Ingegneria delle Telecomunicazioni

Satellite Communications

12. Let There be Light – Optical Sat Links

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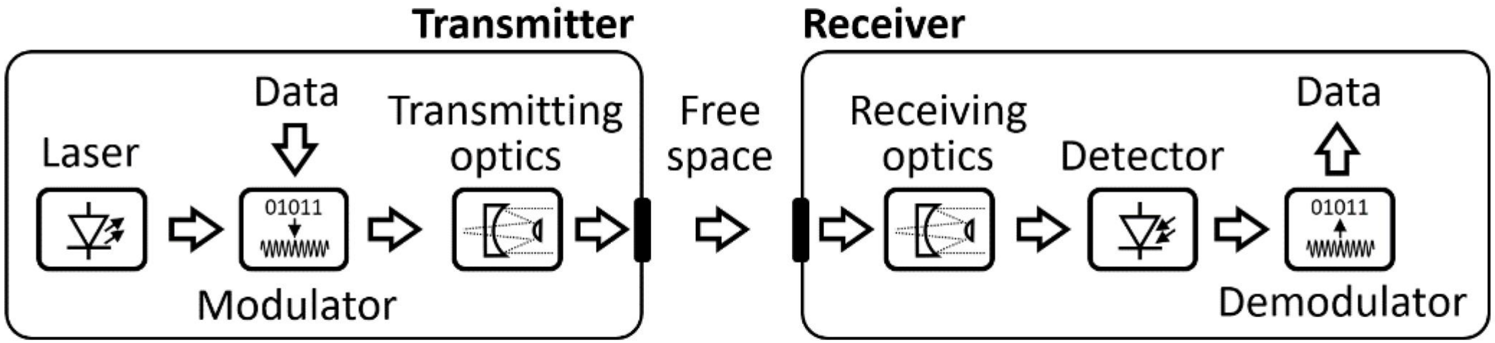
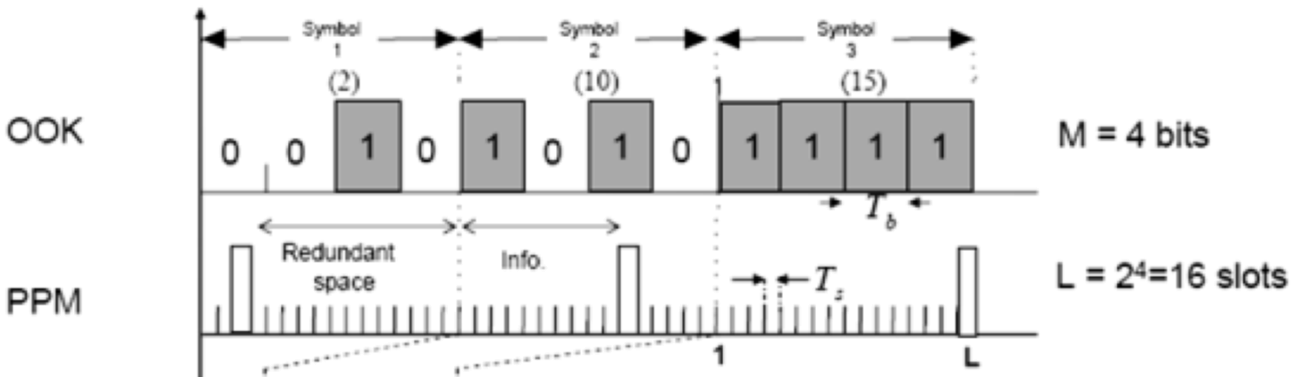
The Mantra Question: (How) Does it Work ?



