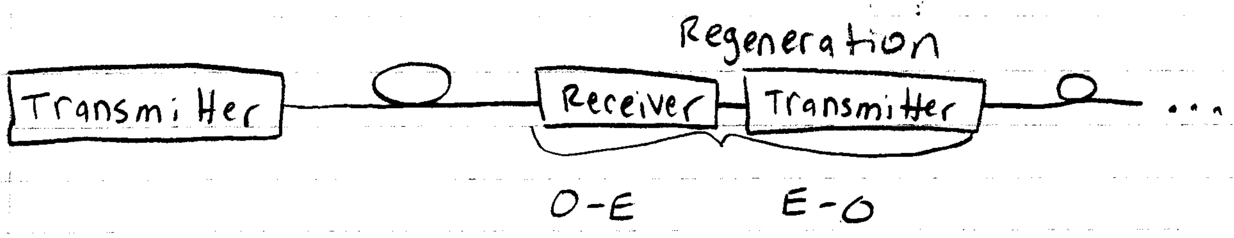
# Chapter 17 Optical Amplification



O-E optical to electrical conversion
E-O electrical to optical conversion

What determines the distance between regeneration?

Signal-to-Noise Ratio : SNR
Dispersion
Signal power (attenuation)

What affects dispersion:
- Fiber dispersion: Dispersion reduction
  - Dispersion compensation
- Laser linewidth: DFB lasers
- Modulation: Direct modulation of lasers
  - External modulators

Signal power: Attenuation
- Fiber
- Component

OPTICAL AMPLIFIERS

Why optical amplifier Vs. regeneration?

Format independent 1Gb/s 40Gb/s

Less complex

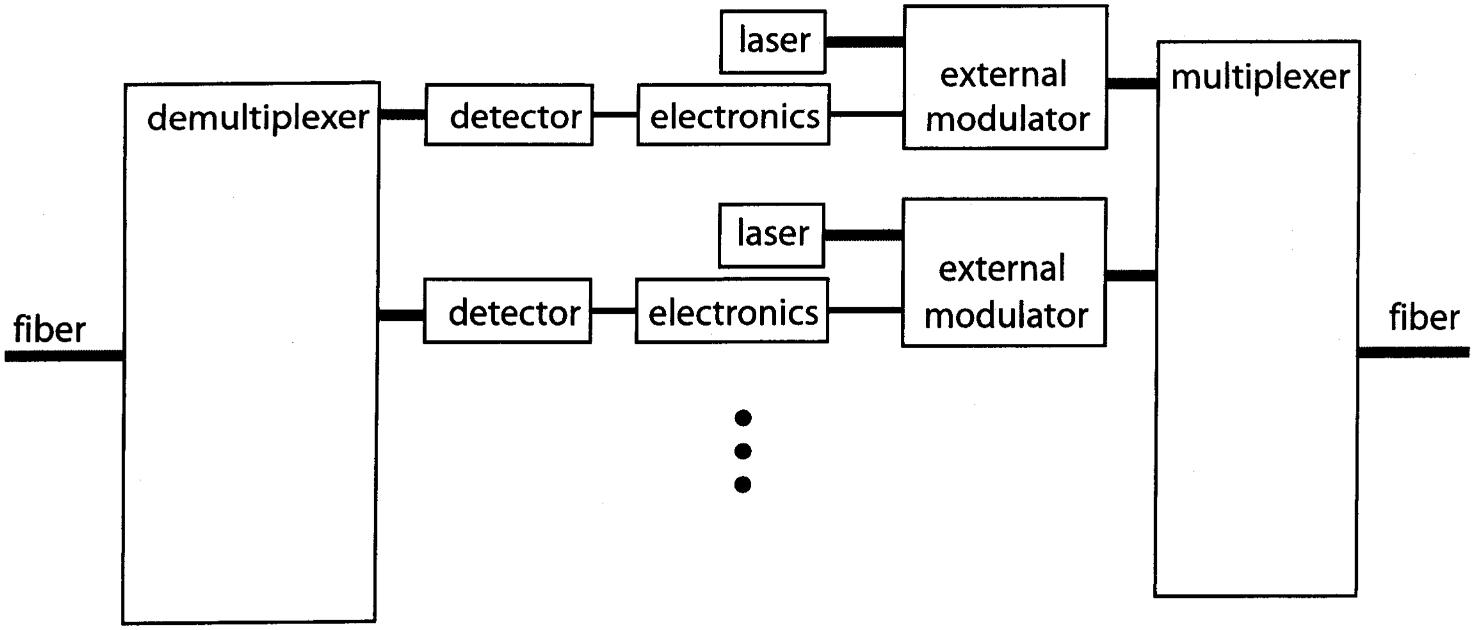
When will Optical Amplification not work?
Dispersion dominates
Too much noise
    Optical amplifier amplifies noise
    Optical amplifier generates noise

Criteria for Optical amplifier

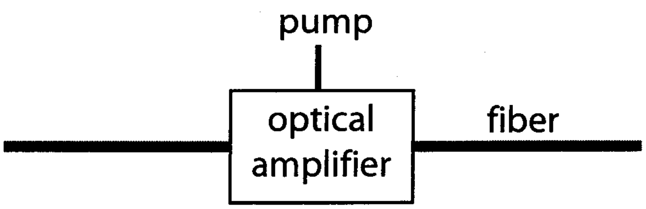
1. High power gain
2. High external pumping efficiency
3. Small saturation effect
4. Large bandwidth
5. Low added noise
6. Small crosstalk
7. Proper operating wavelength
8. Low insertion Loss

