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OPTICAL AMPLIFIERS

Notes prepared for EE 6310

by

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AMPLIFIERS FOR OPTICAL COMMUNICATIONS

- Configurations

  Booster amplifier following transmitter

  In-line amplifier

  - Functions as a non-regenerative repeater

  Preamplifier before receiver

- Technologies

  Semiconductor optical amplifiers (SOAs)

  Rare-earth-doped fiber amplifiers (EDFAs, EDFFAs, PDFAs, etc.)

- Classifications

  Narrowband (**Fabry-Pérot amplifiers** such as SOAs)

  Broadband (**traveling-wave amplifers** such as EDFAs)

GAIN OF A TWO-ENERGY-LEVEL MEDIUM

- For a lossless traveling-wave amplifier (the simplest case!),

$$\frac{dP}{dz} = gP \qquad \text{where } P = \text{power, } g = \textbf{gain coefficient}$$

- If all atoms or ions have the same difference of energy, $\hbar\omega_0$, between excited and ground states, then the medium is **homogeneously broadened** and the frequency dependence of the gain coefficient is

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

where P_s = **saturation power**, T_2 = **dipole relaxation time**, g_p = peak gain coefficient

At powers well below the saturation power,

$$P \ll P_s \Rightarrow g(\omega) \approx \frac{g_p}{1 + (\omega - \omega_0)^2 T_2^2}$$

AMPLIFICATION FACTOR

- For a traveling-wave amplifier with loss and with imperfect mode confinement,

$$\frac{dP}{dz} = \gamma(g - \alpha)P$$

  where α = attenuation coefficient and γ = confinement factor

- The **amplification factor** is the ratio of power out to power in,

$$G = \frac{P_{\mathrm{out}}}{P_{\mathrm{in}}}$$

  At powers well below the saturation power,

$$G = e^{\gamma(g-\alpha)L}$$

  where L = length of active medium

GAIN NARROWING

- Single-pass amplification factor:

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

γ = confinement factor, γ = small-signal gain per unit length,
α = attenuation coefficient, L = length of active region

$G(\omega)$ may be much narrower than $g(\omega)$, depending on γ and L

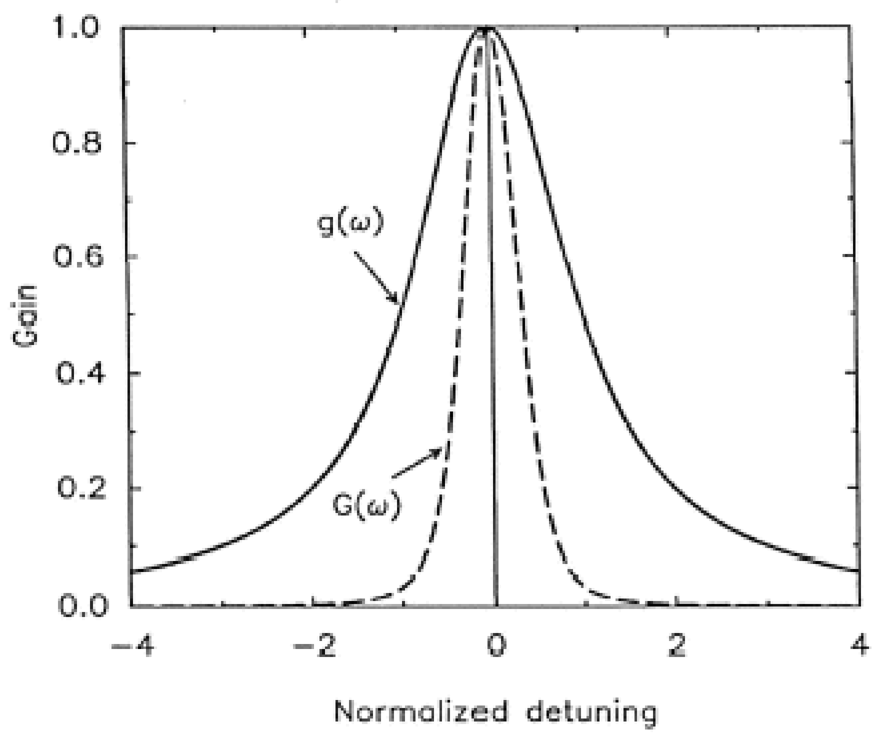
The half-width at half-maximum of G is such that

$$e^{\gamma(g(\omega_0+\Delta\omega_G)-\alpha)L} = G(\omega_0+\Delta\omega_G) = \tfrac{1}{2}G(\omega_0) = e^{-\ln 2+\gamma(g(\omega_0)-\alpha)L}$$

$$\Rightarrow \frac{g(\omega_0) - g(\omega_0+\Delta\omega_G)}{g(\omega_0)} = \frac{\ln 2}{\gamma L g(\omega_0)}$$

If $\gamma L g(\omega_0) \gg 1$ (as it must be for laser action), then a very small relative change in g changes G by a factor of 2

ILLUSTRATION OF GAIN NARROWING



G. P. Agrawal, *Fiber-Optic Communication Systems*, 2nd Edition, Fig. 8.1

USABLE AMPLIFIER BANDWIDTH (1)

