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FIBER-OPTIC COMMUNICATIONS

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CONTENTS

6. OPTICAL AMPLIFIERS

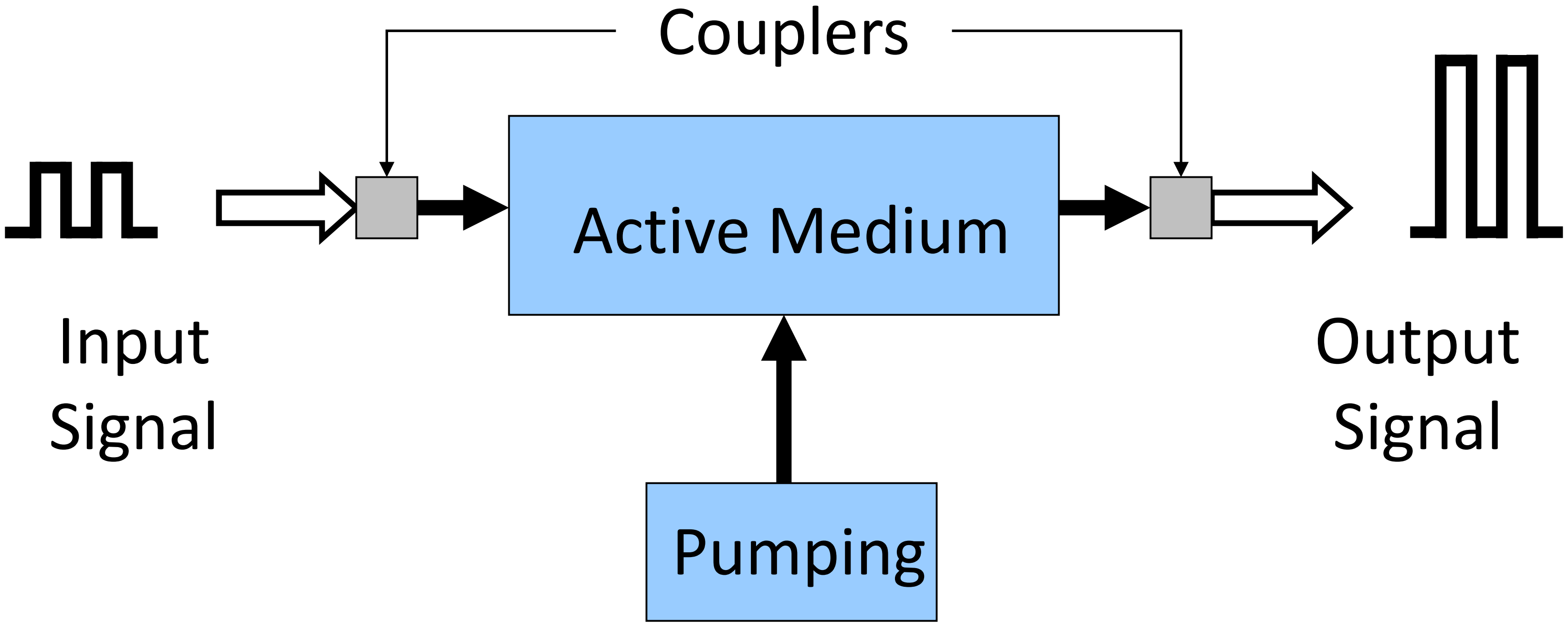
- ☐ GENERAL CONCEPTS
  - ☐ SYSTEM APPLICATIONS
  - ☐ AMPLIFIER GAIN
  - ☐ TYPES OF OPTICAL AMPLIFIERS
- ☐ SEMICONDUCTOR OPTICAL AMPLIFIER (SOA)
  - ☐ SOA CONCEPT
  - ☐ TYPES OF SOA
    - ☐ FABRY-PEROT OPTICAL AMPLIFIER (FPOA)
    - ☐ TRAVELLING-WAVE OPTICAL AMPLIFIER (TWOA)
  - ☐ SOA'S DYNAMICS

- ❑ FIBER AMPLIFIER
  - ❑ ERBIUM-DOPED FIBER AMPLIFIER (EDFA)
    - ❑ EDFA CONCEPT
    - ❑ EDFA FIGURES OF MERIT
    - ❑ EDFA ARCHITECTURES
  - ❑ RAMAN AMPLIFIER
    - ❑ RAMAN AMPLIFIER CONCEPT
    - ❑ DISTRIBUTED GAIN
- ❑ NOISE IN OPTICAL AMPLIFICATION
  - ❑ AMPLIFIED SPONTANOUS EMISSION (ASE)
  - ❑ AMPLIFIER STATISTICAL MODEL
  - ❑ NOISE FIGURE
  - ❑ OPTICALLY PREAMPLIFIED RECEIVERS

GENERAL CONCEPTS

GENERAL CONCEPTS

Generic Optical Amplifier



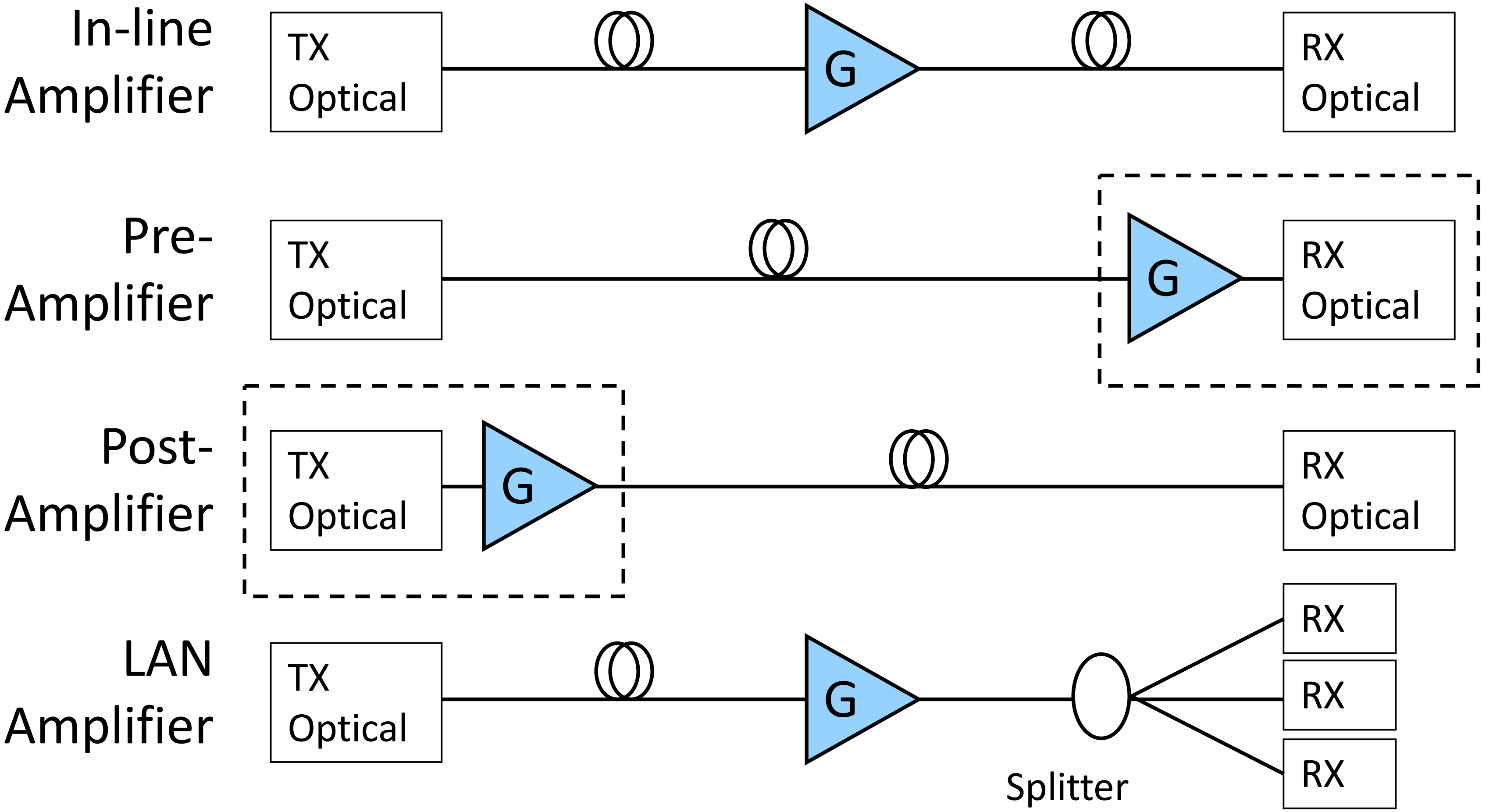
General Concepts

Desirable Characteristics

- ✓ OPERATION FREQUENCY
- ✓ AMPLIFICATION BANDWIDTH
- ✓ GAIN
- ✓ SATURATION POWER
- ✓ NOISE FACTOR
- ✓ SWITCHING SPEED
- ✓ DIMENSIONS
- ✓ COST
- ✓ POWER CONSUMPTION

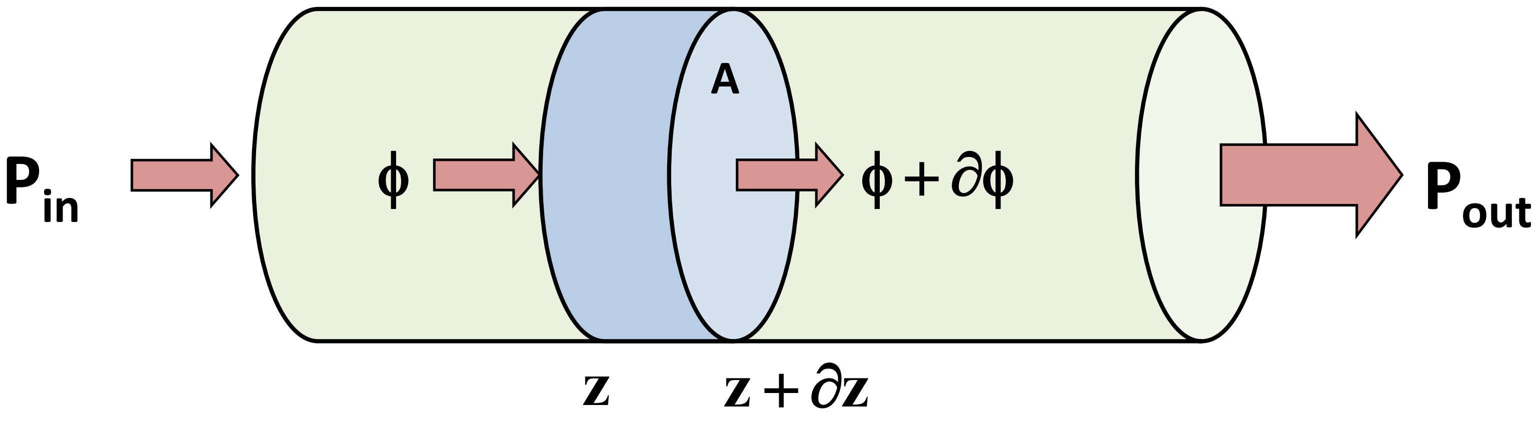
General Concepts

System Applications of Optical Amplifiers



General Concepts

Amplifier Gain



$\phi = \frac{P}{hf \cdot A}$ photon flux $[s^{-1}m^{-2}]$

$\frac{\partial\phi}{\partial z} = g_0\,\phi \rightarrow \frac{\partial P}{\partial z} = g_0\,P$ $[s^{-1}m^{-3}]$ g_0: small-signal Gain Coefficient

$$P_{out} = P_{in}\,\underbrace{e^{g_0 L}}_{G_0} \Rightarrow \boxed{G_0 \equiv \frac{P_{out}}{P_{in}} = e^{g_0 L}}$$

G_0: small-signal Gain

General Concepts

Gain Coefficient Model

Homogeneously broadened 2-level system

small-signal gain coeff.

$$g(\omega, P) = \frac{g_0}{1 + (\omega - \omega_0)^2 T_2^2 + P/P_{sat}}$$

frequency profile

lorentzian

saturation

T_2: dipole relaxation time → **FWHM**

P_{sat}: saturation power → **Maximum Power**

Govind P. Agrawal, “Fiber-Optic Communication Systems”, John Wiley & Sons, 3rd edition 2002, Chapter 6.

