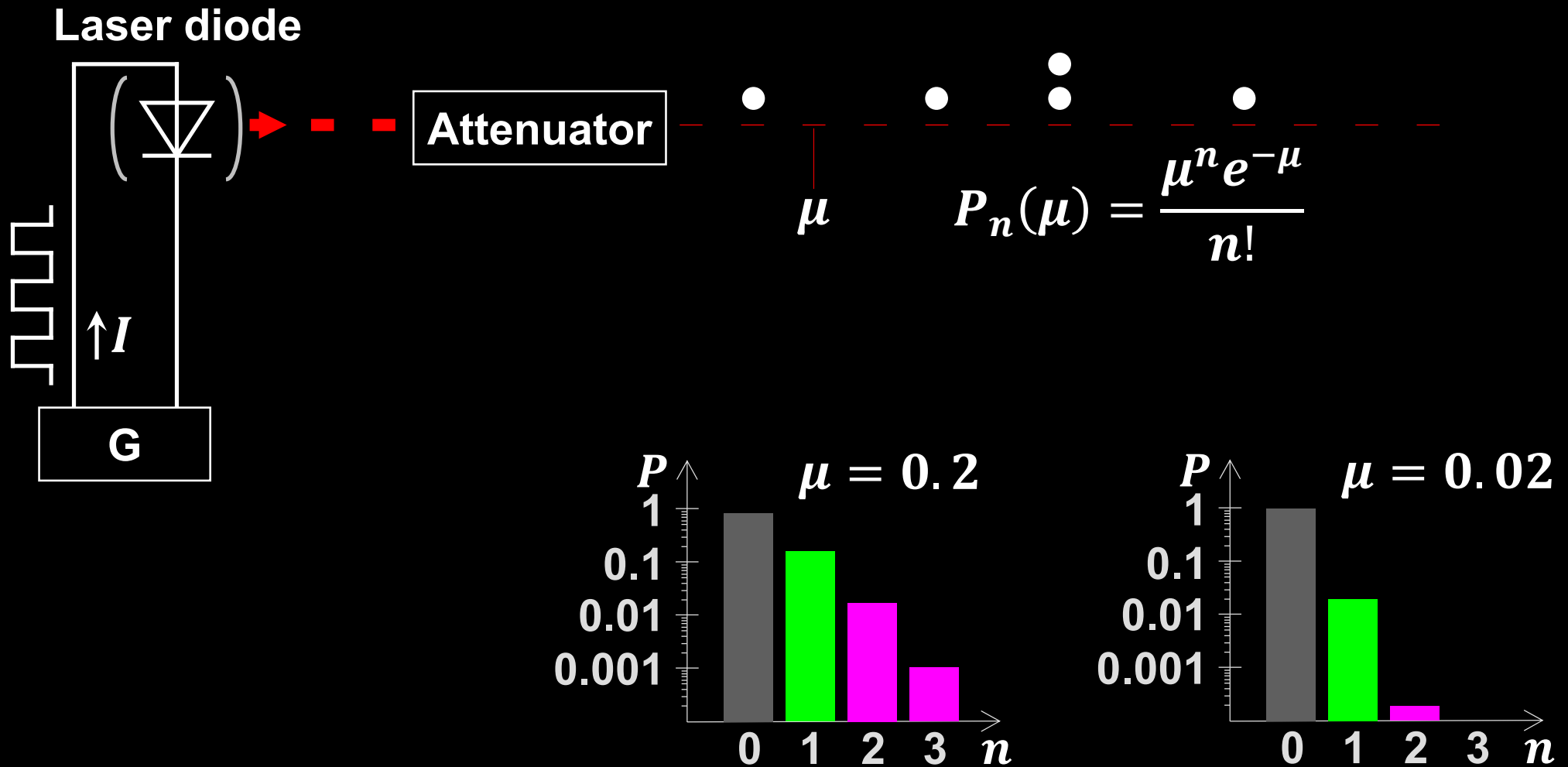


Components of quantum-optical systems

Photon _____ **Transmission** _____ **“Processing”** _____ **Photon**
sources **channels** **elements** **detectors**

Attenuated laser source



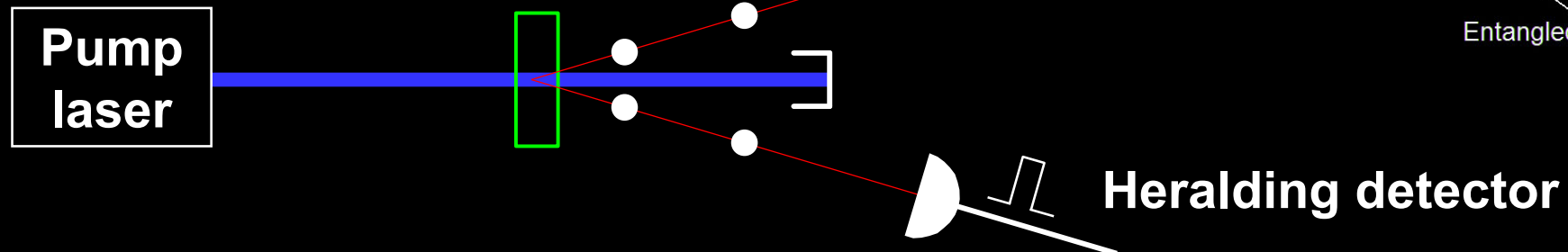
Spontaneous parametric down-conversion

Energy conservation: $\omega_p = \omega_s + \omega_i$

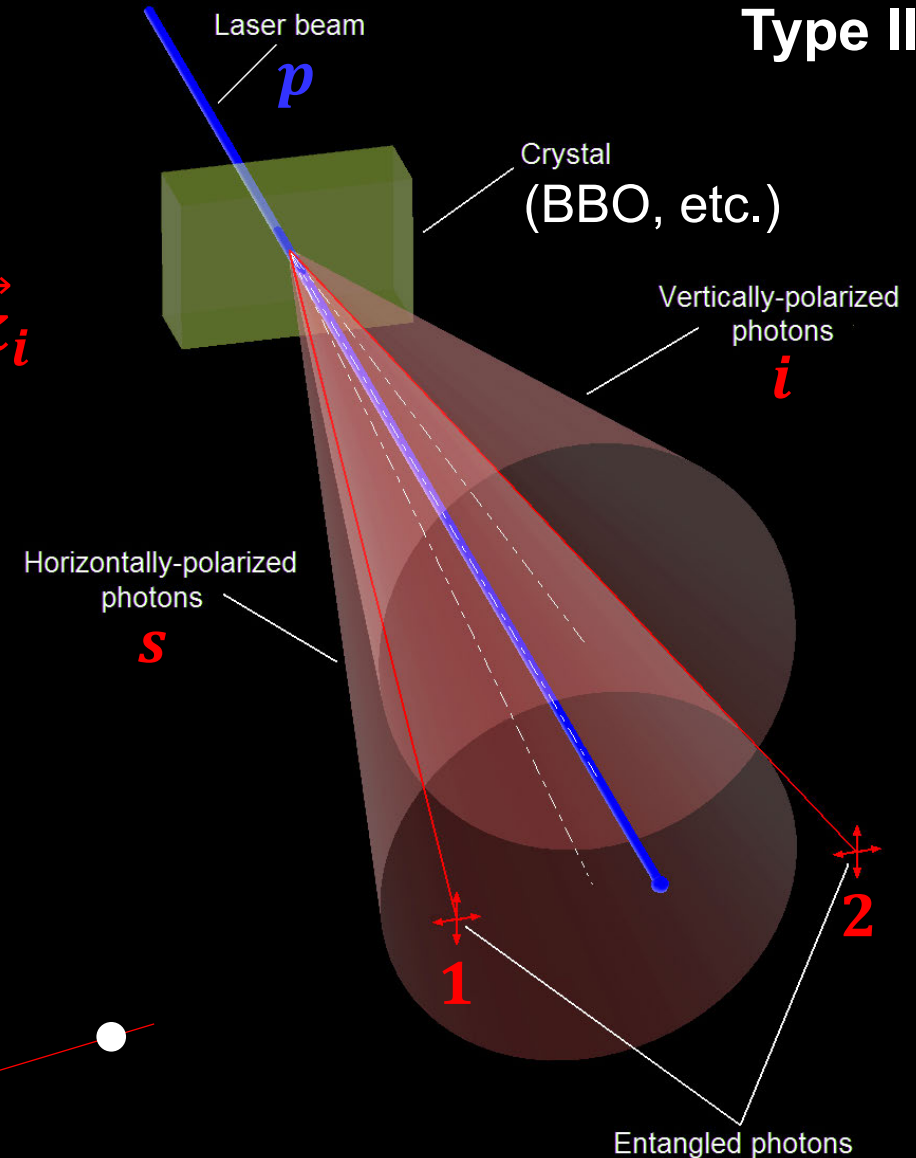
Momentum conservation: $\vec{k}_p = \vec{k}_s + \vec{k}_i$

