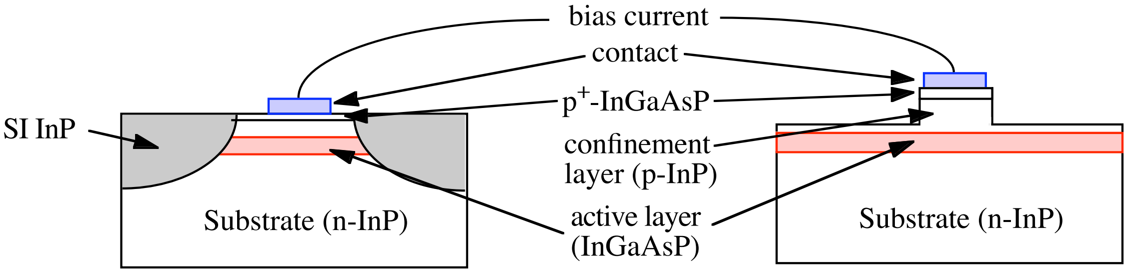
Lecture 10: Semiconductor Optical Amplifiers

Semiconductor Optical Amplifiers

- Active waveguides fabricated in semiconductor waveguides
- Gain usually achieved by electronic current injection
- Can be integrated with other device structures
- Gain is related to SC bandgap (1.55 and 1.3 micron wavebands)
- Relatively broad bandwidth (30 - 100nm)
- Fast carrier dynamics (can be advantage or disadvantage)
- Polarization dependence is an important issues as is linear vs. non-linear operation

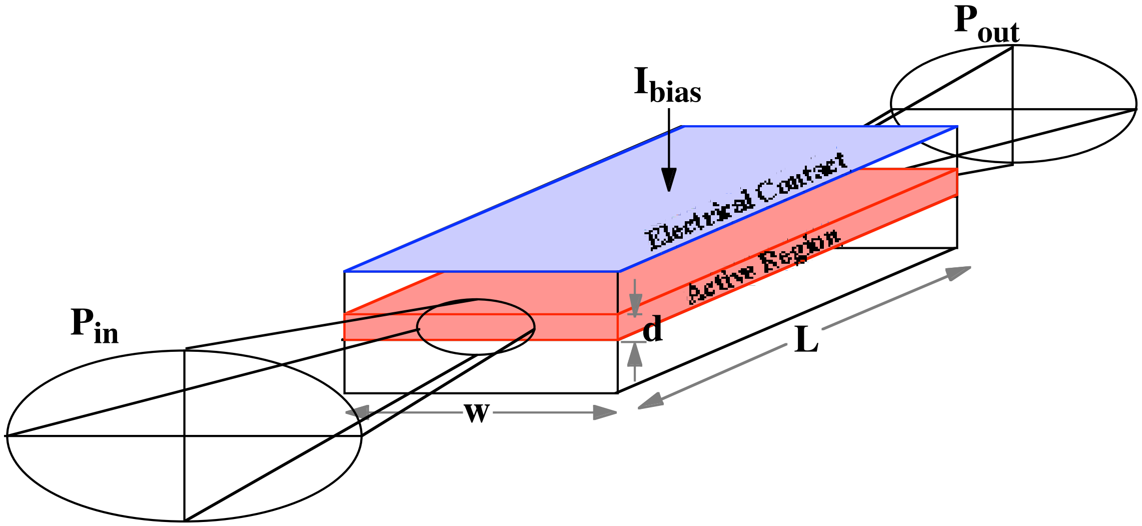
Semiconductor Optical Amplifiers (SOAs)

- SOA is an SC laser without mirrors
- Optical signal experiences gain while traveling once through device
- State-of-the-art amplifiers are polarization insensitive
- Can be used for a variety of purposes including
    - Post, in-line or preamplifiers
    - Multiwavelength amplifiers when gain clamping is used
    - Optical wavelength converter
    - Optical modulator
    - Gating element in an optical switch