General Concepts

Gain Bandwidth

$$g(\omega)=\frac{g_0}{1+(\omega-\omega_0)^2T_2^2}$$

Gain Coefficient

$$g(\omega)$$

$$\frac{\cancel{g_0}}{1+(\omega-\omega_0)^2T_2^2}=\frac{\cancel{g_0}}{2}$$

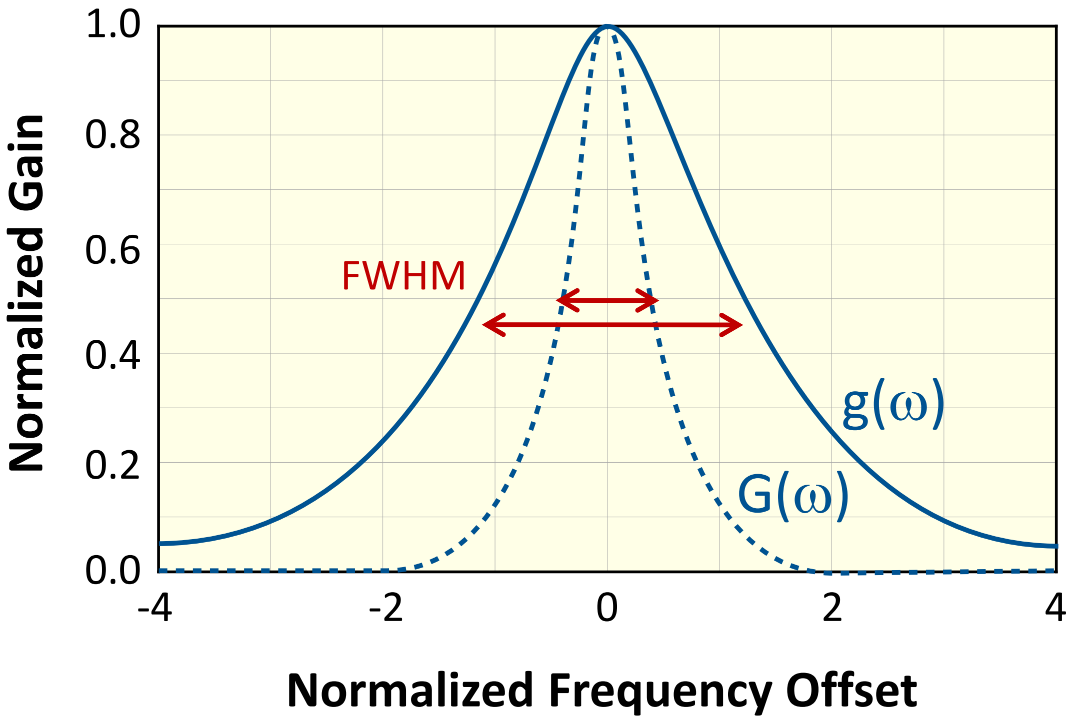
$$\Delta f_{FWHM-g}=\frac{1}{\pi T_2}$$

Gain

$$G(\omega)=e^{g(\omega)L}$$

$$e^{\frac{g_0L}{1+(\omega-\omega_0)^2T_2^2}}=\frac{1}{2}e^{g_0L}=G_0$$

$$\Delta f_{FWHM-G}=\frac{1}{T_2}\left(\frac{\ln 2}{g_0L-\ln 2}\right)^{\frac{1}{2}}=\frac{1}{T_2}\left(\frac{\ln 2}{\ln(G_0/2)}\right)^{\frac{1}{2}}$$



General Concepts

Gain Saturation

$$\frac{\partial P}{\partial z} = g(P)\cdot P$$

$$\boxed{g(P) = \frac{g_0}{1+P/P_{sat}}}$$

$$\partial P = g(P)\cdot P\cdot \partial z = \frac{g_0}{1+P/P_{sat}}P\cdot\partial z \rightarrow \quad g_0\partial z = \left(\frac{1}{P}+\frac{1}{P_{sat}}\right)\partial P$$

Transcendental equation

$$\underbrace{\int_0^L g_0\partial z}_{g_0L} = \int_{P_{in}}^{P_{out}}\left(\frac{1}{P}+\frac{1}{P_{sat}}\right)\partial P = \ln\left(\frac{P_{out}}{P_{in}}\right)+\frac{P_{out}-P_{in}}{P_{sat}} = \boxed{\ln G+\frac{P_{in}}{P_{sat}}(G-1)}$$

extreme cases

$$\ln\left(\frac{P_{out}}{P_{sat}}\right)+\frac{P_{out}}{P_{sat}} = \ln\left(\frac{P_{in}}{P_{sat}}\right)+\frac{P_{in}}{P_{sat}}+g_0L \xrightarrow{P_{in}\ll P_{sat}} P_{out} = P_{in}\,\overbrace{e^{g_0L}}^{G_0}$$

(linear)

$$\xrightarrow{P_{in}\gg P_{sat}} P_{out} = P_{in}+P_{sat}g_0L$$

(saturated)

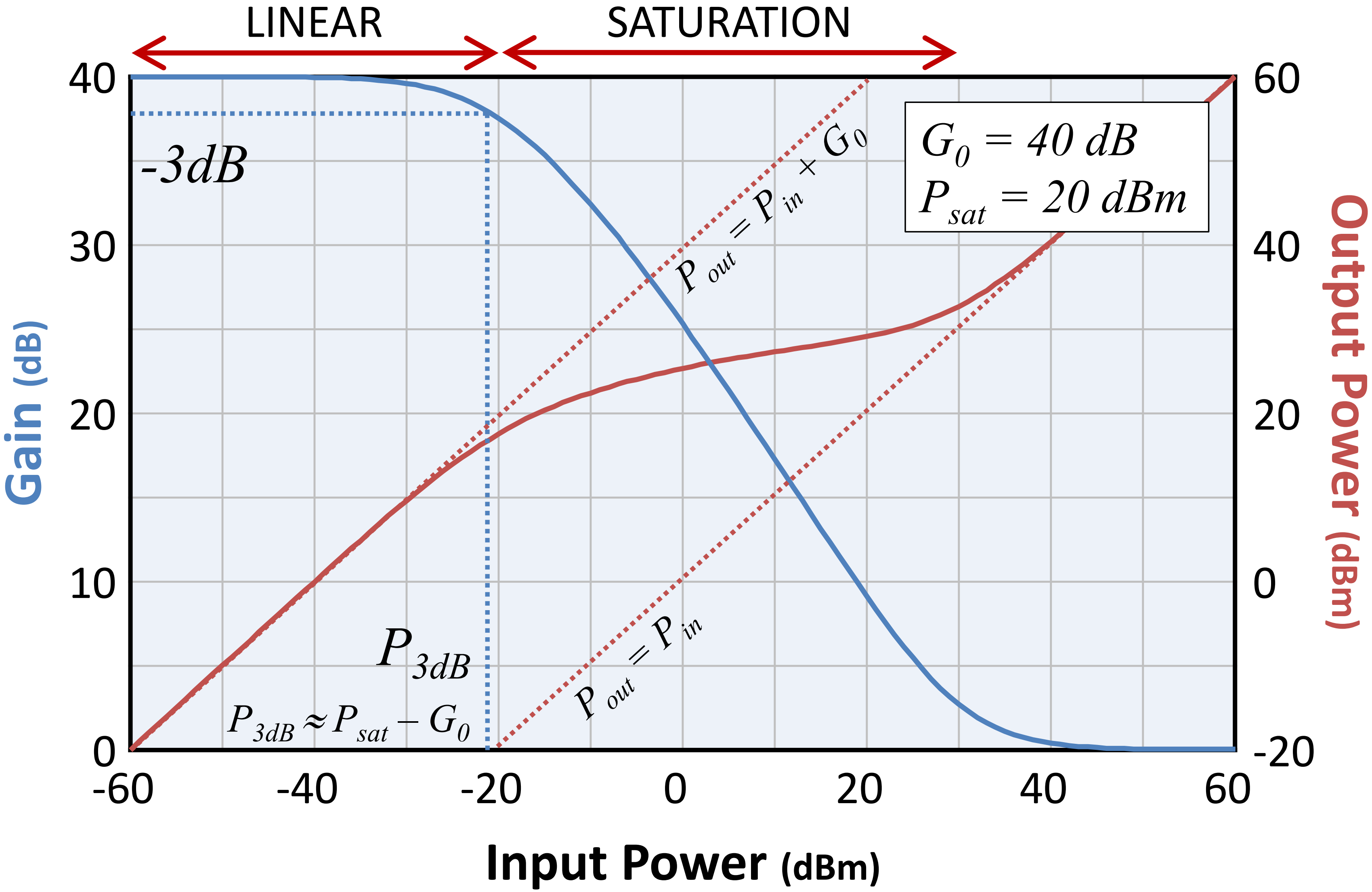
3dB point

$$\cancel{g_0L} = \underbrace{\ln\frac{G_0}{2}}_{\cancel{\ln G_0}-\ln 2}+\frac{P_{3dB}}{P_{sat}}\left(\frac{G_0}{2}-\underbrace{\cancel{1}}_{G_0\gg 1}\right)\rightarrow \ln 2 \approx \frac{P_{3dB}}{P_{sat}}\frac{G_0}{2}$$

$$\boxed{P_{3dB} = \frac{P_{sat}}{G_0}2\ln 2}$$

General Concepts

Gain Saturation



General Concepts

Types of Optical Amplifiers

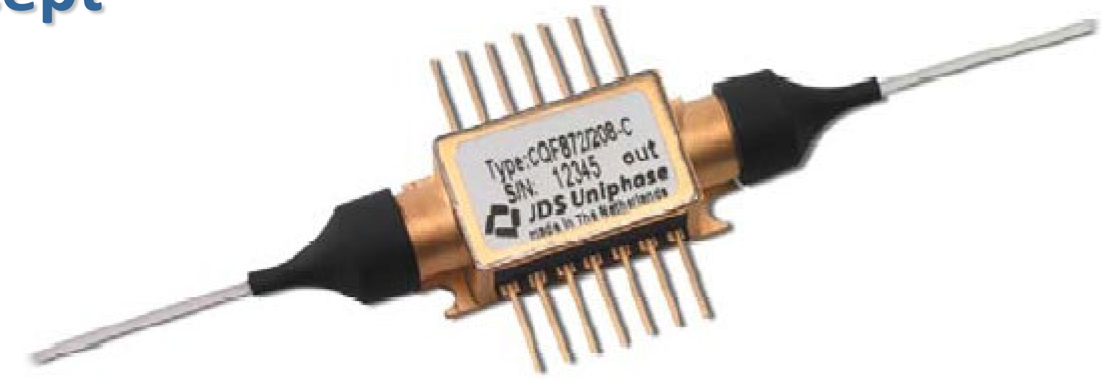
- ☐ Semiconductor Optical Amplifier (SOA)
- ☐ Fiber Optical Amplifier
  - ☐ Doped-Fiber Amplifier
    - ☐ Erbium-Doped Fiber Amplifier (EDFA)
  - ☐ Non-Linear Fiber Amplifier
    - ☐ Raman Amplifier

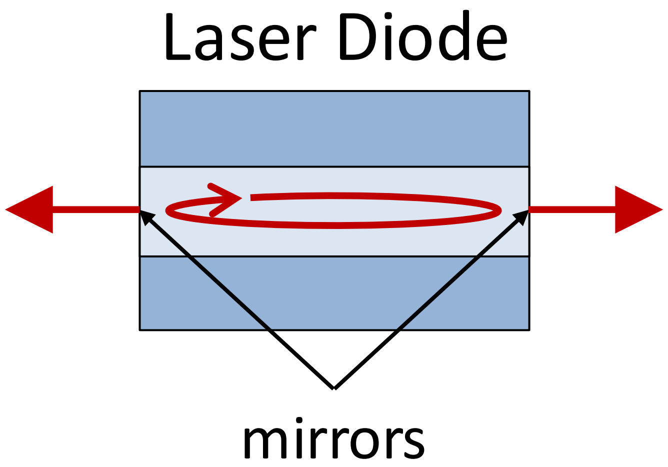
SEMICONDUCTOR OPTICAL AMPLIFIERS

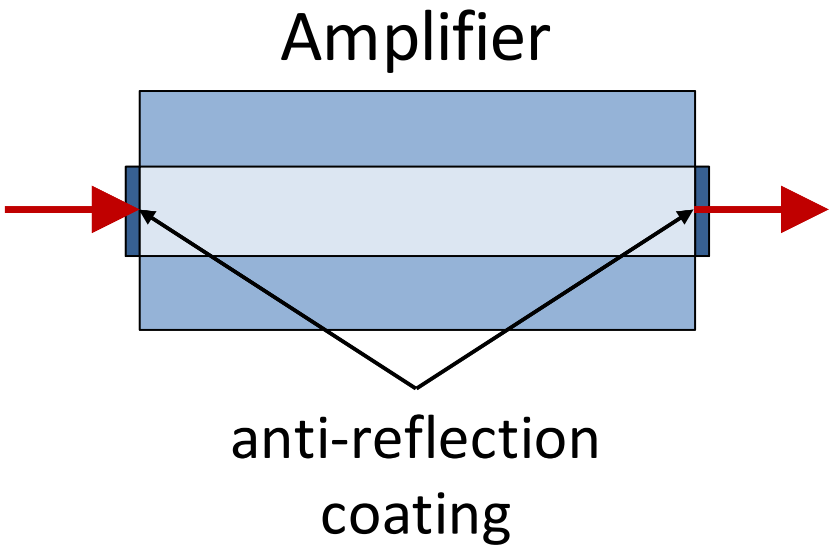
SOA

(SEMICONDUCTOR OPTICAL AMPLIFIER)

