science & Applications, doi: 10.1038/lsa.2016.187.

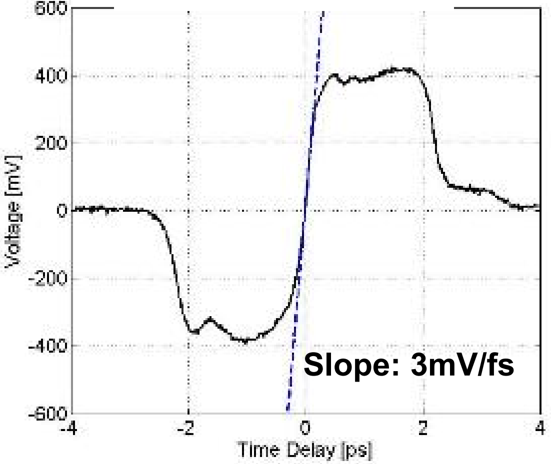
Integrated Optics
BOC and (BOMPD)

Integrated Waveguide BOCs

- **Packaged waveguide BOC module with miniaturized coupling optics:**



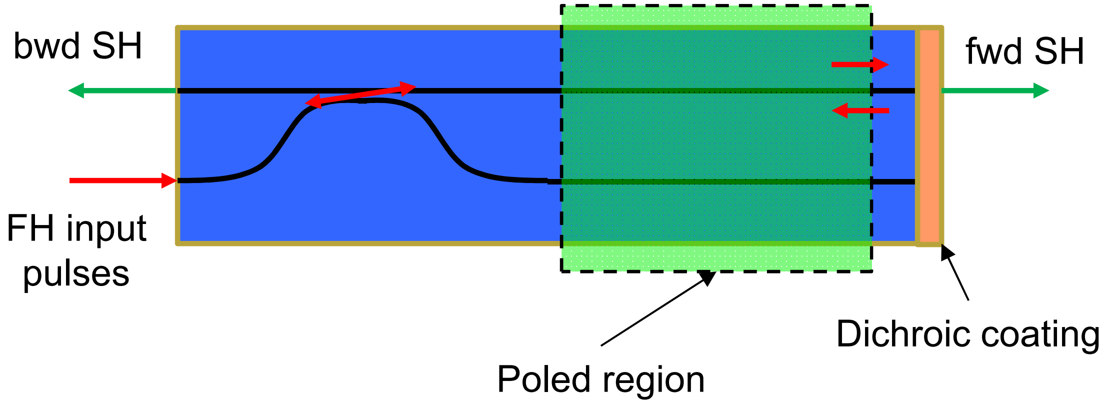
Double-pass scan:



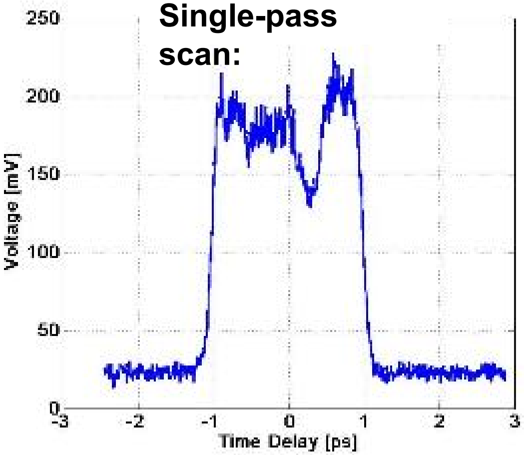
Input:
P_{avg} = 10 mW
f_{rep} = 80 MHz
τ = 200 fs

With TIA
P_{avg} = 2 mW
f_{rep} = 80 MHz
τ = 200 fs
30mV/fs

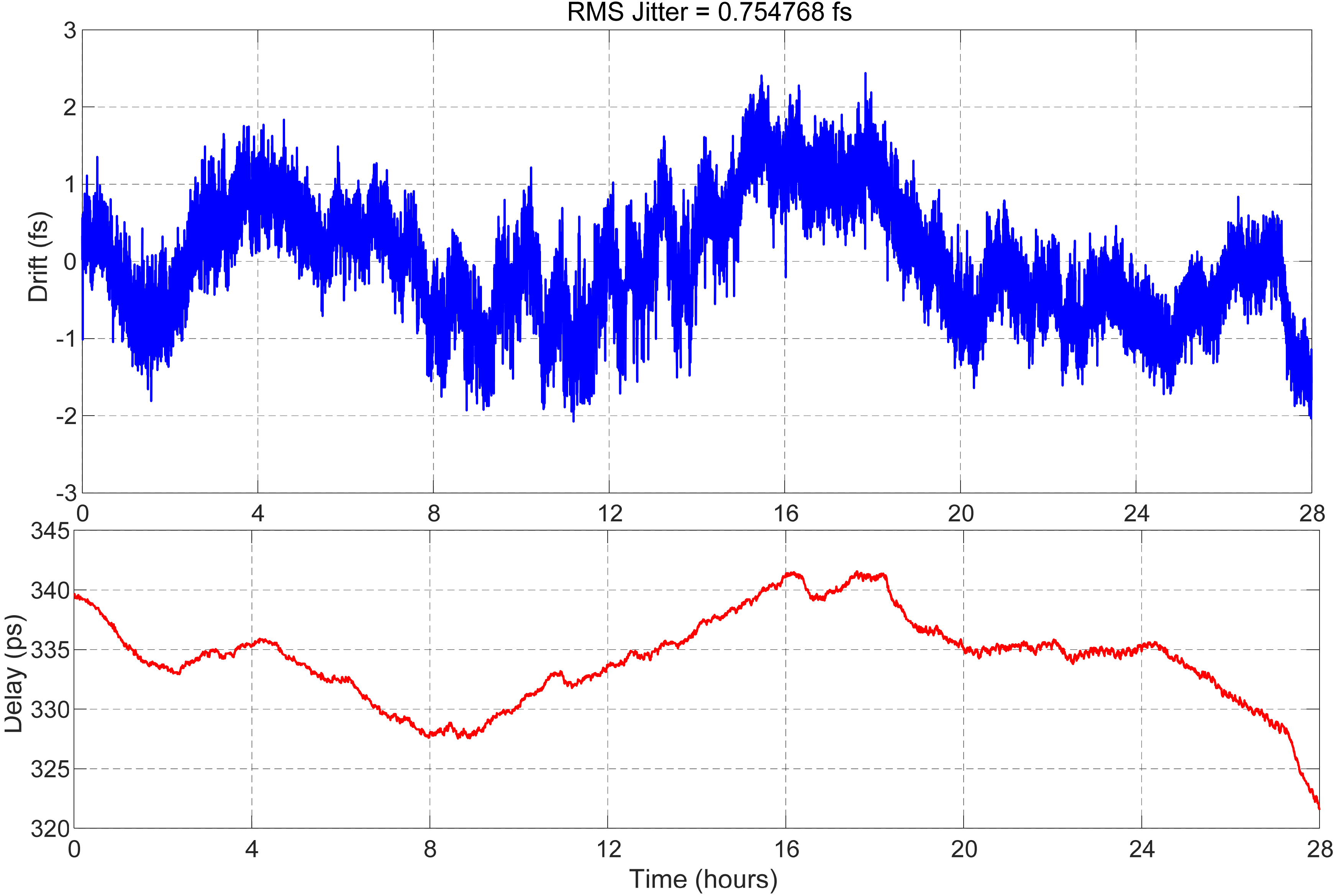
- **Next generation devices: KTP waveguides with integrated WDM couplers**



Single-pass scan:



First Results



Photonic ADCs

Why Photonically Assisted ADCs?

- **Enables extremely low jitter (attoseconds) sampling and high speed information transmission and demultiplexing (Tbit/s)**

- **Electronics enables high-speed information processing (multi-Gbits/s), electrons directly interact**

- **Integration of both technologies enables maximum information aquisition, transport and processing on the multi-Tbit/s level, low parasitics, easier cross channel calibration**

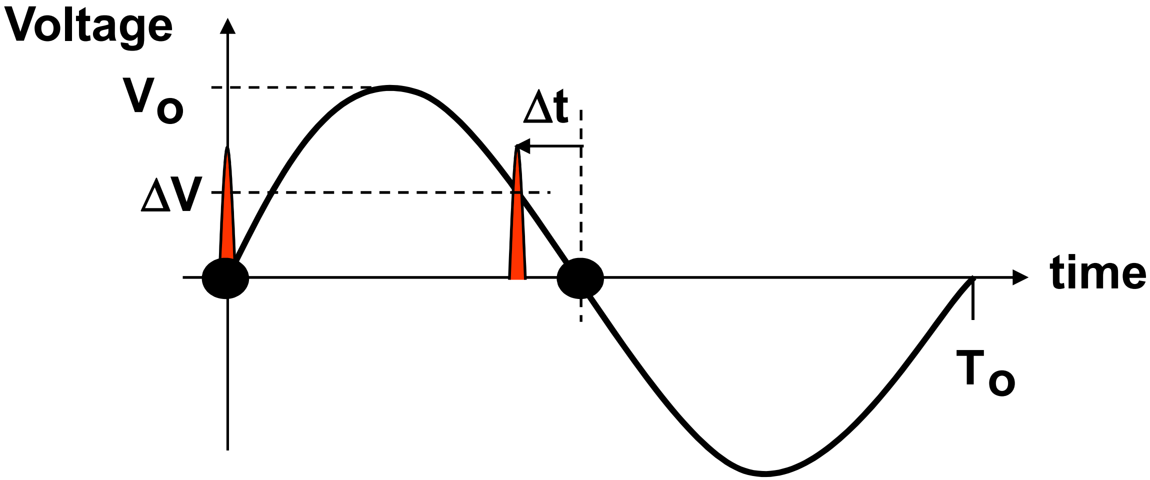
- **Integration on a common silicon-platform enables**

  → reduced size, cost and power at much increased performance

Applications

- Cognitive radio
- Wideband high resolution spectral detection
- Multisensor input, Radar
- High-speed optical communication systems
- RF test equipment
- Essentially eliminating analog microwave hardware downwards from the antenna for systems operating up to 50 GHz

Challenge in Sampling of Microwaves

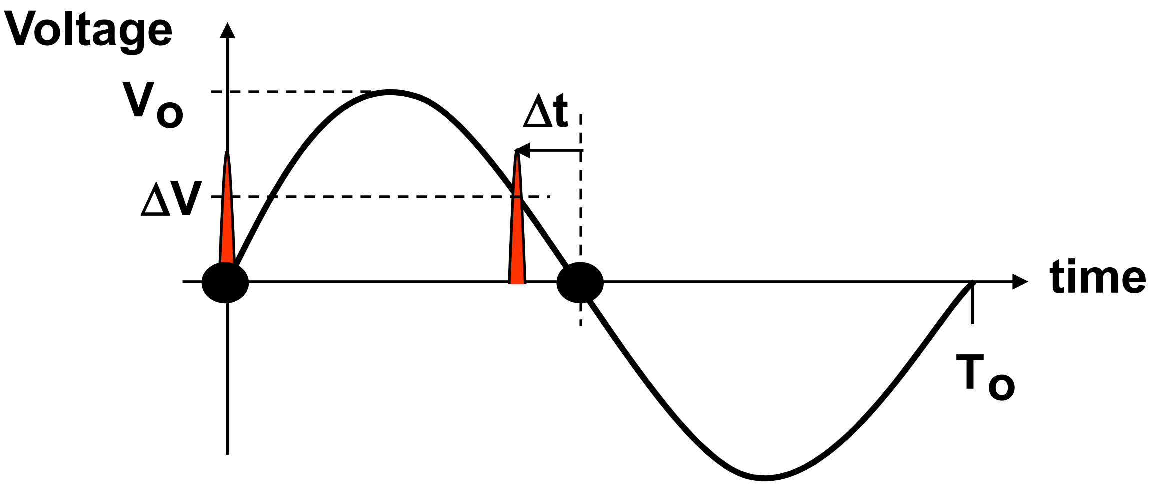


$$\frac{\Delta V}{V_0} = 2\pi \frac{\Delta t}{T_0} = \frac{1}{\sqrt{3} \cdot 2^N}$$

$$\Delta t = \frac{T_0}{2\pi\sqrt{3} \cdot 2^N}$$

Required sampling jitter

Challenge in Sampling of Microwaves



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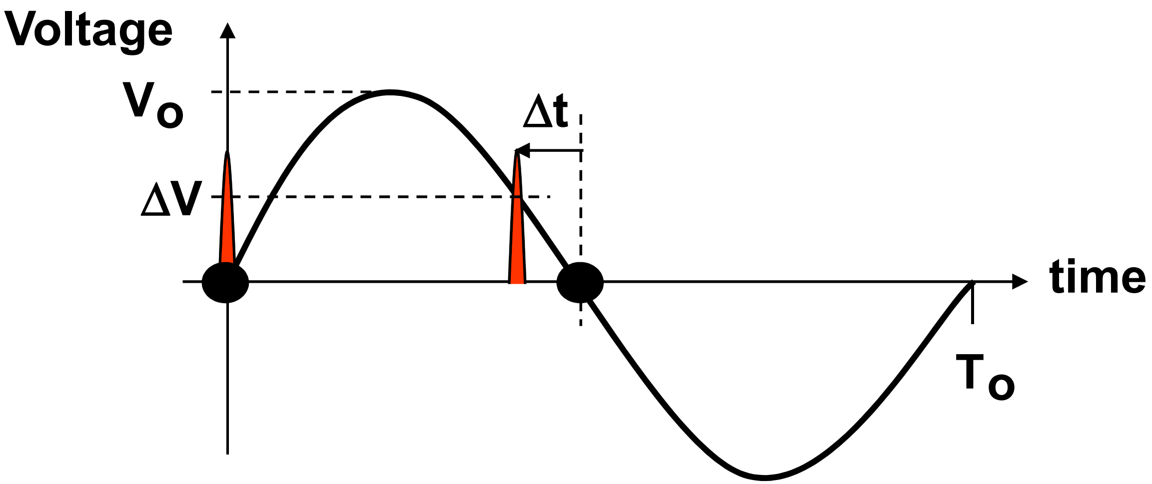
Challenge in Sampling of Microwaves



$$\frac{\Delta V}{V_0} = 2\pi \frac{\Delta t}{T_0} = \frac{1}{\sqrt{3} \cdot 2^N}$$

$$\Delta t = \frac{T_0}{2\pi \sqrt{3} \cdot 2^N}$$

Targeted resolution	**Required sampling jitter**	
	10 GHz	50 GHz
14-bit	**0.5 fs**	**0.1 fs**
12-bit	**2 fs**	**0.4 fs**
10-bit	**9 fs**	**1.8 fs**
8-bit	**36 fs**	**7.2 fs**
6-bit	**144 fs**	**30 fs**