- Transmitting/receiving optics are optical lenses (telescopes) to appropriately focus or de-focus the laser beam
- The optics needs to be oriented since optical emission is very very focused
- The digital format is similar to what is used on fibers: OOK, PPM, Coherent QPSK



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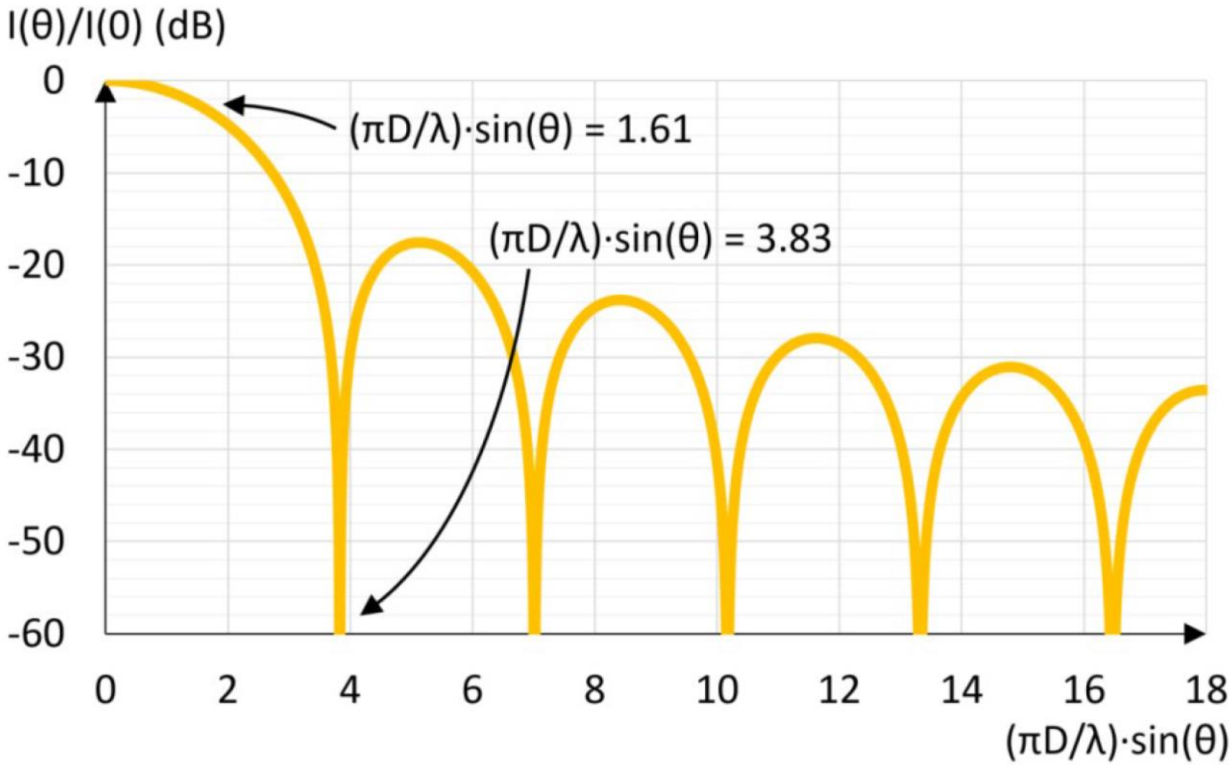
The Aperture of an Optical Beam

- **This picture describes the so-called *diffraction limit* of a telescope of diameter *D*, and is the equivalent of the $J_1(\cdot)$ radiation pattern of an RF (parabolic) antenna**

The aperture of the beam is defined as the first-null angle and can be evaluated by the usual formula

$\theta_0 = 1.22\lambda/D$

With a 50-cm telescope and $\lambda = 1.55\ \mu m$ we get from GEO altitude a spot on Earth of *d*=270 m !



Why FSO (Free-Space Optics) ?

