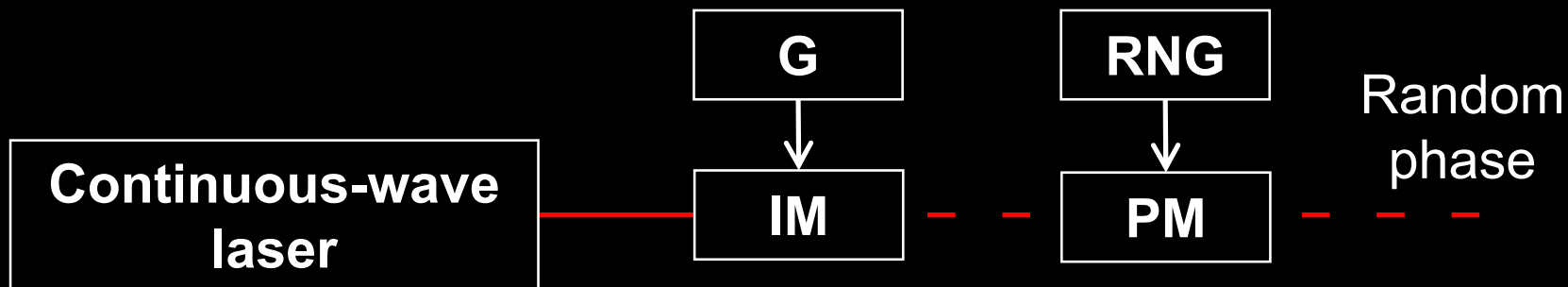
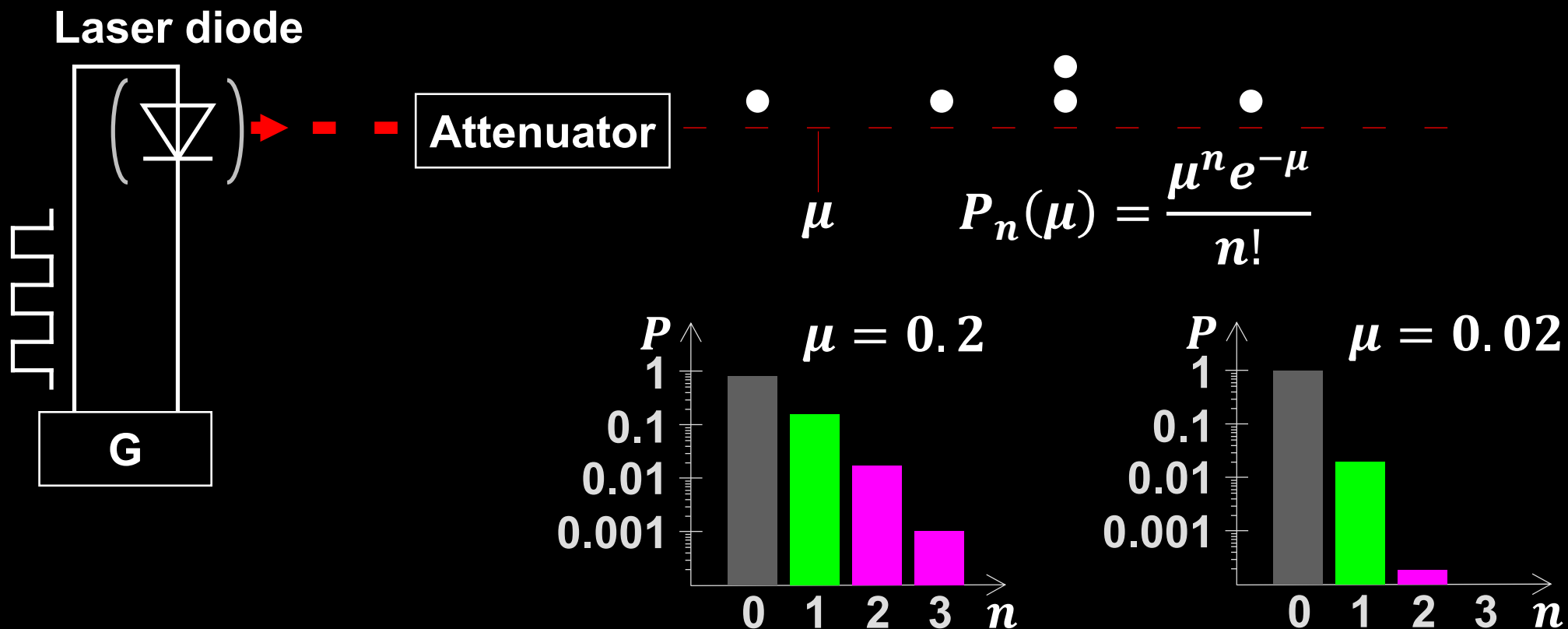


Components of quantum-optical systems

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

Attenuated laser source



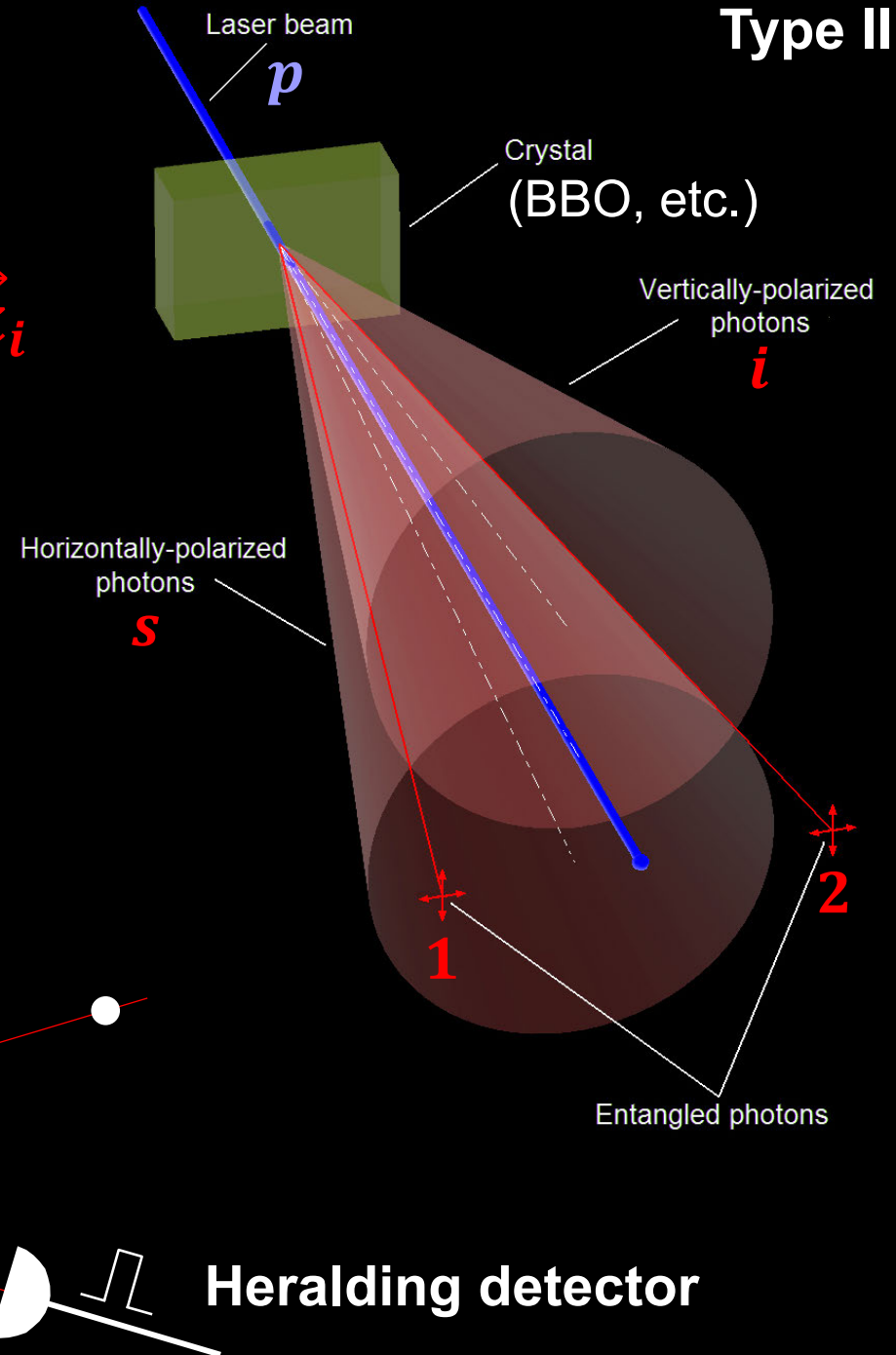
Spontaneous parametric down-conversion

Type II

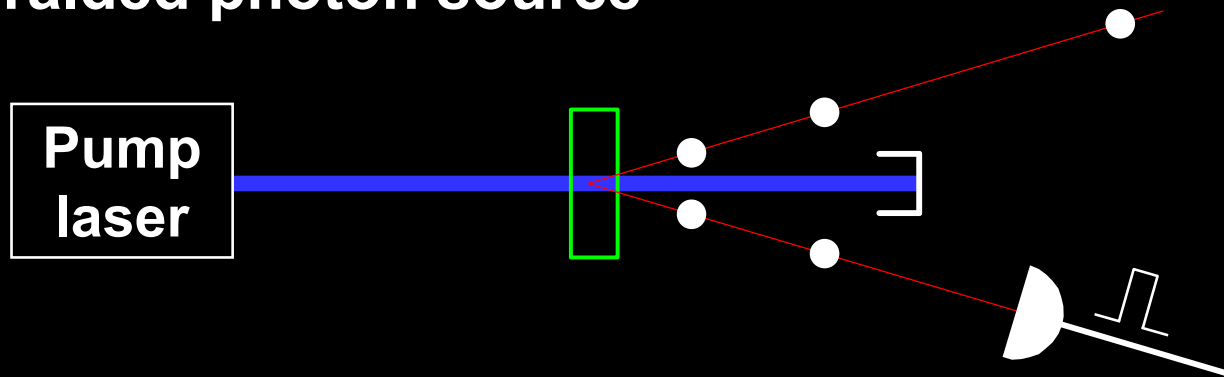
Energy conservation: $\omega_p = \omega_s + \omega_i$

