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# OPTICAL FIBRE AMPLIFIERS

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## OUTLINE

- Advantages of erbium-doped fibre amplifiers (EDFA)
- Fabrication of rare-earth-doped fibres
- Amplifier fundamentals
- Spectroscopy of erbium
- Pump requirements
- Amplifier gain and saturation
- Interchannel crosstalk
- Noise
- System performance

## PRIMARY ADVANTAGES OF ERBIUM FIBRE AMPLIFIERS

| | |
|---|---|
| • Low coupling losses | High fibre-to-fibre gain (>40dB)<br>Low feedback & passband ripple<br>Good noise figure (~3dB) |
| • Polarisation insensitive | No polarisation controller |
| • Large energy storage | Operate deep in saturation<br>Low interchannel crosstalk<br>Low pump noise feedthrough |

## SECONDARY ADVANTAGES OF ERBIUM FIBRE AMPLIFIERS

- High saturation output power (>10dBm)
  (Depends on pump power)

- Gain passband insensitive to temperature
- Reproducible gain passband

} Simplifies amplifier cascades

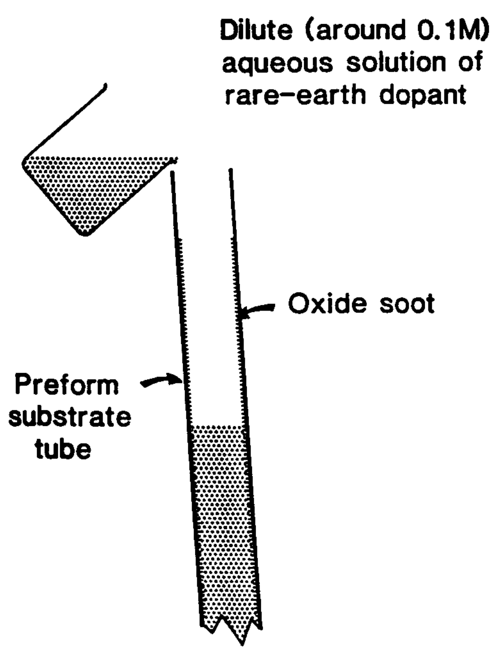
## ADVANTAGES OF DIODE AMPLIFIERS

- Integratable into complex switchable arrays
- Direct injection pumping
- Not restricted to 1.5μm wavelength

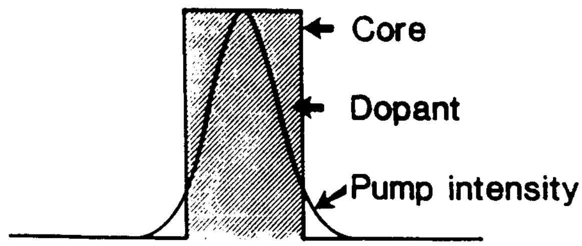
FABRICATION OF RARE-EARTH-DOPED OPTICAL FIBRES

- 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

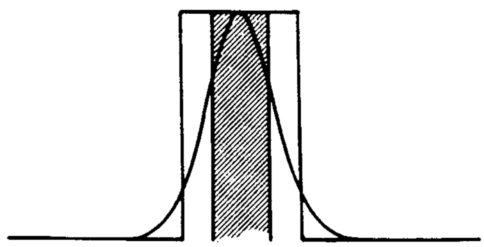
ADDITION OF RARE-EARTH IONS
TO PREFORMS



## OPTIMISED FIBRE DESIGN




Poor pump/dopant overlap

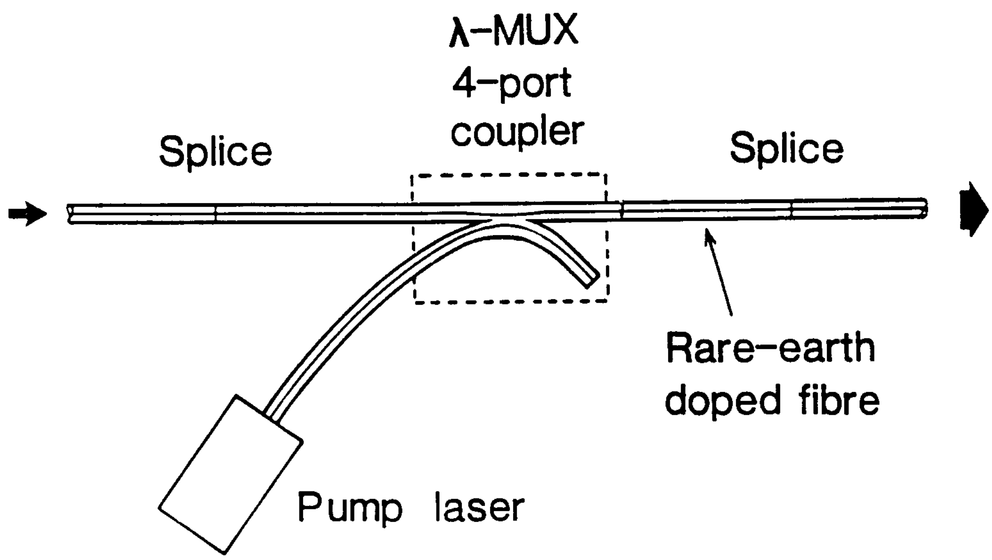


Good pump/dopant overlap

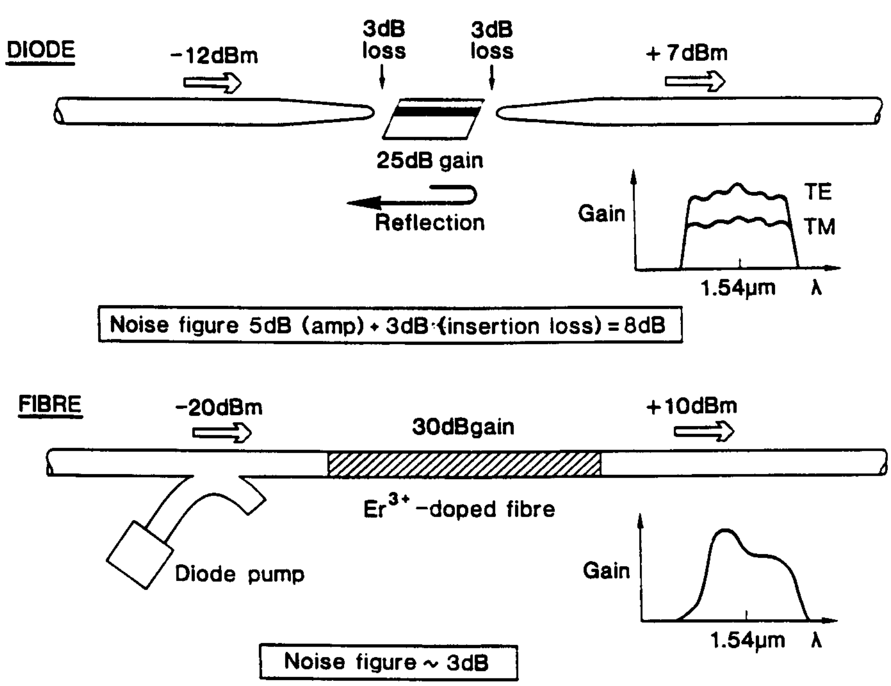
## APPLICATIONS OF OPTICAL AMPLIFIERS

- **Line amplifiers** - **greatly reduce number of regenerators required.**
  - **allow transparent transmission**
- **Pre-amplifiers** - **improve SNR in high bit-rate direct-detection systems.**
- **Power amplifiers** - **boost signals to compensate branching losses in multi-terminal networks.**