SOA Concept

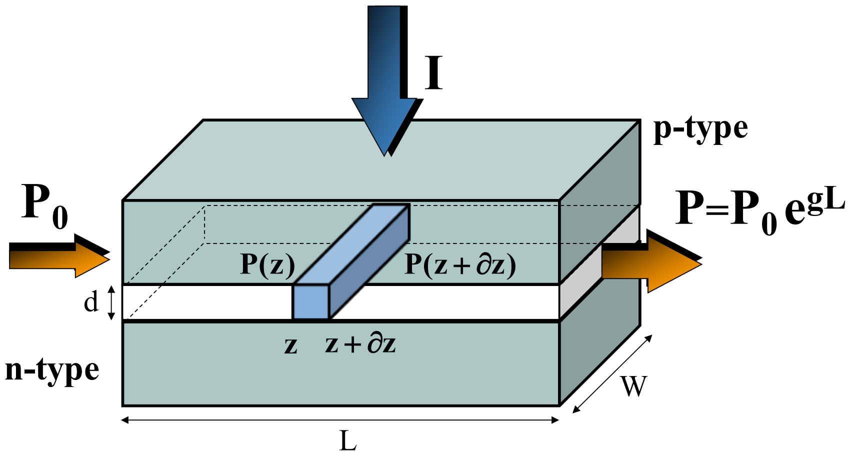


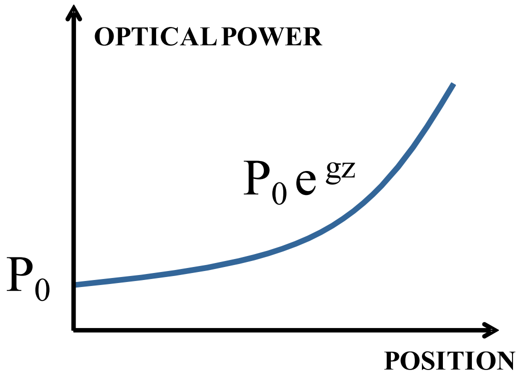




Working Principle

MATERIAL GAIN



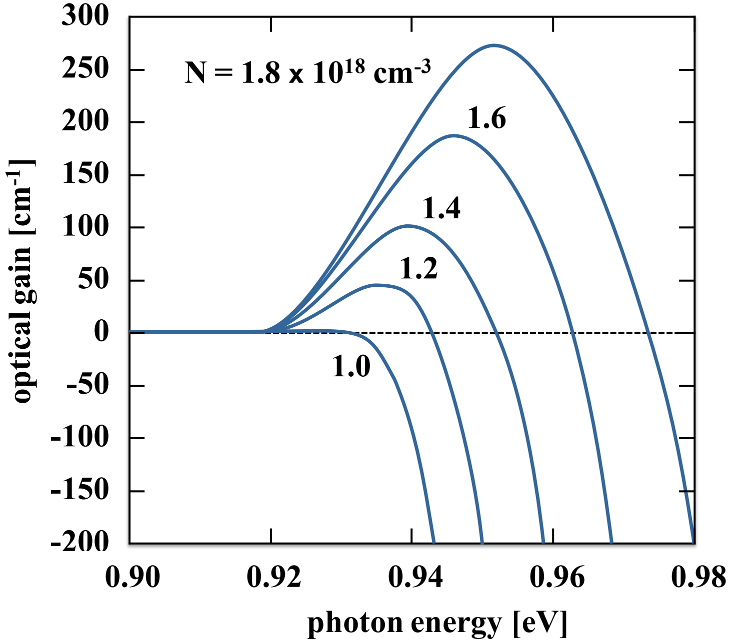


$$\frac{\partial P}{\partial z} = gP$$

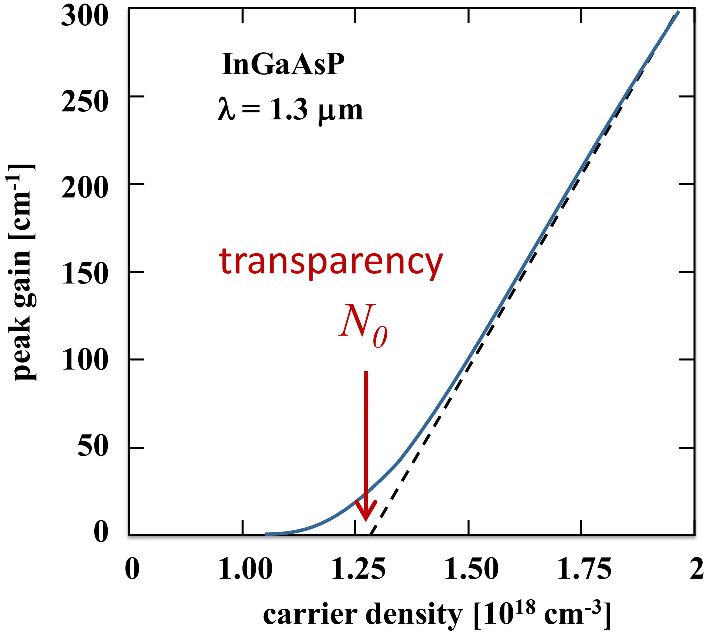
$$\updownarrow$$

$$P(z) = P_0 e^{gz}$$

g ≡ material unity gain [m^{-1}]

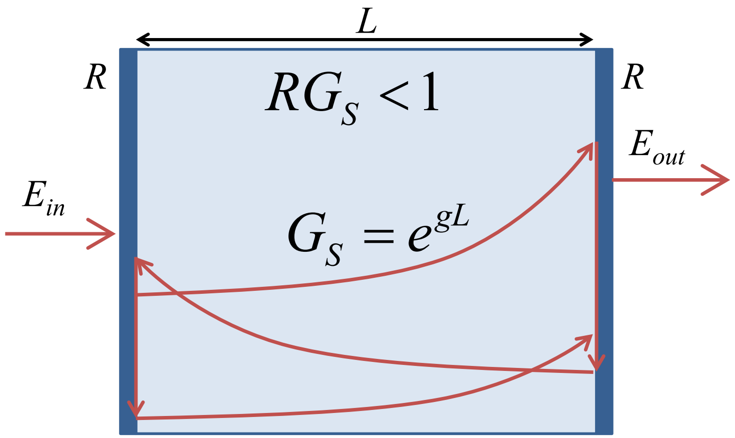


$$\boxed{\lambda = \frac{hc}{q} E[eV]}$$



Working Principle

CAVITY INFLUENCE



FP Laser below threshold

Free-Spectral Range

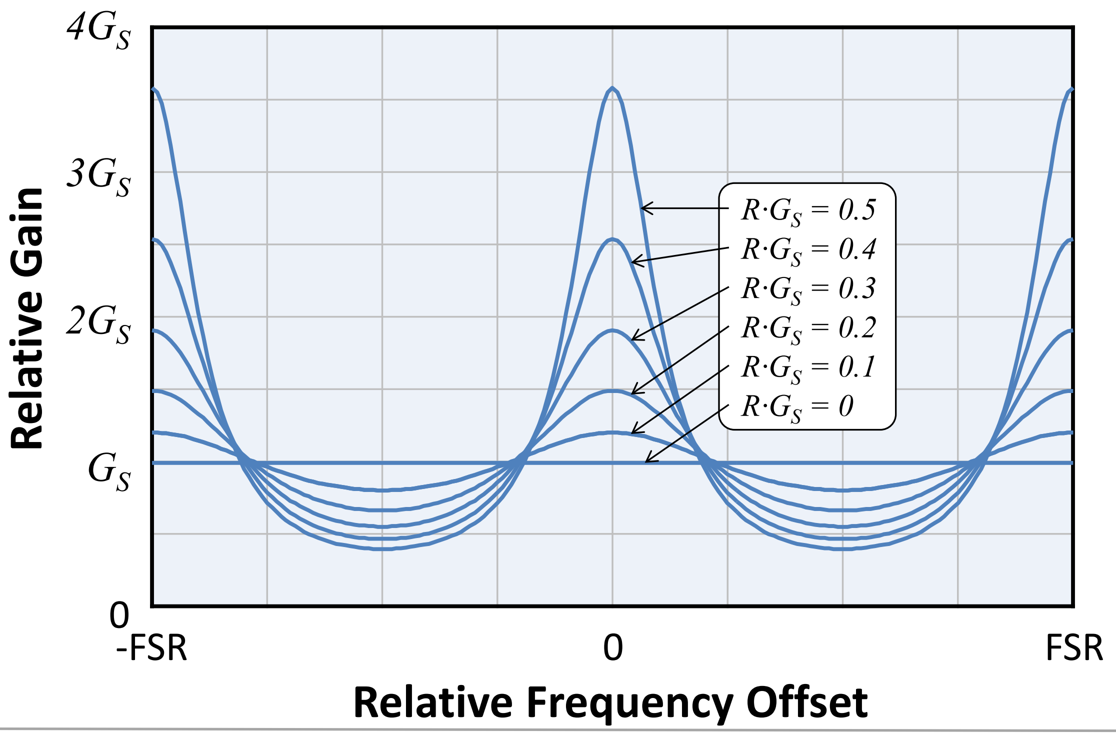
$$FSR = \frac{c}{2nL}$$

3dB-Bandwidth

$$B_{3dB} = \frac{FSR}{2} \frac{a\sin\left\{\frac{1-Re^{gL}}{2\sqrt{Re^{gL}}}\right\}}{\pi}$$

$$\boxed{G = \frac{(1-R)^2 e^{gL}}{\left(1-Re^{gL}\right)^2 + 4Re^{gL}\sin^2(\beta L)}}$$

$$\Delta G \triangleq \frac{G_{max}}{G_{min}} = \frac{\left(1+Re^{gL}\right)^2}{\left(1-Re^{gL}\right)^2} < 2 \rightarrow Re^{gL} < \frac{\sqrt{2}-1}{\sqrt{2}+1} \approx 0.17$$



Types of SOA

- <u>**Fabry-Perot (FPOA)**</u>
  - **Reflectivity 30%**
  - **BW small (1 nm)**
  - **Gain large (25 dB)**
  - **High Temp. Sensitivity**

Under-threshold Laser

- <u>**Traveling Wave (TWOA)**</u>
  - **Reflectivity 10^{-4}, 10^{-5}**
  - **BW large (40 nm)**
  - **Gain moderate (15 dB)**
  - **Moderate Temp. Sensitivity**
  - **Reduced Noise**

Single-Pass

SOA Dynamics

Rate Equation (single pass)

bandwidth not an issue

$$\boxed{\frac{\partial N}{\partial t} = \frac{I}{qV} - R_S - \frac{N}{\tau_r}}$$

$$R_S \equiv g\,v\,S = \Gamma a v\left(N - N_0\right)S$$

$$S = \frac{P}{v\,hf\,Wd}$$

incident photon density $\left[\frac{\text{fotons}}{m^3}\right]$

Stationary Regime

$$\frac{\partial N}{\partial t} = 0 \rightarrow \frac{I}{qV} = R_S + \frac{N}{\tau_r} = g\frac{P}{hf \cdot Wd} + \frac{1}{\tau_r}\left(\frac{g}{\Gamma a} + N_0\right)$$

$$\rightarrow g = \frac{\frac{I}{qV} - \frac{N_0}{\tau_r}}{\frac{P}{hf \cdot Wd} + \frac{1}{\Gamma a \tau_r}} = \frac{\Gamma a \tau_r\left(\frac{I}{qV} - \frac{N_0}{\tau_r}\right)}{1 + \Gamma a \tau_r \frac{P}{hf \cdot Wd}}$$

gain coefficient

$$\boxed{g = \frac{g_0}{1 + P/P_{sat}}}$$

$$\boxed{g_0 \equiv \Gamma a \tau_r\left(\frac{I}{qV} - \frac{N_0}{\tau_r}\right)}$$