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

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

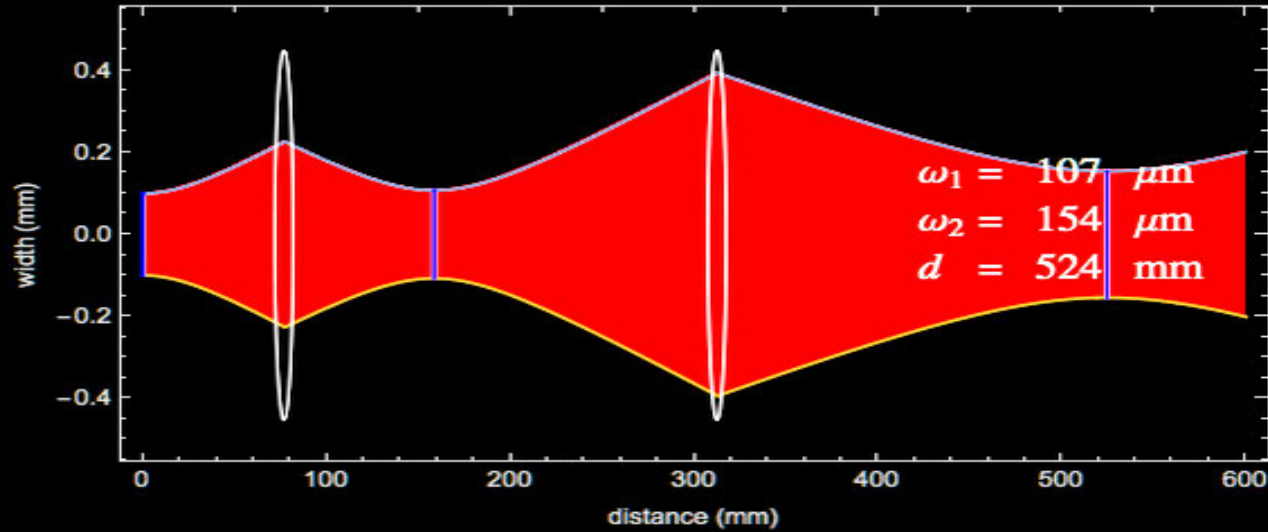


Heralded photon source

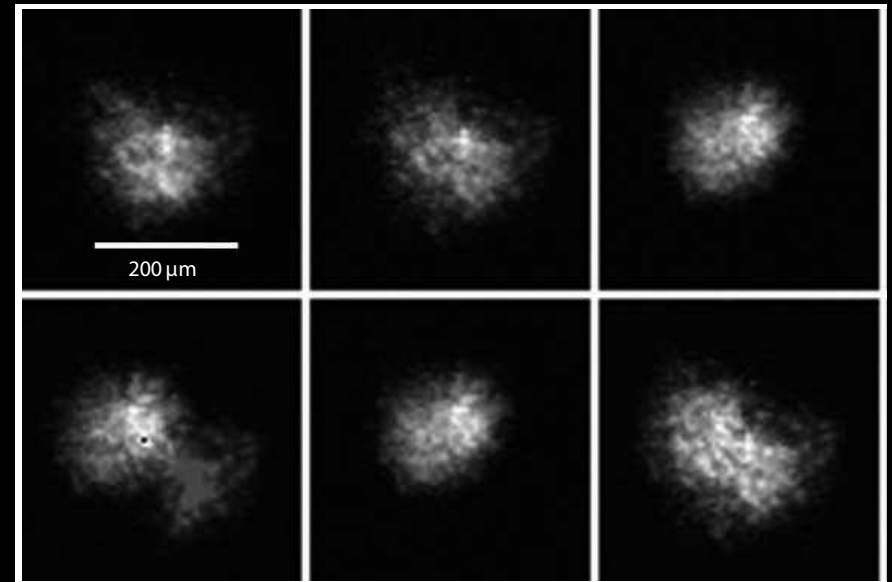
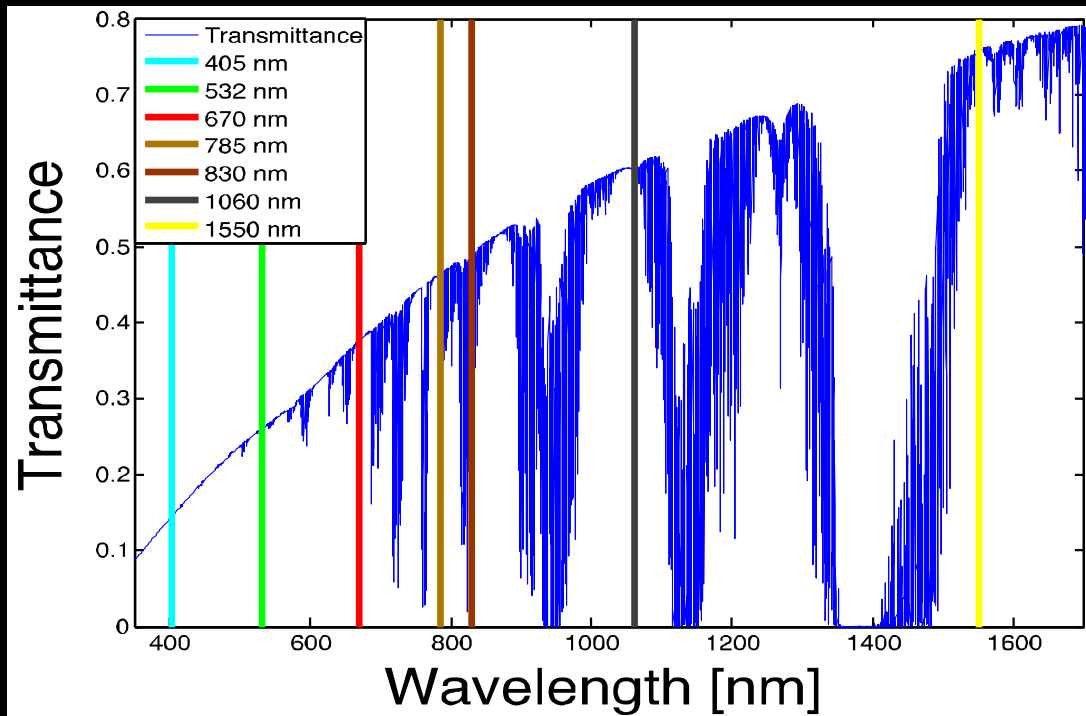


Transmission in free space

Vacuum:
Gaussian optics



Atmosphere: loss, turbulence

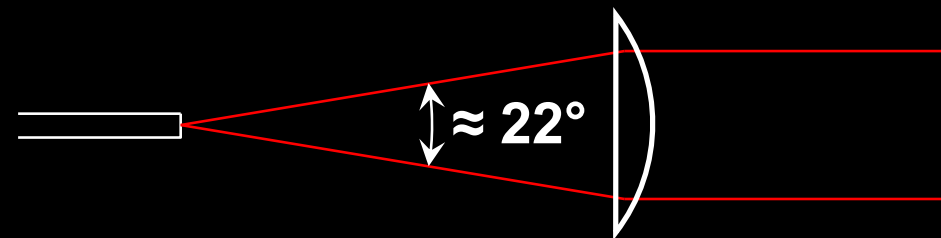
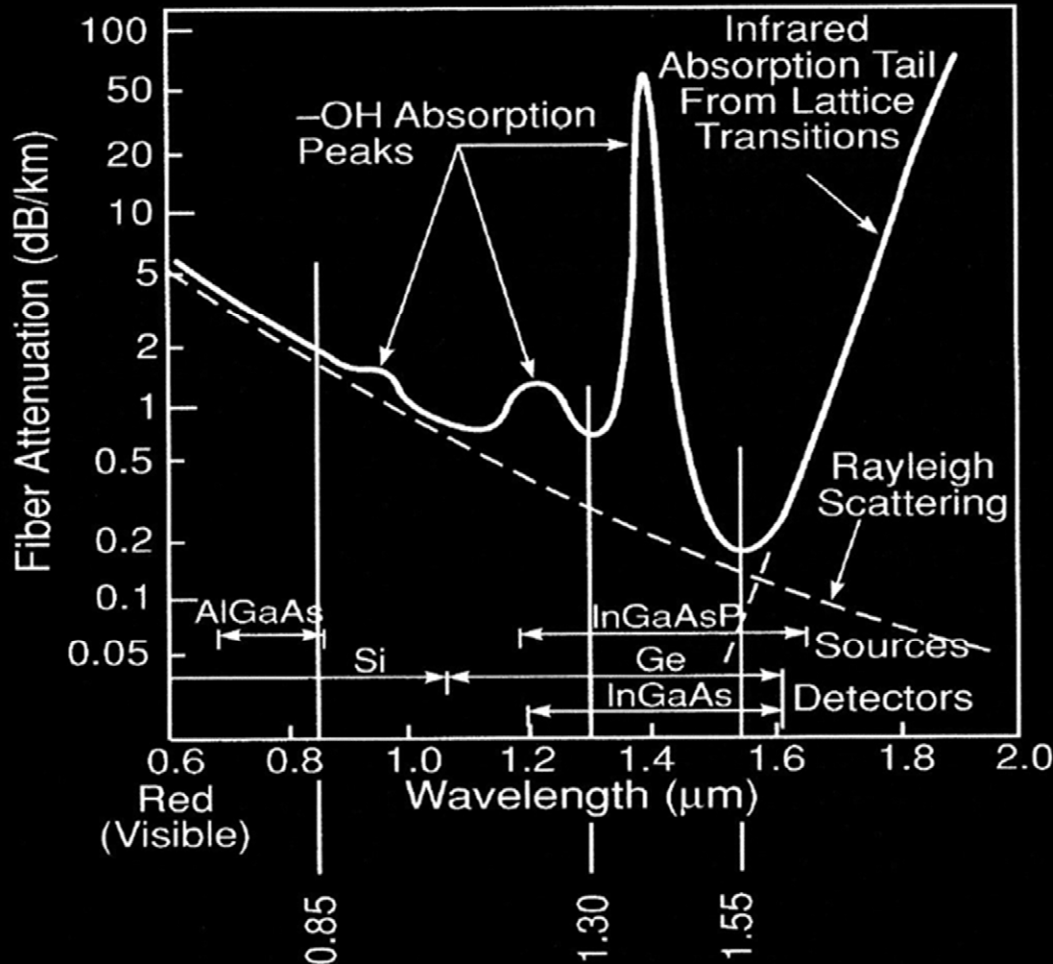
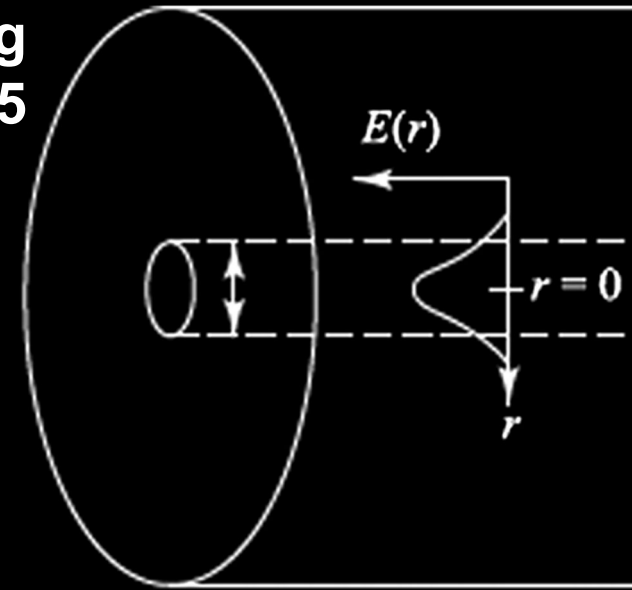