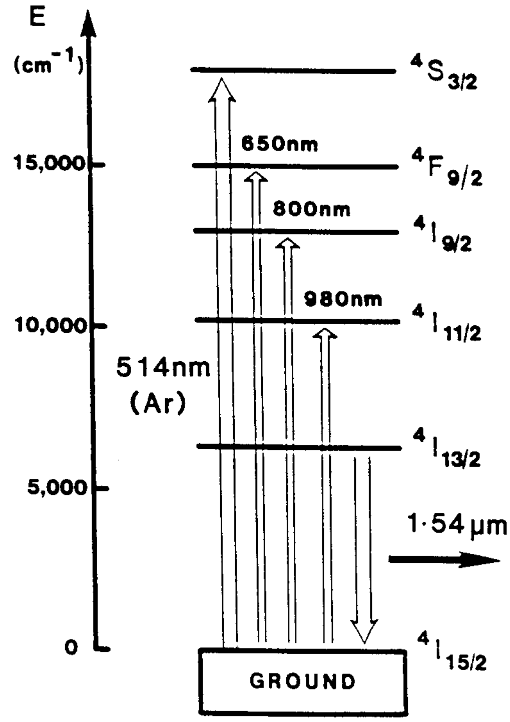
## BASIC ERBIUM AMPLIFIER CONFIGURATION



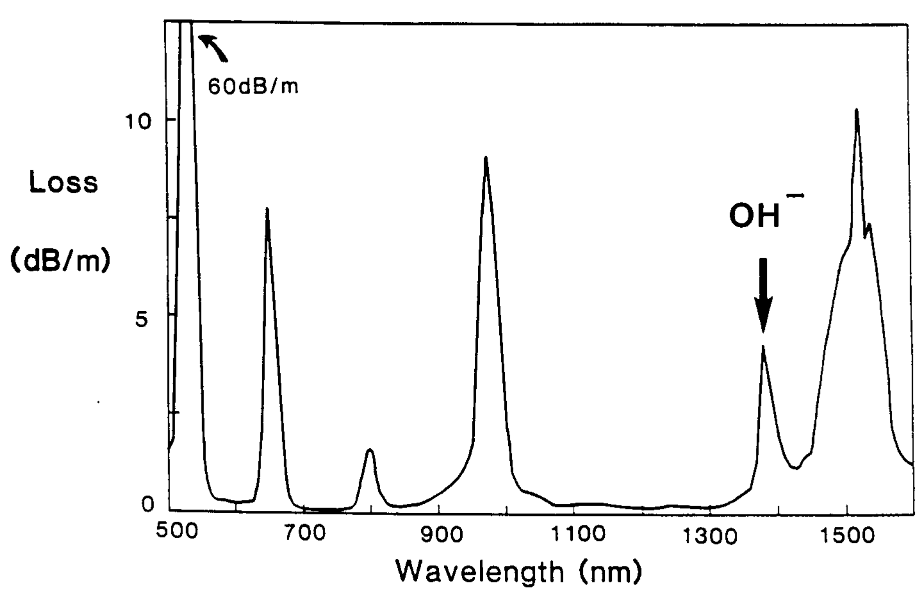

## COMPARISON OF DIODE AND FIBRE AMPLIFIERS



## ERBIUM ENERGY LEVELS

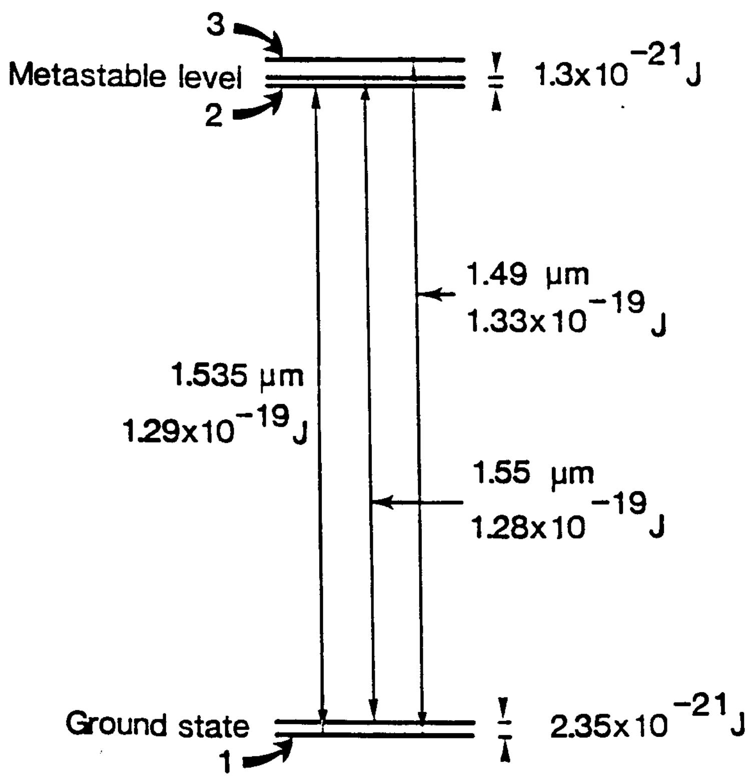



## ABSORPTION SPECTRUM OF FIBRE DOPED WITH $Er^{3+}$ IONS

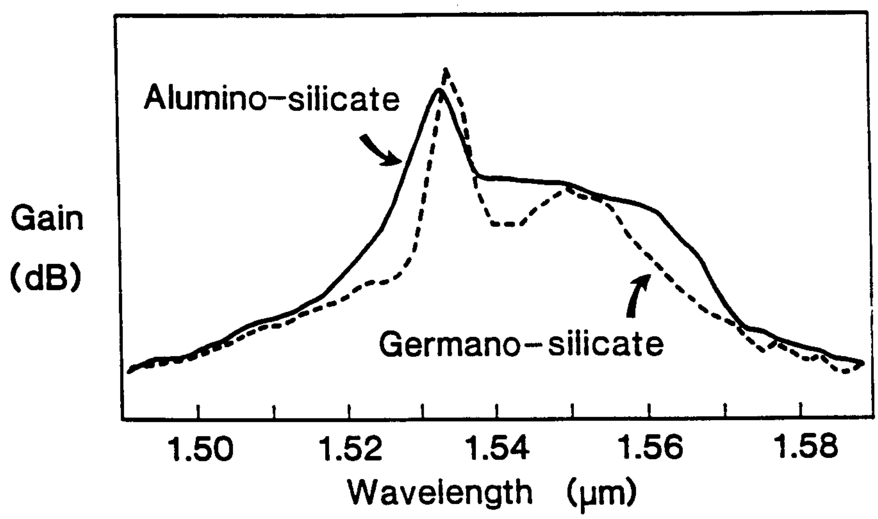


## ERBIUM ENERGY LEVEL DIAGRAM

DISPLAYING THE SPLIT LEVELS OF THE METASTABLE AND GROUND-STATES PRIMARILY RESPONSIBLE FOR OBSERVED SPECTRA

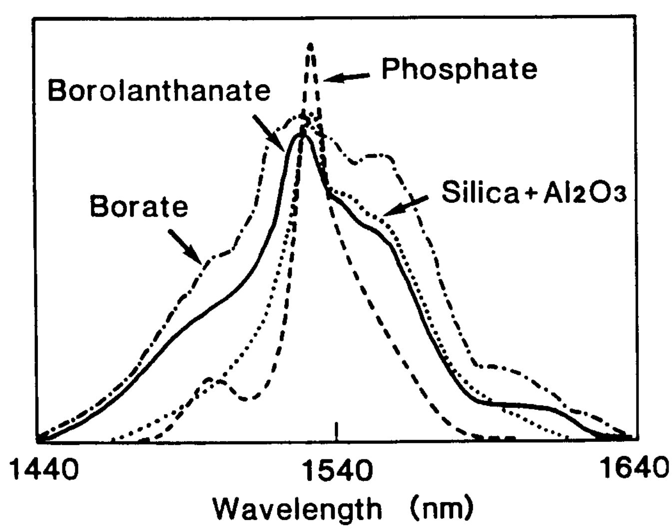


ERBIUM FIBRE AMPLIFIER: Effect of MCVD host glass




