Center of Excellence for
Biosensors, Instrumentation
and Process Control (COBIK)

Chasing Femtoseconds – How Accelerators Can Benefit from Economies of Scale in Other Industries time-transfer & synchronization systems: advantages, physical limitations and practical implementations

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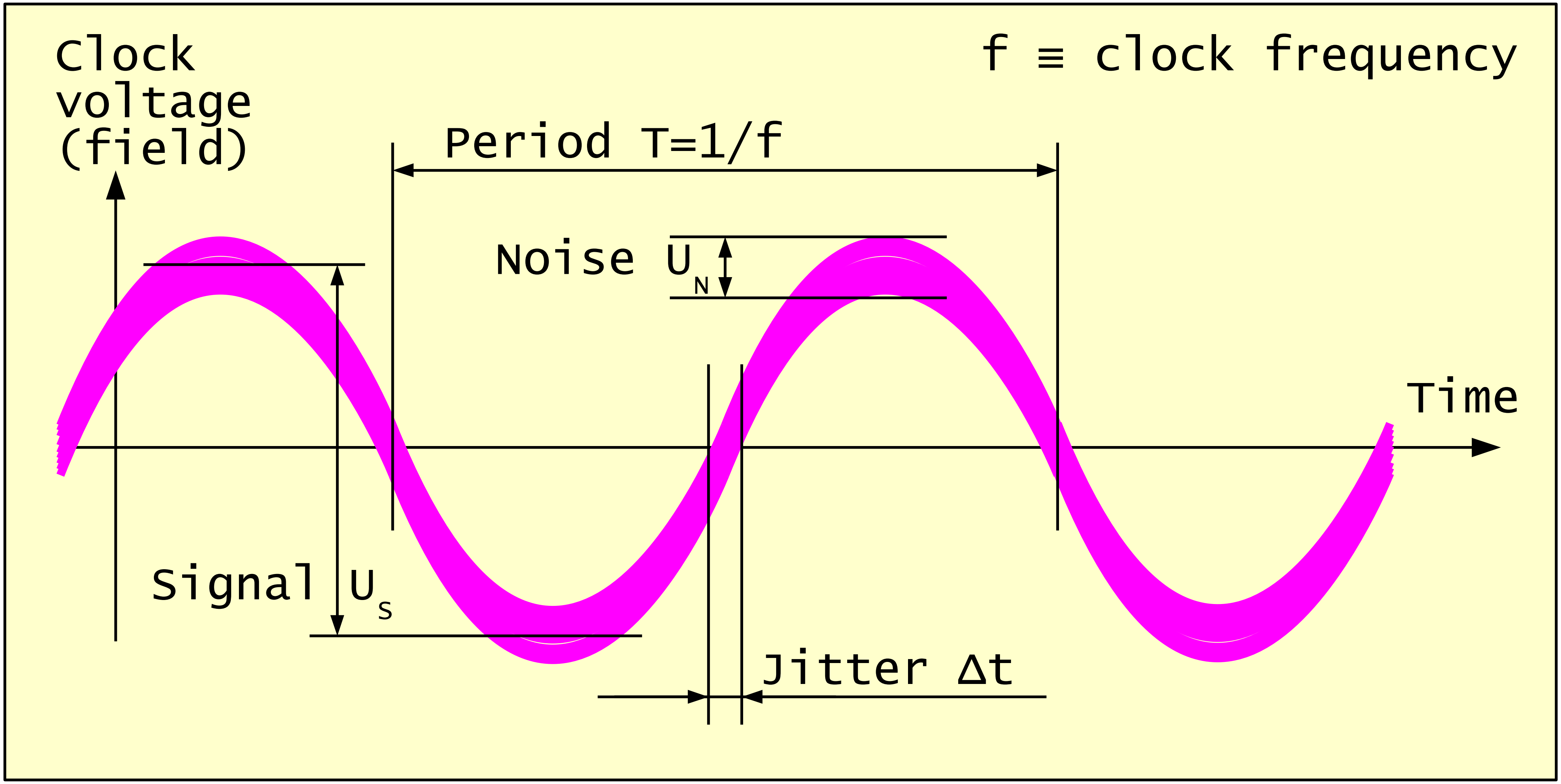
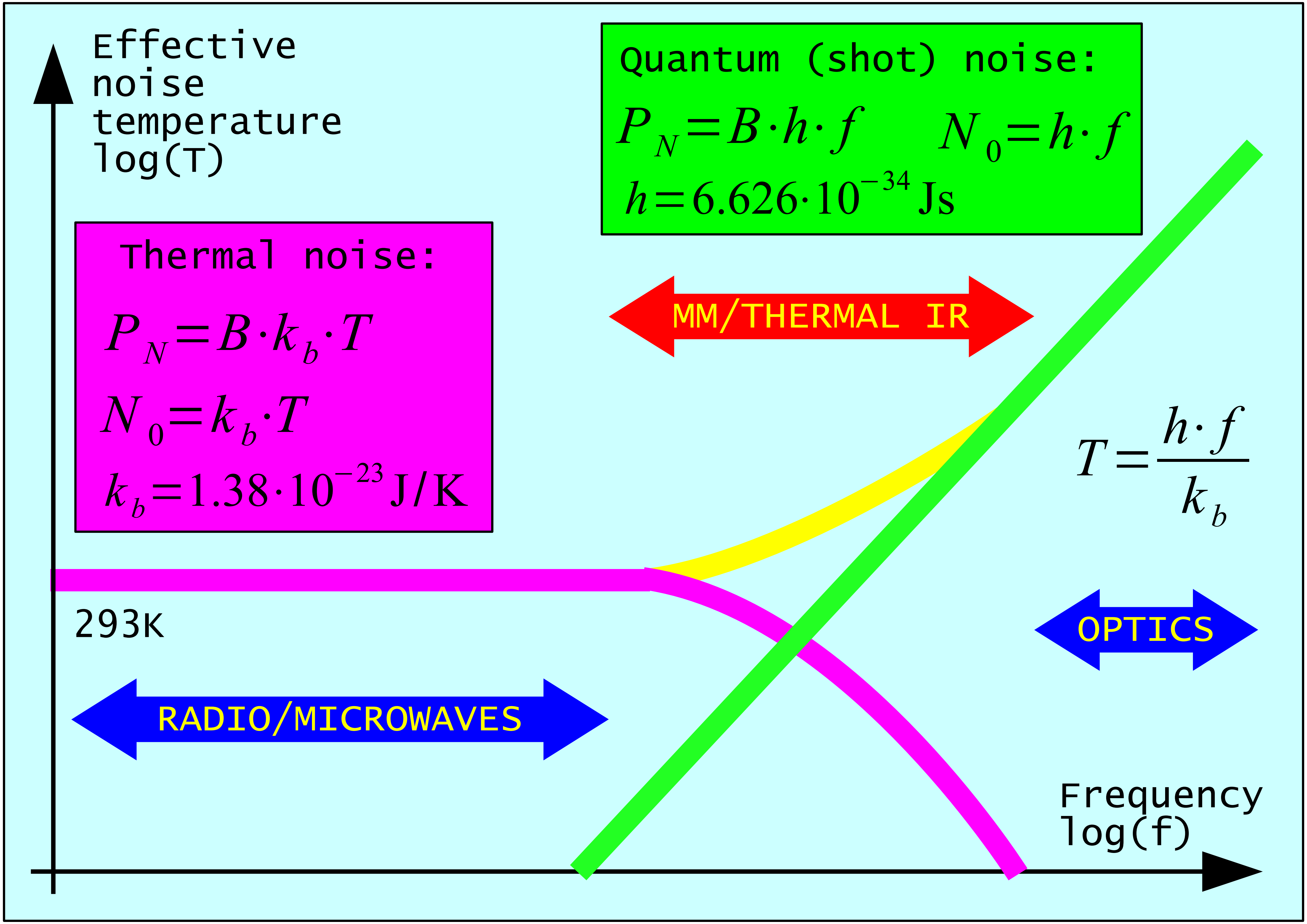


Timing jitter

$$\Delta t = \frac{T}{2\pi}\cdot\frac{U_N}{U_S} = \frac{1}{2\pi\cdot f}\cdot\sqrt{\frac{P_N}{P_S}}$$

Timing jitter as a function of signal-to-noise ratio



Thermal and quantum noise as function of frequency

$$P_N = B \cdot N_0 = \frac{f}{Q} \cdot N_0 \longrightarrow \Delta t = \frac{1}{2\pi} \cdot \sqrt{\frac{N_0}{f \cdot Q \cdot P_S}}$$

$B \equiv bandwidth$

$N_0 \equiv noise\ spectral\ density$

$Q \equiv resonator\ (filter)\ quality\ factor$

Microwave timing jitter

$$N_0 = k_b \cdot T \longrightarrow \Delta t = \frac{1}{2\pi} \cdot \sqrt{\frac{k_b \cdot T}{f \cdot Q \cdot P_S}}$$

Optical timing jitter

$$N_0 = h \cdot f \longrightarrow \Delta t = \frac{1}{2\pi} \cdot \sqrt{\frac{h}{Q \cdot P_S}}$$

Microwave and optical timing jitter

Reliability: only high-volume production (million series) guarantees reliability in electronics! Custom components very unreliable!

