INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
I.C.T.P., P.O. BOX 586, 34100 TRIESTE, ITALY, CABLE CENTRATOM TRIESTE

UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION
INTERNATIONAL CENTRE FOR SCIENCE AND HIGH TECHNOLOGY

H4.SMR/540-25

Second Training College on Physics and Technology of Lasers and Optical Fibres

21 January - 15 February 1991

Optical Amplifiers

James Wilkinson
Optoelectronics Research Centre
The University
Southhampton, U.K.

OUTLINE

- Advantages of optical amplification
- Applications of optical amplifiers
- Major types of optical amplifier
- Noise in optical amplifiers
- Principles of optical amplification
- Semiconductor optical amplifier
- Erbium-doped fibre amplifier
- Raman optical fibre amplifier
- System performance

ADVANTAGES OF OPTICAL AMPLIFICATION

- Simplicity
  - Low cost
  - Reliability
- Transparency
  - Flexible bit-rate & modulation format
  - Direct or coherent detection systems
  - Upgrade number of channels
- Wide optical bandwidth
  - Multichannel operation
  - Very high data rates

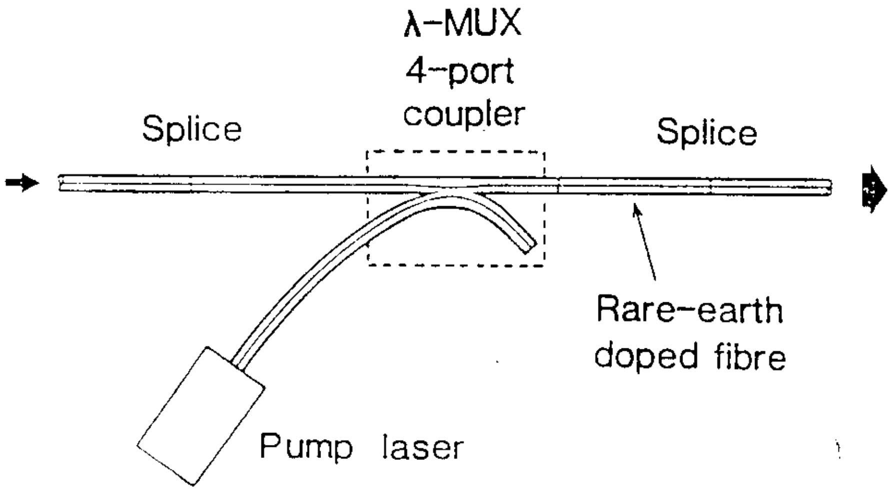
APPLICATIONS OF OPTICAL AMPLIFIERS

- Line amplifiers
  - Reduce number of regenerators
  - Allow transparent transmission
- Preamplifiers
  - Improve SNR in high bit-rate direct detection systems
- Power amplifiers
  - Boost signals to compensate branching losses in multi-terminal networks

MAJOR TYPES OF OPTICAL AMPLIFIER

- o Erbium-doped optical fibre amplifier (EDFA)
- o Semiconductor laser optical amplifiers (SCLA)
- o Raman optical fibre amplifier (RFA)

BASIC ERBIUM AMPLIFIER CONFIGURATION



ADVANTAGES OF ERBIUM DOPED FIBRE AMPLIFIERS

o Low fibre coupling loss

High fibre-fibre gain (>40dB)

Low feedback & passband ripple

Good noise figure (~3dB)

o Polarisation insensitive

No polarisation controller

o Large energy storage

Low interchannel crosstalk

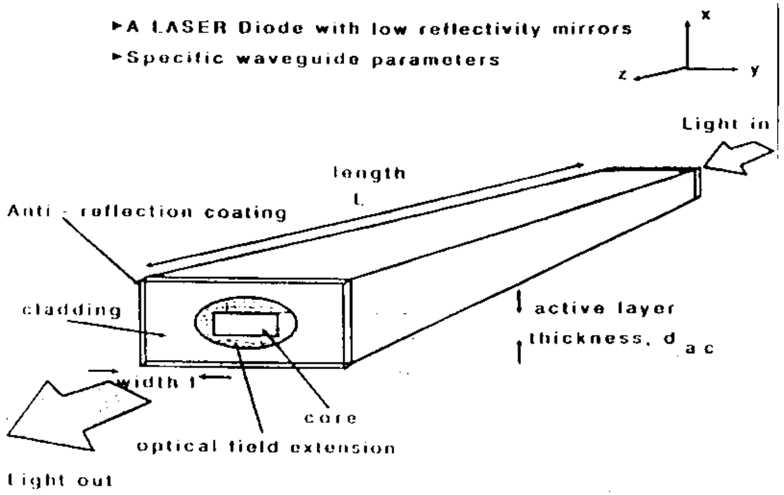
Low pump noise feedthrough

Operates deep in saturation

o High saturation o/p power (>10 dBm)

o Gain passband insensitive to temperature

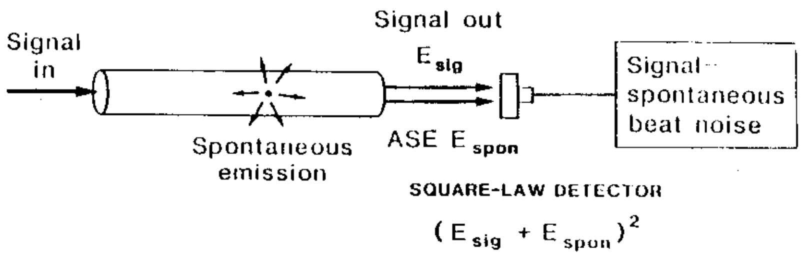
BASIC STRUCTURE OF THE SEMICONDUCTOR AMPLIFIER