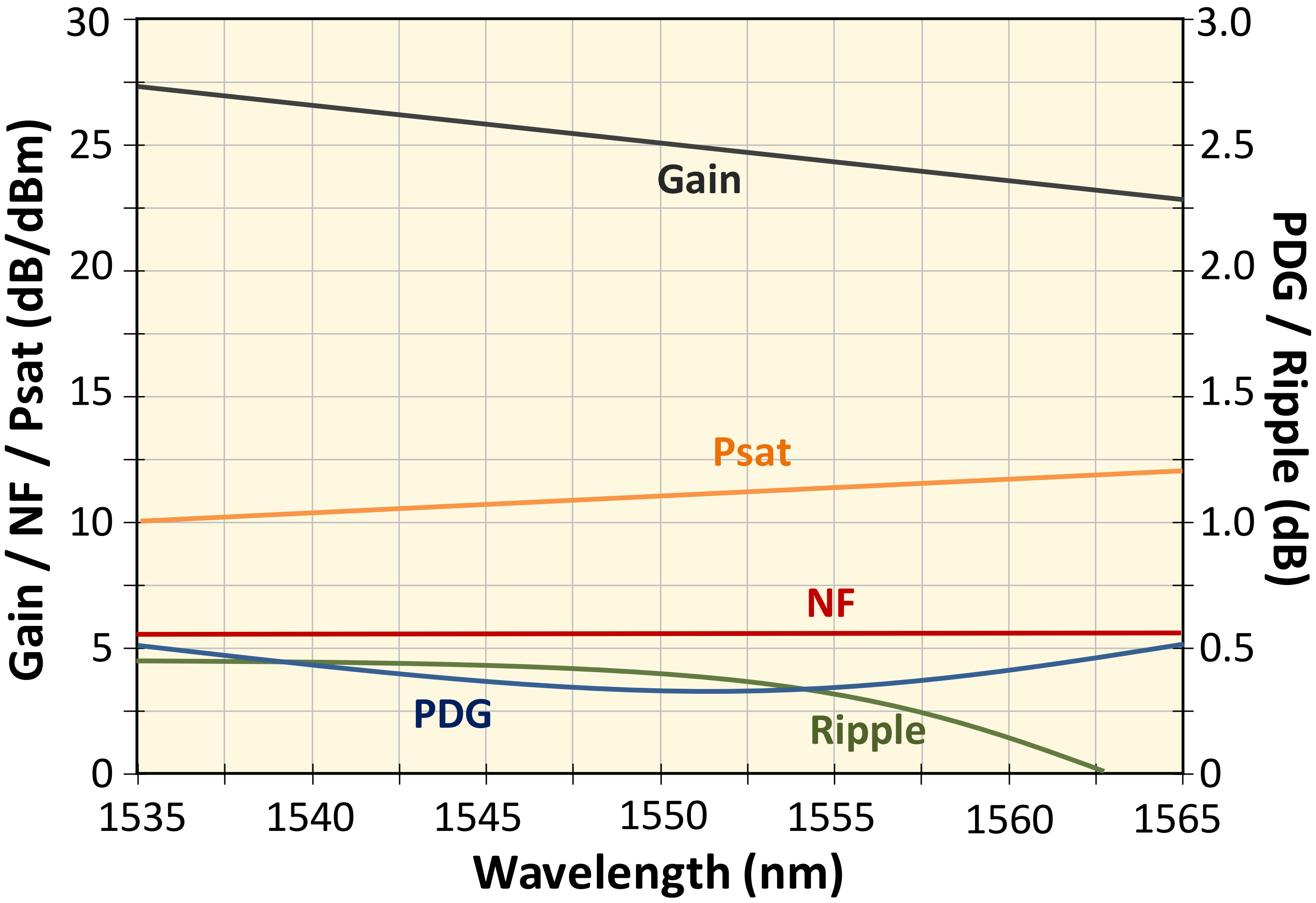
small-signal gain coefficient

$$\boxed{P_{sat} \equiv \frac{hf \cdot Wd}{\Gamma a \tau_r}}$$

saturation power

SOA Performance

SOA performance



ERBIUM-DOPED FIBER AMPLIFIERS

EDFA

(ERBIUM-DOPED FIBER AMPLIFIER)

input signal

1530 - 1570 nm

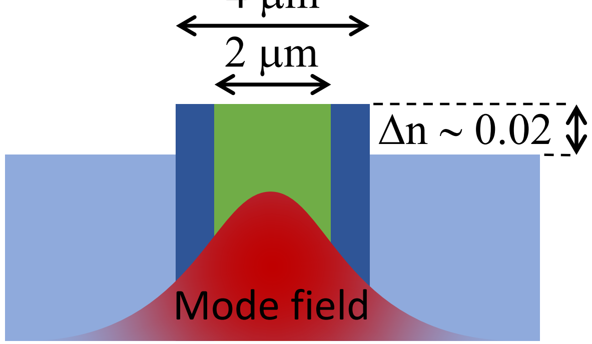
erbium-doped fiber

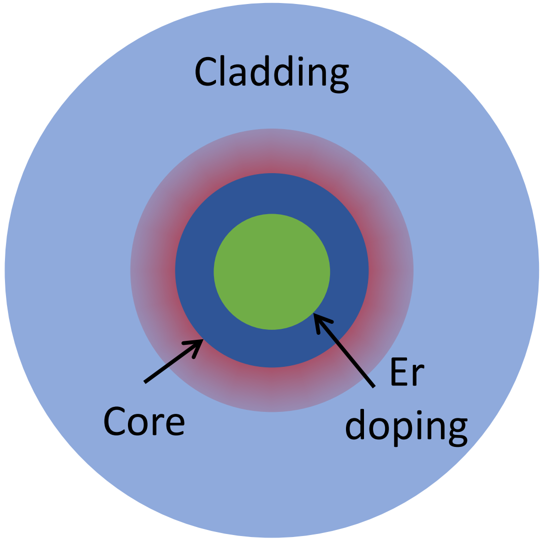
output signal

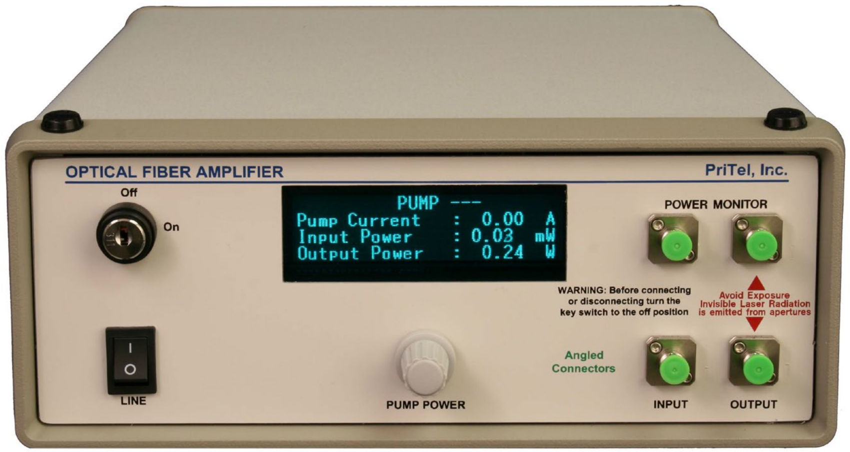
1530 - 1570 nm

pump signal

980 or 1480 nm







Benchtop Laboratory EDFA

Other Dopants (Rare Earth)

Thulium → 1875 nm

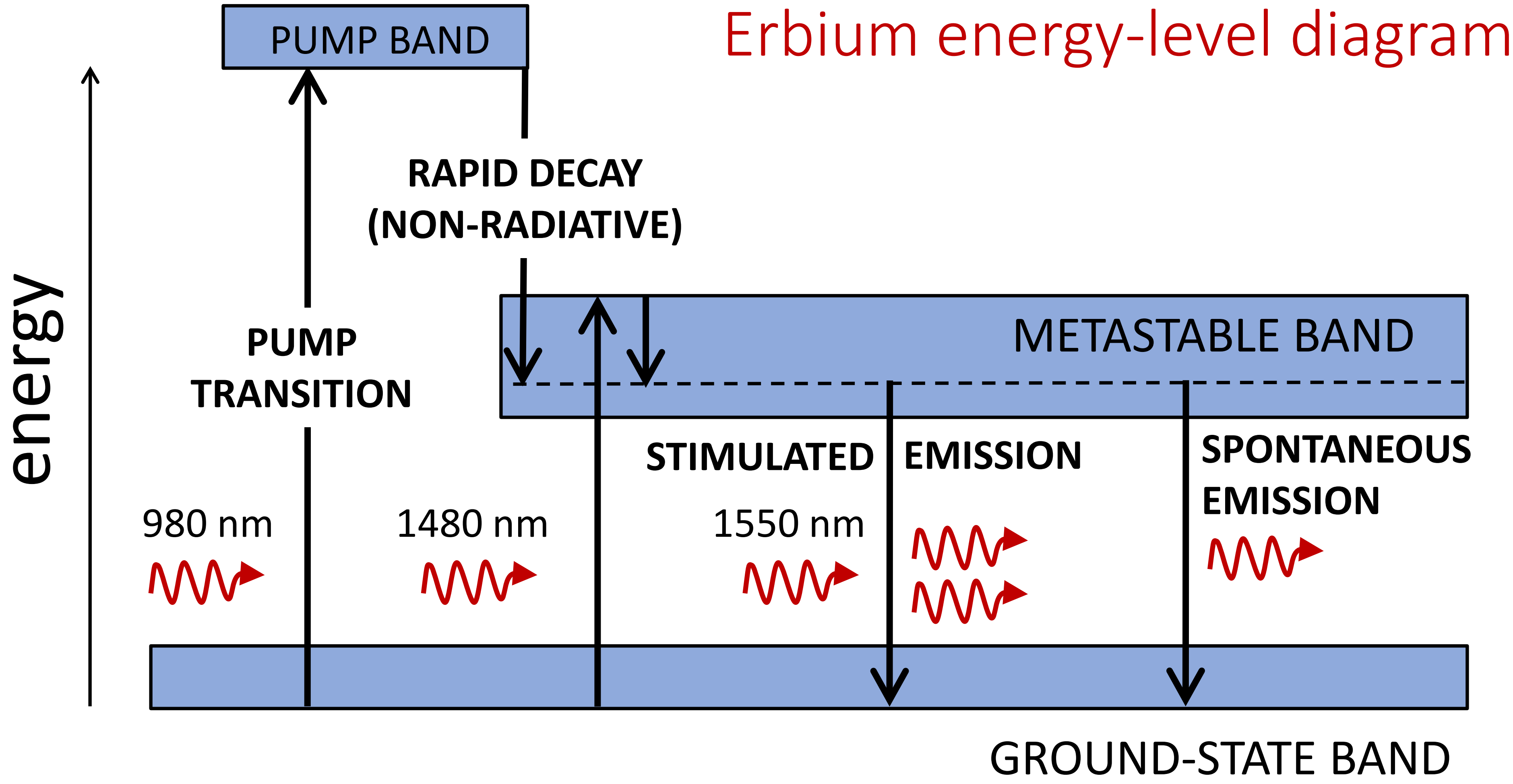
Praseodymium → 1300 nm

Ytterbium → 1000 nm

Working Principle

Amplification Mechanism

Erbium energy-level diagram



Working Principle

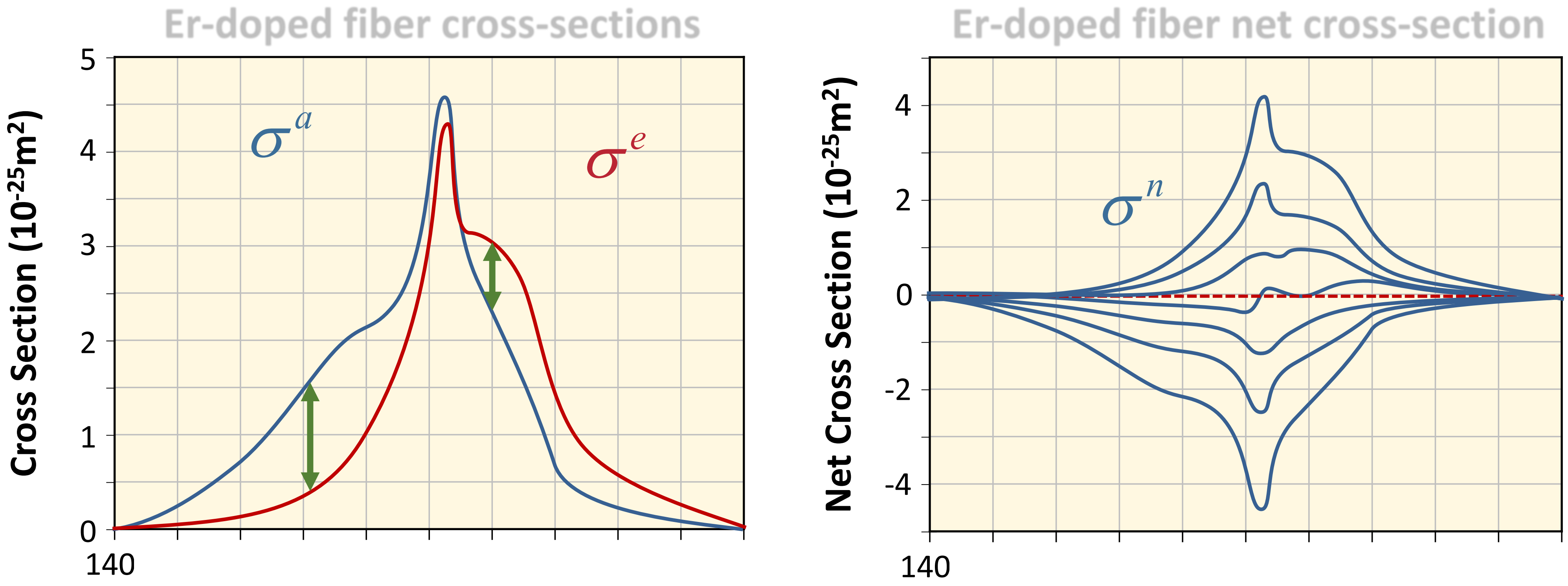
Conversion Efficiency & Gain

Population Inversion

Gain Parameter

$$g=\sigma^e \underset{\uparrow}{N_2}-\sigma^a \underset{\uparrow}{N_1} = \xrightarrow{N_1+N_2=N} = \underbrace{\left\{\sigma^e \frac{N_2}{N}-\sigma^a\left(1-\frac{N_2}{N}\right)\right\}}_{\sigma^n} N$$

