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Applications of Erbium-doped Fibre Amplifiers in Communications

R. I. Laming, D. N. Payne and G. J. Cowle

Introduction

Erbium-doped single-mode fibre amplifiers (EDFA) which operate around $\lambda = 1.54\mu m$, coinciding with the low-loss region of silica optical fibre, show great promise for use in future high-performance telecommunication systems[1,2]. This is due to a combination of high saturation power[3], low noise[4–6], immunity to crosstalk[7–9], low power requirement[10] and the ability to work at high data rates[11]. In addition, compatibility with existing fibre components is excellent, allowing all-optical fibre circuitry to be assembled with both active and passive components. This is particularly beneficial for the fibre amplifier, where splicing of the active fibre into the telecommunications link virtually eliminates troublesome Fresnel-reflection feedback which normally limits the gain in semiconductor laser amplifiers[12]. As such the application of EDFAs to high-data rate long-haul communications[13,14], multichannel distribution networks[15] and analog video distribution[16] have been successfully demonstrated.

This paper will discuss the characteristics of EDFAs, highlight their advantages and review current applications.

Pumping of erbium-doped fibre amplifiers

The configuration of an EDFA is shown in Figure 1. The amplifier can be optically pumped using any one of a number of pump wavelengths. However, their application in transmission systems will be limited unless highly-reliable, low-power diode pump sources can be found. Reference to the absorption spectrum of an erbium-doped fibre shows that potential practical pump bands exists at 807nm, 980nm and 1490nm. Unfortunately, the 807nm pump band suffers pump excited-state absorption (ESA), a phenomenon which particularly plagues three-level, longitudinally-pumped optical amplifiers. The effect occurs when a further transition is present above the (highly-populated) upper laser level with an energy difference corresponding to that of the pump photons. In this case an additional absorption occurs at the pump wavelength which drains pump power and limits the available gain. Thus pumping at 807nm requires high pump power to overcome the poor pump efficiency and an undesirably large NA fibre to increase the pump intensity before high gain can be achieved.

Fortunately both the 980nm and the 1490nm pump bands are entirely free of ESA and these two wavelengths are therefore the preferred diode-pump choices. However, significant differences in amplifier performance result from the use of one or other of these potential pump bands. For example, when pumping in-band at 1490nm, it is not possible to fully invert the erbium gain medium for reasons outlined schematically in Figure 2. Consequently, this pump wavelength gives a somewhat lower pump efficiency[3] (2.1dB/mW), which should be compared with a value of 4dB/mW for 980nm pumping[10]. However, a compensation for this lower efficiency is that the gain passband for 1490nm pumping is flatter than that for 980nm pumping.

Figure 1: Fibre line amplifier.

Figure 2: Comparison of 980nm and 1490nm pumping of the erbium system.

It remains to be determined which of the two available diode pump wavelengths is the better choice. The availability of 1490nm diode lasers has meant that, to date, most systems experiments have been conducted using this pump wavelength. However, 980nm diodes are expected to become commercially available shortly.

Amplifier saturation characteristics

An important parameter for systems applications is the amplifier output power at which 3dB gain compression occurs, known as the amplifier saturation power. The gain characteristics of a typical EDFA pumped at 980nm are shown in Figure 3(a). The Figure plots the amplifier gain against signal output power for various values of pump power and illustrates that the output power at which gain compression occurs depends upon the magnitude of the pump power. This behaviour is an appealing characteristic of the EDFA, since the need for a higher saturation output power can always be satisfied by the use of a larger pump power, provided this is available. The effect is clarified in Figure 3(b) where the dependence of saturation output power on pump power is shown. For this fibre an output saturation power of 5mW was obtained using a pump power of 40mW, which represents a pump to signal photon conversion efficiency of 12%.

Noise in erbium-doped-fibre amplifiers

The output from an optical fibre amplifier is a combination of amplified signal and broad-spectrum amplified spontaneous emission (ASE). If the input signal is coherent, its noise contribution is the usual shot noise associated with the amplified signal level. There is also shot noise associated with the level of the ASE. Additional noise terms are introduced by the mixing on the detector of the amplified signal and the spectral components of the ASE to give signal- spontaneous beat noise and spontaneous-spontaneous beat noise[17].

Figure 3: (a) Dependence of gain on amplified signal output power showing saturation. (b) Variation of amplifier output saturation power with pump power.

The amplifier noise can therefore be expressed as the sum of three components; signal + ASE shot noise, signal-spontaneous beat noise and spontaneous-spontaneous beat noise. When operating at high bit rates and signal input levels of interest to optical communications (i.e. $<10^{-9}$ BER), it transpires that the noise is dominated by signal-spontaneous beat noise. Under these conditions the parameter 2μ represents the amplifier noise figure (NF = Power SNR$_{IN}$/POWER SNR$_{OUT}$)[4], where μ is the amplifier inversion $N_2/(N_2 - N_1)$, N_1 and N_2 being the population densities of the ground and metastable states. The parameter μ can be found by integration of the spontaneous emission along the fibre length. When the medium is fully inverted, μ has a minimum value of unity and the best possible amplifier noise figure is 3dB.