$$|\psi\rangle = (|H_1, V_2\rangle + |V_1, H_2\rangle) / \sqrt{2}$$

Heralded photon source

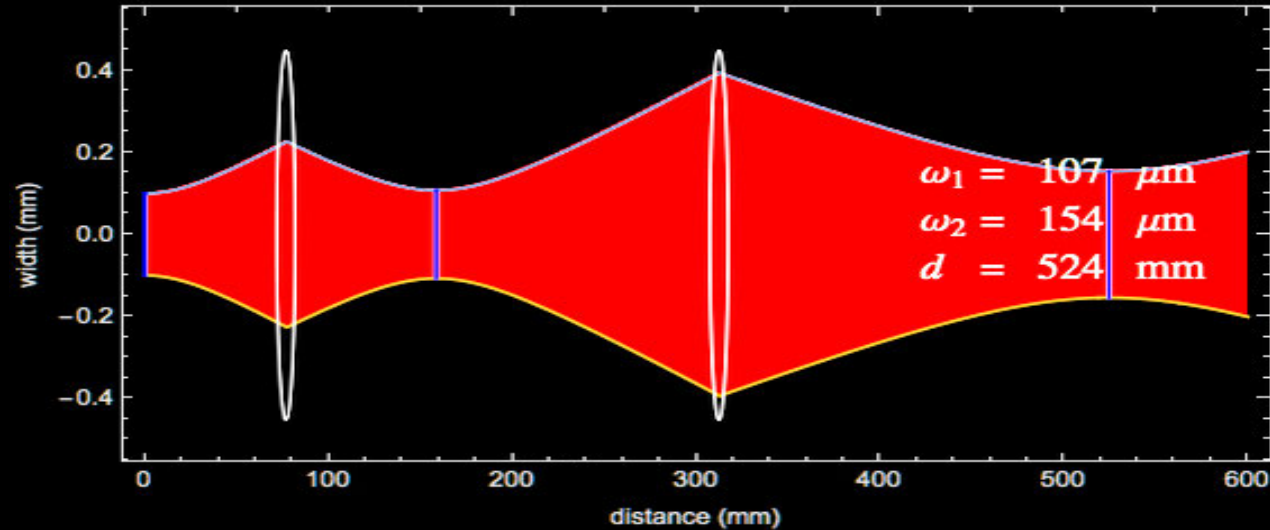


Type II

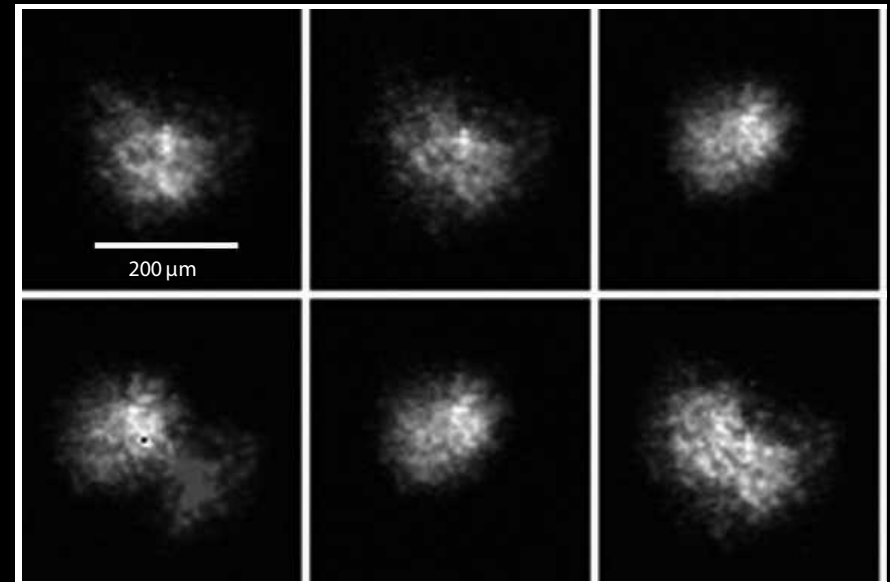
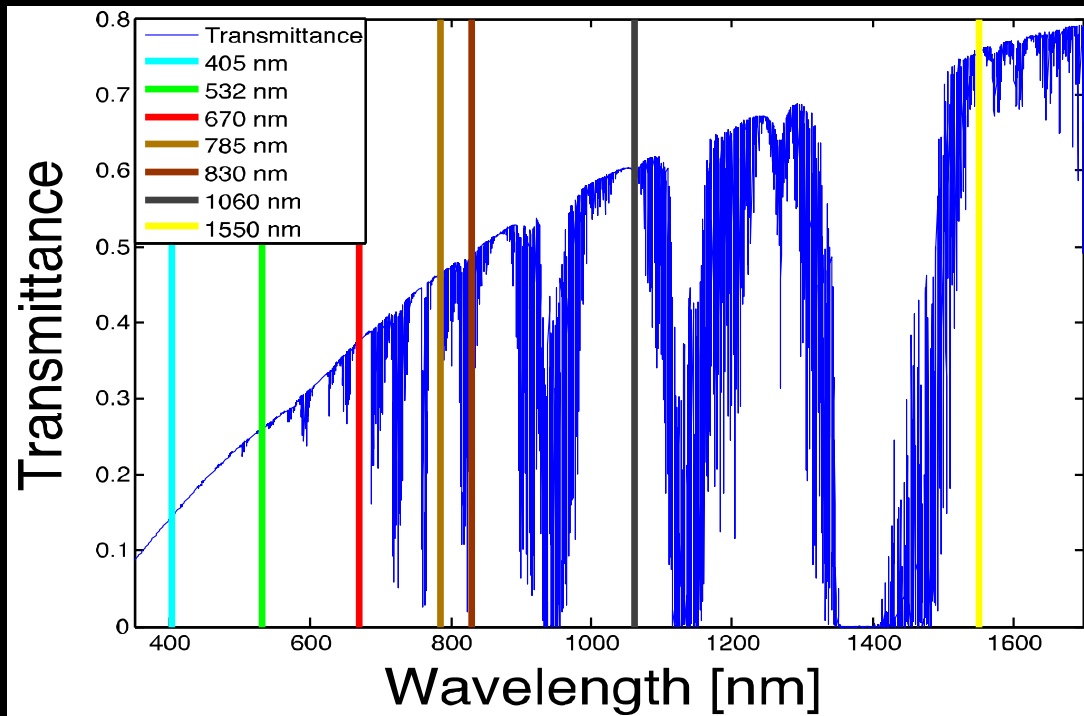


Transmission in free space

Vacuum:
Gaussian optics



Atmosphere: loss, turbulence

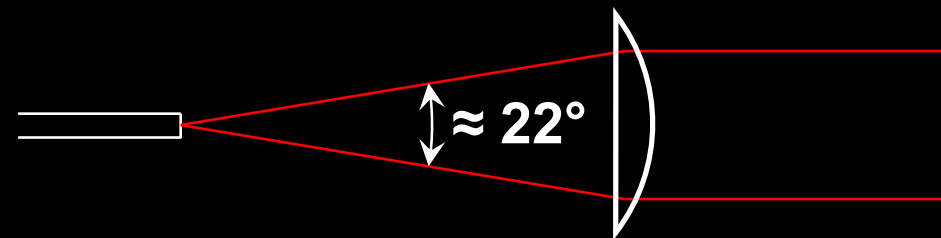
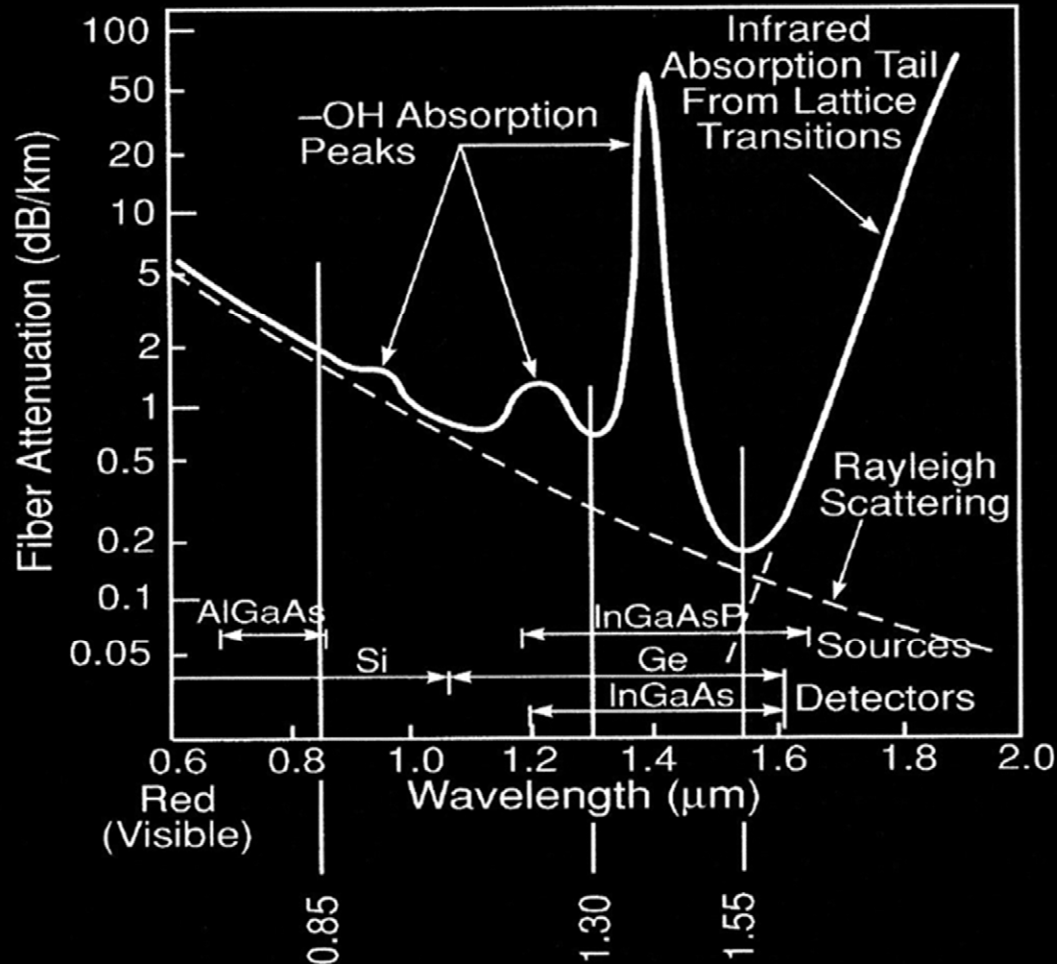
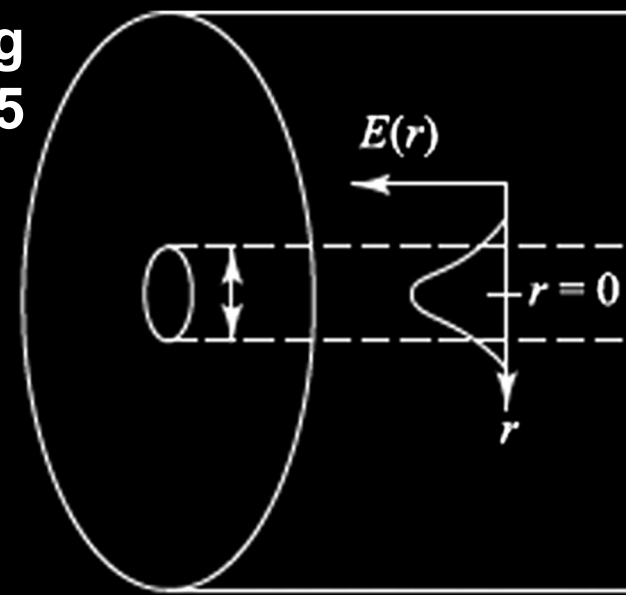


Transmission in optical fiber

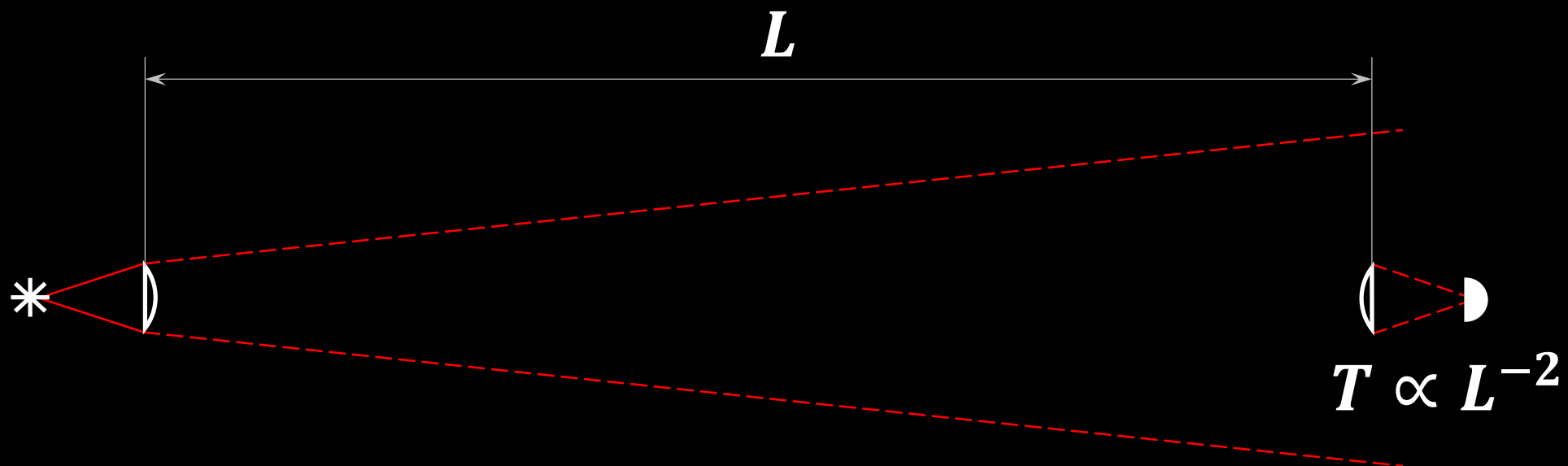
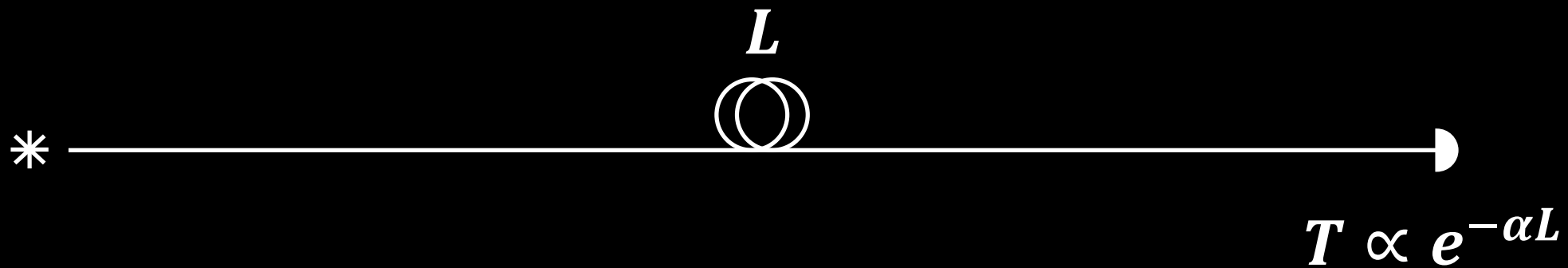
Single-mode fiber