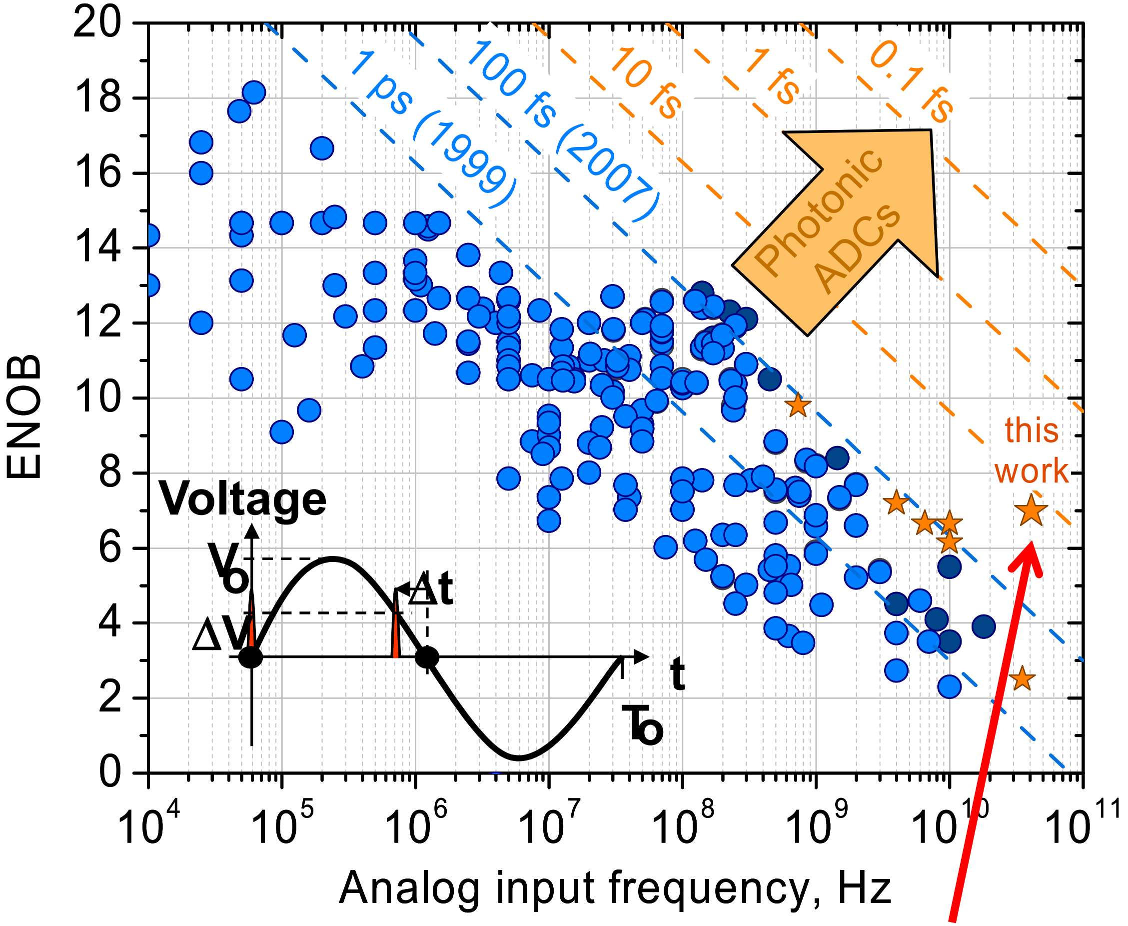
State of the Art Electronic ADC and Beyond

Nortel Inc.: 40 GSa/s CMOS
Y. M. Greshishchev, et al. ISSCC, paper 21.7 (2010).

Fujitsu Inc.: 65 GSa/s CMOS
http://www.fujitsu.com

RPI: 40 GSa/s SiGe ADC
M. Chu, et al. IEEE J. Solid State Circuits 45, 380 (2010).

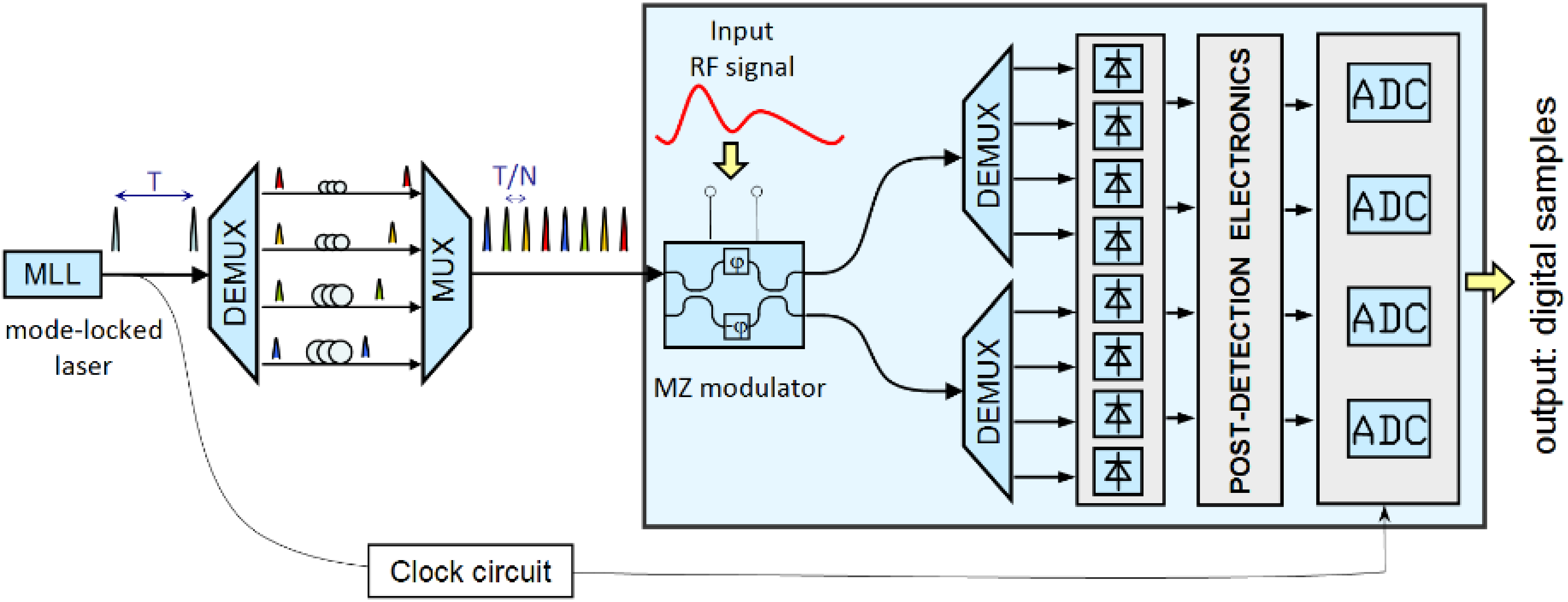
„Walden Plot“ Photonic ADCs



40.99 GHz, 7.0 ENOB, 16 fs jitter

G. C. Valley, Opt. Express 15, 1955 (2007)
R. H. Walden, ADC in the early 21st century, IMS 2007.

Wavelength Multiplexed Optical Sampling



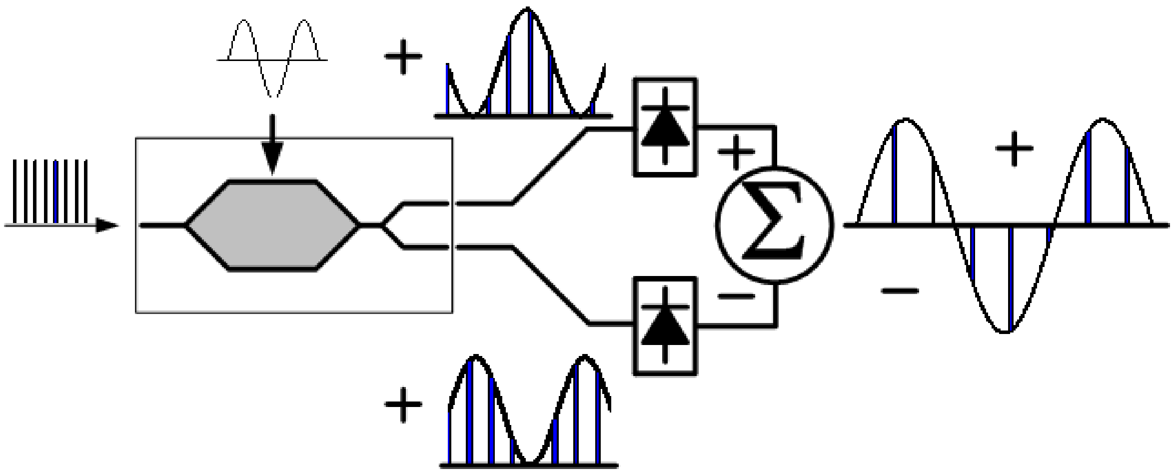
- Effective sampling rate = laser rep rate (1/T) x number of multiplexed channels (N)
- Sampling jitter is set by MLL timing jitter
- Digitization is performed in electronic domain
- Down counting by WDM

T. Clark, “Time and wavelength interleaved phot. Sampler”, PTL 99.

DARPA EPIC
2004 - 2009

Eliminate aperture jitter,
demultiplex to lower rate channels

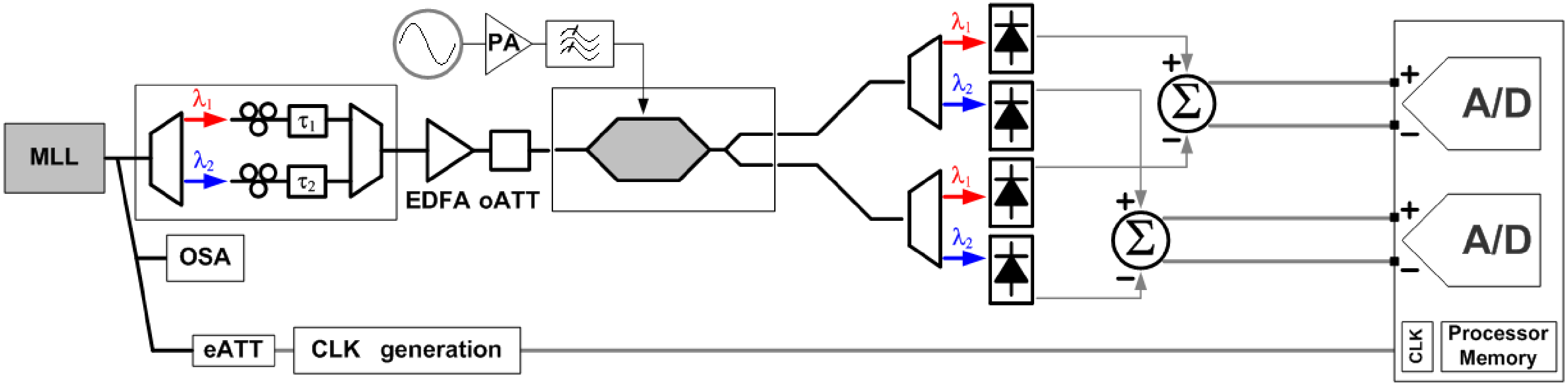
Balanced Detection – Enhanced S/N



- Outputs of MZ intensity modulator are 180º out-of-phase
- Single photodetector can only generate a unipolar (positive) electrical signal
- Balanced detection generates a bipolar signal
- Voltage (x2) → Signal Power (↑ 6 dB)

Twichell, et al. Phase encoded optical sampling for analog-to-digital converters. IEEE PTL, 12(9), 1237 (2000).

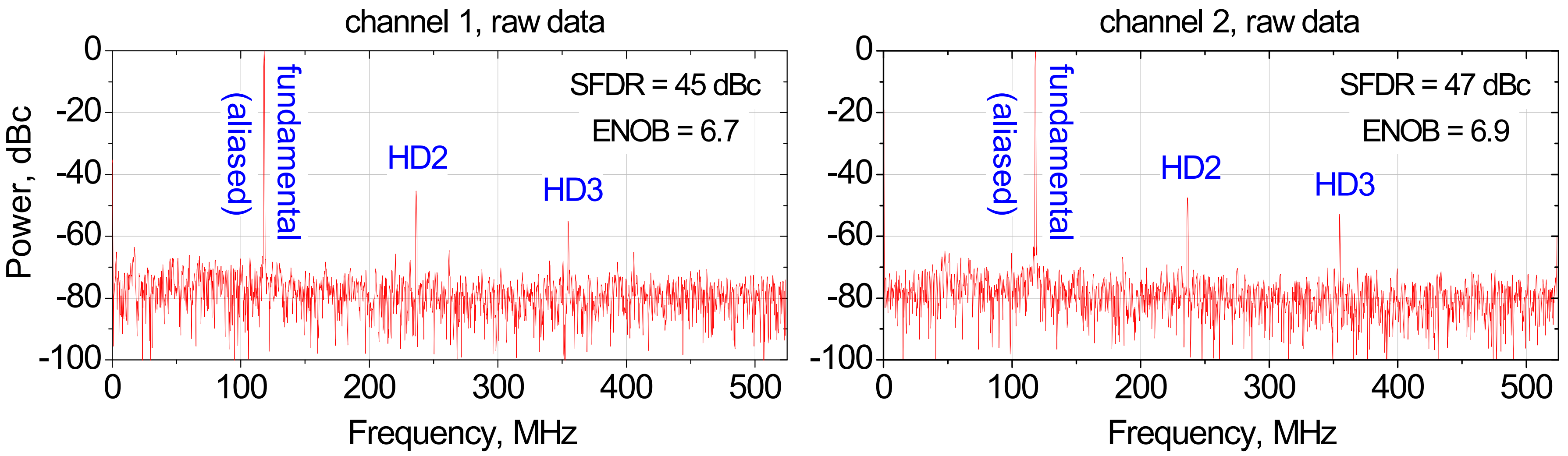
Two Wavelength Channel COTS System



- **High performance ADCs: National Semiconductors 1 GSa/s, 9 ENOB**
- **EO-Space 40 GHz bandwidth modulator**
- **MLL rep rate = 1.048 GHz → Sampling rate = 2.1 Gsa/s**
- **RF freq = 40.99 GHz**