Figure 4 shows the measured noise figure for an EDFA with input signals in the range −40dBm to −8dBm at the pump powers shown. The amplifier consisted of 11m of erbium-doped germanosilicate fibre characterised by an NA of 0.2 and λ_{cutoff} at 965nm. For a pump power of only 7.4mW at 980nm, the amplifier gave a gain of 25dB. From the figure we see that over the range of input signals between −35dBm and −15dBm, the amplifier is operating with a noise figure of 2.9dB ±0.4dB. These results confirm that the erbium-doped fibre amplifier can be operated very near to the 3dB signal-spontaneous quantum noise limit, even at low pump powers. For low input signals, a sharp increase in noise figure occurs owing to the increase in the relative importance of the spontaneous-spontaneous beat noise. This rise can be eliminated by optical filtering below the 3.5nm optical bandwidth used in the experiment. For large input signals, a small increase in noise figure is also observed and this is caused by the amplifier being driven into saturation. In this case the amplifier inversion is depleted (i.e. $\mu>1$), resulting in an increase in noise figure.

Figure 4: Measured noise figure for a 980nm pumped EDFA.

It should be noted that when pumped at 1490nm, the EDFA noise figure has been measured[19] as ~5dB. This increased noise figure compared to that reported here results directly from the fact that the amplifier cannot be fully inverted using this pump wavelength. Thus the amplifier inversion parameter $\mu>1$, as depicted in Figure 2.

Power spectral density of the signal-spontaneous beat noise is independent of the optical bandwidth, whereas spontaneous-spontaneous beat noise is a direct function of optical bandwidth. Thus reducing the optical bandwidth reduces the spontaneous-spontaneous beat noise contribution. To eliminate it altogether and thus obtain the maximum receiver sensitivity, it is always necessary to filter to a bandwidth corresponding to that of the modulated signal. For low bit-rate systems, this optical bandwidth is impractically small and thus optical pre-amplifiers operating at low bit rates are not advantageous. For example Pettitt *et al*[20] have demonstrated a direct detection fibre preamplifier operating at 140Mbits^{-1} with a sensitivity of −46dBm, which is only comparable to the sensitivity of III-V APD-based receivers[20]. Whereas, at a higher bit rate of 1.8Gbits^{-1} Giles *et al*[19] have demonstrated a sensitivity of −43dBm, a 6dB improvement over the sensitivity of typical III-V APD-based receivers[21].

Amplifier phase noise

Coherent systems employing PSK or FSK may suffer from spectral broadening due to phase noise introduced by chained erbium-doped-fibre amplifiers and this may limit the number of amplifiers which can be concatenated in an optical link. To quantify the effect, we have recently measured the spectral broadening due to an EDFA.

Phase noise in a fibre amplifier arises due to various effects, but is thought to be dominated by the addition of randomly-phased spontaneous photons to the signal field. These phase variations will add to the intrinsic phase fluctuations of the signal, causing the signal linewidth to be broadened.

Spectral broadening in an EDFA was measured using a novel Mach-Zehnder interferometer containing the amplifier in one arm[22]. Provided that the optical paths in the interferometer are matched in length such that the propagation time difference between the light passing through the two arms is much less than the coherence time of the DFB laser source, the technique effectively deconvolves the DFB laser spectrum from the amplifier spectral broadening. The interferometer thus provides an output which consists solely of the amplifier spectral broadening response to a zero-linewidth input spectrum.

Figure 5: Measured spectral broadening induced by phase noise in an EDFA.

The measured power spectral density (PSD) is shown in Figure 5. The amplifier was an 11m length of Er^{3+}-doped, single-mode optical fibre, pumped at 980nm through a dichroic coupler. The DFB laser had a linewidth of ~30MHz at a wavelength of $1.535\mu m$. At a pump power of 20mW and signal input power of $50\mu W$, the amplifier had a gain of 17dB. The spectral broadening gave rise to a PSD with an approximately Lorentzian lineshape (Figure 5), having a half-power width of less than 20kHz. This corresponds to an increase in spectral width which is negligible compared to typical DFB linewidths of a few tens of megahertz.

The implications for these results in coherent systems are that Er^{3+}-doped fibre amplifiers will introduce negligible penalty as far as phase noise and spectral broadening are concerned, even in chained- amplifier systems. If only spectral broadening in the amplifier is considered, over 1000 amplifiers could be employed before a signal having a 20MHz linewidth was significantly broadened.

These excellent phase noise characteristics have been further confirmed in an FSK-coherent transmission experiment[14]. Where $2.5Gbits^{-1}$ signal transmission was successfully achieved over 2,223km by employing 25 cascaded EDFAs.

WDM/gain dynamics

Several authors have independently and theoretically investigated the gain dynamics and multichannel operation of EDFAs[7–9]. All show that as a consequence of the long fluorescence lifetime in an Er^{3+}-doped fibre amplifier, interchannel crosstalk and pump-noise breakthrough are minimal for modulation frequencies >100kHz.