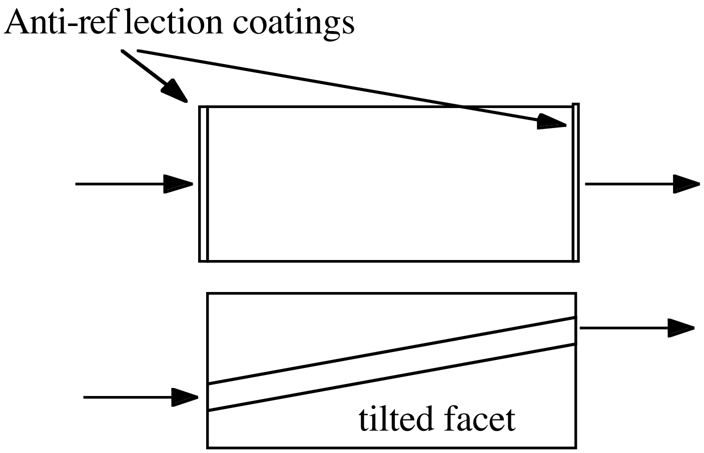
Strongly Guiding

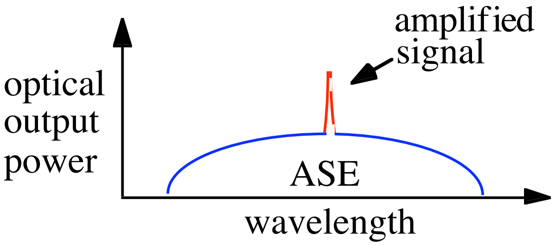
Weakly Guiding



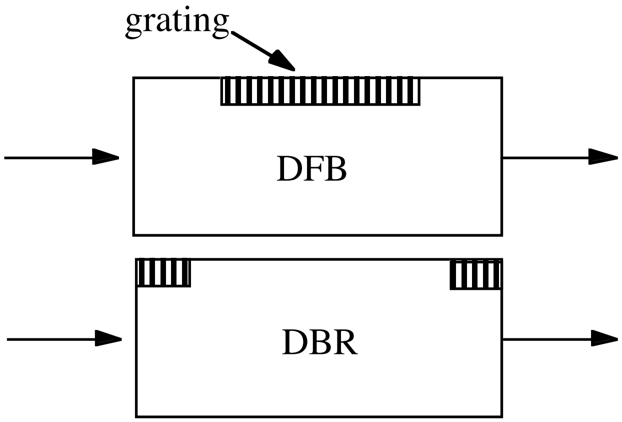
SOA Classes

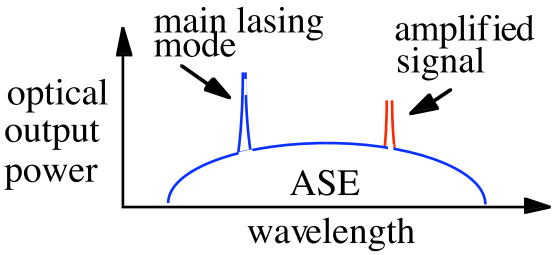
Non-Lasing



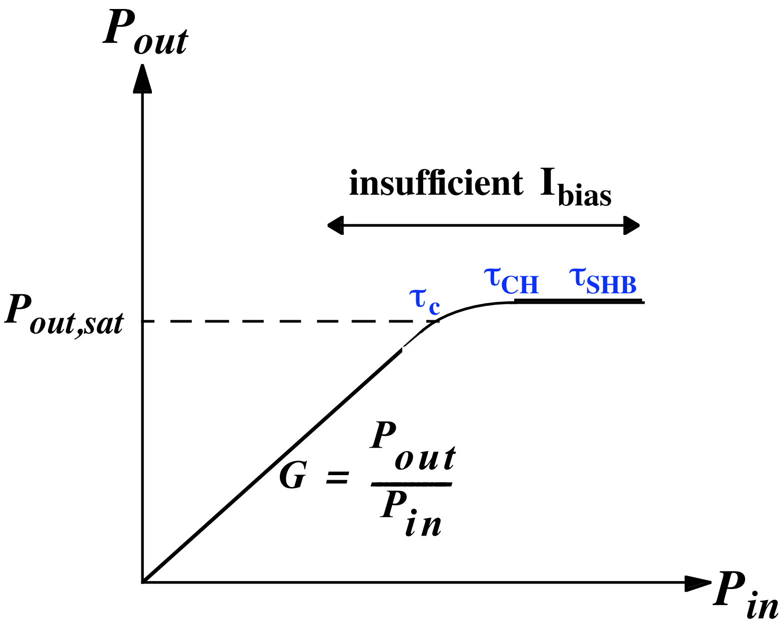


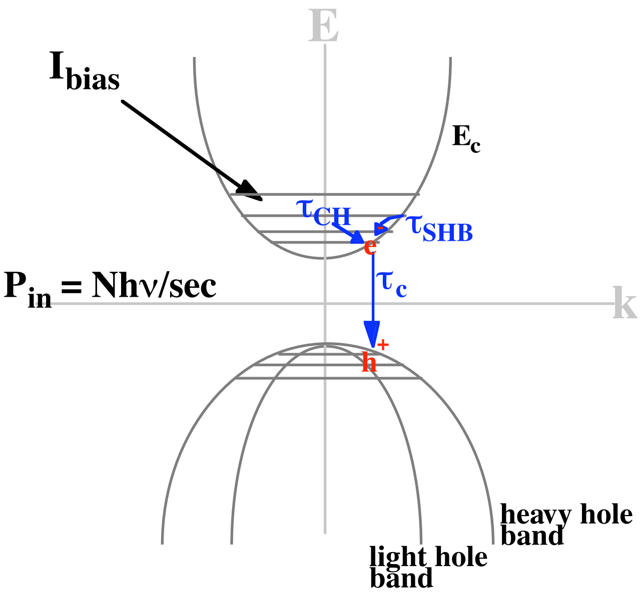
Gain Clamped





Linear and Non-Linear Gain





$\tau_c > \tau_{CH} > \tau_{SHB}$

τ_c = 200 ps

τ_{CH} = 650 fs

τ_{SHB} = 50 fs

SOA as an amplifier

- Linear amplification only to avoid pattern effects (described later in this lecture)
- SOAs have high gain, so making a linear amplifier is quite difficult, there are several approaches that are used
    - Physically tapered structure to reduce the intensity as the power increases