Transmission in optical fiber

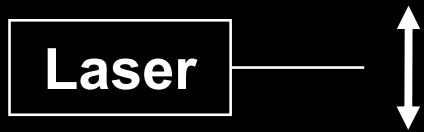
Single-mode fiber

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

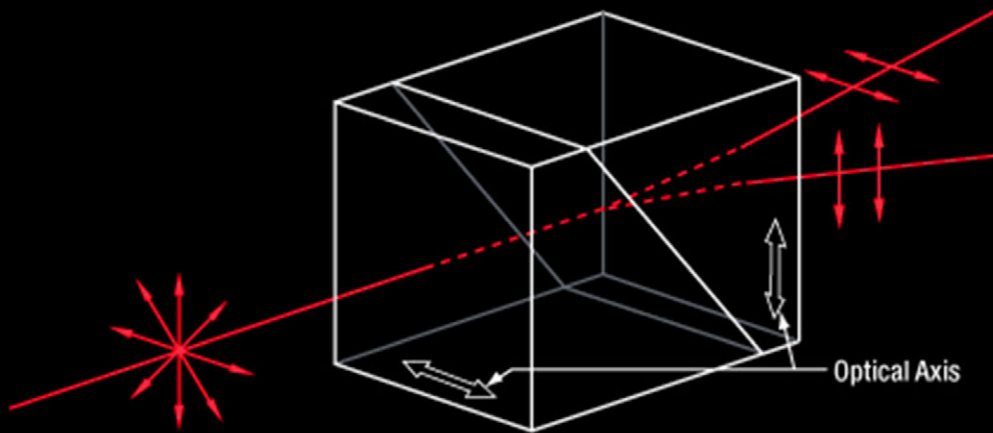
8 μm diameter core
 $n_2 > n_1$



Polarizers

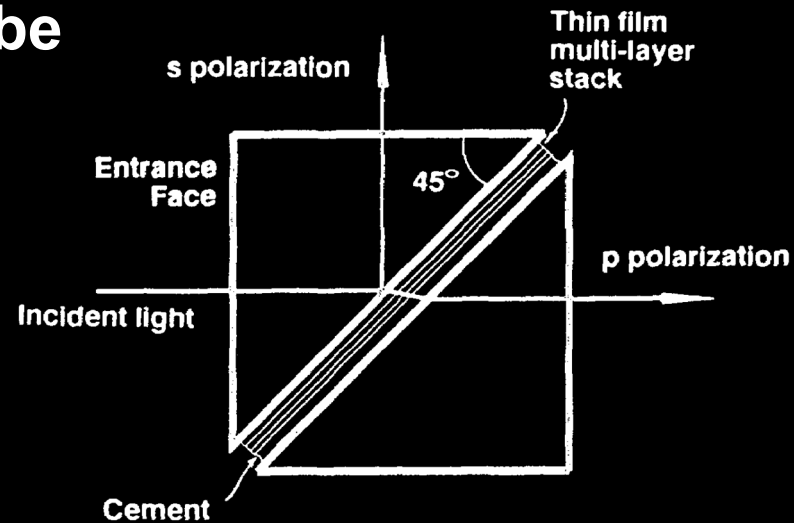
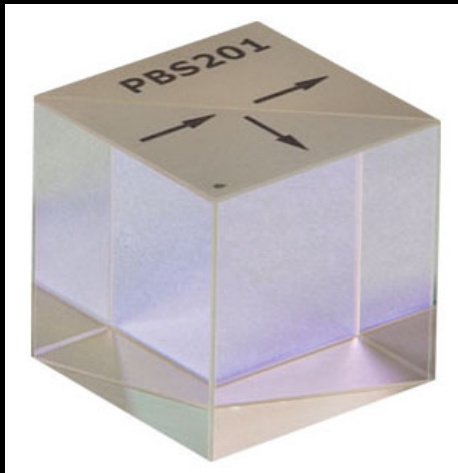


Birefringent polarizing beamsplitter



Wollaston prism

Polarizing beamsplitter cube



Beamsplitters

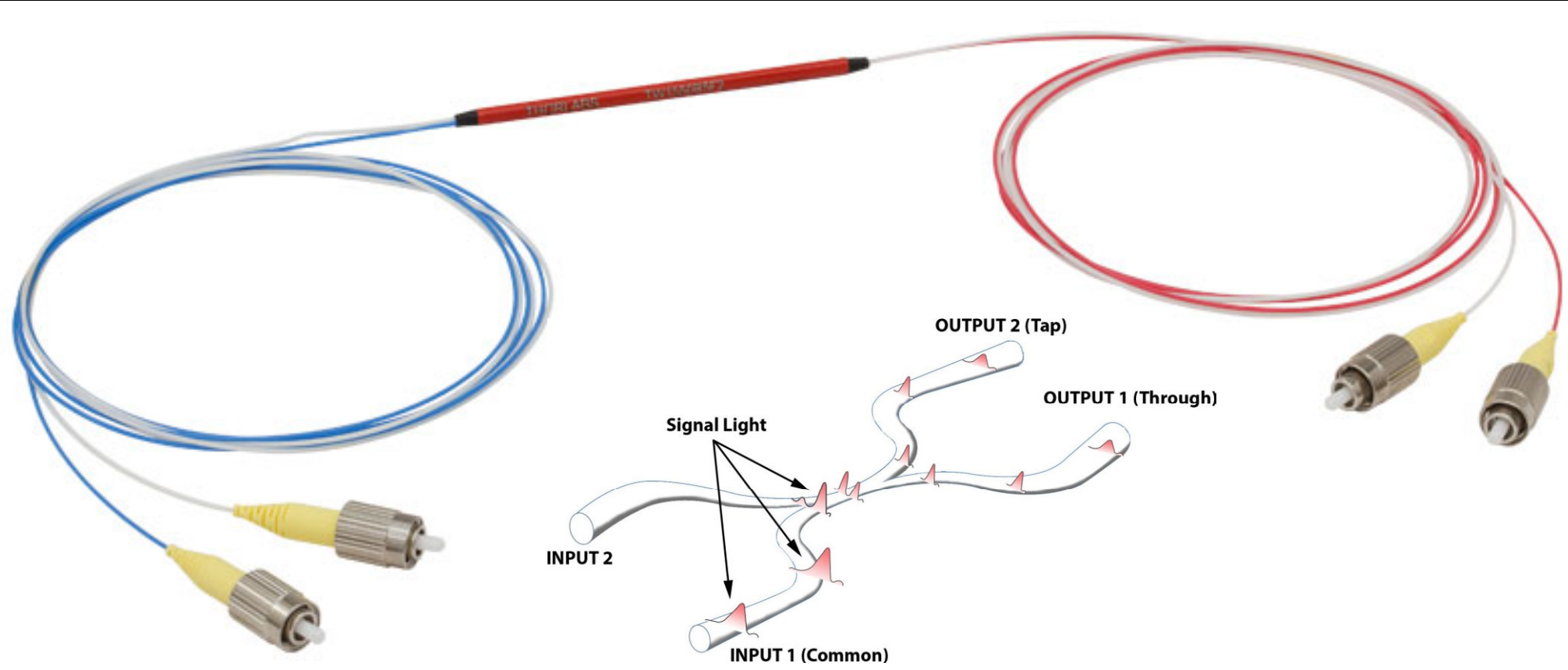


50:50

10:90

1:99

Fiber-optic fused beamsplitter (or coupler)