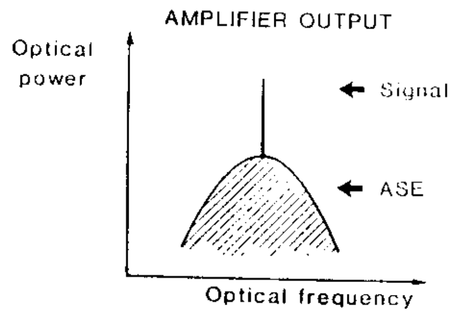
ADVANTAGES OF SEMICONDUCTOR OPTICAL AMPLIFIERS

- **Direct injection pumping**
- **Not restricted to 1500nm wavelength band**
- **Integrable into complex switchable arrays**
- **Compatible with optoelectronic integration**

NOISE IN OPTICAL AMPLIFIERS



NOISE MECHANISMS



- Signal heterodynes with ASE ➔ signal-spontaneous beat noise
- ASE heterodynes with itself ➔ spontaneous-spontaneous beat noise
- Amplified signal shot noise (negligible)

Noise in Optical Amplifiers

Assuming a detector of unit quantum efficiency, the noise power spectral density due to amplified signal and ASE is :

$$< i^2 > = \frac{2e^2}{h\nu}(A + B + C)$$

$A = P_S + P_{SP}$ — shot noise term

$B = 2\mu P_S(G-1)$ — signal/spontaneous beat term

$C = 2\Delta\nu \cdot h\nu[\mu(G-1)]^2$ — spont./spont. beat term

n_{SP} = Inversion factor

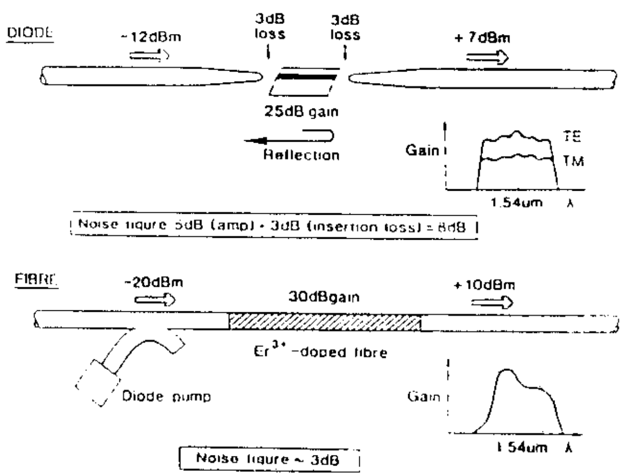
$\Delta\nu$ is the ASE spectral width, G is the amplifier gain, P_S and P_{SP} are the signal and spontaneous optical powers at the output.

For most applications B dominates and Noise Figure is:

$$\mathrm{NF} = \frac{\text{Input sig./noise power ratio}}{\text{Output sig./noise power ratio}} = \left[\frac{P_{in}}{P_{out}}\right]^2 \frac{\text{Noise}_{in}}{\text{Noise}_{out}} = \frac{1}{G^2} \cdot \frac{B}{P_S/G} \simeq 2\mu$$

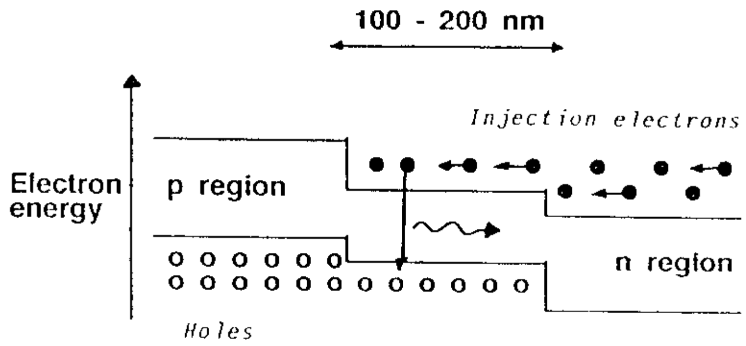
For a fully inverted amplifier $\mu = 1$ and NF = 3dB

COMPARISON OF DIODE AND FIBRE AMPLIFIERS



PRINCIPLES OF SEMICONDUCTOR OPTICAL AMPLIFIERS

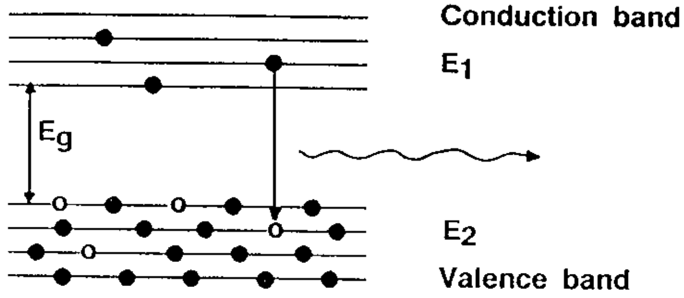
PN Double Heterostructure



Narrow band-gap material with high refractive index inserted between n & p regions, forming two heterojunctions.