Component grades: the distinction among consumer, industrial & military grades is disappearing!

Military: Commercial Off The Shelf (COTS)!

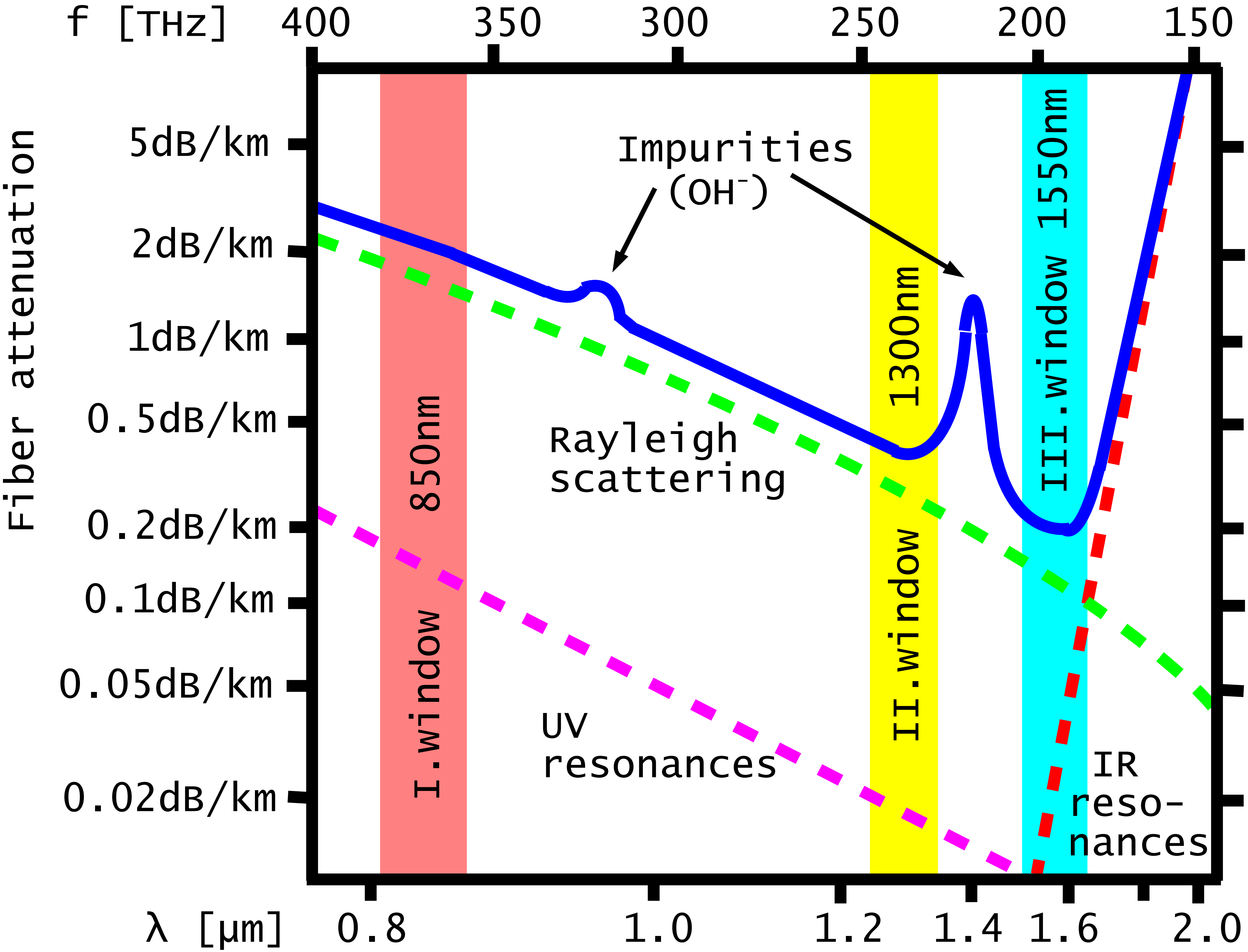
Design: only high-volume parts may be used! Specialized and/or custom components extremely expensive and rather unreliable!

Availability: "obsolete" products dropped quickly! Parts for commercially uninteresting frequencies, wavelengths and applications unavailable!

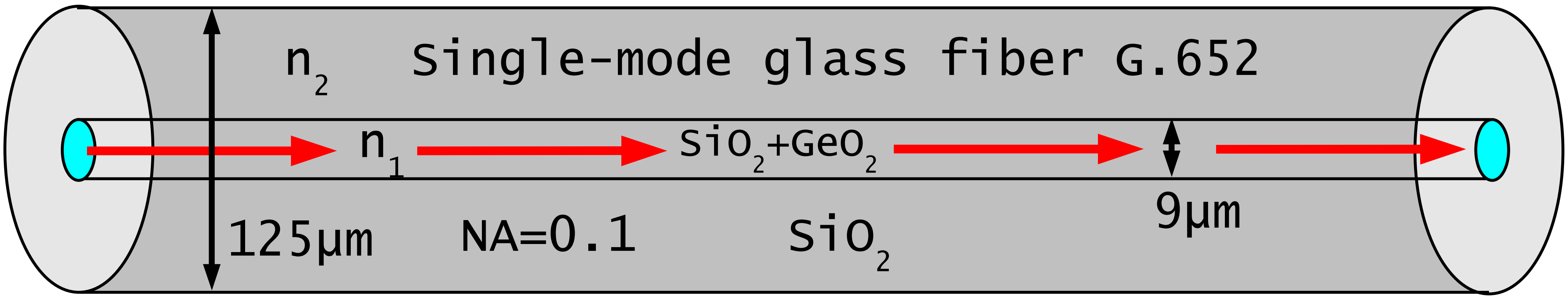
Recent trends in electronic-component technology

Technology SUCCESSES:	Technology FAILURES:
Analog radio/microwave electronics	Millimeter-wave electronics
High-speed digital electronics	Micro-electro-mechanical devices (MEMS)
(Electronic) digital signal processing (DSP)	Long-wave (thermal) IR optics
Silica-glass optical fiber (waveguide)	Fiber-optic LASER sources (oscillators): CW, pulsed, mode-locked
Semiconductor lasers, modulators and photo-detectors	Optical signal processing (holography, nonlinear optics)
Erbium-doped fiber LASER amplifier (EDFA)	Optical computing

Technology successes and failures



Silica-glass fiber attenuation & telecom windows



Linear properties:

Chromatic dispersion
D≈17ps/nm.km!

PMD: D_{PMD}≈0.02ps/sqrt(km)

Temperature coefficient
tc≈40fs/m.K! Much larger and unpredictable with improper (tight) cabling!

Microphonics!

Nonlinear properties:

Nonlinear refraction index
Kerr effect @ P>100mW!