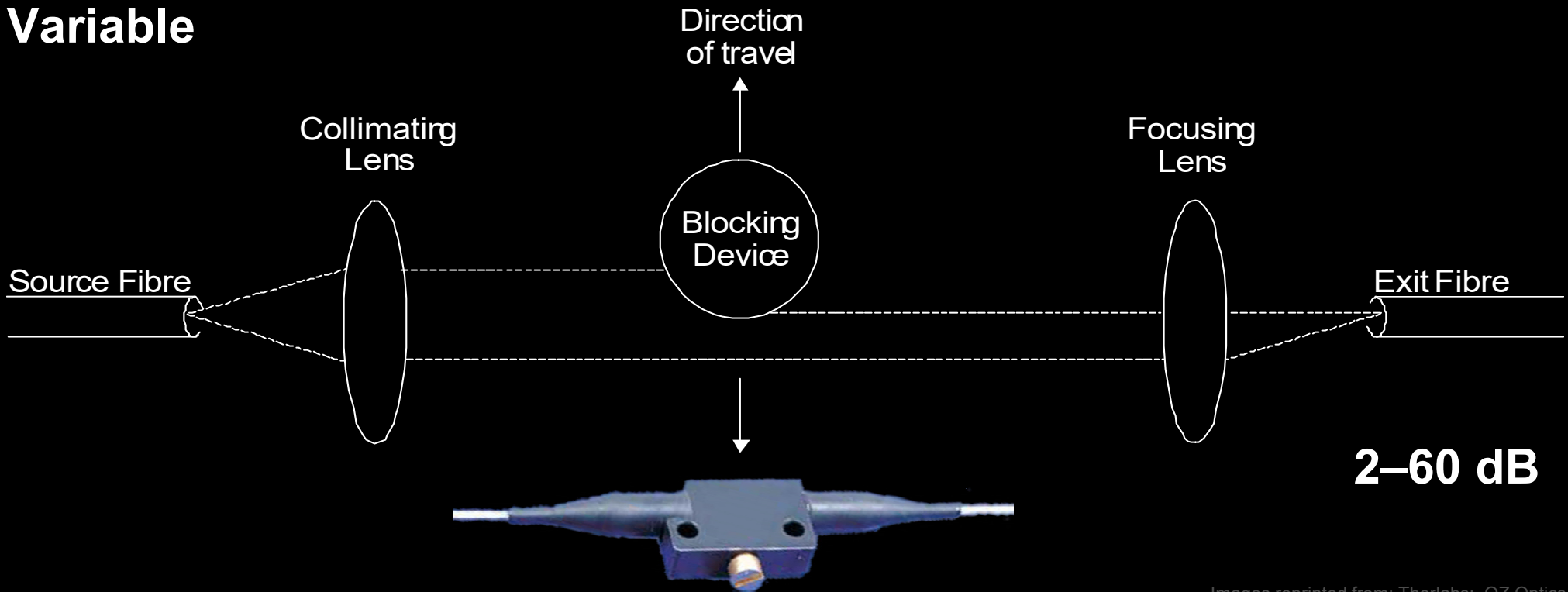


Attenuators

Absorbing or partially reflecting coated glass

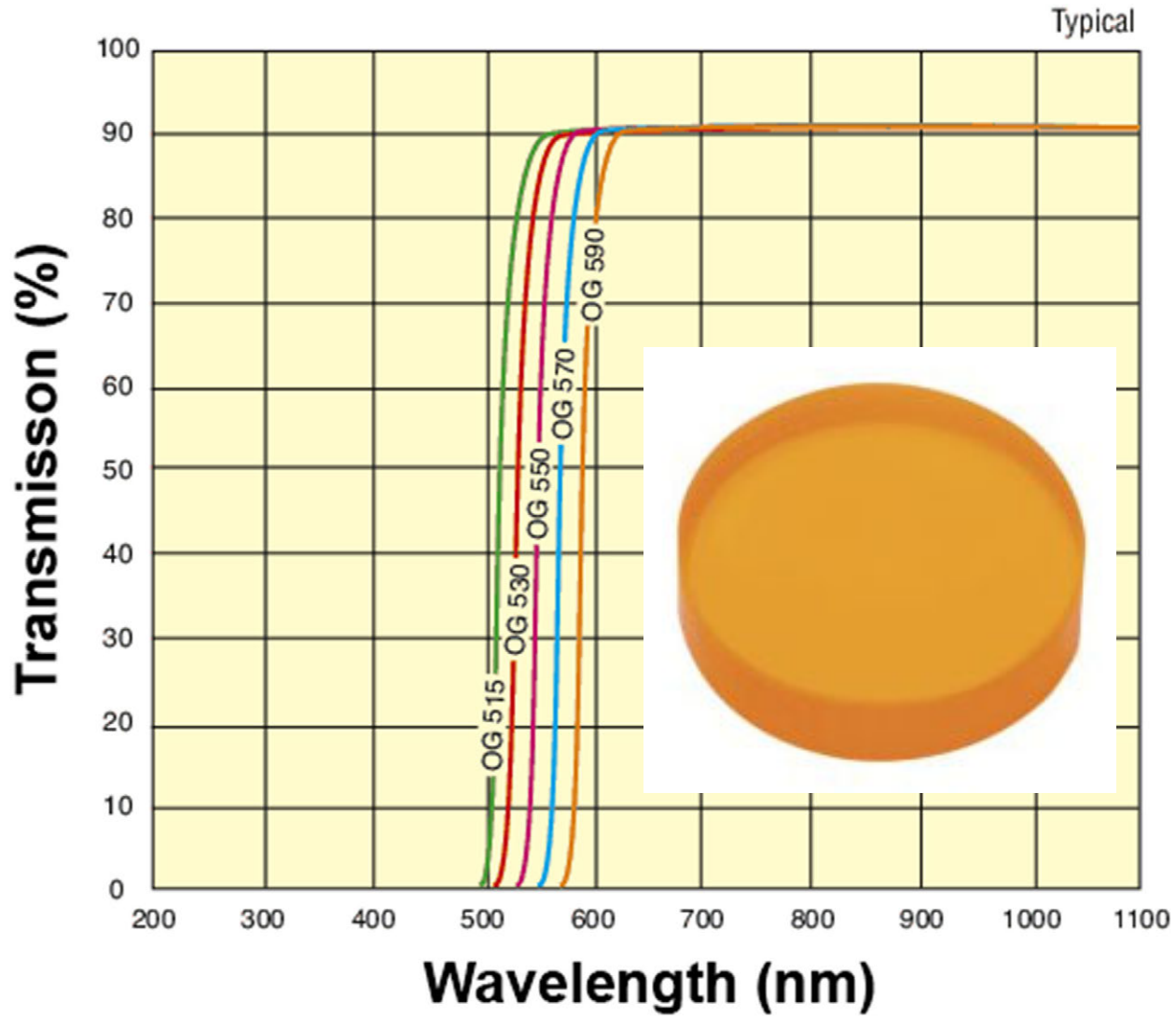


Variable



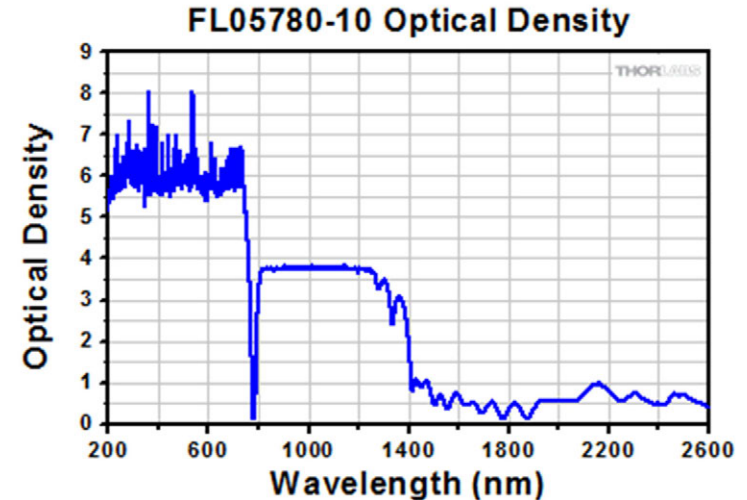
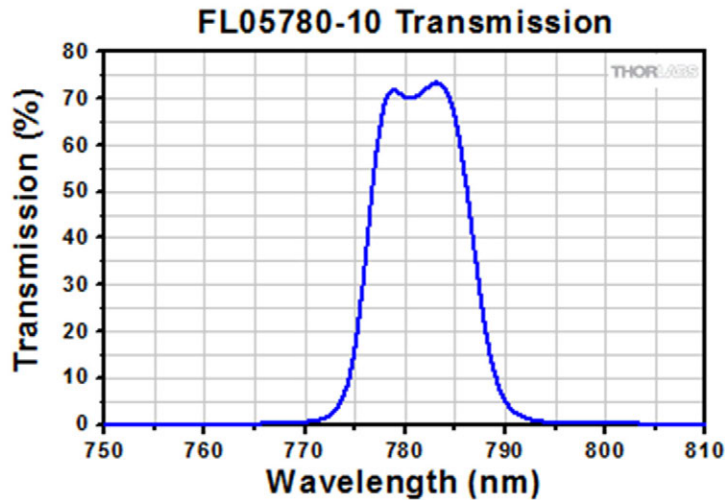
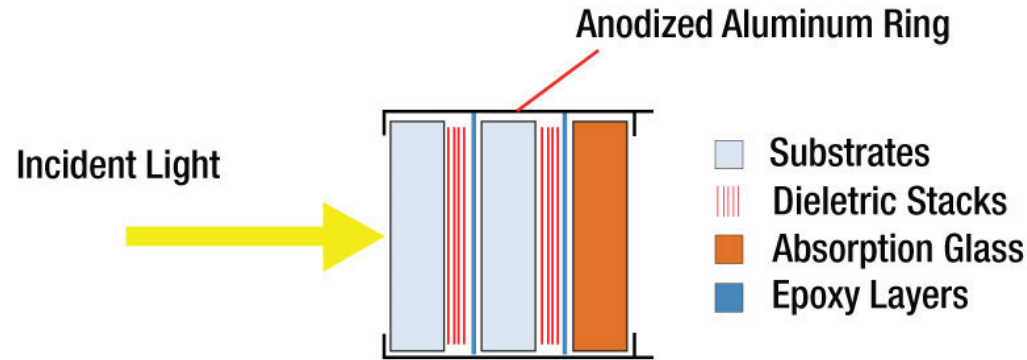
Wavelength filters

Colored glass

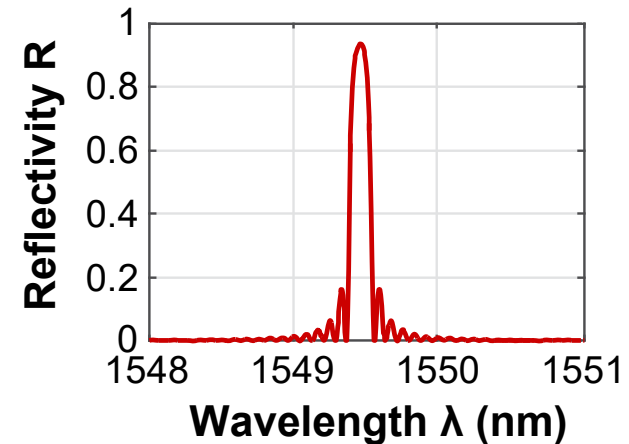
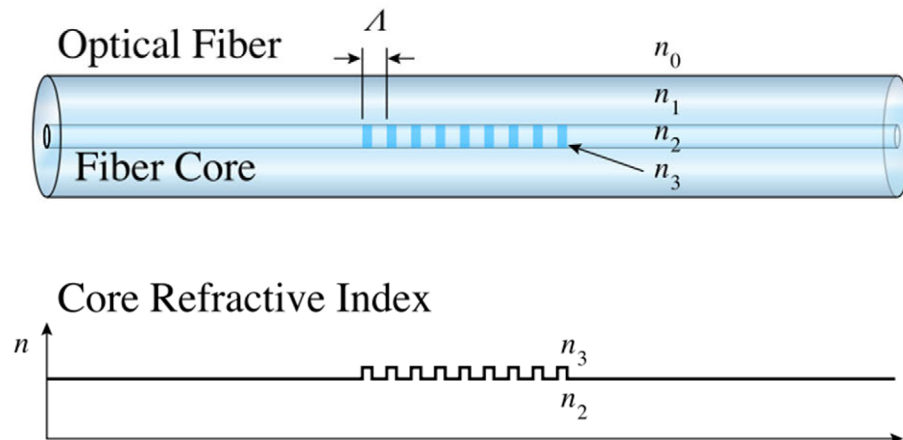


Wavelength filters

Interference filter



Fiber Bragg grating



Polarization controller (slow)