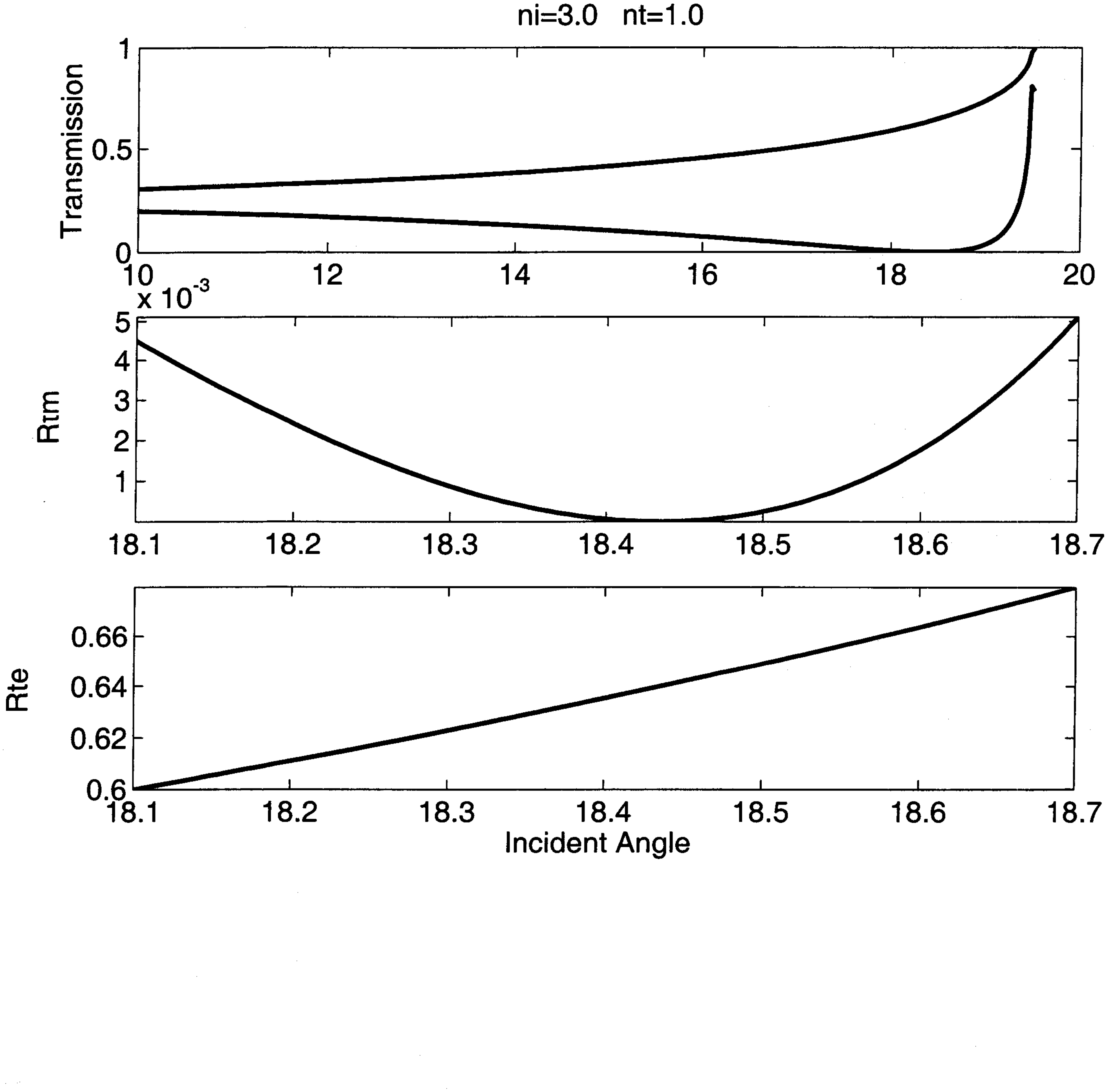
Common amplifiers : Semiconductor amplifier
Erbium doped fiber amplifier

## WDM Regenerator



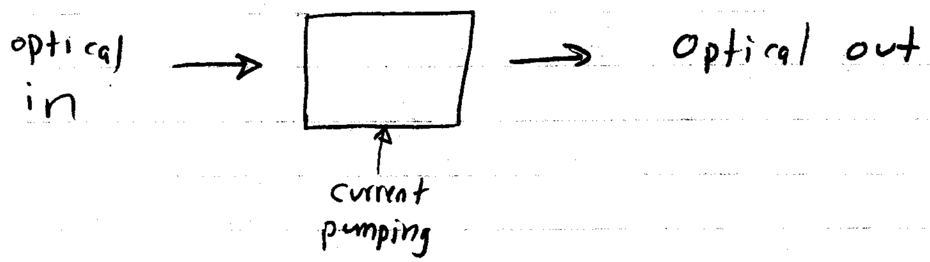
## Optical Amplifier




ni=3.0 nt=1.0
Transmission
1
0.5
0
10
12
14
16
18
20
x 10^-3
Rtm
5
4
3
2
1
18.1
18.2
18.3
18.4
18.5
18.6
18.7
Rte
0.66
0.64
0.62
0.6
18.1
18.2
18.3
18.4
18.5
18.6
18.7
Incident Angle

# Semiconductor Optical Amplifier

Laser cavity biased below threshold



$$\text{gain (dB)} = \frac{(1-r_L^2)(1-r_R^2)\,G_0}{\left|1-G_0 r_R r_L e^{j2\beta L}\right|^2}$$

Variation in gain with wavelength

$$\text{variation} = \left(\frac{1+G_0 r_R r_L}{1-G_0 r_R r_L}\right)^2$$

Example:

For a gain of 20dB ($G_0 = 100$) what is the minimum reflectivity for a peak gain variation of 1dB

$$10^{.1} = 124 = \left(\frac{1+100\, r_R r_L}{1-100\, r_R r_L}\right)^2$$

$$\sqrt{1.24}\,(1-100\, r_R r_L) = 1+100\, r_R r_L$$

$$\frac{\sqrt{1.24}-1}{100+\sqrt{1.24}\,(100)} = r_R r_L = 5.37\times10^{-4}$$

Very small

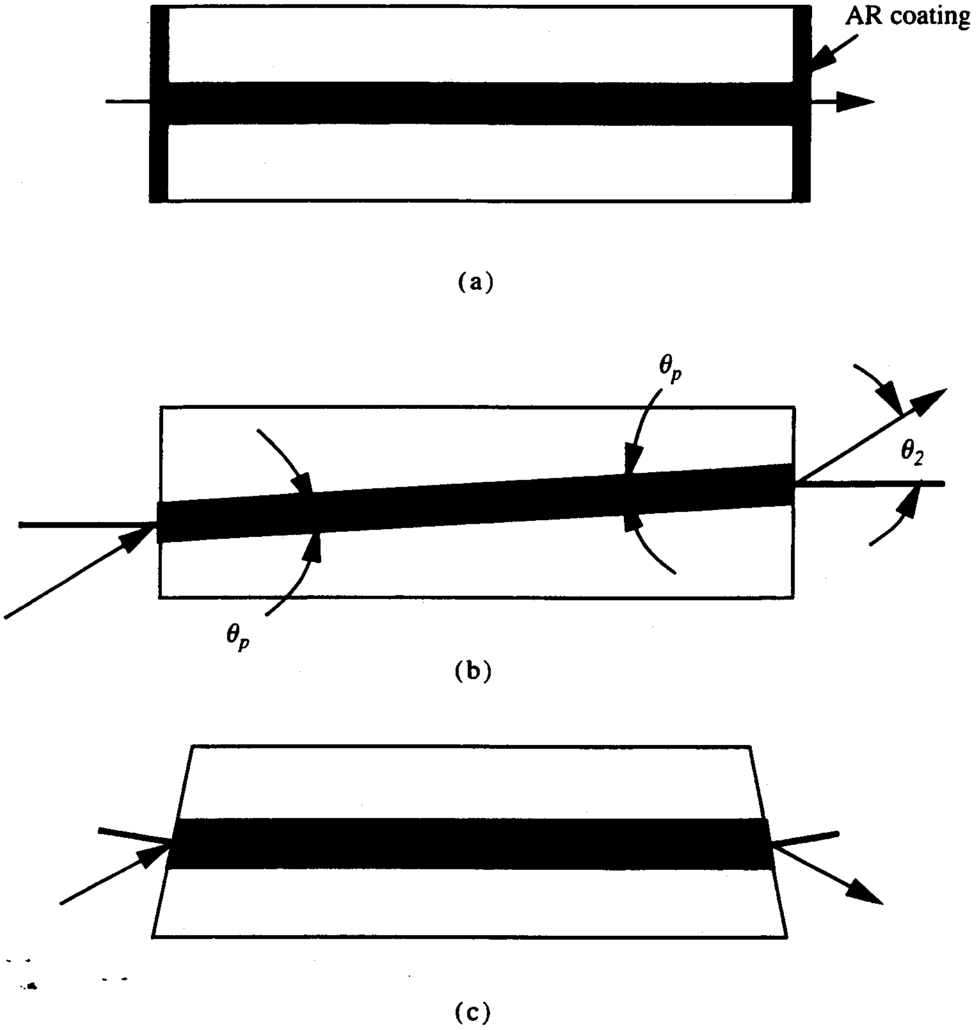
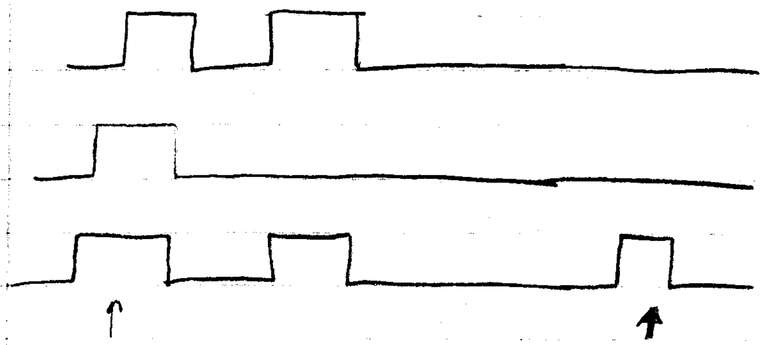