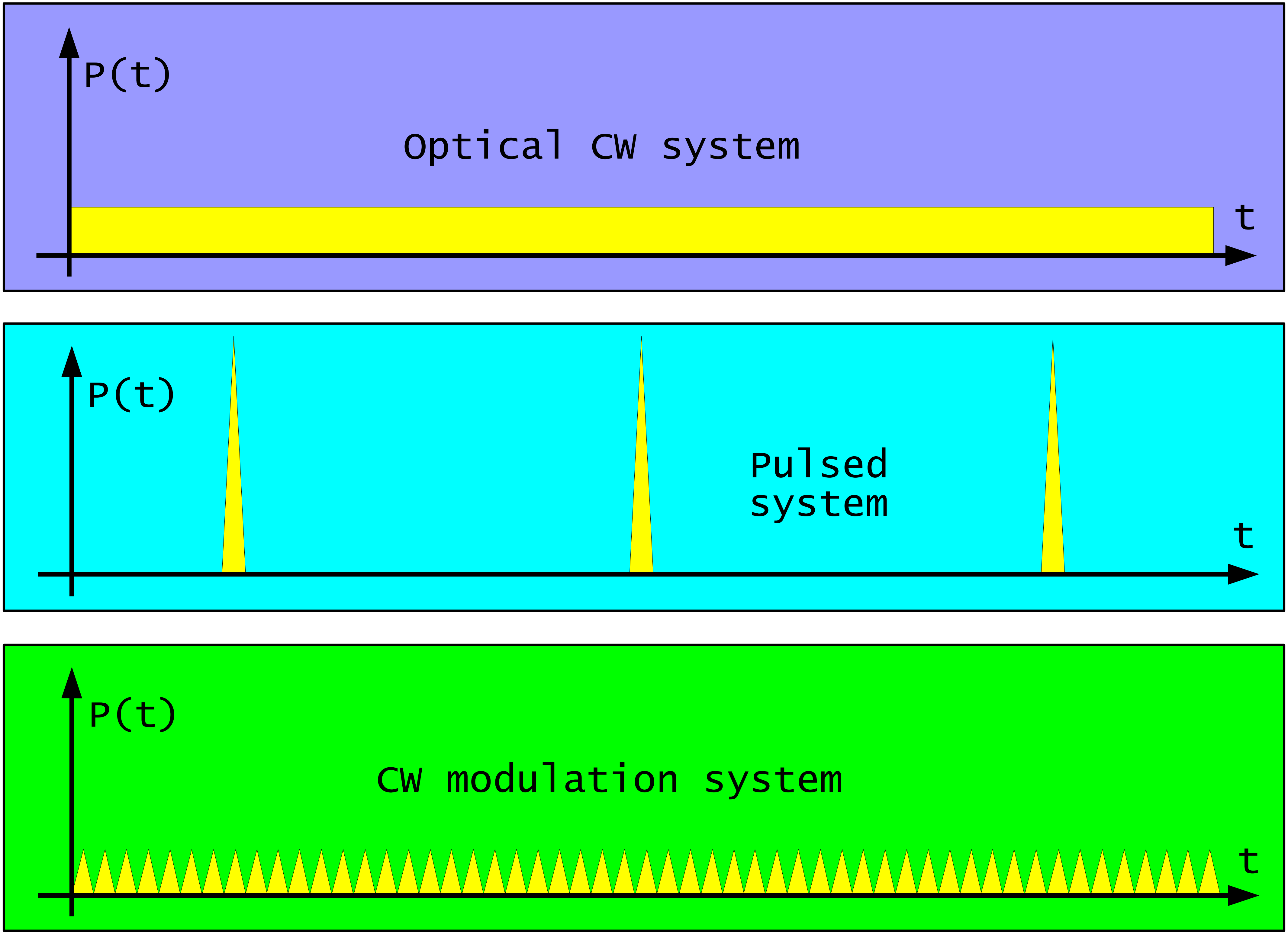
Brillouin scattering P>1mW
(narrow-band CW only)!

Raman scattering P>100mW!

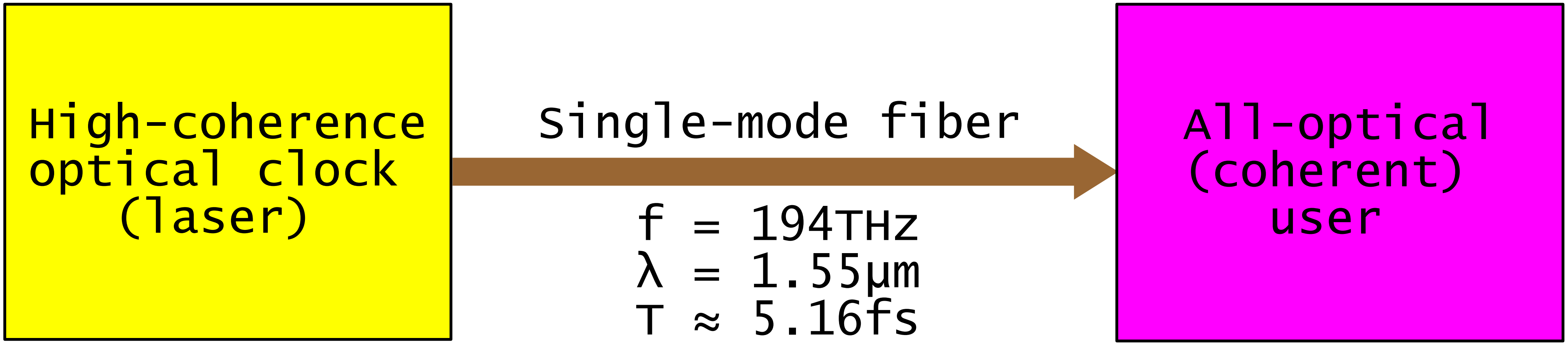
Connector breakdown P>1W!

Fiber breakdown P>10W!

Single-mode optical-fiber properties



Optical timing systems



ADVANTAGES:

Highest resolution!

Highest accuracy!

DRAWBACKS:

5fs timing ambiguity?

Optical cycle slips?

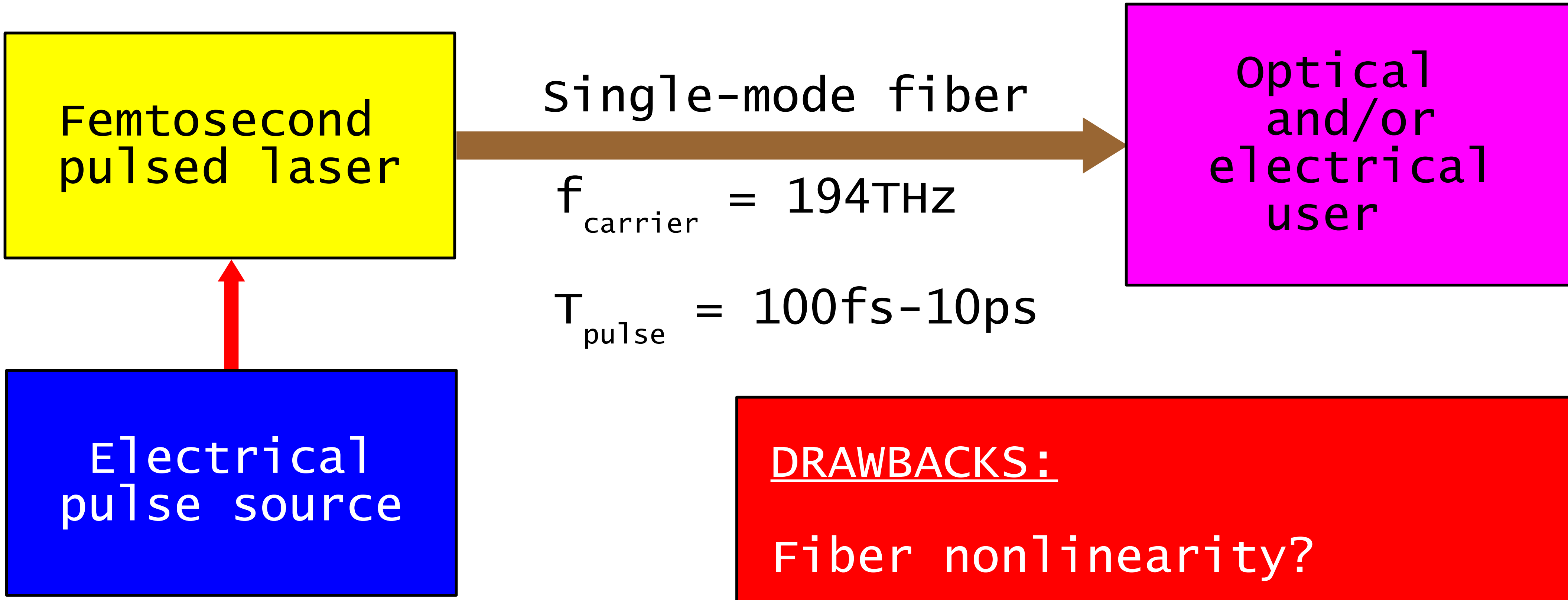
Interferometric noise?