ERBIUM FIBRE AMPLIFIER

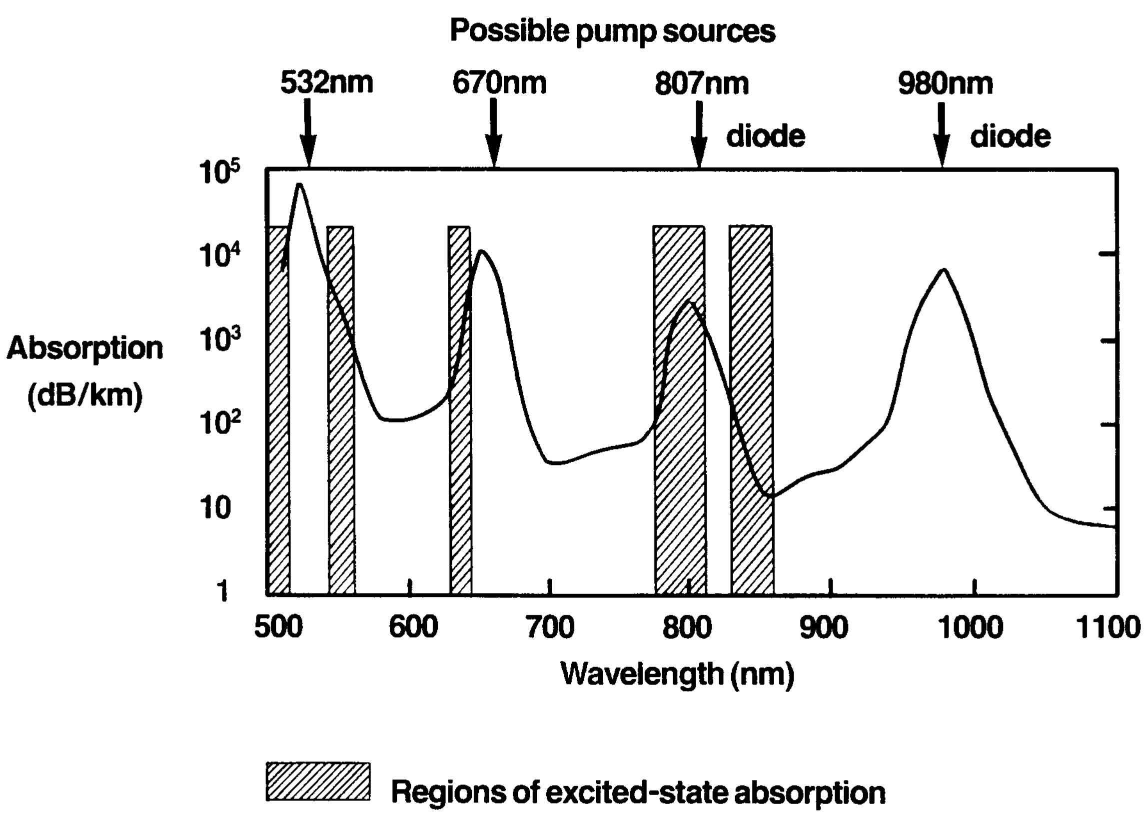
GAIN SPECTRUM BROADENING IN VARIOUS HOST GLASSES



## 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
- **1547nm**
  Diodes available
  Noise disadvantage

## $Er^{3+}$-doped fibre absorption spectrum

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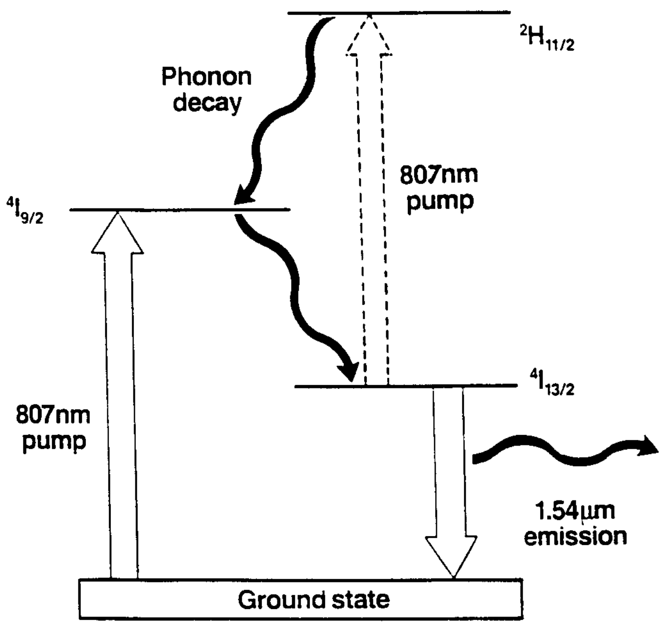
## 807nm PUMP EXCITED - STATE ABSORPTION IN $Er^{3+}$

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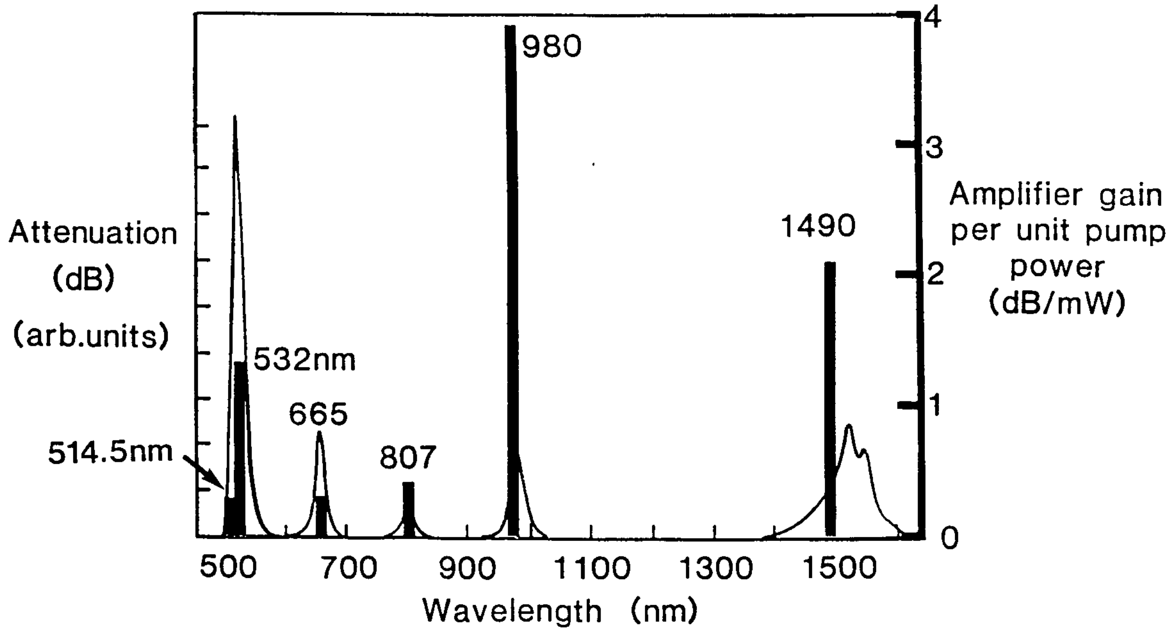
## PUMP WAVELENGTHS FOR ERBIUM FIBRE AMPLIFIERS

