Semiconductor Optical Amplifiers (SOAs, pp. 232-243 in Agrawal)

- Amplifier Design
  - requirements on the mirror reflectivities
- Amplifier Characteristics
  - Saturation power
  - Gain clamping
  - Noise figure
  - Polarization sensitivity
  - Pattern effect
- Pulse Amplification (next lecture)

SOA Design

We already discussed basic SOA design in the general lecture about optical amplifiers where we emphasized that a traveling wave (TW) amplifier, which relies on a single-pass gain, ideally has no mirror reflections and is the most desirable layout. This is typically achieved by either AR coatings on the cleaved mirror facets and/or a tilted waveguide with respect to the facets. Remember that any reflections from the mirror facets are usually undesirable because they can severely modulate the amplifier gain and also considerably narrow the amplifier bandwidth. The effect of these reflections on a TW amplifier is called "gain ripple." Any design that deliberately uses this feature to enhance the gain due to cavity resonance is called a Fabry-Perot (FP) amplifier. The SOA schematics are repeated below from the previous lecture.
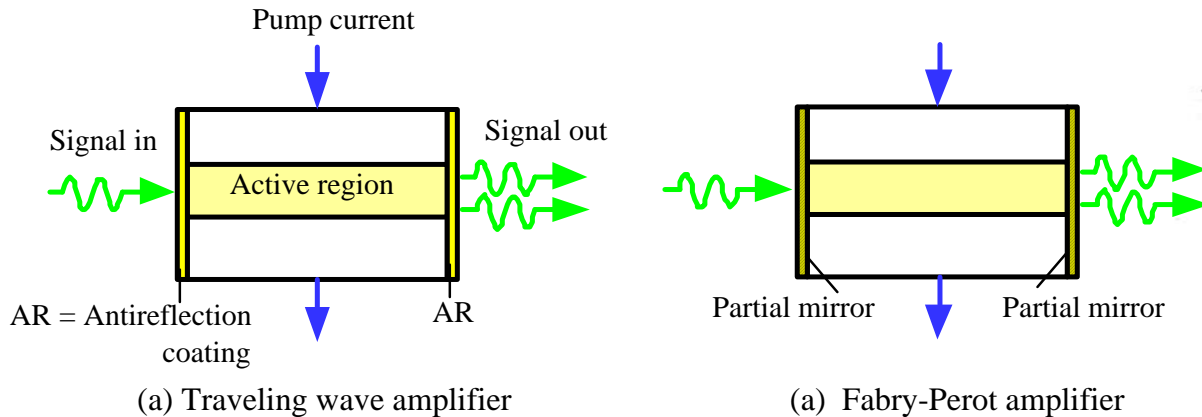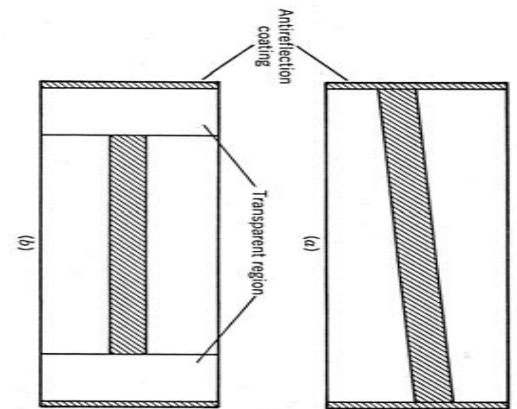

(a) Traveling wave amplifier

(a) Fabry-Perot amplifier

Simplified schematic illustrations of two types of laser amplifiers

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Equations for SOA Design

Assuming the facets of the SOA have reflectivities, R_1 and R_2, a single-pass gain of G, Fabry-Perot cavity resonance frequencies v_m (eqn. 3.3.5 in the text), and frequency spacings Δv_L (p. 96), the amplification factor of the SOA is:

$$G_{FP}(v) = \frac{(1-R_1)(1-R_2)G(v)}{\left(1-G\sqrt{R_1 R_2}\right)^2 + 4G\sqrt{R_1 R_2}\,\sin^2\left[\pi(v-v_m)/\Delta v_L\right]}$$

Essentially this is the equation for the residual gain ripple in a traveling-wave (TW) SOA. In other words, what we ideally want in a TW SOA is $G_{FP}(v) = G(v)$. In FP SOA's we use the $G_{FP}(v)$ expression to calculate the amplifier gain enhancement around one of the cavity resonance frequencies, v_m.