125 μm diameter cladding
fused quartz, $n_1 = 1.45$

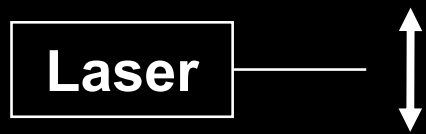
8 μm diameter core
 $n_2 > n_1$



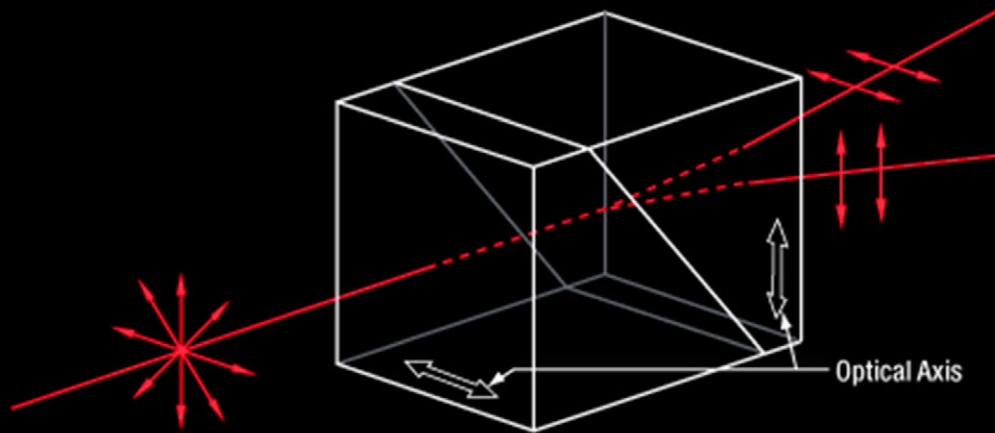
Fiber vs. beam in vacuum: loss scaling



Polarizers

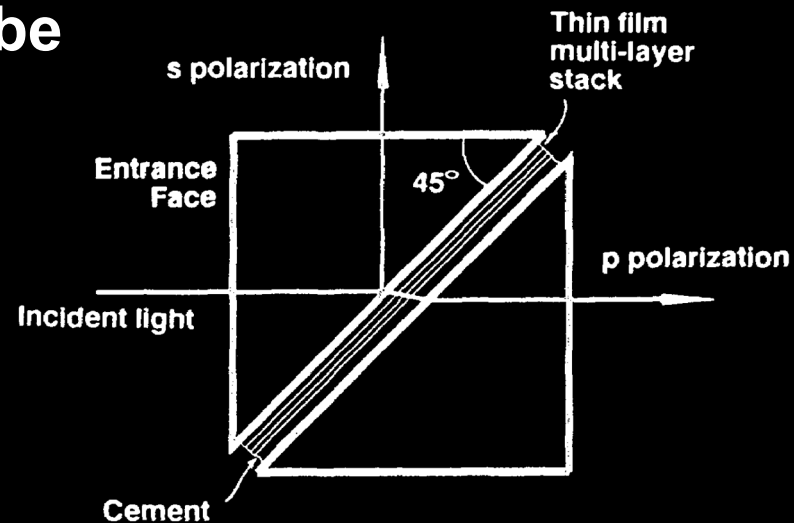
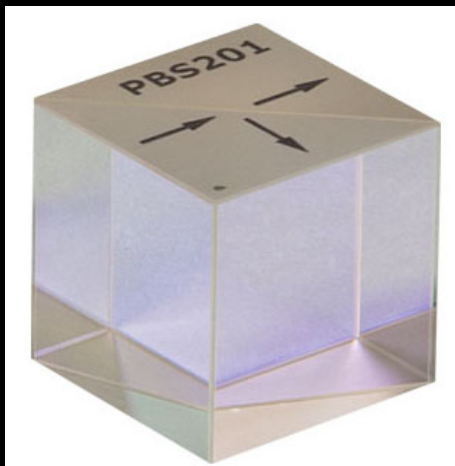


Birefringent polarizing beamsplitter



Wollaston prism

Polarizing beamsplitter cube



Beamsplitters

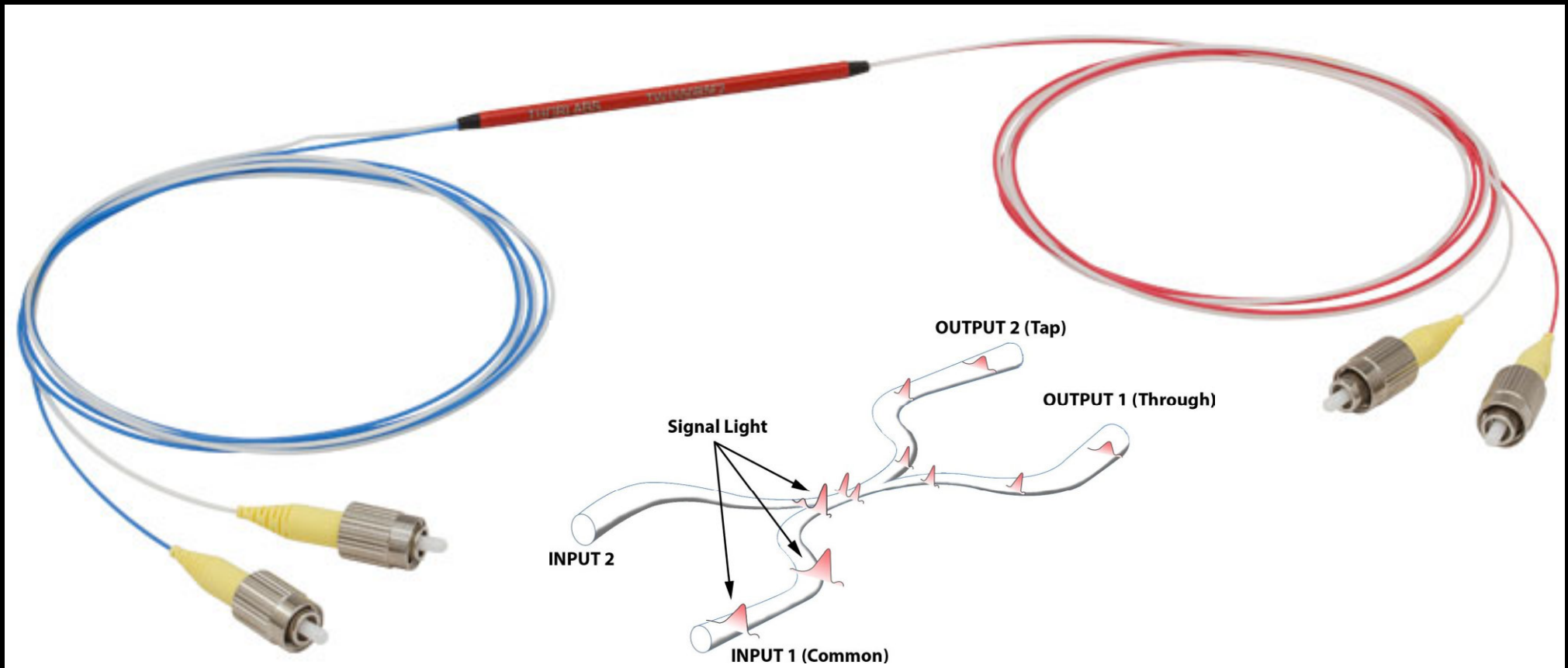


50:50

10:90

1:99

Fiber-optic fused beamsplitter (or coupler)

