Review – Wireless Radio Links:

(1) $$G_t(\theta,\phi) = \frac{P_r(\theta,\phi,r)}{P_T / 4\pi r^2}$$ (P_T is at antenna input) "Gain over isotropic"

(2) $$P_{rec} = P_r(\theta,\phi,r) A_e(\theta,\phi) = P_r(\theta,\phi,r) G_{rec}(\theta,\phi) \lambda^2 / 4\pi$$

$$= G_t(\theta,\phi)\left(P_T / 4\pi r^2\right) G_{rec}(\theta,\phi) \lambda^2 / 4\pi$$

$$P_{rec} = P_T G_t G_{rec} (\lambda / 4\pi r)^2$$

(3) $E_b >\sim 4 \times 10^{-20}$ Joules/bit (radio),

$$P_{rec}[\text{Watts} = J/s] = M[b/s] E_b [J/b]$$

(4) $R_r = P_T / \left\langle i^2(t) \right\rangle$ Radiation resistance

[calculated for antenna driven by i(t)]

WIRELESS LINKS (2)

Example – Interstellar Communications at r = 1 light year:

$r = \sim 3 \times 10^8$ [m/s] $\times 3 \times 10^7$ [s/y] $= 9 \times 10^{15}$ meters

Assume $G = 10^7$ for both transmitter and receiver,
$M = 1$ bit/second, $\lambda = 0.1$ m

$$P_{rec} = ME_b = 4 \times 10^{-20}$$

$$P_R = P_{rec}/[G_t G_{rec}(\lambda/4\pi r)^2]$$

$$= \sim 4 \times 10^{-20}/[10^7\ 10^7\ (0.1/4\pi\ 9\times 10^{15})^2] = 512\ [W]$$

Therefore a 1.3-MWatt transmitter could provide 2.4 kbps internet access (SLOW), or sports broadcasts.

PHOTONIC LINKS

(5) $E = hf$ is Photon energy [J], $h = 6.625 \times 10^{-34}$ [Js],
f = frequency [Hz]

Example:

Photons/bit in radio regime (say $f = 10^9 = 1$ GHz) is:

$E_b/hf \cong 4 \times 10^{-20}/(6.6 \times 10^{-34} \times 10^9)$ (see (3) and (5))

$\cong 6 \times 10^4$ radio frequency photons/bit at threshold

(photons $\leftrightarrow$ waves)

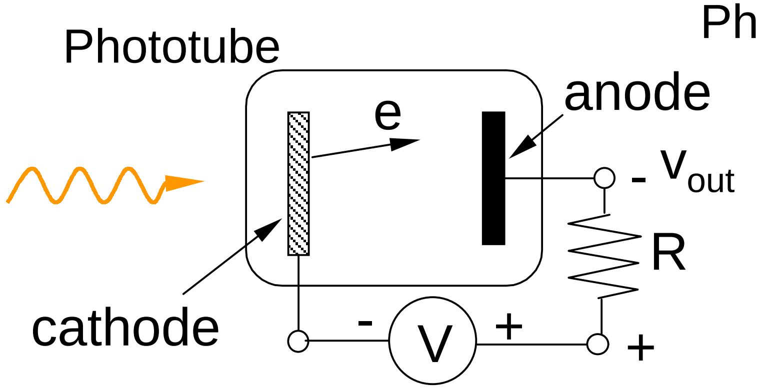
In optical regime we want >5 – 50 photons/bit

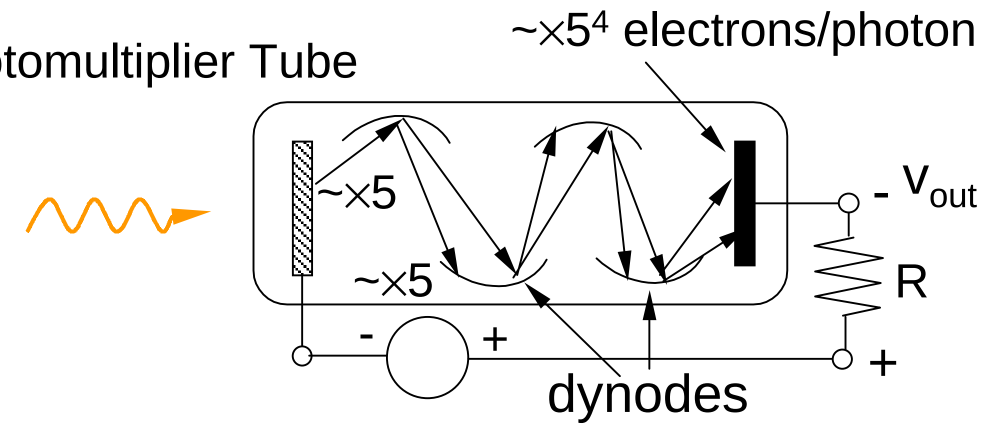
if noise power $\lesssim$ signal power

PHOTONIC LINKS (2)

