Sensitive Optical Receivers for Deep-Space Communications

Peter A. Andrekson

Fiber Optic Communications Research Centre (FORCE)
Department of Microtechnology and Nanoscience
Chalmers University of Technology
Gothenburg, Sweden

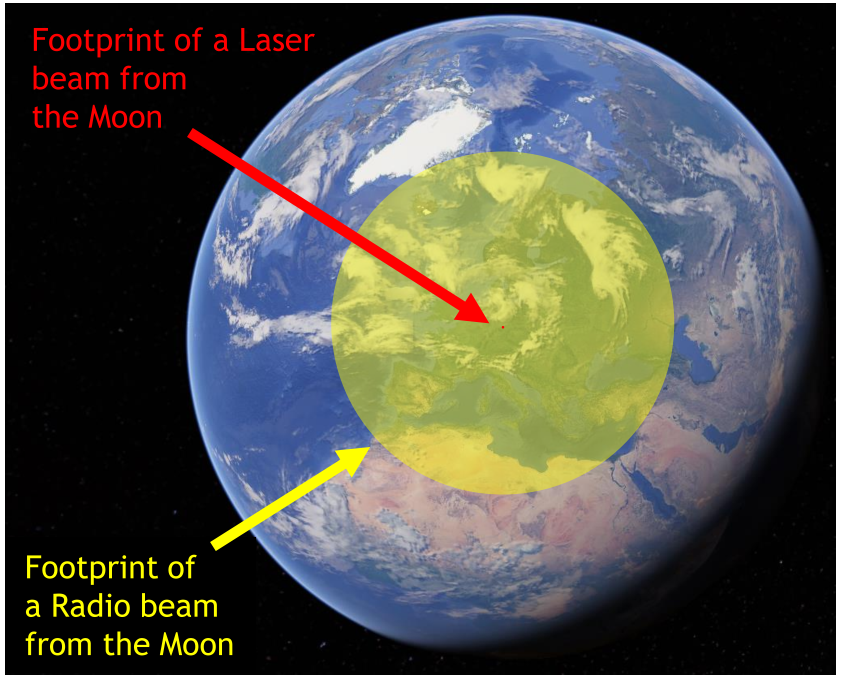
- Basic capacity limitations in deep-space links
- Ultralow noise optical parametric amplifiers
- Receiver sensitivity experiments

Vetenskapsrådet

Knut och Alice Wallenbergs Stiftelse

Deep-space communication

Even though RF antennas are much larger (x100) than optical apertures, laser communication will be needed in long-distance free-space links:
➔ *Lower link loss and higher capacity*



Diffraction loss in free space is quadratic with reach:

$$\frac{P(r,z)}{P_0} = 1 - exp\left(-\frac{2r^2}{\omega(z)^2}\right) \cong \frac{2r^2}{\omega(z)^2} \; with \; \omega(z) \cong \frac{\lambda z}{\pi\omega_0} \; and \; r \; is \; aperture \; radius$$

Loss to the Moon (400,000 km) at 1550 nm with 10 cm aperture ~ 80 dB

"To transmit a 1-foot resolution map of entire Mars surface requires 9 years at 5 Mbps (best Ka band)"

*"Higher data rates will be required to break through the present-day **science return bottleneck**"*

Aside from the many challenges in free-space optical links, such as beam steering & tracking, turbulence, radiation tolerance, energy, weight, etc. there are three fundamental metrics for reach and throughput limitations:

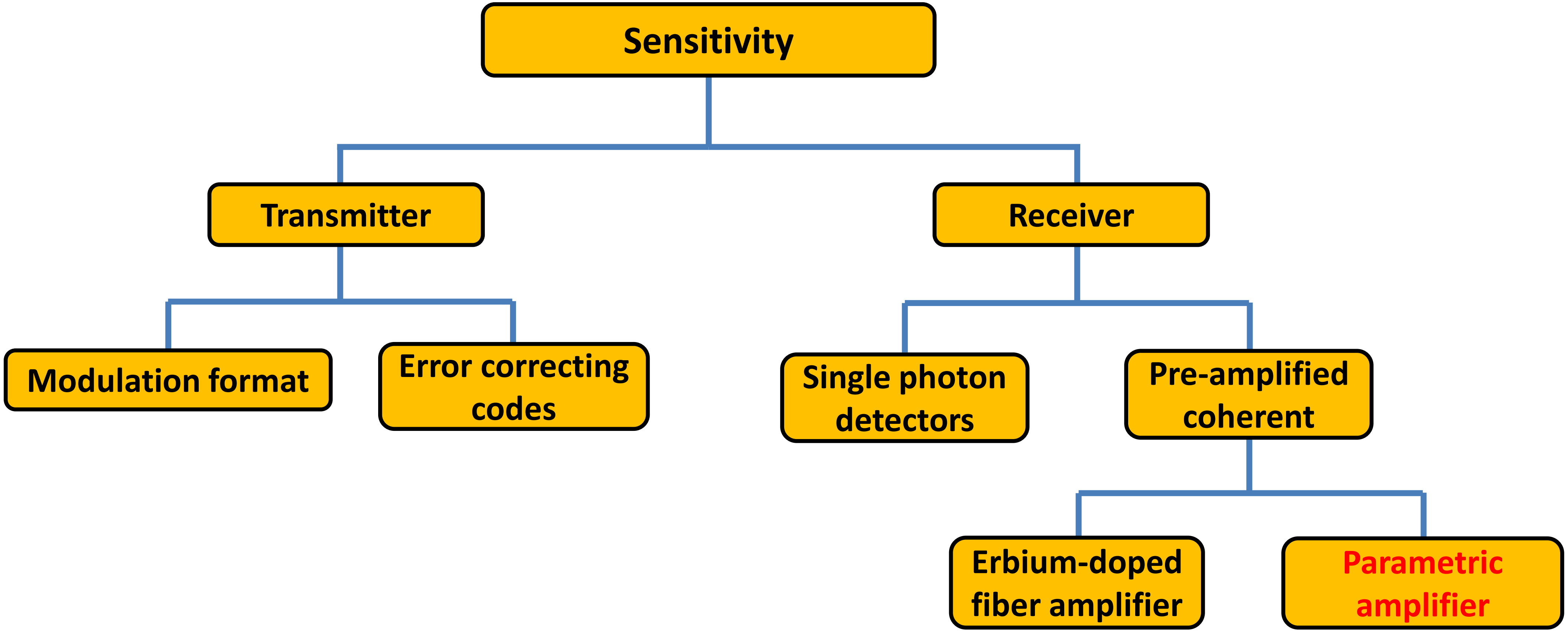
Limited by engineering capabilities

- Transmitted power (10-30 W average power with SM-EDFAs is available)
- Diffraction-induced link loss (aperture sizes)

Limited by vacuum noise

- **Receiver sensitivity** (average power needed for bit-error-free operation, often expressed in photons per bit, PPB)

What determines the receiver sensitivity?



Strong FEC is widely considered;
100% FEC overhead can reduce a BER >10% to <10^{-6}, resulting in coding gain >10 dB
→ improved sensitivity at expense of data rate.

Spectral efficiency (SE) bits/s/Hz

Is spectral efficiency important in space communication? No and Yes!

Short answer: It is important if the target bit rate is high.

- Optical SE is not limiting performance (available bandwidth is vast)
- Electrical SE can be a limiting factor, depending on modulation format used, given transmitter and receiver analog bandwidth limitations.

Fundamentally, there is always a trade-off between sensitivity and the achievable data rate. The achievable data rate = SE x available bandwidth, be it limited by optics or by electronics.

→ Tb/s fiber communication

→ Gb/s space communication

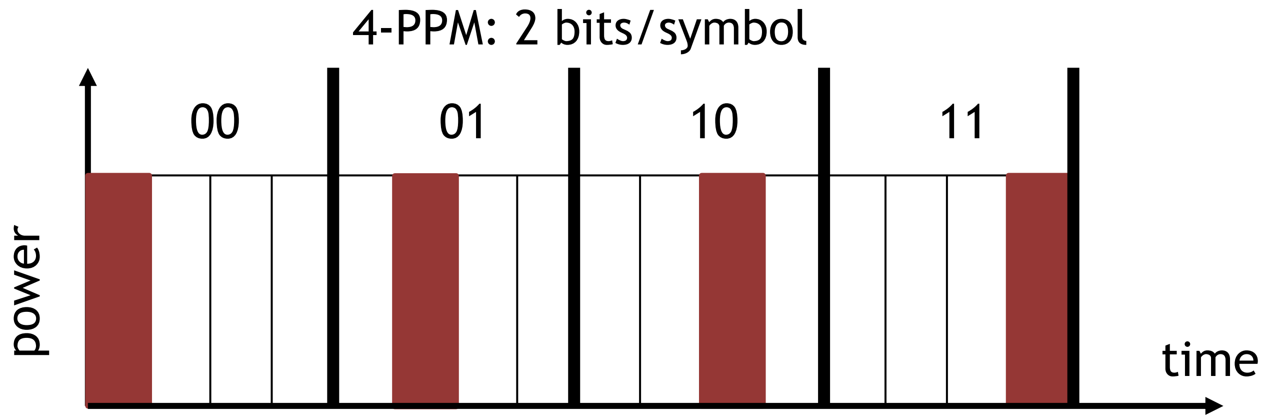
Capacity $C = B \times \log_2(1 + SNR)$

At very low SNR: $C \simeq D \cdot B \cdot SNR / \ln(2)$ since $\log(1+x) \propto x$
SNR and B are thus equally important.