**Figure 17.7** Methods to reduce the cavity end reflection: (*a*) antireflection coating, (*b*) cavity tilted at the Brewster angle, and (*c*) cavity facet tilted at the Brewster angle. In (*b*) and (*c*), note that the incident and output light is not parallel to the longitudinal direction of the cavity

With multiple wavelength channels the carrier concentration varies randomly.



gain saturation / no gain saturation

Variance of change in gain

$$E[\Delta g^2] \approx \begin{cases} E[\Delta g_0^2] & T \gg \tau \\ E[\Delta g_0^2]\left(\frac{T}{\tau}\right)^3\left(\frac{1}{3}\right) & T \ll \tau \end{cases}$$

$$\Delta g_0 = g(N)\,\frac{\Delta N_{ph}}{N_{ph,sat} + N_{ph,0}}$$

$\Delta N_{ph}$ : one channel

$N_{ph,0}$ : average

For semiconductor amplifiers

$$T \gg \tau$$

# Semiconductor Optical Amplifiers (SOA)

High gain ~ 20dB
High Saturation power 5-10 dBm
Large BW
Can operate at any wavelength
Compact
Easy integration
Integration into arrays

Polarization dependent
High noise
cross talk between WDM channels

The crosstalk limits SOA in WDM applications

# Erbium Doped Fiber Amplifier (EDFA)

Dope the core of an optical fiber with the rare earth ion $Er^{+3}$

The energy diagram has a meta-stable state with an emission wavelength around $\lambda = 1530$ nm. and quick transitions into this state.

The population inversion is acheived by optically pumping at $\lambda = 980$nm or 1480nm.

The optical pumping is longitudinal rather than transverse resulting in better absorption of the optical pump.

The basic component of an EDFA are
pump laser
isolator

Coupler to combine signal and pump
Erbium doped fiber
Filter : to eliminate pump light

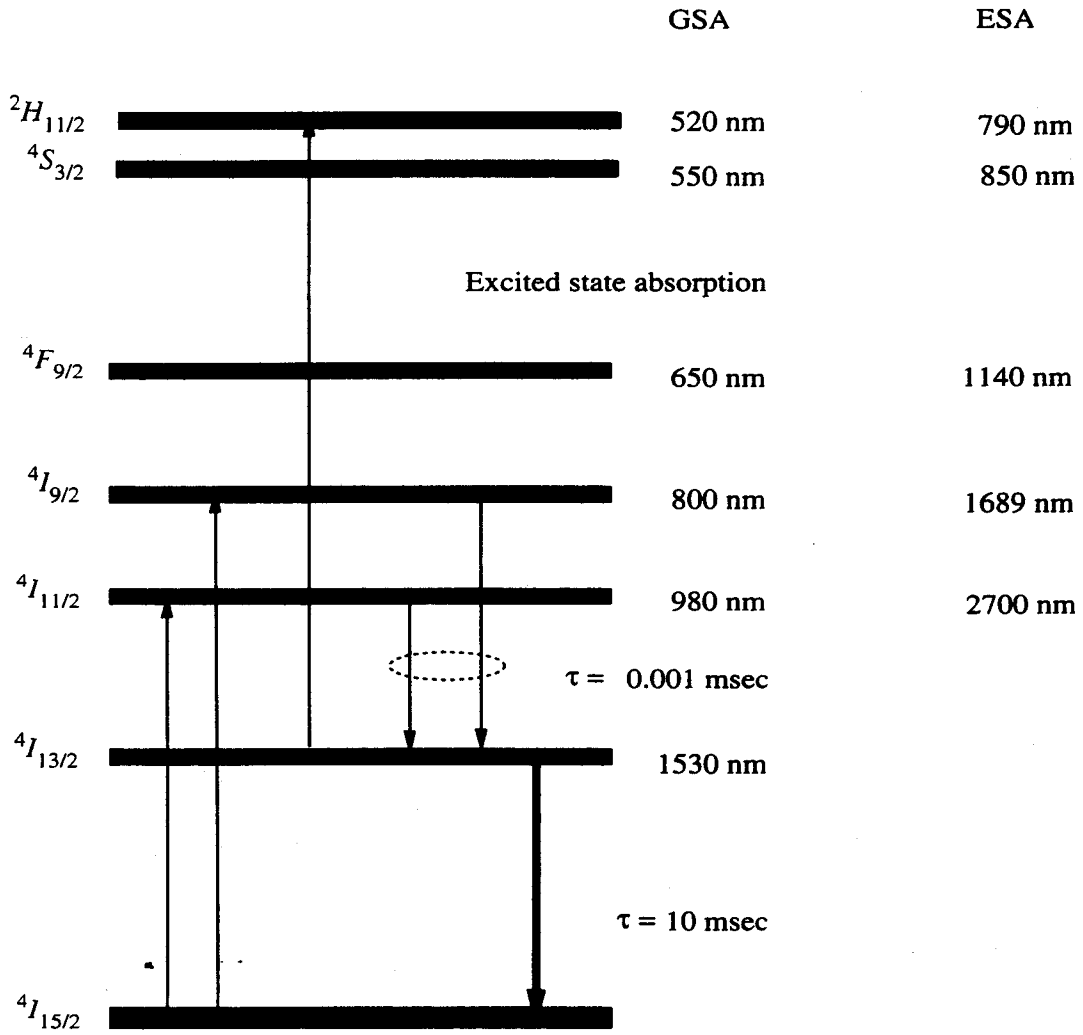
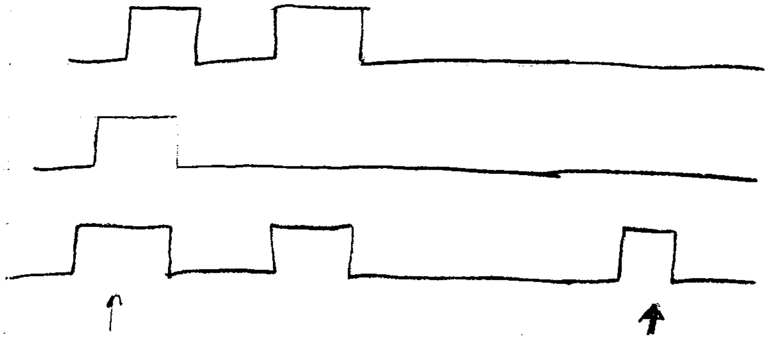


**Figure 17.9** Energy levels of $Er^{3+}$. For each level, the ground state absorption (GSA) wavelength is the light wavelength needed to excite carriers from the ground state to the given level, and the excited state absorption (ESA) wavelength is the light wavelength needed to excite carriers from the given level to the metastable state $^4I_{13/2}$.