Photon Detectors

Photo-electric effect; ejects electron into vacuum (with quantum efficiency η) if $hf > \Phi$ (work function) ~2-6 volts for metals





Current pulses larger than thermal noise

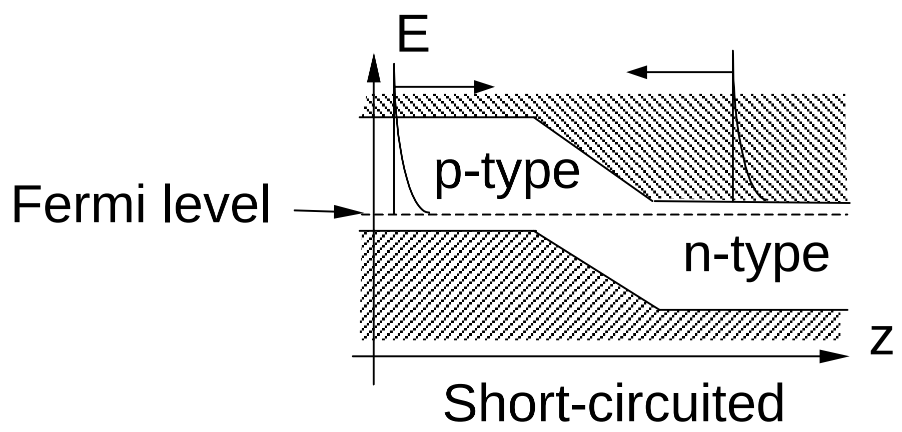
Output current proportional to photon flux (#/s) and EM power

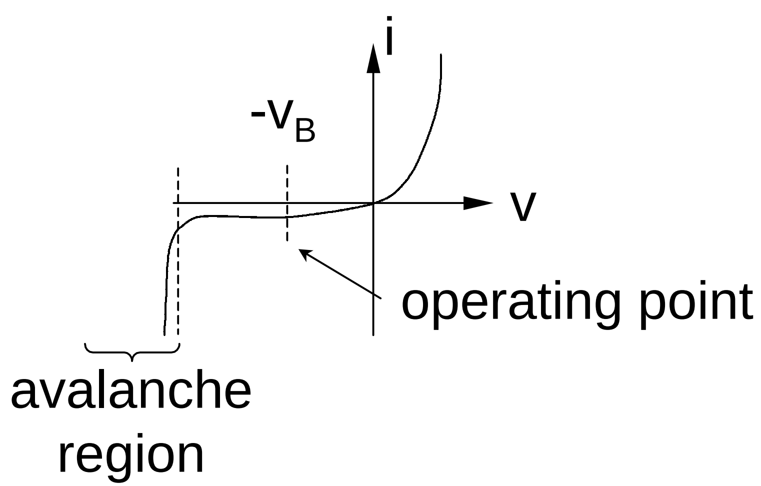
Telescopes

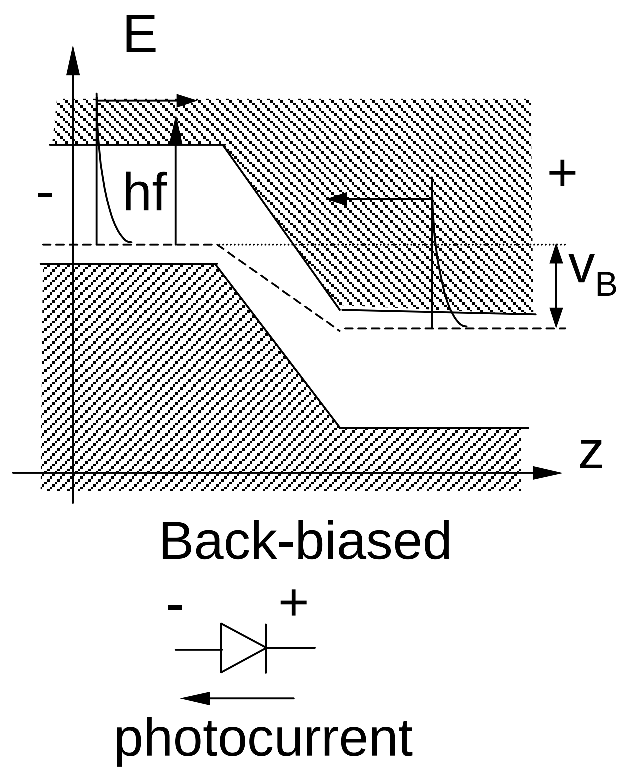
$$A_{physical} \cong A_{eff} = G_o \lambda^2 / 4\pi$$