→ Distributing available power among different polarizations or wavelengths will not increase throughput!

Pulse position modulation (PPM) – a power efficient format

Widely considered for deep-space links



M-PPM: $log_2(M)$ bits/symbol

$$photons\ per\ bit\ (PPB) = \frac{MP_{rec}}{h\nu B_{rec} log_2(M)}$$

Sensitivity (photons/bit, PPB) & Spectral Efficiency (bits/s/Hz) trade-off for M-PPM assuming Poisson statistics and photon counting:

$$PPB_{min} = \frac{1}{log_2(M)} \qquad SE_{max} = \frac{log_2(M)}{M}$$

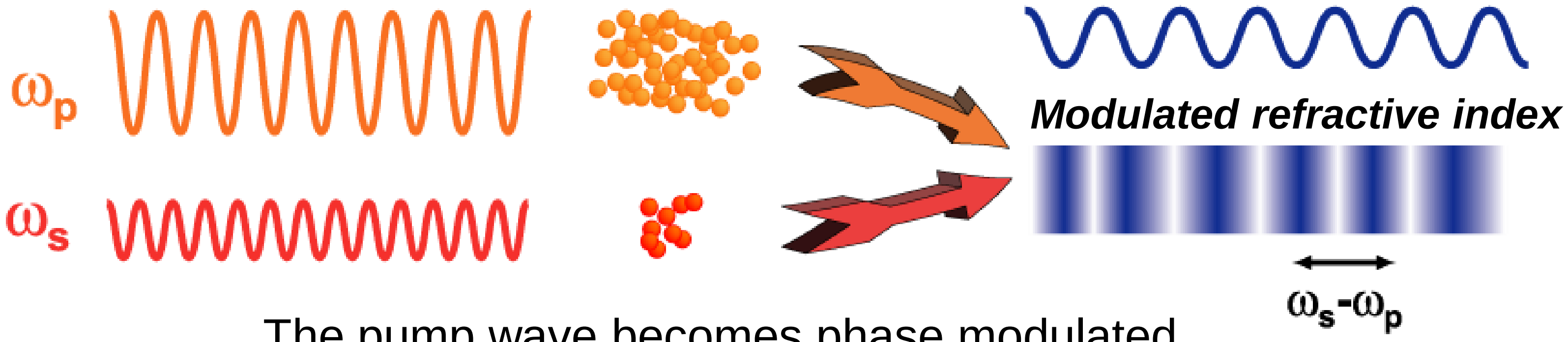
Theoretical 32-PPM example limits: 0.2 PPB and 0.16 b/s/Hz (not simultaneously)

Moving to higher level PPM improves sensitivity at expense of spectral efficiency (and rate limitation)

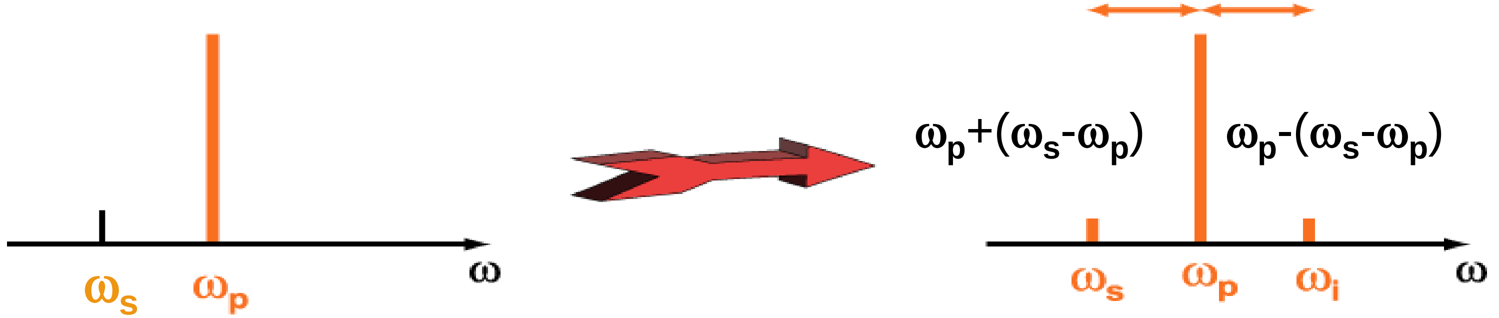
Optical Parametric Amplifiers (OPA)