Note: what Agrawal calls the "amplification factor", G, (unit-less) is also frequently called the "amplifier gain". Remember to distinguish this from the "gain coefficient", g, which has units of cm^{-1}.
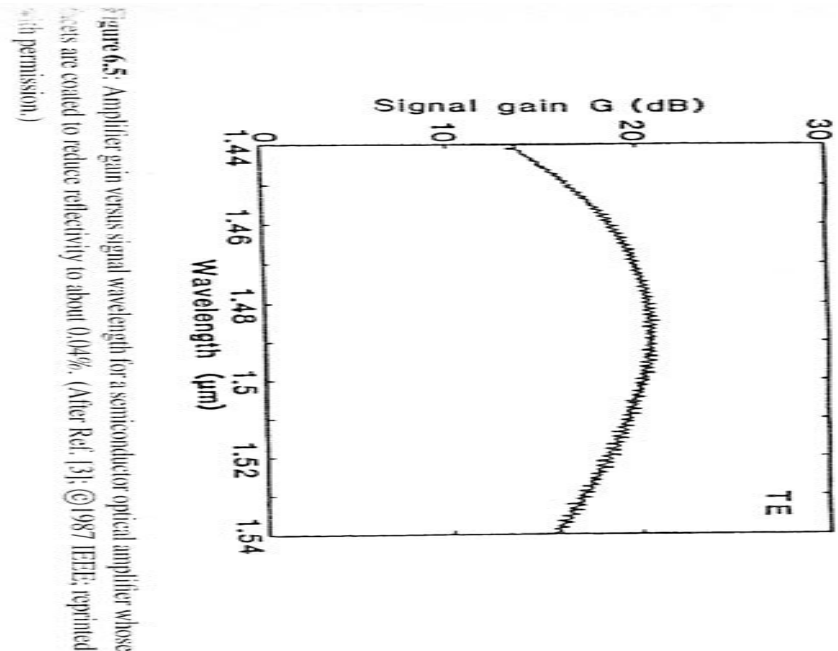
SOA Design continued

I don't have a good figure showing lots of gain ripple, but if you look closely, you can see the residual gain ripple in the TW amplifier data shown below.

Note: FP amplifiers can achieve a very large cavity enhancement of the amplifier gain when $v = v_m$ and $G(R_1R_2)^{1/2}$ is close to 1, but the tradeoff is a very, very narrow amplifier bandwidth. Here's the equation for the 3-dB bandwidth of an FP SOA:

$$\Delta v_A = \frac{2\Delta v_L}{\pi}\sin^{-1}\left(\frac{1-G\sqrt{R_1R_2}}{\left(4G\sqrt{R_1R_2}\right)^{1/2}}\right)$$

Plugging in typical numbers for an FP SOA, we get a Δv_A of only 10 GHz, less than one channel spacing in a WDM system. Thus, FP SOA's are undesirable for most lightwave system applications

Figure 6.5. Amplifier gain versus signal wavelength for a semiconductor optical amplifier whose facets are coated to reduce reflectivity to about 0.04%. (After Ref. [3]; ©1987 IEEE; reprinted with permission.)

SOA Design continued

The clear way to reduce gain ripple in a TW SOA is to reduce the reflectivities, R_1 and R_2. But what do those values need to be? At worst, the gain ripple, ΔG, cannot exceed 3 dB. Otherwise the amplifier bandwidth is determined by cavity resonances. It is easy to show from our previous equation that the gain ripple is:

$$\Delta G = \frac{G_{FP}^{\max}}{G_{FP}^{\min}} = \left(\frac{1 + G\sqrt{R_1 R_2}}{1 - G\sqrt{R_1 R_2}} \right)^2$$

A typical TW SOA gain is 30 dB, so to keep $\Delta G < 3$ dB, $(R_1 R_2)^{1/2} < 0.017\%$. **Since R_1 is usually chosen to equal R_2 in the design of the SOA, that means each facet must be AR-coated to around 0.017% reflectivity**. That is very difficult to achieve over let's say a 50 nm bandwidth (C-band). Hence, the need for a tilted waveguide geometry, which can easily achieve 0.1% reflectivity with a 7° tilt angle. Combining the AR coating and the tilted waveguide gives some added cushion to achieve about 0.01% reflectivity.