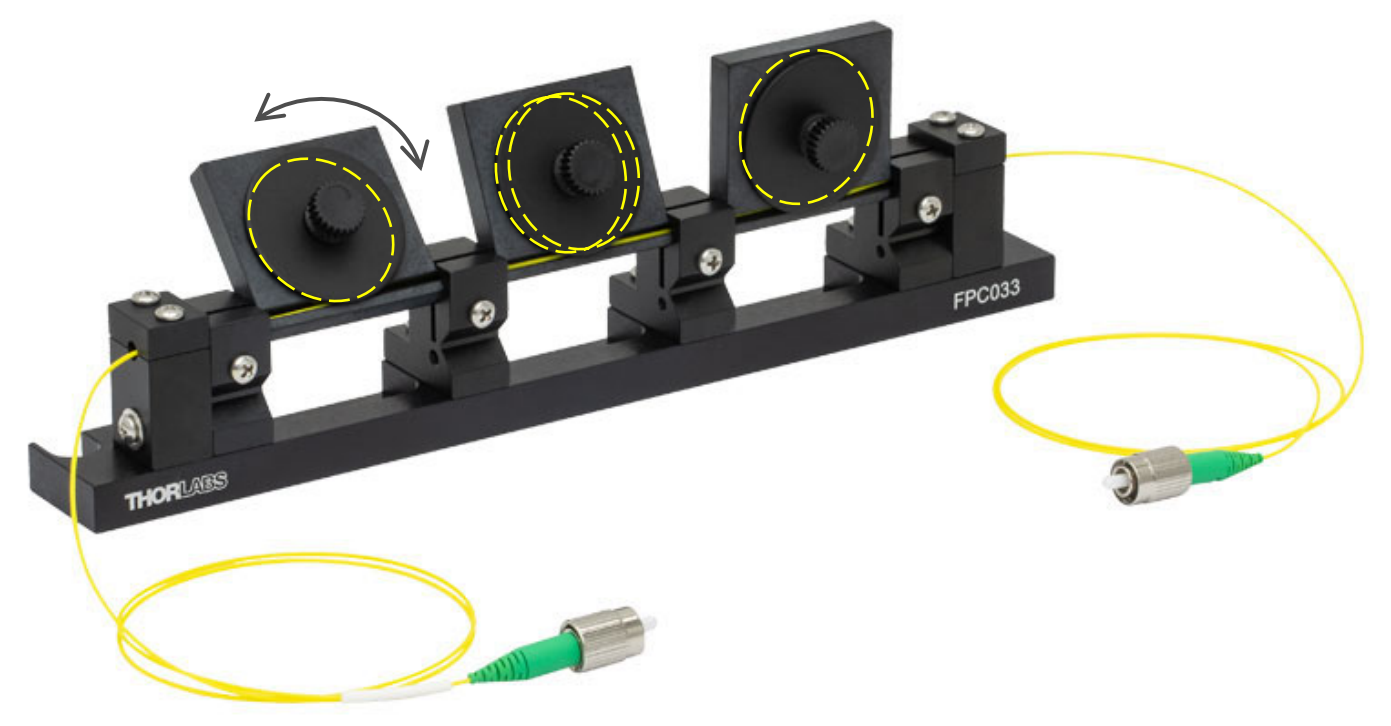
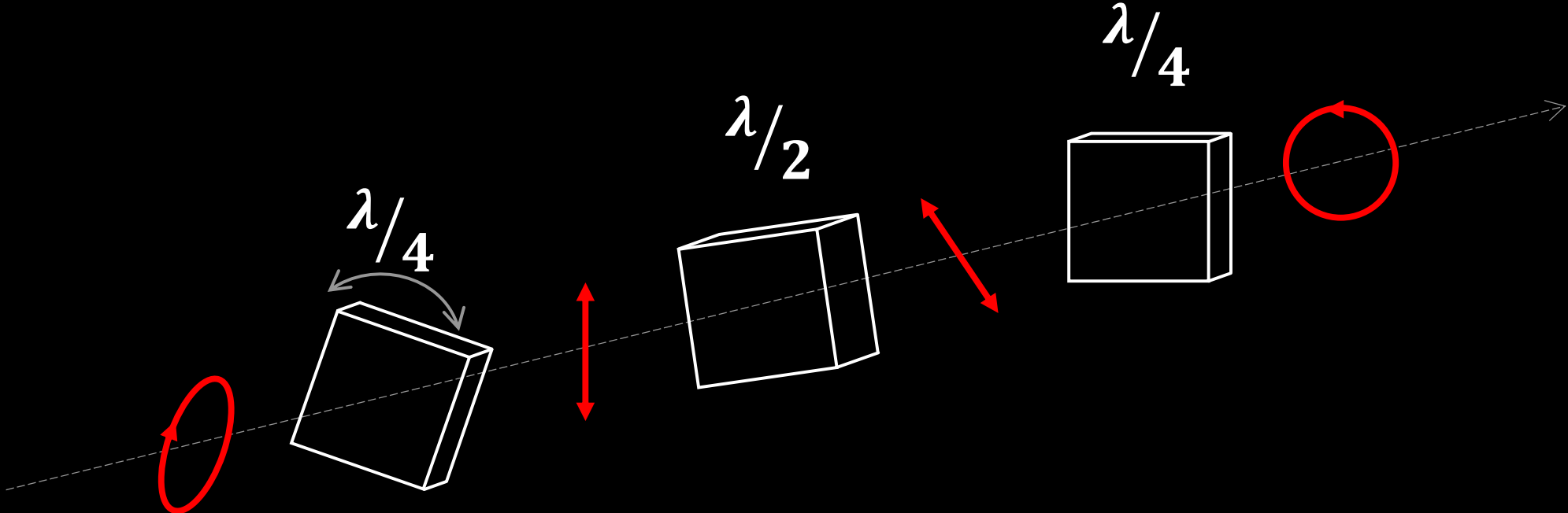
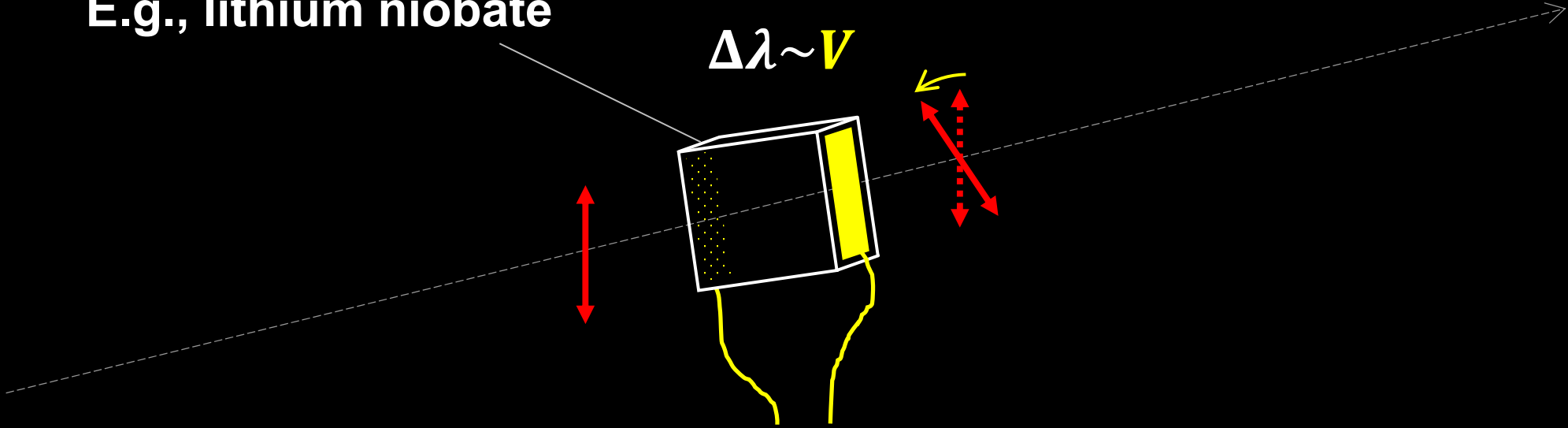


Image reprinted from: Thorlabs

Polarization modulator (fast)