Figure 6: Experimental configuration for measuring crosstalk in a fibre amplifier.

Figure 6 shows a typical experimental set up for the measurement of crosstalk[7]. In this case, crosstalk was measured by modulating diode B with a 5MHz, 100% modulated sinusoidal signal whilst simultaneously modulating signal A at frequencies ranging from 10Hz to 20kHz. Since the population in the upper lasing level changes in step with the low-frequency modulation of laser A, the population inversion and hence gain seen by the signal from laser B is modulated. This mixes the signals and gives sidebands on the 5MHz signal. However, as the low-frequency modulation increases in frequency, the population inversion ceases to follow the modulation and a reduced gain modulation is seen. Two regimes of operation were considered: (a) signals A and B large ($A=27\mu W$, $B=19\mu W$), i.e. saturated operation and (b) signals A and B small (A=20nW, B=18nW) i.e. small-signal operation. The ratio of upper sideband to fundamental power for these two conditions is plotted in Figure 7. The crosstalk is seen to roll off at high frequencies due to the slow change in the population inversion and, provided the signal contains no information at frequencies <100kHz, crosstalk will be suppressed by >40dB.

Figure 7: Dual wavelength crosstalk in a fibre amplifier.

In addition, since the amplifier gain is effectively constant for signal modulation frequencies ≥100kHz the amplifier will exhibit negligible distortion even under saturated operation. This attribute makes the amplifier ideal for use in analog video distribution networks, as was clearly demonstrated by Way *et al*[16].

Conclusions

Erbium-doped fibre amplifiers are poised to become a standard component in telecommunications systems. They exhibit excellent gain (>30dB) and noise characteristics and can be readily spliced into networks. Moreover, unlike diode optical amplifiers, they are polarisation-insensitive.

Pump diodes at a wavelength of 1490nm are now commercially available and will be followed shortly by 980nm diodes. The general availability of both these wavelengths will offer an interesting choice to the designer, who may well opt for the greater pump efficiency and lower power consumption provided by the 980nm pump band. On the other hand, the flatter gain spectrum afforded by the use of 1490nm pumping may also prove persuasive, together with the opportunity for remote pumping of the amplifier using the low-loss properties of the fibre at this wavelength.

Measurements of noise in erbium fibre amplifiers show that under normal signal conditions they behave as ideal quantum amplifiers with a noise figure close to 3dB for 980nm pumping and 5dB for 1490nm pumping. Spectral broadening due to phase noise is so small as to be negligible for the great majority of cases. These results make fibre amplifiers an attractive proposition for practical in-line repeaters, power and pre-amplifiers.

Acknowledgements

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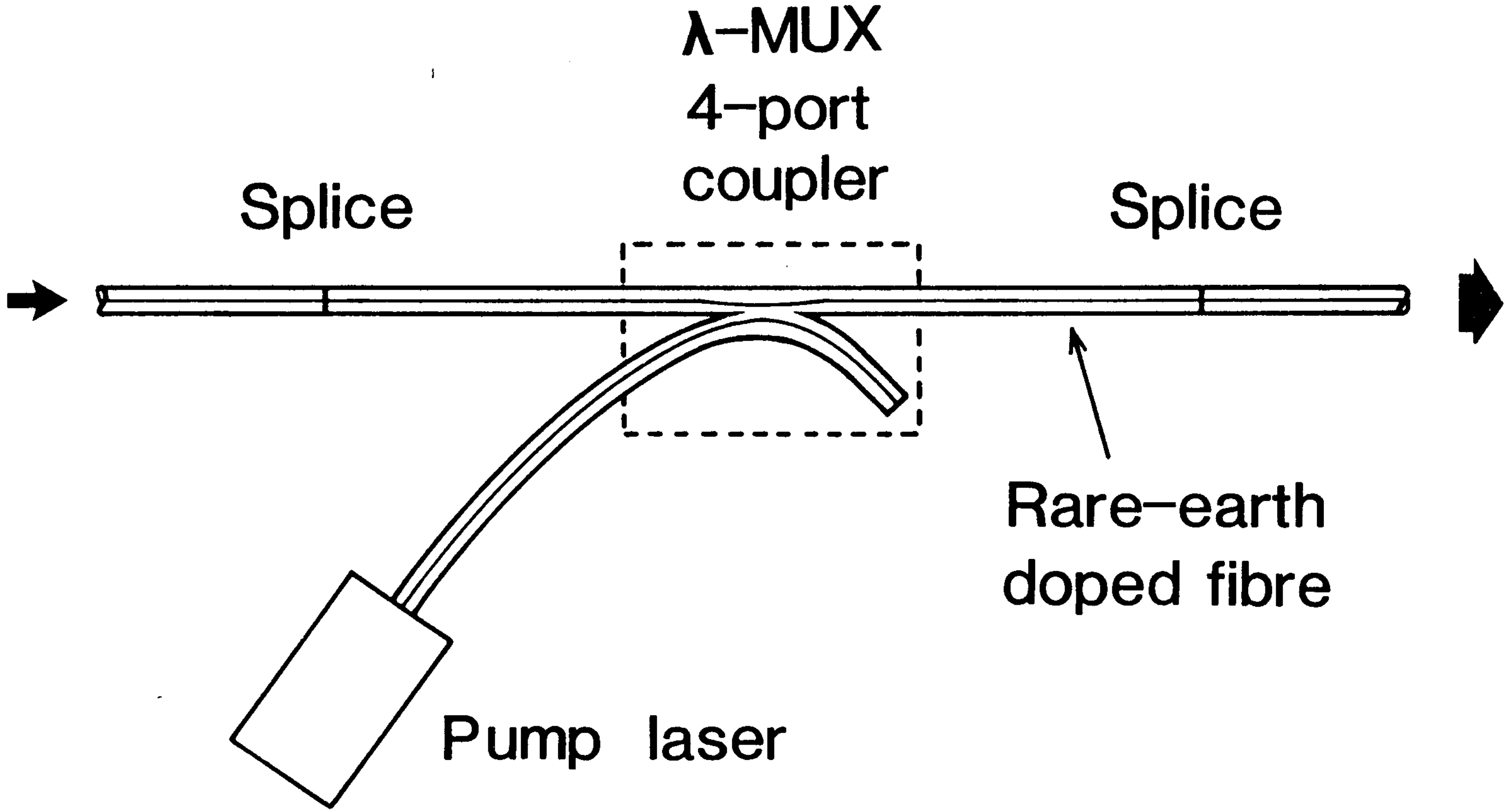