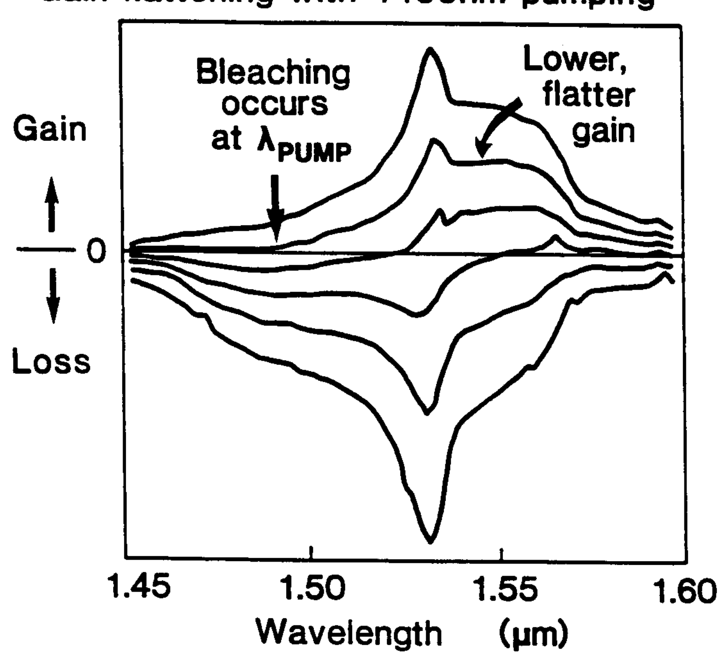
| | 980nm | 1490nm |
|---|---|---|
| Pump/signal λMUX | Easy | Difficult |
| Reported pump efficiency | 4.0 dB/mW | 2.1 dB/mW |
| Spectral gain | Peaky? | Smoother |
| Anticipated power amplifier efficiency | Large pump/ signal shift | Small shift |
| Noise figure | ~3dB | ~ 5dB |

COMPARATIVE EFFICIENCY OF THE AVAILABLE PUMP BANDS



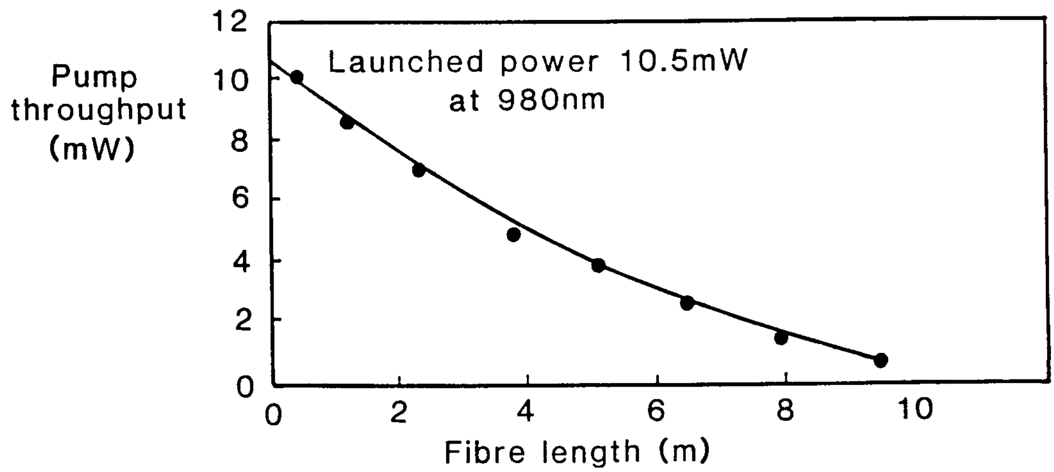

**ERBIUM FIBRE AMPLIFIERS**

**Gain flattening with 1490nm pumping**

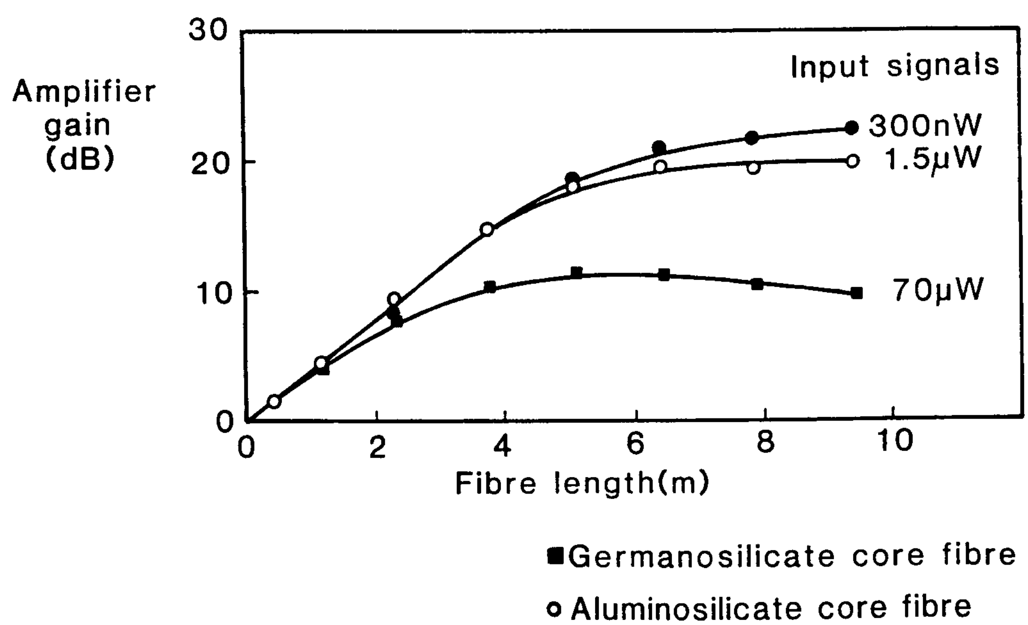


# AMPLIFIER GAIN AND SATURATION

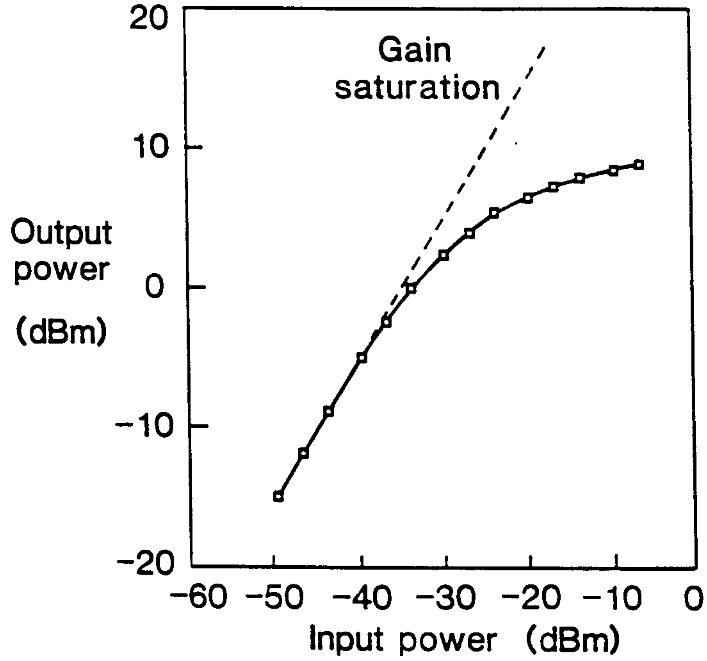
## PUMP THROUGHPUT POWER vs FIBRE LENGTH FOR 980nm PUMPING




## AMPLIFIER GAIN vs FIBRE LENGTH FOR 980nm PUMPING



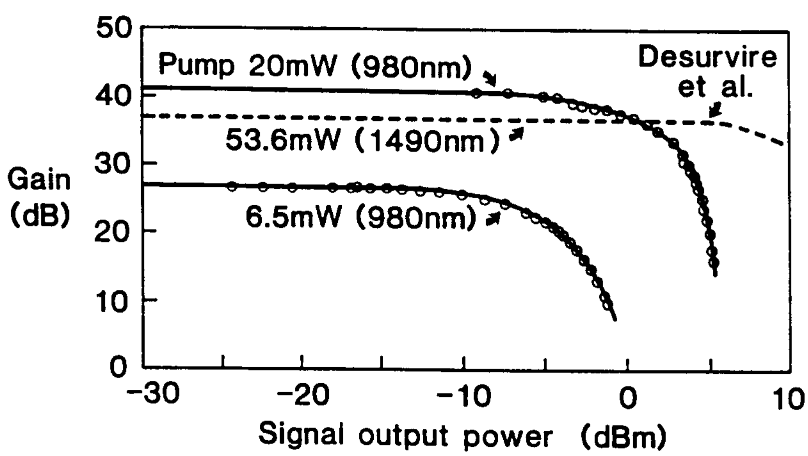
## AMPLIFIER INPUT / OUTPUT CHARACTERISTICS