- High injection efficiency
- Carriers confined to thin active region
- Photons confined to thin active region
- Outer regions transparent to radiation
- Lattice mismatch leads to nonradiative recombination
- Internal quantum efficiency 60 - 80 %

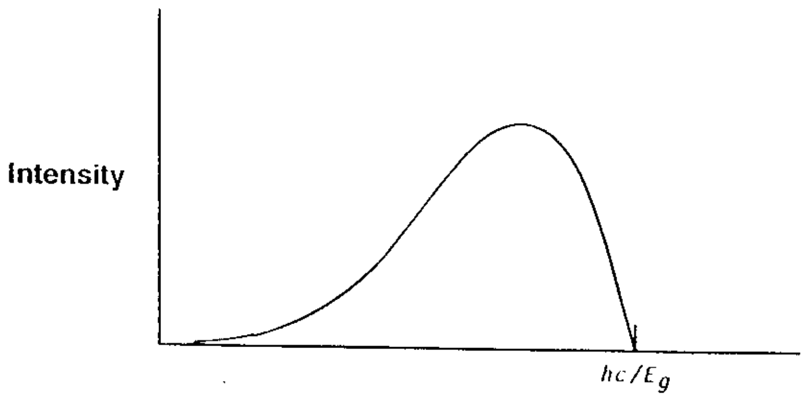
Spontaneous Emission



Emitted photon energy, $E_{ph} = E_1 - E_2$

Planck's law gives $\lambda = hc / E_{ph}$

Light is emitted with arbitrary phase and direction



Spontaneous Emission Spectrum

Spectral Linewidth

Analysis of the carrier energies in the valence and conduction bands shows that the spectral width (HPFW) of spontaneous emission is given approximately by:

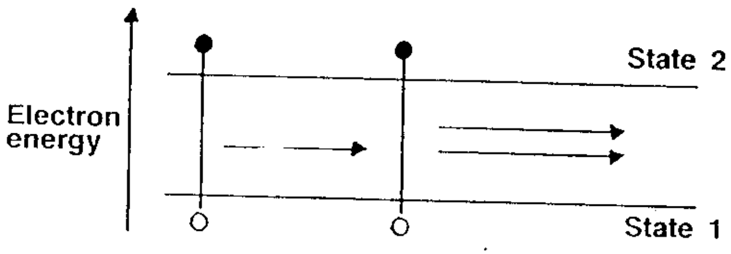
$$\frac{\Delta\lambda}{\lambda} = 2kT / E_{ph}$$

This leads to the following approximate values for the linewidth of LED's:

Wavelength (nm)	Linewidth (nm)
850	30
1300	70
1550	100

These linewidths are low estimates in practice, due to high doping levels, lattice interactions & high-temperature

Stimulated Emission



Photon stimulates recombination creating a further photon

- same energy
- same phase
- same direction

} Coherent emission

Requires conduction electrons & holes

If there are more electrons in state 2 than in state 1:

- Stimulated emission is more probable than absorption
- The medium has gain

Stimulated emission has short carrier lifetime

Active Layer Composition

Active layer material:

- must have band-gap smaller than substrate
- must have higher index than substrate
- must emit at desired wavelength
- must be lattice matched to substrate

$Ga_{1-x}Al_xAs$ system:

- Composition ranges $0 < x < 0.37$ for direct band-gap
- Wavelength ranges $870nm > \lambda > 650nm$
- GaAs and AlAs have very similar lattice constants

  Hence few dangling bonds on GaAs substrate

$In_{1-x}Ga_xAs_yP_{1-y}$ system on InP substrate:

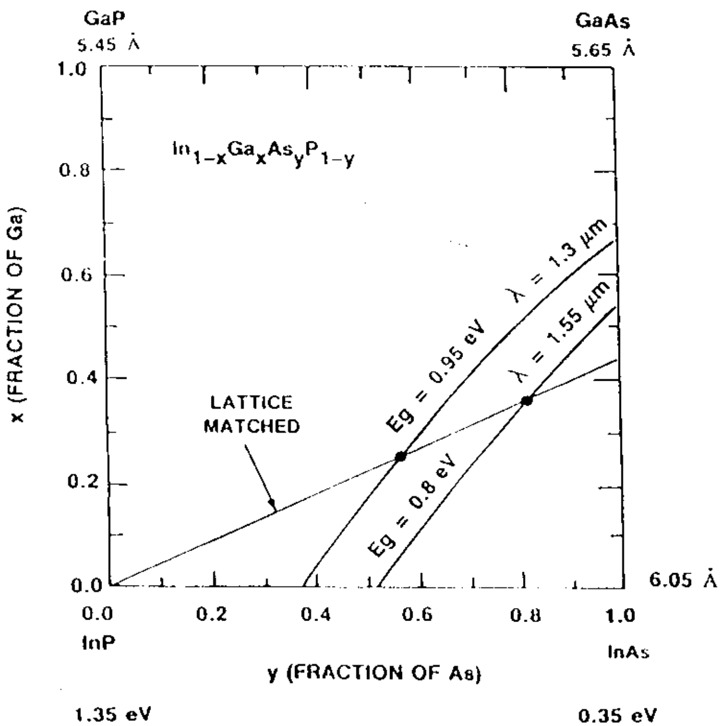
- Composition ranges $0 < x < 0.47$

  $0 < y < 1$
- Wavelength ranges $920nm < \lambda < 1670nm$
- Choice of x & y allows lattice matching to InP

Lattice Matching for Long-Wavelength Sources

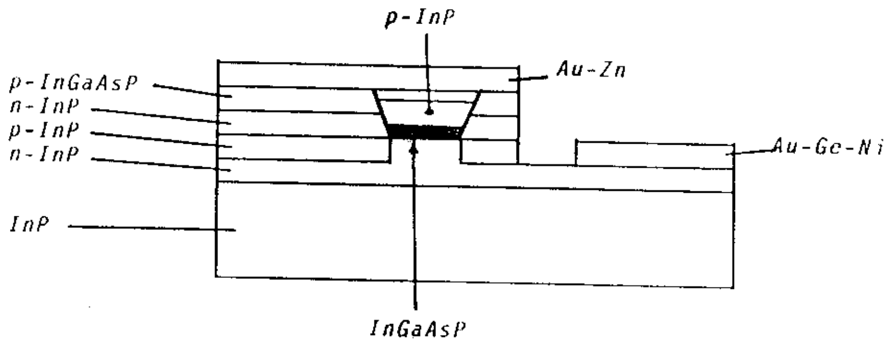
Lattice constant must match substrate (0.587nm for InP)