    - Use a very fast carrier lifetime material like a quantum dot SOA
- In the end, in this regime we want to avoid the amplifier being saturated anywhere inside the amplifier

Time Averaged Gain

- For an unsaturated amplifier

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

- Can be approximated by

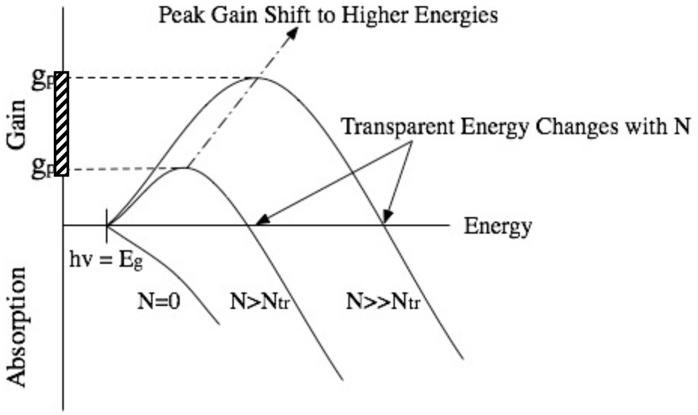
$$g(\omega) = \frac{g_0}{1 + (\omega - \omega_0)^2 T_2^2}$$

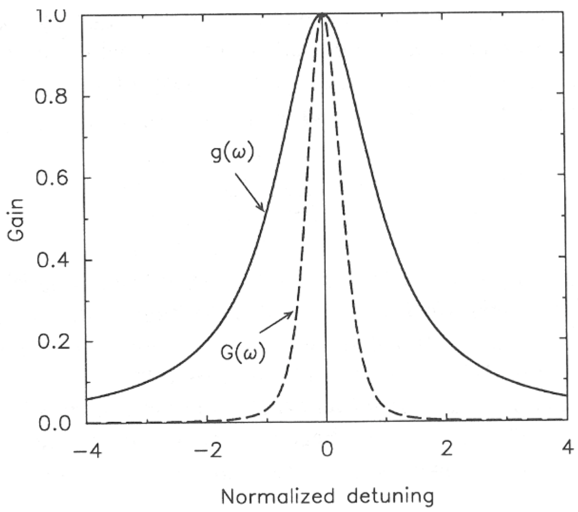
- We can define the amplifier material bandwidth as

$$\Delta\nu_g = \frac{1}{\pi T_2}$$

- And the amplifier bandwidth using G(ω) = exp[g(ω)L]over the length L (treating as lumped)

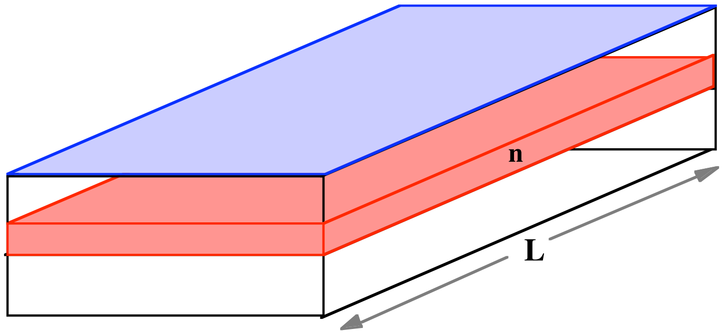
$$\Delta\nu_A = \Delta\nu_g \left(\frac{\ln 2}{g_0 L - \ln 2} \right)$$