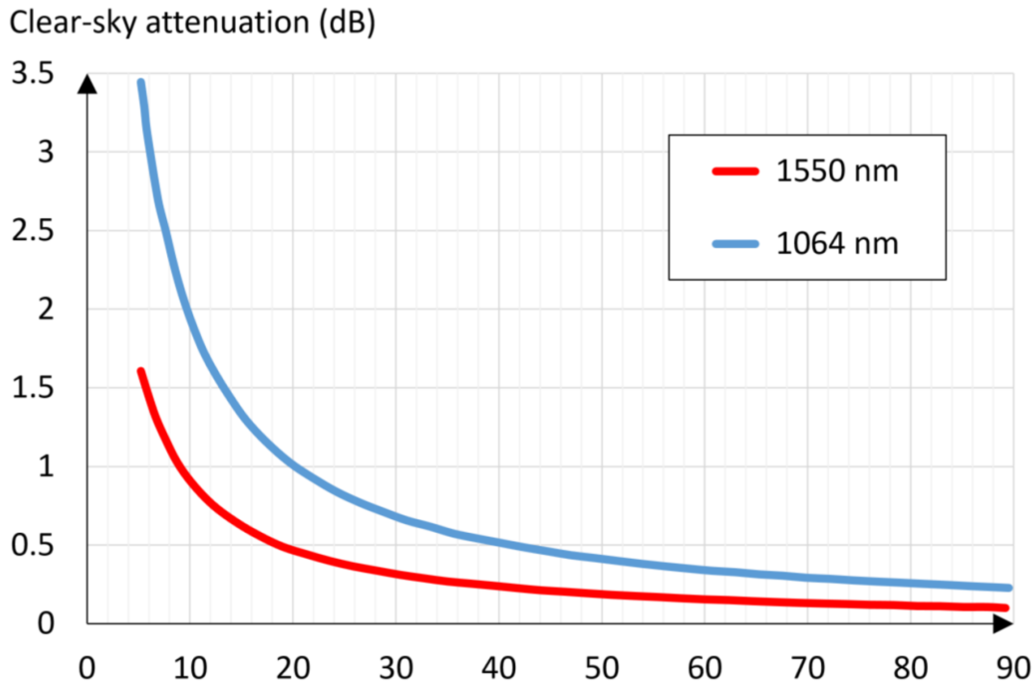
- **Potentially Ultra-Wide Bandwdith**
  - same as on fibers
- **Very narrow beam**
  - very easy space-division multiple access
  - Ideal for extra-terrestrial communications
- **Ultra high "antenna" (i.e., telescope) gain**
  - Very efficient link with modest optical power on-board

Sample LEO-to-Ground Optical Link Budget

Transmitted power P_T (dBm)	15.40
Transmitting gain G_T (dB)	85.08
Transmitter loss L_T (dB)	1.97
Pointing loss L_P (dB)	5.70
Free-space loss L_S (dB)	259.06
Atmospheric loss L_A (dB)	2.66
Receiving gain G_R (dB)	126.14
Receiver loss L_R (dB)	7.40
Received power P_R (dBm)	-50.18

Why NOT FSO ?

- **Pointing of telescopes is critical**
  - Accurate tracking systems are needed
- **Atmospheric attenuation in clear sky is not critical BUT**
- **ATTENUATION OF CLOUDS AND FOG IS UP TO 300 dB/km (yes, 300, no mistakes)**
  - Critical for ground links, especially in some zones of the Earth
  - Ideal for Inter-Satellite Links (ISLs)
- **Other issue in the atmosphere is *turbulence* that de-focuses beams**