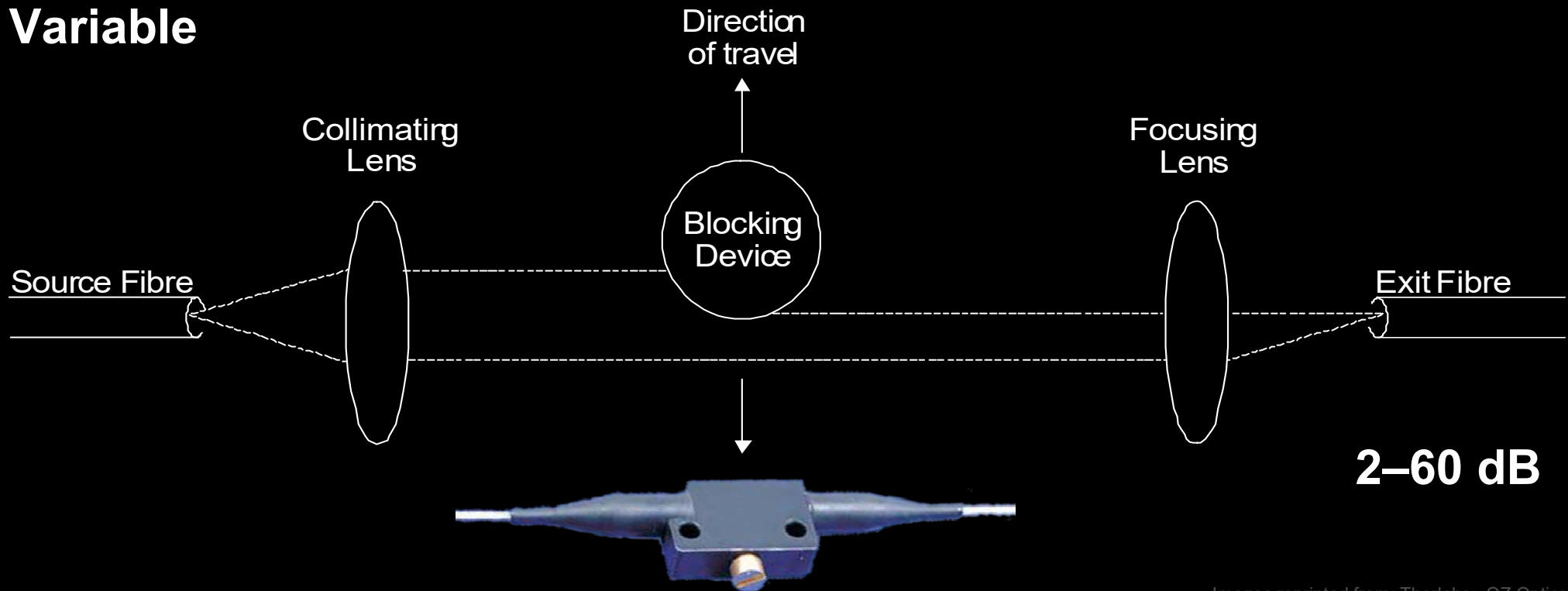


Attenuators

Absorbing or partially reflecting coated glass

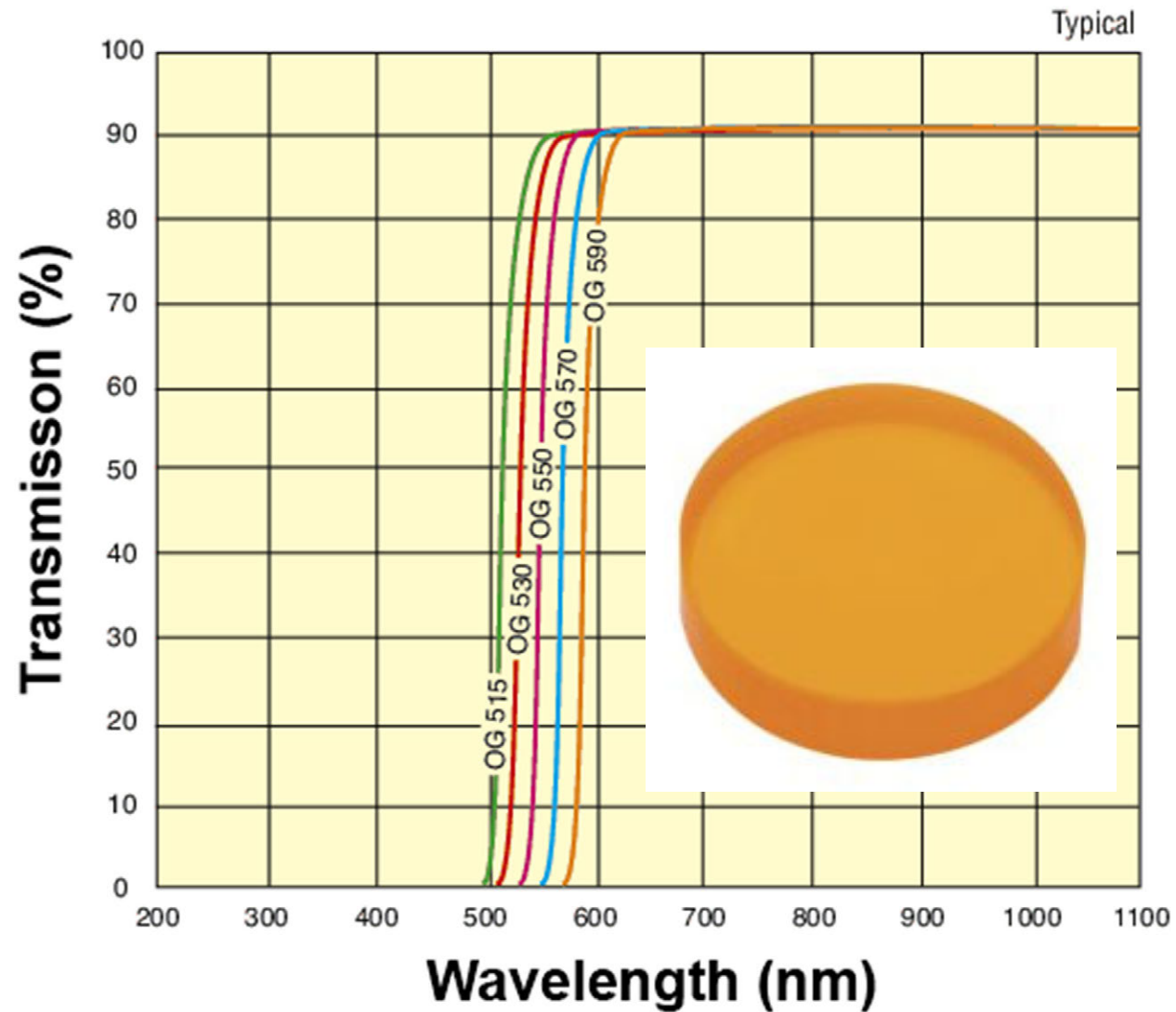


Variable



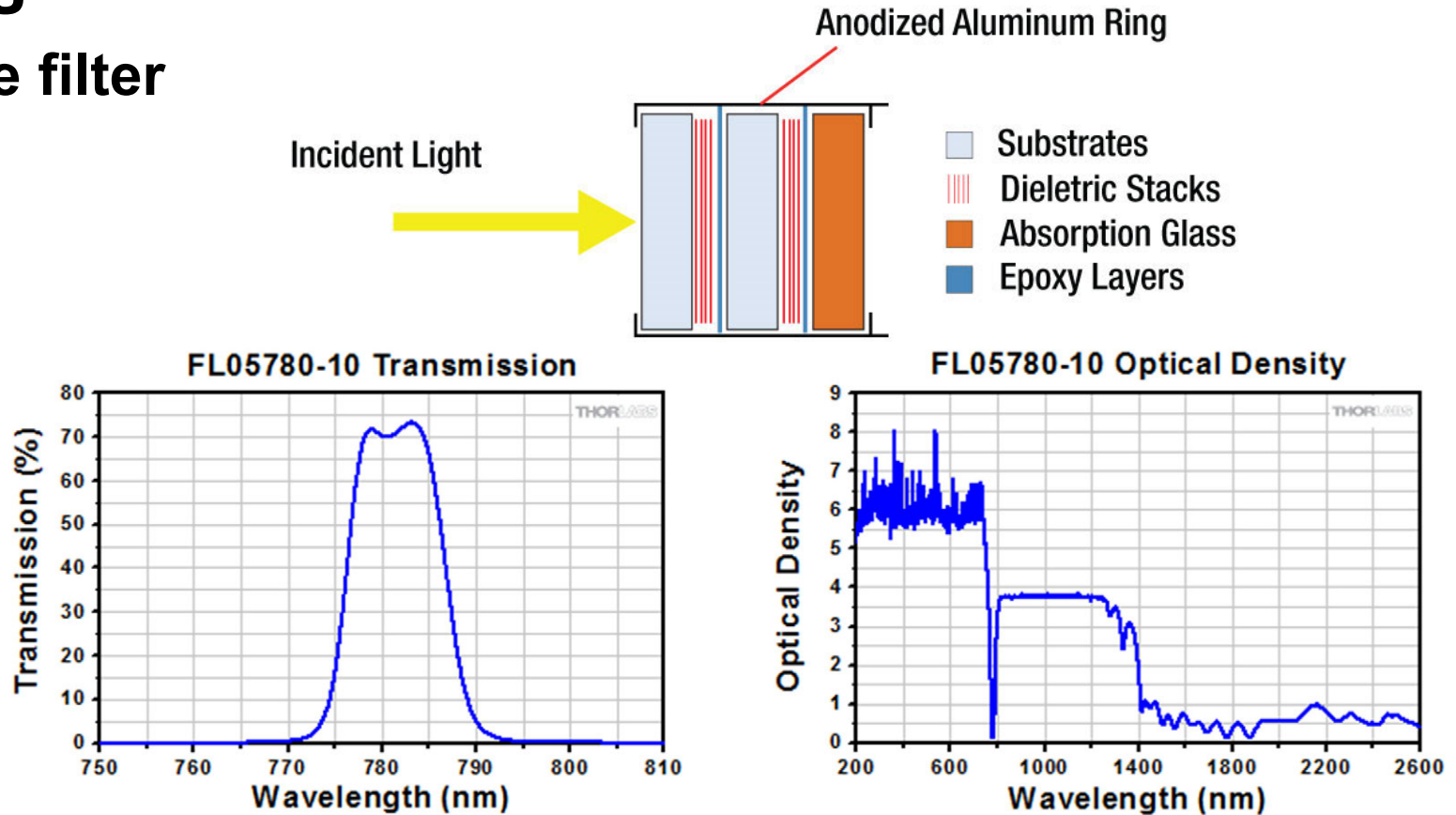
Wavelength filters

Colored glass

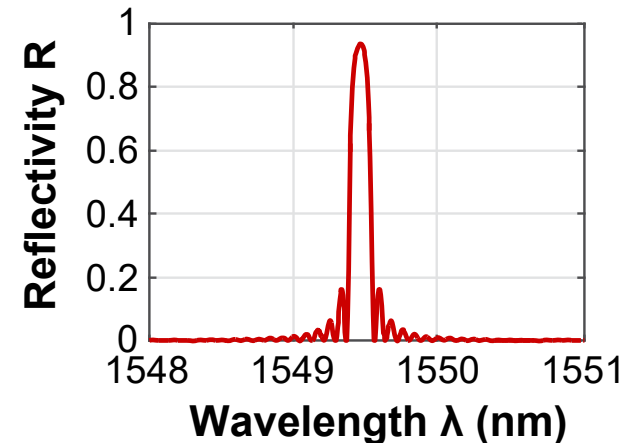
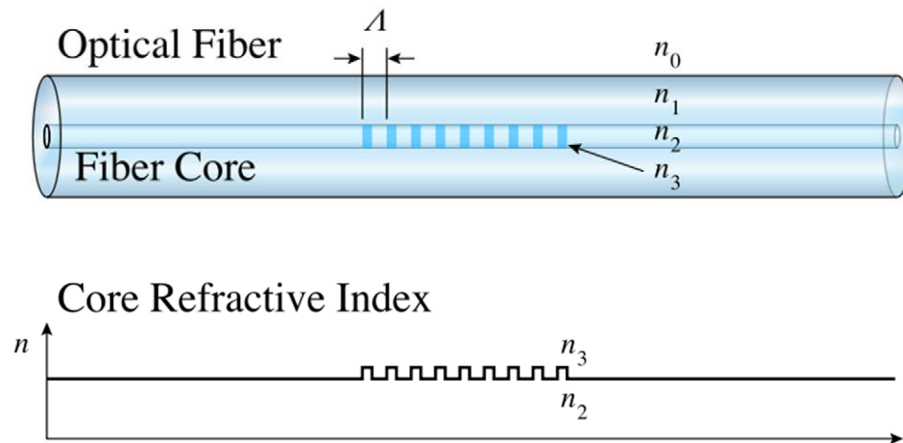