Intersection of curves of - constant bandgap
- constant lattice spacing
dictates composition of quaternary compound:



Index-Guided or Buried Heterostructure Laser

Lateral index-guiding ensures single transverse mode:
- Linear power / current characteristic
Cavity length 250 microns; width 2.5 microns



Emission at 1500 nm
Threshold current below 40mA

T.Matsuoka et al. Electron.Lett., 17, 12, (1981)

REQUIREMENTS FOR AMPLIFIERS

- o Low mirror reflectivity (<0.0001)

  Semiconductor materials have high index

  - Antireflection coatings
  - Angled facets
  - Buried facets

- o Weak polarisation sensitivity

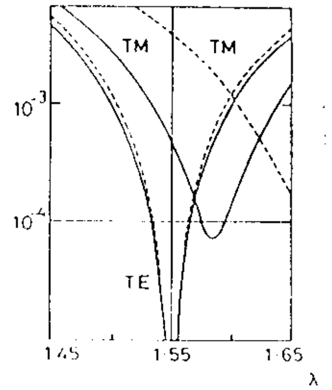
  Gain in standard devices is highly polarisation-dependent

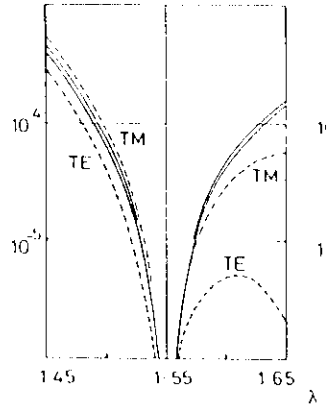
  - New waveguide design
  - Polarisation-insensitive configurations

DESIGN OF ANTIREFLECTION COATINGS

Vassallo, El.Lett. 1988

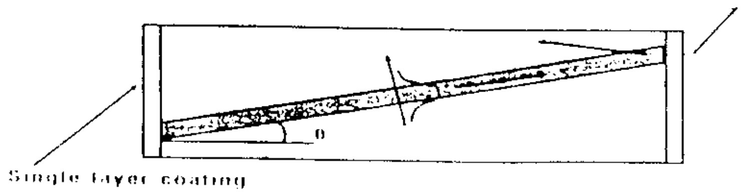
- o Double layer ar coating for low polarisation sensitivity
- o 0.5% thickness tolerance for R < 0.0001





ANGLED FACET AMPLIFIER

- o Relaxes tolerances on ar coating - single layer acceptable
- o Very good for weakly-guiding (low NA) waveguide amplifiers



POLARISATION INSENSITIVE WAVEGUIDE DESIGN

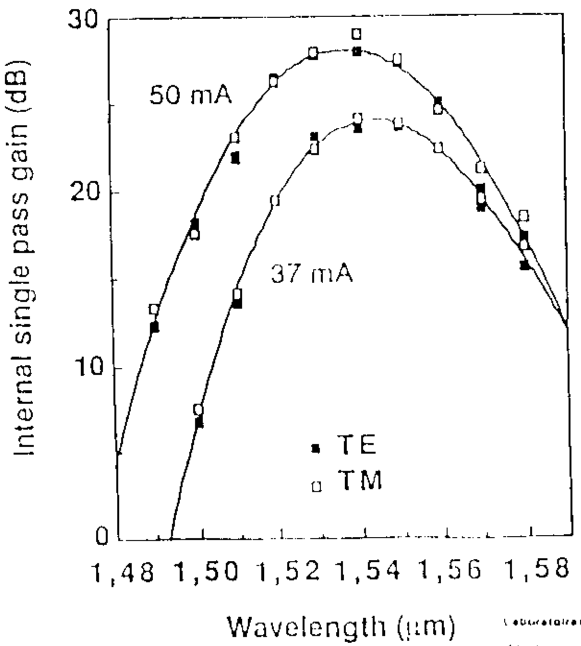
Laboratoires de Marcoussis; Centre de Recherches de la CGE

CEC RACE 1027

- **Waveguide depth = 400nm**
- **Waveguide width < 1000nm**
- **Amplifier langth = 0.4mm**

Internal gain of optical amplifier

High gain : 28 dB at low bias current (50 mA)
Low polarization sensitivity : ΔG < 1 dB



STC plc
Laboratoires de Marcoussis
CNET
Electromagnetics Institute
University of Athens
CSELT
Telettra SpA
Telefonica

NONLINEAR OPTICAL EFFECTS IN SEMICONDUCTOR AMPLIFIERS

- **Carrier density, N_2, depends on signal intensity, I.**
- **Waveguide refractive index depends upon carrier density.**
    - **Four-wave mixing**
    - **Crosstalk & intermodulation**
- **Gain $\propto$ [N_2 - N_1]**
    - **Signal dependent gain**

GAIN SATURATION IN SEMICONDUCTOR AMPLIFIERS

- **Output power saturates at between 3mW & 10mW**
- **Multi Quantum Well devices between 12mW & 45mW**

NOISE FIGURE OF SEMICONDUCTOR AMPLIFIER

Inversion parameter, $\mu = N_2 / [N_2 - N_1]$

- o Ratio of spontaneous to stimulated transitions
- o Semiconductor laser amplifier:

$$\mu = [1 - \exp\{(E - \Delta f)/kT\}]^{-1}$$

where:

E = Photon energy

Δf = Quasi-Fermi level separation

k = Boltzmann's constant

T = Temperature

μ approximately 1.3 yielding NF of 4dB

Plus:

Contribution of input coupling loss to noise figure approx 3 dB

Contribution of semiconductor waveguide loss to noise figure 4dB

Total NF is approximately 11 dB

GAIN AND NOISE IN A SEMICONDUCTOR AMPLIFIER

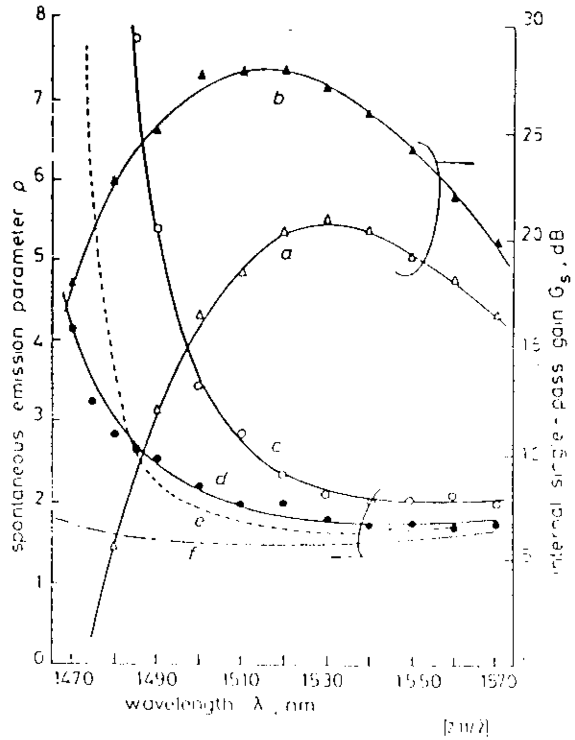
J.-C. Simon et al; Electronics Letters v25 p434, 1989.

Internal gain and noise parameter against wavelength

a,b Gain at $2I_{th}$ & $3I_{th}$ respectively

c,d Spontaneous emission parameter, u

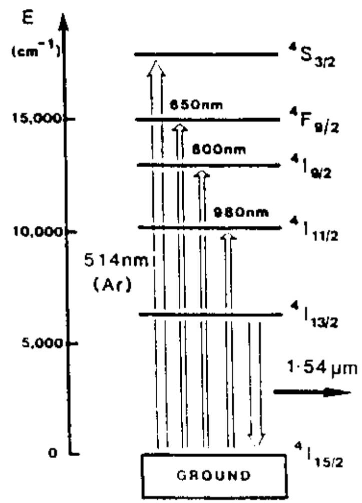
e,f Waveguide loss parameter



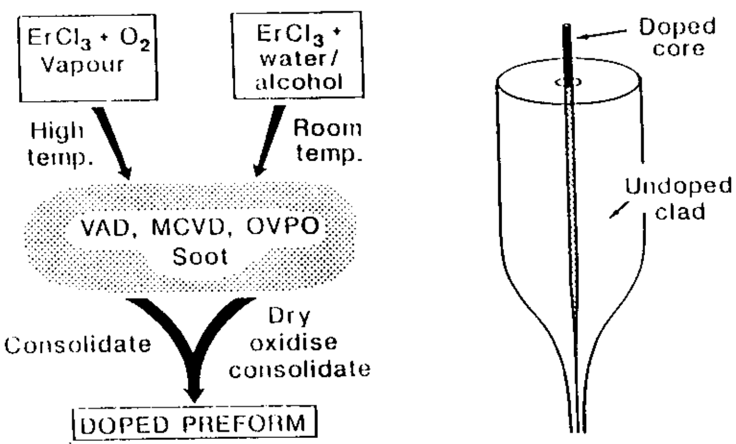
FABRICATION OF RARE-EARTH-DOPED OPTICAL FIBRES

- MCVD vapour-phase method
    - o Versatile, gives low losses
    - o Low concentrations of rare-earth
- MCVD-frit vapour-phase method
    - o Higher concentrations possible
- Solution-doping method
    - o Very versatile
    - o Applicable to MCVD, OVPO and VAD
    - o High concentrations possible
    - o Drying required
- Rod-in-tube
    - o Compound glass e.g. phosphate