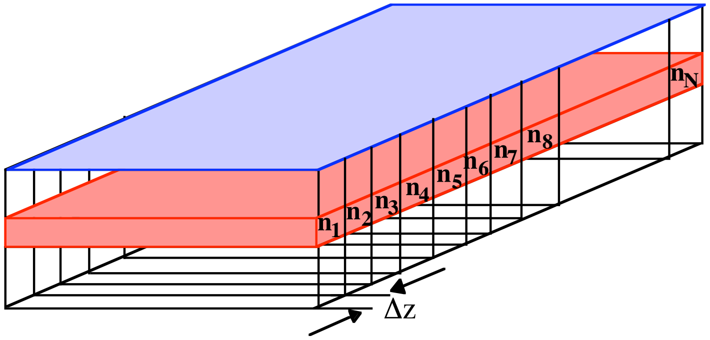




Lumped vs. Distributed Models

- Lumped
  - Carrier density averaged over amplifier length
  - Analytic expressions obtainable
  - $n(\lambda,t)$ is independent of z
  - Analytic expression do not predicted behavior that depends on z varying n.
- Distributed
  - Amplifier discretized into N sections, each of length Δz with $n_i(\lambda,t)$ averaged over Δz.
  - Analytic expressions difficult
  - Requires numerical modeling
  - $n(\lambda,t, z)$
  - Predicts z dependent behavior
    - Frequency response
    - Wavelength dependent gain

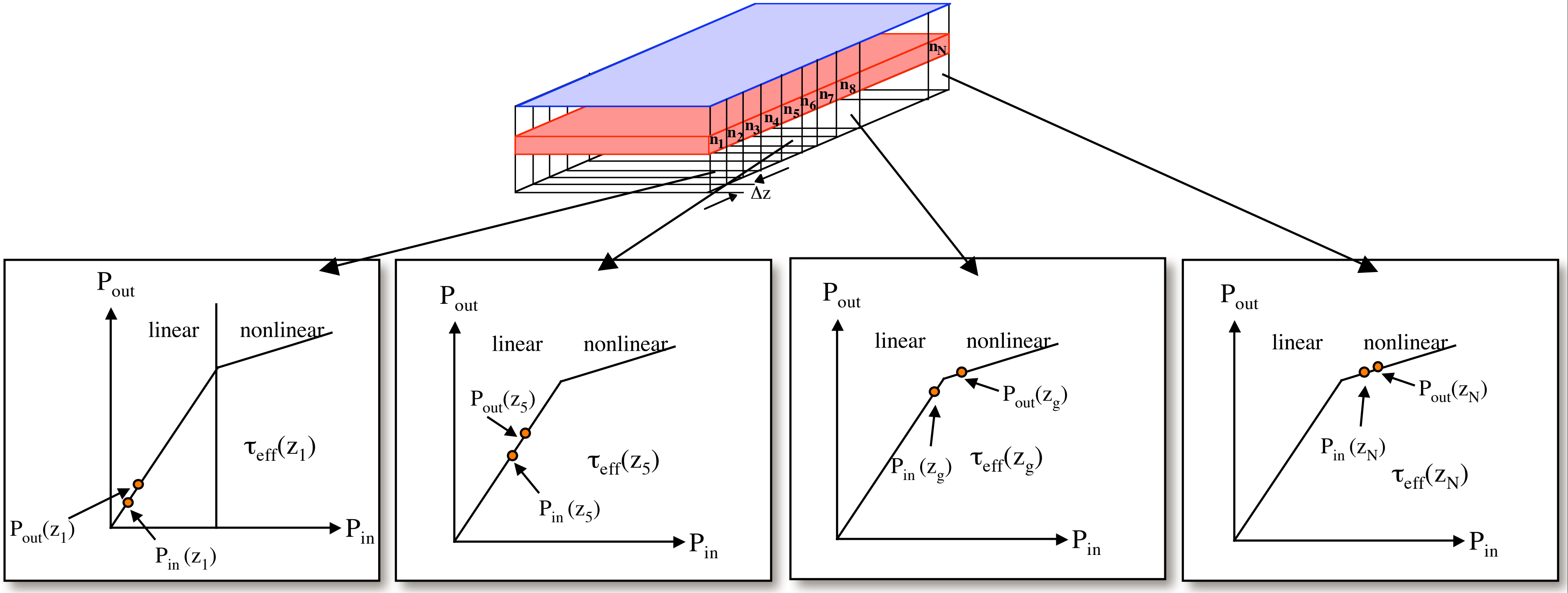




z-Dependence of Carrier Lifetime and Gain Saturation

- ⇨ Both the carrier lifetime (effective) and the optical signal power relative to gain saturation can change as a function of z!
- ⇨ Define an effective time constant