With multiple wavelength channels the carrier concentration varies randomly.



gain saturation no gain saturation

Variance of change in gain

$$E[\Delta g^2] \approx \begin{cases} E[\Delta g_0^2] & T \gg \tau \\ E[\Delta g_0^2]\left(\frac{T}{\tau}\right)^3\left(\frac{1}{3}\right) & T \ll \tau \end{cases}$$

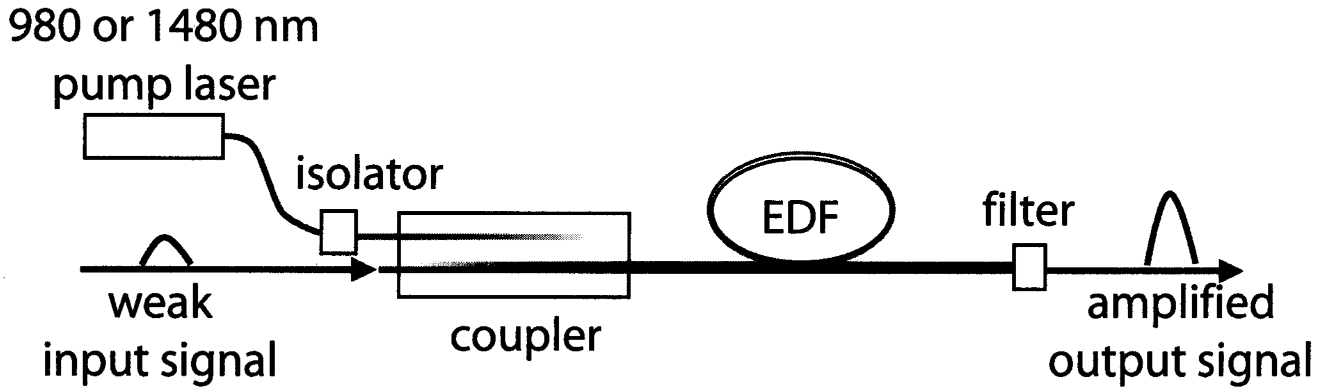
$$\Delta g_0 = g(N)\,\frac{\Delta N_{ph}}{N_{ph,sat} + N_{ph,0}}$$

$\Delta N_{ph}$ : one channel

$N_{ph,0}$ : average

For semiconductor amplifiers

$$T \gg \tau$$


980 or 1480 nm
pump laser
isolator
EDF
filter
weak
input signal
coupler
amplified
output signal

The external pump rate is

$$R_p = W_p N_1$$

where $N_1$ is the ground state population

$$W_p = \frac{\sigma_a P_p}{h f_p A} \quad s^{-1}$$

$h f_p$ is the photon energy of the pump
$A$ is the core area
$\sigma_a$ is the absoiption cross section
$P_p$ is the pump power

The gain is given by

$$g = \sigma_e (N_2 - N_1)$$

$N_2$ is the concentration in the metastable state
$N_1$ is the concentration in the ground state
$\sigma_e$ is the emission cross-section

The stimulated emission rate becomes

$$R_s = V_g \, g \, N_{ph}$$

$$P_{in} = (V_g)(N_{ph} A)(h f_s)$$

$$R_s = \frac{\sigma_e P_{in}}{h f_s A} (N_2 - N_1) \triangleq W_s (N_2 - N_1)$$

$$W_s \triangleq \frac{\sigma_e P_{in}}{h f_s A} \quad s^{-1}$$

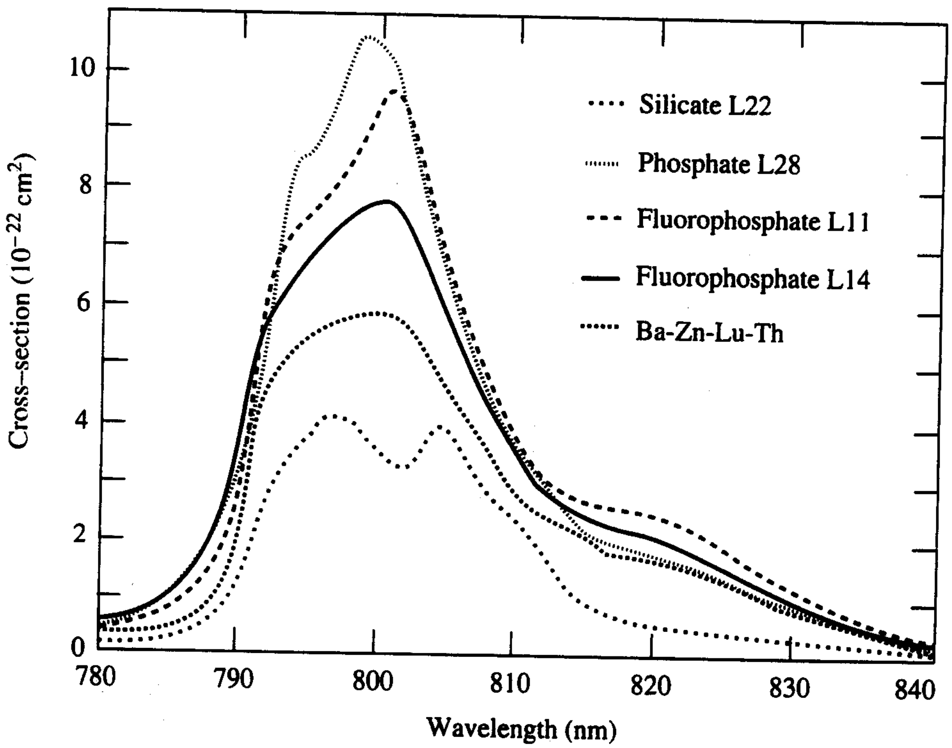


**Figure 17.13** Absorption cross section of $Er^{3+}$ at 800 nm.

Source: Reprinted, by permission, from Miniscalco, "Erbium-Doped Glasses for Fiber Amplifiers at 1500 nm," Figure 11 [10]. © 1991 by IEEE.