Wavelength filters

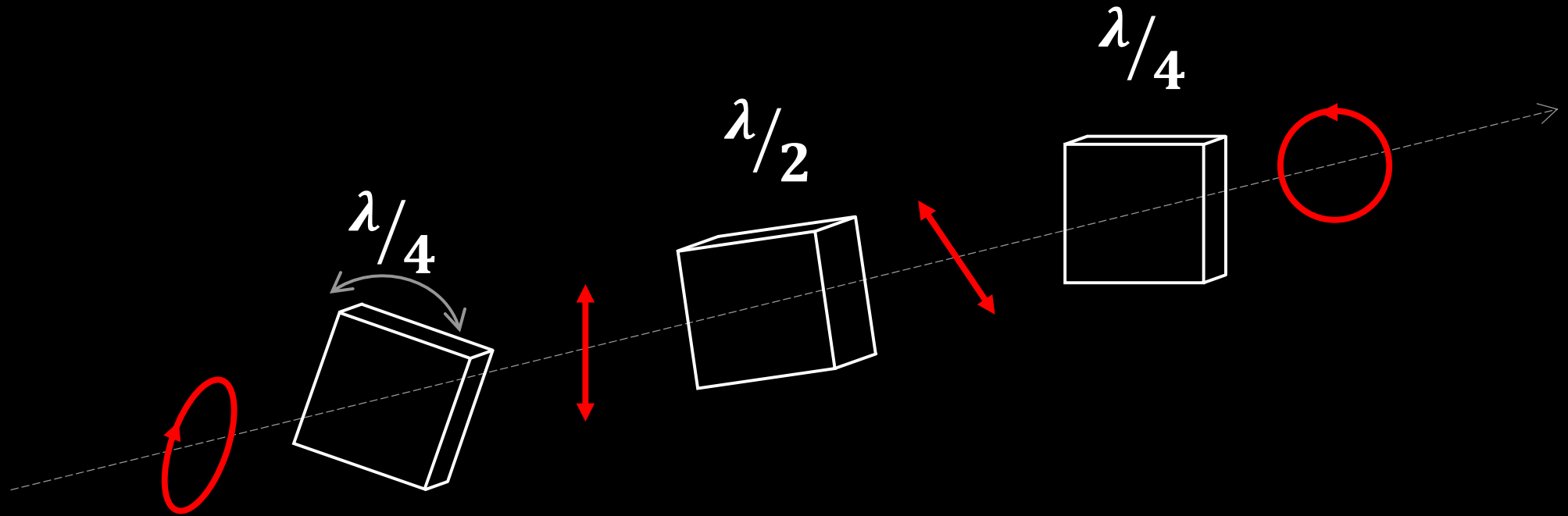
Interference filter



Fiber Bragg grating

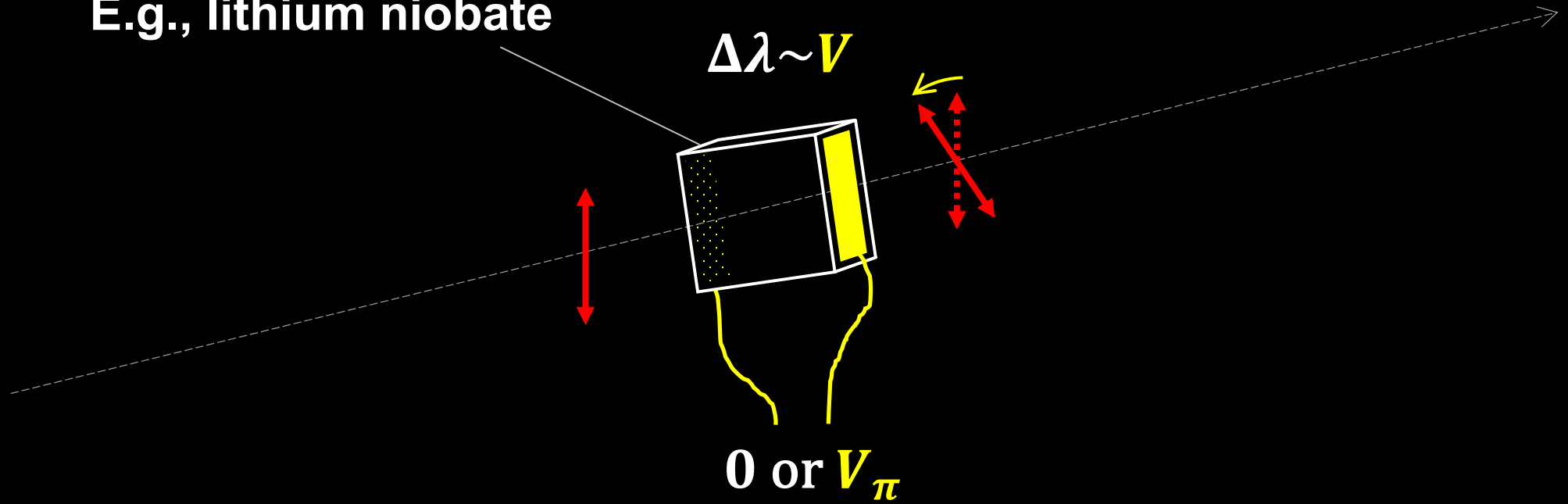


Polarization controller (slow)



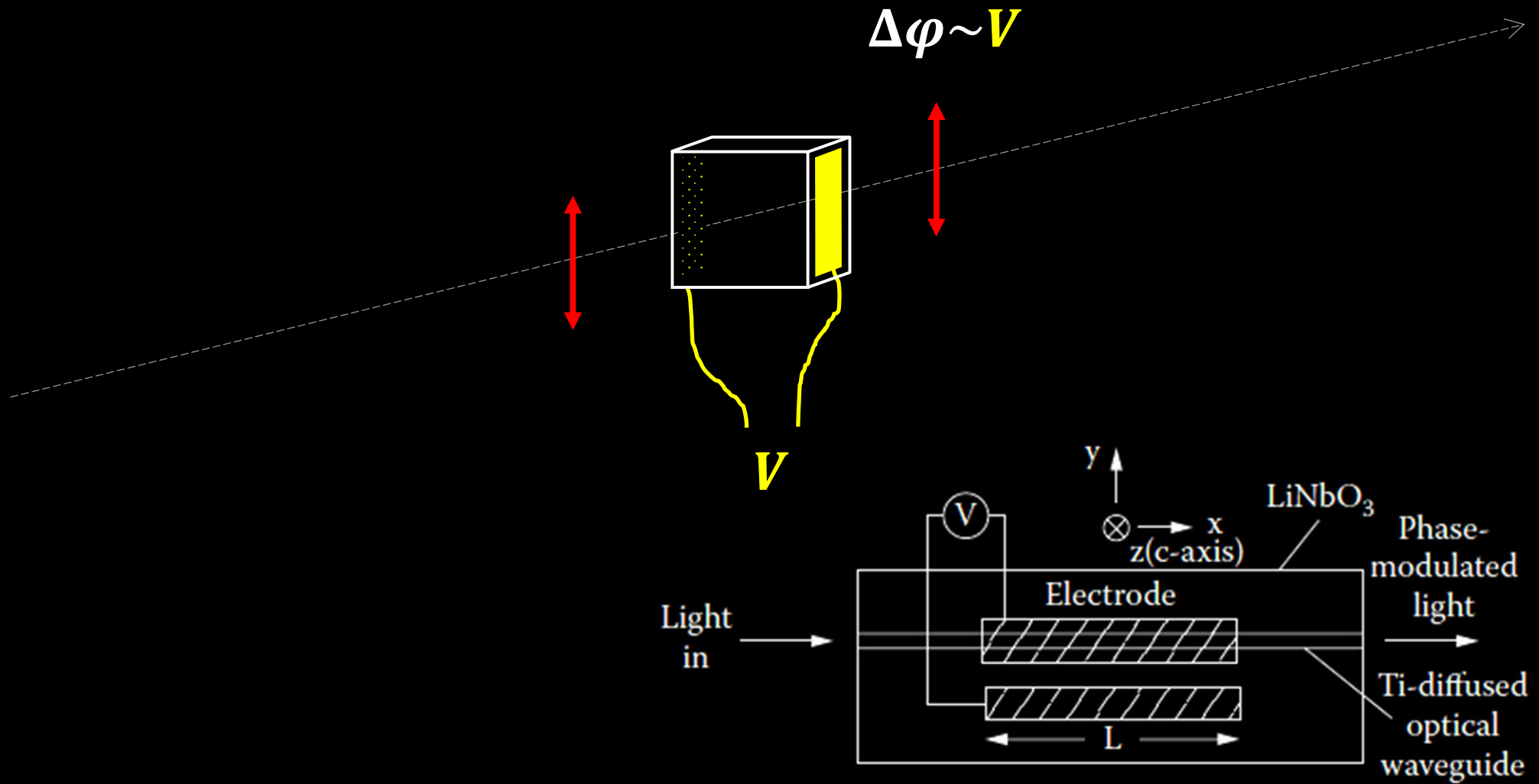
Polarization modulator (fast)

E.g., lithium niobate

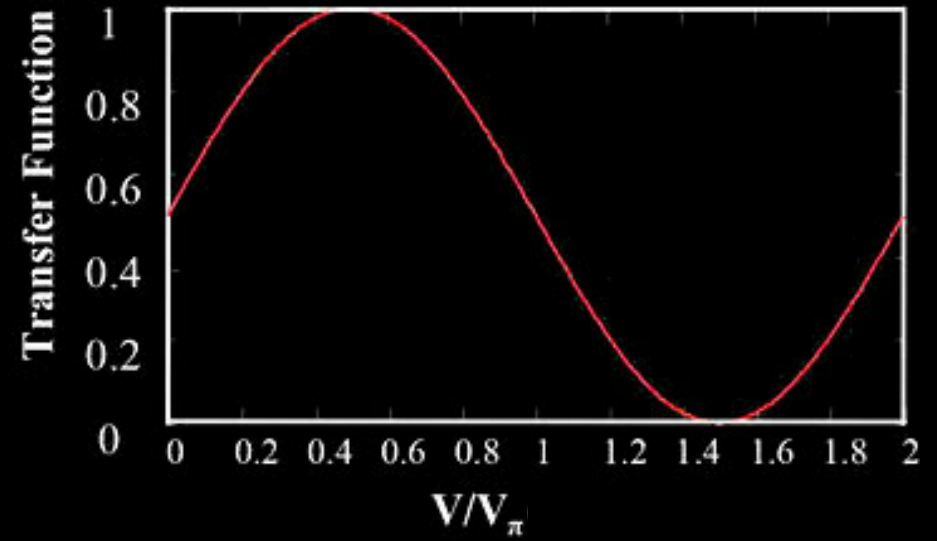
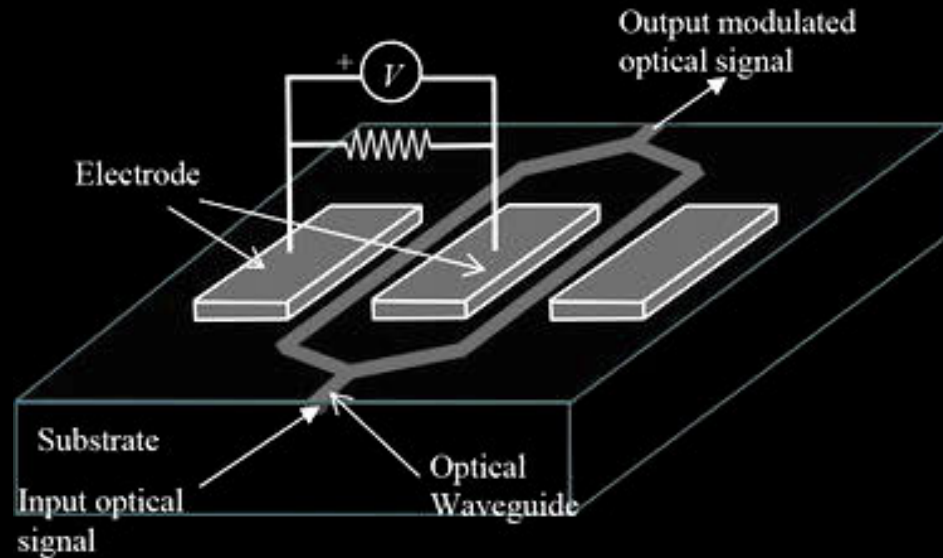


