

Laboratorij za Sevanje in Optiko

Fakulteta za Elektrotehniko

Univerza v Ljubljani

Optical-fiber time-transfer &
synchronization systems: advantages,
physical limitations and practical
implementations

Matjaž Vidmar

matjaz.vidmar@fe.uni-lj.si

<http://www.s5tech.net/s53mv/>

Optical-technology

ADVANTAGES:

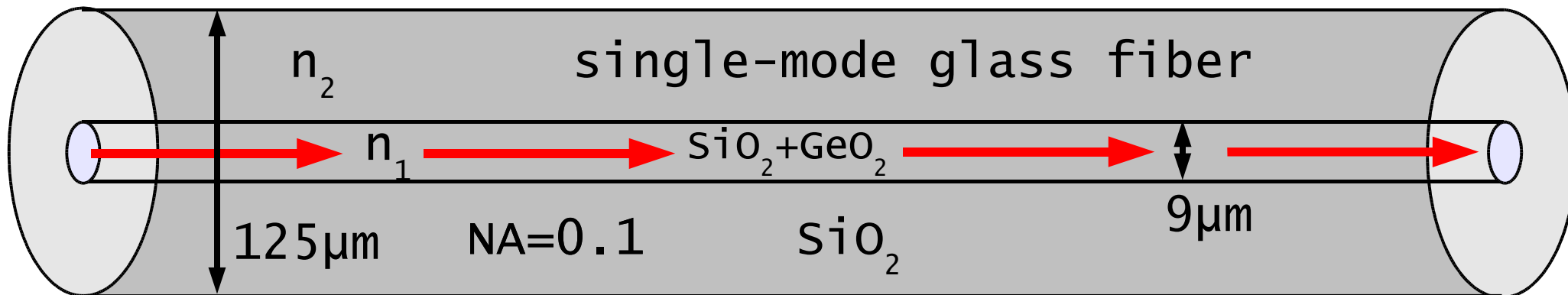
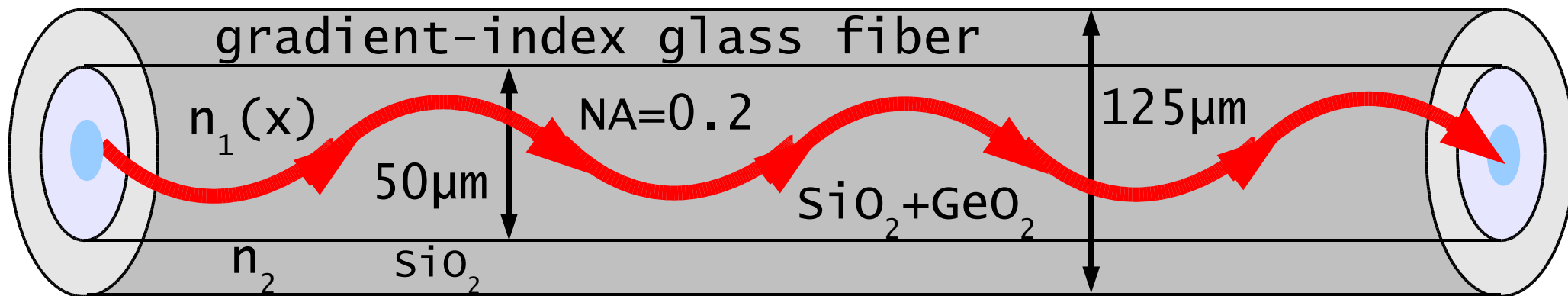
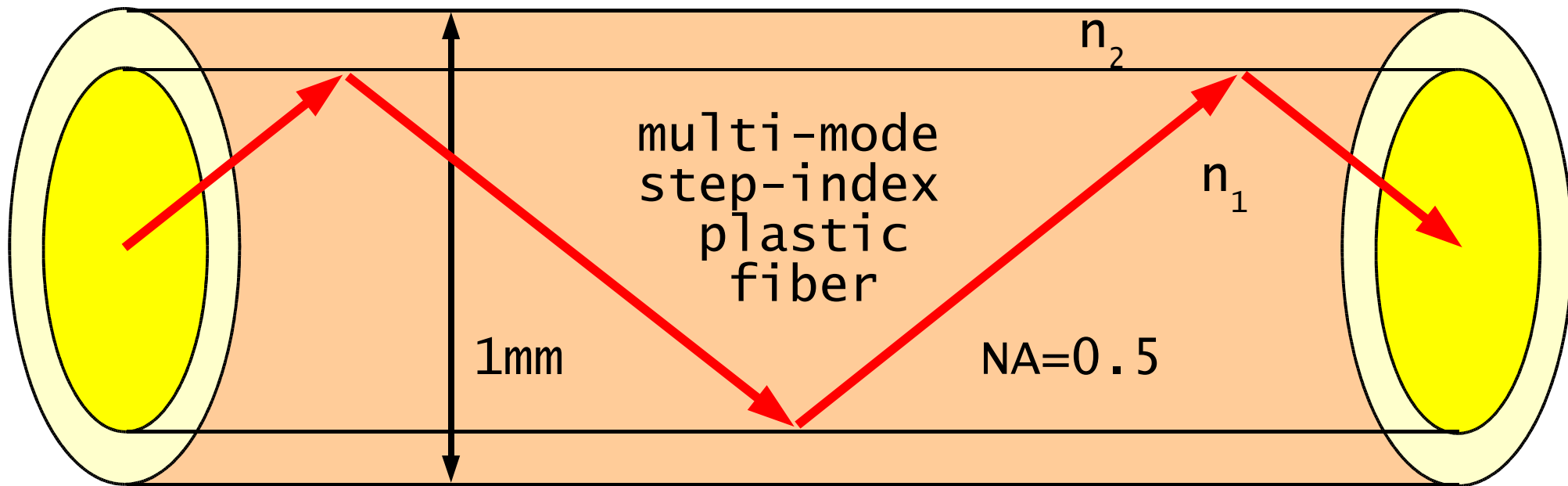
very high frequency
very large bandwidth
very low loss
very high peak power
small size optical-fiber
cables
low cost optical-fiber
hardware
electromagnetic immunity