E.g., lithium niobate

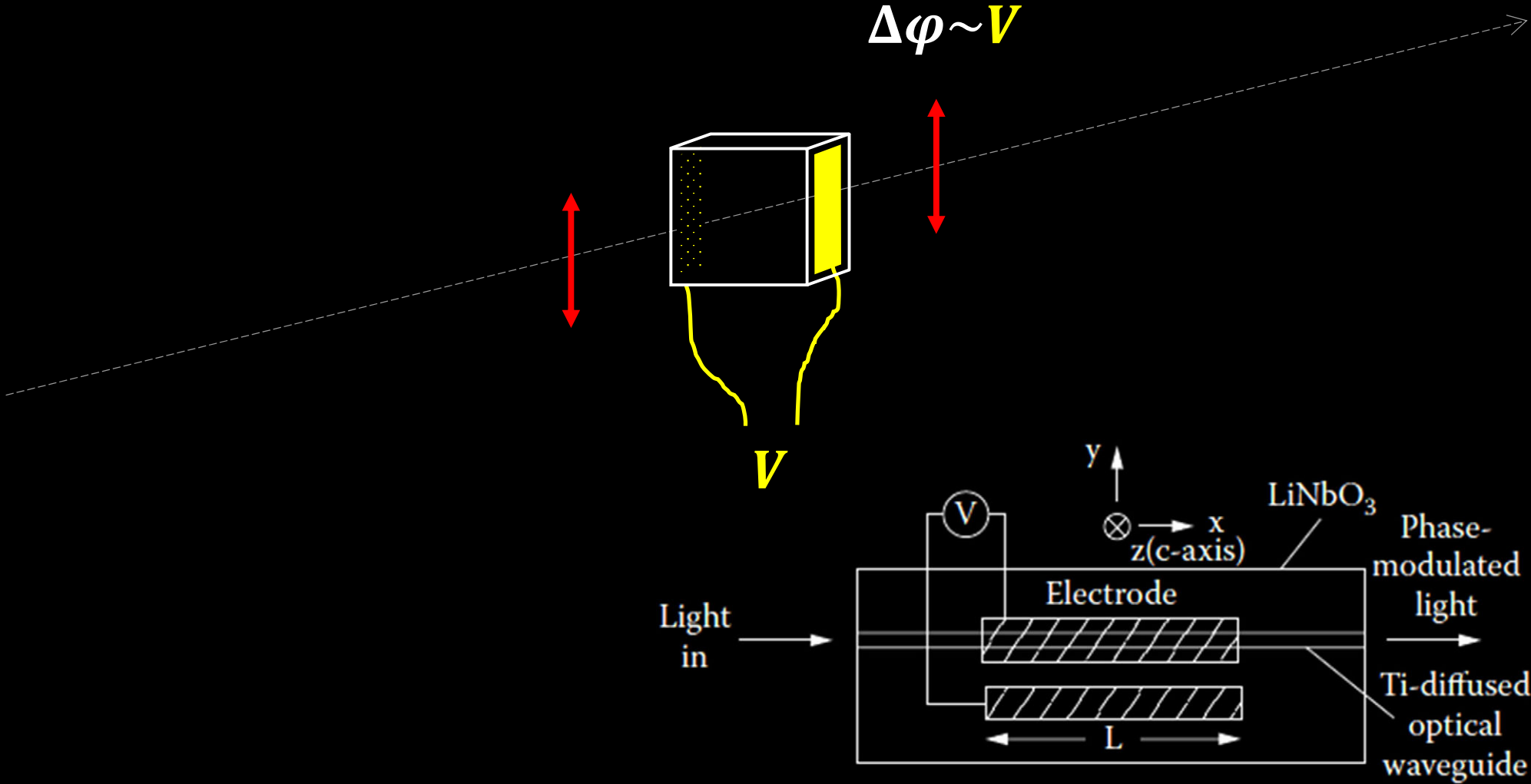


$$\Delta\lambda \sim V$$

0 or V_{π}

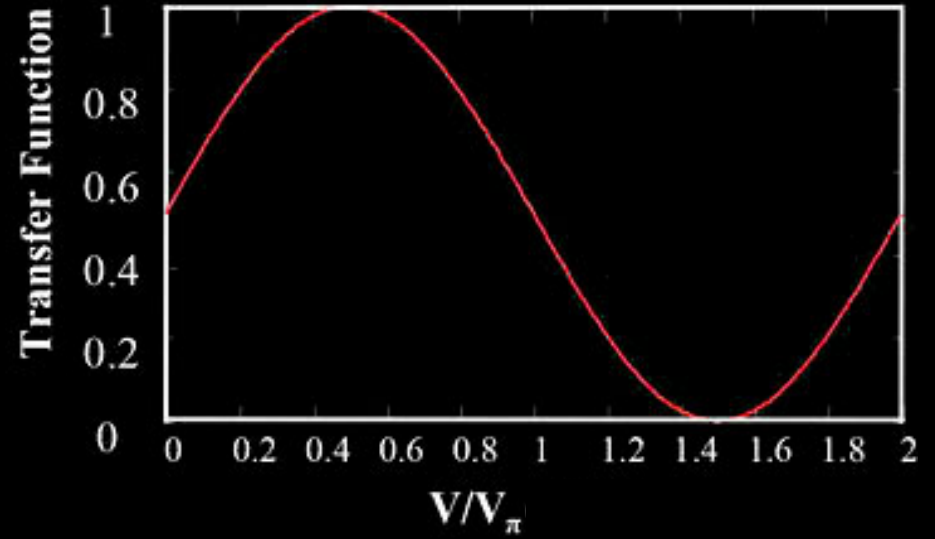
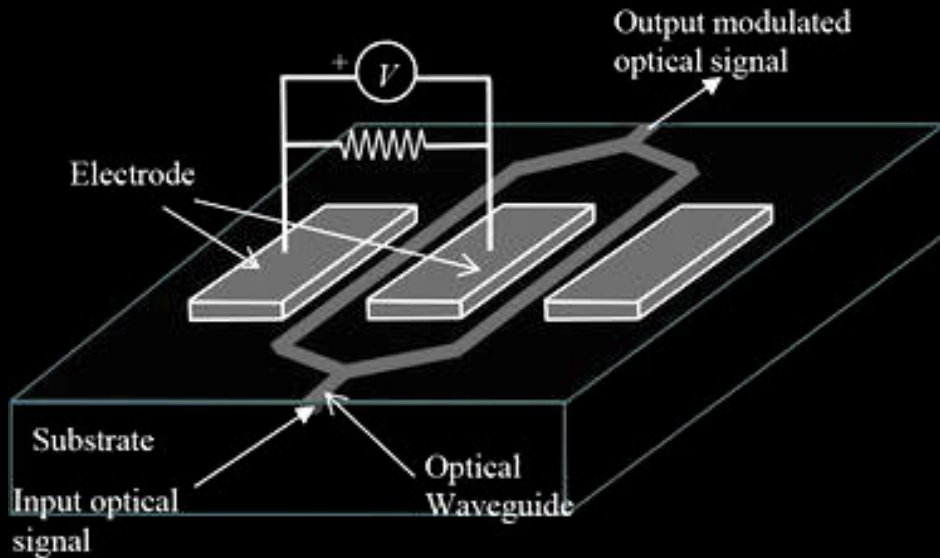
Pockels cell

Phase modulator



Images reprinted from: A. E.-N. A. Mohamed *et al.*, Int. J. Multidiscip. Sci. Eng. 2, 13 (2011); ixblue Photonics

Intensity modulator

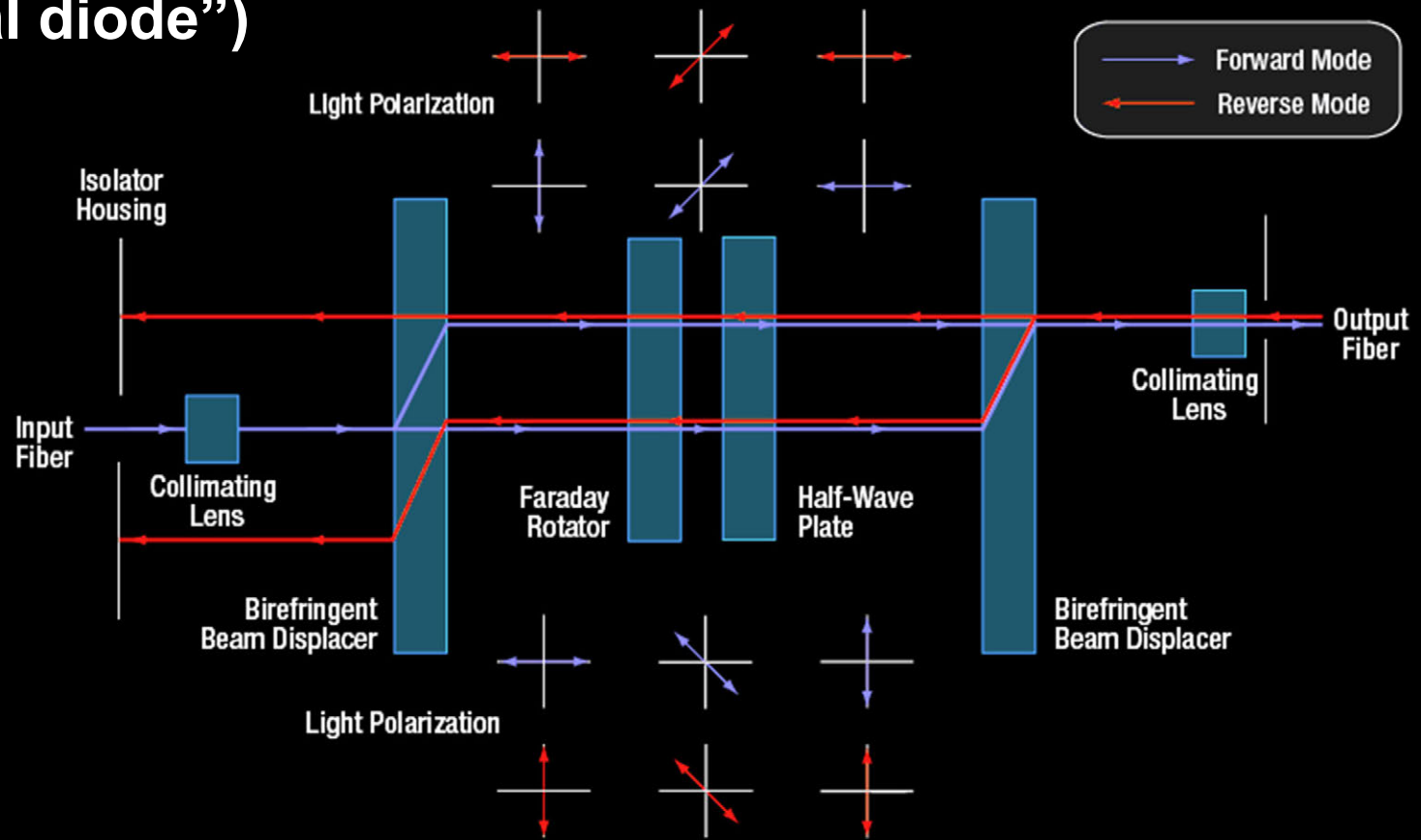
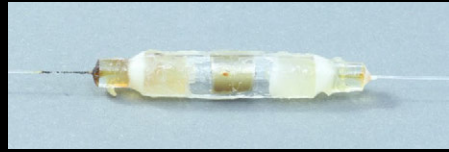
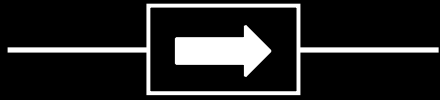


Mach-Zehnder interferometer

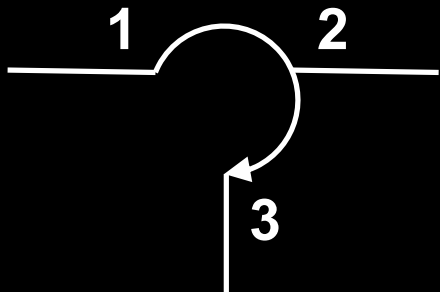


Directional elements

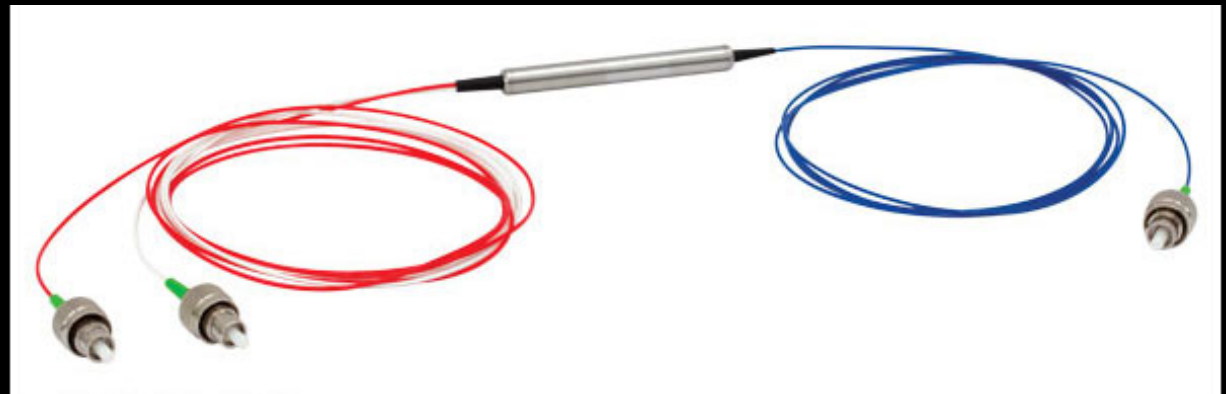
Isolator (an "optical diode")