SOA Characteristics-
The Saturation Power, P_s

We talked generally about power saturation in optical amplifiers in the last lecture, but let's investigate the physical origins of P_s in SOA's specifically.

Following Agrawal's derivation on pp. 234-235, it is now more convenient to use the peak gain coefficient, $g(N)$ (cm^{-1}), the optical confinement factor, Γ (unitless), the differential gain, σ_g (cm^2), the cross-sectional area of the waveguide mode, σ_m (cm^2), the active region volume, V (cm^3), the carrier number, N (unitless), the transparency carrier number, N_0 (unitless),the carrier lifetime, τ_c, the injection current, I (mA), and the signal power, P (mW). I also will remind you that the amplifier has a length L.

One important concept here is that the optical mode volume (where the photons are) does not equal the active region volume (where the gain is). In other words,

$$\sigma_m L \neq V \qquad \text{also} \quad \Gamma = \frac{V}{\sigma_m L}$$

SOA Power Saturation continued

Here are the relevant equations for the peak gain coeffecient and the time rate of change of the carrier number (or population):

$$g(N) = \left(\Gamma \sigma_g / V\right)\left(N - N_0\right)$$

(Compare this to eqn. (3.5.3) in which the units are s^{-1})

$$\frac{dN}{dt} = \frac{I}{q} - \frac{N}{\tau_c} - \frac{\sigma_g\left(N - N_0\right)}{\sigma_m h \nu} P$$

Compare this to eqn. (3.5.2). It's in the same units, but expressed just a little differently

The differential gain, σ_g, is basically the active region cross-section. If σ_g is large, then the gain medium is easy to stimulate with photons. It's very responsive. We will see, however, that this also makes the gain medium easier to saturate.

SOA Saturation Power continued

To find the steady-state value for the carrier number, N, we set $dN/dt = 0$ and solve for N. Then we put the solution for N into the peak gain coefficient expression and we find that the optical gain saturates as:

$$g = \frac{g_0}{1 + P/P_s}$$

Note: the SOA saturates in the same way as the simple 2-level system described in the general optical amplifier lecture

Where the small-signal gain, g_0, is:

$$g_0 = \left(\Gamma \sigma_g / V\right)\left(I\tau_c/q - N_0\right)$$

And, most importantly, the saturation power of the SOA is:

$$P_s = h\nu\sigma_m \Big/ \left(\sigma_g \tau_c\right)$$

Desirable features for high P_s in an SOA

$$P_s = h\nu\sigma_m \big/ \left(\sigma_g \tau_c \right)$$

• Large cross-section for the optical mode, i.e., for a given power, the photons are spread out.
• Small differential gain, which means that the gain medium should have a small cross-section. It is more difficult to stimulate for a given gain value.
• A fast carrier lifetime, the resupply of carriers to the gain medium should be fast.

Remember from last lecture that the saturation output power of the 2-level system is:

$$P_{out}^s \approx 0.69 P_s$$

Typical saturation output powers nowadays for SOA's are 10-30 mW (better than what Agrawal quotes)

Gain-clamped (GC) SOA's

We want to eliminate the gain saturation effect in SOA's because in multichannel applications the gain saturation leads to severe crosstalk. The channels are trying to rob gain from each other. Why don't we just operate in the linear regime of the amplifier? Answer: then you don't get enough power output.