Optical-technology

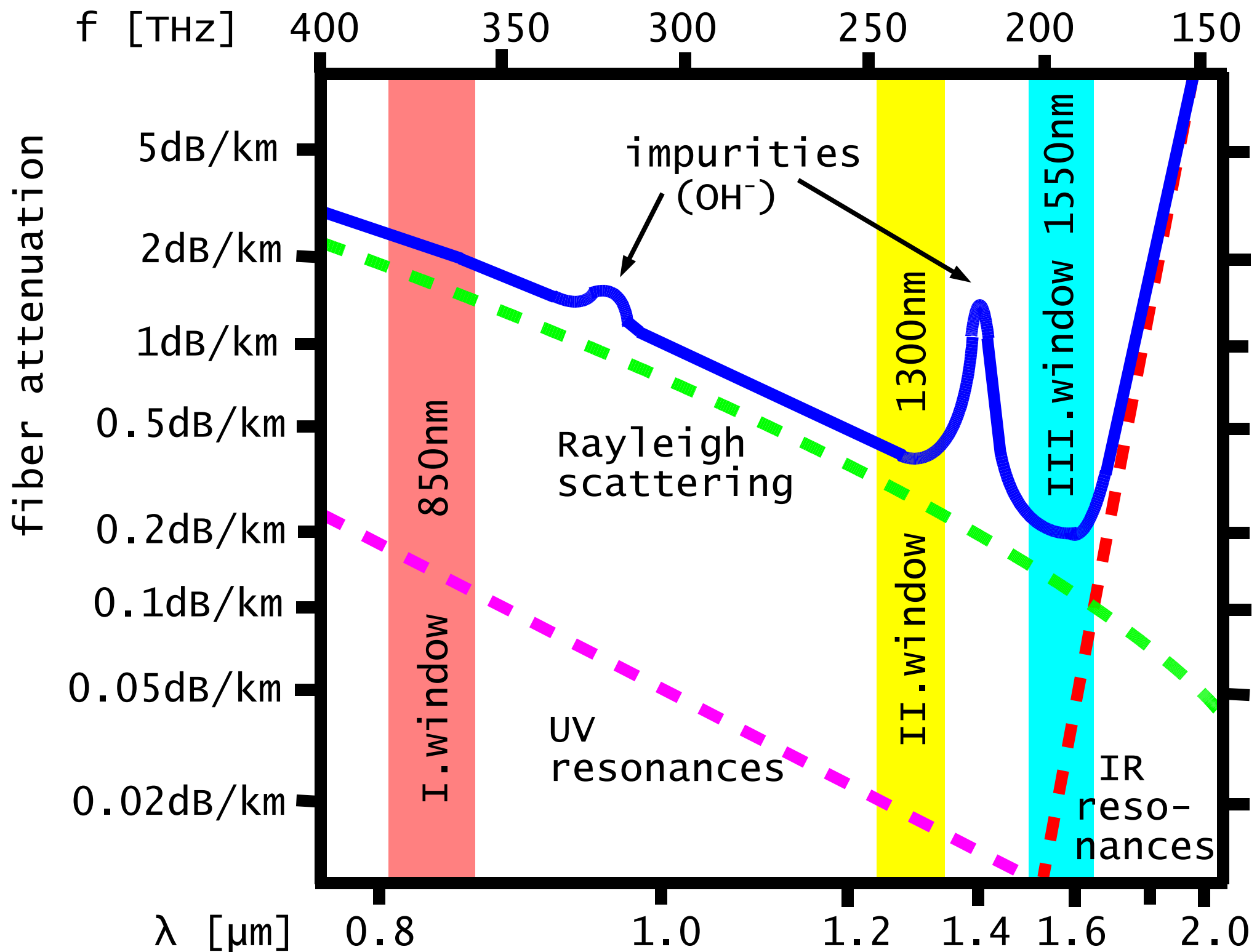
DRAWBACKS:

fiber dispersion
fiber nonlinearities
microphonics and
sensitivity to vibration
high fiber thermal
coefficient
difficult optical-signal
processing/conversion
incompatibility with
existing equipment

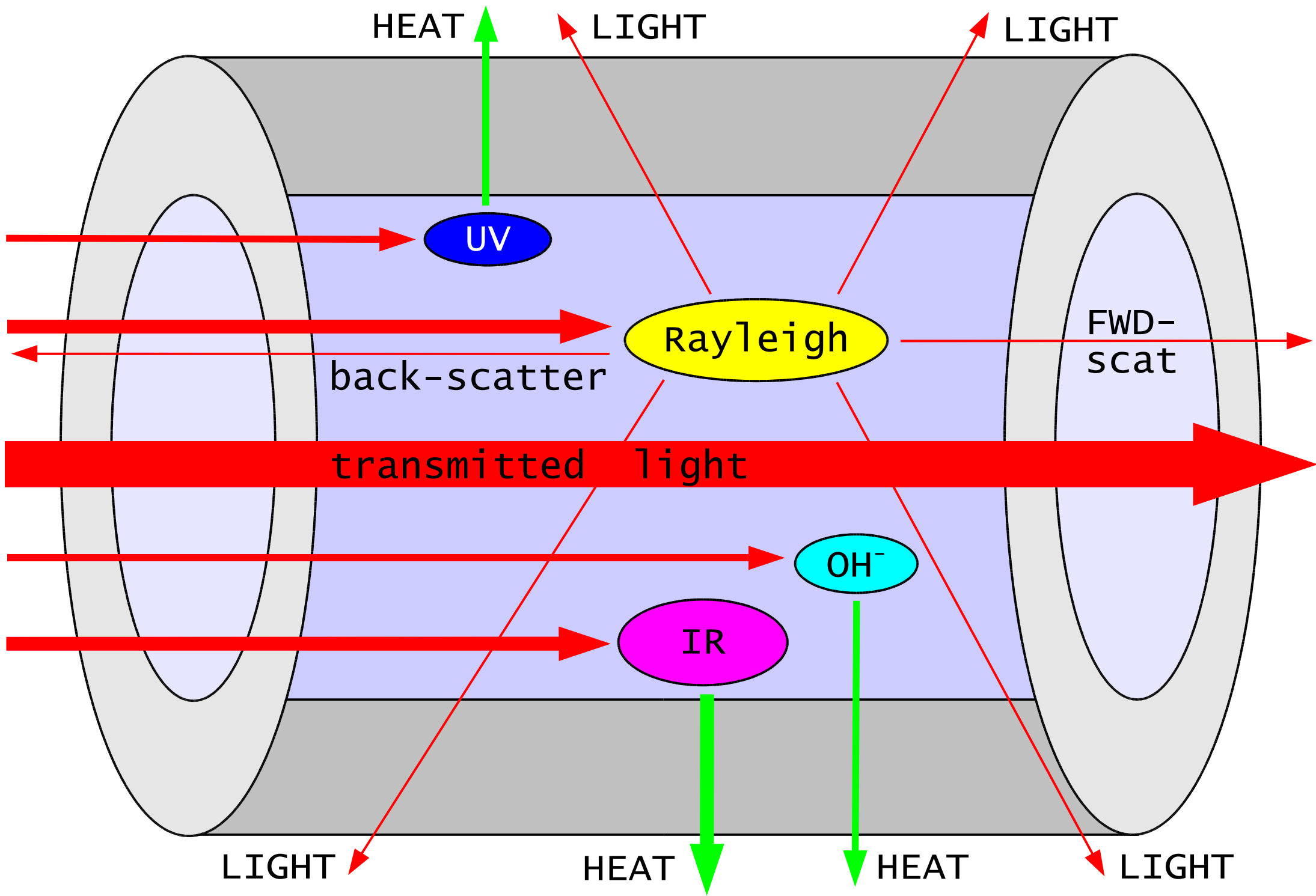
Optical-technology advantages and drawbacks