Er^{3+} concentration



Working Principle

Conversion Efficiency & Gain

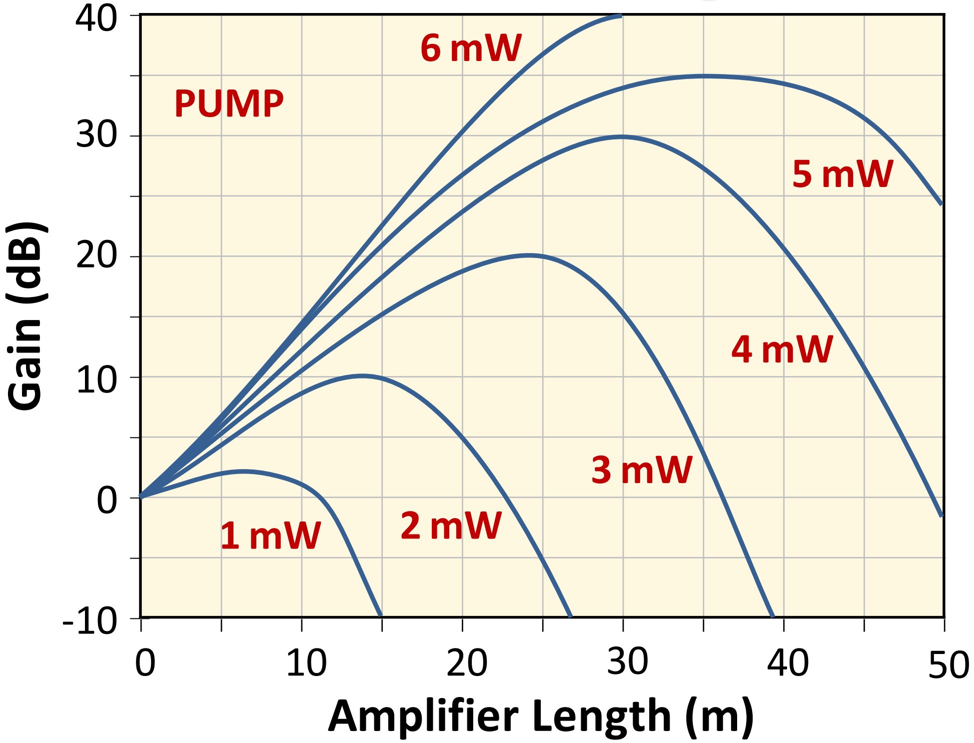
Net Gain Parameter

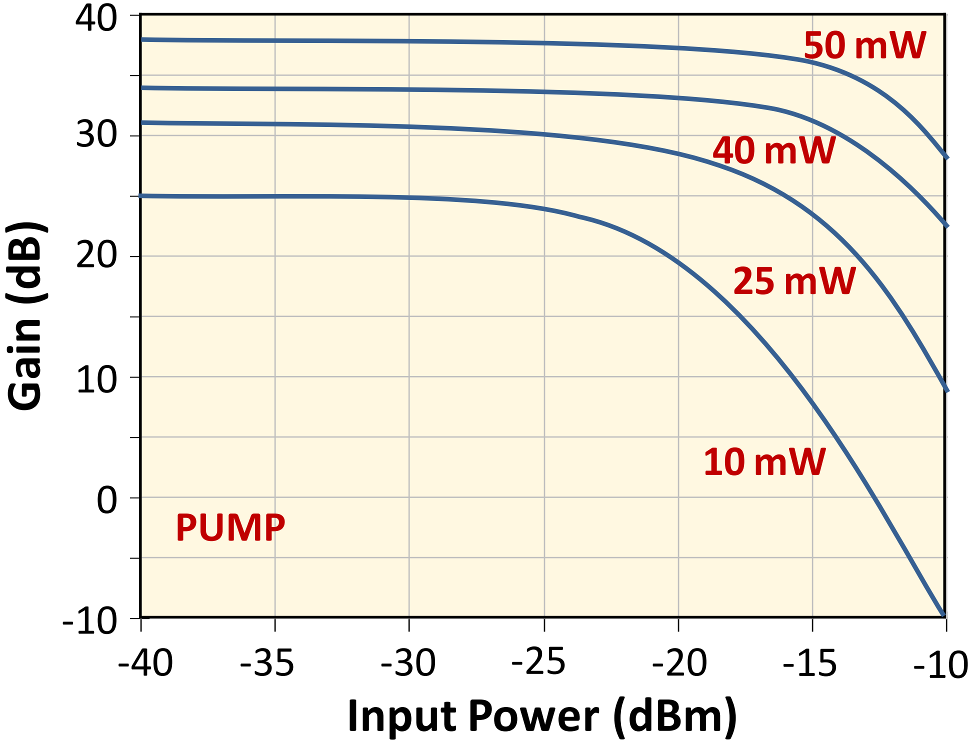
$$g_n = \underset{\substack{\uparrow \\ \text{Confinement}}}{\Gamma}\left\{\sigma^e N_2 - \sigma^a N_1\right\} - \underset{\substack{\uparrow \\ \text{Losses}}}{\alpha}$$