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

Pump quantum efficiency at 8.5dBm out is 44%

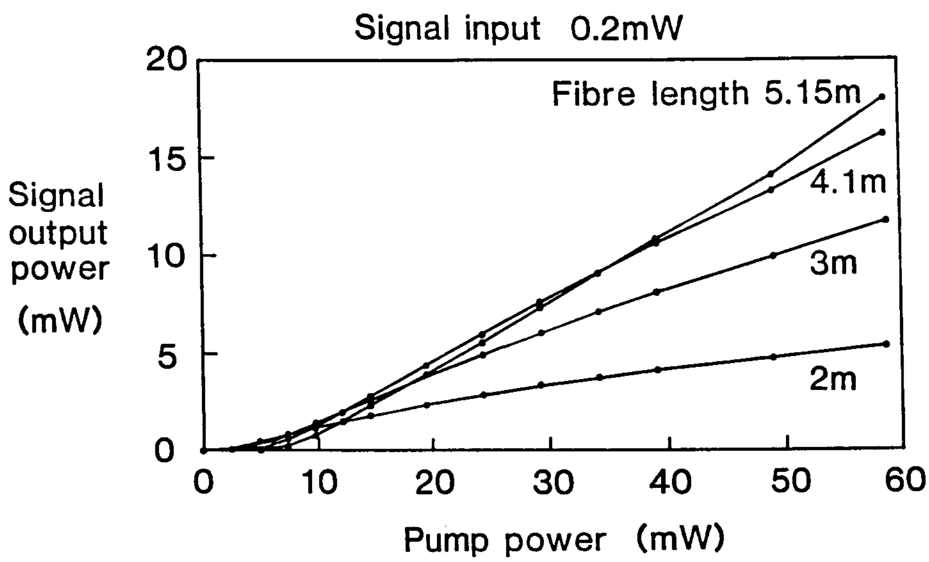
## ERBIUM FIBRE AMPLIFIER GAIN–SATURATION CHARACTERISTICS




FIBRE CHARACTERISTICS

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

## SATURATED AMPLIFIER PERFORMANCE



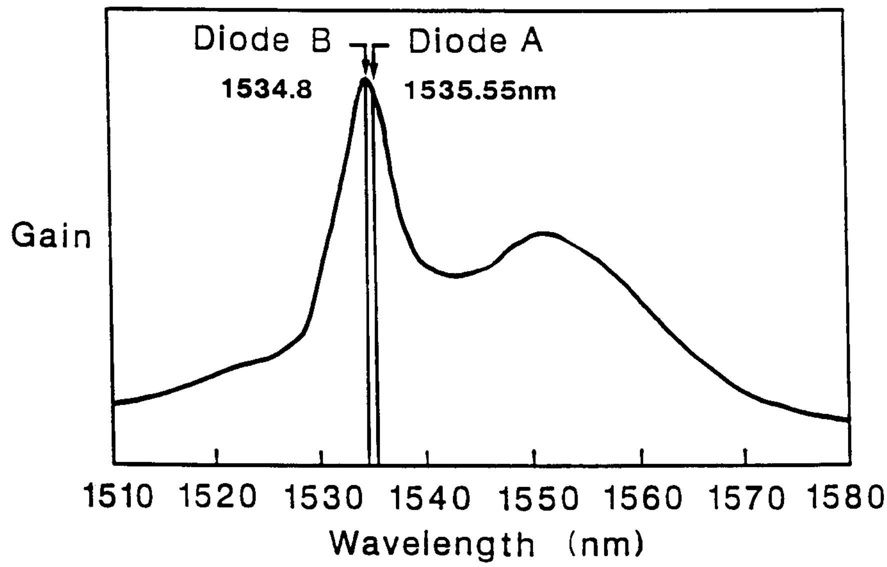

**FIBRE CHARACTERISTICS**

**N.A.** **0.18**

**Cutoff** **920nm**

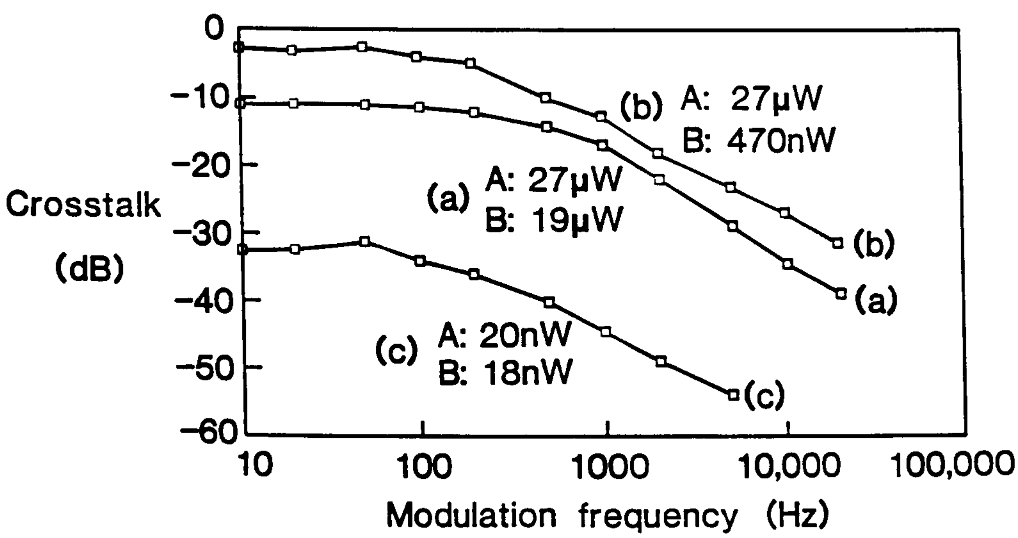
Note: Saturated output power increases with pump power