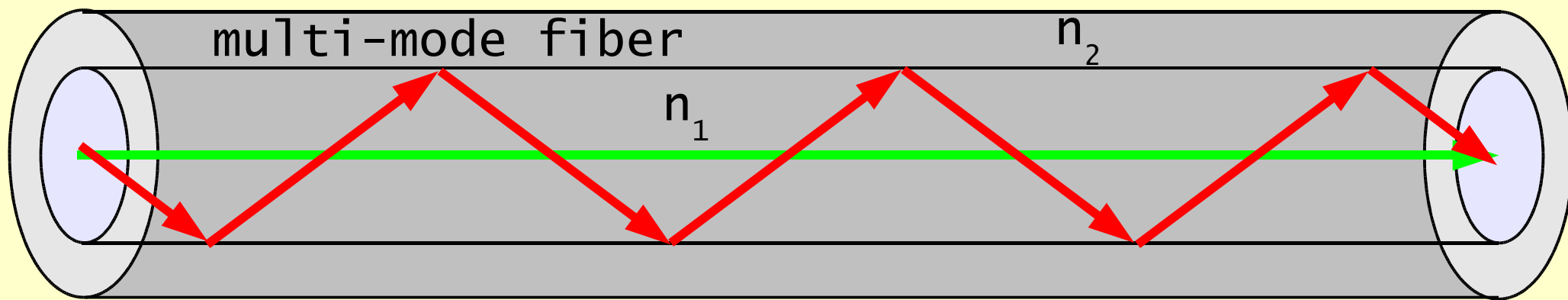
Main types of optical fibers



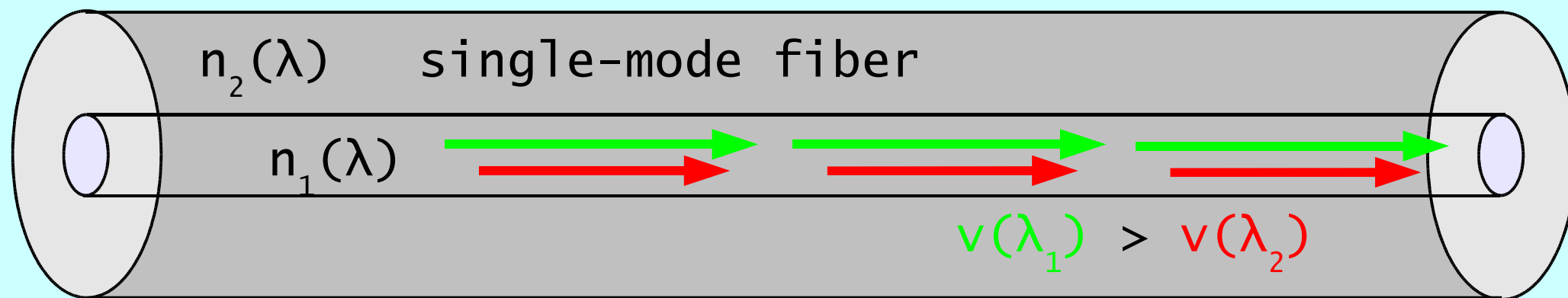
Single-mode fiber attenuation & telecom windows



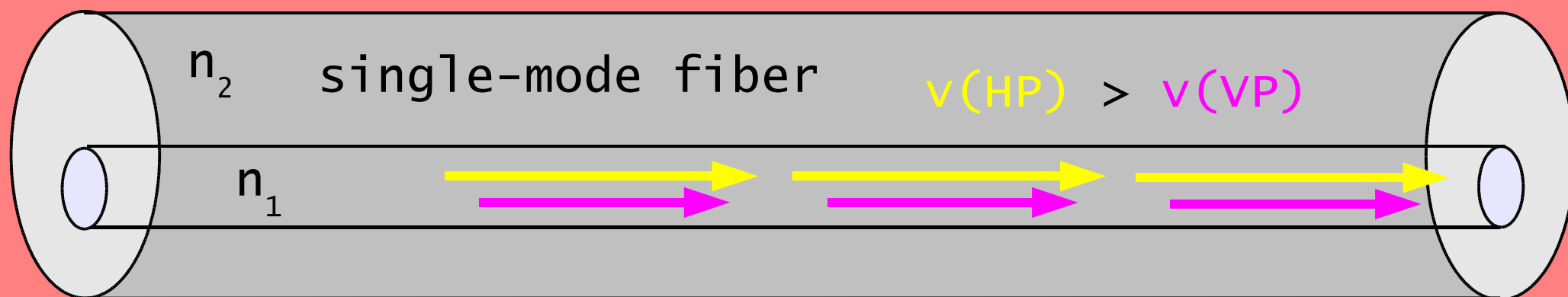
single-mode fiber-attenuation side effects



different paths \longrightarrow multi-mode dispersion



$n_1(\lambda), n_2(\lambda), \text{waveguide} \longrightarrow$ chromatic dispersion



non-symmetry \longrightarrow polarization-mode dispersion

Multi-mode, chromatic and polarization-mode dispersion

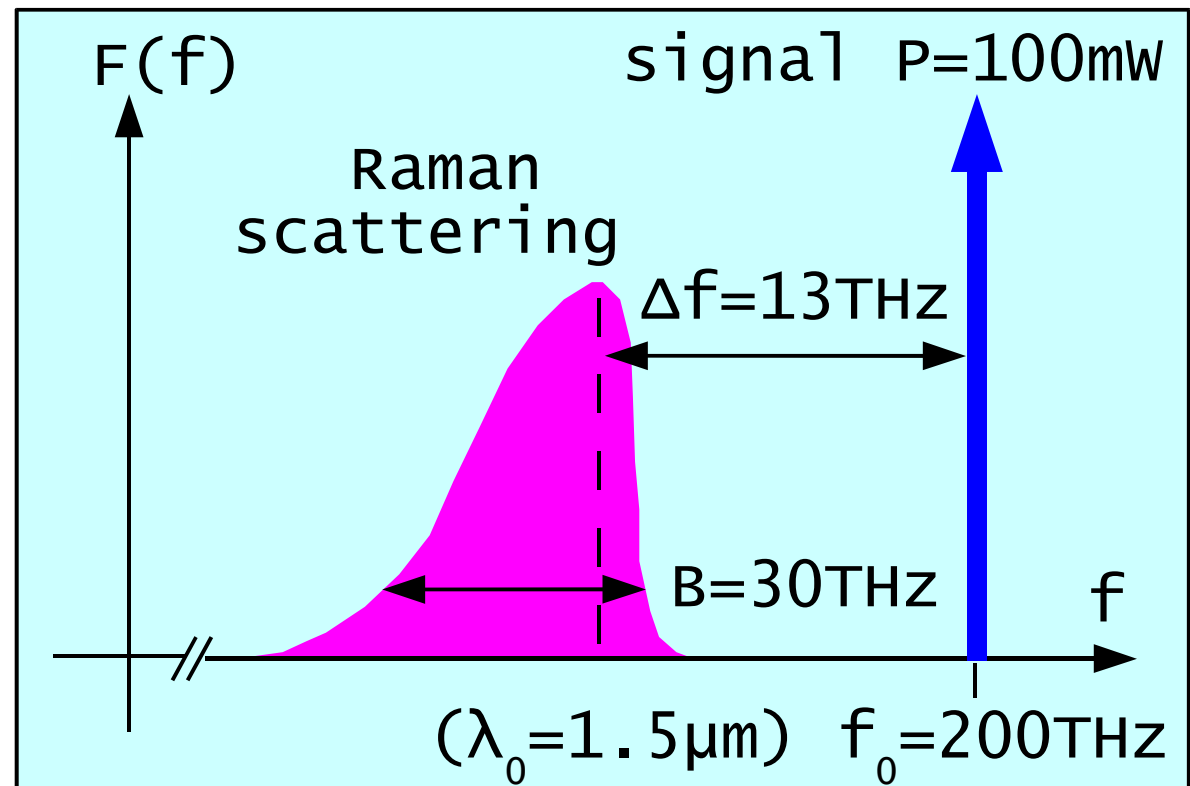
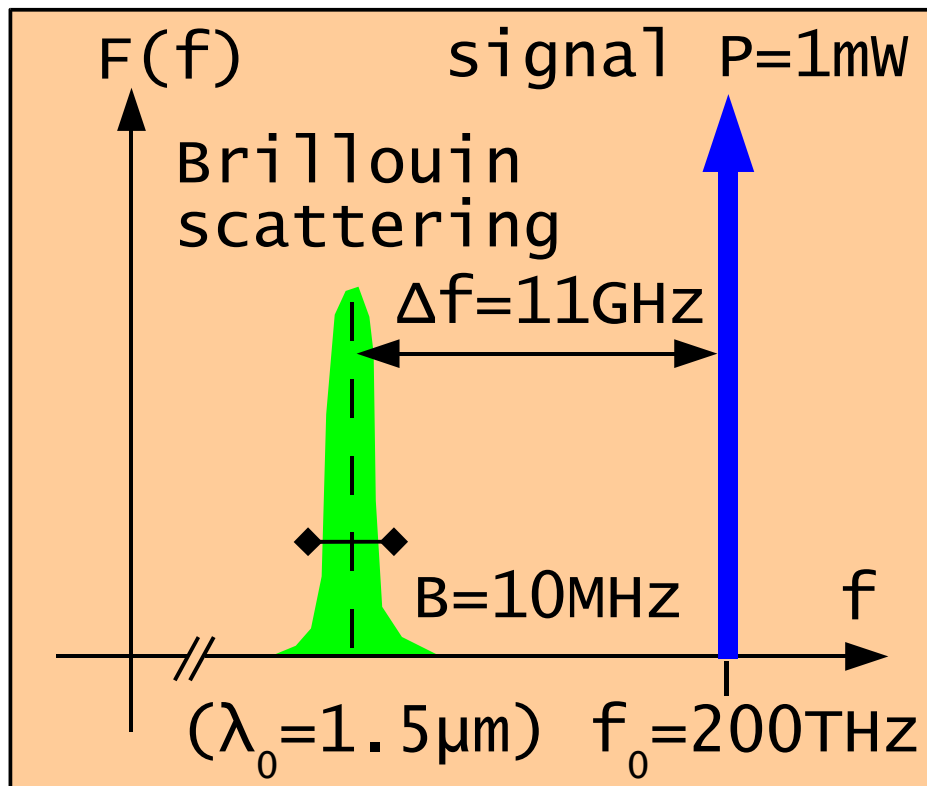
non-linear refraction index: $n = n_0 + n_2 \cdot S$