ERBIUM ENERGY LEVELS



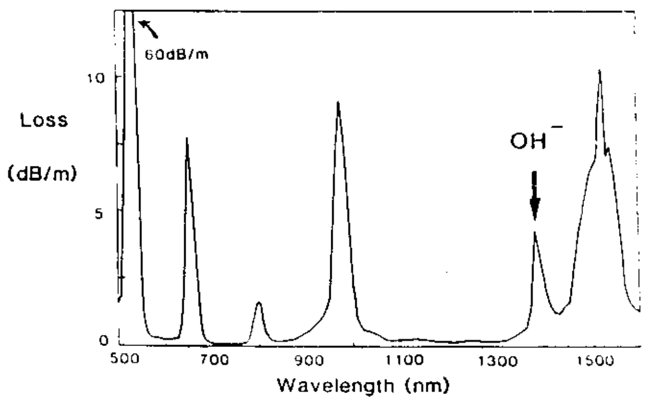
ERBIUM-DOPED FIBRE FABRICATION



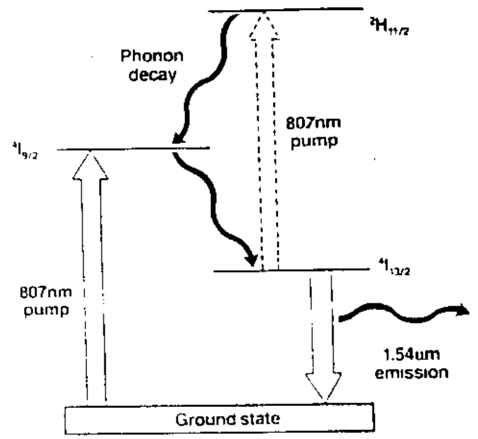
SOOT PROCESSES

COMPOUND GLASS

ABSORPTION SPECTRUM OF FIBRE DOPED WITH Er^{3+} IONS



807nm PUMP EXCITED - STATE ABSORPTION IN Er^{3+}



SOUTHAMPTON UNIVERSITY UK

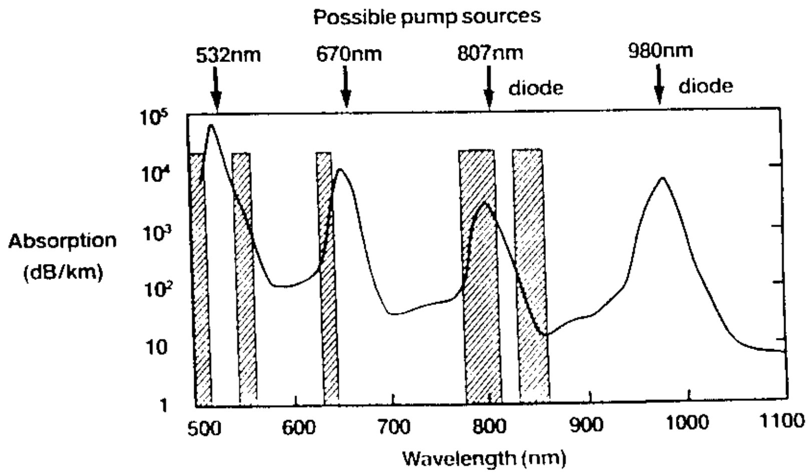
PUMP WAVELENGTHS FOR ERBIUM FIBRE AMPLIFIERS

	980nm	1490nm
Pump/signal λMUX	Easy	Difficult
Reported pump efficiency	4.0 dB/mW	2.1 dB/mW
Spectral gain	Peaky?	Smoother
Anticipated power amplifier efficiency	Large pump/ signal shift	Small shift
Noise figure	~3dB	~ 5dB

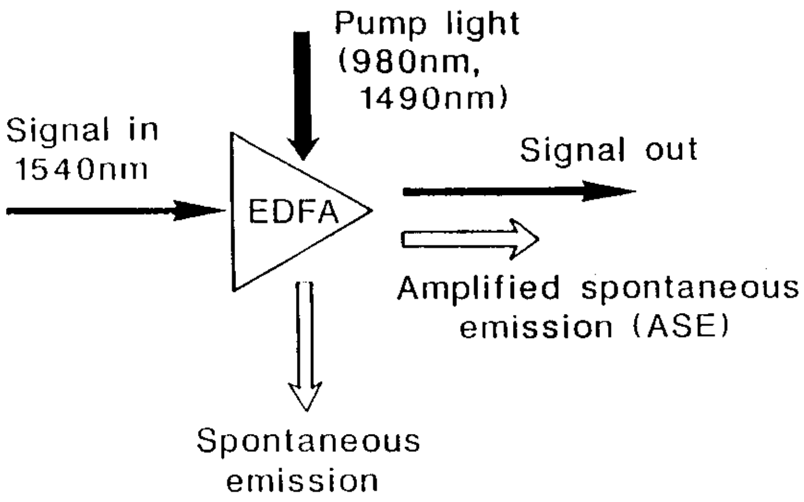
POSSIBLE PUMP WAVELENGTHS FOR ERBIUM AMPLIFIERS

- **807nm**
  Poor efficiency owing to excited-state absorption (ESA)
- **532nm**
  Sources available (expensive)
- **980nm**
  Gain efficient (4.0dB/mW pump)
  Diode pumps available soon
- **1047nm**
  Diodes available
  Noise disadvantage

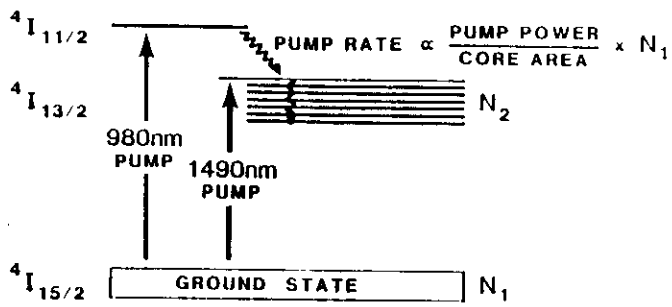
Er^{3+} - DOPED FIBRE ABSORPTION SPECTRUM SHOWING REGIONS OF EXCITED - STATE ABSORPTION



ERBIUM-DOPED FIBRE AMPLIFIER BASICS



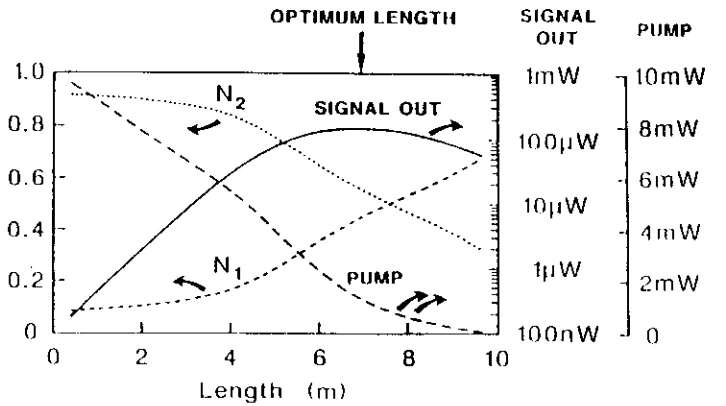
ENERGY FLOW RATES IN ERBIUM-DOPED GLASS



- **Pump-rate ∝ Pump intensity x N_1**
- **Low pump-rate due to**
  - **Long fluorescent decay time**
  - **Negligible non-radiative decay**
- **Large energy stored wrt pump rate**
- **Spontaneous emission ∝ N_2/t_{sp}**
- **Amplified signal ∝ Signal intensity x $(N_2 - N_1)$**
- **Gain ∝ $(N_2 - N_1)$**
- **Amplified spontaneous emission (ASE) power**