A. Nejadmalayeri *et al.*, CLEO 2011
A. Khilo *et al.*, Opt. Exp. (20) 4454 (2012)

Results: RF Spectra – individual channels



$$y_1 = \arcsin(\alpha_1 + \beta_1 \cdot x_1)$$ **Wavelength #1**

$$y_2 = \arcsin(\alpha_2 + \beta_2 \cdot x_2)$$ **Wavelength #2**

$$\alpha \approx \frac{1}{100}(\beta \cdot x)$$

$$\max(y_1) - \min(y_1) = \max(y_2) - \min(y_2)$$ **Constraint**

- *x*: outputs of the balanced photoreceivers / *y*: RF signals

A. Nejadmalayeri *et al.*, CLEO 2011
A. Khilo *et al.*, Opt. Exp. (20) 4454 (2012)

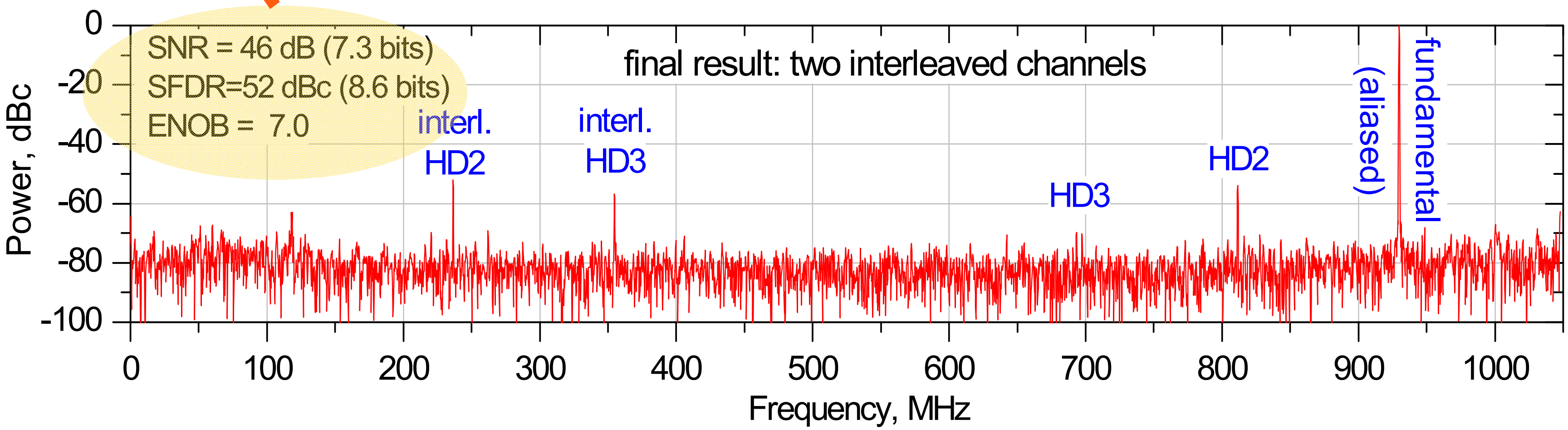
Results: Aggregate RF Spectra

- Noise limited
- Aperture jitter: 15 fs
- SNDR = Signal(dB) – Noise(dB) – Total-Distortion(dB)

$$ENOB = \frac{SNDR(dB) - 1.76}{6.02}$$

Frequency, MHz

Frequency, MHz



SNR = 46 dB (7.3 bits)
SFDR=52 dBc (8.6 bits)
ENOB = 7.0

A. Nejadmalayeri *et al.*, CLEO 2011
A. Khilo *et al.*, Opt. Exp. (20) 4454 (2012)

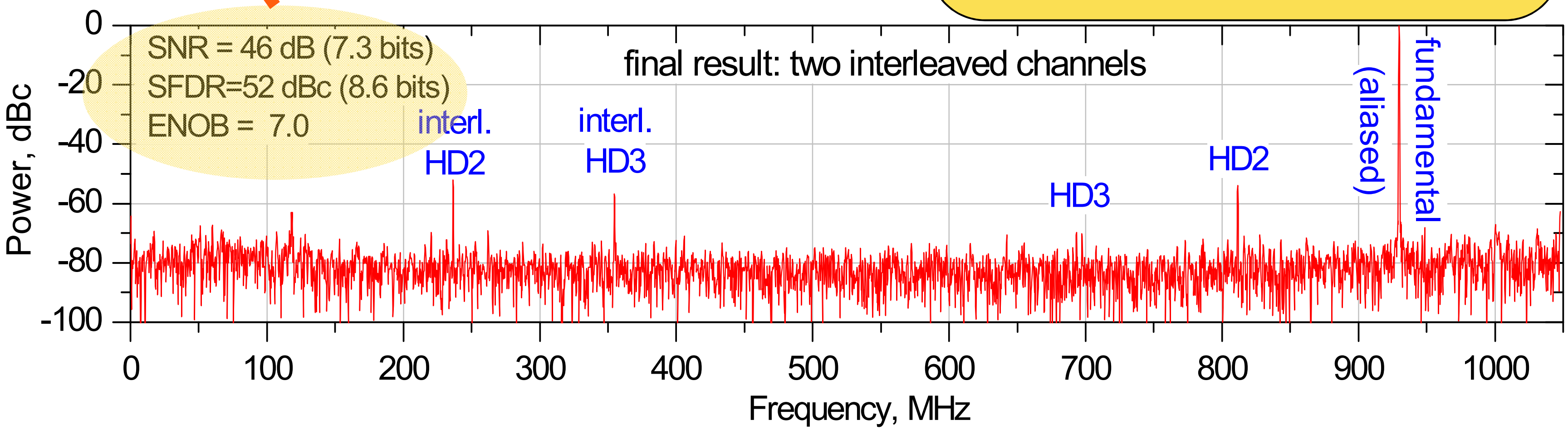
Results: Aggregate RF Spectra

- **Noise limited**
- **Aperture jitter: 15 fs**
- **SNDR = Signal(dB) – Noise(dB) – Total-Distortion(dB)**

$$ENOB = \frac{SNDR(dB) - 1.76}{6.02}$$

7.0 ENOB @ 41 GHz

Frequency, MHz



SNR = 46 dB (7.3 bits)
SFDR=52 dBc (8.6 bits)
ENOB = 7.0

final result: two interleaved channels

A. Nejadmalayeri *et al.*, CLEO 2011
A. Khilo *et al.*, Opt. Exp. (20) 4454 (2012)

Integrated Photonic ADC

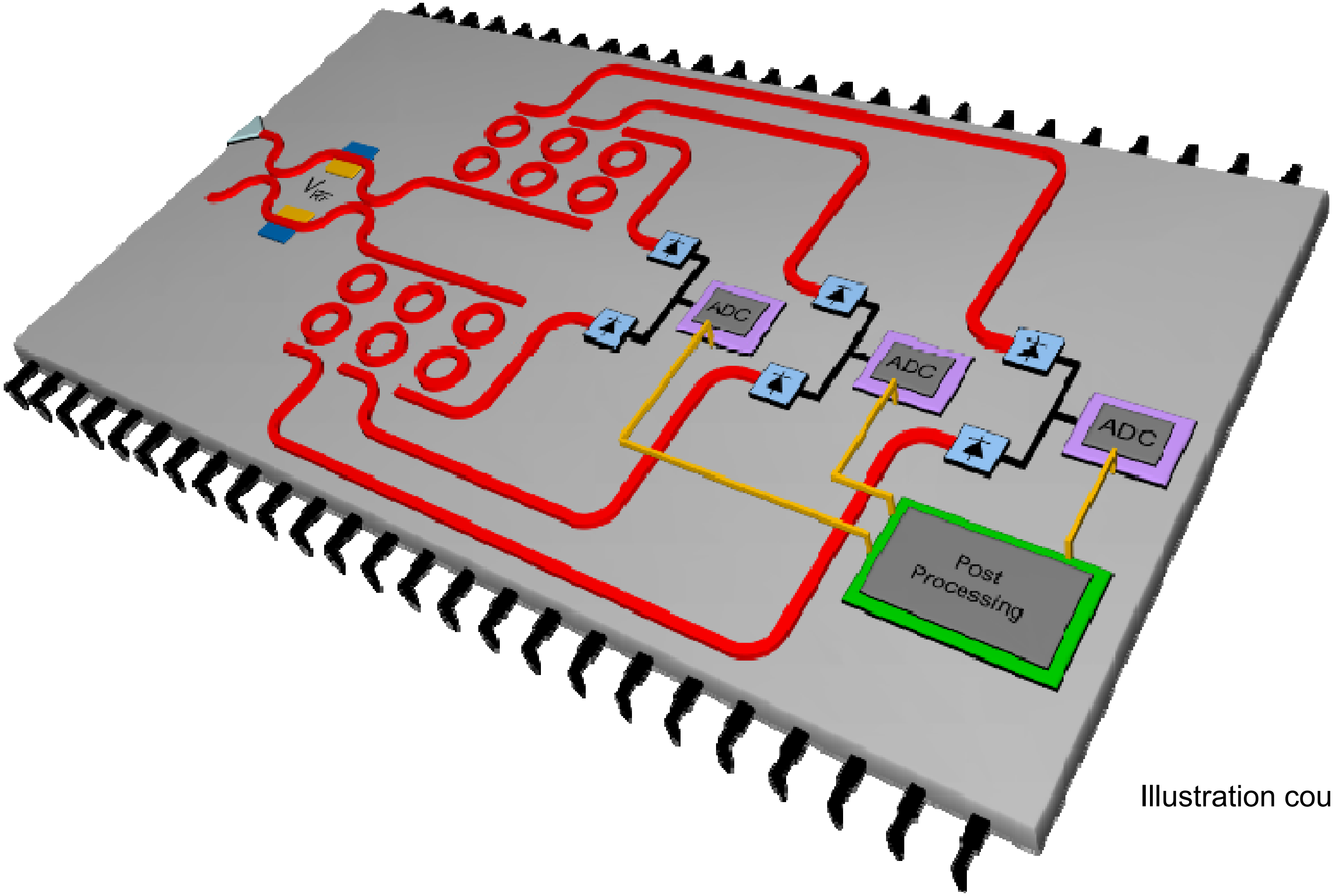


Illustration courtesy of Marcus Dahlem

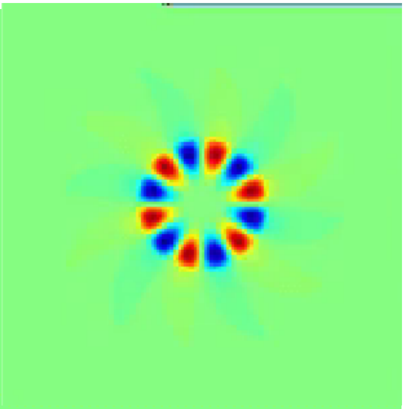
Khilo *et al.*, Opt. Exp. (20) 4454 (2012)

High Index Contrast Integrated Photonics

- **Optical resonators** - no good conductors
  - optical confinement by index discontinuity

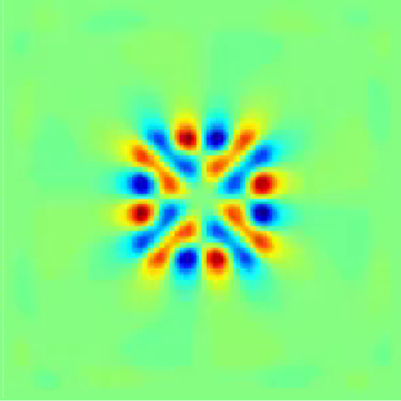
- **High Index Contrast:** ~50-200% (conventional <2%)
  - Material is Si:SiN:SiO_2:air = 3.5:2.2:1.45:1.0
  - Dimensions: waveguide <1 μm,
    ring resonators <15 μm

HIC Benefits	HIC Challenges
Low radiation loss (large free spectral range: FSR)	Reduce scattering loss (sidewall roughness)
	Fiber-chip coupling
Dense integration small size, efficient interaction with carriers	Polarization sensitivity (res. frequency, coupling)



Traveling-wave resonator

in Si:air (3.0:1.0 index)



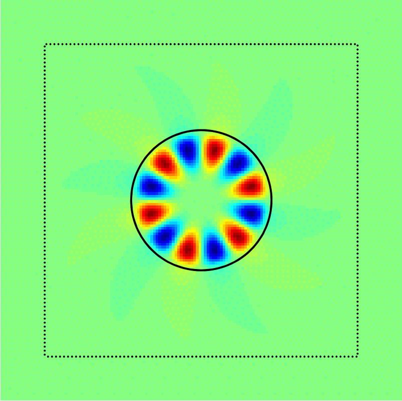
Standing-wave resonator

Silicon Photonics

- **Optical resonators** - no good conductors
  - optical confinement by index discontinuity

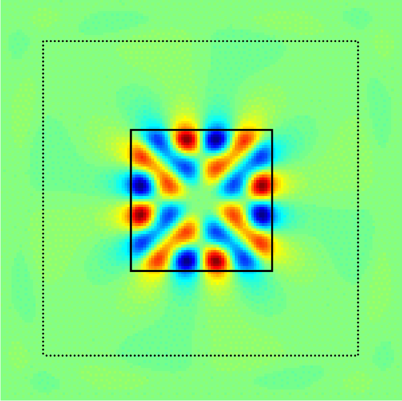
- **High Index Contrast:** ~50-200% (conventional <2%)
  - Material is Si:SiN:SiO$_2$:air = 3.5:2.2:1.45:1.0
  - Dimensions: waveguide <1 μm, ring resonators <15 μm

HIC Benefits	HIC Challenges
Low radiation loss (large free spectral range: FSR)	Reduce scattering loss (sidewall roughness)
	Fiber-chip coupling
Dense integration small size, efficient interaction with carriers	Polarization sensitivity (res. frequency, coupling)



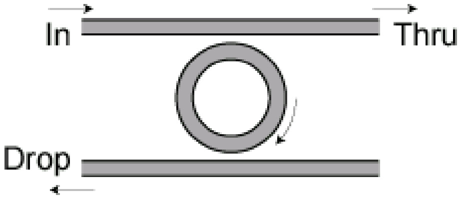
Traveling-wave resonator

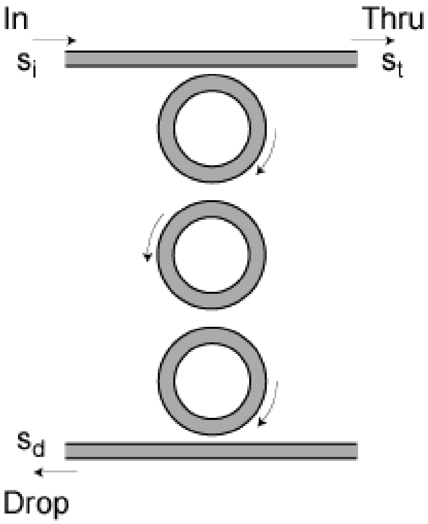
in Si:air (3.0:1.0 index)