Gain clamping extends the linear regime of the amplifier and thus the useful output power. Within the same waveguide, gain clamping is accomplished by introducing laser action at a wavelength remote from the signal wavelength. Once lasing begins the carrier population is clamped at a fixed value. This has the effect of making the amplifier gain relatively insensitive to the input signal power. Wavelength selective feedback is accomplished with either a DFB grating throughout the optical cavity or at the ends in which case it is called a distributed Bragg reflector or DBR mirror. Notice the very hard saturation of the GC-SOA in the figure on the right. Compare that to Fig. 6.2 in Agrawal for a typical 2-level optical amplifier.
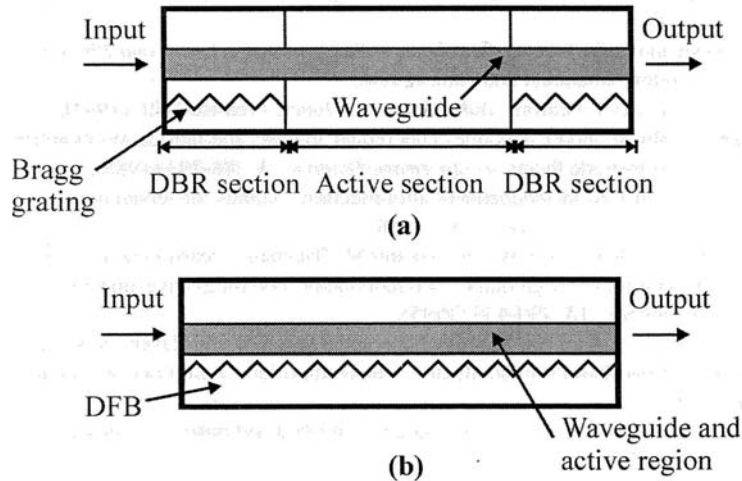
14. GC-SOAs with (a) DBR and (b) DFB regions.
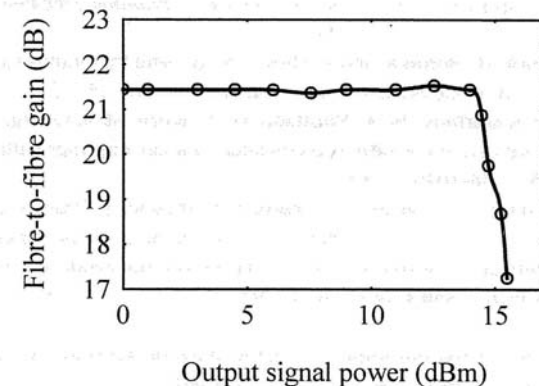
3.15. Typical GC-SOA gain versus output optical power characteristic. The gain is linear for output powers below the saturation output power (after [31] with sion of the IEEE).

SOA Noise Figure

The noise figure expression for an SOA is pretty simple. From the last lecture, remember the general expression for the optical amplifier noise figure, F_n:

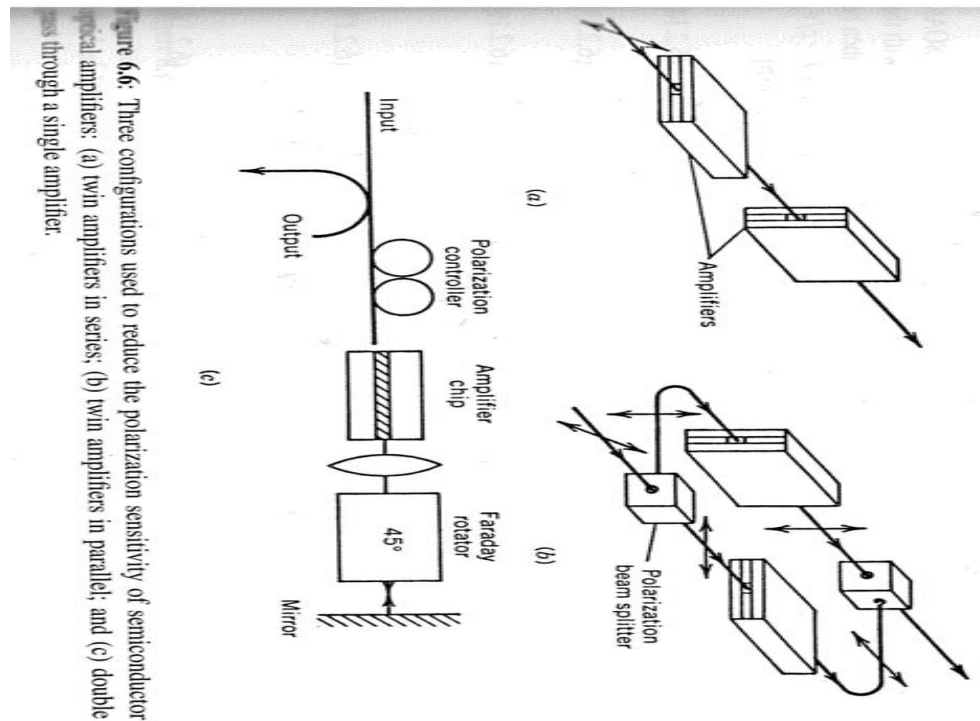$$F_n \approx 2n_{sp} = 2\frac{N_2}{N_2 - N_1} \approx 2\frac{N}{N - N_0}$$

Looking at this equation, we need to minimize N_0, which takes into account the carrier population that generates those noisy spontaneous emission photons that get amplified by the gain.