## TWO - WAVELENGTH INTERCHANNEL CROSSTALK MEASUREMENTS
## BOTH CHANNELS MODULATED



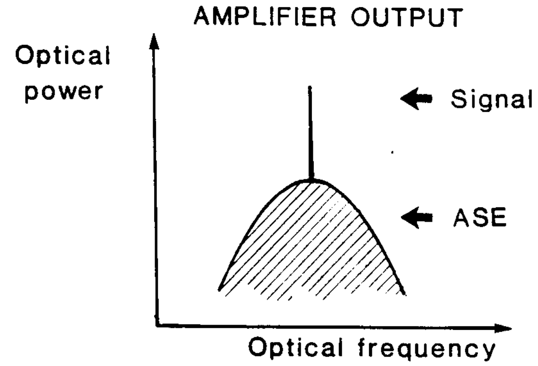

## DUAL WAVELENGTH CROSSTALK

Diodes A & B at various input power levels




Crosstalk small above 10kHz

## 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

$\mu =$ Inversion factor

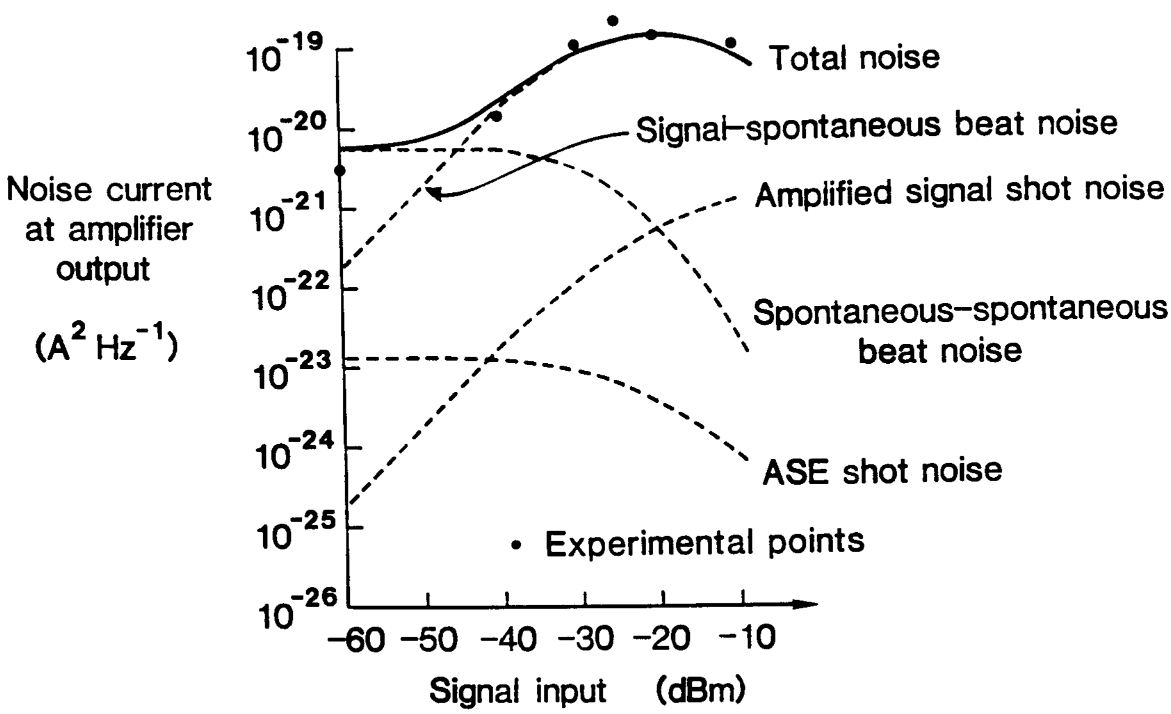
$\Delta\nu$ is the ASE spectral width, $G$ is the amplifier gain, $P_S$ and $P_{SP}$ are the signal and spontaneous optical powers at the output.

For most applications $B$ dominates and Noise Figure is:

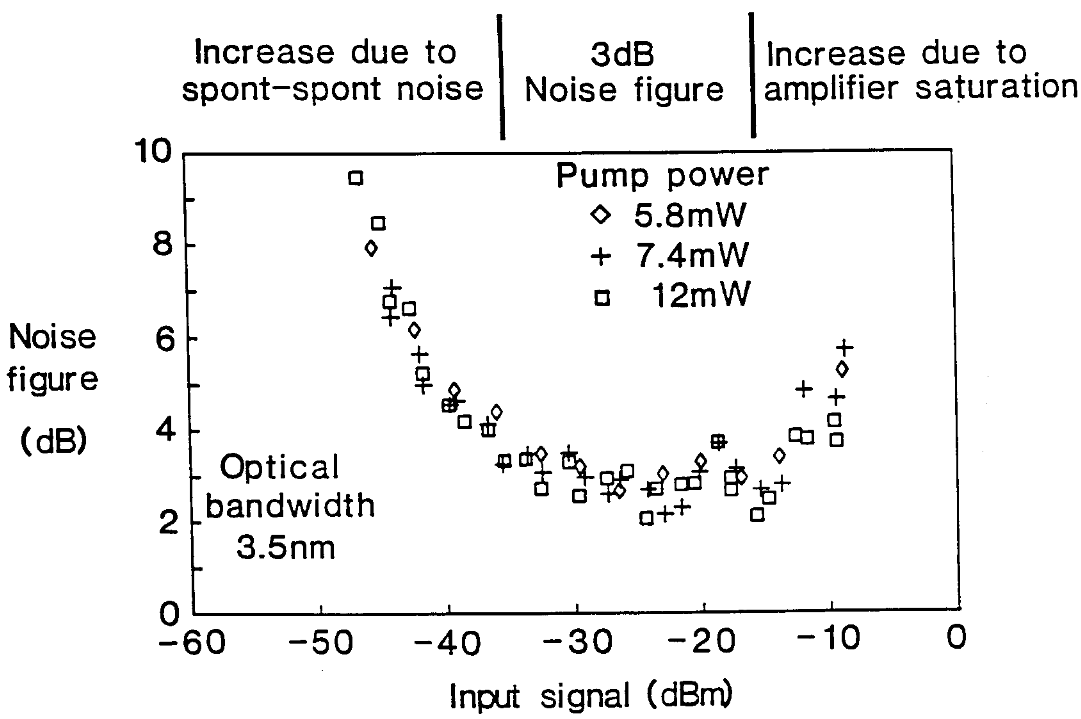
$$\text{NF} = \frac{\text{Input sig./noise power ratio}}{\text{Output sig./noise power ratio}} = \left[\frac{P_{in}}{P_{out}}\right]^2 \frac{\text{Noise}_{\text{in}}}{\text{Noise}_{\text{out}}} = \frac{1}{G^2} \cdot \frac{B}{P_S/G} \simeq 2\mu$$

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

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

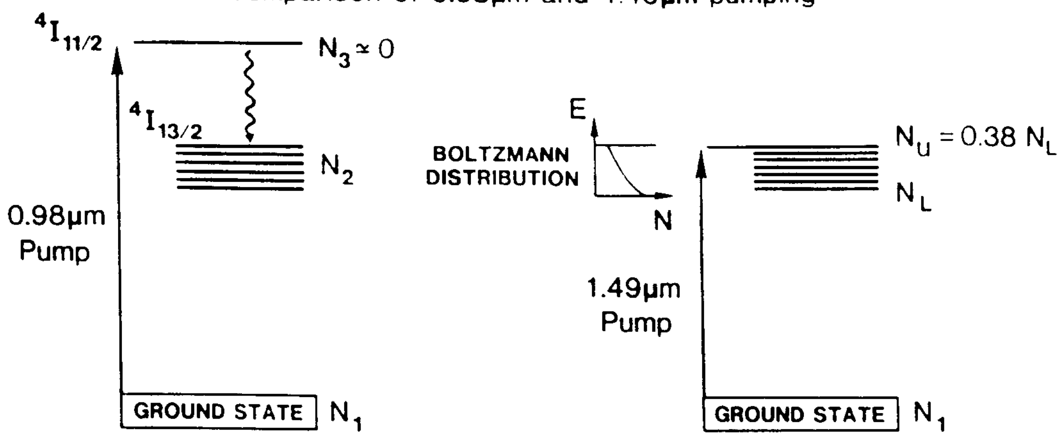



## MEASURED NOISE FIGURE FOR 980nm PUMPED AMPLIFIER



## ERBIUM FIBRE AMPLIFIER NOISE FIGURE

Comparison of 0.98µm and 1.49µm pumping




Pump transparency when $N_1 = N_3 \simeq 0$

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

Noise figure 3dB

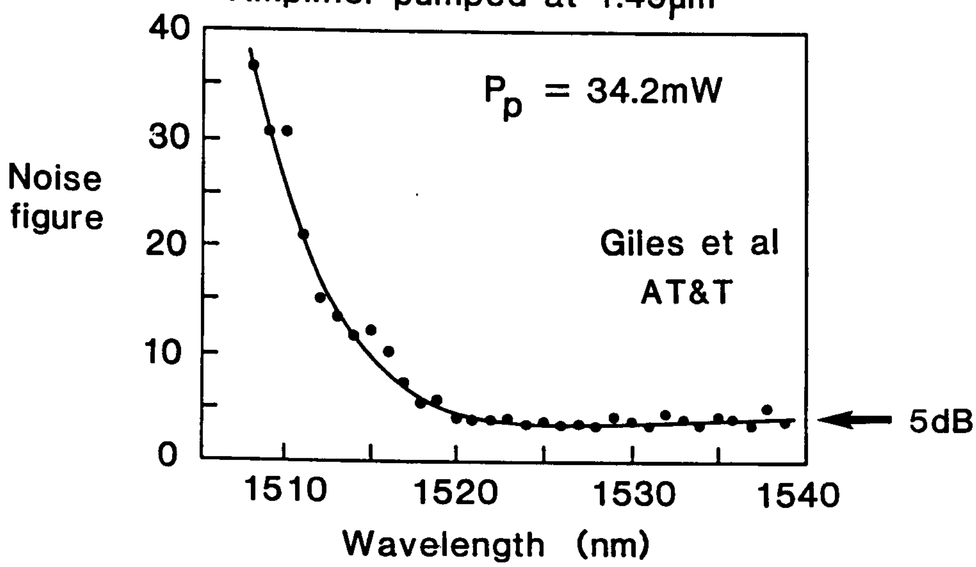
Pump transparency when $N_1 = N_U = 0.38 N_L$