Pockels cell

Phase modulator



Intensity modulator

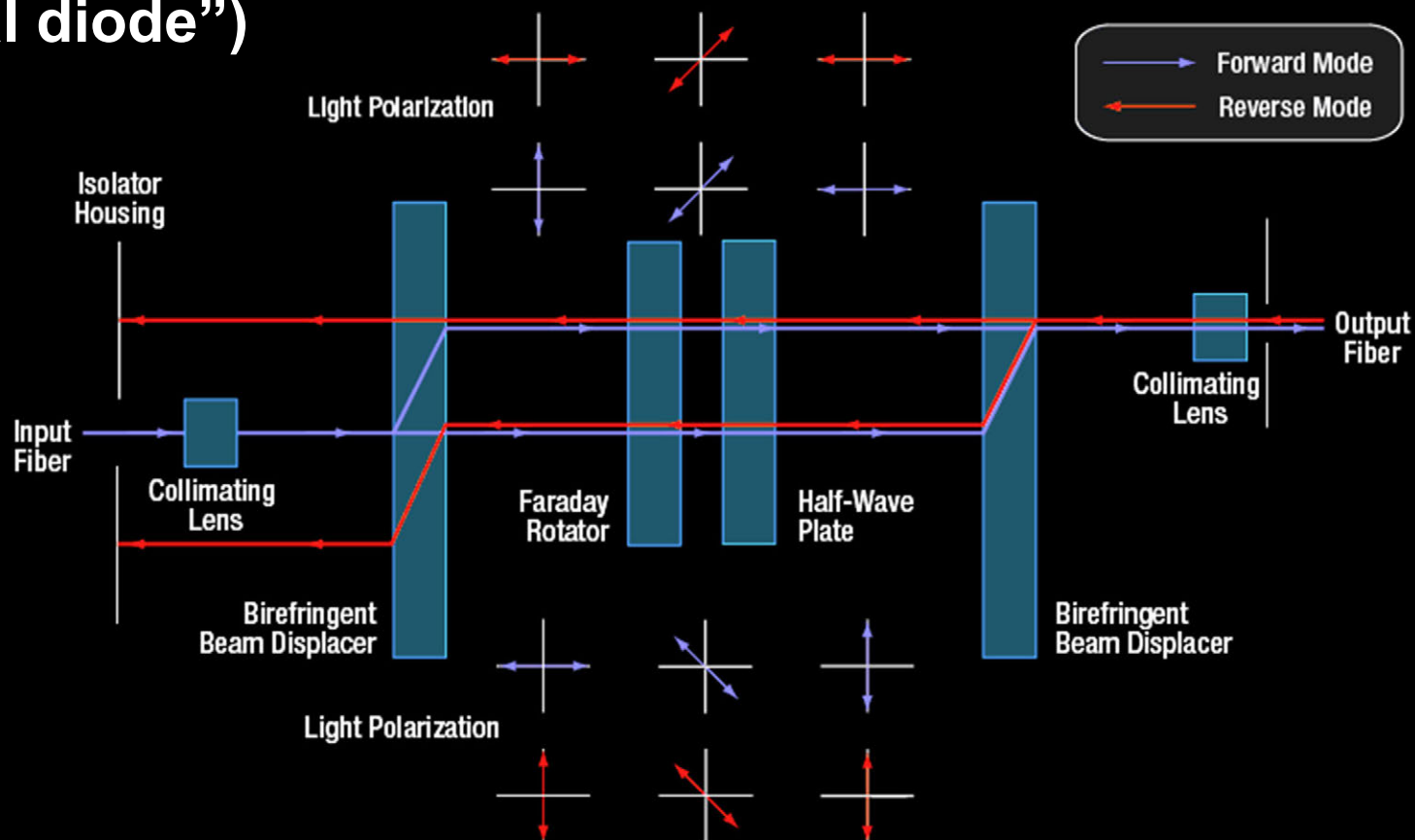
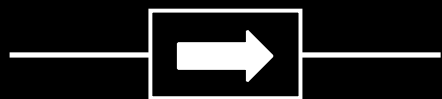


Mach-Zehnder interferometer

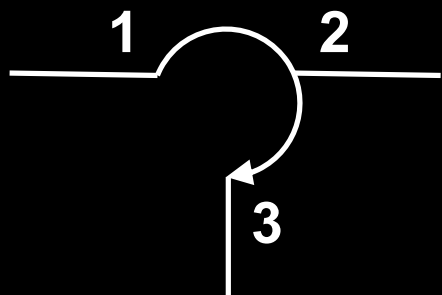


Directional elements

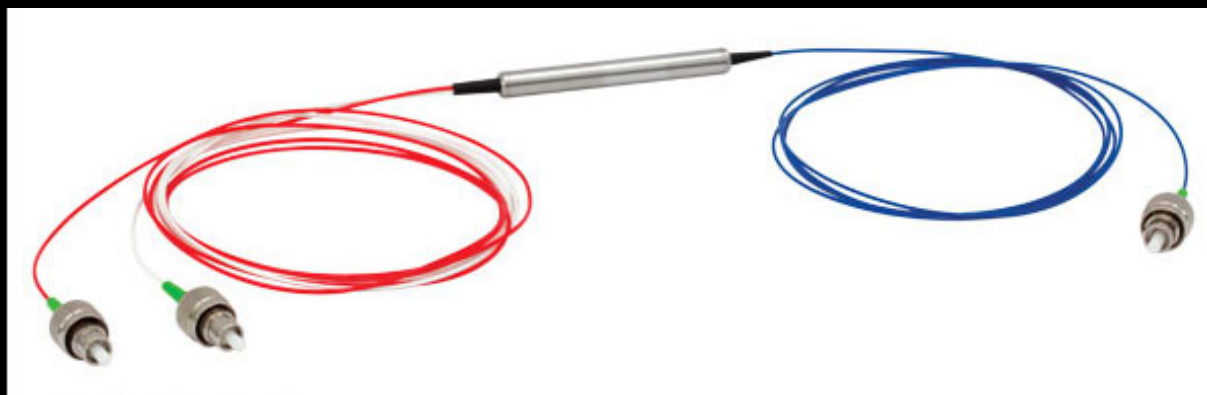
Isolator (an “optical diode”)



Circulator



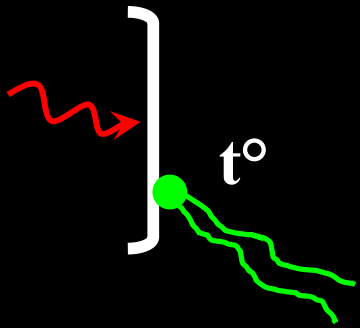
1 → 2
2 → 3



Optical power meters

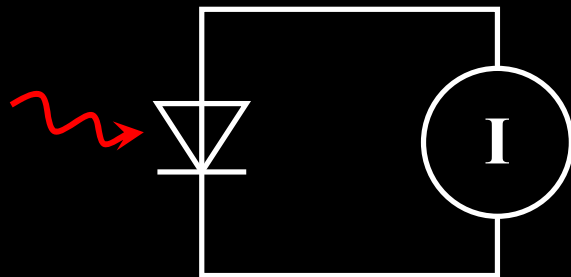
Thermal

$> 10 \mu\text{W}$



Photodiode

$> 0.1 \text{ nW}$



Single-photon detectors

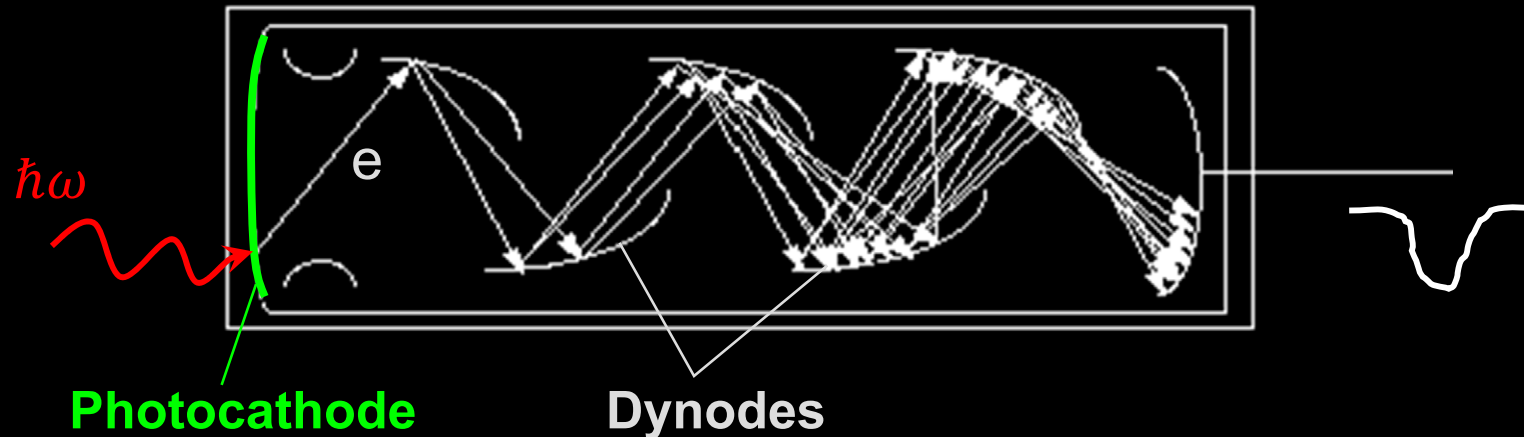
Photon energy

$$E = \frac{hc}{\lambda} = \frac{19.9 \times 10^{-26}}{1.55 \times 10^{-6}} = 1.28 \times 10^{-19} \text{ J}$$