➡

Amplifier's Gain

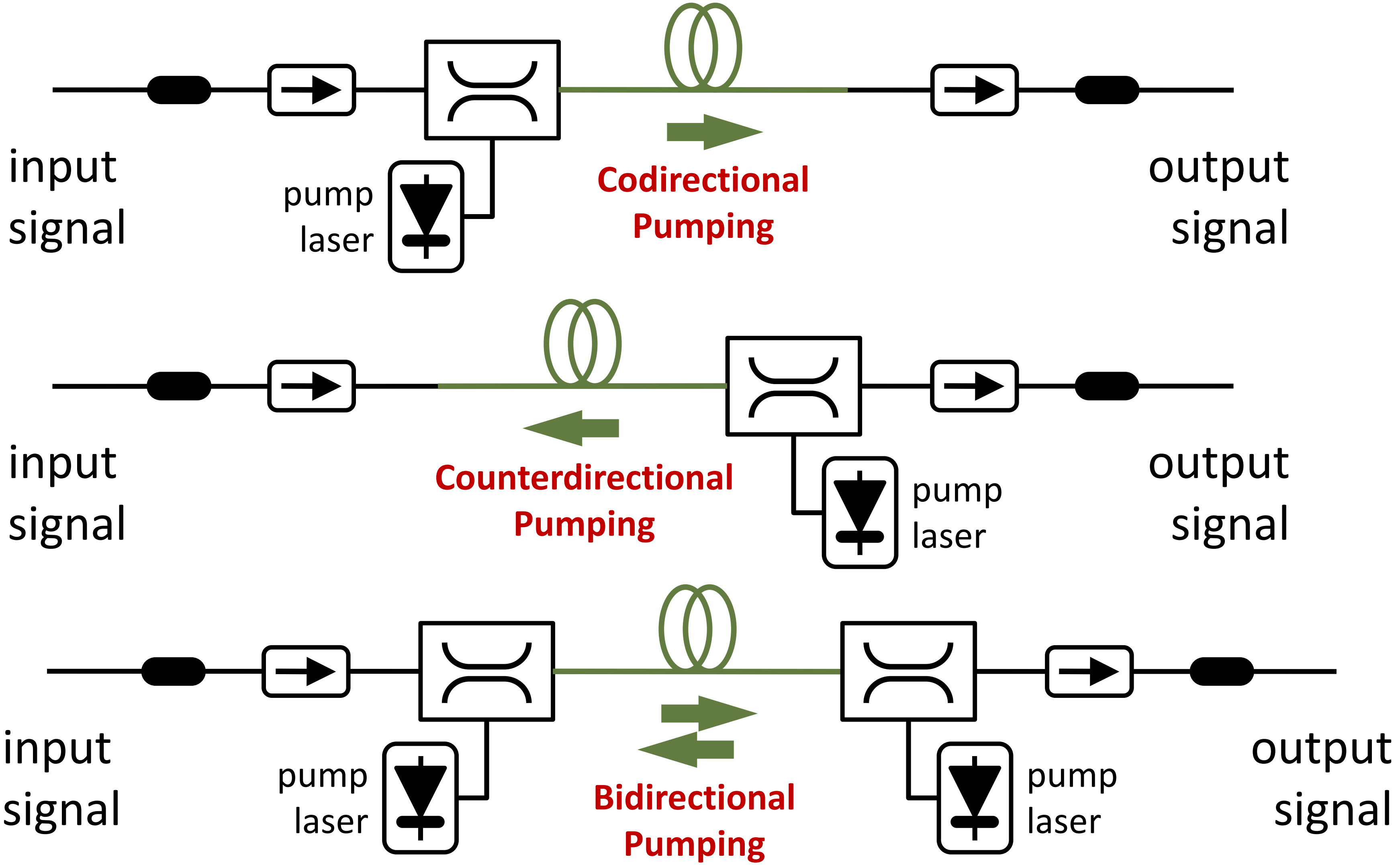
$$G = e^{\int_0^L g_n(z)\, dz}$$


Gain vs EDFA length

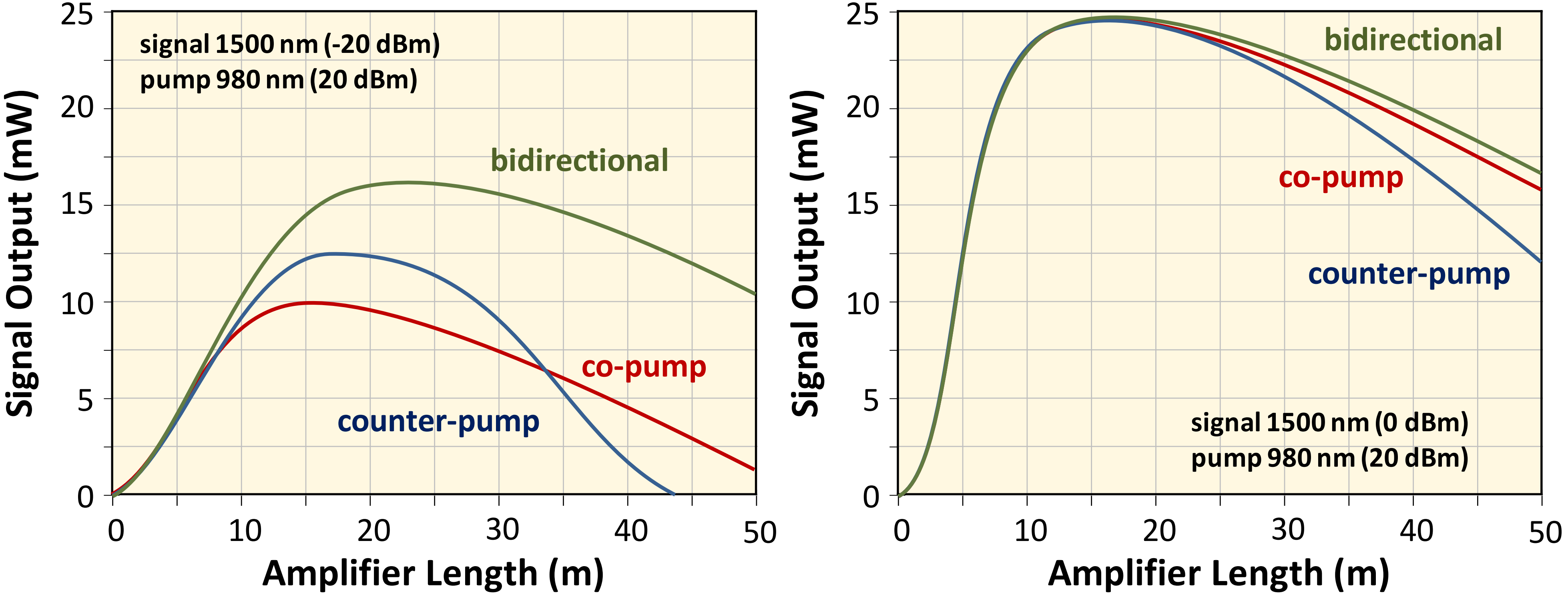

Gain vs Input Power

EDFA Architectures

EDFA Architectures – pumping direction

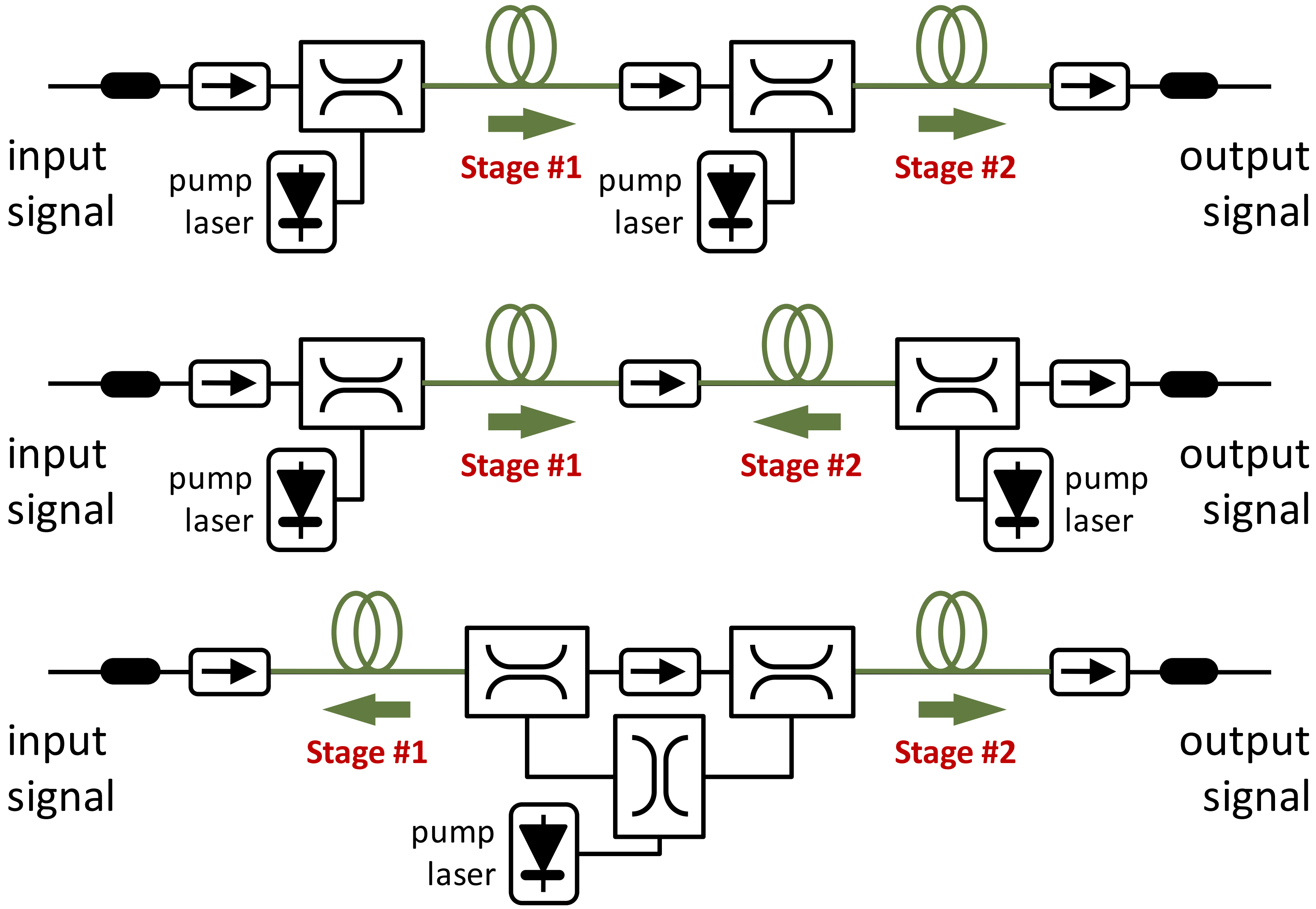


EDFA Architectures – pumping direction



EDFA Architectures

EDFA Architectures – multistage



EDFA Performance

EDFA vs SOA

SOA

- Gain → 15-20 dB
- Bandwidth → 40 nm
- Saturation → 8-10 dBm
- Noise → Moderate
- Polarization → Sensitive
- Crosstalk → High
- Switching → Fast
- Integrable → Yes
- Cost → Moderate

EDFA

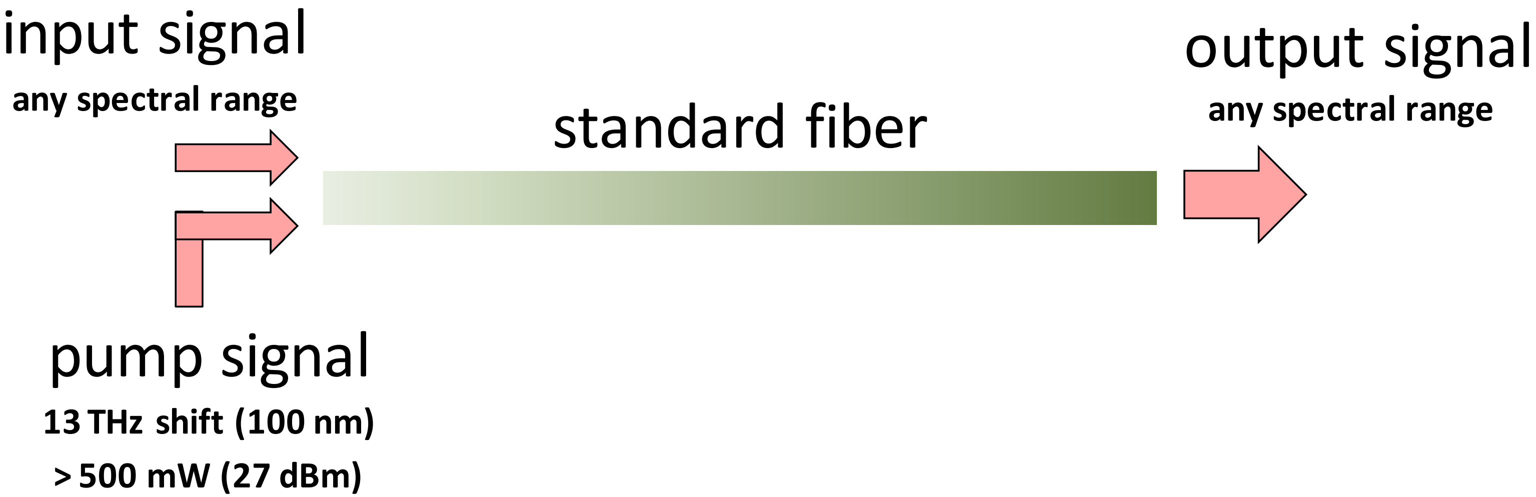
- Gain → 30-40 dB
- Bandwidth → 30 nm
- Saturation → 20 dBm
- Noise → Low
- Polarization → Indep.
- Crosstalk → Low
- Switching → Slow
- Integrable → No
- Cost → High

RAMAN AMPLIFIERS

RAMAN AMPLIFIER

RAMAN AMPLIFIER

Raman Amplifier Concept


input signal

any spectral range

standard fiber

output signal

any spectral range

pump signal

13 THz shift (100 nm)

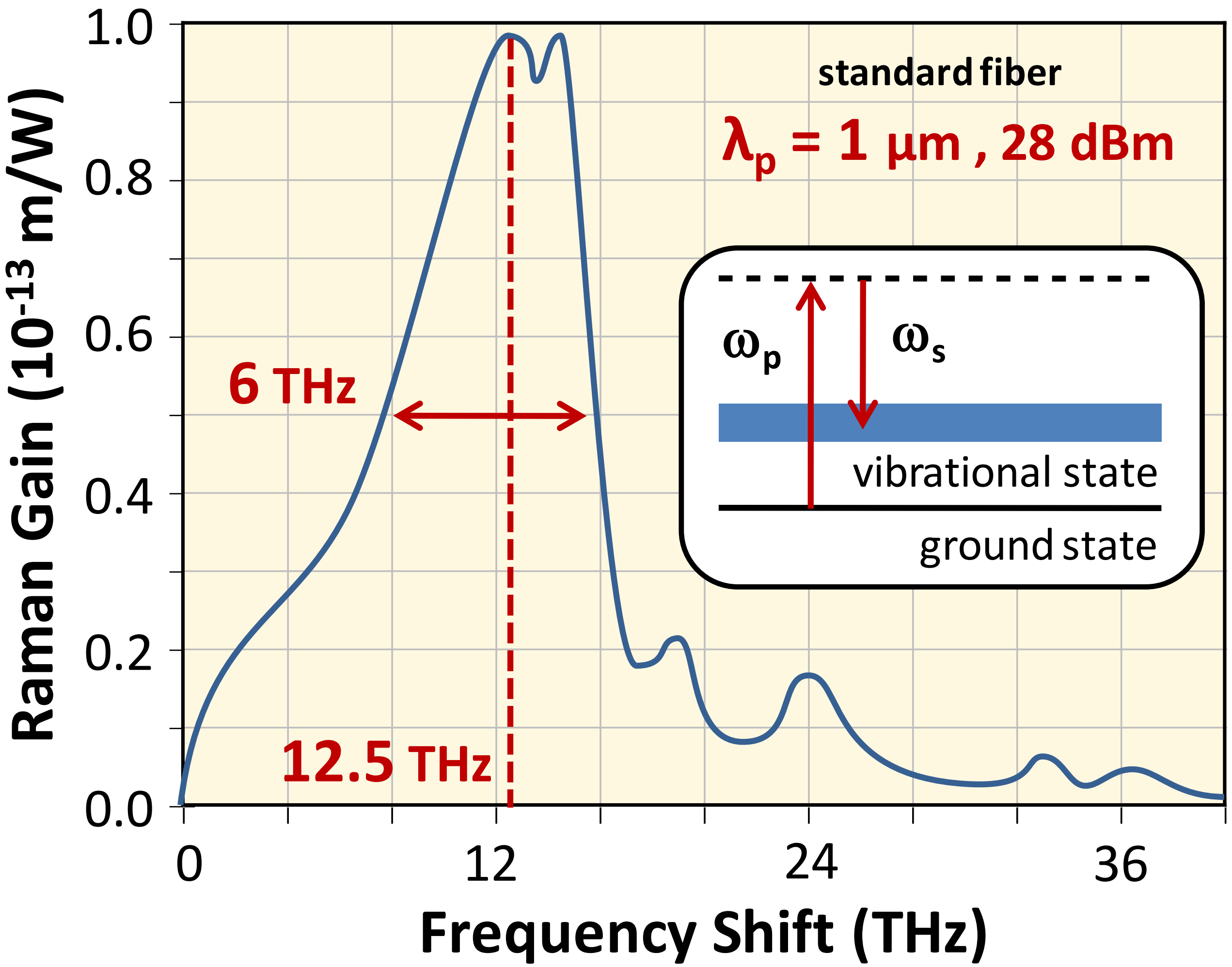
> 500 mW (27 dBm)

Main Characteristics

1. forward/backward capability
2. 13 THz frequency shift
3. 40 THz bandwidth
4. any frequency window
5. longer fiber lengths (>1Km)

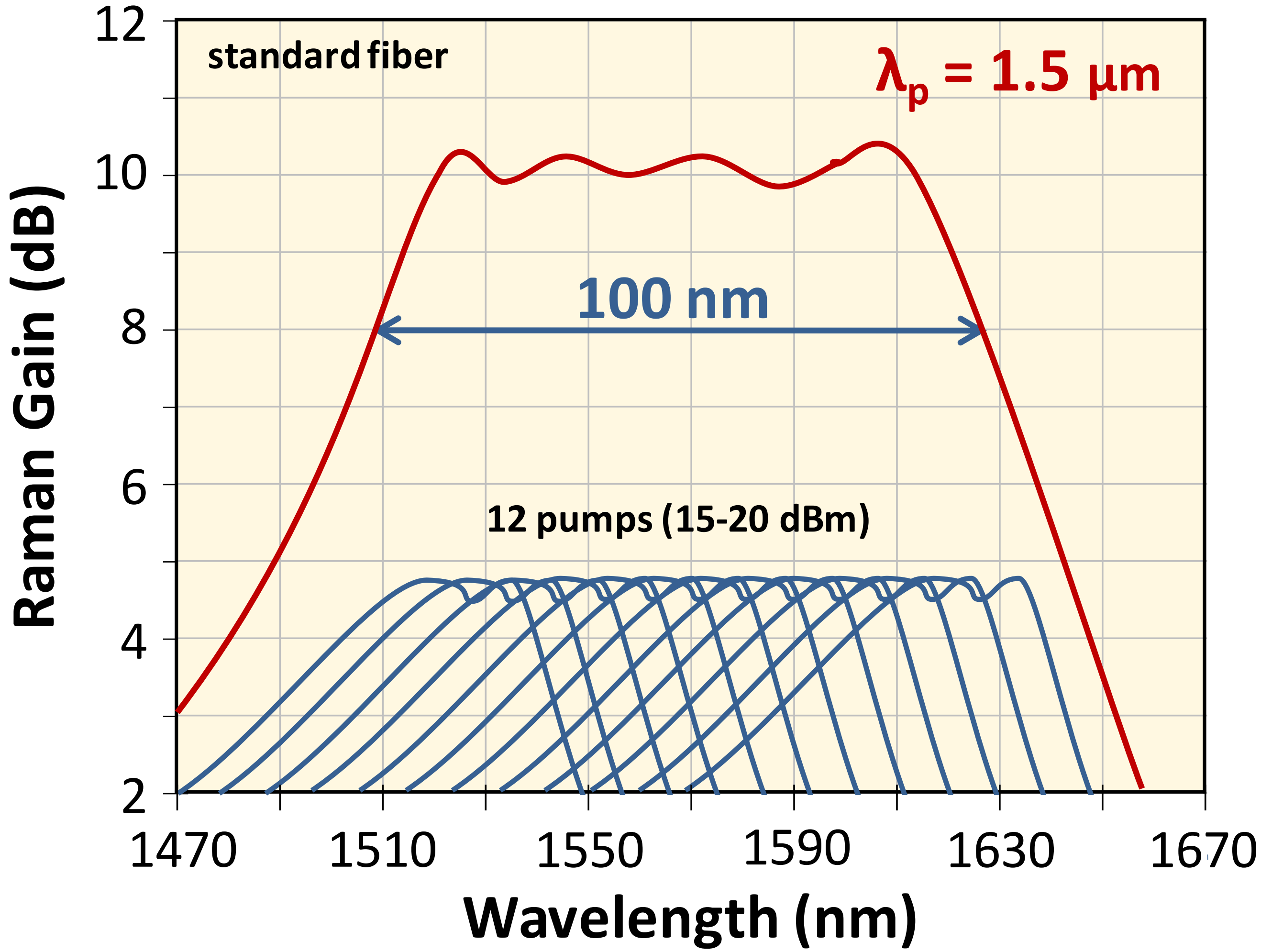
Working Principle

Stimulated Raman Scattering (SRS)