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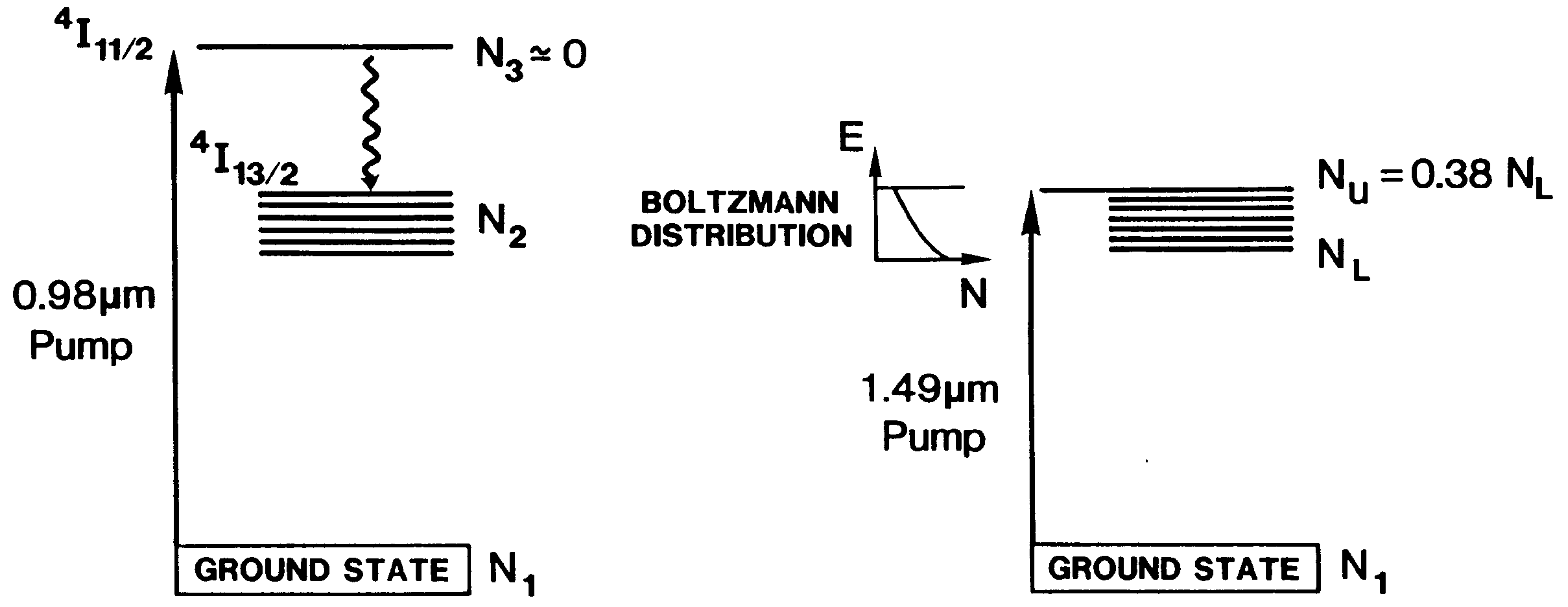
~~ERBIUM FIBRE AMPLIFIER NOISE FIGURE~~