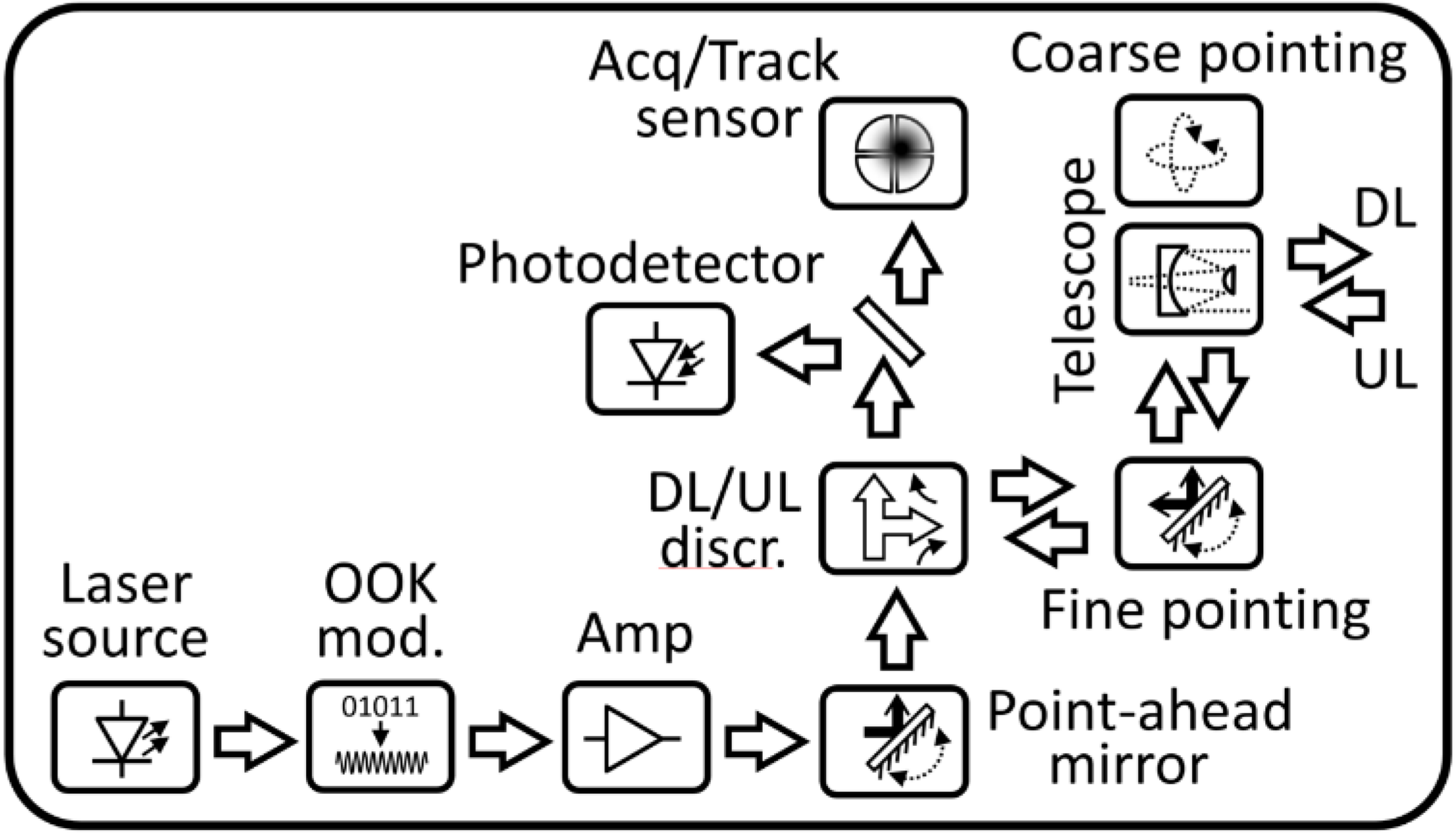


Examples of Optical Communication Technologies

- The European Champion: TESAT

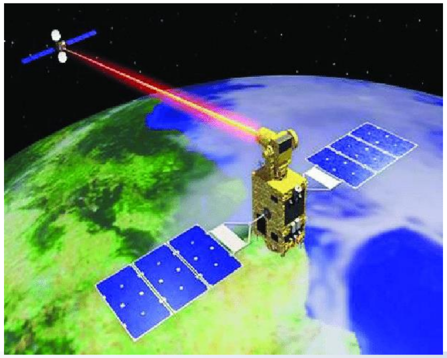
- SpaceX provider? Mynaric

Typical Optical Front-End of a LEO Transceiver



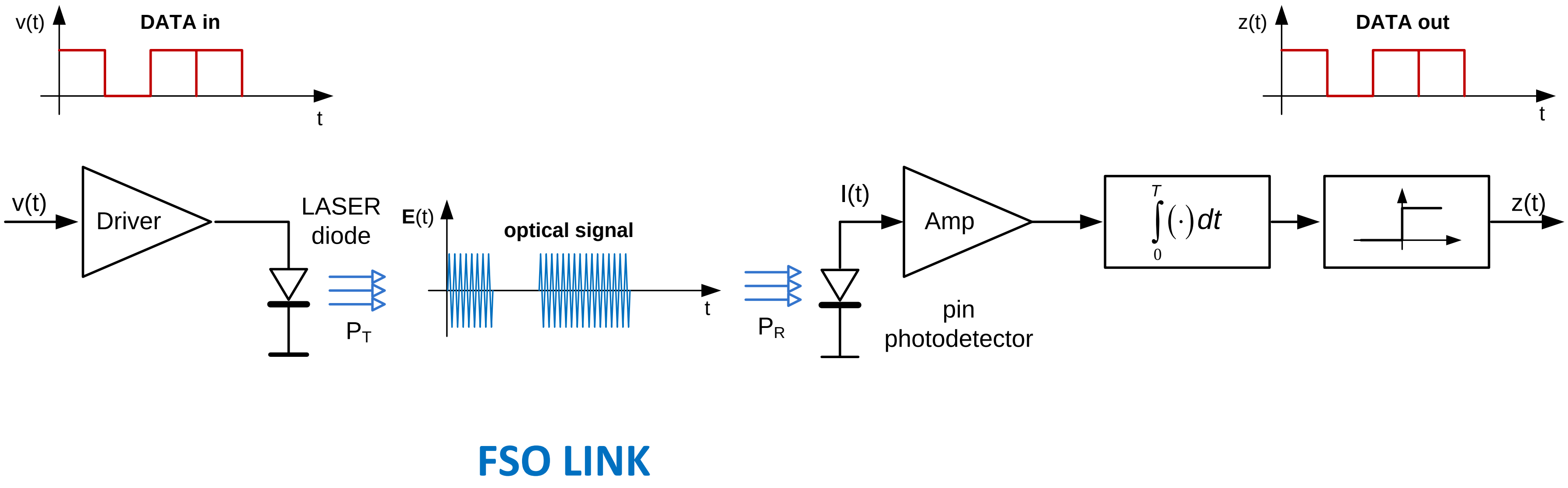
The need of (Optical) ISLs in Megaconstellations

- **StarLink Satellites are belived to bear an optical ISL from 2023 onward. Why?**
  - Coverage of remote or hostile ground areas & Oceans: the LEO satellite collecting or delivering traffic to the user may not have any ground station in visibility to handle it…
  - In general, high-capacity ISLs ease ground stations planning and operation – intersatellite routing can be implemented