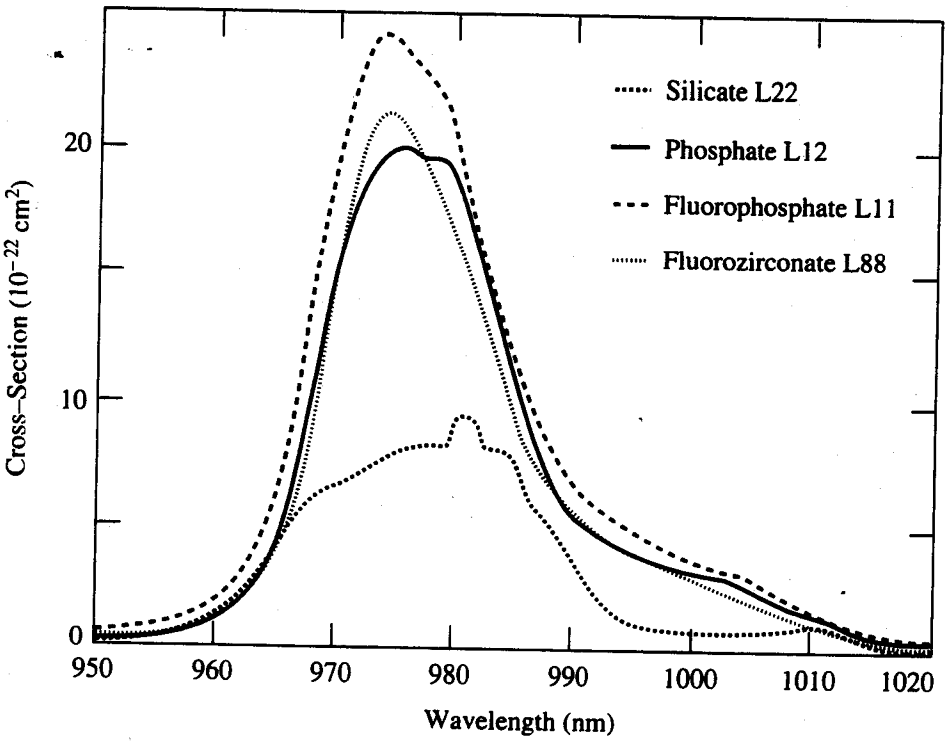


**Figure 17.14** Absorption cross section of $Er^{3+}$ at 980 nm.

Source: Reprinted, by permission, from Miniscalco, "Erbium-Doped Glasses for Fiber Amplifiers at 1500 nm," Figure 12 [10]. © 1991 by IEEE.

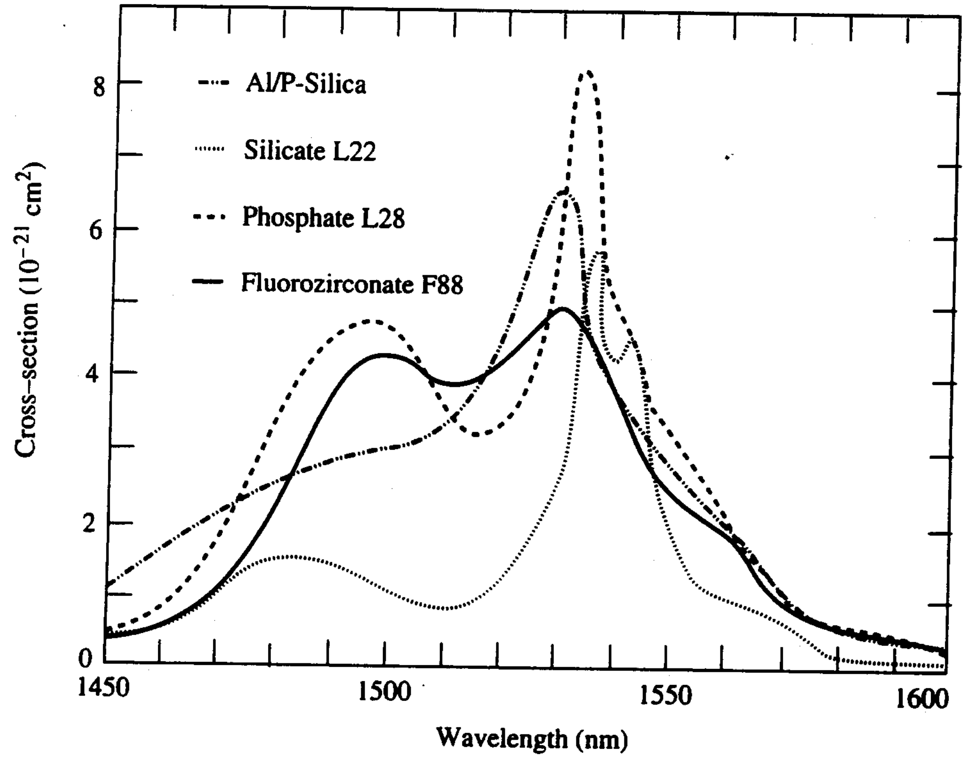


**Figure 17.15** Absorption cross section of $Er^{3+}$ at 1450 nm.

Source: Reprinted, by permission, from Miniscalco, "Erbium-Doped Glasses for Fiber Amplifiers at 1500 nm," Figure 7 [10]. © 1991 by IEEE.

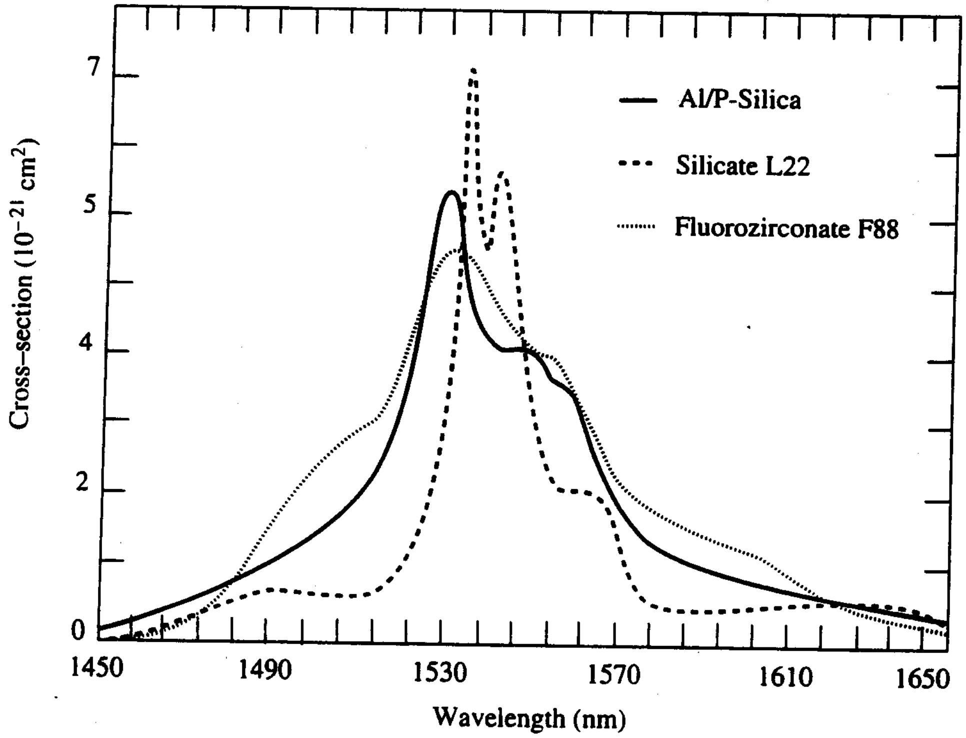


**Figure 17.16** Emission cross section of $Er^{3+}$ at 1540 nm.

Source: Reprinted, by permission, from Miniscalco, "Erbium-Doped Glasses for Fiber