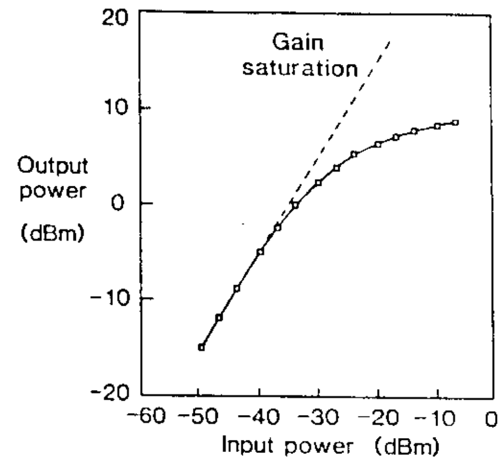
$$= \mu . h\nu . \Delta\nu \, (G-1)$$

VARIATION OF EDFA PARAMETERS WITH LENGTH



Pump wavelength = 980nm
Fibre NA = 0.2
λ_{cutoff} = 970nm

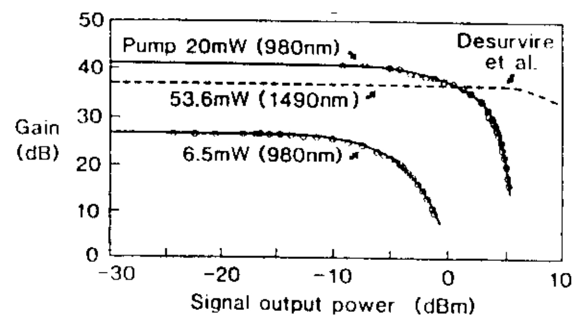
AMPLIFIER INPUT / OUTPUT CHARACTERISTICS



FIBRE N.A.	0.16
CUTOFF	975nm
LENGTH	8.7m
980nm PUMP POWER	15mW

Pump quantum efficiency at 8.5dBm out is 44%

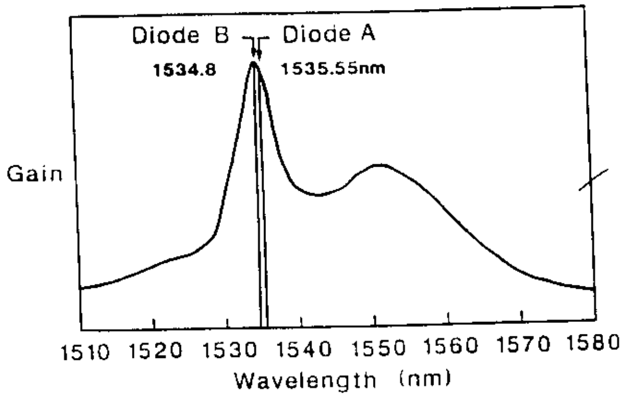
ERBIUM FIBRE AMPLIFIER GAIN-SATURATION CHARACTERISTICS



FIBRE CHARACTERISTICS

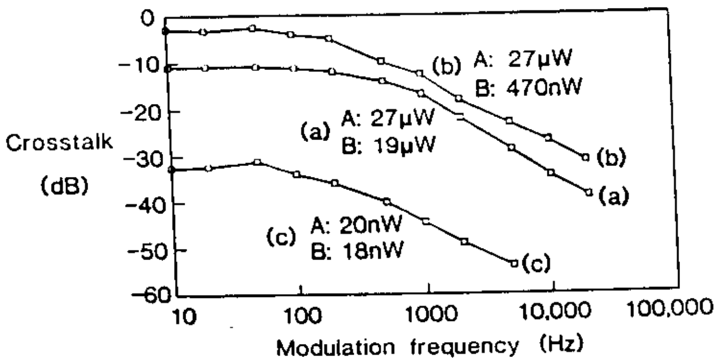
	980nm	1490nm
NA	0.21	0.23
Cutoff	955nm	970nm
Length	11.5	47m