Nonlinear index of refraction; $n = n(I)$

Pump and signal waves mix in a nonlinear media creating a dynamic grating



The pump wave becomes phase modulated

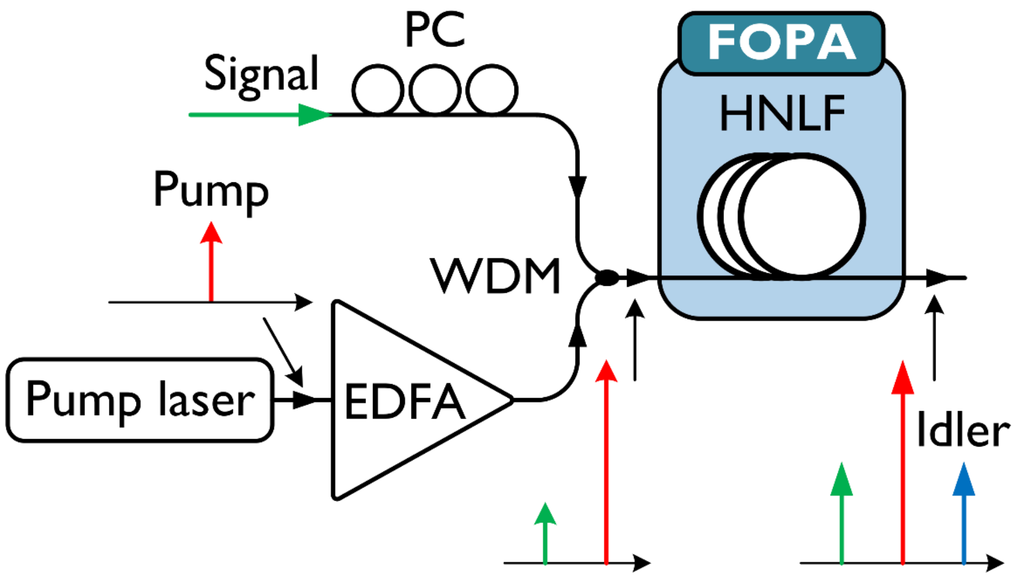


Power is transferred from pump to signal (at ω_s) and to ω_i (the "idler")

Commonly, low-dispersion highly nonlinear optical fiber (HLNF) is used as the nonlinear medium

OPA properties

- Uni-directional and polarized, transparent in absence of pump
- Instantaneous response time (fs) → many applications aside from amplification
- Gain spectrum can be designed and can potentially cover 100s of nm