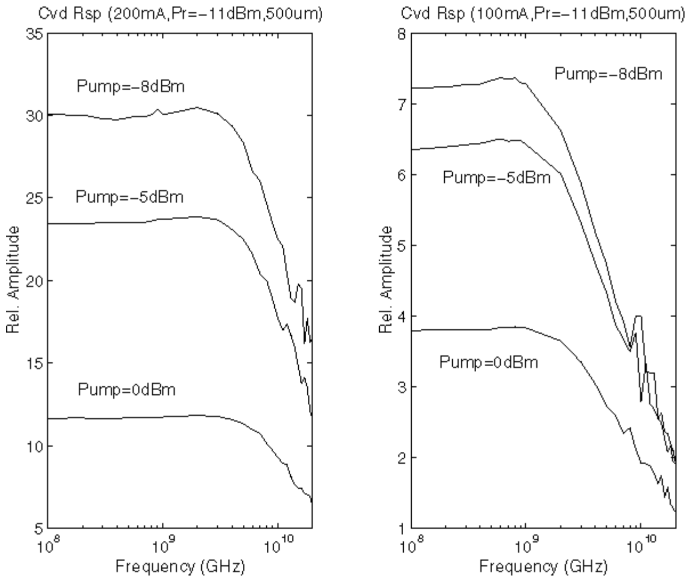
$$\frac{1}{\tau_{eff}(\lambda,z)} = \frac{1}{\tau_C(\lambda,z)} + \sum_{i=1}^{N} \frac{1}{\tau_i(\lambda,z)}$$



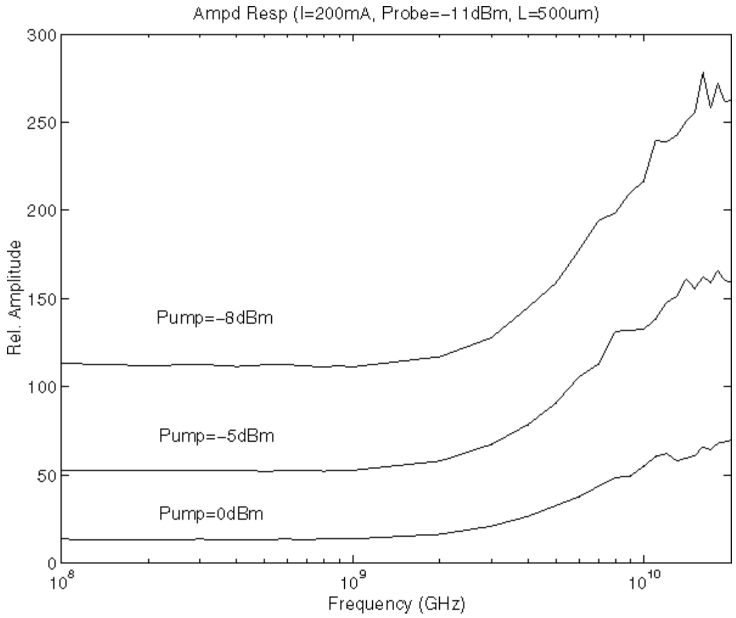
Small Signal Frequency Response

- Depends on evolution of t_{eff} as signal propagates through amplifier
  - Depends on time average photon density at location z
  - Depends on amplifier P_{sat}
  - Depends on input power and wavelength
  - Depends gain profile at each section