~~Comparison of 0.98µm and 1.49µm pumping~~



Pump transparency when $N_1 = N_3 \simeq 0$

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

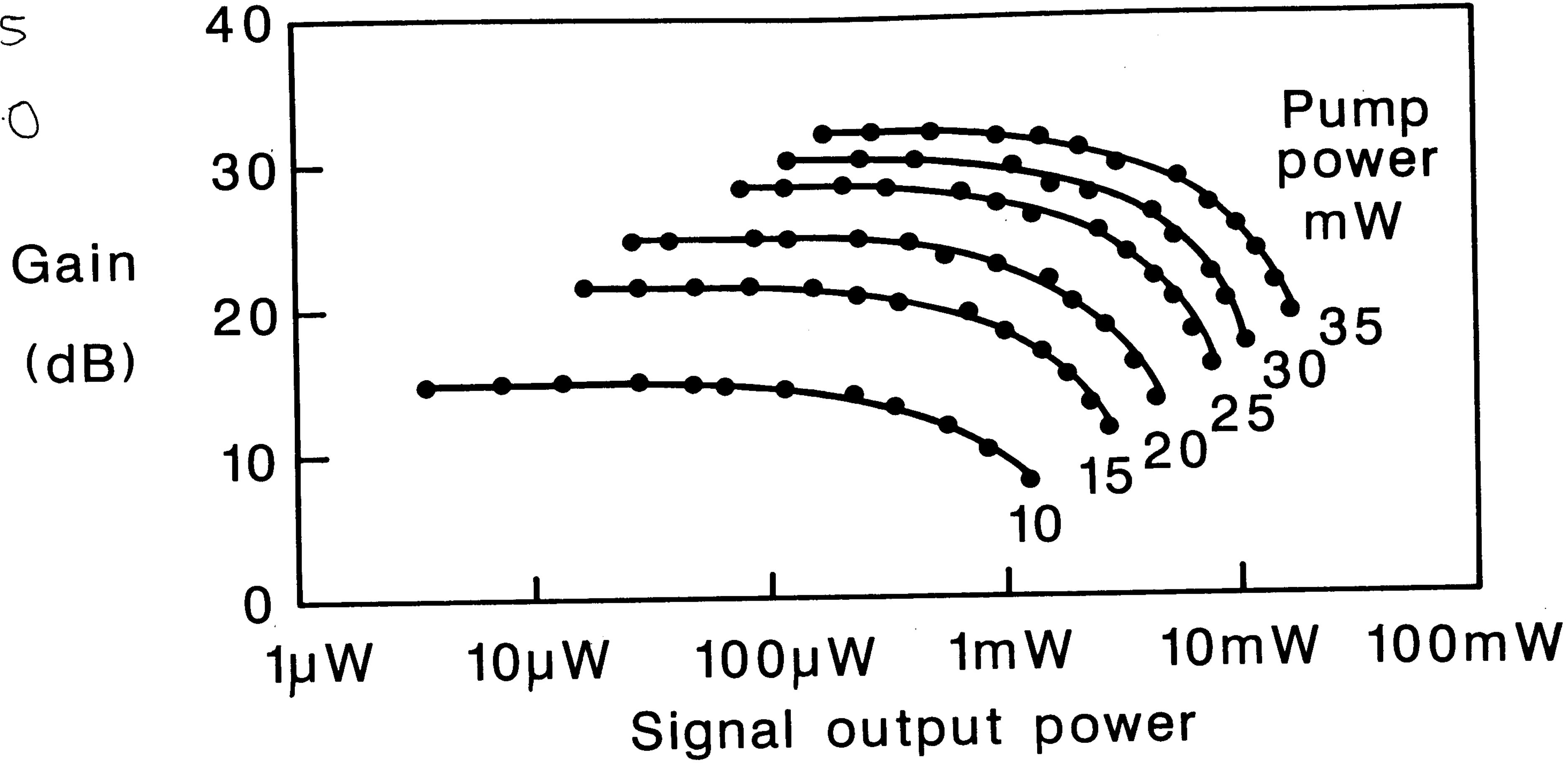
Noise figure 3dB