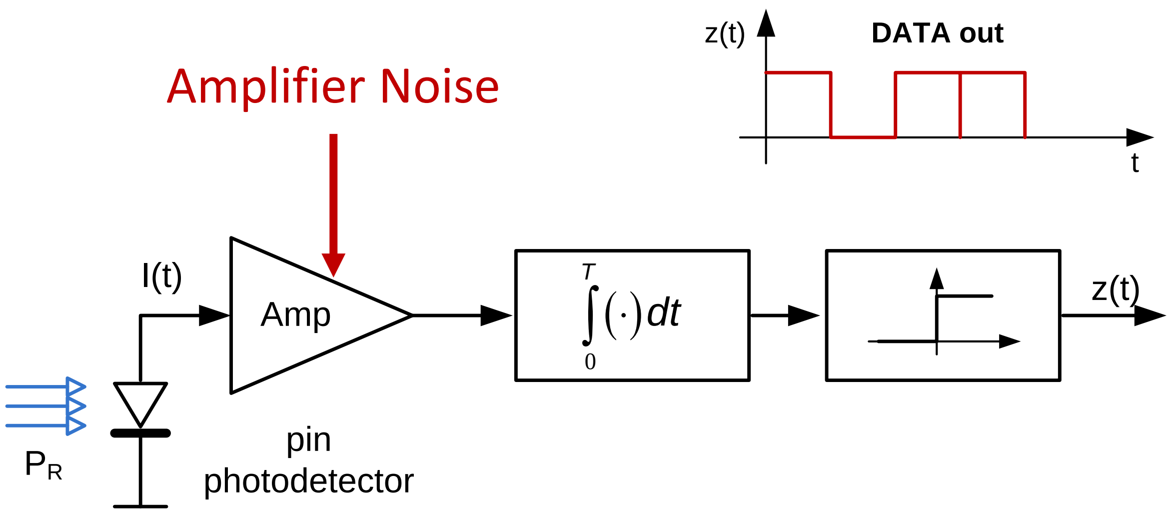
FSO DD receiver

- Suited to IM/DD formats like OOK and PPM



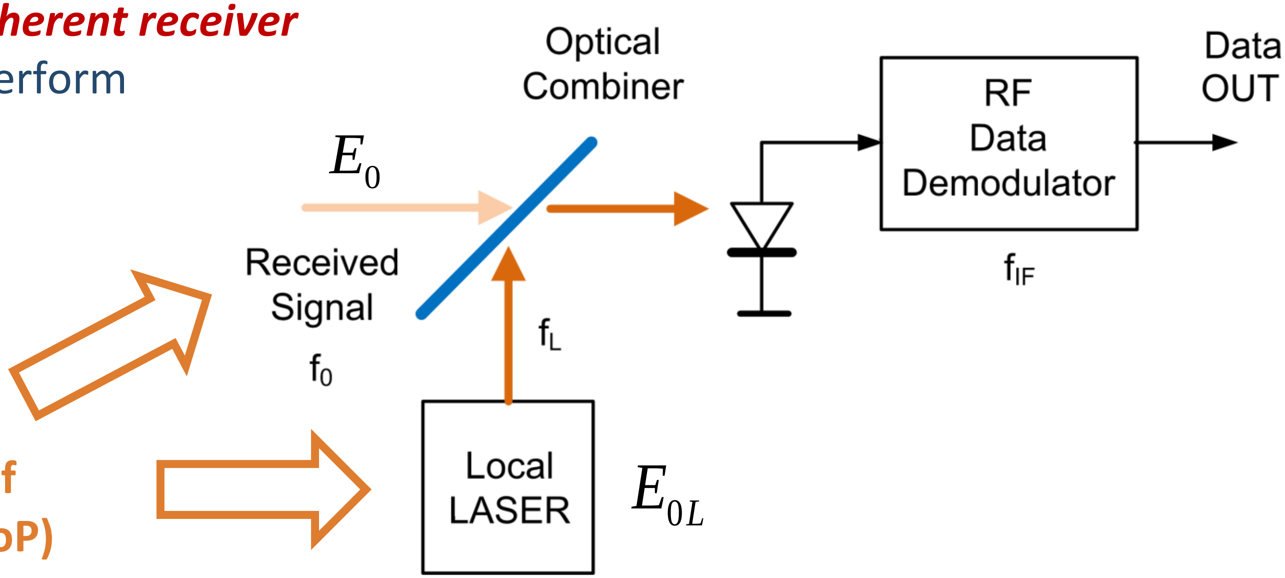
The Achille's Hell of the DD receiver

- The Electrical Pre-Amplifier is NOISY and its noise overwhelms the photodetector's own shot noise: the performance is NOT shot-noise limited, it is rather THERMAL-NOISE-LIMITED and it's 10 dB away form the Quantum Limit



Coherent FSO Receiver

- With modern LASERS and/or external modulators, we can implement any amplitude/phase modulation on the optical transmitted beam
- Phase modulation *cannot be detected by a DD receiver*, that only senses envelope variations of the optical wave
- We can resort to a ***coherent receiver*** with ***local LASER*** to perform frequency conversion