SiO₂: $n_0 = 1.46$, $n_2 = 3.2 \cdot 10^{-20} \text{ m}^2/\text{W}$

(self) phase modulation: $\Delta \phi = \Delta n \cdot k_0 \cdot l$

$P = 100 \text{ mW}$, $S = 1.43 \text{ GW}/\text{m}^2$ \longrightarrow $\Delta n = n_2 \cdot S = 4.58 \cdot 10^{-11}$

$l = 50 \text{ km}$, $\lambda_0 = 1.55 \mu\text{m}$ \longrightarrow $\Delta \phi = \Delta n \cdot (2\pi/\lambda_0) \cdot l = 9.3 \text{ rd}$



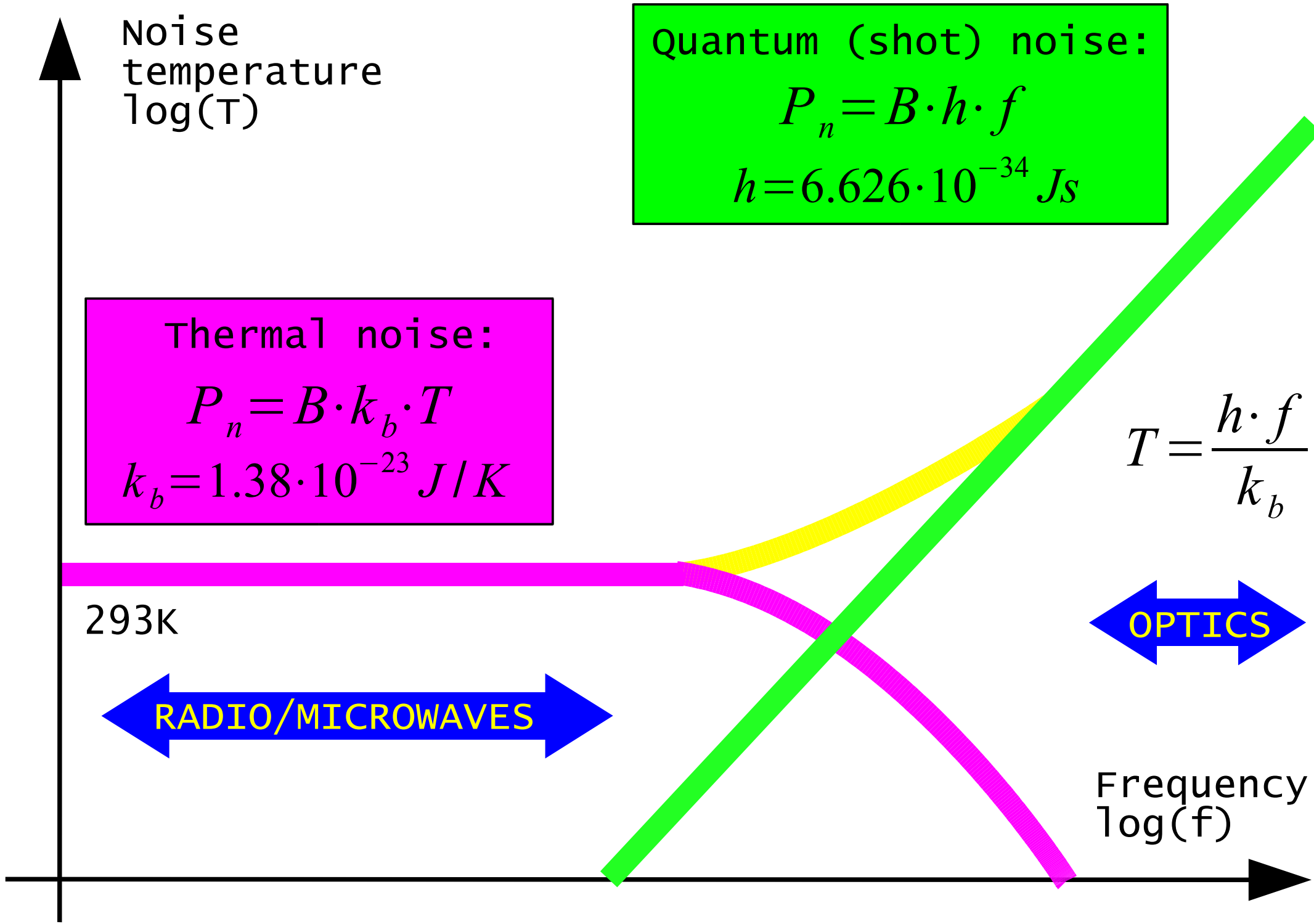
Nonlinearities: non-linear n , Brillouin & Raman

pulse broadening @ $l = 10\text{km}$		
multi-mode dispersion	step-index	$\Delta t = 500\text{ns}$
	gradient-index	$\Delta t = 5-50\text{ns}$
chromatic dispersion $\Delta\lambda = 1\text{nm}$	G.652 @ $\lambda=1.3\mu\text{m}$	$\Delta t \approx 20\text{ps}$
	G.652 @ $\lambda=1.55\mu\text{m}$	$\Delta t \approx 170\text{ps}$
PMD	G.652 old	$\Delta t \approx 10\text{ps}$
	G.652 new	$\Delta t \approx 300\text{fs}$

$P_{\text{MAX}} \approx 100\text{mW}$ (Raman and/or non-linear n)

$P_{\text{MAX}} \approx 1\text{mW}$ (Brillouin in narrowband systems)

Comparison of limitations of optical fibers



Quantum (shot) noise:

$$P_n = B \cdot h \cdot f$$

$$h = 6.626 \cdot 10^{-34} \text{ Js}$$

Thermal noise:

$$P_n = B \cdot k_b \cdot T$$

$$k_b = 1.38 \cdot 10^{-23} \text{ J/K}$$

$$T = \frac{h \cdot f}{k_b}$$

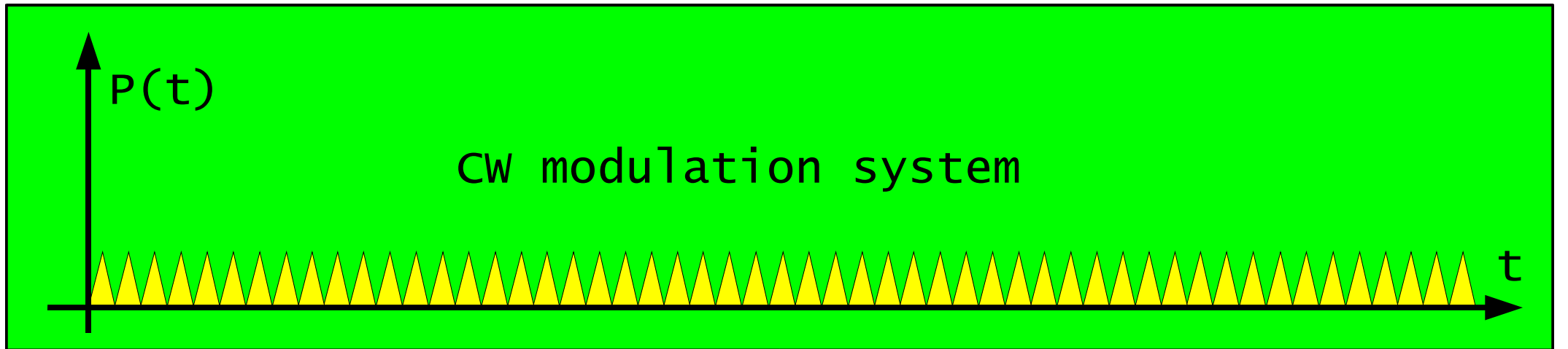
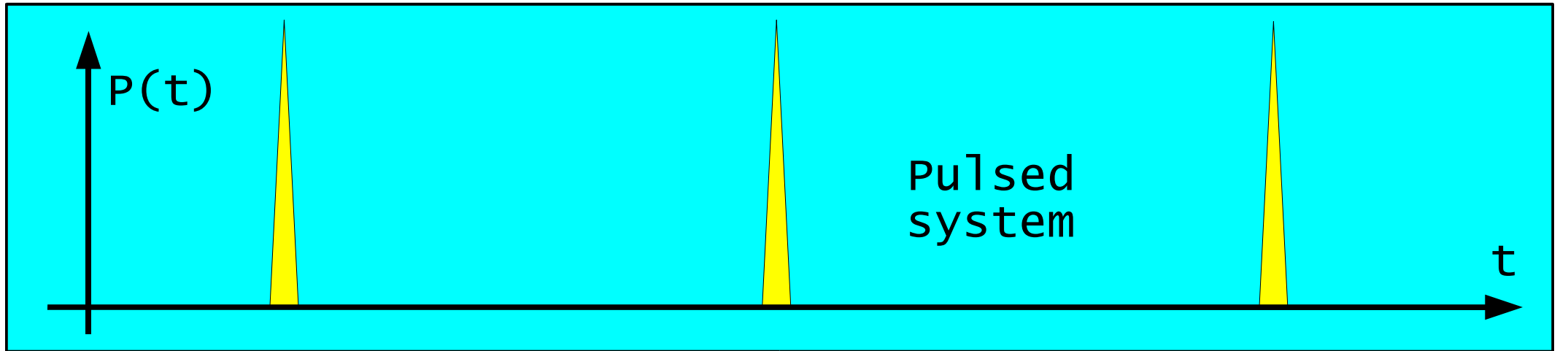
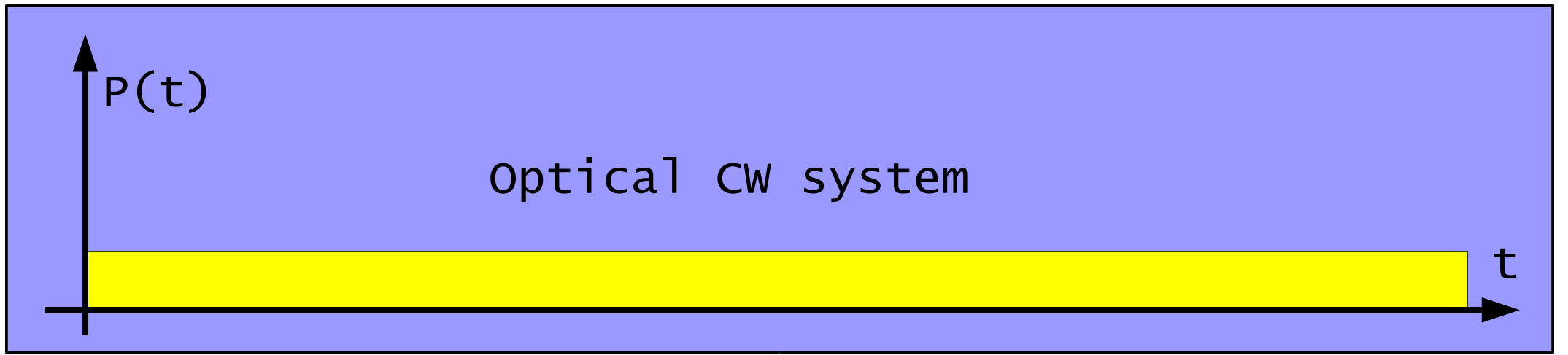
293K

RADIO/MICROWAVES

OPTICS

Frequency $\log(f)$

Thermal and quantum noise as function of frequency



Optical timing systems

High-coherence
optical clock
(laser)

single-mode fiber

$$\begin{aligned} f &= 194\text{THz} \\ \lambda &= 1.55\mu\text{m} \\ T &\approx 5\text{fs} \end{aligned}$$

All-optical
(coherent)
user

ADVANTAGES:

highest resolution
highest accuracy

DRAWBACKS:

5fs timing ambiguity?
interferometric noise?
Brillouin scattering?
PMD effects?
user-equipment availability?

Optical CW system

Femtosecond
pulsed laser

Electrical
pulse source

ADVANTAGES:
high resolution
high accuracy

single-mode fiber

$$f_{\text{carrier}} = 194\text{THz}$$

$$T_{\text{pulse}} = 100\text{fs}-10\text{ps}$$

Optical
and/or
electrical
user

DRAWBACKS:

fiber nonlinearity?

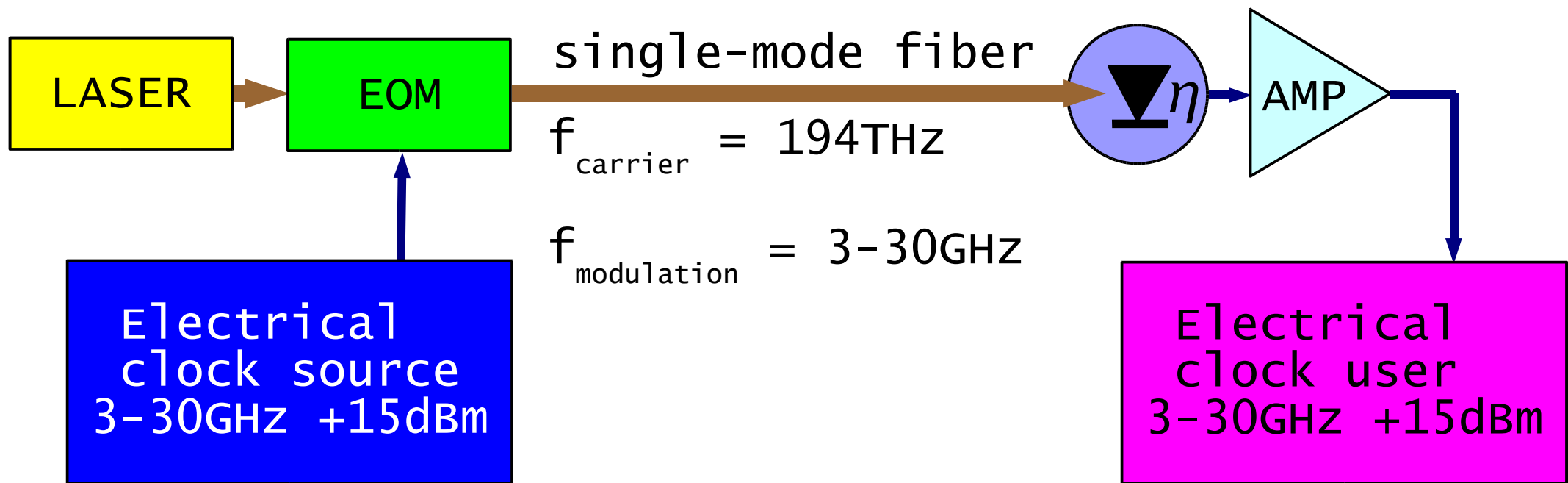
fiber chromatic dispersion?

fiber thermal compensation?

electrical SNR?

optical pulse processing?