- The gain bandwidth (HWHM) is

$$\Delta\omega_g = \frac{1}{T_2}$$

where T_2 is the dipole relaxation time

- The usable amplifier bandwidth, $\Delta\omega_G$, is

$$\Delta\omega_G \approx \Delta\omega_g \sqrt{\frac{\ln 2}{\ln G_0}}$$

where

$$G_0 = e^{\gamma(g(\omega_0)-\alpha)L}$$

Multiple channels can be amplified simultaneously if they all lie within the amplifier bandwidth

USABLE AMPLIFIER BANDWIDTH (2)

- Derivation of

$$\Delta\omega_G \approx \Delta\omega_g \sqrt{\frac{\ln 2}{\ln G_0}}\;:$$

Parabolic approximation to g near its peak at $\omega = \omega_0$:

$$g(\omega_0 + \Delta\omega_G) \approx g(\omega_0)\left[1 - \left(\frac{\Delta\omega_G}{\Delta\omega_g}\right)^2\right]$$

Expression for the amplification factor at half-maximum:

$$\frac{G_0}{2} \approx \exp\left\{\gamma L g(\omega_0)\left[1 - \left(\frac{\Delta\omega_G}{\Delta\omega_g}\right)^2\right]\right\}$$

Rearrange to get

$$\frac{\Delta\omega_G}{\Delta\omega_g} \approx \sqrt{1 - \frac{\ln(G_0/2)}{\ln G_0}} = \sqrt{\frac{\ln G_0 - \ln(G_0/2)}{\ln G_0}} = \sqrt{\frac{\ln 2}{\ln G_0}}$$

GAIN SATURATION

- On resonance ($\omega = \omega_0$), the equation for the optical power in a traveling-wave amplifier is

$$\frac{dP}{dz} = \gamma\left(\frac{g(\omega_0)}{1+P/P_s} - \alpha\right)P \approx \frac{\gamma g(\omega_0)}{1+P/P_s}P$$

if the gain greatly exceeds the attenuation

An implicit equation for the resulting amplification factor is

$$G = G_0 \exp\left(-\frac{G-1}{G}\frac{P(L)}{P_s}\right)$$

The **saturation output power** is the output power for which the amplification factor is reduced by 3 dB as a result of saturation:

$$P_{\mathrm{s,out}} = \frac{G_0 \ln 2}{G_0 - 2}P_s$$

In practical amplifiers $G_0 \gg 2$, making

$$P_{\mathrm{s,out}} \approx \ln 2 P_s$$

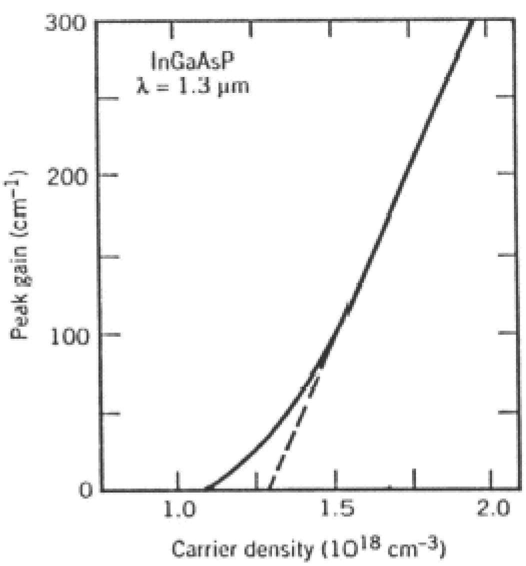
PEAK GAIN COEFFICIENT IN A SEMICONDUCTOR LASER

- Peak gain coefficient of a semiconductor medium:

$$g_p = \sigma_g(N - N_T)$$

N_T = value of carrier density that makes the medium transparent

- Peak gain coefficient of InGaAsP vs. N:



G. P. Agrawal, *Fiber-Optic Communication Systems*, 2nd Edition, Fig. 3.10

FABRY-PEROT AMPLIFIER

- The amplification factor when significant facet reflections are present is not the same as the gain without reflections

  Amplification factor with reflections:

  $$G_{\mathrm{FP}}(\omega) = \frac{(1 - R_1)(1 - R_2)G(\omega)}{(1 - G\sqrt{R_1 R_2})^2 + 4G\sqrt{R_1 R_2}\,\sin^2[(\omega - \omega_m)/2\Delta\omega_L]}$$

  $\Delta\omega_L$ = longitudinal mode spacing, R_1, R_2 = facet reflection coefficients

  The denominator is periodic

  - This produces Fabry-Pérot resonances with a spacing equal to the longitudinal mode spacing

OPTICAL FIBER AMPLIFIER TECHNOLOGIES

- EDFAs

  Erbium-doped fiber amplifiers

  ◦ Began as a university research project

  Optically pumped at 980 nm or 1480 nm

  Most commonly used in the C band (1530–1560 nm)

- EDFFAs

  Erbium-doped fluoride fiber amplifiers

- PDFAs

  Praseodymium-doped fiber amplifiers