Same State of Polarization (SoP)

$$E_R(t) = E_0 A(t)\cos\left(2\pi f_0 t + \phi(t)\right) + E_{0L}\cos(2\pi f_L t + \phi_L)$$

Optical-to-RF conversion

- The photodetector detects the (instantaneous) power of the combined signal (*R* photodetector responsivity)

$$I(t) = R\left[\sqrt{2P_M}\,A(t)\cos\left(2\pi f_0 t + \phi(t)\right) + \sqrt{2P_L}\,\cos(2\pi f_L t + \phi_L)\right]^2$$

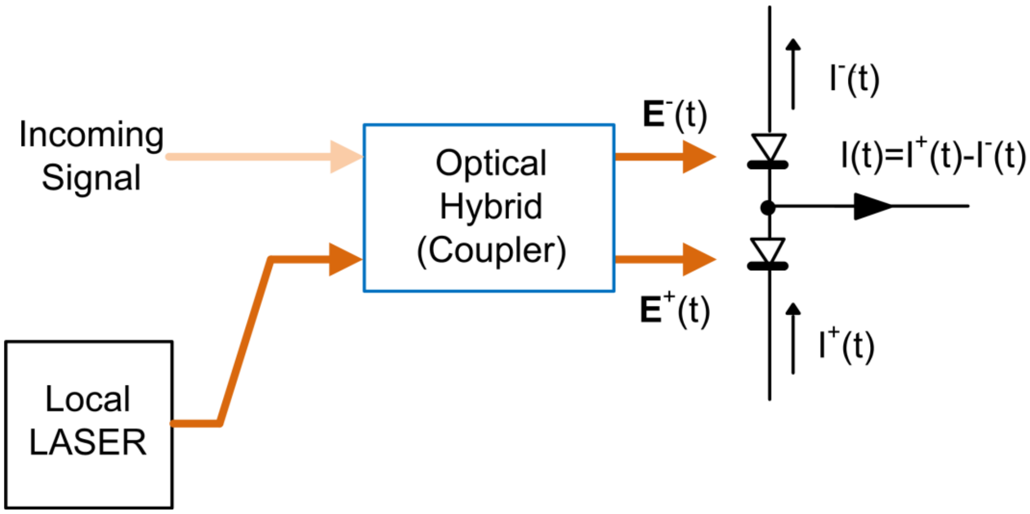
- Doing the computation and removing optical-frequency terms, we are left with

$$I(t) = RP_M A^2(t) + RP_L + 2R\sqrt{P_M P_L}\,A(t)\cos\left(2\pi f_{IF} t + \phi(t) - \phi_L\right)$$

- The amplitude/phase modulation of the incoming optical signal is transferred onto the IF radio signal at frequency $f_{IF}=f_0-f_L$
- We can now use a standard digital radio receiver to demodulate the digital data ! Any constellation !

Balanced Coherent Receiver

- The low-frequency terms are automatically removed by a *balanced* configuration, wherein the Optical Hybrid splits the local laser wave with 180 degrees phase shift



- The combined shot-noise term *i*(*t*) for the two detectors sums up to the useful signal, driving the sensitivity of the receiver
- The noise psd is proportional just to the power of the local LASER (the power of the incoming signal is negligible):

$$I(t) = 2R\sqrt{P_M P_L}A(t)\cos\left(2\pi f_{IF}t + \phi(t) - \phi_L\right) + i(t) \quad , \quad S_i(f) = qRP_L$$

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How Good is it?

$$I(t) = 2R\sqrt{P_M P_L}\, A(t)\cos\left(2\pi f_{IF} t + \phi(t) - \phi_L\right) + i(t) \quad , \quad S_i(f) = qRP_L$$