Pulsed system



ADVANTAGES:

simple temperature compensation

standard electrical interfaces

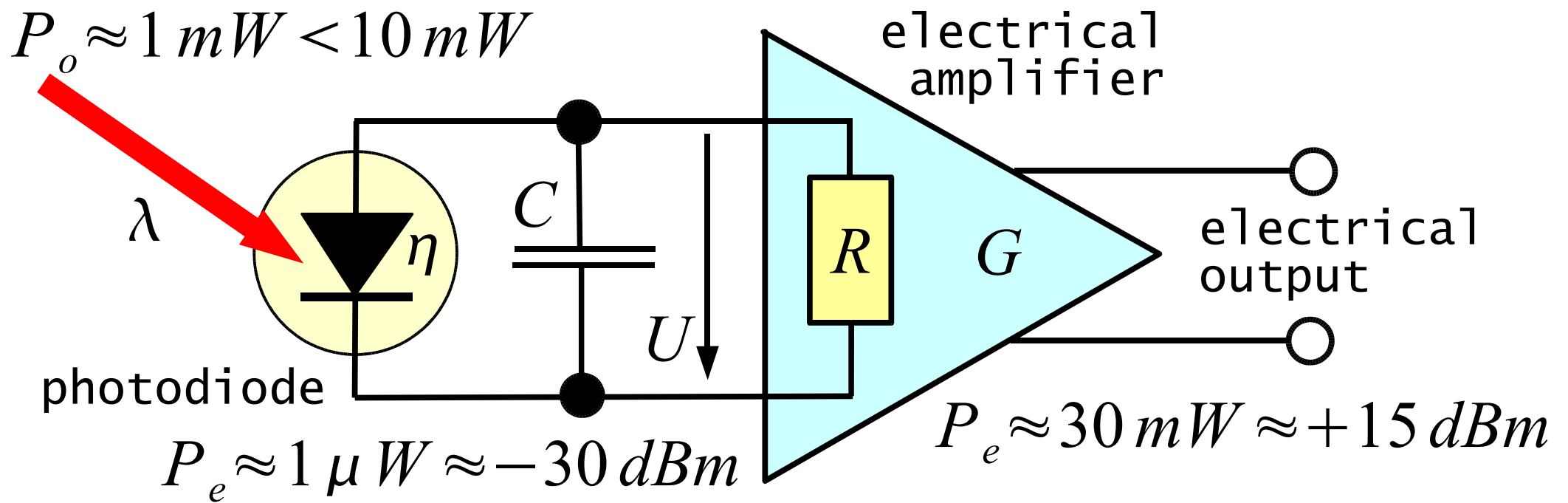
standard hi-rel telecom components

DRAWBACKS:

high photodetector electrical noise:
jitter 1-10ps

low timing resolution?