The carrier rate equation is

$$\frac{dN_2}{dt} = \underset{\underset{\text{pump rate}}{\uparrow}}{W_p} N_1 - W_s \underset{\underset{\text{net stimulated emission rat}}{\uparrow}}{(N_2 - N_1)} - \underset{\underset{\text{spontaneous recombination rate}}{\uparrow}}{\frac{N_2}{\tau_{sp}}} = -\frac{dN_1}{dt}$$

$\tau_{sp} \sim 10\,ms$

at steady state

$$0 = W_p N_1 - W_s (N_2 - N_1) - \frac{N_2}{\tau_{sp}}$$

$$0 = 2W_p N_1 - 2W_s (N_2 - N_1) - \frac{2N_2}{\tau_{sp}}$$

$$0 = W_p (N_1 + N_2) - W_p (N_2 - N_1) - 2W_s (N_2 - N_1) - \frac{1}{\tau_{sp}} (N_2 - N_1) - \frac{1}{\tau_{sp}} (N_1 + N_2)$$

$$(N_2 - N_1)(W_p + 2W_s + 1/\tau_{sp}) = (N_1 + N_2)(W_p - 1/\tau_{sp})$$

$$N_2 - N_1 = \frac{(W_p - 1/\tau_{sp})}{W_p + 2W_s + 1/\tau_{sp}} N_t$$

$N_t = N_1 + N_2$ is the total carrier density

23

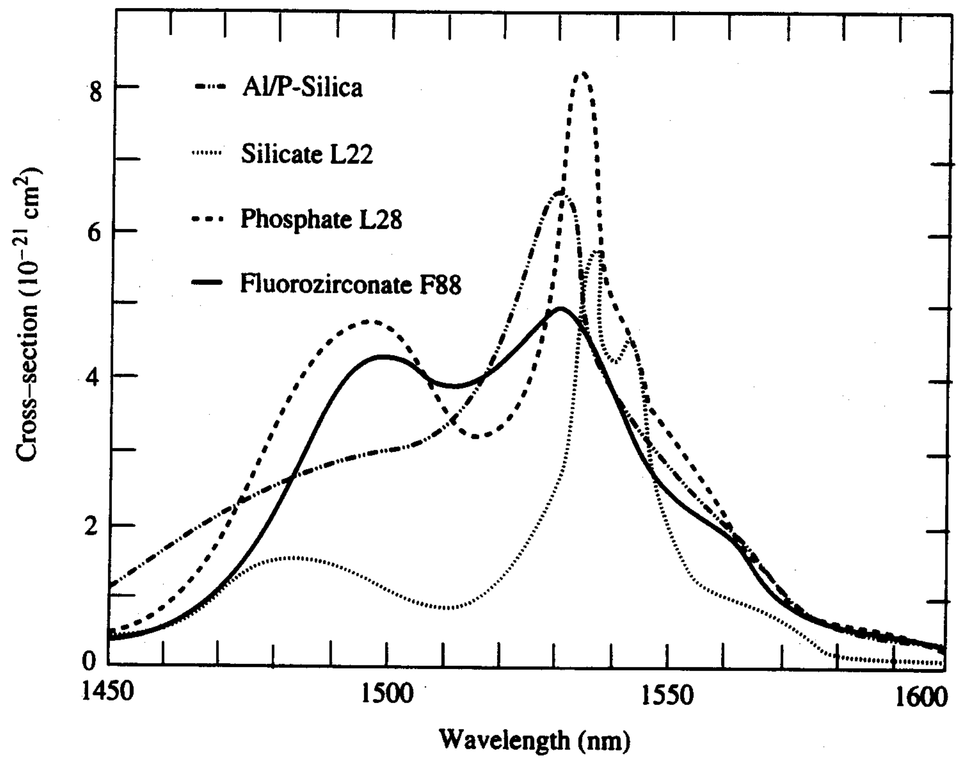


**Figure 17.15** Absorption cross section of $Er^{3+}$ at 1450 nm.

Source: Reprinted, by permission, from Miniscalco, "Erbium-Doped Glasses for Fiber Amplifiers at 1500 nm," Figure 7 [10]. © 1991 by IEEE.

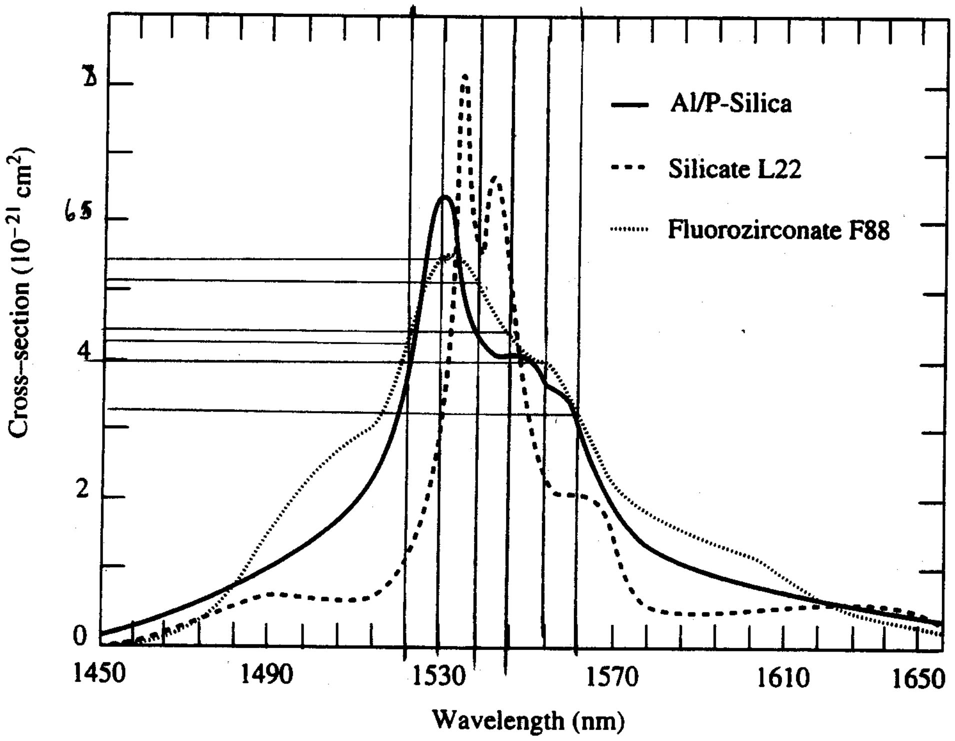


**Figure 17.16** Emission cross section of $Er^{3+}$ at 1540 nm.

3/4

Source: Reprinted, by permission, from Miniscalco, "Erbium-Doped Glasses for FIber Amplifiers at 1500 nm," Figure 8 [10]. © 1991 by IEEE.