Circulator



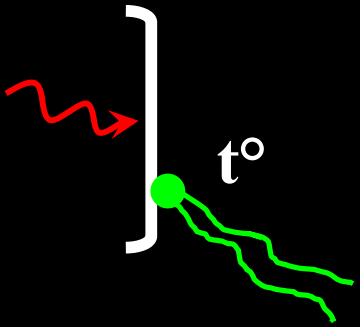
1 → 2
2 → 3



Optical power meters

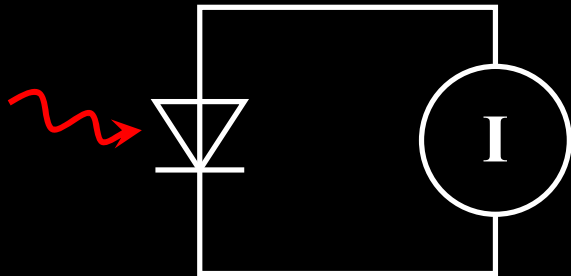
Thermal

$> 10 \mu\text{W}$



Photodiode

$> 0.1 \text{ nW}$



Single-photon detectors

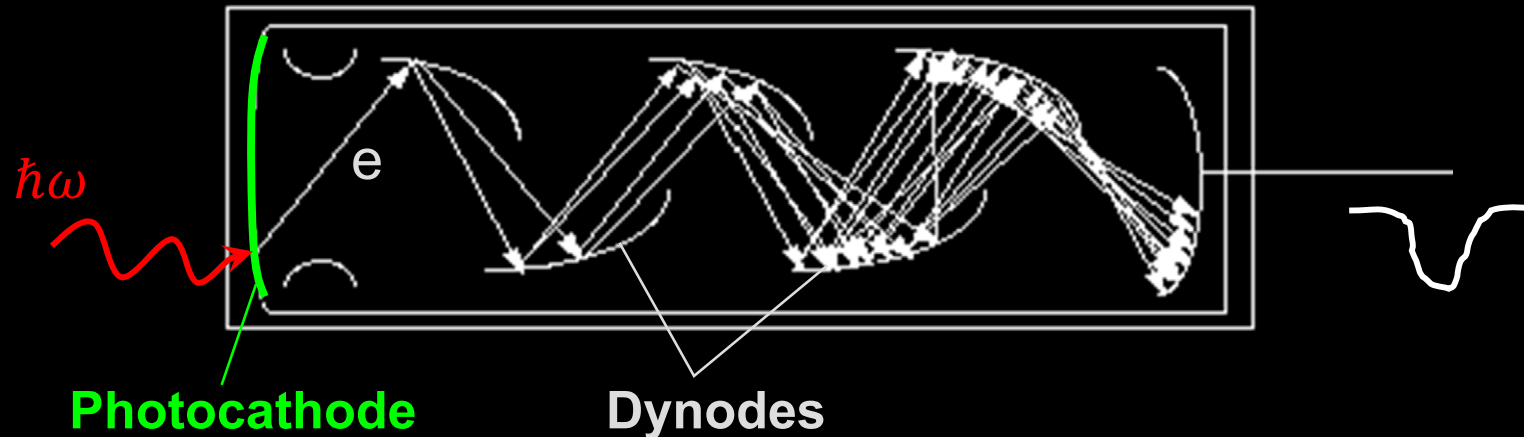
Photon energy

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

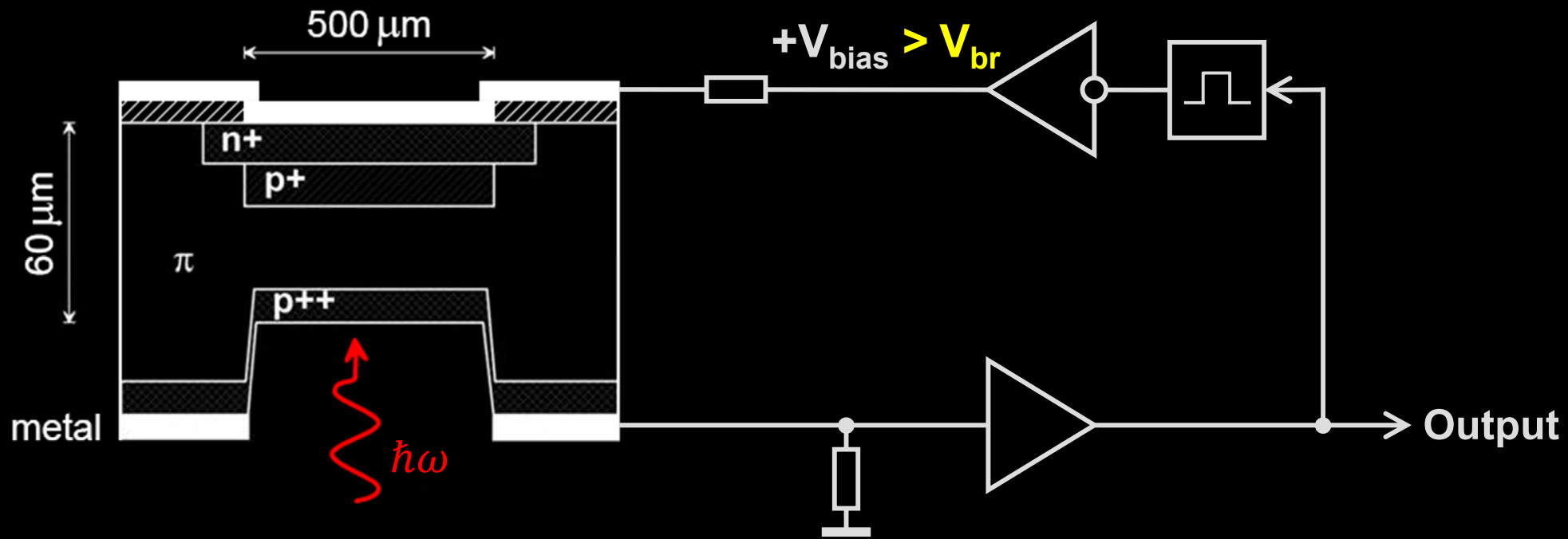
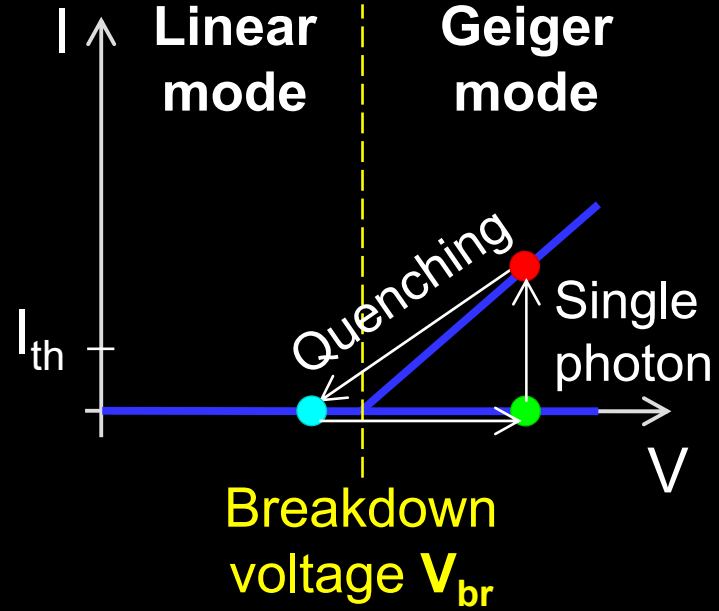
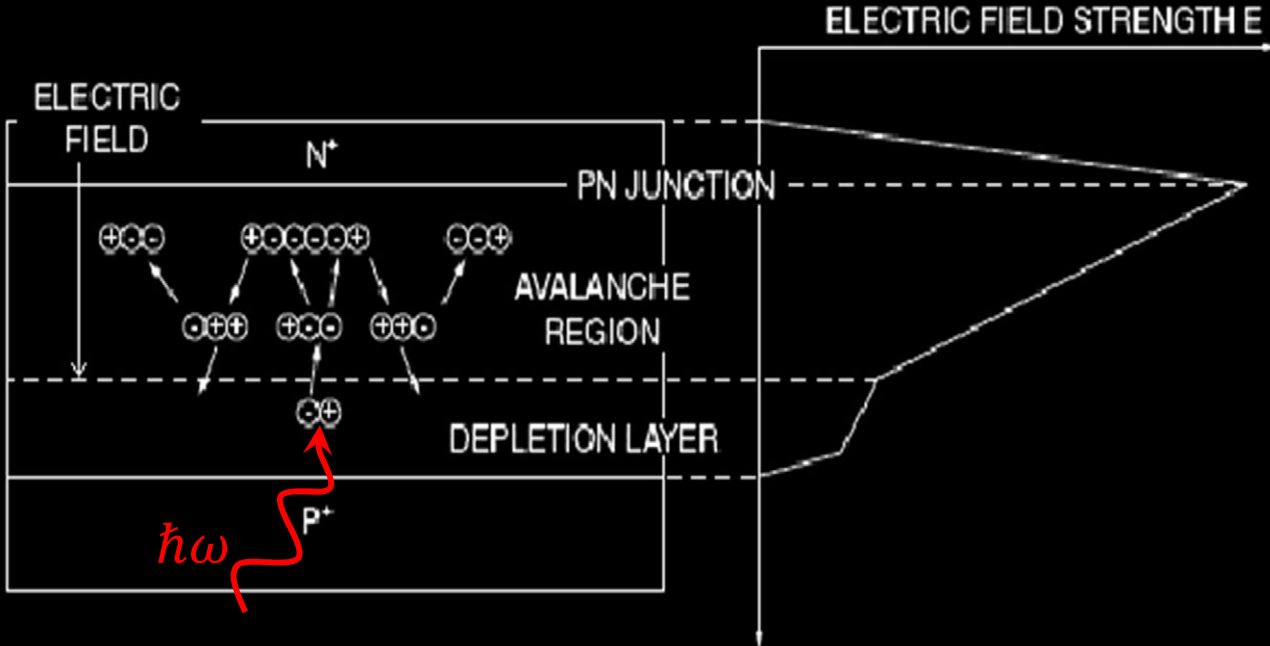


Need a gain mechanism

Photomultiplier tube



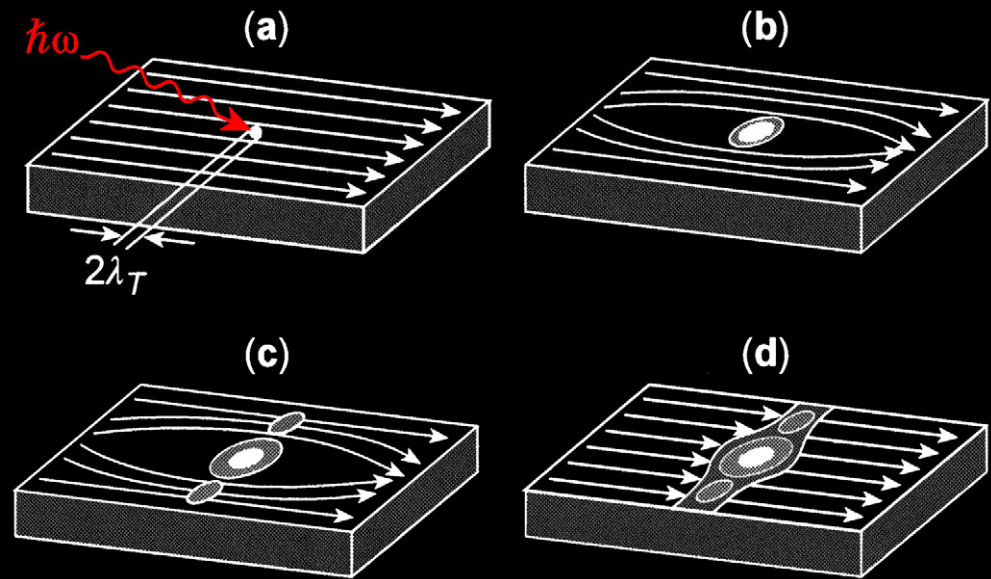
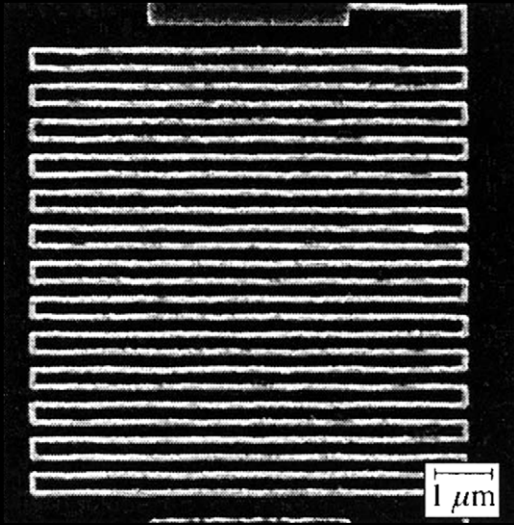
Single-photon avalanche photodiode



Images reprinted from: <https://www.photonicsonline.com/doc/avalanche-photodiodes-theory-and-applications-0001>; S. Cova *et al.*, J. Mod. Opt. 51, 1267 (2004)