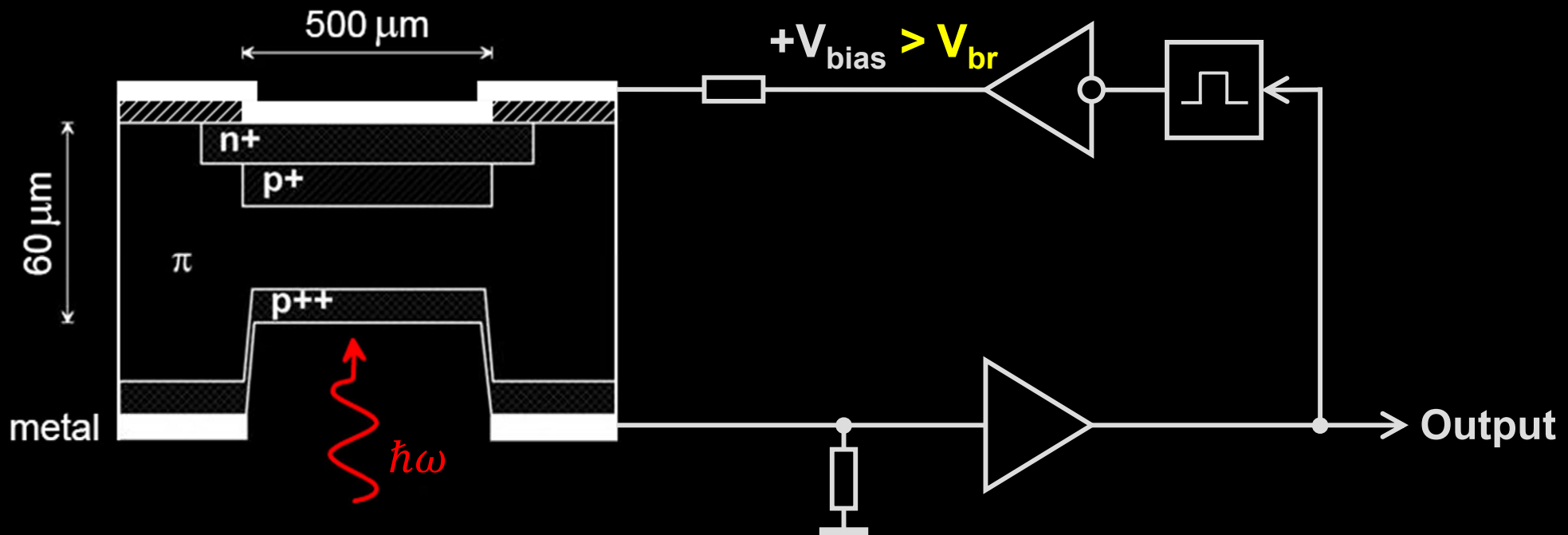
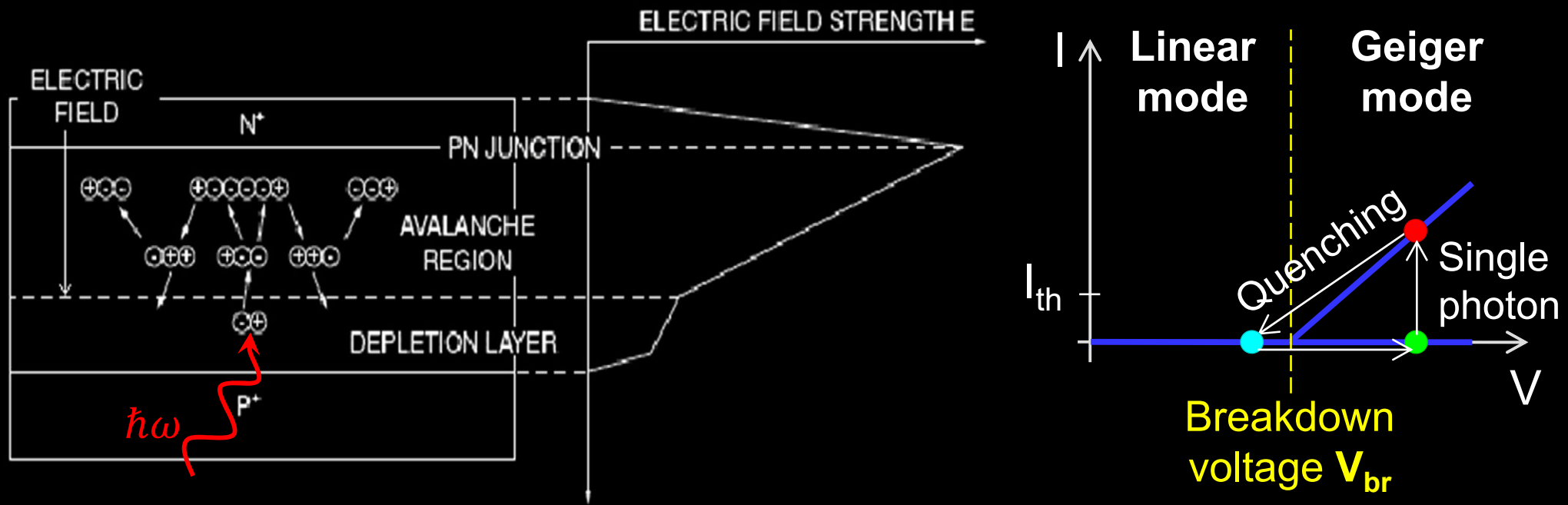


Need a gain mechanism

Photomultiplier tube

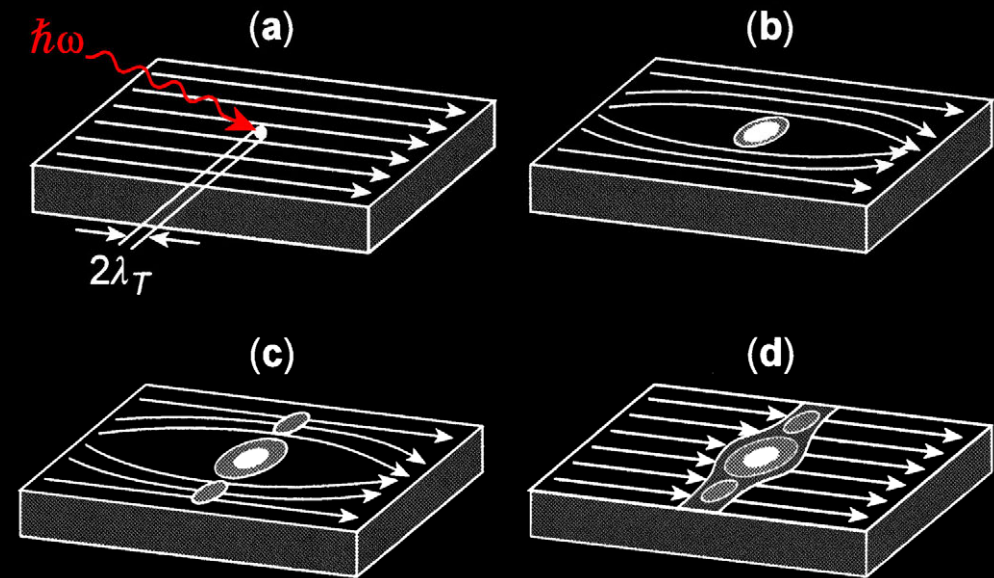
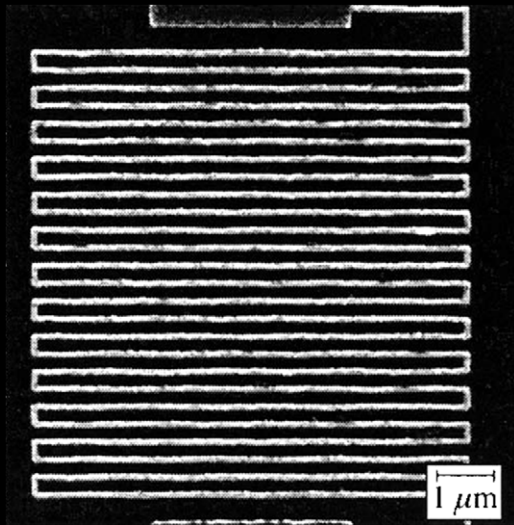


Single-photon avalanche photodiode



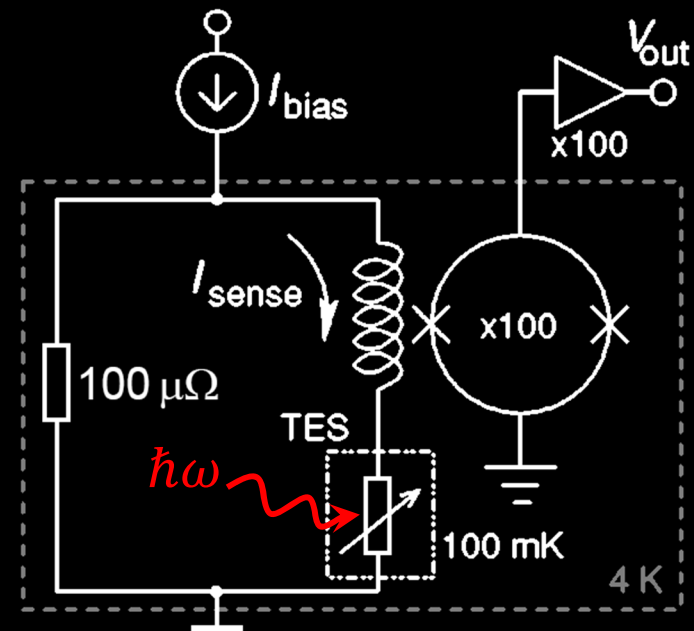
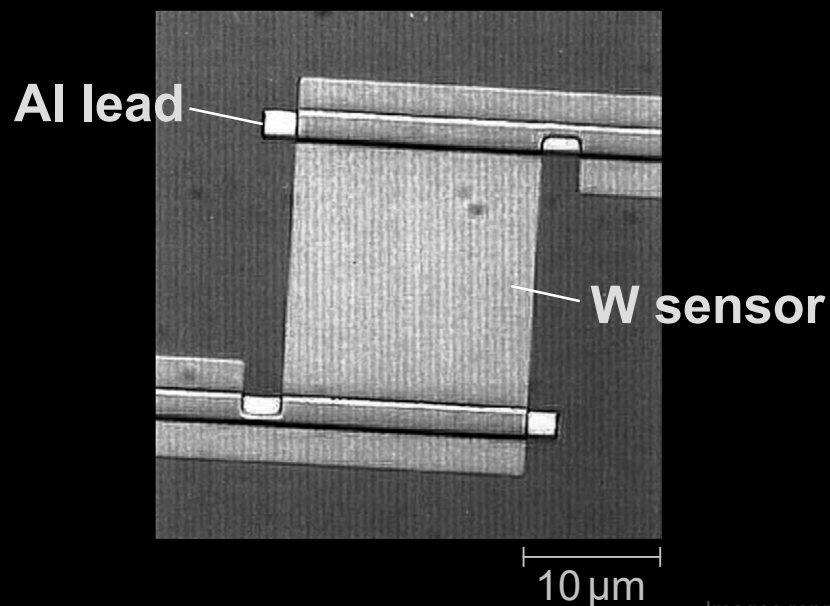
Superconducting single-photon detectors

Superconducting nanowire



Images reprinted from: R. Sobolewski *et al.*, IEEE Trans. Appl. Supercond. 13, 1151 (2003)

Transition-edge sensor

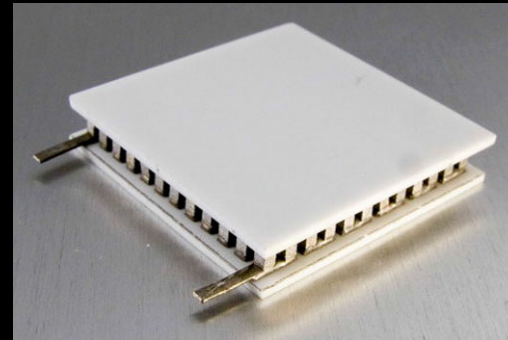


Images reprinted from: B. Cabrera *et al.*, Appl. Phys. Lett. 73, 735 (1998); A.J. Miller *et al.*, Appl. Phys. Lett. 83, 791 (2003)