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

Consequences: Higher noise figure 5 dB
Lower pump efficiency

## NOISE FIGURE vs SIGNAL WAVELENGTH

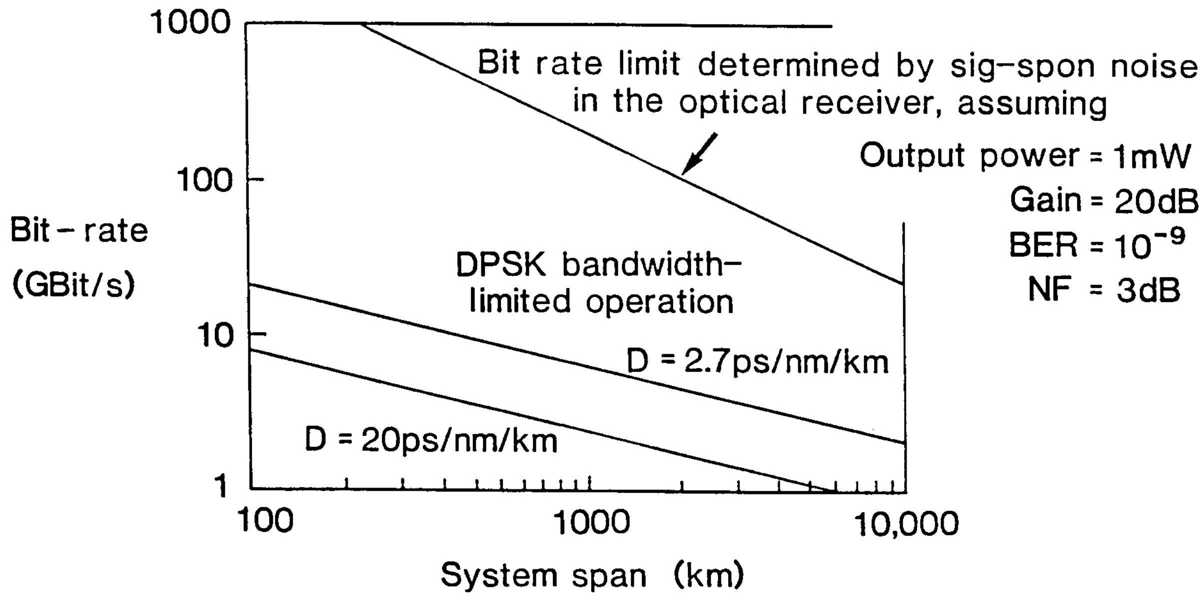
Amplifier pumped at 1.49µm



# SYSTEMS PERFORMANCE

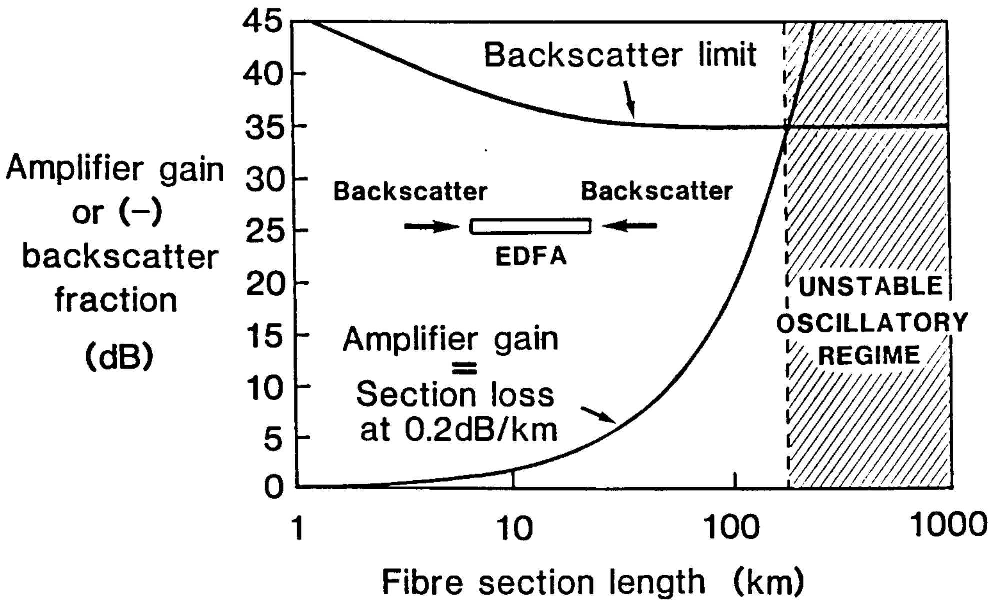
## NOISE AND DISPERSION-LIMITED BIT RATES vs SPAN