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

24.5
TO
8.0



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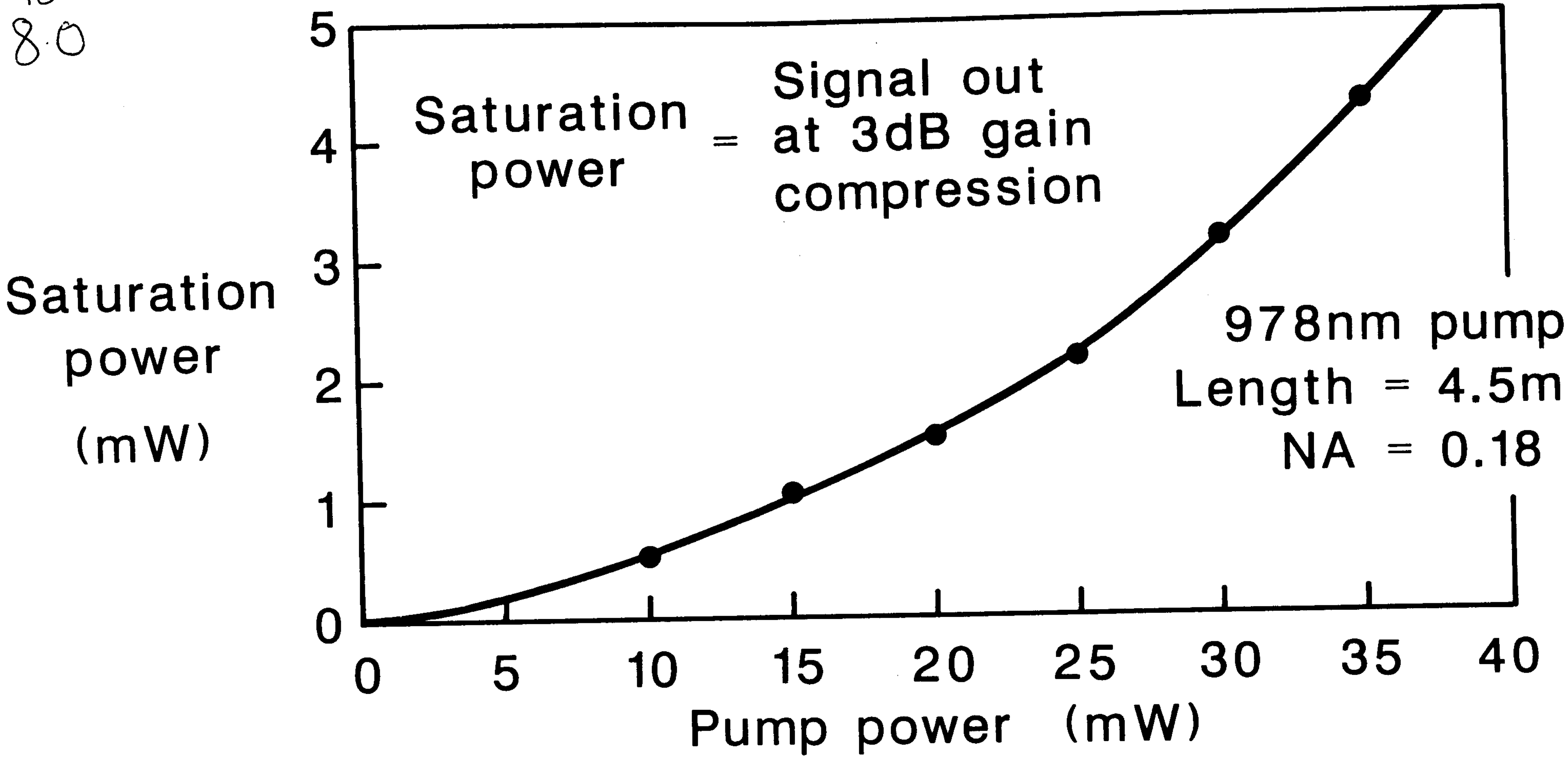
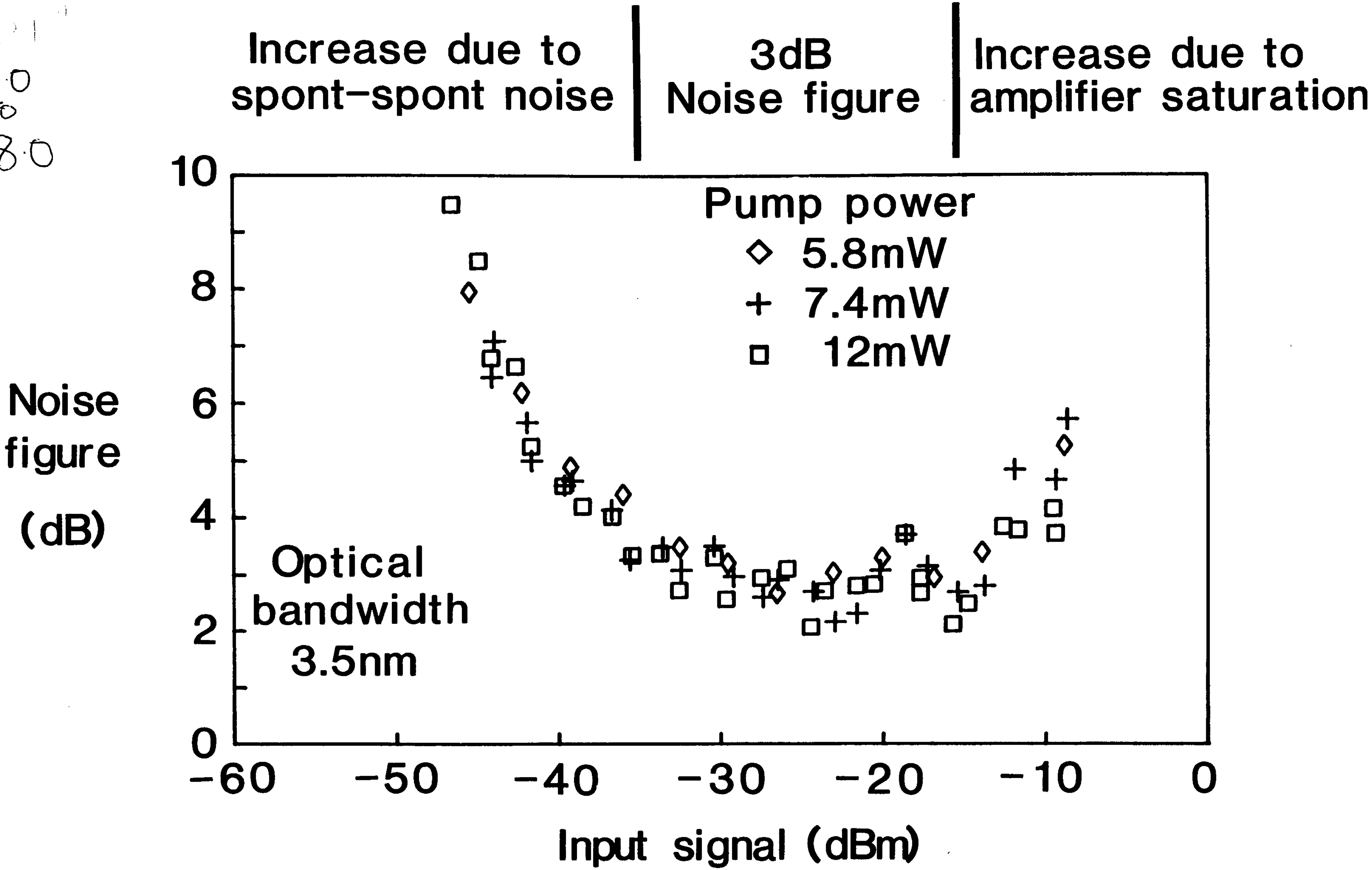