Brillouin scattering?

Polarization & PMD effects?

User-equipment availability?

Optical CW system



ADVANTAGES:

Reasonable resolution and accuracy!

User-community understanding!

DRAWBACKS:

Fiber nonlinearity?

Fiber chromatic dispersion?

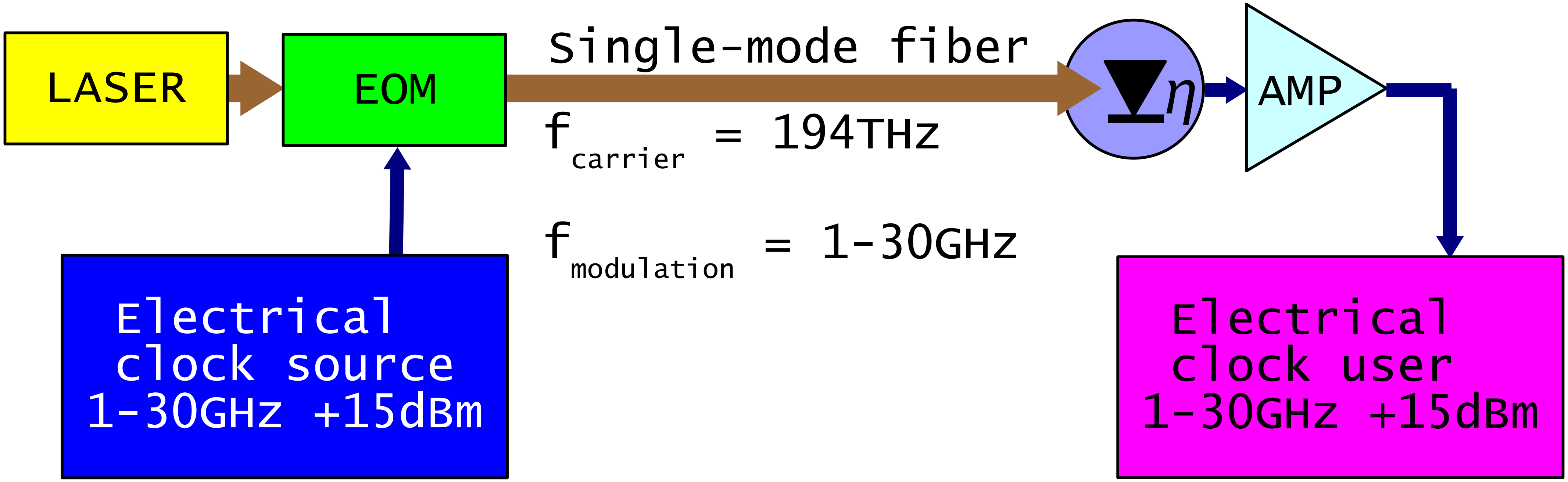
PMD pulse distortion?

Fiber thermal compensation?

Electrical SNR?

Optical pulse processing?

Pulsed system



ADVANTAGES:

Simple temperature compensation!

Standard electrical interfaces!

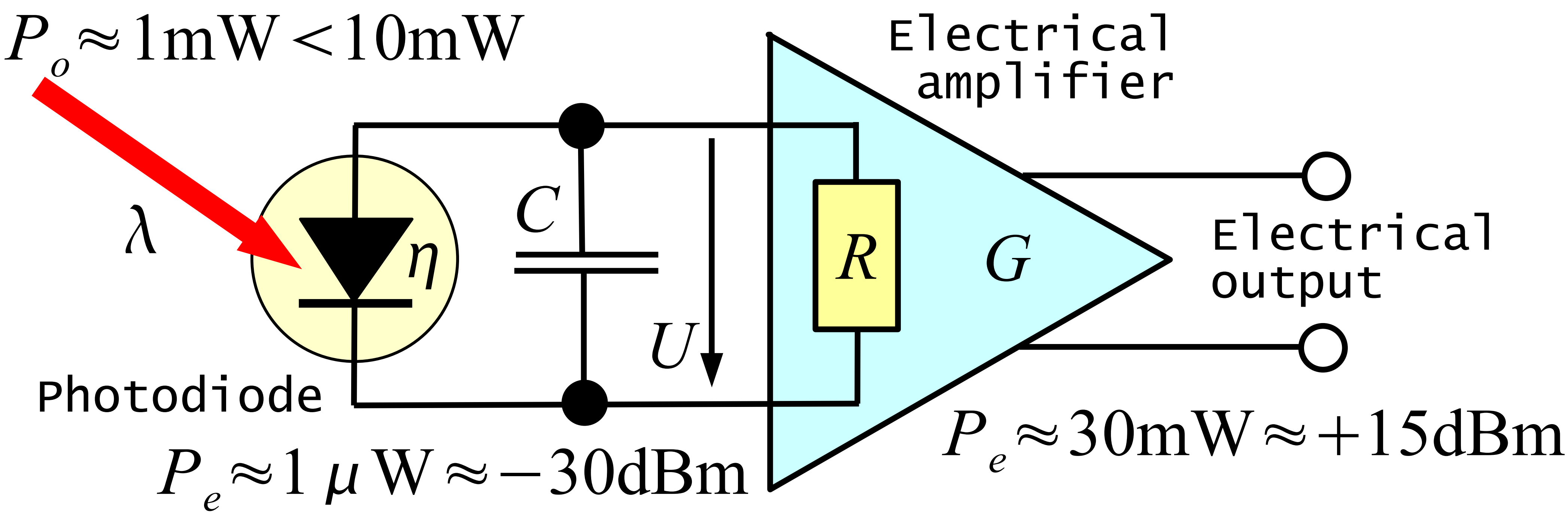
Standard hi-rel telecom components!

DRAWBACKS:

High photodetector electrical noise: jitter 1-10ps?

Low timing resolution?

