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

- SOA is a strongly guiding device
- SOA is a weakly guiding device

- Substrate (n-InP)
- Strongly Guiding
- Weakly Guiding
- SI InP
- p⁺-InGaAsP confinement layer (p-InP)
- Active layer (InGaAsP)
- Bias current contact
- Electrical Contact
- Active Region
- P_out
- I_bias
- P_in
- w
- L
- d
SOA Classes

Non-Lasing
Anti-reflection coatings

Gain Clamped
grating

optical output power
wavelength
main lasing mode
amplified signal
ASE
ASE

optical output power
wavelength
main lasing mode
amplified signal
Linear and Non-Linear Gain

\[ G = \frac{P_{out}}{P_{in}} \]

\[ P_{out, sat} \]

\[ P_{in} = N\hbar/\text{sec} \]

\[ \tau_c > \tau_{CH} > \tau_{SHB} \]

\[ \tau_c = 200 \text{ ps} \]

\[ \tau_{CH} = 650 \text{ fs} \]

\[ \tau_{SHB} = 50 \text{ fs} \]
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

\[
g(\omega) = \frac{g_0}{1 + (\omega - \omega_0)^2 T_2^2 + \frac{P}{P_s}}
\]

⇒ 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 \( G(\omega) = \exp[g(\omega)L] \) 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 \( \Delta z \) with \( n_i(\lambda,t) \) averaged over \( \Delta z \).
  - 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

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

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

At output, linear operation only

At output, nonlinear operation
Amplified Spontaneous Emission (ASE)

\[ \text{Pin} \rightarrow A_{st} \rightarrow A_{sp} \rightarrow A_{st} \rightarrow E_c \rightarrow \text{GP}_\text{in} + P_{\text{ASE}} \rightarrow E_v \]

ASE Power Spectrum at Various Bias Currents

SOA Power Spectrum with and without signal (\(I_{\text{bias}} = 150\text{mA}\))
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
\[ S_{sp}(v) = (G - 1)n_{sp}h\nu \]

⇒ 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)
\[ F_n = \frac{2n_{sp}(G - 1)}{G} \approx 2n_{sp} \]
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
  - Amplifier design parameters (geometrical and physical)
Gain Compression and Recovery

SOA output power

- Very Fast Risetime
- stimulated emission rate

peak input power

gain compression time constant $\tau_{\text{eff}}$

gain recovery time constant $\tau_{\text{eff}}$
or carrier diffusion time

stimulated emission rate

output power $t$
Pattern Dependent Gain

Gain compression
Time constant

\[ \tau_{\text{eff}} \]

Digital input
Holding signal
SOA
Filter
Digital output

\[ \lambda_1 \]
\[ \lambda_2 \]
\[ \tau_{\text{eff}} \]
\[ P_s \]
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.