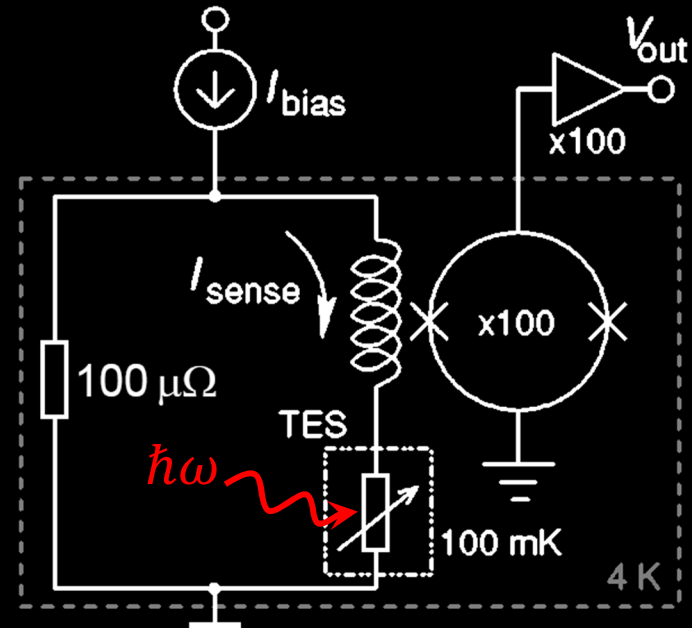
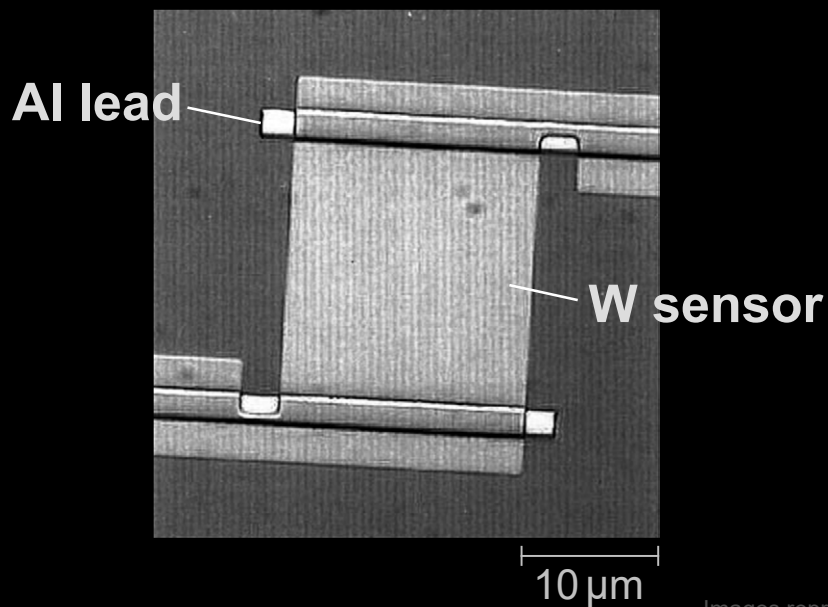
Superconducting single-photon detectors

Superconducting nanowire



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

Transition-edge sensor

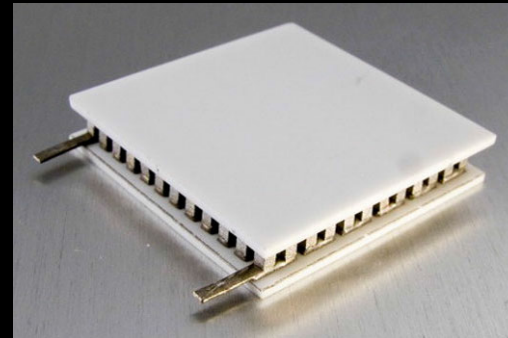


Images reprinted from: B. Cabrera *et al.*, Appl. Phys. Lett. 73, 735 (1998); A.J. Miller *et al.*, Appl. Phys. Lett. 83, 791 (2003)

Cooling requirements

Photomultiplier: room temperature

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



Thermoelectric cooling

0 5 mm

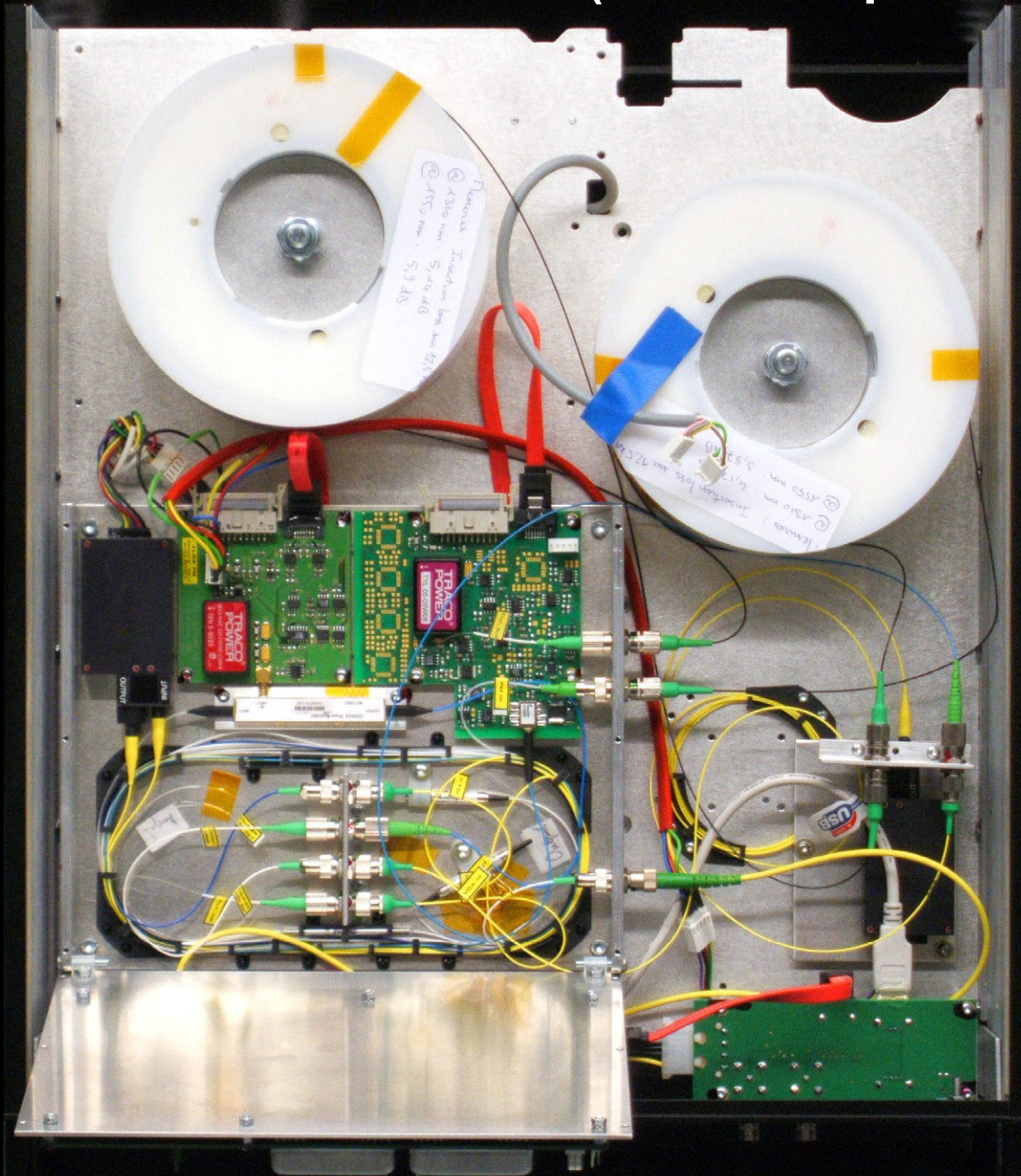
Superconducting nanowire: 4 K

Transition-edge sensor: 100 mK



Assembled fiber optics

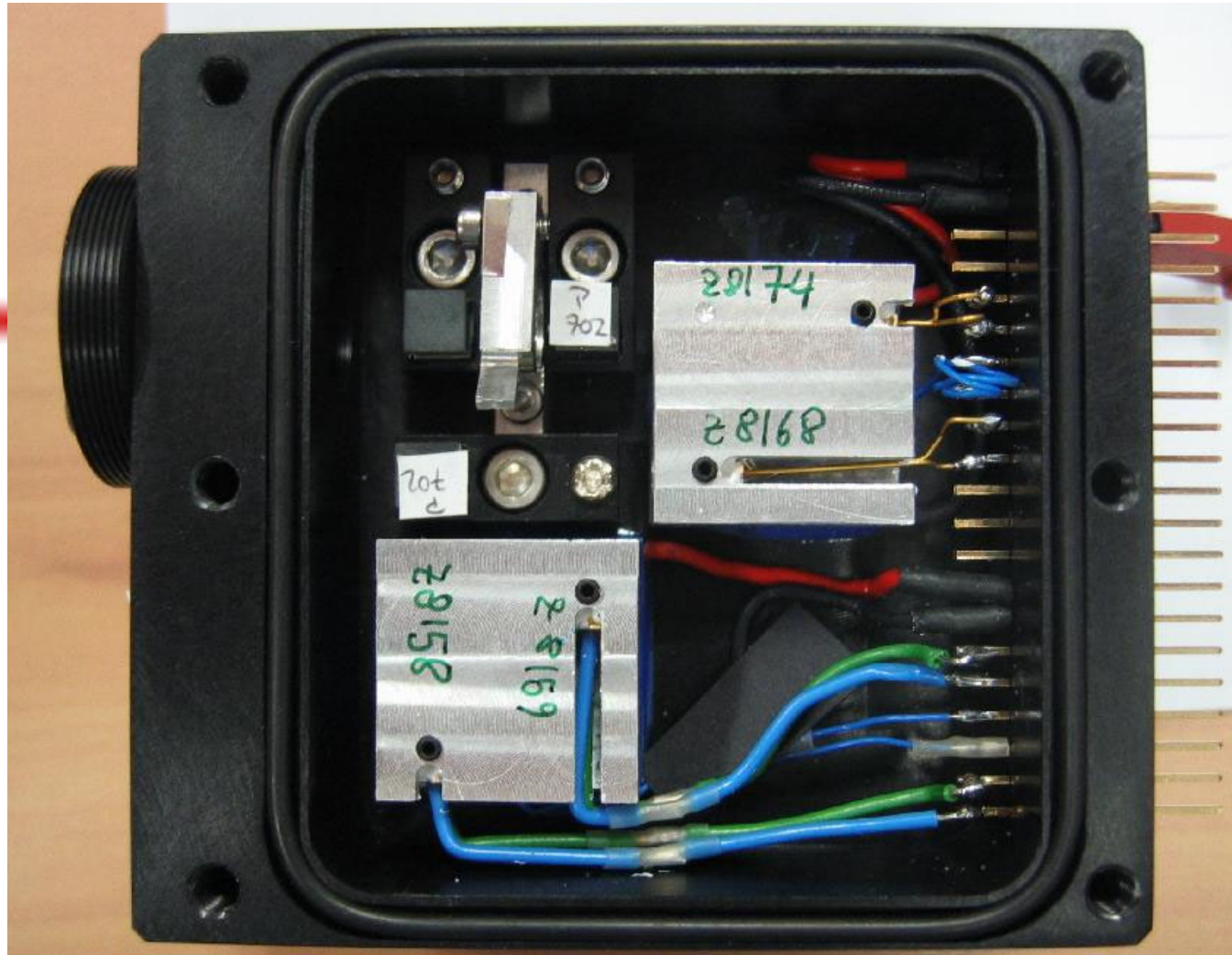
Quantum key distribution unit Alice (ID Quantique Clavis2)



0 100 mm

Assembled free-space optics

Bob's polarization analyzer with single-photon detectors



Emerging: integrated optics

Quantum key distribution system