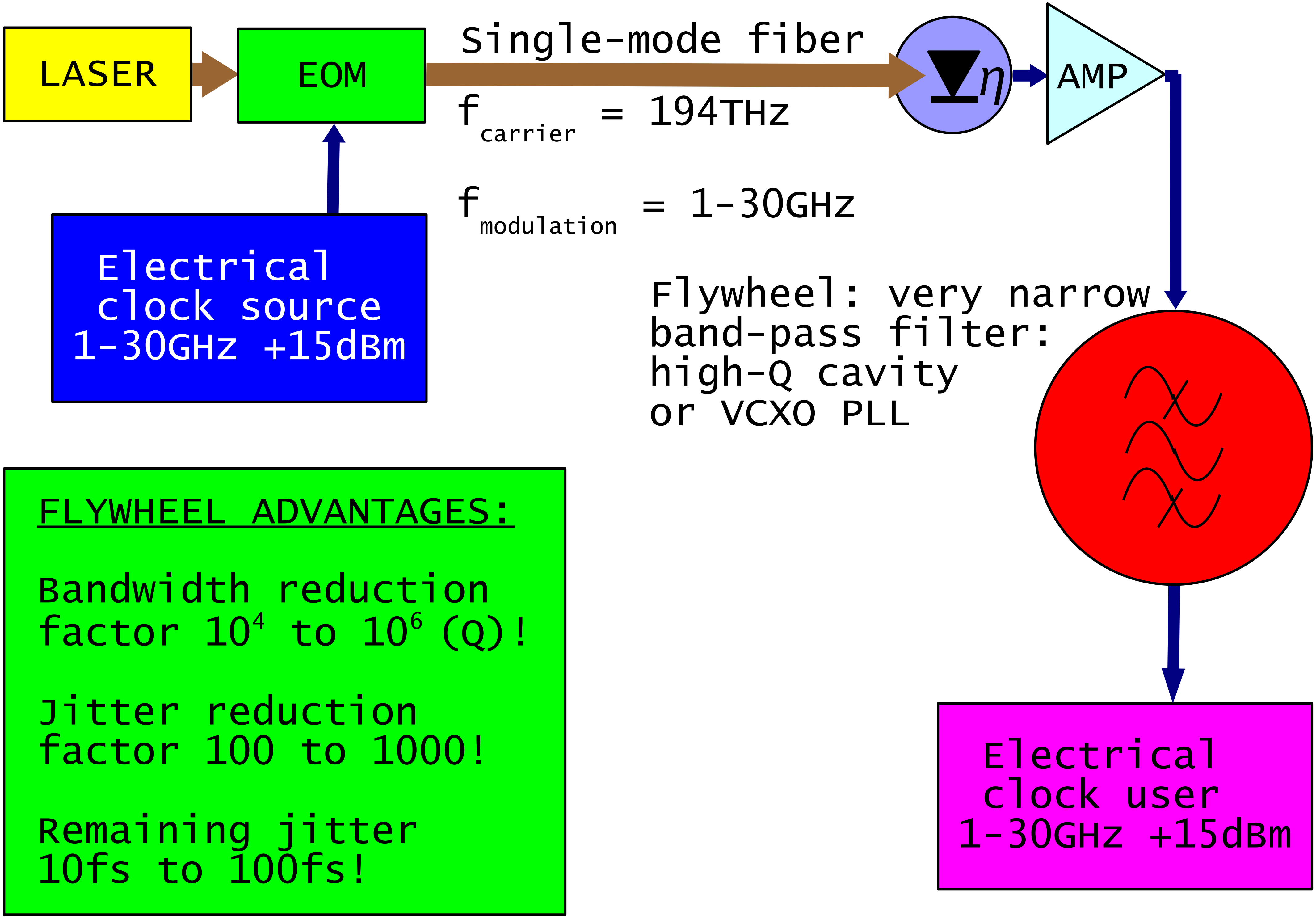
CW modulation system



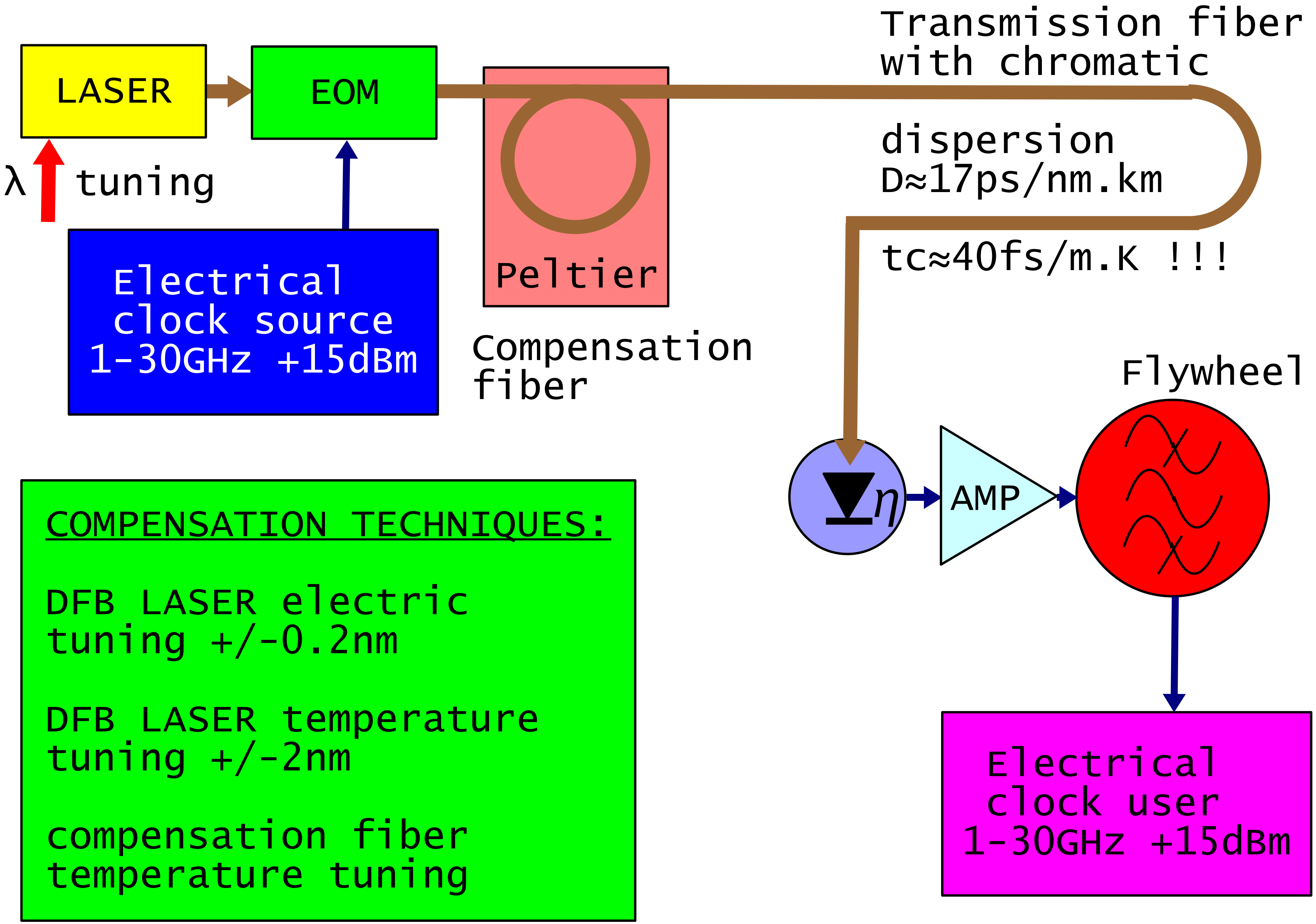
$$U_{Neff} = \sqrt{P_N \cdot R} \qquad P_N = B \cdot k_b \cdot T \qquad B = \frac{1}{2\pi \cdot R \cdot C}$$

$$U_{Neff} = \sqrt{\frac{k_b \cdot T}{2\pi \cdot C}} = 25.7\,\mu\mathrm{V}_{\mathrm{eff}}$$ @ C=1pF, T=300K