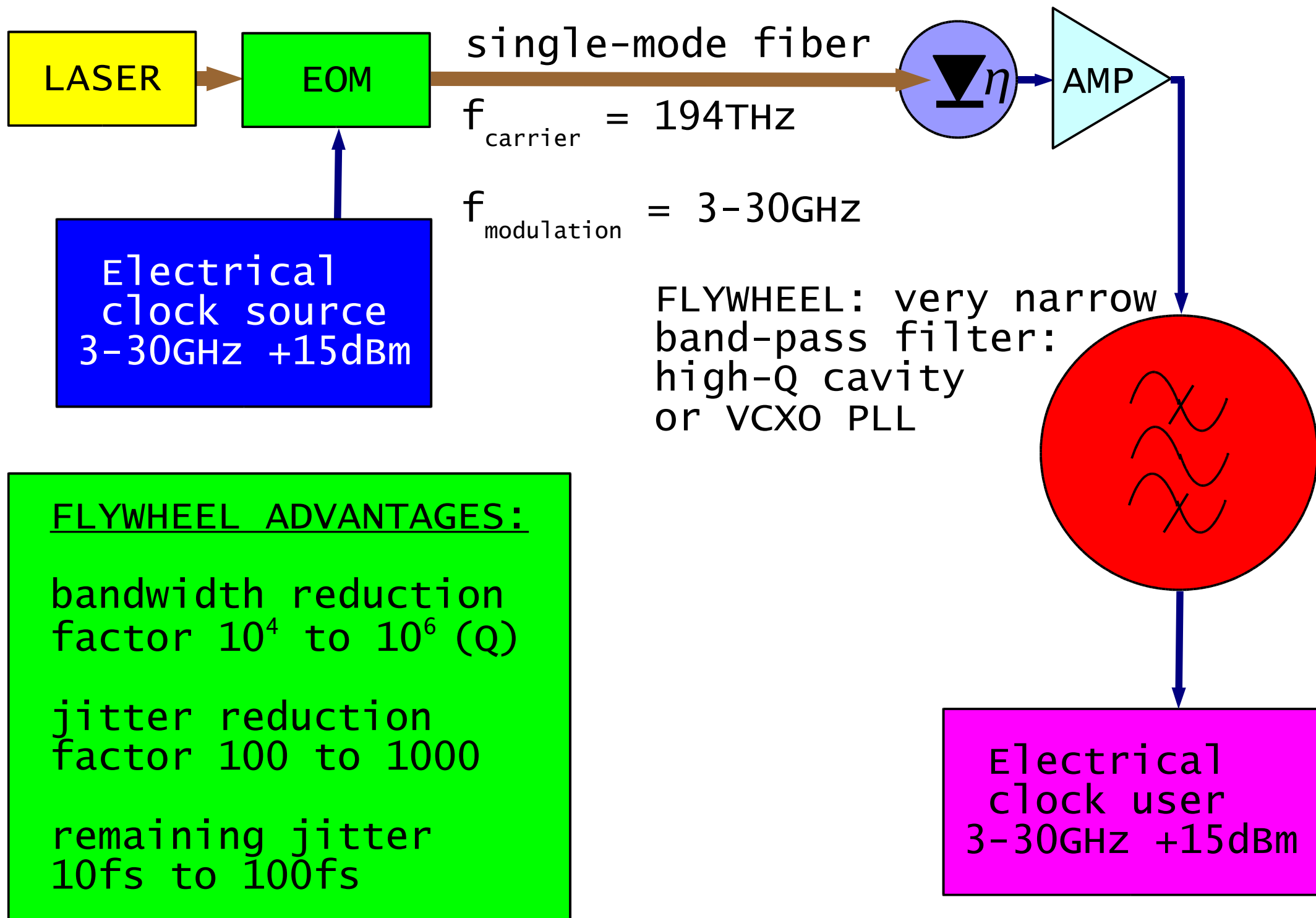
CW modulation system



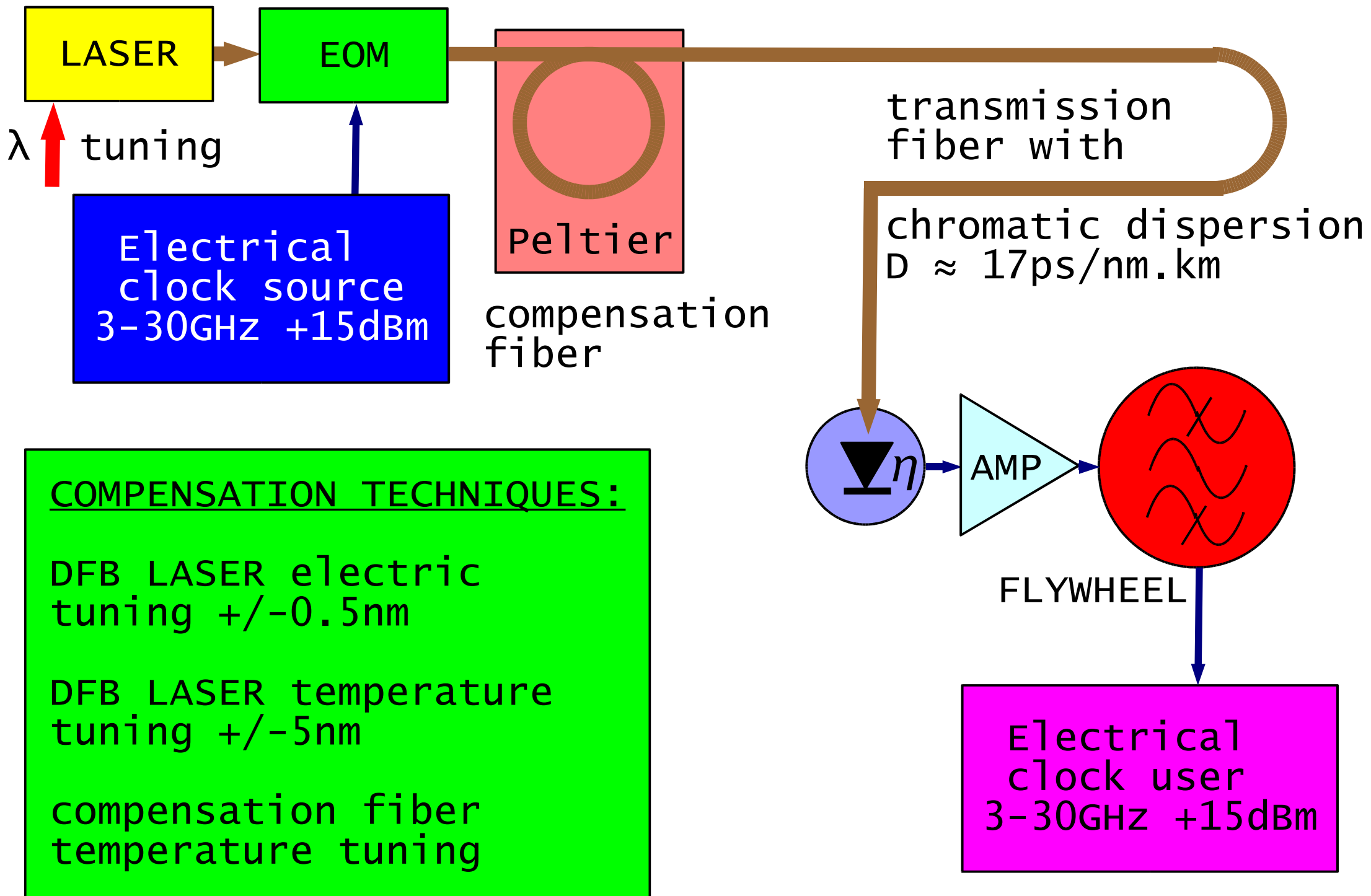
$$U_{neff} = \sqrt{P_n \cdot R} \quad P_n = B \cdot k_b \cdot T \quad B = \frac{1}{2\pi \cdot R \cdot C}$$

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

Photodiode electrical noise



CW modulation system with flywheel



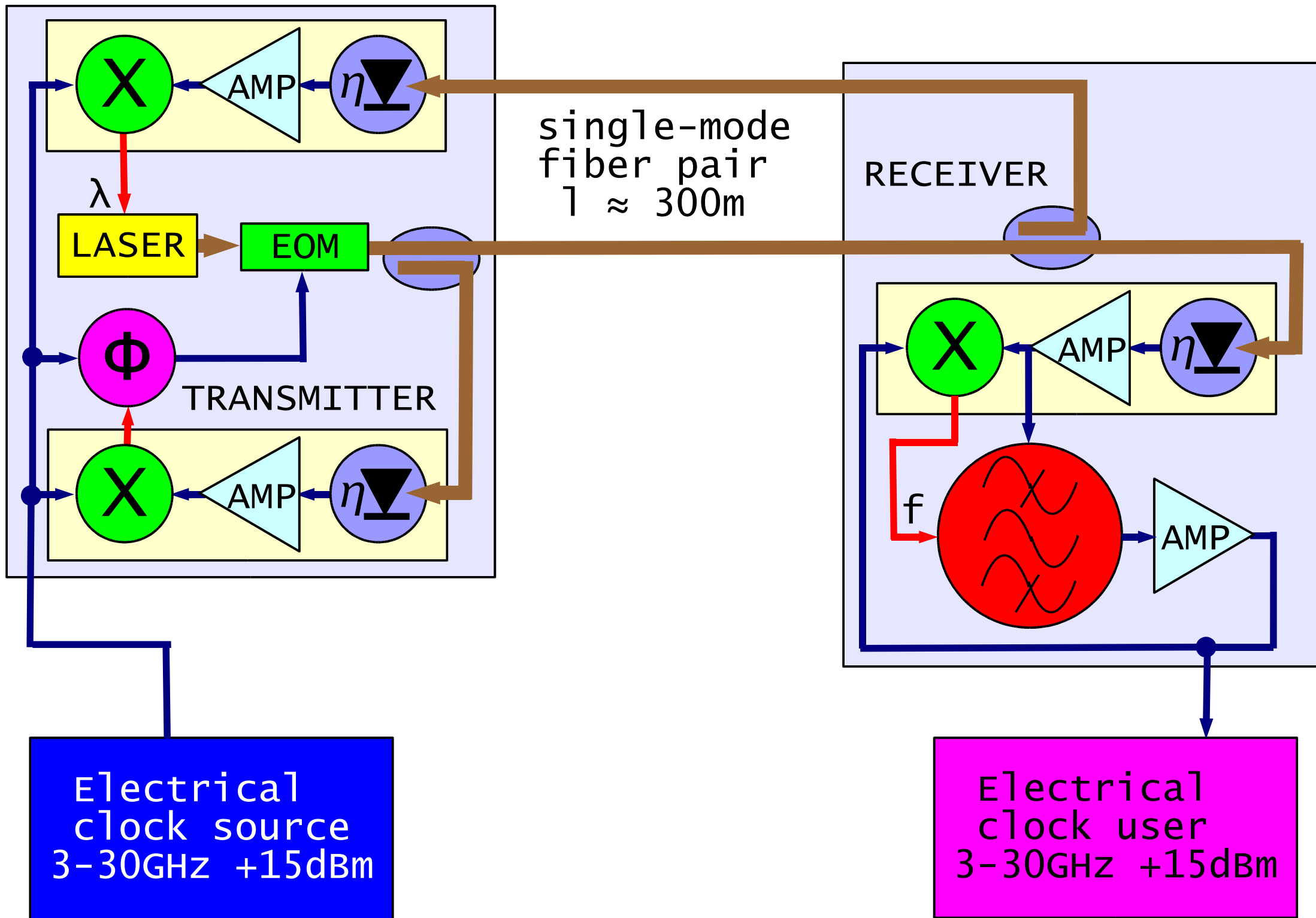
COMPENSATION TECHNIQUES:

DFB LASER electric tuning $\pm 0.5\text{nm}$

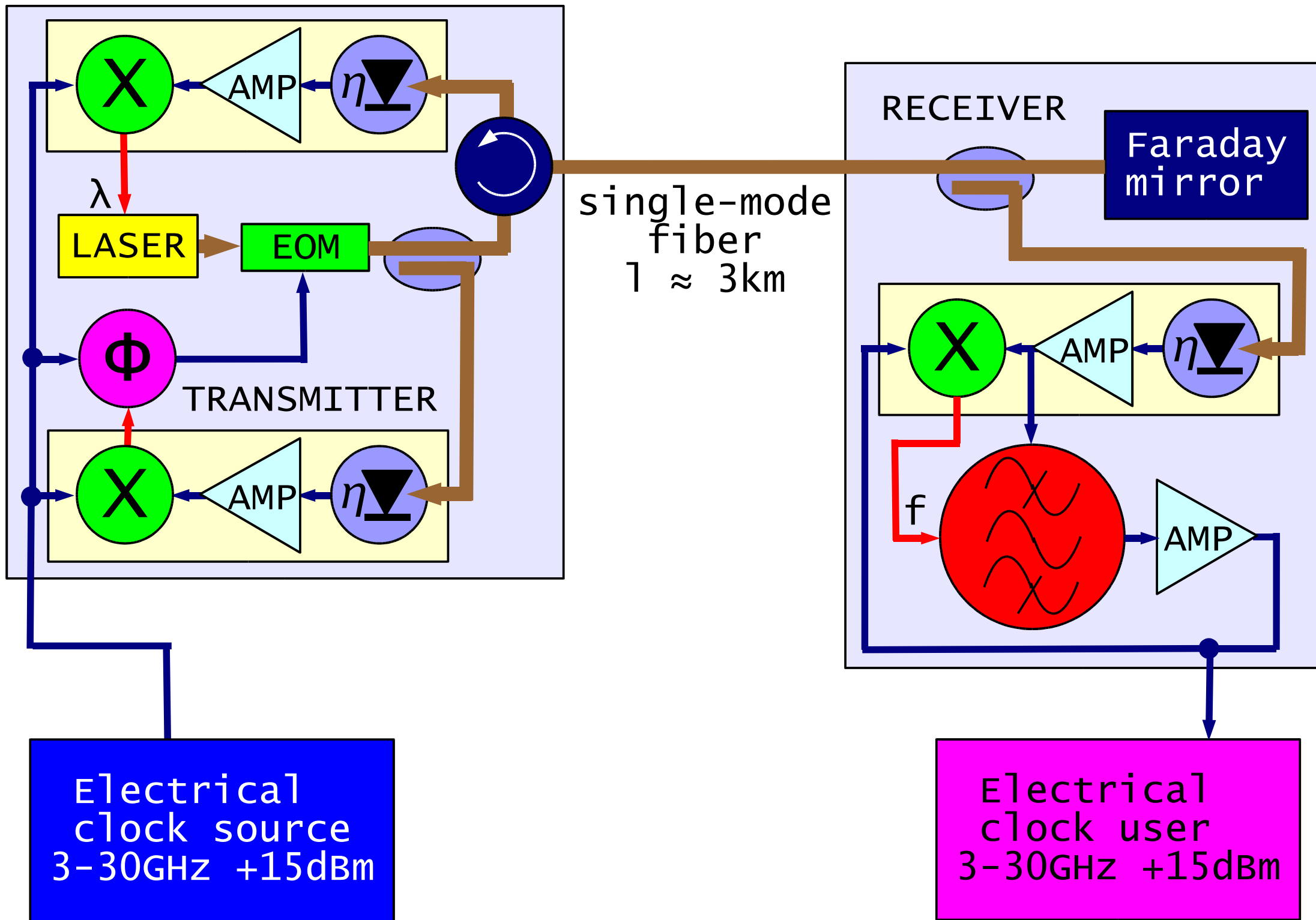
DFB LASER temperature tuning $\pm 5\text{nm}$

compensation fiber temperature tuning

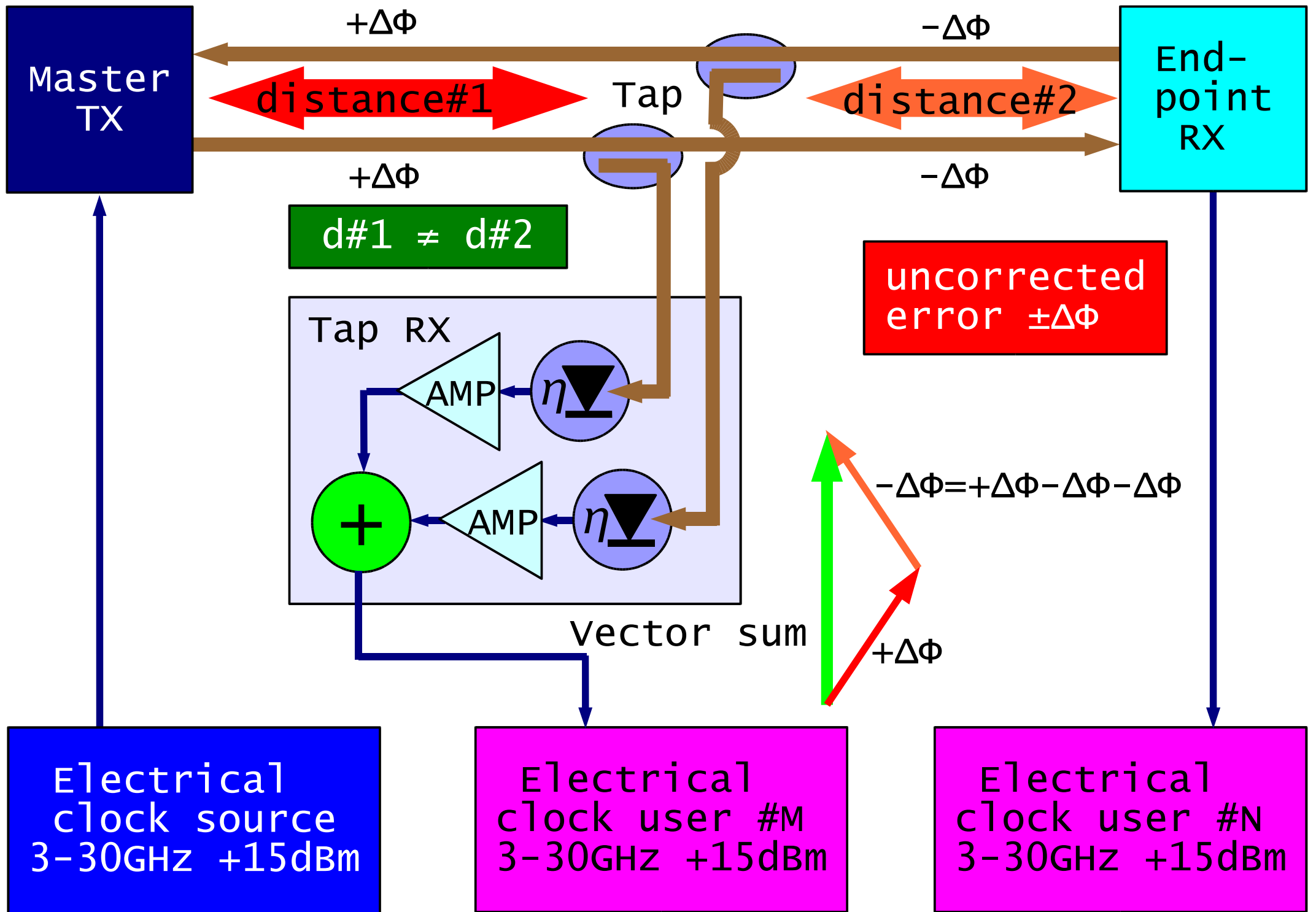
Delay-variation compensation techniques



CW modulation system with temperature compensation



CW modulation system with PMD compensation



Multi-point chain clock distribution

OPTICAL FIBER:

long-term, temperature
& PMD characterization

connector performance

ferrite components:
isolators, circulators
& Faraday mirrors

FLYWHEEL TECHNOLOGY:

ceramic materials for
dielectric resonators

VCXO characterization

low-noise frequency
multipliers and
dividers

LASER TECHNOLOGY:

high-speed electronic
wavelength tuning

low-coherence sources

direct laser modulation

safety & reliability

USER REQUIREMENTS:

optical input & output?

pulsed input & output?

integration with other
equipment?

diagnostics?

Future-development action list