Pettitt-STC



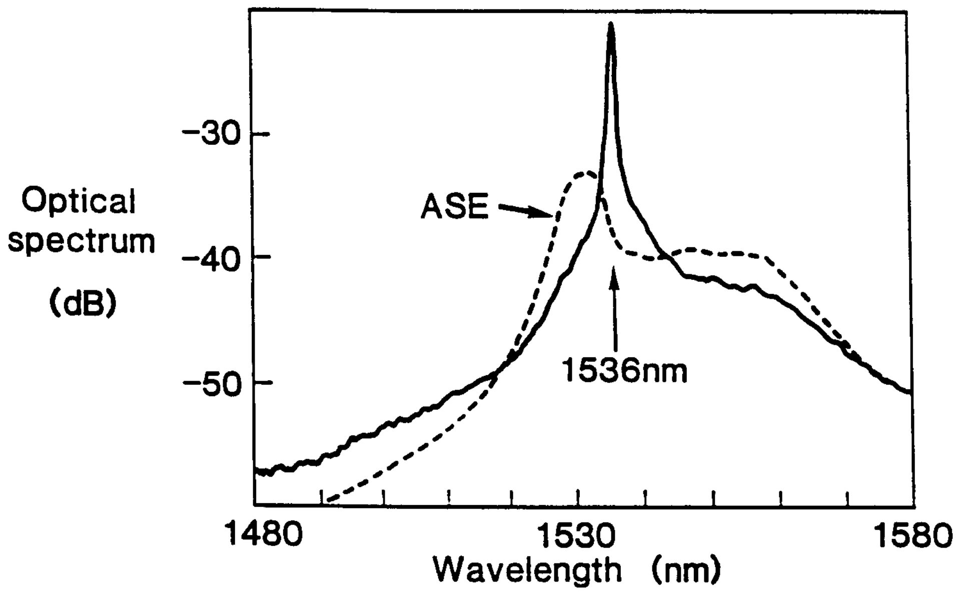

## LINE AMPLIFIER AND BACKSCATTER REFLECTIONS DETERMINE MAXIMUM SECTION LENGTH

Pettitt -STC



## ERBIUM FIBRE AMPLIFIER TESTED AT 15GHz

Spectra with and without 1536nm signal

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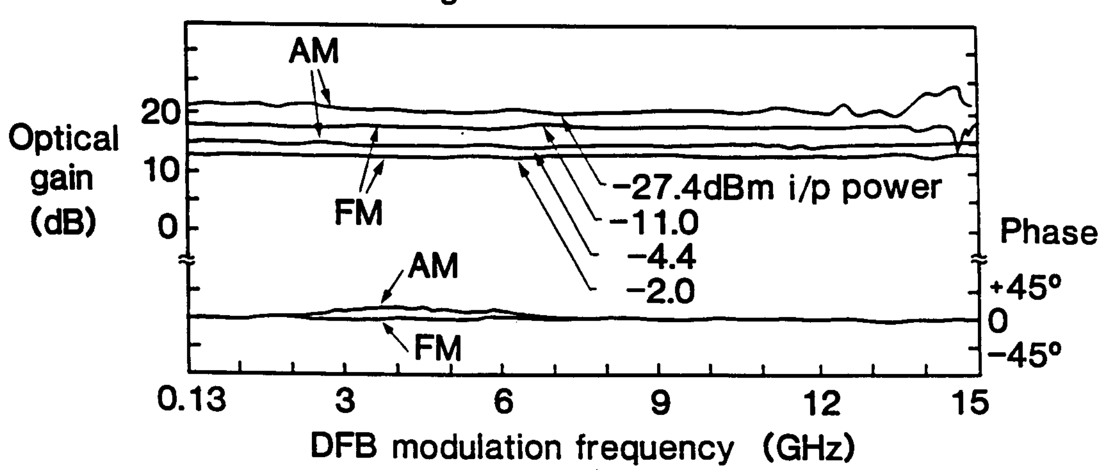
## ERBIUM FIBRE AMPLIFIER AM AND FM RESPONSE

Signal at 1536nm

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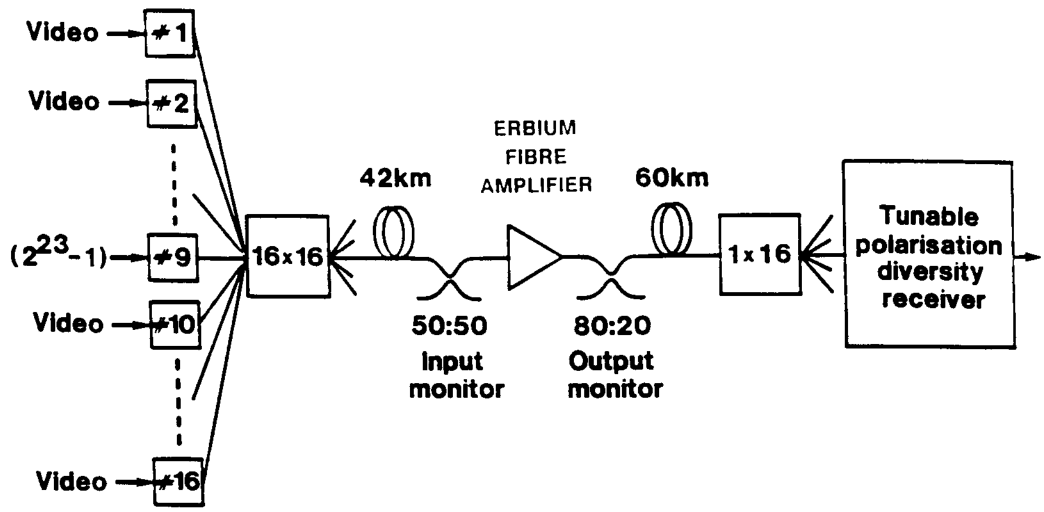
## 155Mb/s 16-CHANNEL COHERENT BROADCAST NETWORK WITH ERBIUM FIBRE LINE AMPLIFIER

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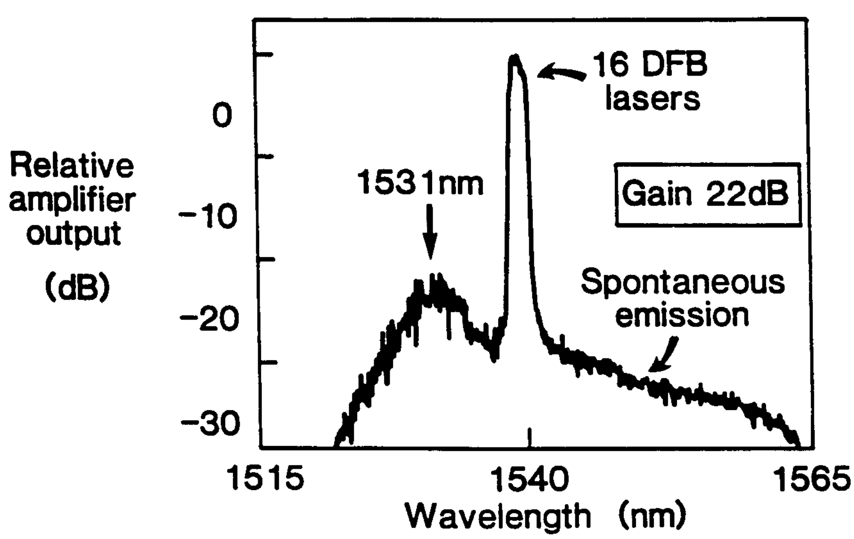
## ERBIUM FIBRE AMPLIFIER IN 16-CHANNEL COHERENT BROADCAST NETWORK




Allows transmission of sixteen 155Mb/s channels to 256 end-users at a distance of 100km

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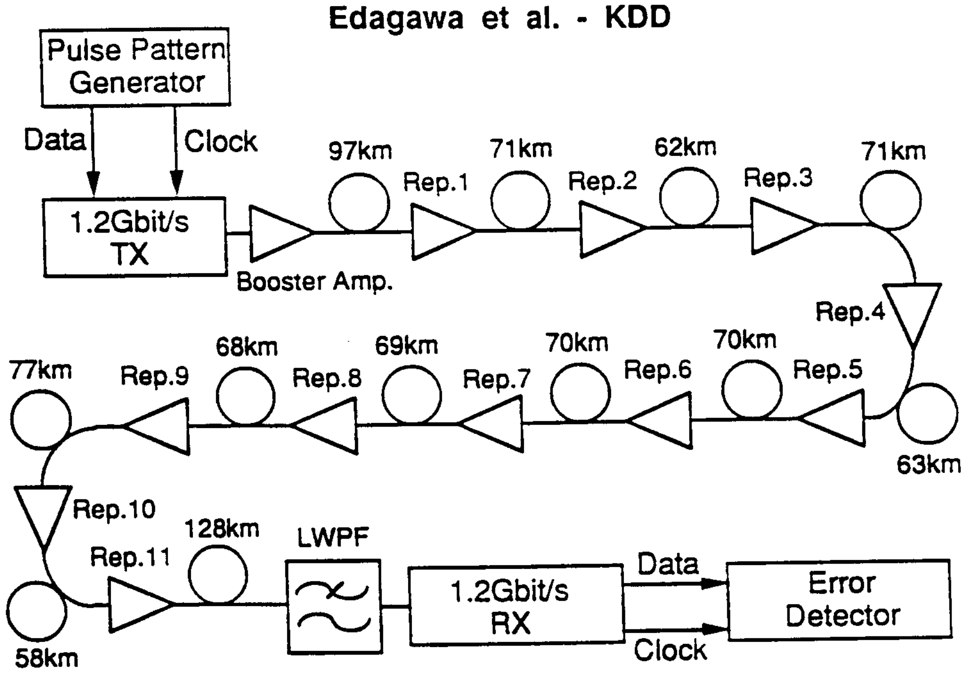
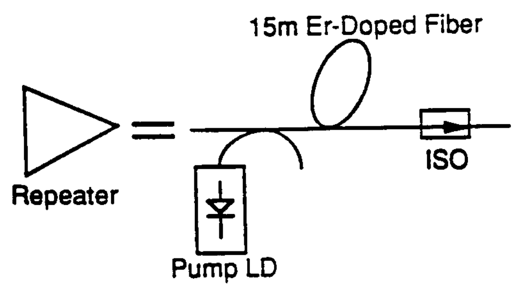
## 12 ERBIUM FIBRE LINE AMPLIFIER EXPERIMENT AT 1.2Gb/s OVER 904km

**Edagawa et al. - KDD**




## 12 AMPLIFIER EXPERIMENT AT 1.2Gb/s BER AND EYE - DIAGRAMS