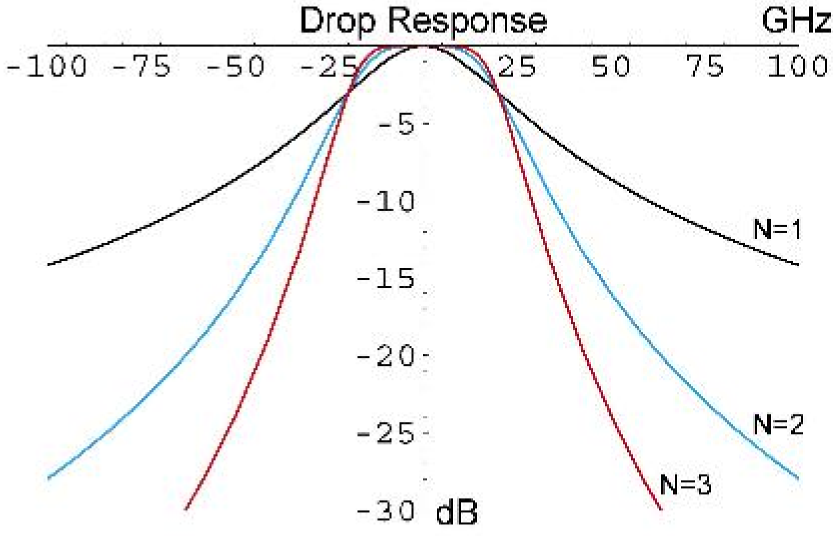


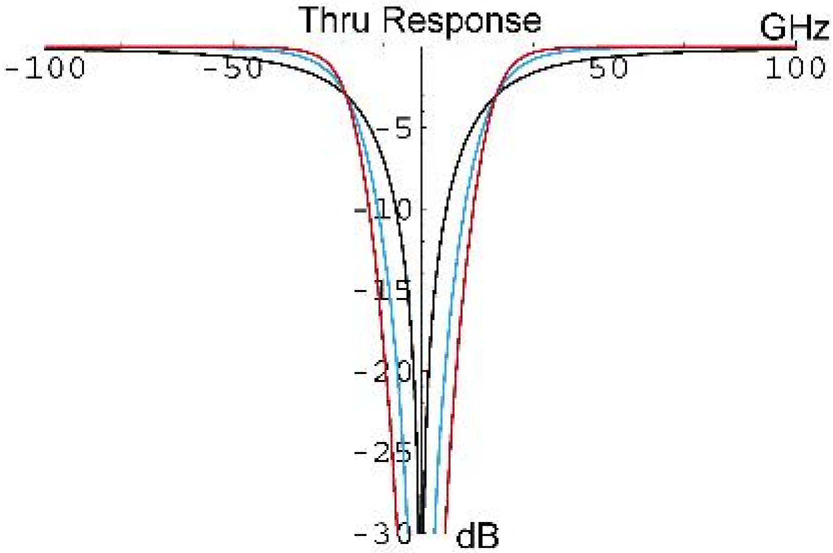
Standing-wave resonator

Microring Resonator Filters



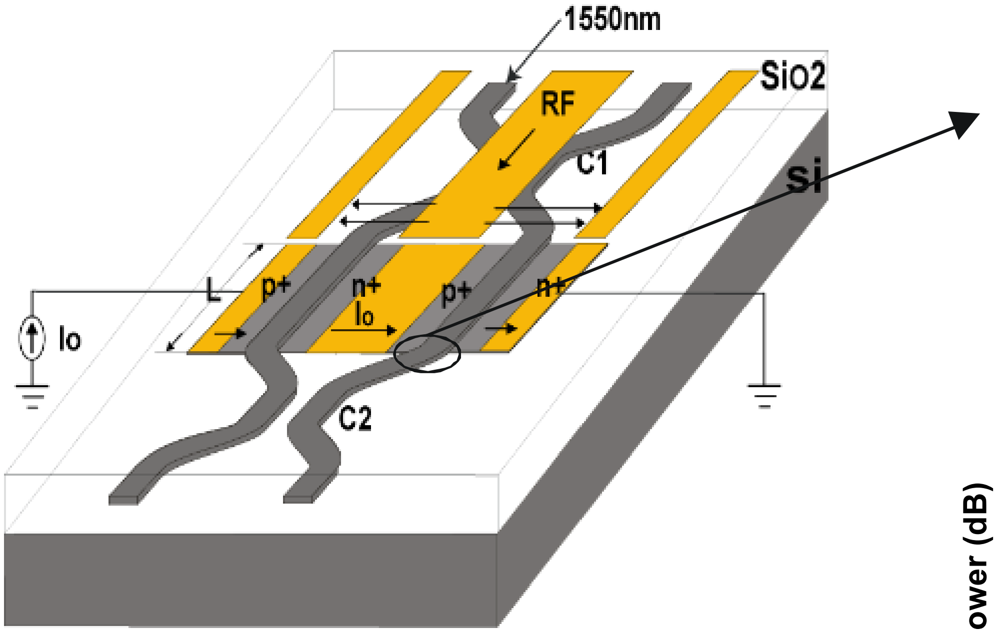






B.E. Little et al., JLT, Sep 1997.

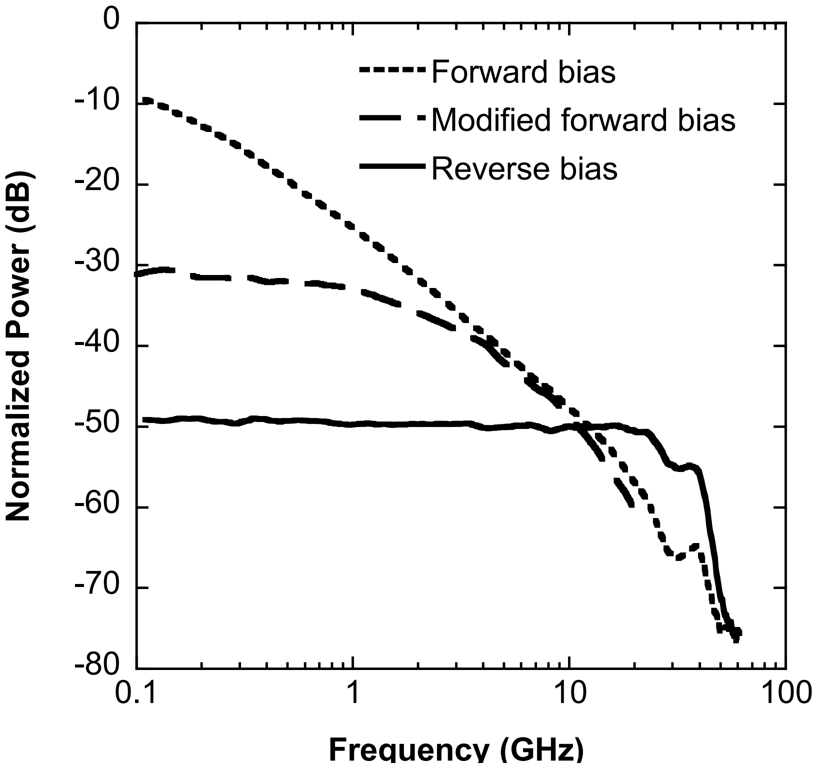
High-Speed Si-Modulator



Forward or reversed biased PIN-sections

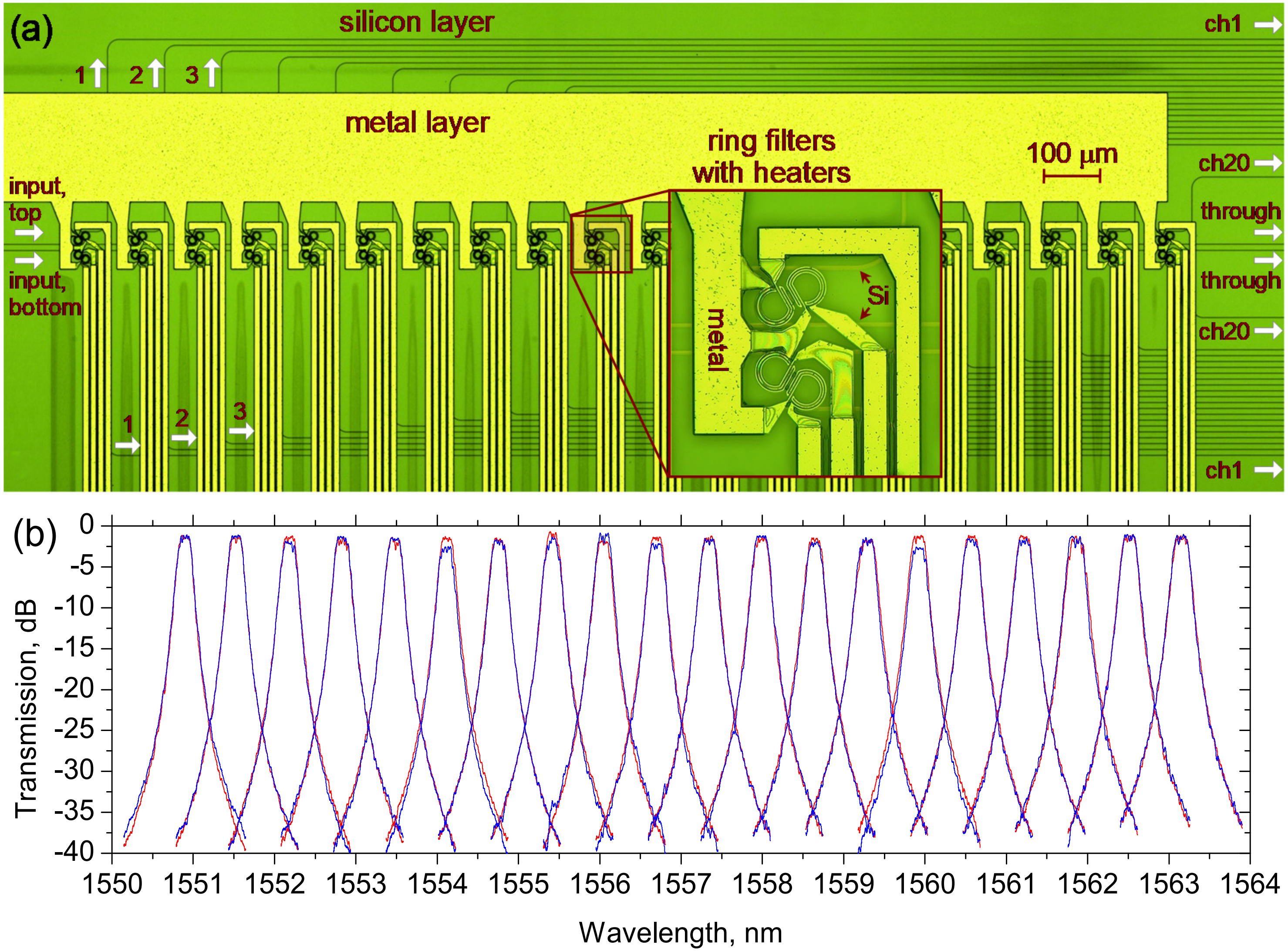
Optimized doping profile:
--> low loss, high-speed > 20GHz

Typical insertion loss: 3-5 dB
$V_\pi L$ ~ 0.5 V·cm



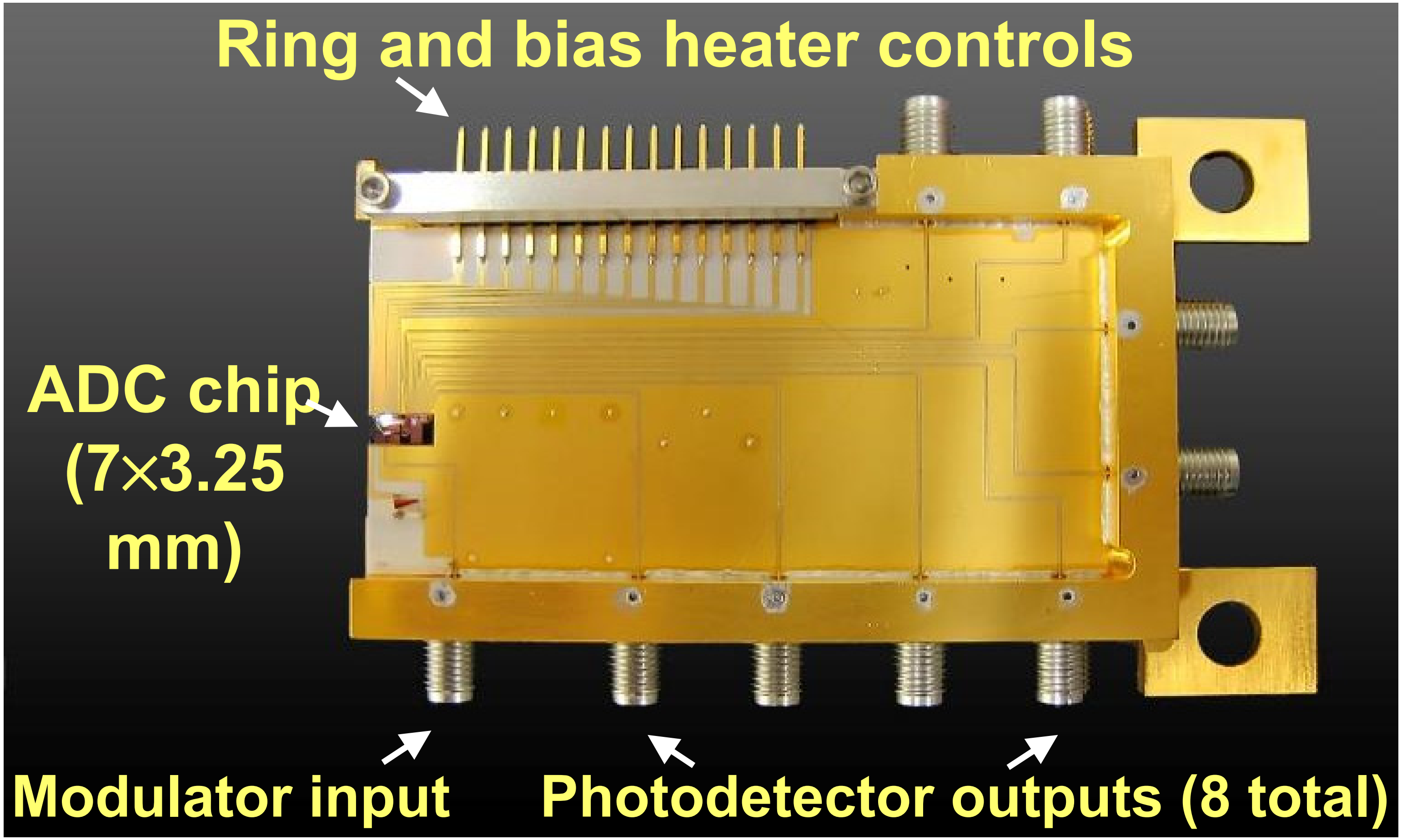
S. Spector et al., IEEE JSTQE 16, p.165 (2010)