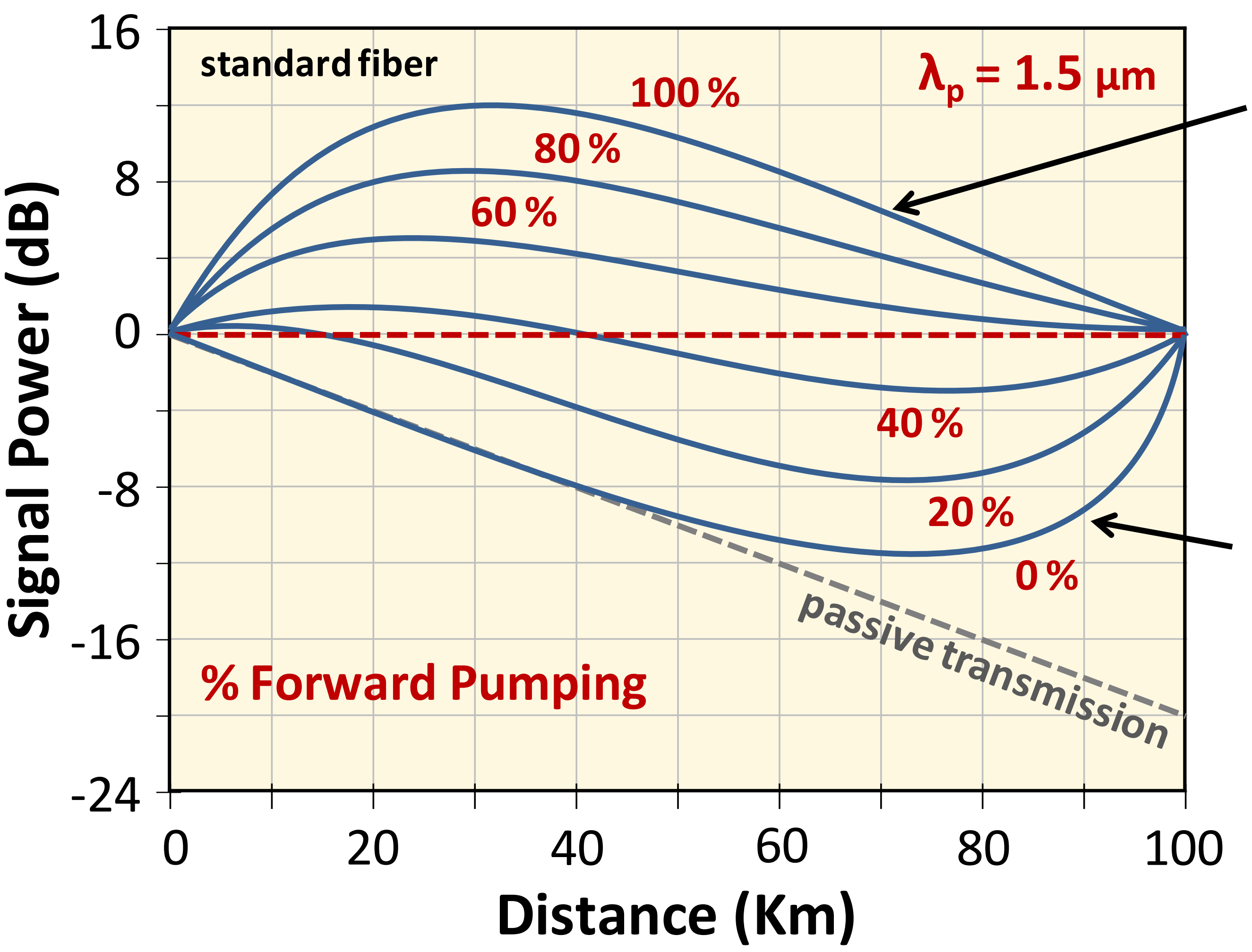
Working Principle

Multiple-Pump Raman Amplifiers



Raman Amplifier Performance

Distributed Raman Amplification



lower noise

lower nonlinearities

Raman Amplifier Performance

Performance Limiting Factors

1. Spontaneous Raman Scattering (noise)
2. Rayleigh Backscattering (multipath interference → most limiting factor)
3. Polarization Dependent Gain (copolarized pumping → high PMD penalty)
4. Pump-Noise Transfer (exponential pump power dependence)

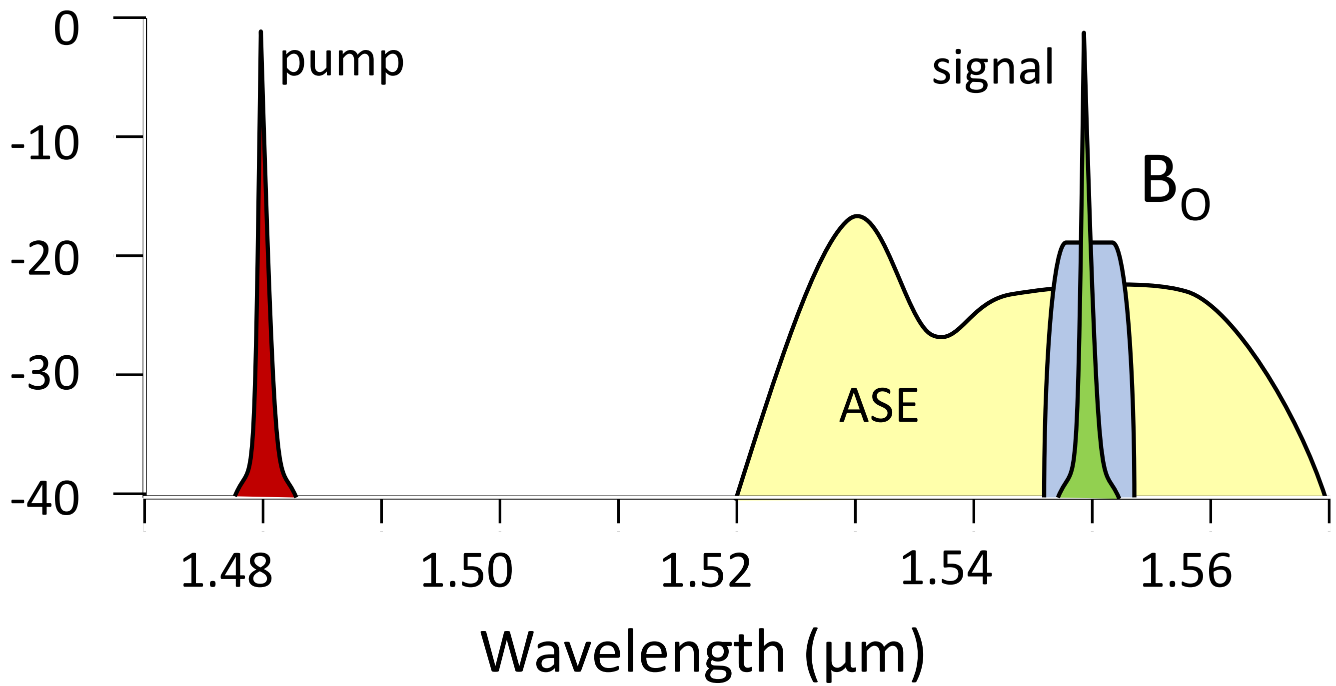
ASE

AMPLIFIED SPONTANEOUS EMISSON

ASE NOISE

Amplified Spontaneous Emission (ASE)

Spontaneous recombination of electron-hole pairs in the active region is the origin of ASE noise



ASE Spectrum

ASE spectrum (2 polarizations)

$$S_{ASE}(f) = hf\left[G(f)-1\right]2\rho$$

$$\rho = \frac{N_2}{N_2 - N_1} \geq 1$$

spontaneous emission factor

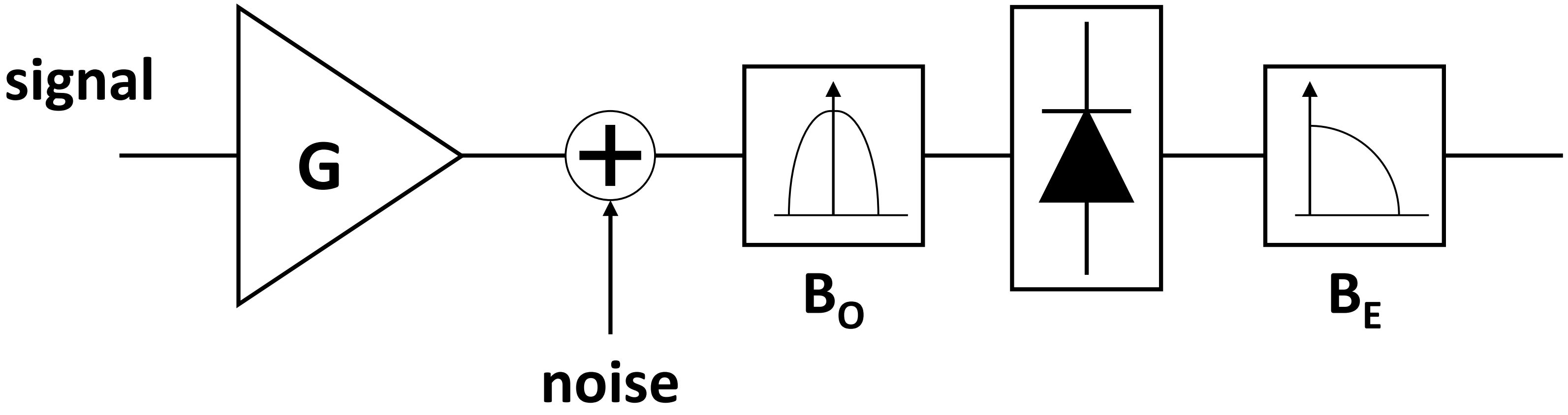
operating bandwidth (B_O)

$$S_{ASE}(f) \approx hf_c\left[G(f_c)-1\right]2\rho = ct$$

← **white noise**

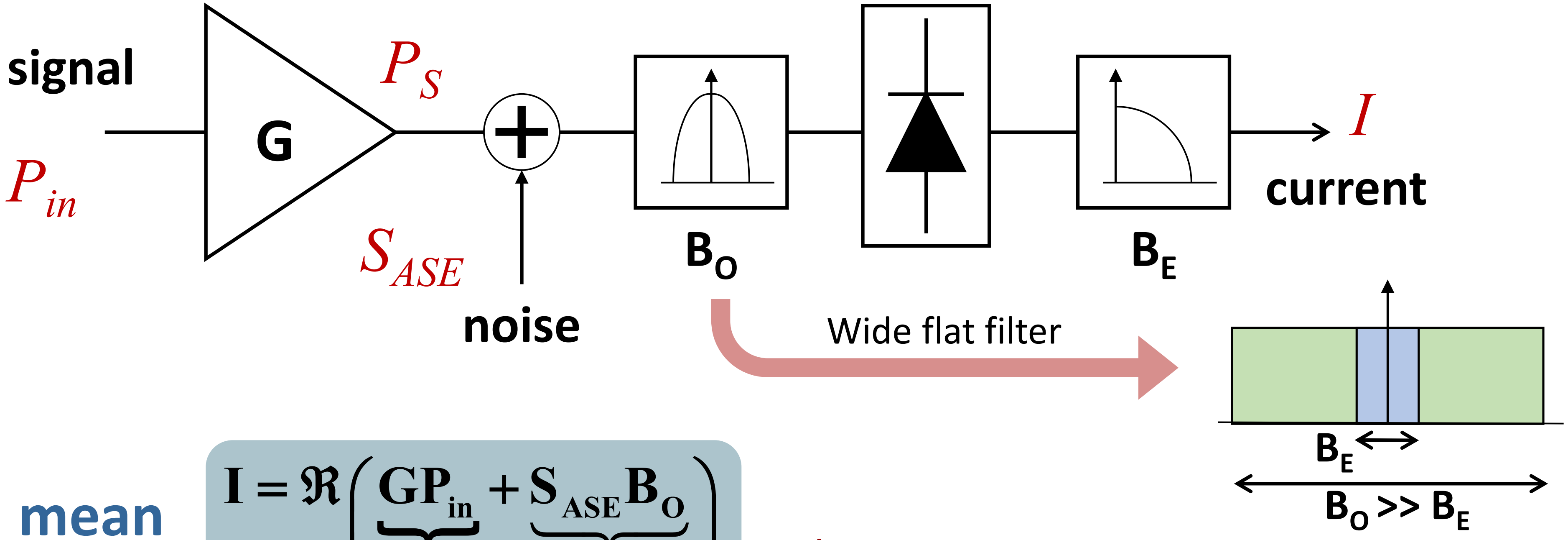
$$P_{out} = GP_{in} + \underbrace{S_{ASE}B_O}_{P_{ASE}}$$