Cooling requirements

Photomultiplier: room temperature

Avalanche photodiode: $-50\text{ }^{\circ}\text{C}$



Thermoelectric cooling

0 5 mm

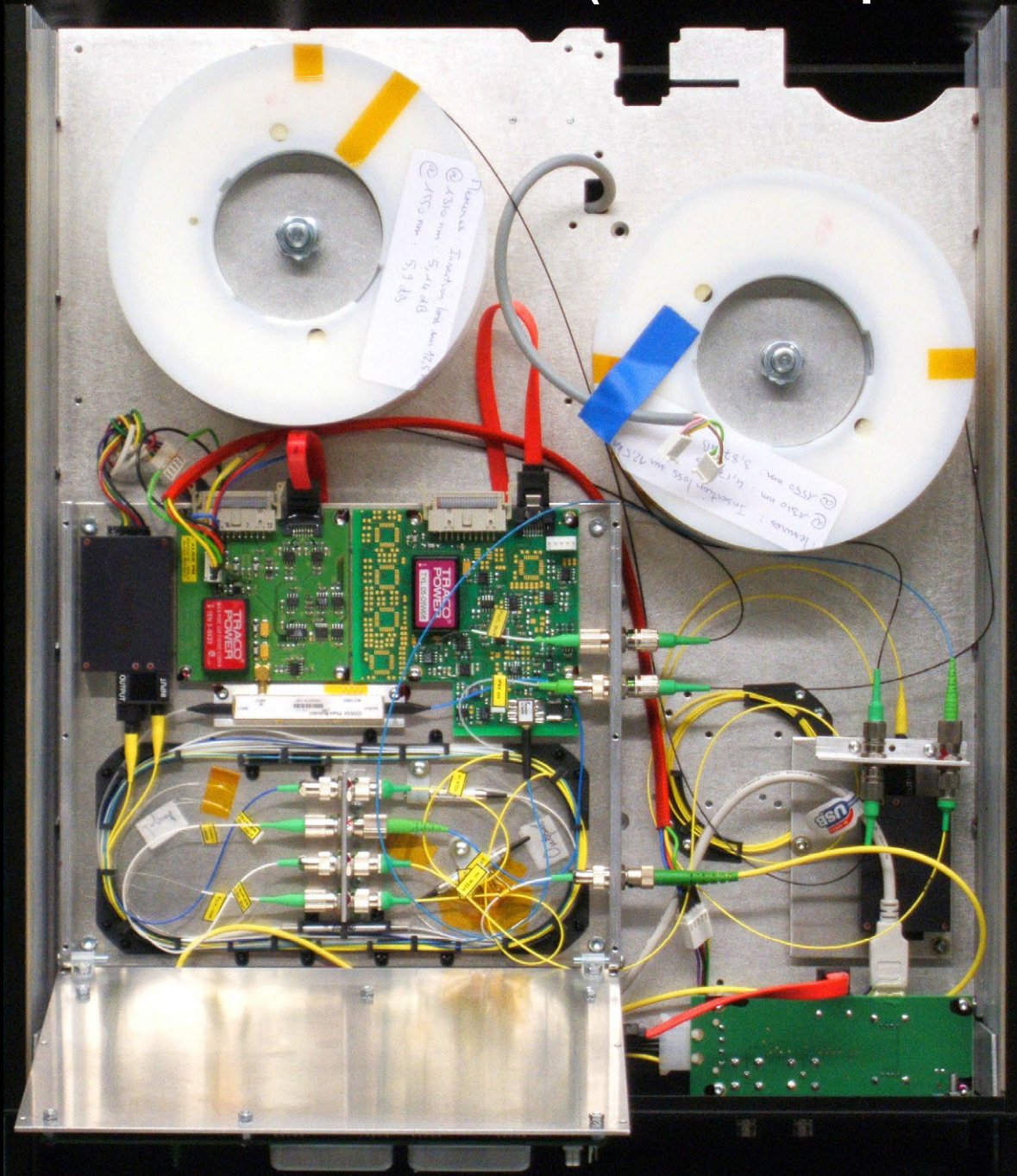
Superconducting nanowire: 4 K

Transition-edge sensor: 100 mK



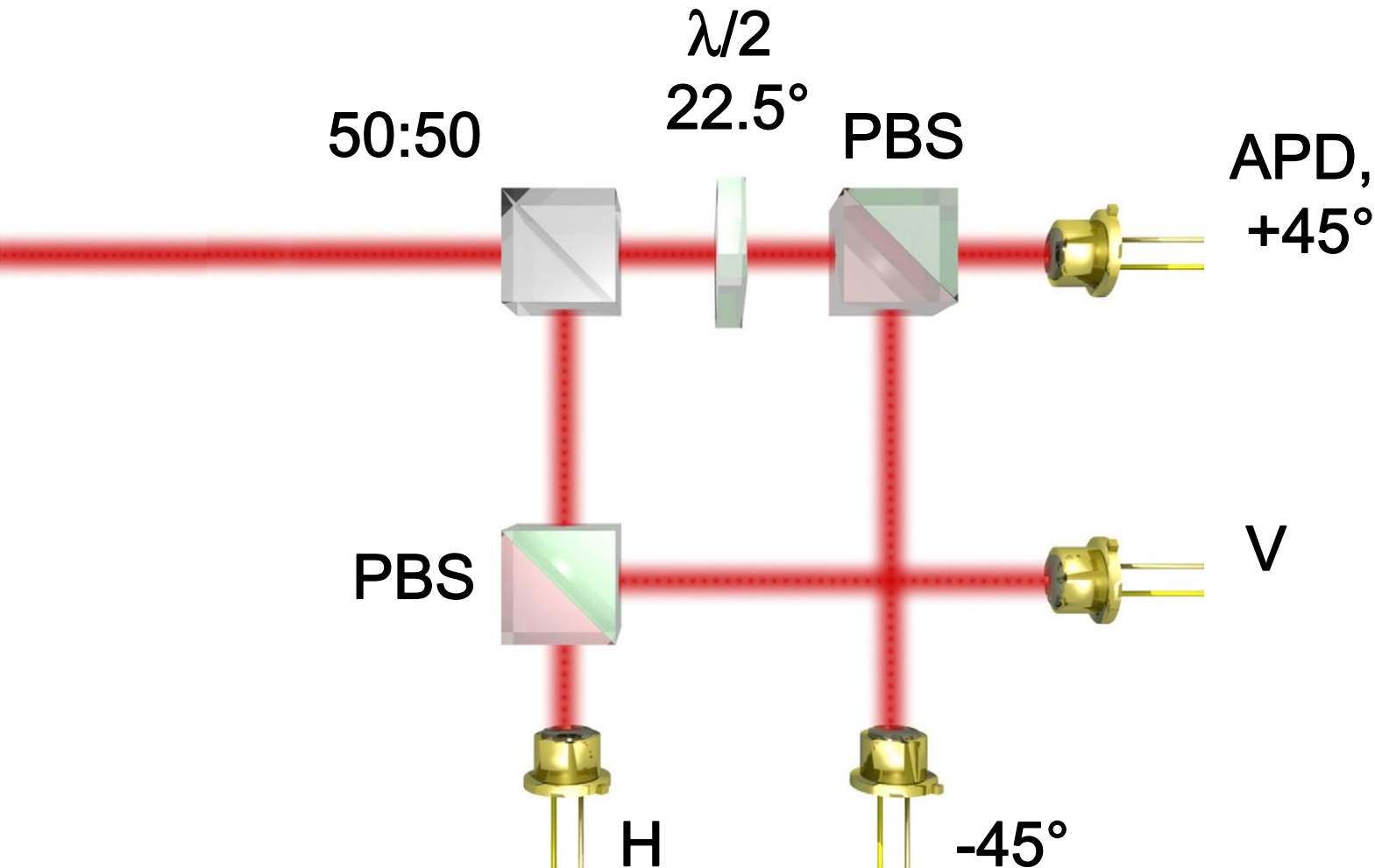
Assembled fiber optics

Quantum key distribution unit Alice (ID Quantique Clavis2)



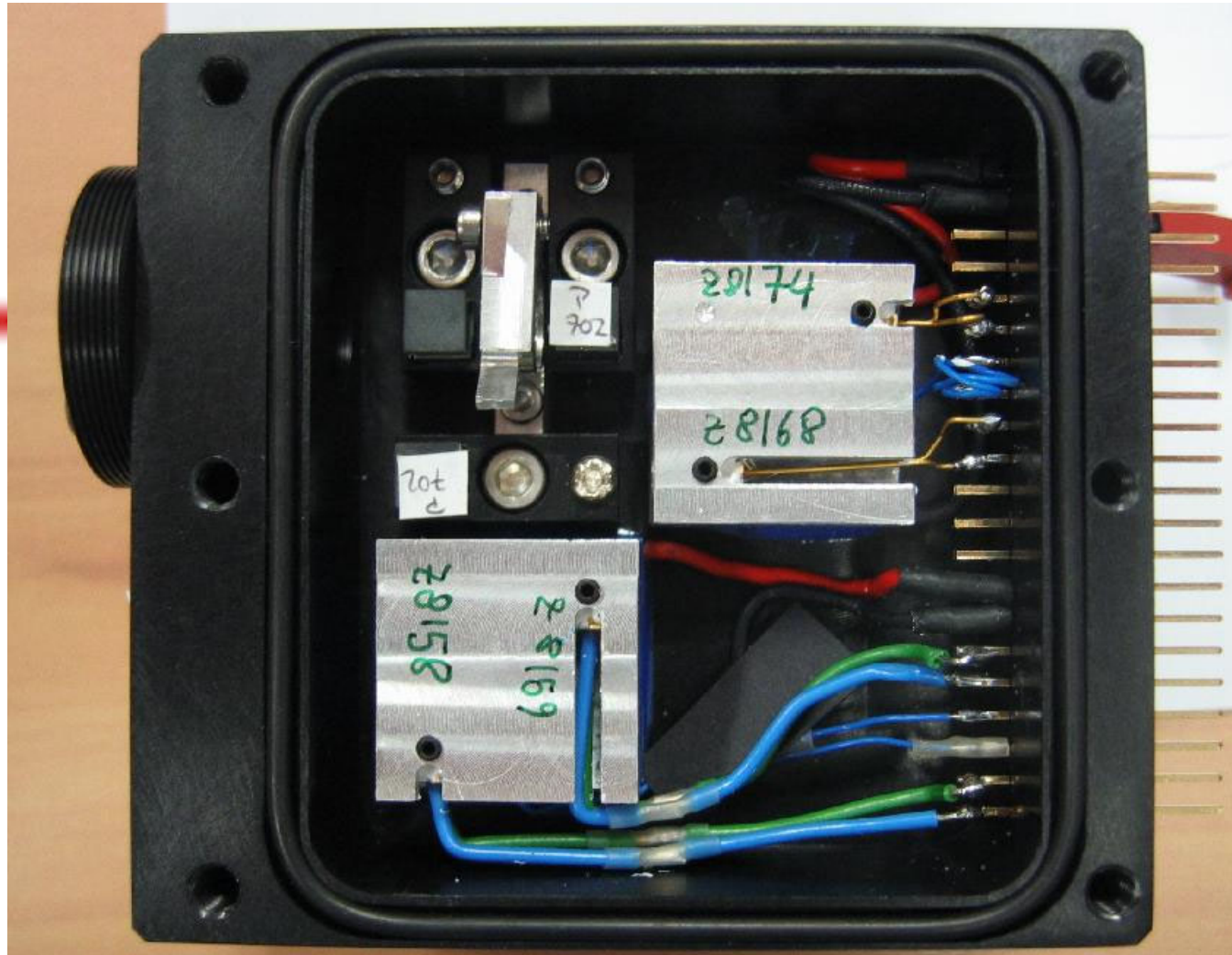
Assembled free-space optics

Bob's polarization analyzer with single-photon detectors



Assembled free-space optics

Bob's polarization analyzer with single-photon detectors



Emerging: integrated optics

Quantum key distribution system