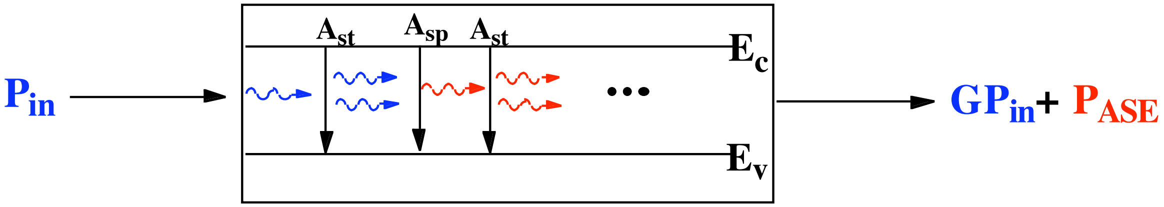
<u>At output, linear operation only</u>



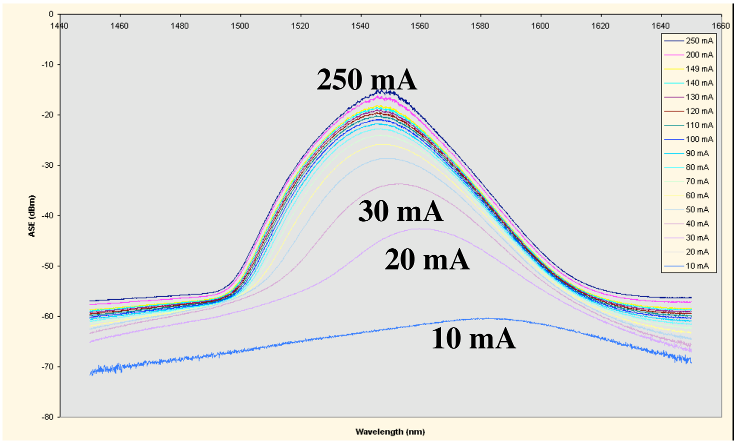
<u>At output, nonlinear operation</u>



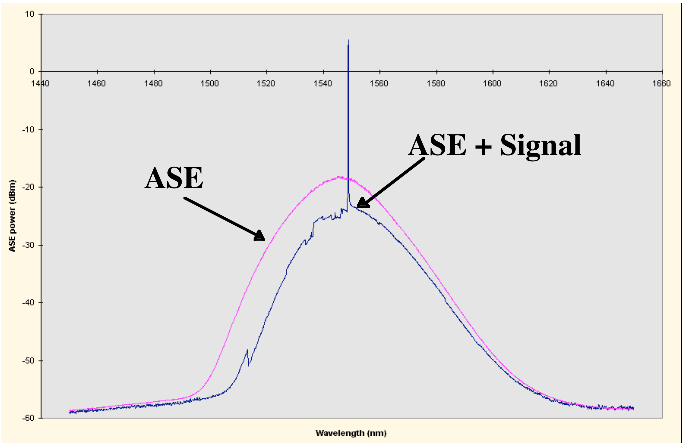
Amplified Spontaneous Emission (ASE)



ASE Power Spectrum at Various Bias Currents



SOA Power Spectrum with and without signal (I_{bias} = 150mA)



Amplifier Noise

- ⇨ Noise figure is defined as

$$F_n = \frac{(SNR)_{in}}{(SNR)_{out}}$$

- ⇨ Assuming the amplifier output is G times the input power, the SNR at the input is given by

$$(SNR)_{in} = \frac{(RP_{in})^2}{2q(RP_{in})\Delta f}$$

- ⇨ At the amplifier output, assuming white additive noise

$$S_{SP}(\nu) = (G-1)n_{sp}h\nu$$

- ⇨ Output SNR can be written as

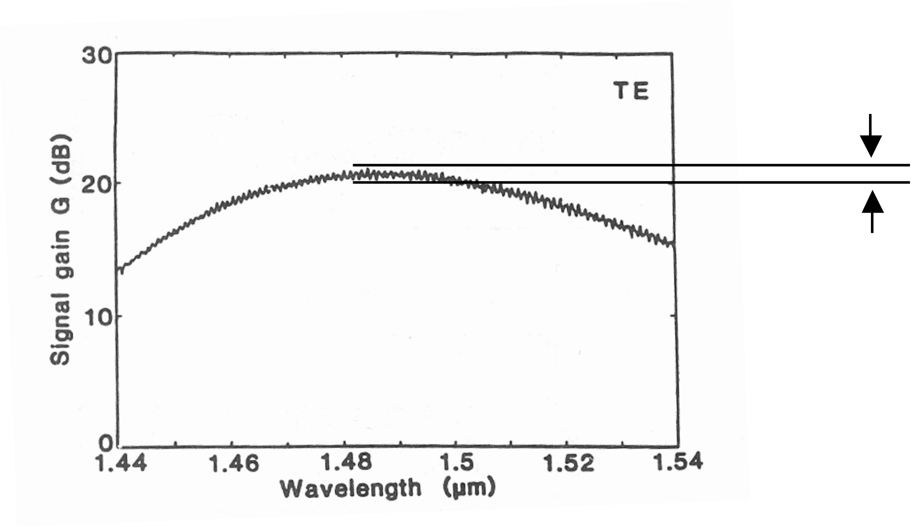
$$(SNR)_{out} = \frac{(RGP_{in})^2}{2q(RP_{in})\Delta f + 4(RGP_{in})(RS_{SP})\Delta f} \approx \frac{(GP_{in})}{4(S_{SP})\Delta f}$$