Saturation power = Signal out at 3dB gain compression
978nm pump
Length = 4.5m
NA = 0.18
Saturation power (mW)
0
1
2
3
4
5
Pump power (mW)
0
5
10
15
20
25
30
35
40

270
TO
8.0



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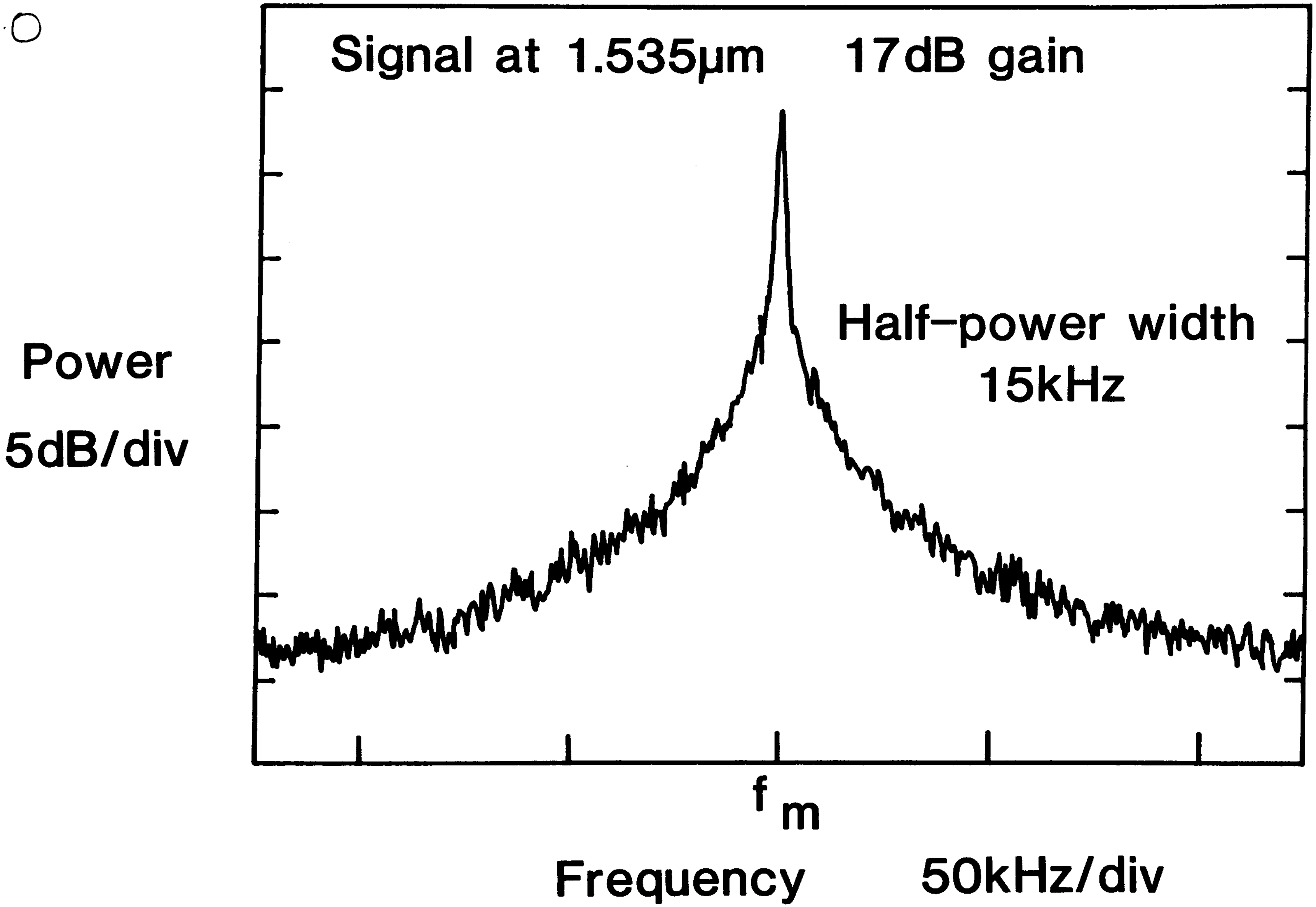
~~MEASURED SPECTRAL BROADENING~~