20-Channel Silicon Photonic Filter Bank



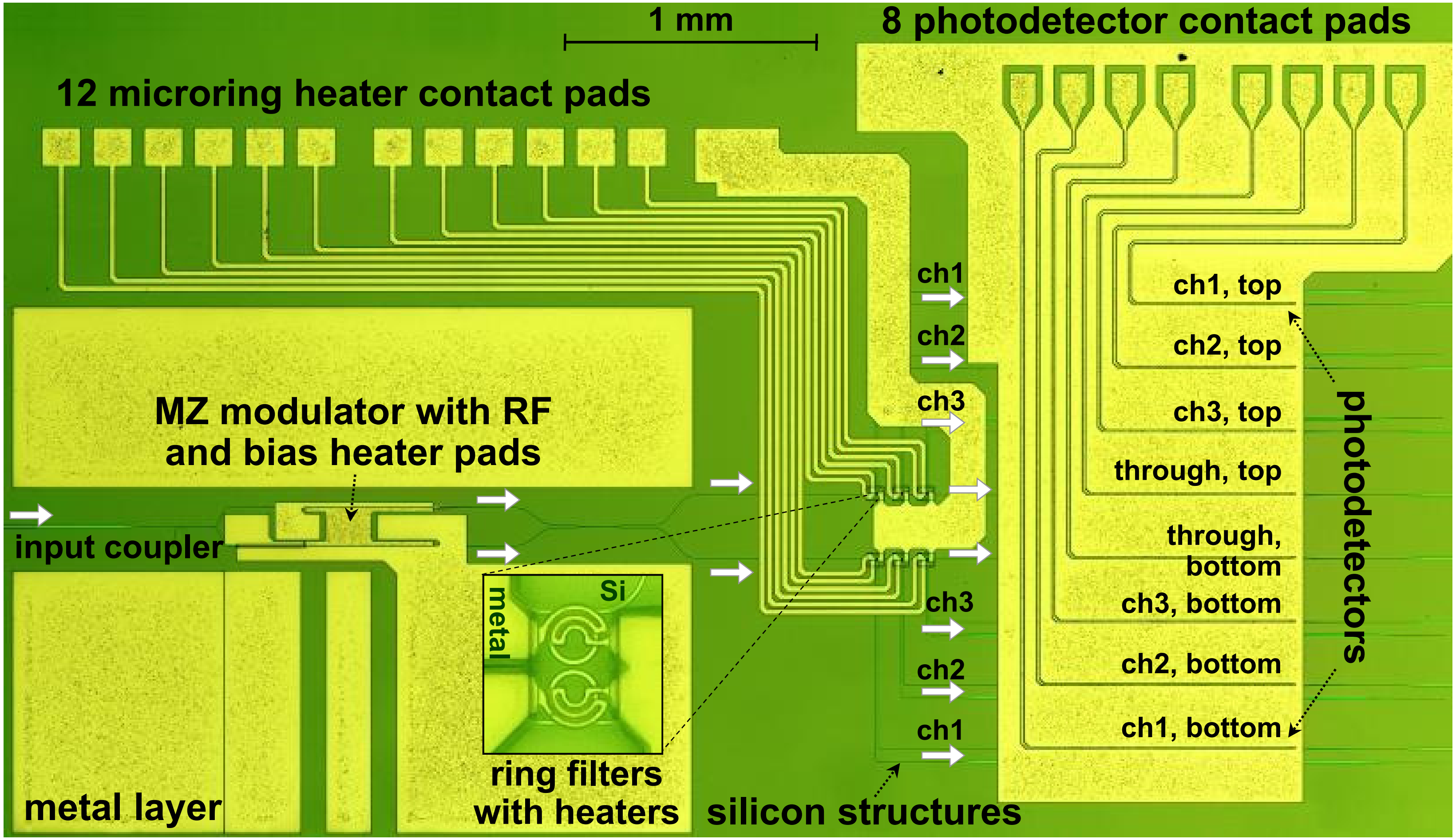
Spector *et al.*, CLEO 2011, paper CWM2
Khilo *et al.*, Opt. Exp. (20) 4454 (2012)

Integrated Silicon Photonic ADC



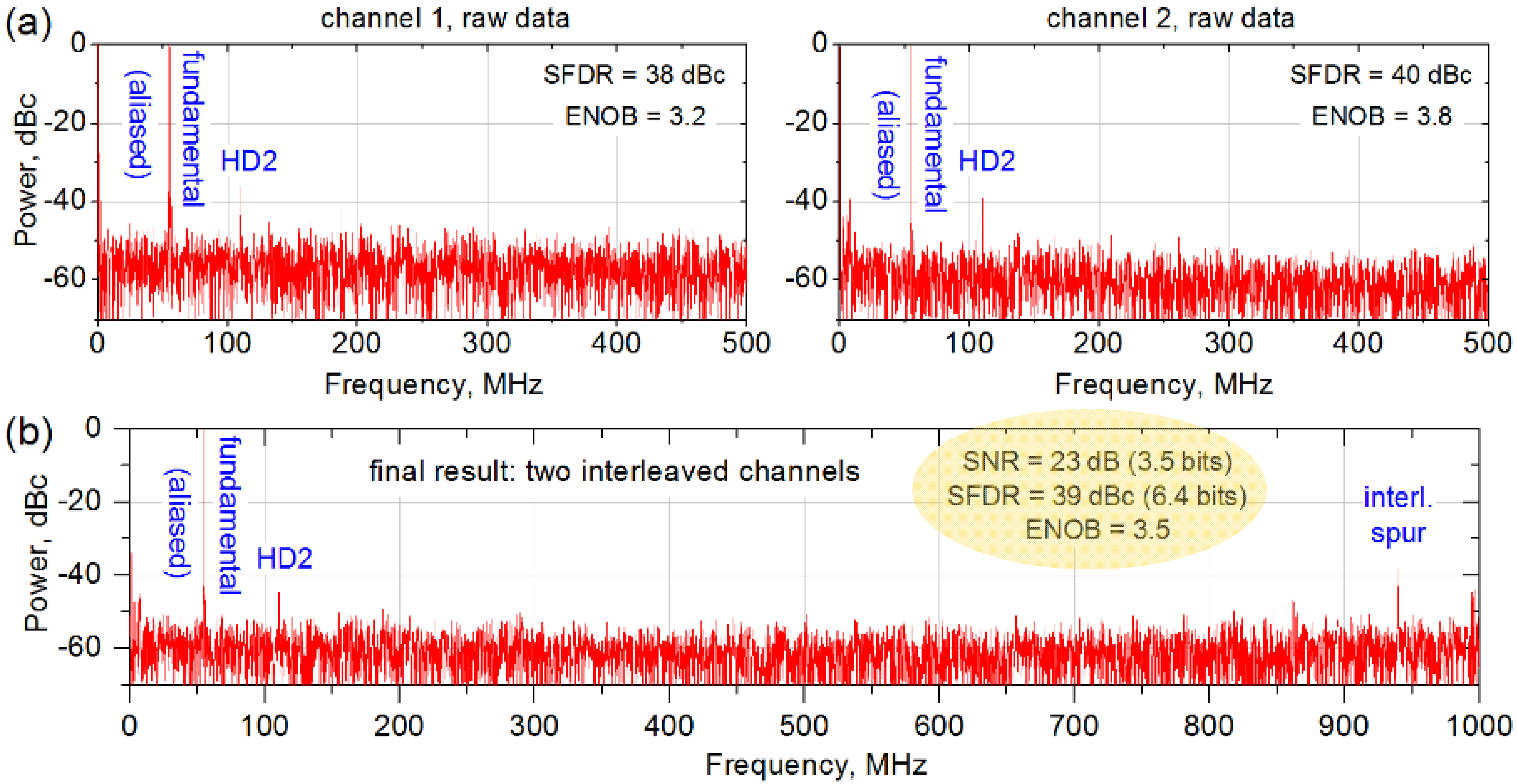
Grein *et al.*, CLEO 2011
Khilo *et al.*, Opt. Exp. (20) 4454 (2012)

Integrated Silicon Photonic ADC



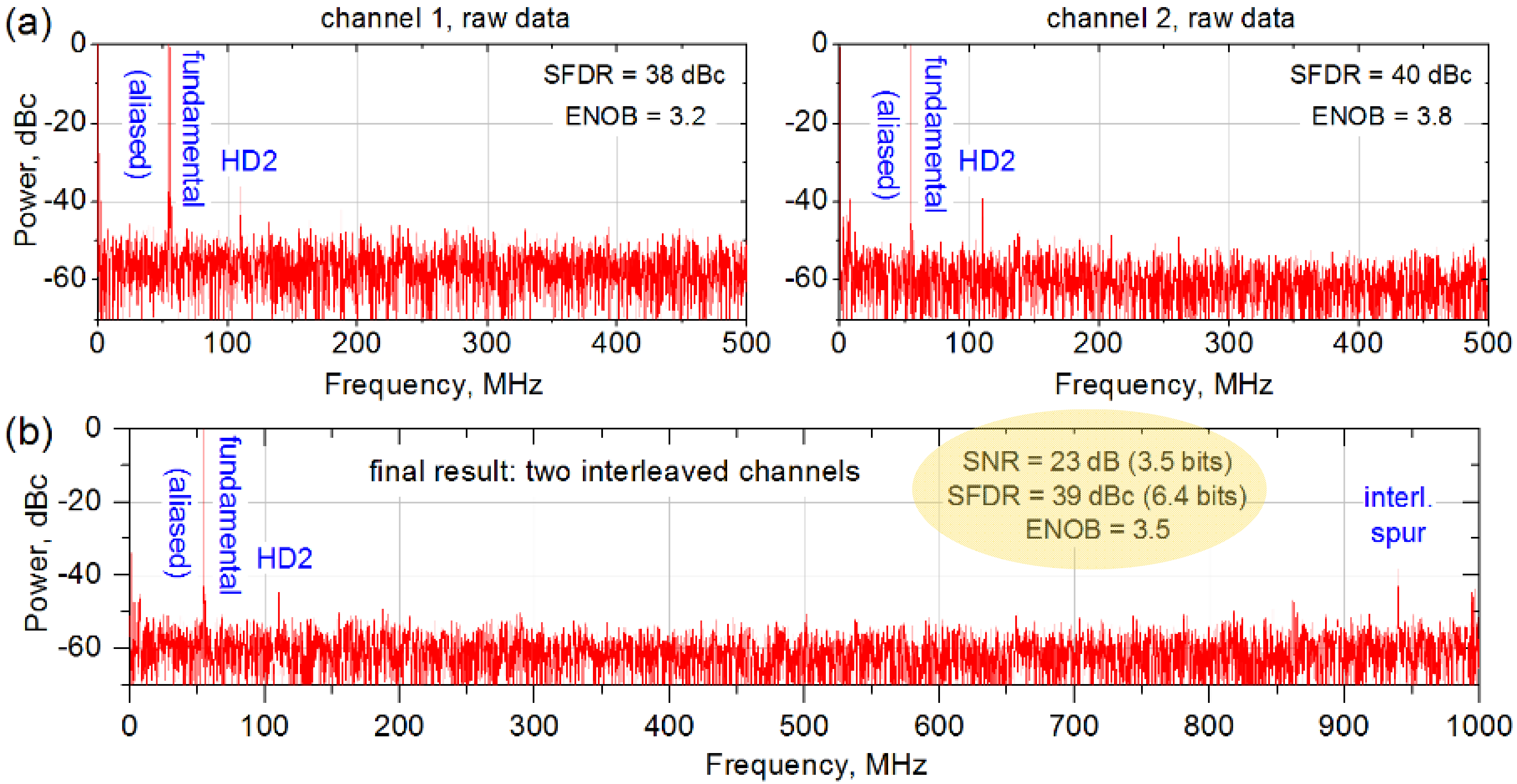
Grein *et al.*, CLEO 2011
Khilo *et al.*, Opt. Exp. (20) 4454 (2012)

Integrated Silicon Photonic ADC



- **2 wavelength channels**

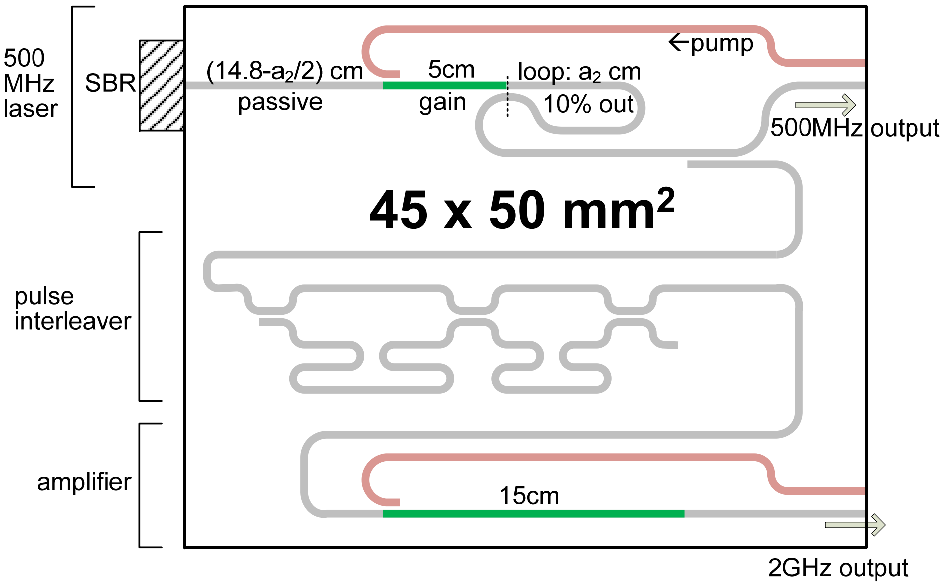
Integrated Silicon Photonic ADC

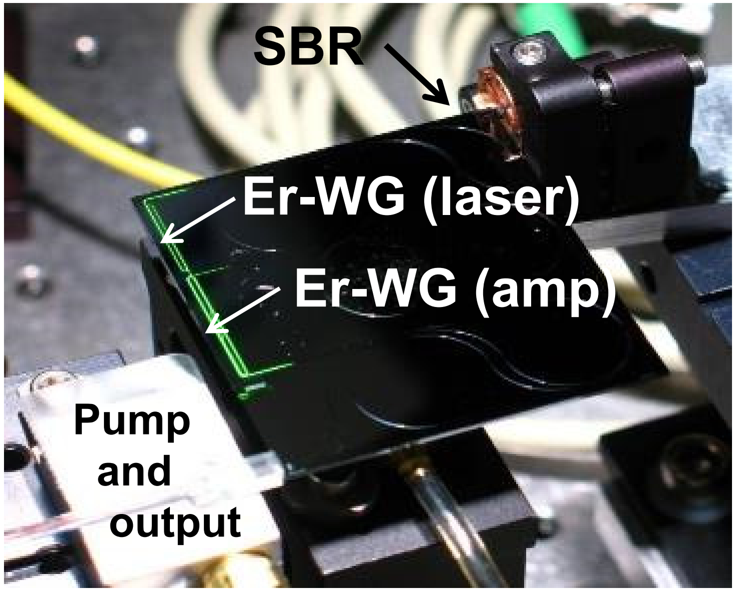


- **2 wavelength channels**

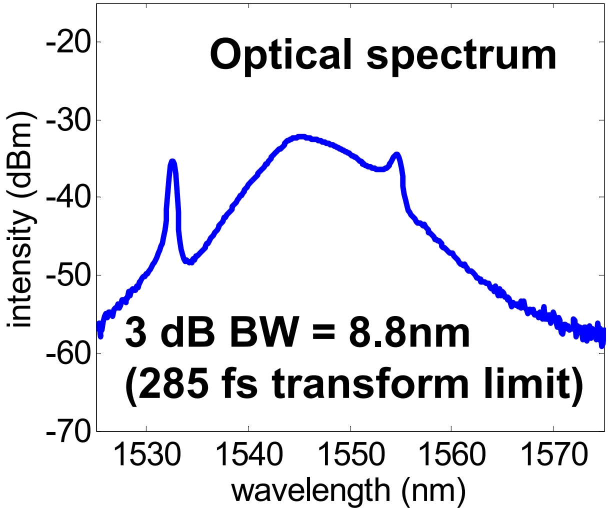
3.5 ENOB @ 1 GHz

2 GHz integrated waveguide lasers

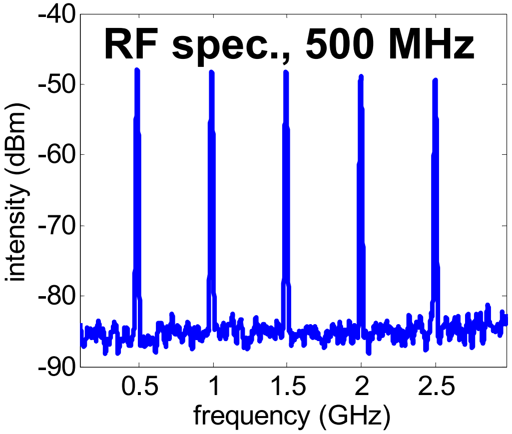


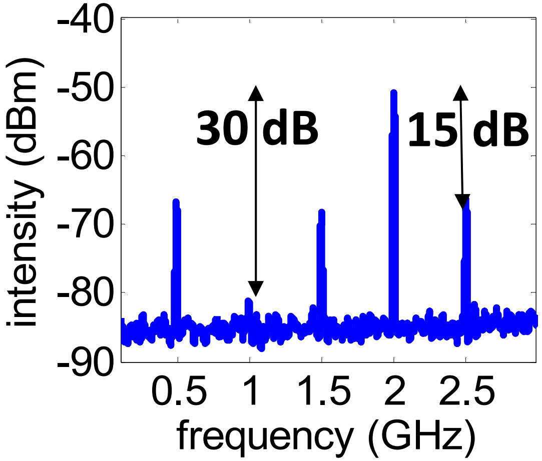


Waveguide laser setup


Optical spectrum

3 dB BW = 8.8nm (285 fs transform limit)