← OSNR



Photocurrent Statistics

Photodetection Statistics – signal + ASE



mean

$$I = \Re\left(\underbrace{GP_{in}}_{P_S} + \underbrace{S_{ASE}B_O}_{P_{ASE}}\right)$$

variance

$$\sigma_i^2 = \underbrace{2qB_E\Re\left(P_S + P_{ASE}\right)}_{\text{shot noise}} + \overbrace{\underbrace{2\Re^2 P_S S_{ASE} B_E}_{\text{signal-ASE beat noise}}}^{\text{dominant term}} + \underbrace{\frac{1}{2}\Re^2 S_{ASE}^2 B_O B_E}_{\text{ASE-ASE beat noise}} + \underbrace{\sigma_{th}^2}_{\text{thermal noise}}$$

$$S_{ASE} = hf\left(G-1\right)2\rho$$

Noise Factor

Noise Factor (NF)

$$\mathrm{ESNR} \equiv \frac{\langle i_s \rangle^2}{\sigma_{tot}^2} \approx \frac{\langle i_s \rangle^2}{\sigma_{s-ASE}^2} = \frac{(\Re G P_{in})^2}{2\Re^2 \underbrace{G P_{in}}_{P_S} \underbrace{hf(G-1)2\rho B_E}_{S_{ASE}}} = \underbrace{\frac{P_{in}}{2hf B_E}}_{SNR_{LQ}} \frac{G}{2\eta\rho(G-1)}$$

Quantum Limit

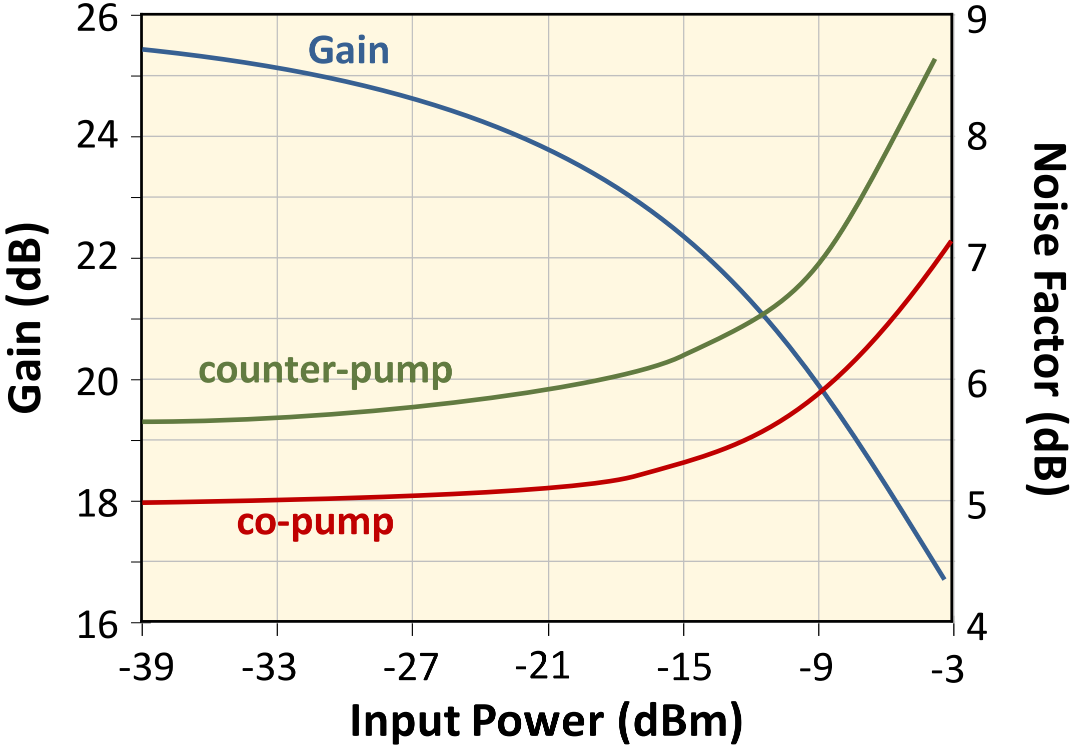
- Coherent light (no ASE)
- Ideal photodetector (η=1, no thermal noise)

$$\boxed{\mathrm{NF} \equiv \frac{\mathrm{SNR}_{LQ}}{\mathrm{SNR}} = \frac{2\rho(G-1)}{G}}$$

$$\mathrm{NF} \xrightarrow{G\gg} 2\rho$$

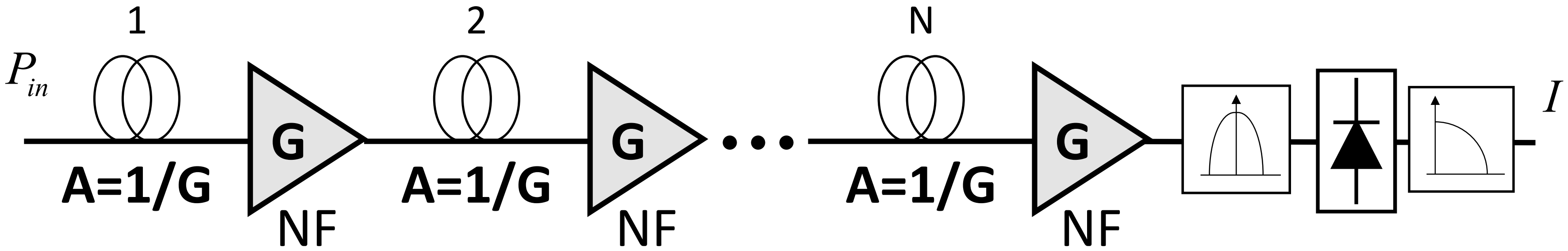
$$\mathrm{NF} \xrightarrow{\rho=1} 2\ (3\mathrm{dB})$$

Ideal Population Inversion



Noise Factor

SNR degradation through transmission

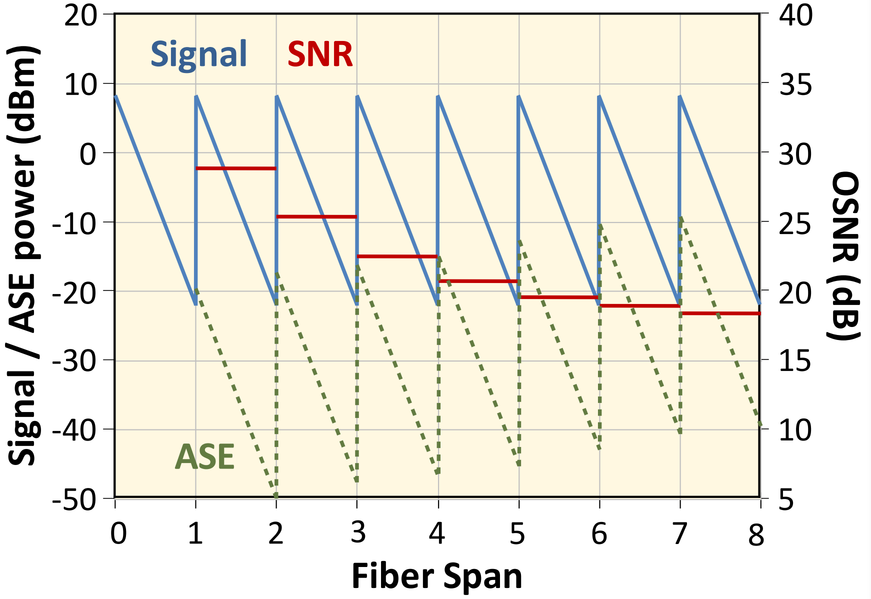


$$ESNR_N \approx \frac{1}{N}\frac{P_{TX}}{\underbrace{2S_{ASE}B_E}_{ESNR_1}} \xrightarrow[\times \frac{2B_E}{B_O}]{} OSNR_N = \frac{1}{N}\frac{P_{TX}}{\underbrace{S_{ASE}B_O}_{OSNR_1}}$$

$$S_{ASE} = hf\,(G-1)\,NF$$

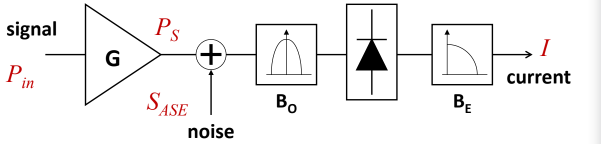
mean $I = \Re\left(P_{TX} + \overbrace{N \cdot S_{ASE}B_O}^{P_{ASE}}\right)$

variance $\sigma_i^2 = 2qB_E\Re\left(P_{TX} + N \cdot S_{ASE}B_O\right) + \underbrace{\overbrace{2\Re^2 P_{TX} N \cdot S_{ASE}B_E}^{\sigma^2_{s-ASE}}}_{\text{dominant term}} + \frac{1}{2}\Re^2 N^2 S_{ASE}^2 B_O B_E + \sigma_{th}^2$



Receiver Sensitivity

Pre-Amplified Receiver Sensitivity



$$\boxed{\begin{aligned} I_1 &= \Re\left(\underbrace{GP_{in}}_{P_S} + P_{ASE}\right) \qquad & \sigma_1^2 &\approx 2\Re^2 P_S P_{ASE}\, B_E/B_O + \Re^2 P_{ASE}^2\, B_E/2B_O \\ I_0 &= \Re P_{ASE} & \sigma_0^2 &\approx \Re^2 P_{ASE}^2\, B_E/2B_O \end{aligned}}$$

$$Q_{OA} = \frac{I_1 - I_0}{\sigma_1 + \sigma_0} \approx \frac{\cancel{\Re} P_S}{\sqrt{2\cancel{\Re^2} P_S P_{ASE}\, B_E/B_O + \cancel{\Re^2} P_{ASE}^2\, B_E/2B_O} + \cancel{\Re} P_{ASE}\sqrt{B_E/2B_O}} \geq Q$$

$$\rightarrow \frac{P_S/P_{ASE}}{Q}\sqrt{\frac{2B_O}{B_E}} - 1 \geq \sqrt{4\frac{P_S}{P_{ASE}} + 1} \rightarrow \left(\frac{P_S}{P_{ASE}}\right)^{\cancel{2}} \frac{2B_O}{Q^2 B_E} - 2\frac{\cancel{P_S}}{\cancel{P_{ASE}}}\sqrt{\frac{2B_O}{Q^2 B_E}} \cancel{+1} \geq 4\frac{\cancel{P_S}}{\cancel{P_{ASE}}} \cancel{+1}$$

$$\rightarrow \frac{P_S}{P_{ASE}} = \boxed{OSNR \geq Q\left(Q\frac{2B_E}{B_O} + \sqrt{\frac{2B_E}{B_O}}\right)} \xrightarrow{B_O = 2B_E} Q(Q+1) \xrightarrow{Q\,=\,6} 16\text{ dB}$$

(Q = 6, ρ= 1)

84 photons/bit

$$\frac{P_S}{P_{ASE}} = \frac{\cancel{G} P_{in}}{hf \cdot 2\rho \cancel{G} \cdot B_O} = \frac{1}{2\rho}\underbrace{\frac{P_{in}}{hf}\overbrace{\frac{1}{2B_E}}^{T_b}}_{\langle n\rangle}\frac{2B_E}{B_O} \rightarrow \boxed{\langle n\rangle \geq 2\rho\cdot Q\left(Q + \sqrt{\frac{B_O}{2B_E}}\right)} \xrightarrow{B_O = 2B_E} 2\rho\cdot Q(Q+1)$$