PHOTODIODES

Energy Diagram







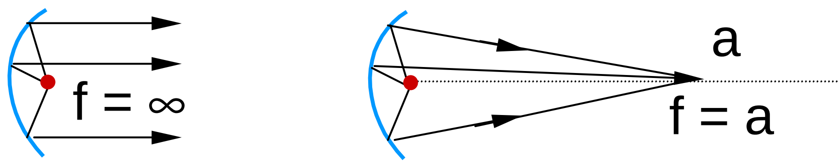
Output current is proportional to photon flux (#/s) and power

Electromagnetic power proportional to volt^2 [in circuit] or (v/m)^2 [in space]

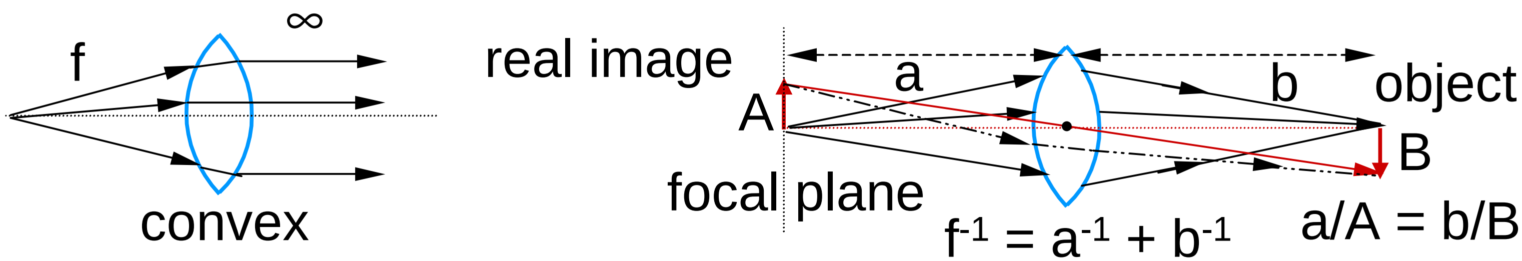
Quantum efficiency = electrons/photon $\lesssim 1$

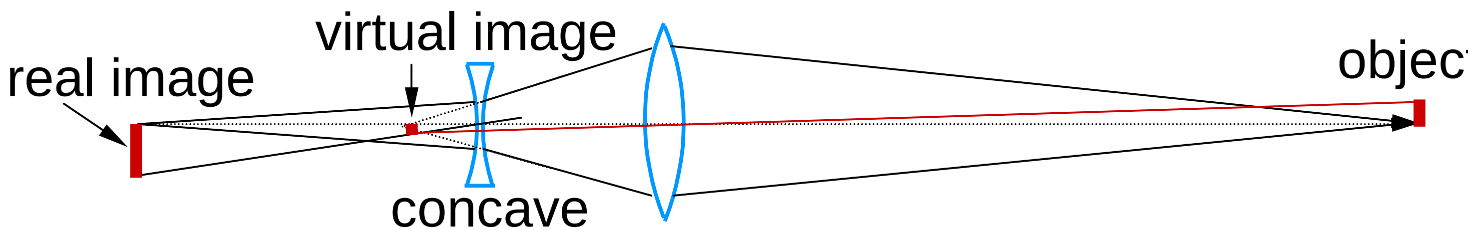
OPTICAL SYSTEMS (ignoring diffraction)

Mirrors:



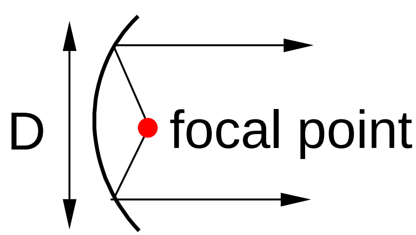
Lenses:

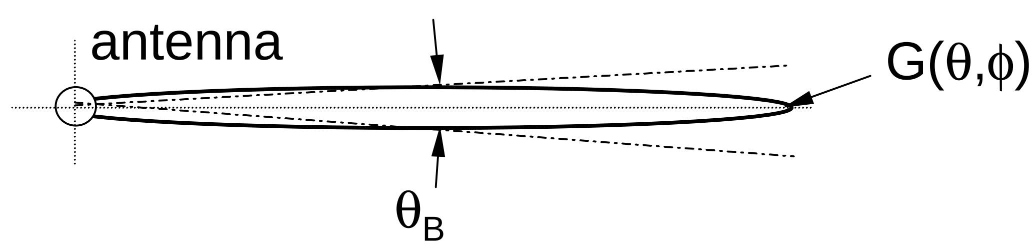




Diffraction-Limited Optical Systems:

Beam width θ_B = ~λ/D where λ is wavelength and D is aperture diameter





OPTICAL COMMUNICATIONS

Example: Interplanetary Optical Communications Systems

Say 1-Watt 0.5-micron laser, 10-cm optics on earth (seeing limited), 1-meter optics on Mars; range r = 10^{11} meters (100 million kilometers), 10 photons/bit. What is maximum data rate M(bps)?

Solution:

Consider Earth transmissions: $\lambda = 5 \times 10^{-7}$ m, A = telescope area [m^2]

$$M = P_{rec}/E_b = \underbrace{G_t(\theta,\phi)\left(P_R/4\pi r^2\right)}_{P_r}\underbrace{G_{rec}(\theta,\phi)\lambda^2/(4\pi\times}_{A_r}\underbrace{10hf}_{E_b})\text{ where } f = c/\lambda \text{ and}$$

$$G_o \cong A4\pi/\lambda^2 = \pi(D/2)^2 4\pi/\lambda^2 = (\pi D/\lambda)^2 \quad \text{Therefore...}$$

$$M = (\pi D_t/\lambda)^2\left(P_R/4\pi r^2\right)(\pi D_r/\lambda)^2\lambda^3/4\pi 10hc = \pi^2 D_t^2 P_R D_r^2/4^2 10hcr^2\lambda$$

$$= \pi^2 0.1^2 \times 1 \times 1^2 \Big/ \left(4^2 \times 10 \times 6.625 \times 10^{-34} \times 3 \times 10^8 \times \left(10^{11}\right)^2 \times 5 \times 10^{-7}\right)$$

= **620 kbps** [Reciprocity applies; delay $\cong$ r/c = $10^{11}/3\times10^8 \cong$ 5.5 minutes]

OPTICAL COMMUNICATIONS (2)

Example: Intra-room Optical Communications System

Say 1-mW photodiode transmitter, isotropic antennas, r < 10 meters,
No reflection loss (multi-bounce).

$$M = P_{rec}/E_b = \overbrace{G_t(\theta,\phi)\left(P_R/4\pi r^2\right)}^{P_r}\overbrace{G_{rec}(\theta,\phi)\ \lambda^2}^{A_r}/(4\pi\times\overbrace{10hf}^{E_b}) \quad \text{where } f = c/\lambda$$

$$M = 1\times\left[10^{-3}/\left(4\pi 10^2\right)\right]\left[1\times\left(5\times10^{-7}\right)^3/\left(4\pi\times10\times6.625\times10^{-34}\times3\times10^8\right)\right]$$

$= 0.004$ bps ☹ What happened? Is Mars easier?

$$G_o = \left(\pi D^2/\lambda\right)^2 = 4\times10^{13}$$ for 1-m telescope, vs 1 (isotropic)

G^2 [optical advantage] vs. $(r/R)^2$ [distance advantage]$\bullet 10^{-3}$ [power penalty]

is 1.6×10^{24} vs. $\left(10^{11}/10\right)^2 10^{-3} = 10^{17}$

Solution: use large-area detectors $\left(A \text{ for } G = 1 \text{ is } G\lambda^2/4\pi \cong 2\times10^{-16}\left[m^2\right]\right)$

e.g. 1 cm^2 detector $\Rightarrow 10^{-4}/2\times10^{-16} = 5\times10^{11}$ detectors in parallel (noise changes)

What is missing from this analysis of links?

Waves

What are they? Power? Energy?

How do they propagate? Is it always $\propto r^{-2}$?

How can we generate them?

Circuit—Wave coupling

Transmitting antennas

Receiving antennas

What determines the antenna pattern?

Systems—Analysis and design

How do we do it?

to be continued…