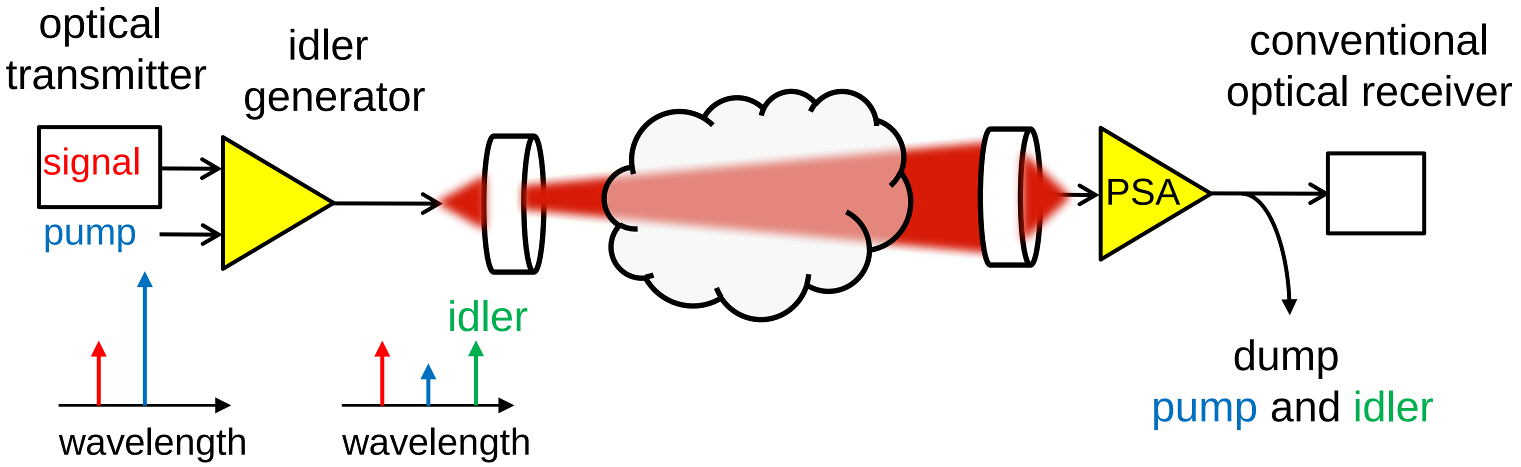


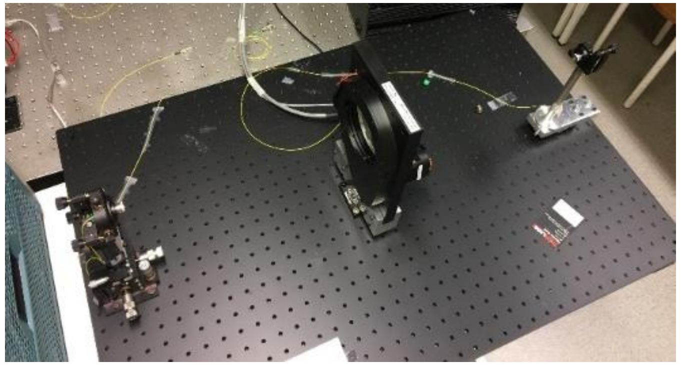
Properties depend on the waves present at the amplifier input, as well as on the dispersion and nonlinearity of the nonlinear medium.

This is in contrast to EDFAs, SOAs etc. in which material cross-sections dictate the gain.

If a phase-locked idler also is present at the input: Amplifier becomes phase sensitive ➔
A **noise figure of 0 dB is possible, no excess noise generation** (conventional amps have a 3-dB limit)