For the SOA, there is another term that we must introduce in the noise figure equations to treat the internal loss of the optical waveguide. This term reflects the fact that not all the gain generated in the optical cavity is coupled to the external world, some of it is scattered and lost. So the final expression is

$$F_n = 2\left(\frac{N}{N - N_0}\right)\left(\frac{g}{g - \alpha_{int}}\right)$$
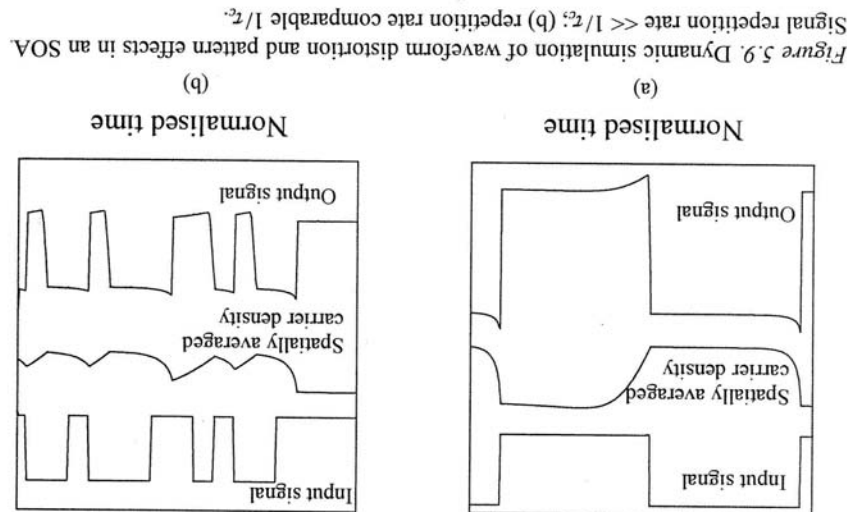
Polarization Sensitivity in SOA's

A typical SOA is dominated by the TE mode as opposed to TM. Please accept this as a fact for right now. This strong TE behavior is undesirable for lightwave systems because the polarization coming out of the optical fiber is random unless we use polarization maintaining fiber (which is relatively expensive). The brute force (and more expensive) methods of getting around this problem are shown below. The more usual solution nowadays is to introduce tensile strain into the SOA bulk active region. This has the effect of balancing the TE and TM gain and only a single amplifier chip is required.

Figure 6.6: Three configurations used to reduce the polarization sensitivity of semiconductor optical amplifiers: (a) twin amplifiers in series; (b) twin amplifiers in parallel; and (c) double pass through a single amplifier.

The Pattern Effect in SOA's

Now the pattern effect is a big deal in SOA's and our text appears to be silent on this matter. Because their carrier lifetime, τ_c, is roughly the same as the bit rate in modern lightwave systems, SOA's when pushed towards gain saturation have the nasty habit of being sensitive to the pattern of the bit signal. This is because as the digital signal rises and falls, the SOA is getting pushed back and forth between the linear and gain saturation regimes. Gain-clamping helps, but not entirely. See the next slide for some real data showing the pattern effect in typical InGaAsP SOA's and its elimination in quantum dot based SOA's. EDFA's don't suffer from this pattern effect problem at all because the fluorescence time (analogous to carrier lifetime) in EDFA's is so long, milliseconds, that the amplifier responds to average signal power, not instantaneous power.

Figure 5.9. Dynamic simulation of waveform distortion and pattern effects in an SOA. Signal repetition rate $\ll 1/\tau_c$; (b) repetition rate comparable $1/\tau_c$.

Quantum Dot 1310 nm SOA - Removes Pattern Effect

• Operation in Saturation Regime is desirable. Typical SOA suffers bit distortion.

• Quantum dot has very fast τ_c < 3 ps (10X faster than typical InGaAsP SOA) solves the problem.