TWO - WAVELENGTH INTERCHANNEL CROSSTALK MEASUREMENTS
BOTH CHANNELS MODULATED



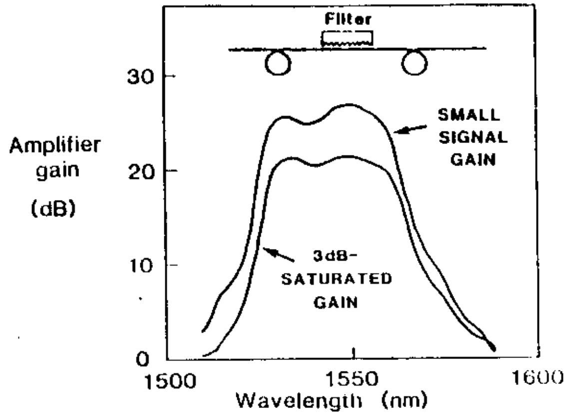
DUAL WAVELENGTH CROSSTALK

Diodes A & B at various input power levels



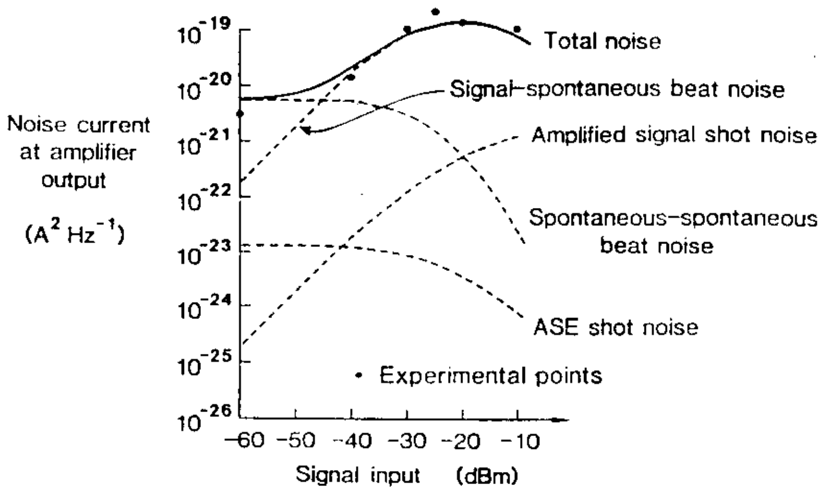
Crosstalk small above 10kHz

SPECTRAL GAIN-SHAPING IN AN EDFA

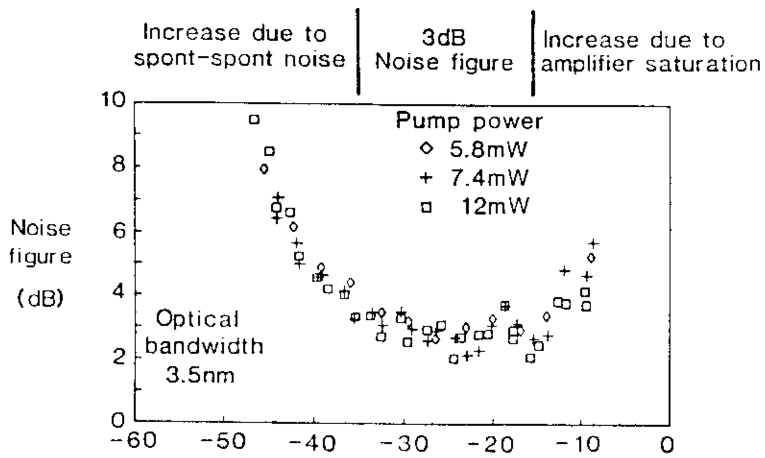


- Note constant spectral gain shape

NOISE PERFORMANCE OF AN Er^{3+} FIBRE AMPLIFIER

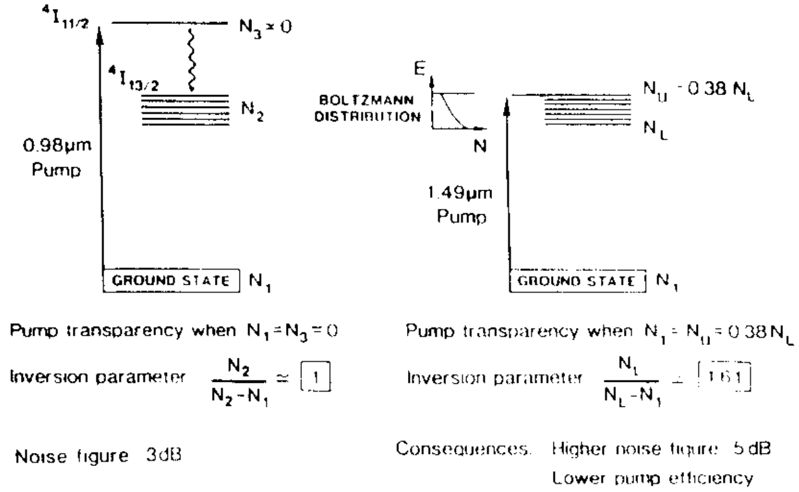


MEASURED NOISE FIGURE FOR 980nm PUMPED AMPLIFIER



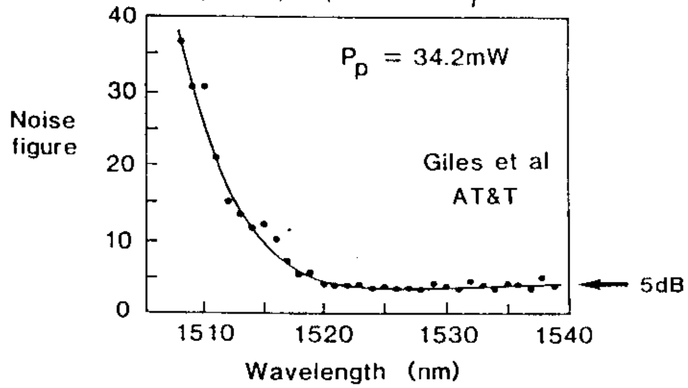
ERBIUM FIBRE AMPLIFIER NOISE FIGURE

Comparison of 0.98μm and 1.49μm pumping



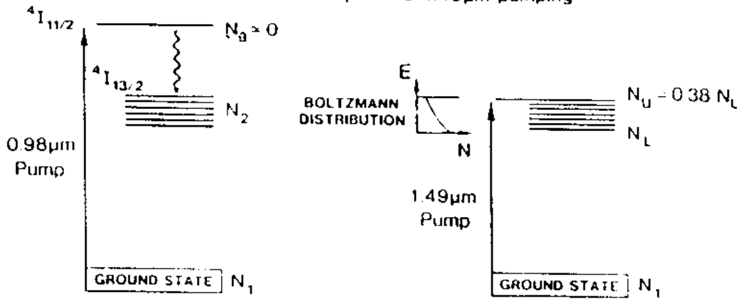
NOISE FIGURE vs SIGNAL WAVELENGTH

Amplifier pumped at 1.49μm



ERBIUM FIBRE AMPLIFIER NOISE FIGURE

Comparison of 0.98µm and 1.49µm pumping



Pump transparency when $N_1 = N_3 = 0$

Inversion parameter $\frac{N_2}{N_2 - N_1} \approx \boxed{1}$

Noise figure 3dB

Pump transparency when $N_1 = N_u = 0.38 N_L$

Inversion parameter $\frac{N_1}{N_L - N_1} = \boxed{1.61}$

Consequences: Higher noise figure 5 dB
Lower pump efficiency

NOISE FIGURE vs SIGNAL WAVELENGTH

Amplifier pumped at 1.49µm