RF spec., 500 MHz



H. Byun, PTL 21, 763 (2009)

Chip-Scale Electronic-Photonic Synthesizer (CS-EPS)

Michael Watts (Principal Investigator), Franz Kärtner, & Erich Ippen, MIT

Si photonic, CW and mode-locked laser/pulse generator, and electronics design and test

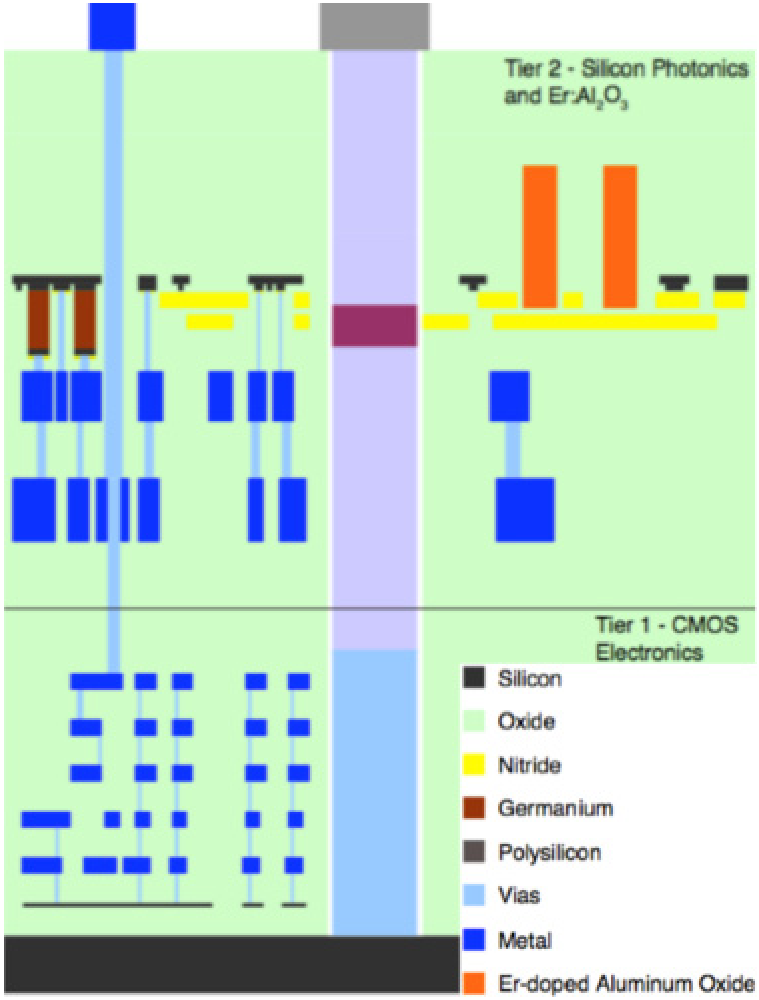
Vladimir Stojanovic, UC Berkeley

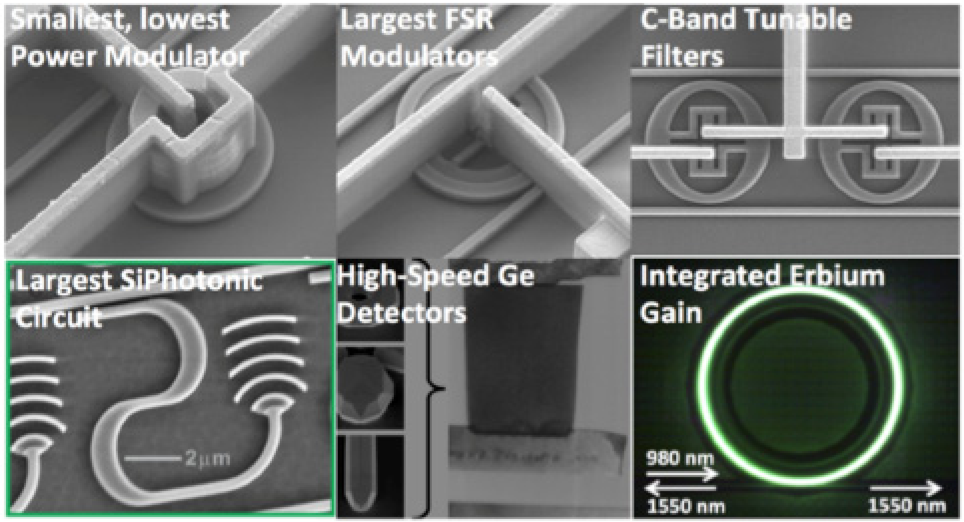
Electronic-photonic system modeling & CMOS loop and component design

Douglas Coolbaugh, SUNY-CNSE

CMOS and silicon photonics fabrication

MIT 3D Electronic-Photonic Integration Platform





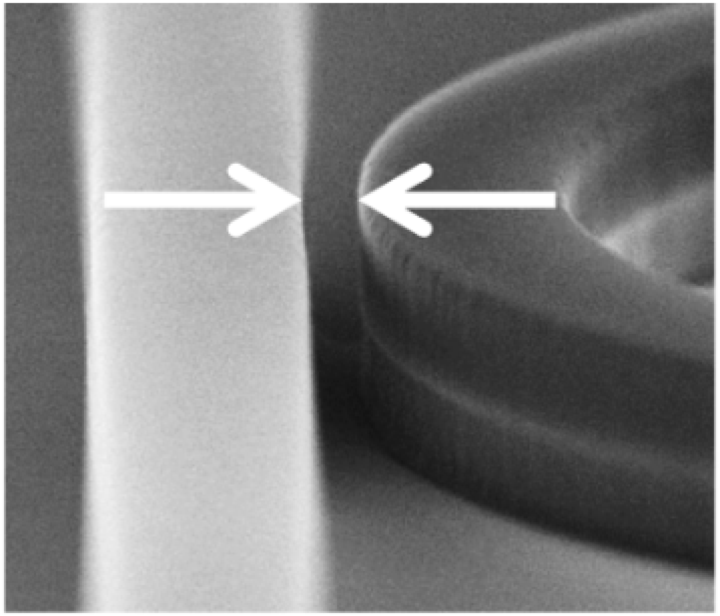
Comprehensive Device Library:

- **Low loss Si, SiN waveguides**
- **Tunable micro-ring filters**
- **Ultralow power modulators, phase shifters, switches, tuners**
- **High speed Ge-detectors**
- **Low loss Si – SiN – transitions**
- **Low loss fiber-to-chip couplers**
- **Erbium/Thulium on-chip gain, lasers**
- **Largest Si-photonic circ. (phased array)**

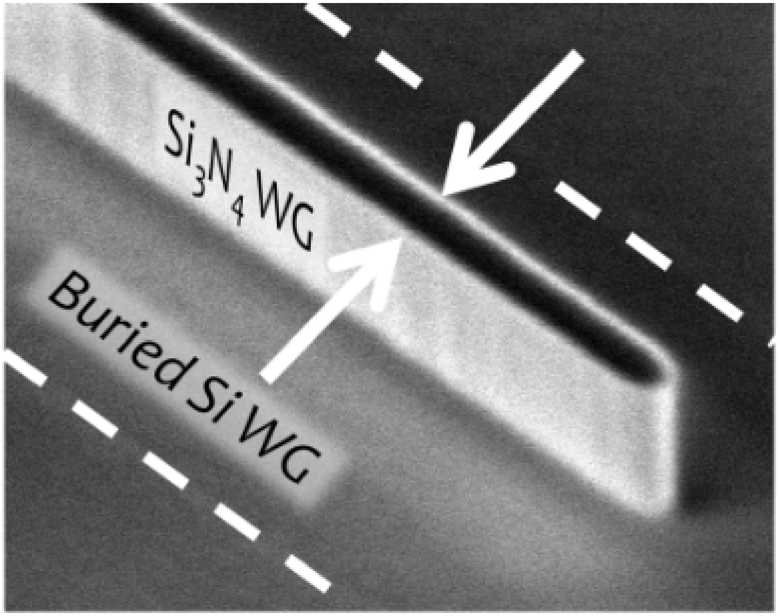
300mm Wafer-Scale Fabrication Capability

Typical Resolution w/ 193mm Immersion, Chrome-on-Glass:

- Current Resolution: 95nm lines and spaces without proximity corrections or phase shift masks.
- CNSE’s Capability: 20nm lines and spaces, but feel the effort below 65nm is too great to be justified for SiPhotonics



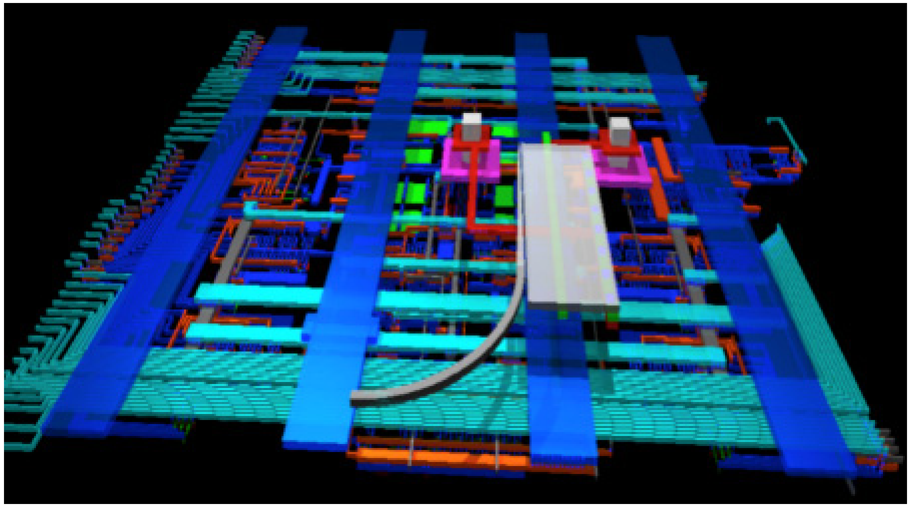
95nm gap in Si.



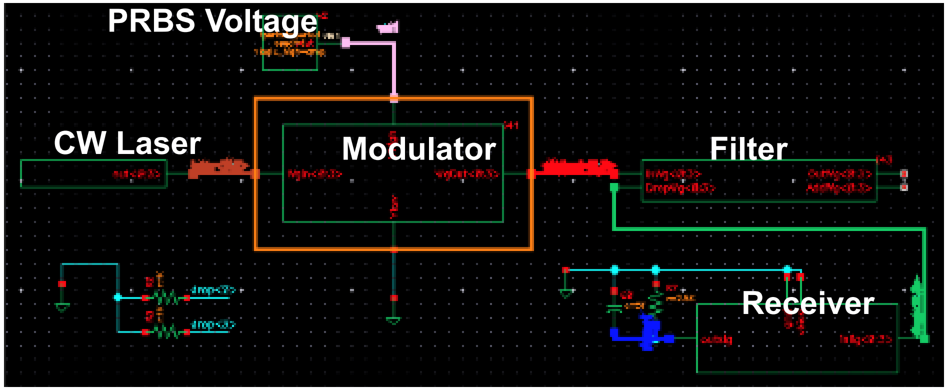
95nm Si3N4 taper on Si waveguide.