Free space optical transmission with OPAs

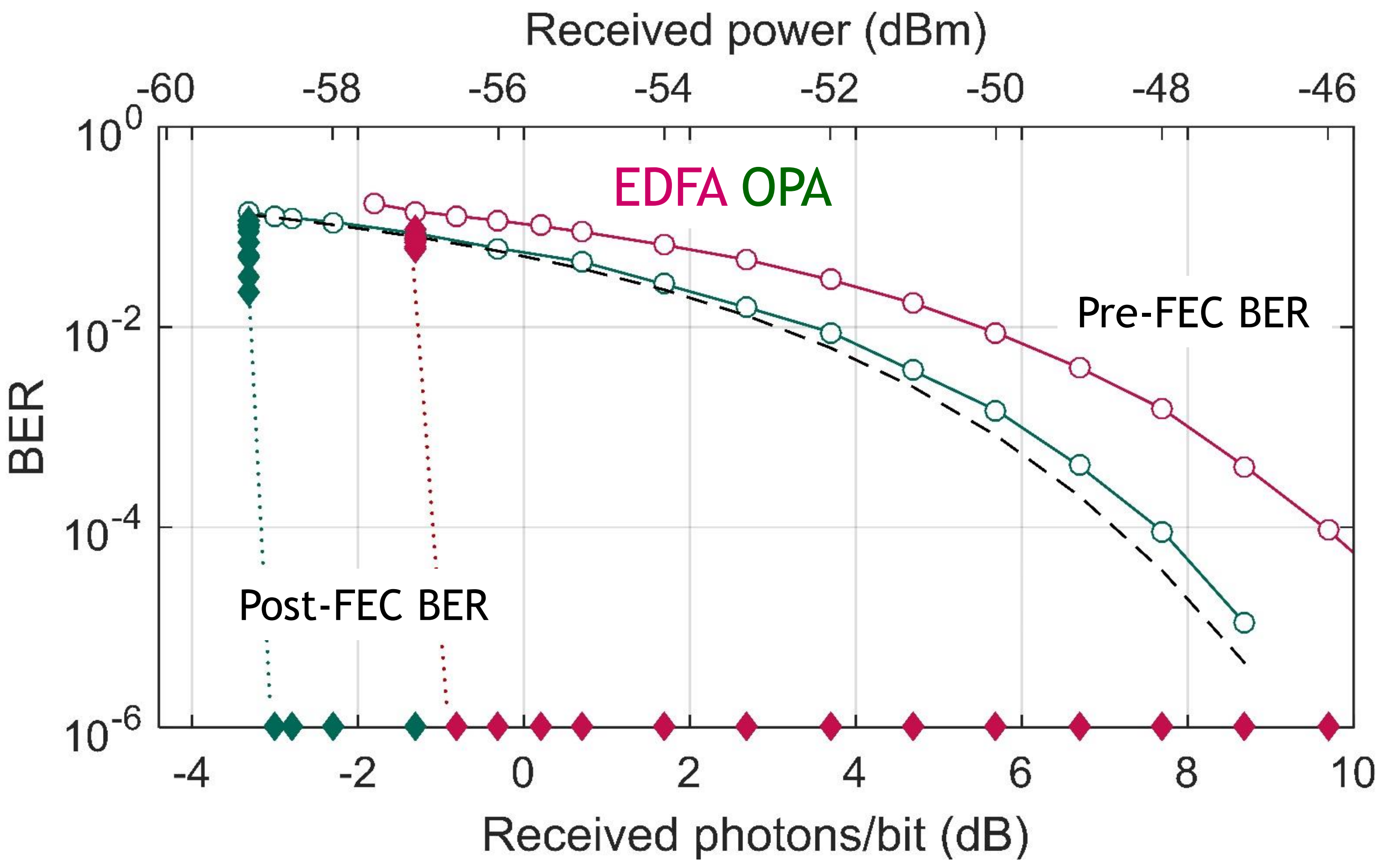




- Only signal is used in the receiver (no need for particular, high BW receiver)
- Pump power needs to be very small! (otherwise impacts power budget) – injection locking

Experimental results at information rate 10.5 Gb/s with QPSK modulation

Standard half-rate FEC code, PSA gain = 21 dB, NF = 1.2 dB



OPA receiver sensitivity: 0.5 PPB @ BER = 10^{-6}
i.e., 1 photon per information bit.

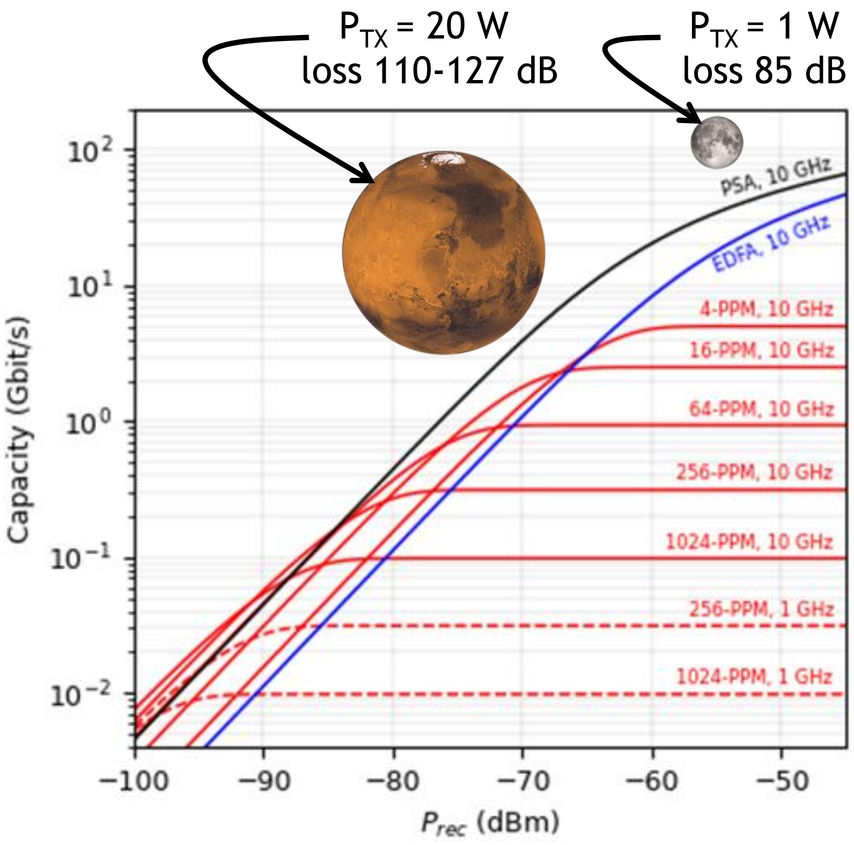
12 dB coding gain (at BER=10^{-5}) in both cases

All incident (not only detected) photons (signal, idler, pump in the case of OPA)

R. Kakarla et al., Light Sci Appl 9, 153 (2020)

Capacity vs. received optical power

Coherent detection with EDFA or OPA (idler ignored) and Photon-counting detection with PPM
No implementation penalty (QE = 100%, NF_{PSA} = 0 dB, etc.) and 10 GHz receiver bandwidth



$$C_{EDFA} = B_{rec} log_2(1 + n_s)$$

$$C_{OPA} = B_{rec} log_2(1 + 4n_s)$$

$$C_{PPM} = B_{rec}(1 - e^{-n_s}) \frac{log_2(M)}{M}$$

n_s = photons per symbol = For EDFA/OPA: $\frac{P_{rec}}{h\nu B_{rec}}$ for PPM: $\frac{MP_{rec}}{h\nu B_{rec}}$