- ⇨ And the noise figure as (for large G)

$$F_n = {2n_{sp}(G-1)}\Big/{G} \approx 2n_{sp}$$

Gain Ripple

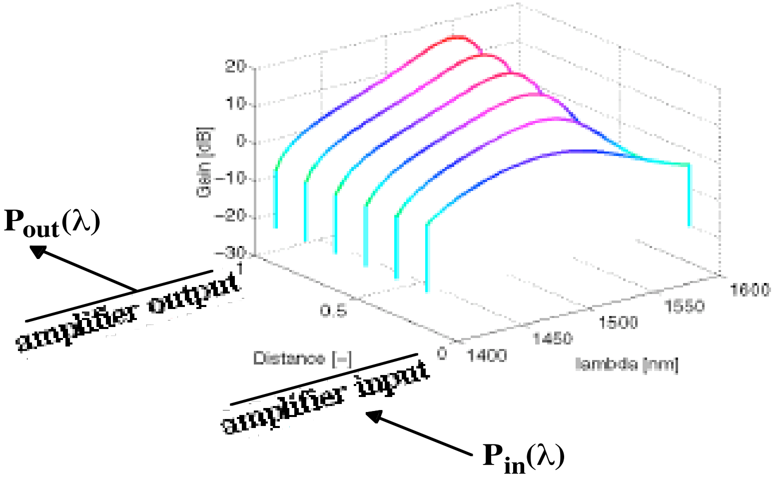
- We define the flatness of the gain over the gain bandwidth as (chip gain G and facet reflectivity R)



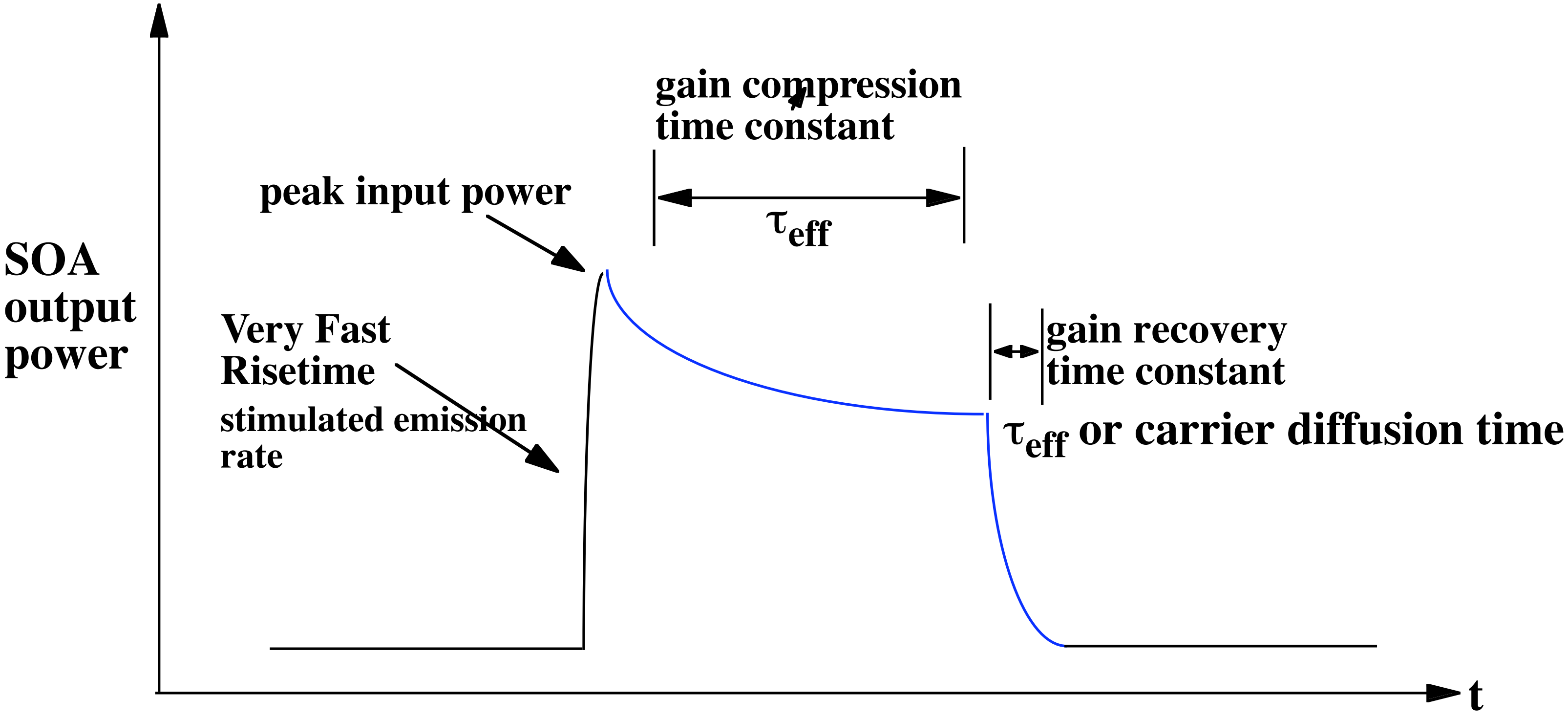
$$\text{Ripple} = \frac{(1+GR)^2}{(1-GR)^2}$$