Modeling: Library-Based Design in CADENCE

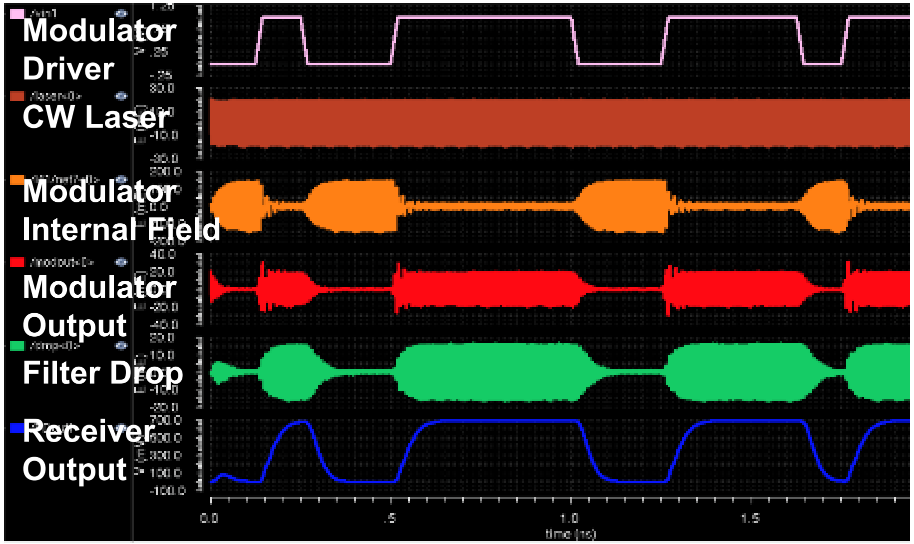
Receiver



Verilog A Schematic: Communication Link



Verilog A Output: Communication Link

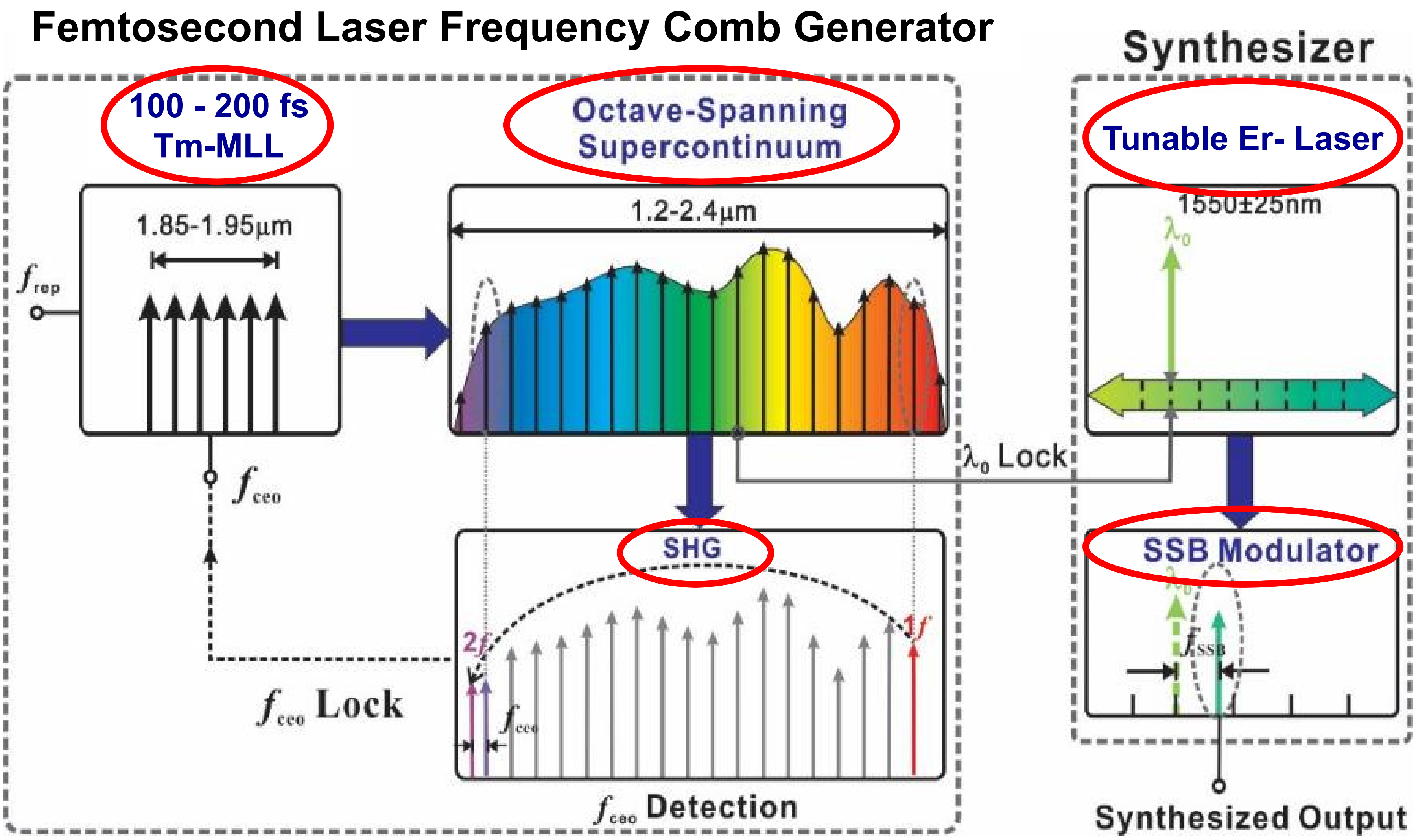


Electronic-Photonic Co-Design:

- CADENCE: All 55 CMOS, Photonic and 3D via layers
- VerilogA: Able to fully simulate both electronic and photonic signals for system output

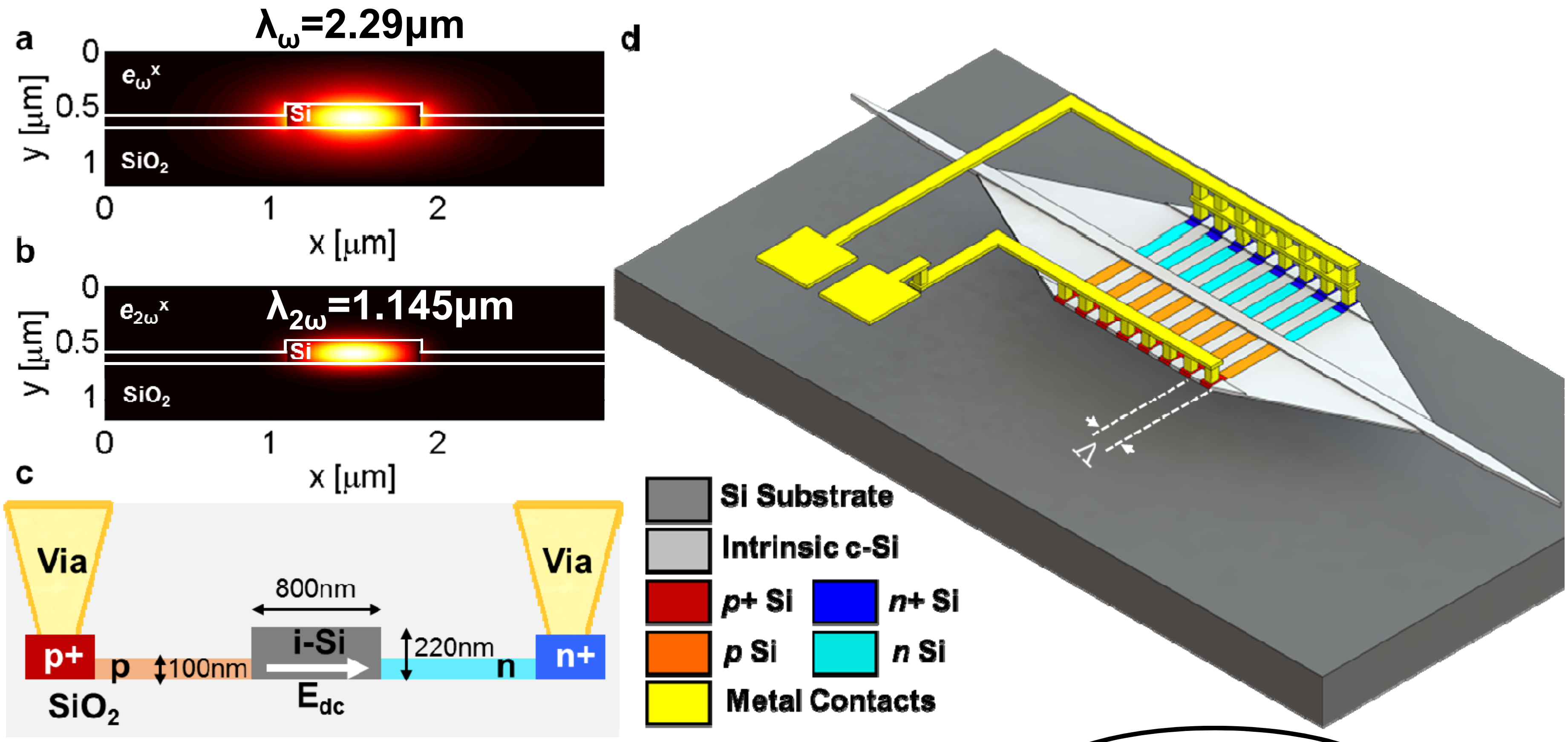
C. Sorace-Agaskar, J. Leu, M. R. Watts, and V. Stojanovic, “Electro-Optical Co-Simulation for Integrated CMOS Photonic Circuits with VerilogA,” Opt. Express, vol. 23, no. 21 (2015).

DARPA – DODOS Program



T. Hänsch & J. Hall, Nobel Prize 2005

Second Harmonic Generation in Silicon by EFISH



- ☐ **Quasi-phase-matching as an alternative**

$$\bar{\chi}^{(2)}_{xxx} = 3\chi^{(3)}_{xxxx}\sqrt{V_i}\int_{V_i} e^{x*}_{2\omega}\, e^{x}_{\omega}\, e^{x}_{\omega}\, E^{x}_{DC}\, dv$$

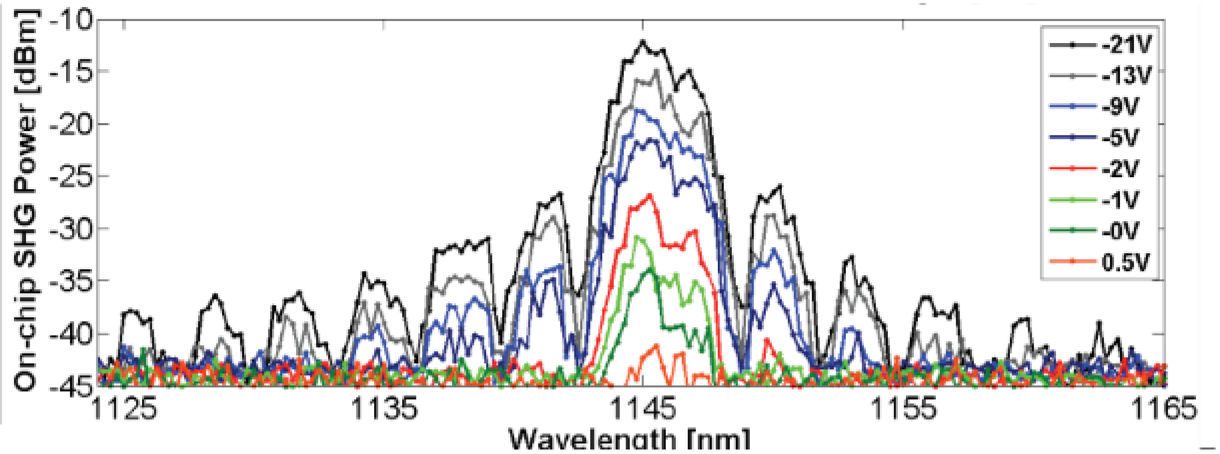
Large Overlap

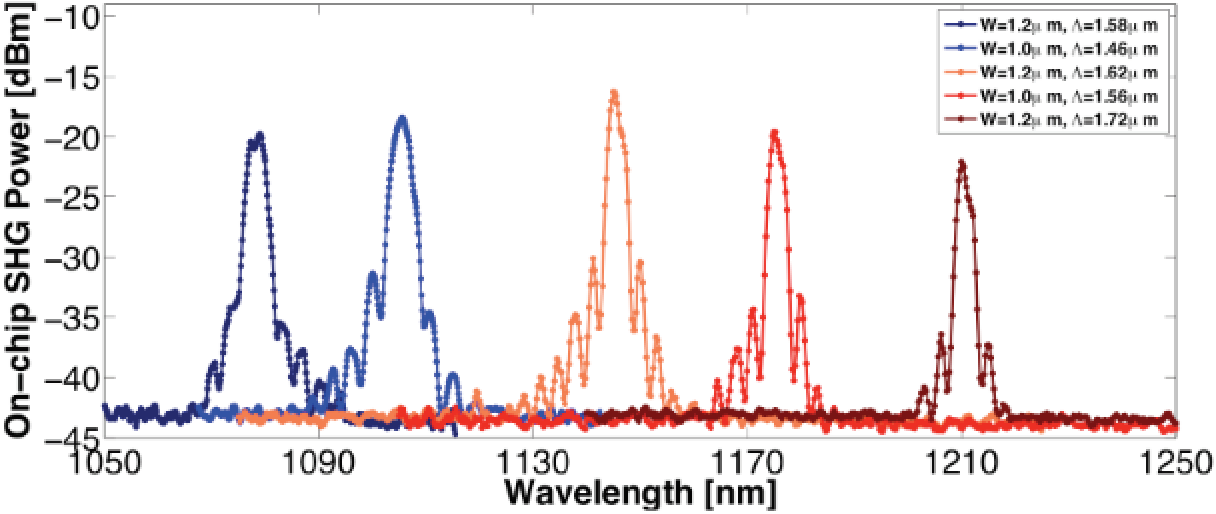
- ☐ **Field induced X^2 in silicon -> break the crystalline symmetry**

E. Timurdogan et al. Nat. Phot. 11, 200 (2017).

Frequency Doubler

- Broadband Second Harmonic Generation in Silicon demonstrated

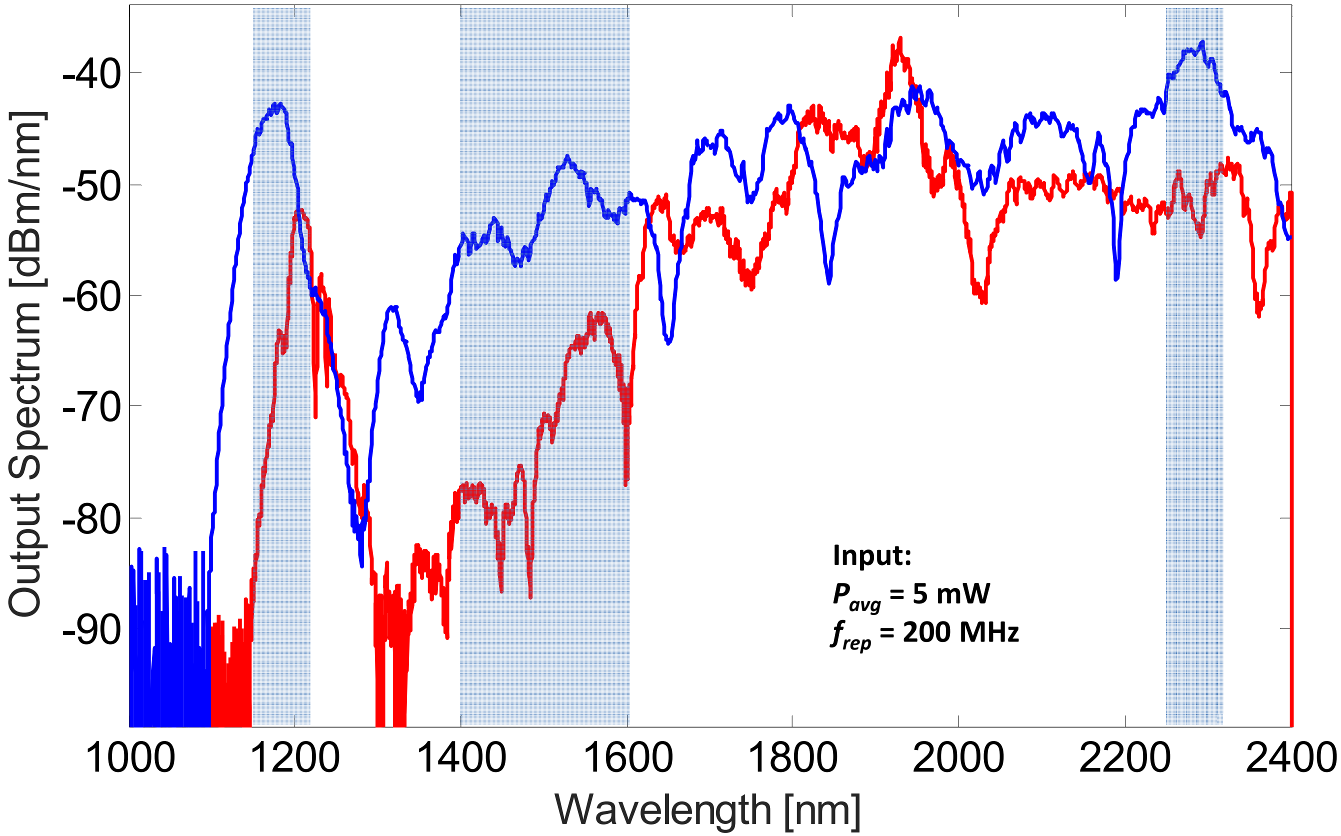




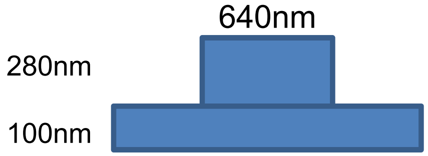
- **13%/W conversion efficiency measured with CW and pulsed input sources**
- **Devices can be optimized for a wide variety of wavelengths by adjusting the phase-matching period**