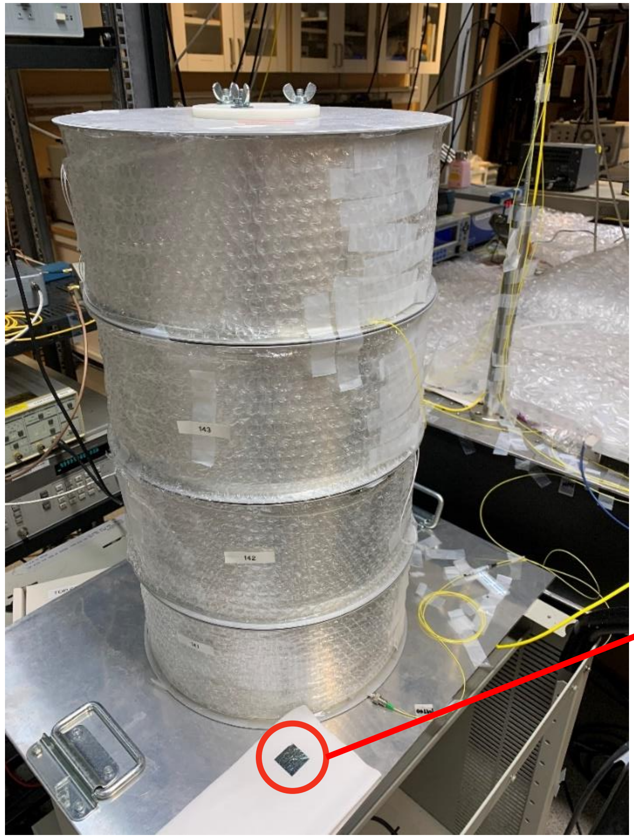
- EDFA outperforms PPM at P_{rec} > -65 dBm
- OPA outperforms PPM at P_{rec} > -85 dBm

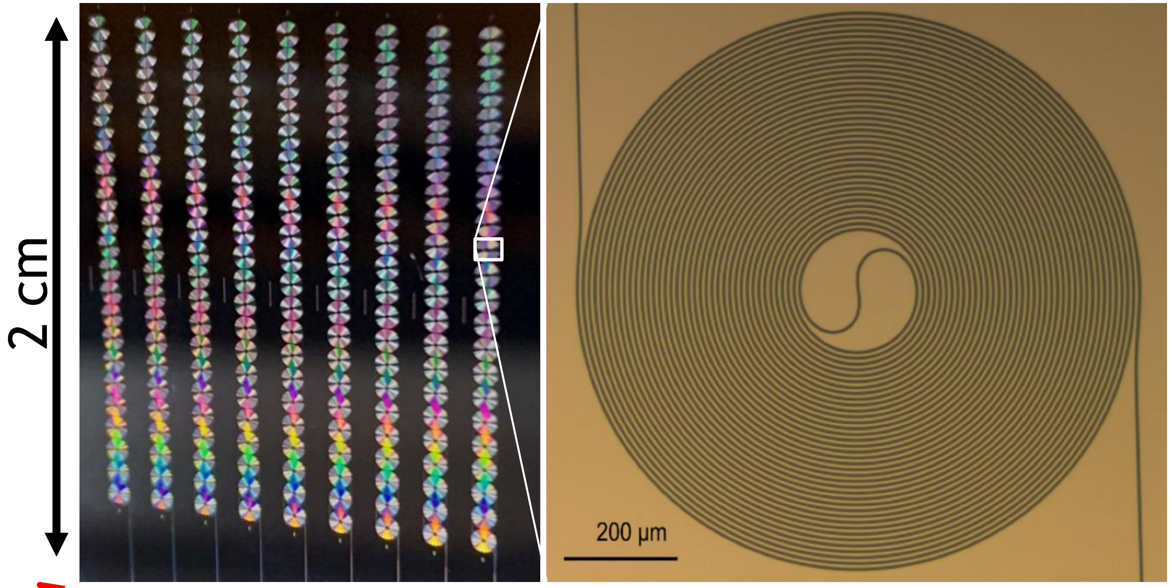
OPA pre-amplified coherent detection with simple QPSK format is an excellent candidate for high bit rate space communication (small implementation penalty, operates at room temperature)

Compact, silicon nitride-based OPAs

broadband transparency window, no or low TPA, FCA, SBS, SRS, PMD

HLNF-based PSA





Chip gain: 9 dB
Chip NF: 1.2 dB

8 waveguide amplifiers. Each has 22 spirals with 1.42 m total length
Loss is 1.4 dB/m, β_2 ~ -36 ps^2/km (C band)

1st demonstration of CW parametric gain in a $\chi^{(3)}$ chip

Conclusions

- At very low SNR/received signal powers, low-noise OPAs can play a key role providing the best sensitivity in coherent receivers.
- QPSK format along with large FEC overhead is suitable in very low SNR situations
- Silicon nitride is a promising platform for compact and broadband PSAs at various wavelengths
- Capturing a large fraction of the beam is important to increase capacity or reduce Tx power