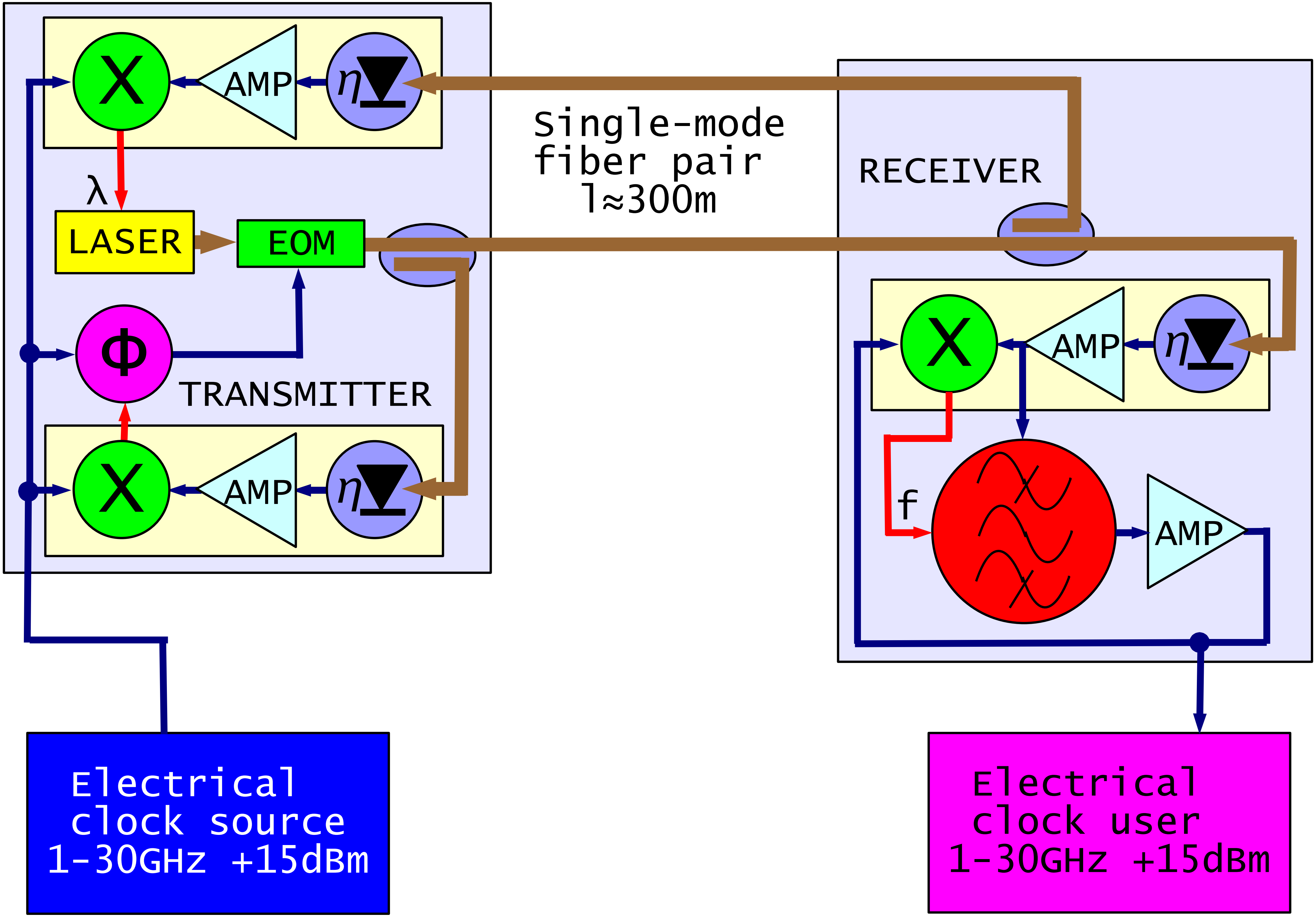
Photodiode electrical noise



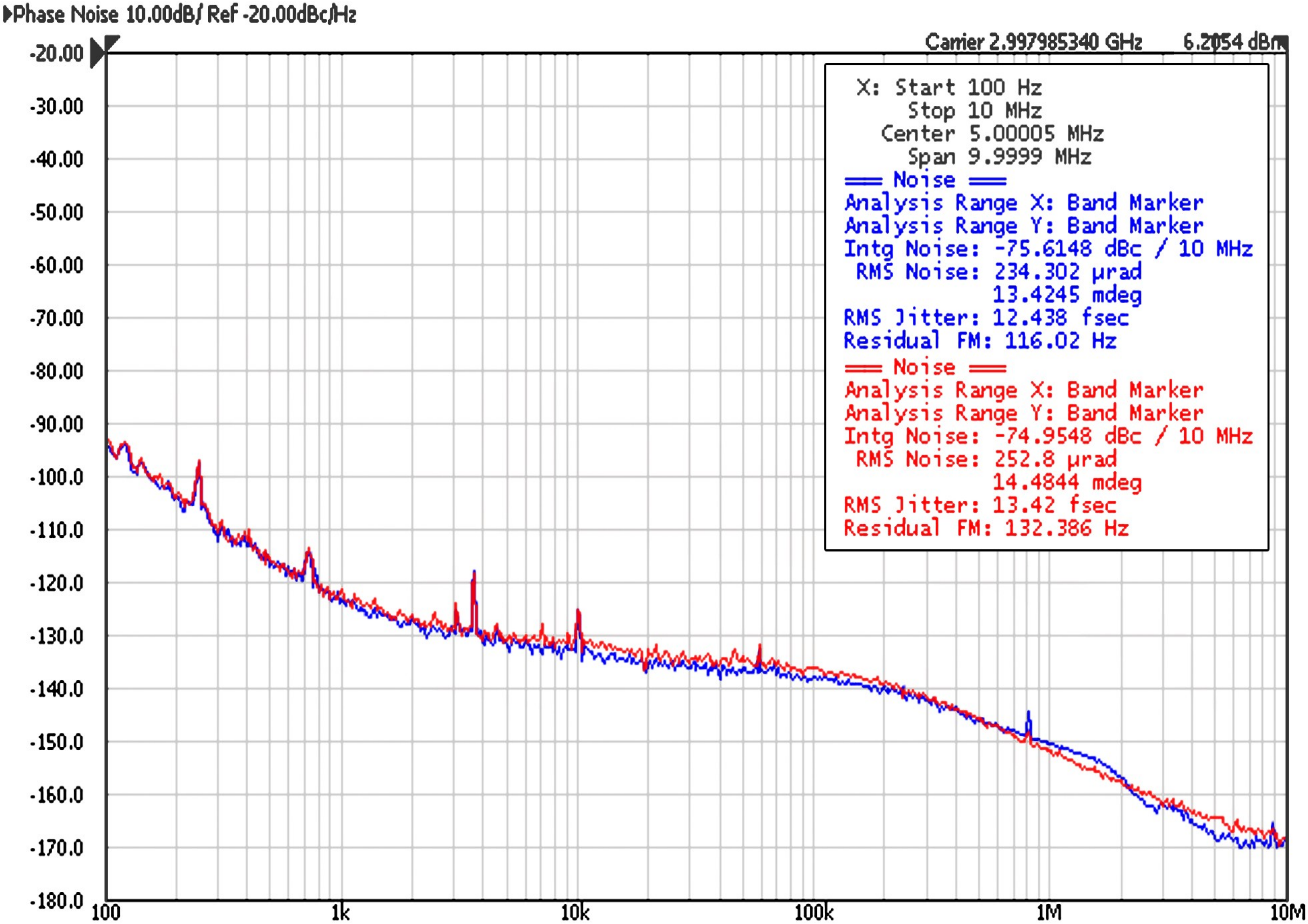
CW modulation system with flywheel



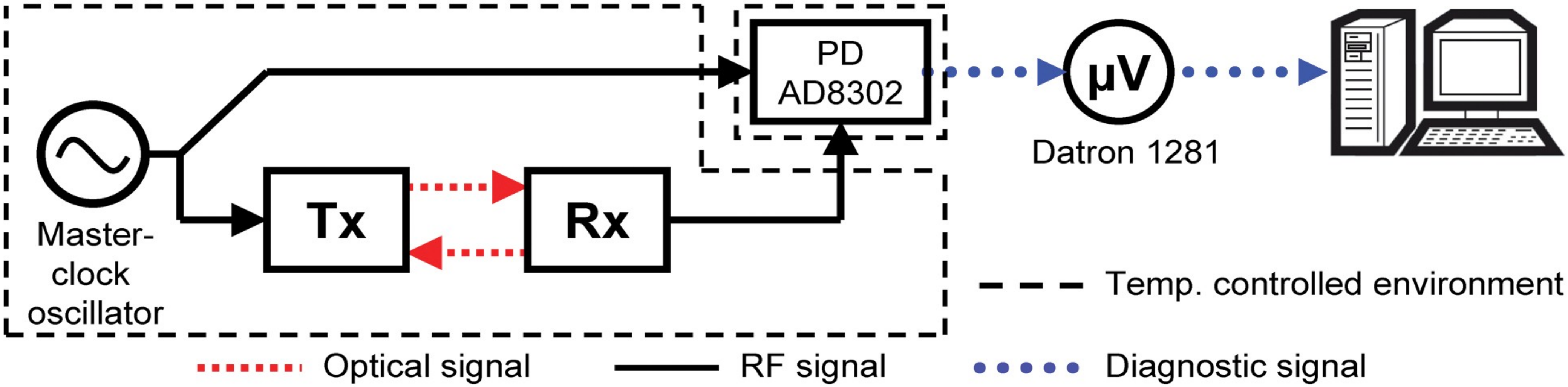
Delay-variation compensation techniques

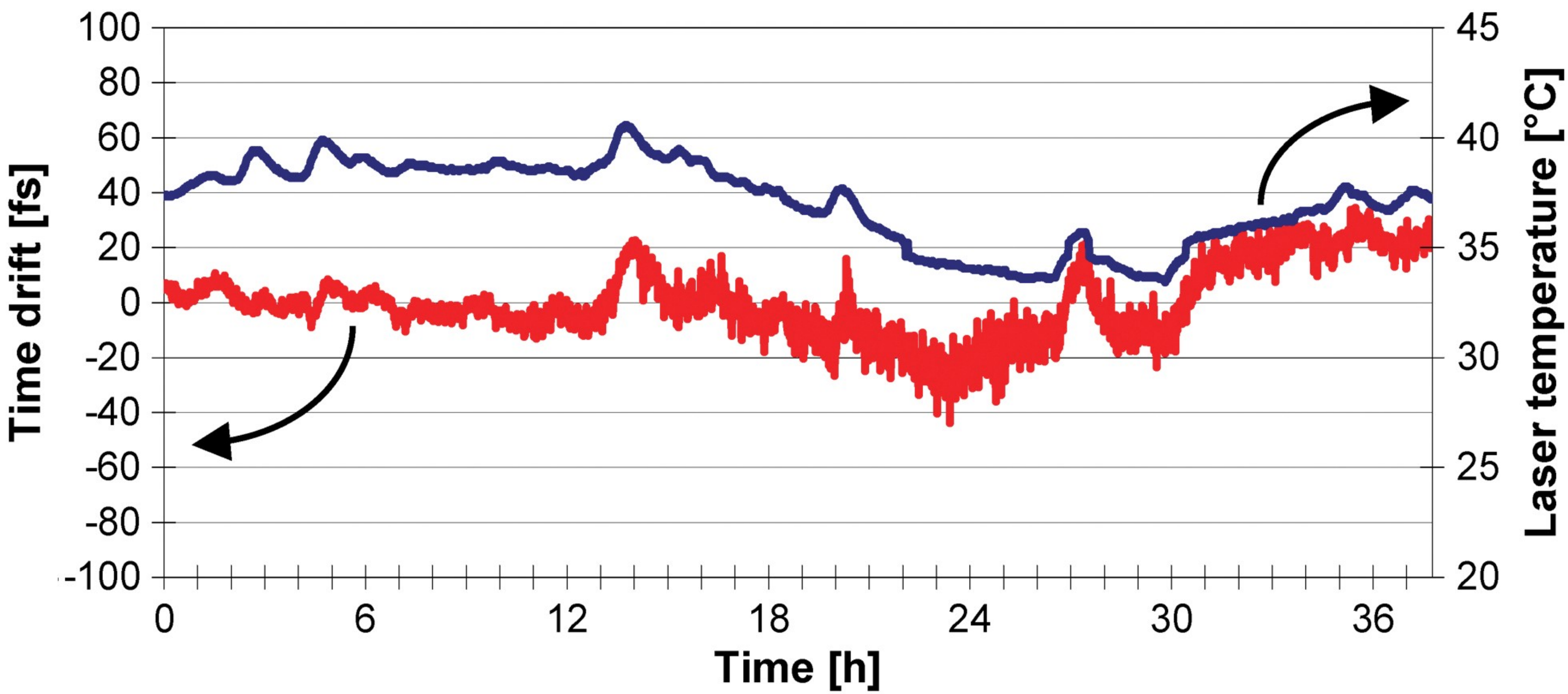


CW modulation system with temperature compensation

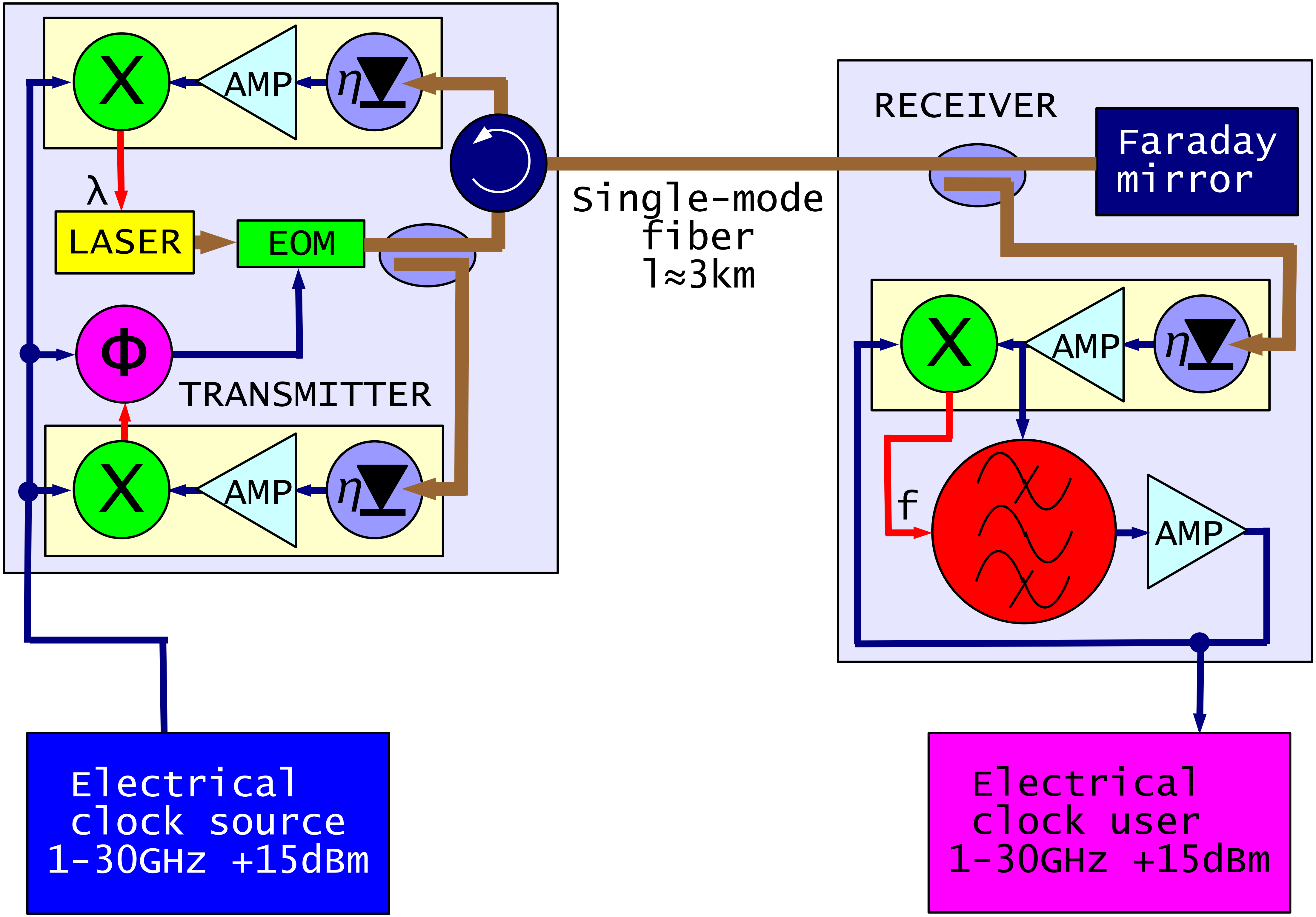


Measured 3GHz CW-modulation-system phase noise & jitter