With a high pumping rate

$$W_p \gg W_s \qquad W_p \gg 1/\tau_{sp}$$

$$N_2 - N_1 = \frac{W_p}{W_p} N_t$$

$$g = \sigma_e (N_2 - N_1) \approx \boxed{\sigma_e N_t \triangleq g^*}$$

$$g = \sigma_e (N_2 - N_1)$$

$$g = \sigma_e \left[ \frac{W_p - 1/\tau_{sp}}{W_p + 2W_s + 1/\tau_{sp}} \right] N_t \qquad N_t = \frac{g^*}{\sigma_e}$$

$$g = g^* \left[ \frac{W_p - 1/\tau_{sp}}{W_p + 2W_s + 1/\tau_{sp}} \right]$$

Example :

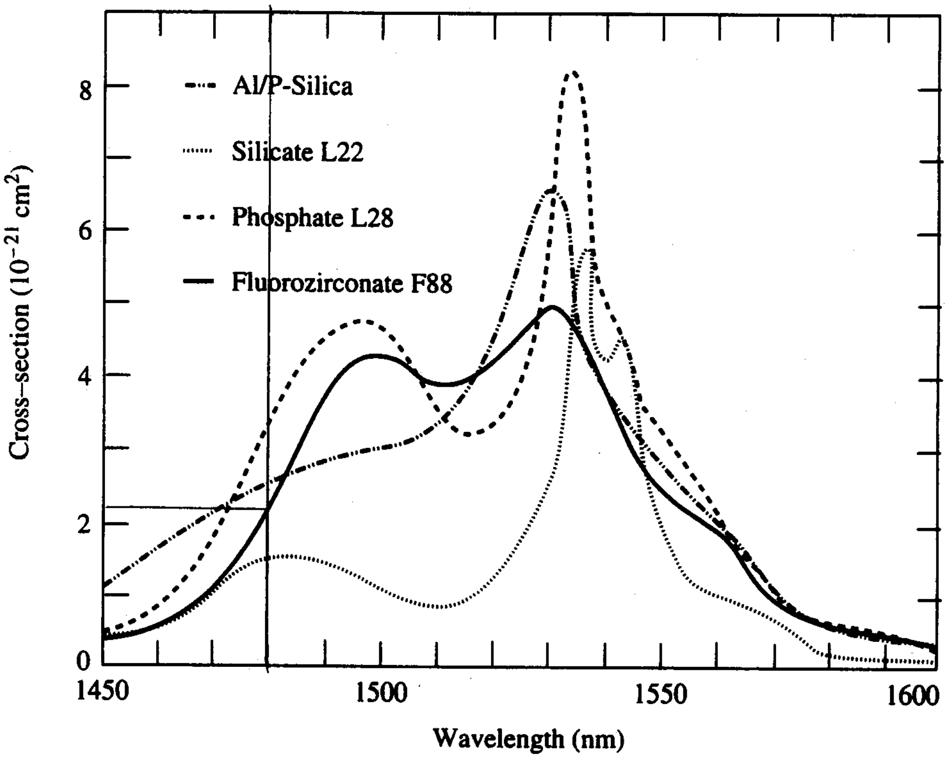


**Figure 17.15** Absorption cross section of $Er^{3+}$ at 1450 nm.

Source: Reprinted, by permission, from Miniscalco, "Erbium-Doped Glasses for Fiber Amplifiers at 1500 nm," Figure 7 [10]. © 1991 by IEEE.

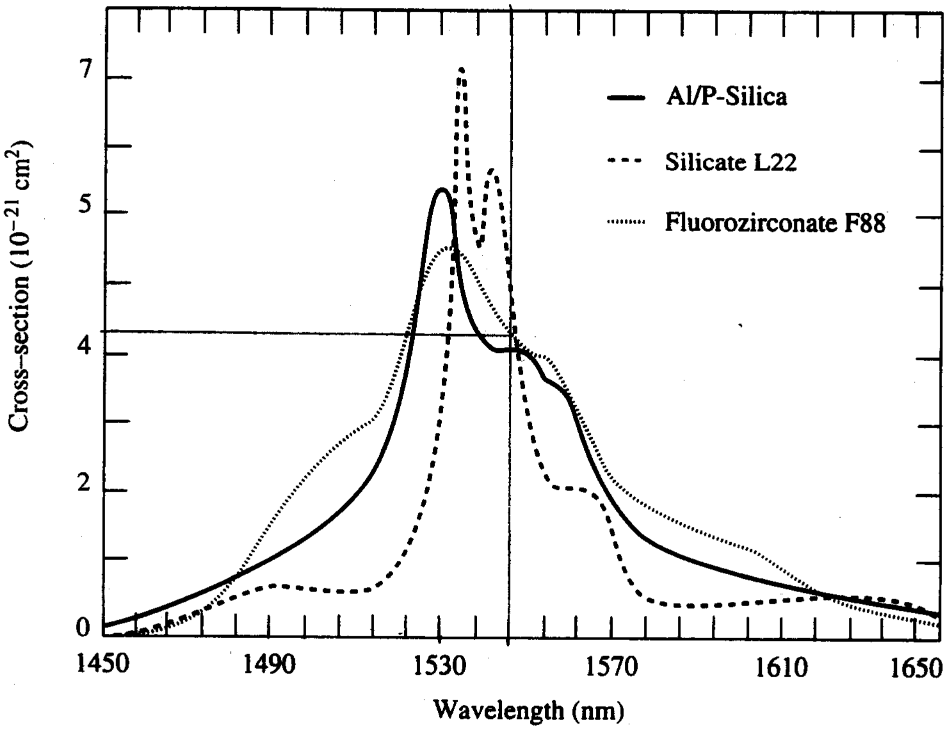


**Figure 17.16** Emission cross section of $Er^{3+}$ at 1540 nm.

Source: Reprinted, by permission, from Miniscalco, "Erbium-Doped Glasses for Fiber Amplifiers at 1500 nm," Figure 8 [10]. © 1991 by IEEE.

Pump at $\lambda_p = 1480\,\text{nm}$ $\sigma_a = 2.2\times10^{-21}\,\text{cm}^2$