E. Timurdogan et al. Nat. Phot. 11, 200 (2017).

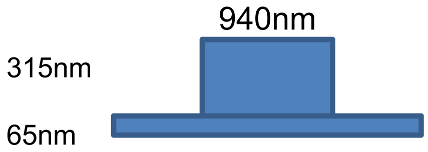
Supercontinuum Generation



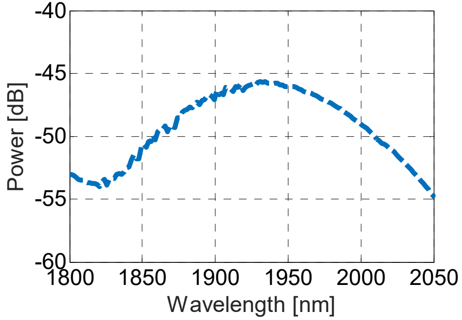
Phase 1 Design (red):



Phase 1.5 Design (blue):



Input Spectrum:



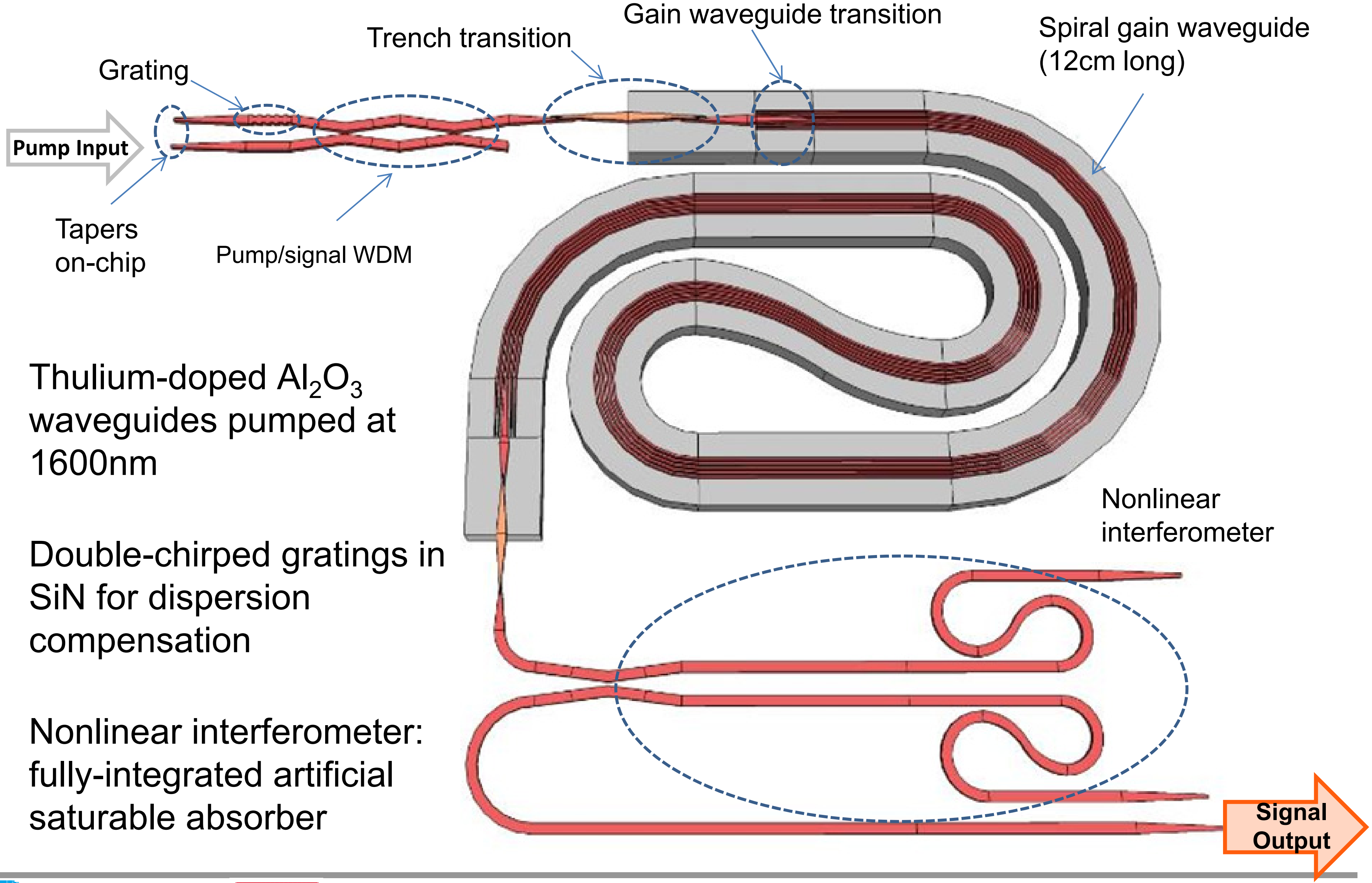
Improved output spectrum with new generation of SC devices

Stronger spectrum around 1550nm

Stronger signal at 1150nm, enables using 2.3um for SHG

N. Sing et al. CLEO 2017.

Integrated Thulium Mode-Locked Laser

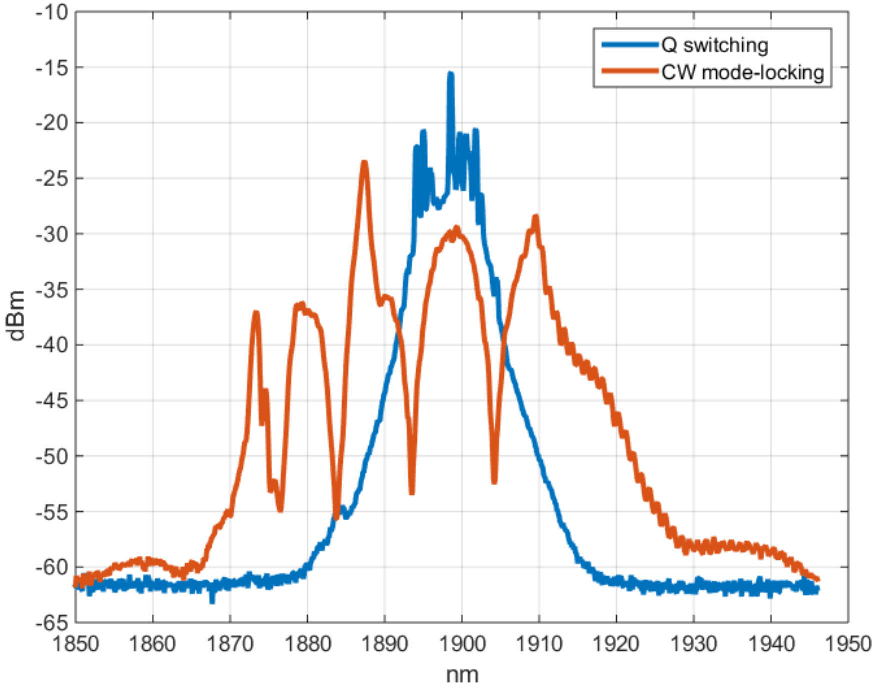


- Thulium-doped Al_2O_3 waveguides pumped at 1600nm
- Double-chirped gratings in SiN for dispersion compensation
- Nonlinear interferometer: fully-integrated artificial saturable absorber

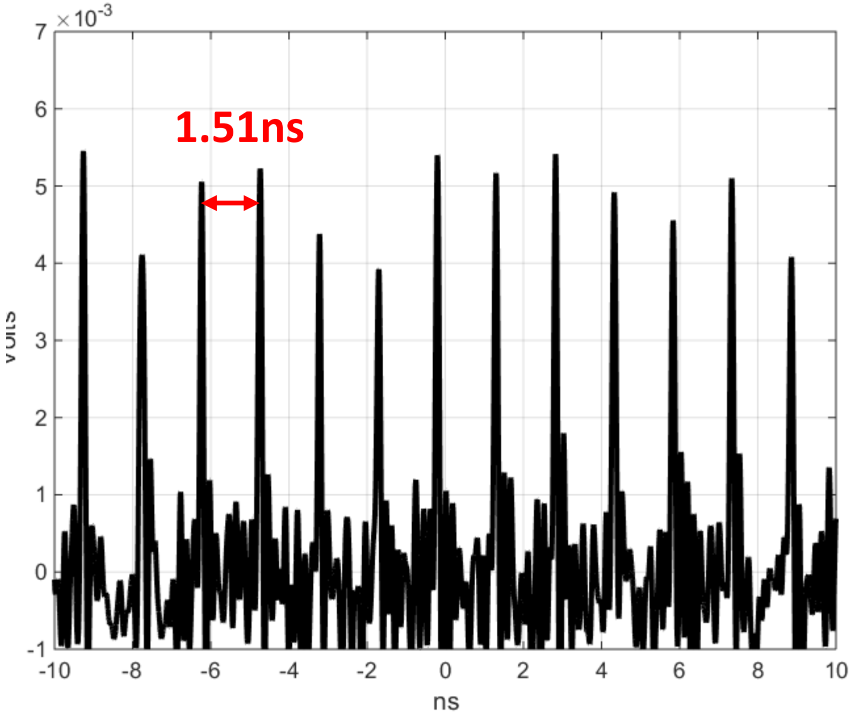
P. Callahan CLEO 2017, paper STh3N2

First Results

Spectral domain data

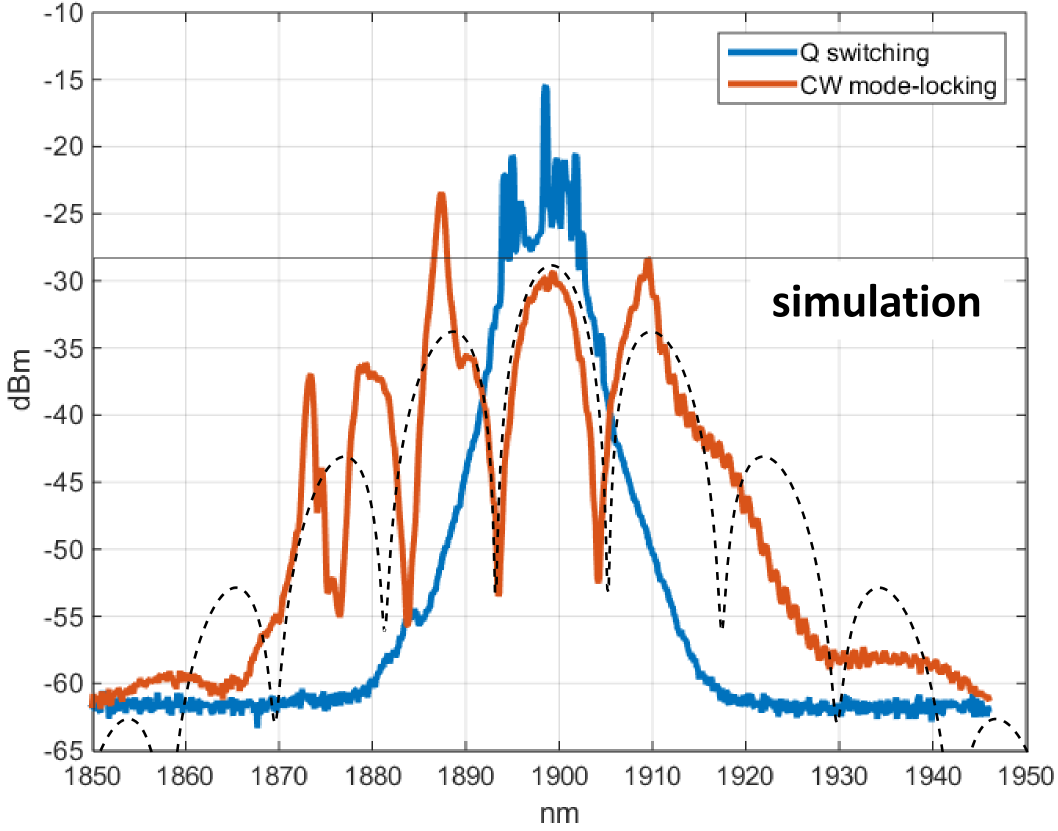


Time-domain data



P. Callahan CLEO 2017, paper STh3N2

First Results



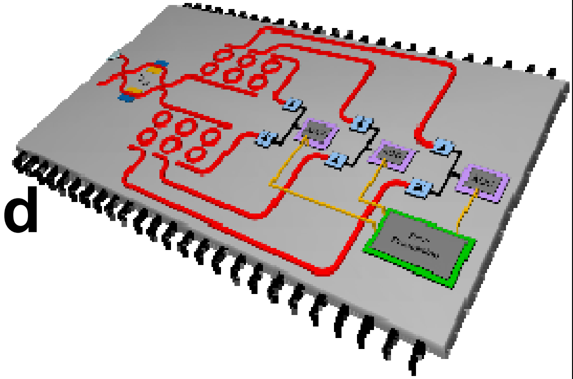
Simulation:

- **Two pulses: 250 fs & 265 fs pulse duration**
- **Delay between pulses: 1ps**

Fringe width is inversely proportional to delay.

Conclusions and Outlook

- Accelerator and XFEL facilities are combined accelerator and laser facility.
- Mode-locked lasers provide low jitter (atto-sec.) pulse trains for timing and diagnostics everywhere
- A down converting sampler at 41 GHz with 2.1 GSa/s and 7.0 ENOB has been demonstrated
  ~ 15 fs jitter
- Enabling High speed, high resolution photonically assisted ADCs
- Complex opto-electronic circuitry, optical table sized, including modelocked lasers will become available on a finger nail sized chip over the next decade.



Thank You!

HELMHOLTZ
ASSOCIATION

DARPA

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
UNITED STATES AIR FORCE