18·9
to
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~~DUAL CHANNEL OPERATION~~
~~EXPERIMENTAL CHARACTERISATION~~

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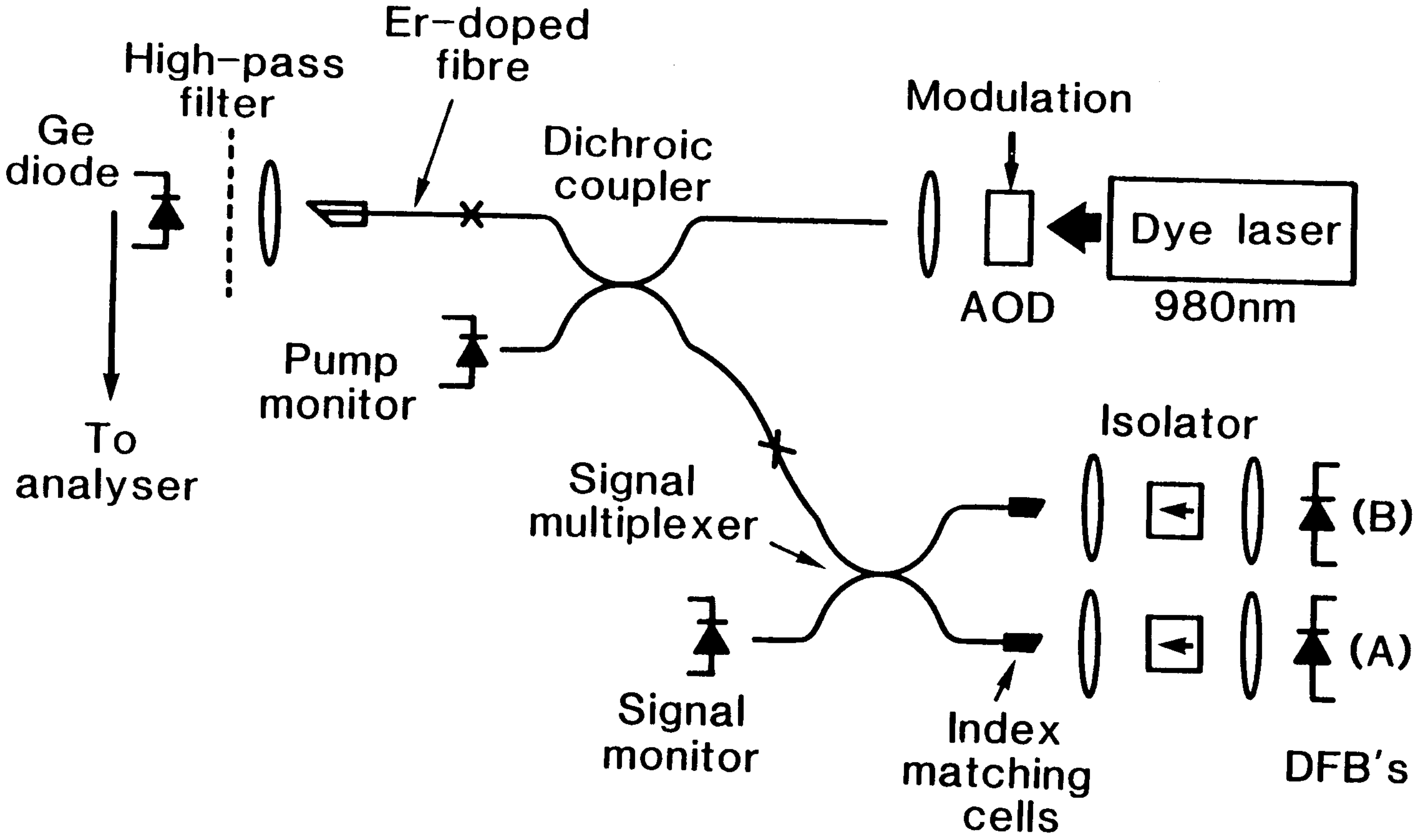

230
TO
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~~DUAL WAVELENGTH CROSSTALK~~