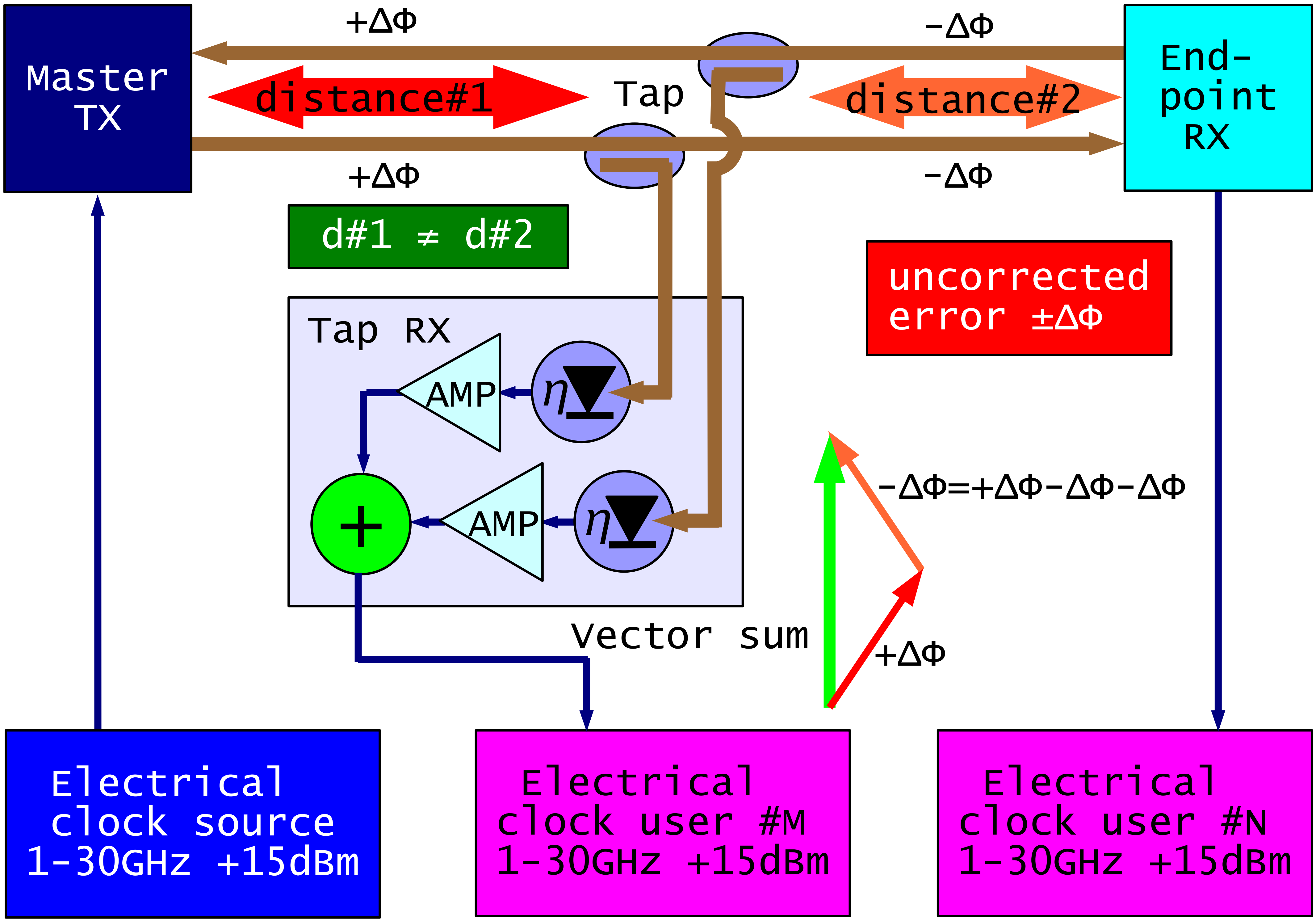




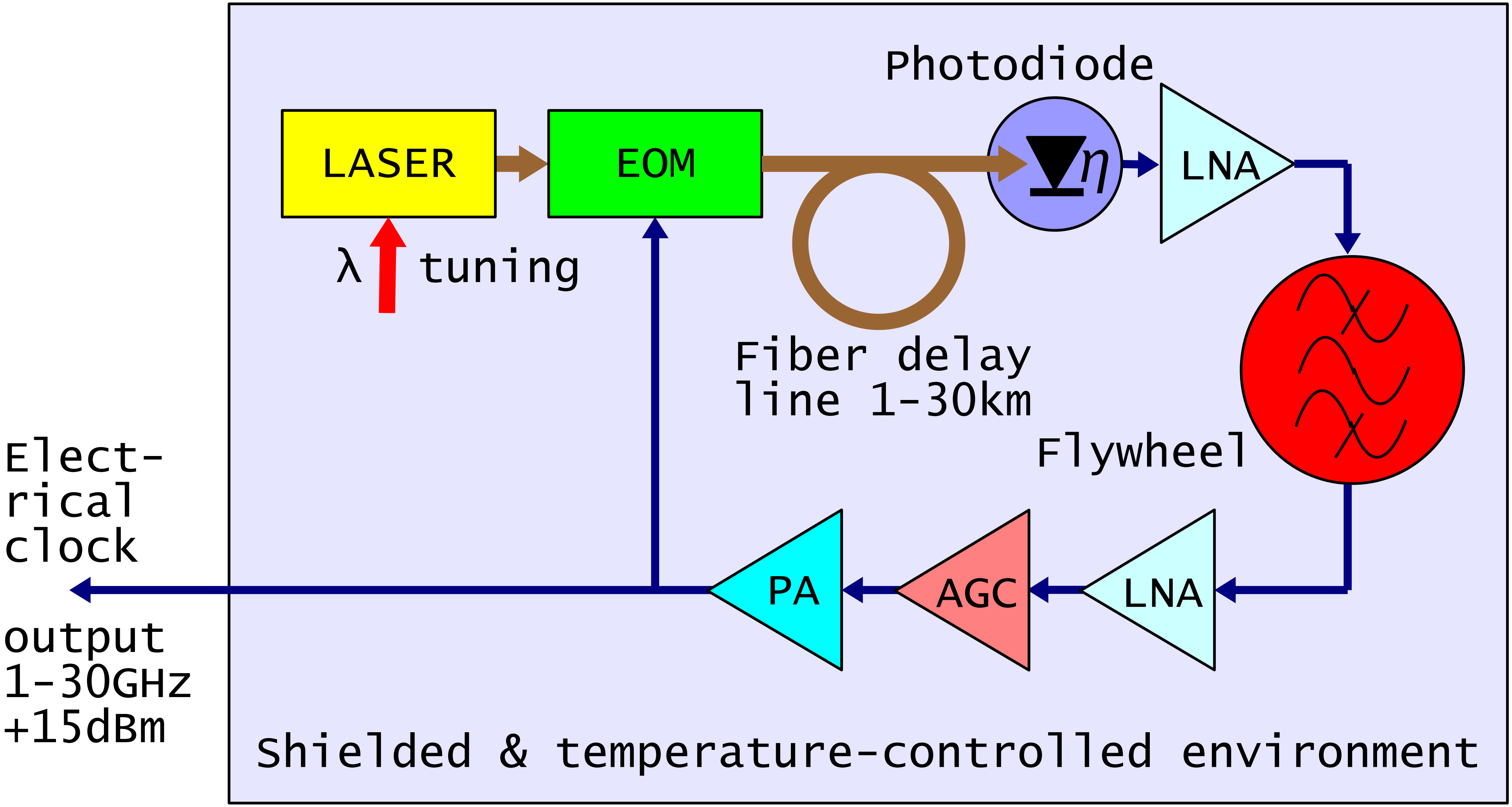
Measured 3GHz CW-modulation-system long-term drift



CW modulation system with PMD compensation



Multi-point chain clock distribution



Fiber delay + flywheel >>> equivalent $Q \approx 10^5 - 10^7$

Electro-optical master oscillator

elettra

FERMI @elettra

Sincrotrone Trieste,
Elettra laboratory:
initial system requirements
initial experiments

Univerza v Ljubljani
Fakulteta za elektrotehniko

LSO Laboratorij za sevanje in optiko

University of Ljubljana,
Faculty of Electrical Engineering,
Laboratory for Radiation and Optics:
initial research

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Biosensors, Instrumentation
and Process Control (COBIK):
current research &
development

Instrumentation Technologies

Instrumentation Technologies:
initial sponsoring &
management, co-development,
industrialization & production