1. **The high-intensity shot noise is Gaussian (white) with**

$$N_0 / 2 = qRP_L$$

2. **Assuming BPSK/QPSK modulation, *A*(*t*)=1 and**

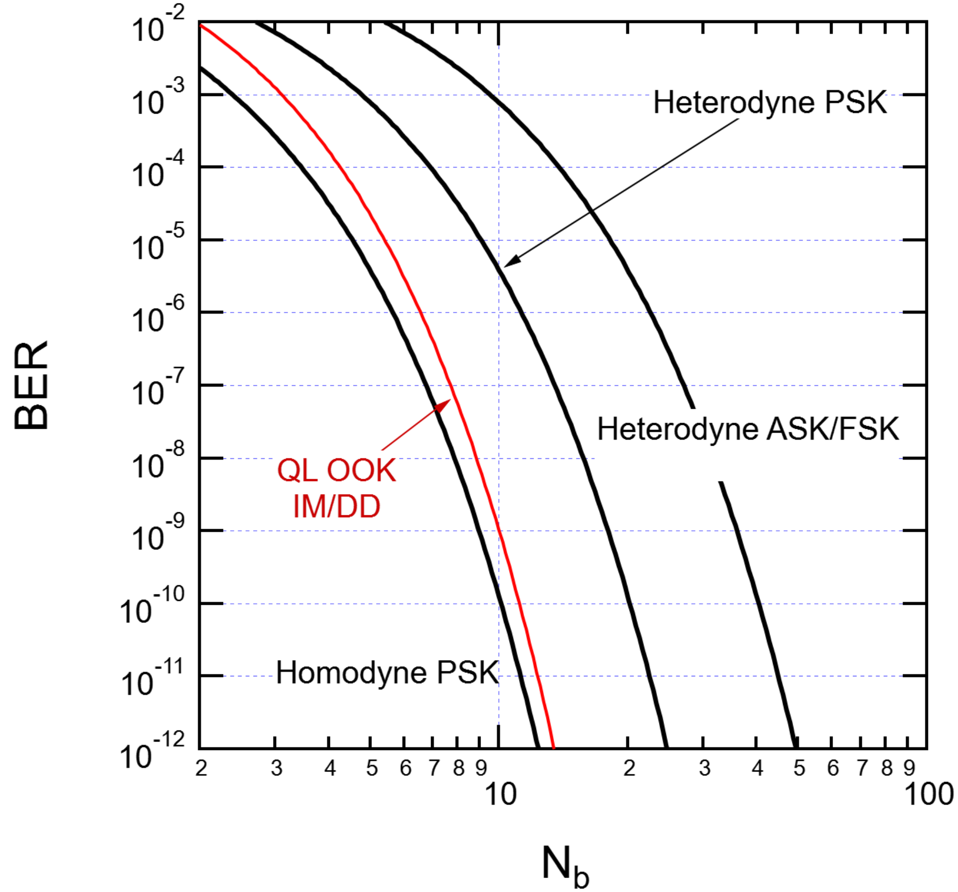
$$E_b = T_b\left(2R\sqrt{P_M P_L}\right)^2 / 2$$

3. **The BER is**

$$Q\left(\sqrt{\frac{2E_b}{N_0}}\right) = Q\left(\sqrt{\frac{T_b\left(2R\sqrt{P_M P_L}\right)^2}{2qRP_L}}\right) = Q\left(\sqrt{\frac{2RP_M T_b}{q}}\right) = Q\left(\sqrt{2N_b}\right)$$

And the performance?

- $N_b = \dfrac{RP_M T_b}{q}$ **is the average number of received photons /bit**



  - No impact of electrical noise (the detected signal is strong)
  - No need of optical (pre)amplifier
  - 3 dB away from QL for OOK
  - Even *better than QL* with homodyne conversion (needs I/Q optical oscillator)

Balanced Homodyne I/Q Receiver – Any Constellations

- The local LASER has the same frequency as the incoming signal
- It is the exact equivalent of an RF I/Q baseband demodulator
- Implemented in a single integrated-optics component