Cumulative Distributed Gain

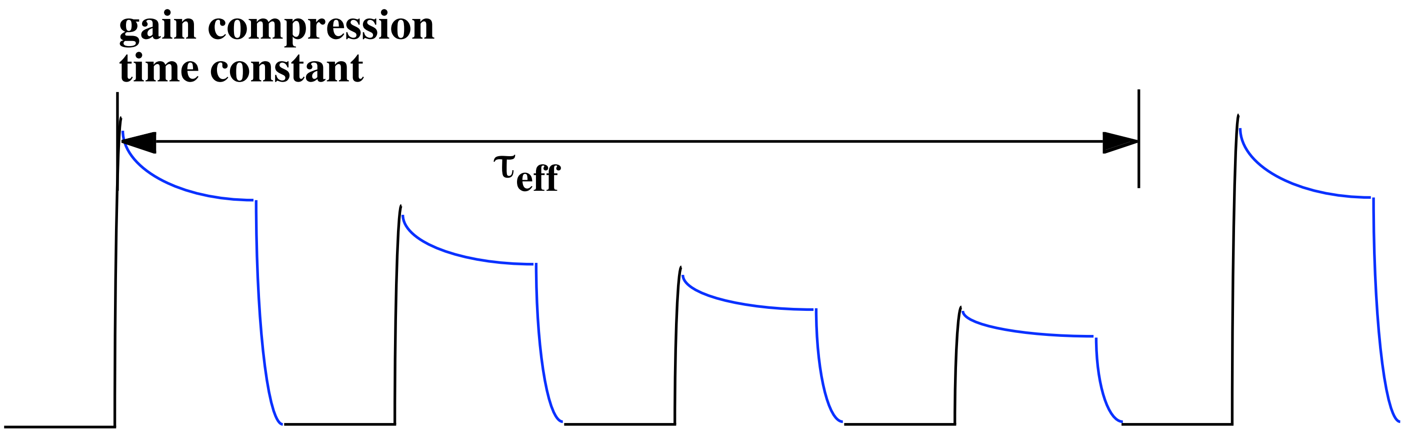
- Total gain-wavelength dependence is function of
  - Input power and wavelength
  - Amplifier saturation power as a function of wavelength
  - Amplifier bias
  - Amplifeir design parameters (geometrical and physical)

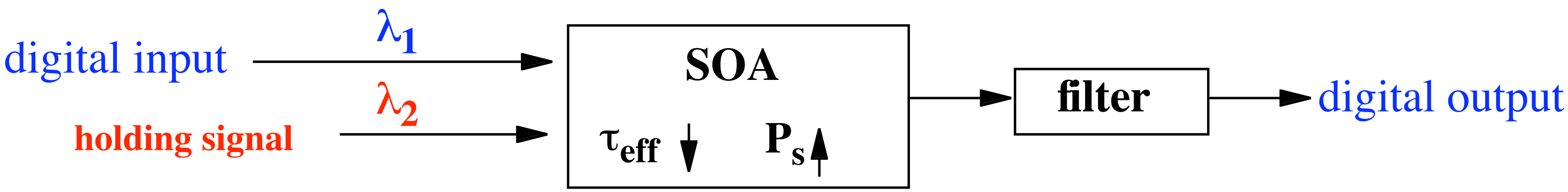


Gain Compression and Recovery



Pattern Dependent Gain





digital input λ_1

holding signal λ_2

SOA

$\tau_{eff} \downarrow$ $P_s \uparrow$

filter

digital output

Crosstalk

- Intersymbol interference due to finite gain recovery at high bit rates
- Intermodulation distortion in a multichannel WDM or OFDM transmission system due to FWM products.
- Intersymbol interference in a multichannel OFDM transmission system due to SPM or CPM.