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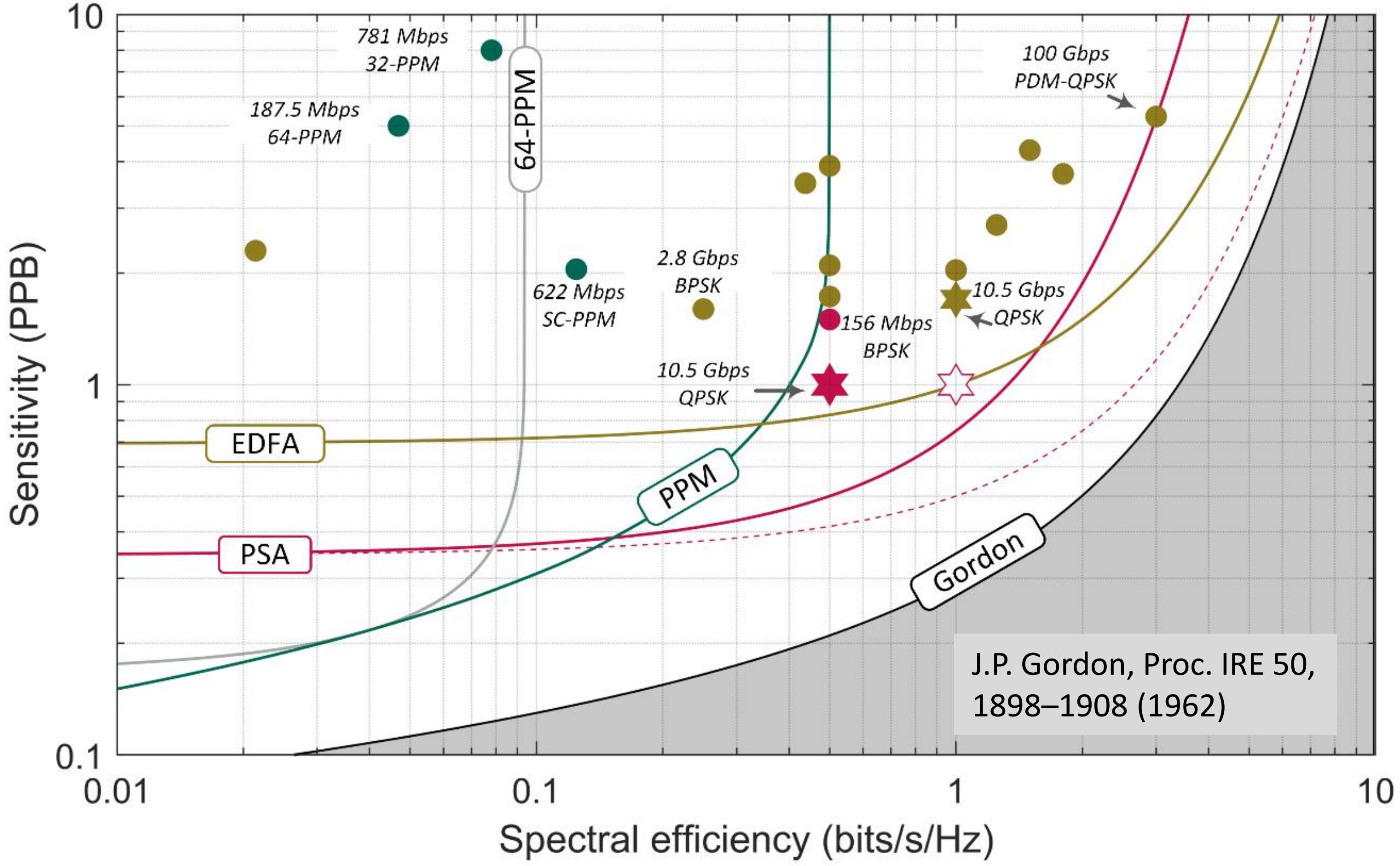
Theoretical and experimental data: "Black-box" performance



PPM/photon counting results

Coherent receiver results

✡ Our results

Experimental gap to theory 3 dB:

NF (1.2 dB), implementation penalty (0.4 dB), FEC (0.7 dB), pump/IL (0.5 dB), coupling losses (0.2 dB).

PSAs offer best sensitivity among all receivers for SE ∈ 0.16 - 1.6 b/s/Hz

Ultimate PSA (DQ coherent Rx) limit at low SNR/SE is 0.35 PPB [0.5 ln(2)]

Dashed red curve considers "electrical SE" (idler ignored)

R. Kakarla et al., Light Sci Appl 9, 153 (2020)