Signal at $\lambda =$ 1522, 1530, 1538, 1546, 1554, 1562 nm

$L = 5\text{m}$

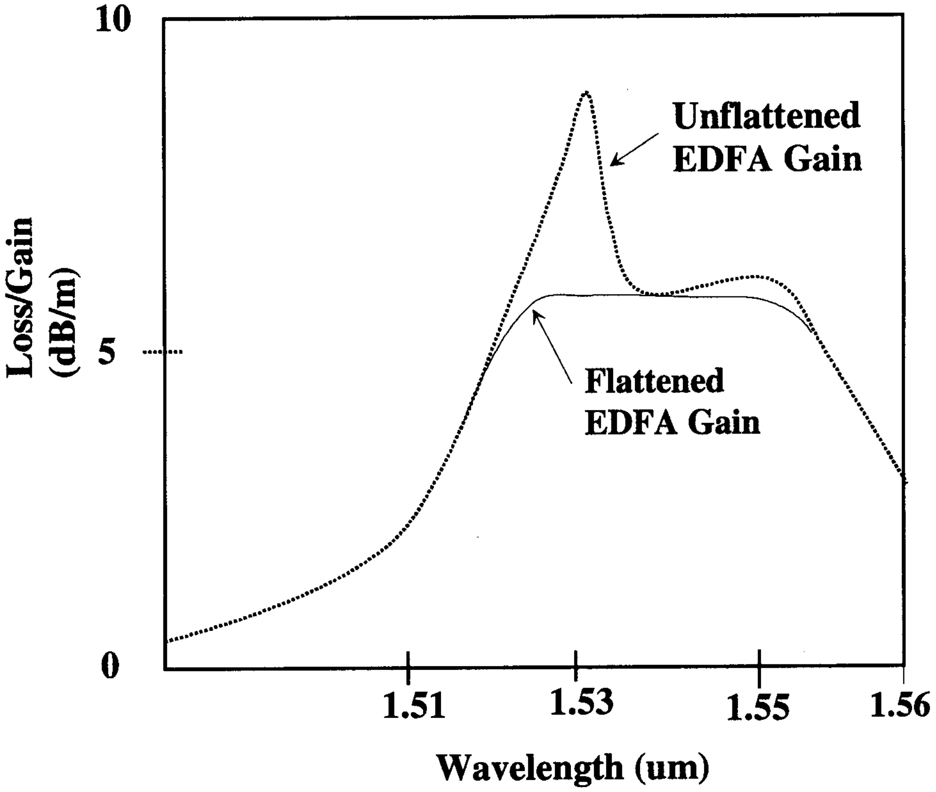
| $\lambda_f$ (nm) | $\sigma_e$ $\times10^{-21}\,\text{cm}^2$ | $g^*$ ($m^{-1}$) | $g$ ($m^{-1}$) | G (dB) |
|---|---|---|---|---|
| 1522 | 4.28 | 3.42 | 1.77 | 38 |
| 1530 | 5.56 | 4.45 | 2.28 | 49 |
| 1538 | 5.22 | 4.18 | 2.14 | 46 |
| 1546 | 4.44 | 3.55 | 1.83 | 40 |
| 1554 | 4 | 3.20 | 1.65 | 36 |
| 1562 | 3.22 | 2.58 | 1.34 | 29 |

$g^* = \sigma_e N_t$

$$g = g^* \frac{W_p - 1/\tau_{sp}}{W_p + 2W_s + 1/\tau_{sp}}$$

$G = (4.34\,g)\,L$

## *EDFA Gain Equalization*



- Gain equalization can be accomplished in several ways:
    a. Thin film filters
    b. Long period fiber gratings
    c. Chirped fiber Bragg gratings

The pump power is actually spatially dependent

$$\frac{dP_p}{dz} = -\sigma_a N_1 P_p$$

To relate $N_1$ to the total carrier density $N_t$ use Eq 17.33

$$N_2 - N_1 = \frac{\left(W_p - 1/\tau_{sp}\right) N_t}{W_p + 2W_s + 1/\tau_{sp}}$$

$$W_p(N_2 - N_1) + 2W_s(N_2 - N_1) + 1/\tau_{sp}(N_2 - N_1) = W_p(N_2 + N_1) - 1/\tau_{sp}(N_2 + N_1)$$

$$W_p(-2N_1) + 2W_s(N_2 - N_1) + 1/\tau_{sp}(2N_2) = 0$$

$$-N_1 W_p + W_s(N_2 + N_1 - 2N_1) + 1/\tau_{sp}(N_2 + N_1 - N_1) = 0$$

$$-N_1(W_p + 2W_s + 1/\tau_{sp}) + N_t(W_s + 1/\tau_{sp}) = 0$$

$$N_1 = \frac{(W_s + 1/\tau_{sp}) N_t}{W_p + 2W_s + 1/\tau_{sp}}$$

use this for pump power

$$\frac{dP_p}{dz} = -\sigma_a N_t P_p \frac{W_s + 1/\tau_{sp}}{W_p + 2W_s + 1/\tau_{sp}}$$

The Signal power is also spatially varying

$$\frac{P_{in}}{dz} = g\,P_{in} \approx \sigma_e (N_2 - N_1)\,P_{in}$$

using Eq. 17.33

$$\frac{dP_{in}}{dz} = g^* \frac{W_p - 1/\tau_{sp}}{W_p + 2W_s + 1/\tau_{sp}} P_{in} = \frac{g_0}{1 + W_s/W_{sat}} P_{in}$$

$$g_0 = g^* \frac{W_p - 1/\tau_{sp}}{W_p + 1/\tau_{sp}}$$

$$W_{sat} = 1/2 \left( W_p + 1/\tau_{sp} \right)$$

---

$W_p$ gets smaller along the propagation direction
Gain saturation effect is stronger at the output end of the amplifier

The optimum Amplifier length is a function of the pump power

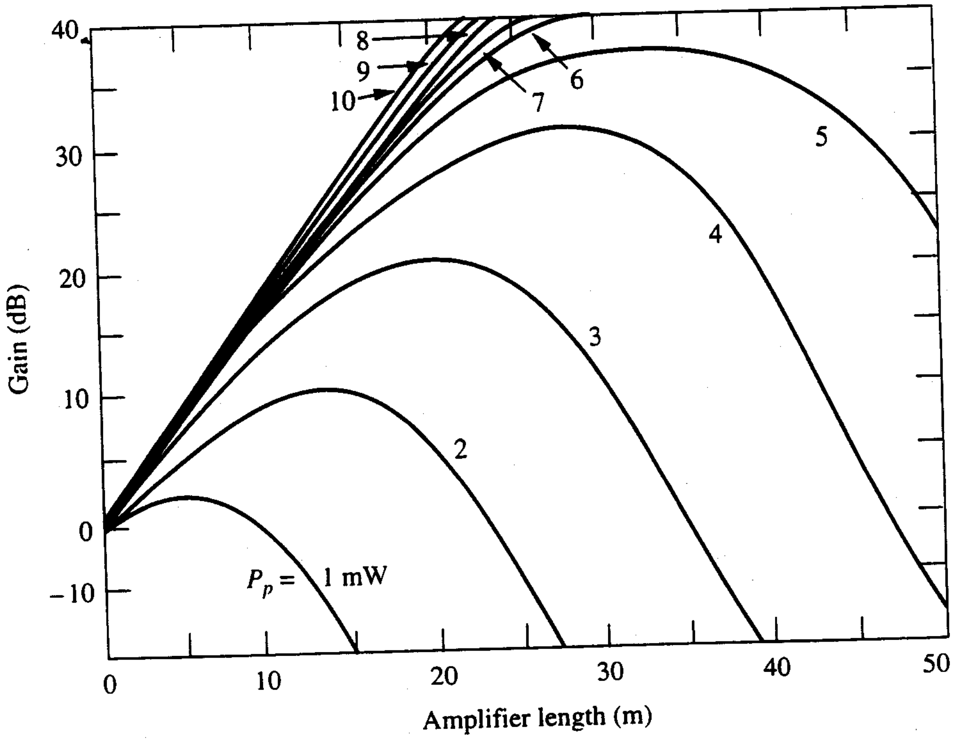


**Figure 17.17** EDFA gain as a function of the amplifier length.

Source: Reprinted, by permission, from Giles and Desurvire, "Modeling Erbium-Doped Fiber Amplifiers," Figure 8b [12]. © 1991 by IEEE.

# Erbium doped fiber amplifiers (EDFA)

High power transfer from pump to signal (>50%)
Saturation output 10 – 25 dBm
Long gain constant ( $\tau$ > 10ms) to overcome
patterning effect and crosstalk
Polarization independent
Already in fiber domain

Large devices m – Km
Amplified spontaneous emission (ASE) noise