NOISE CHARACTERISTICS OF ERBIUM-DOPED FIBRE AMPLIFIER PUMPED AT 980nm.

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ABSTRACT.

We show that quantum-limited noise operation of an erbium-doped fibre amplifier is possible when pumped at 980nm. A noise figure of 2.9 ± 0.4dB was measured for pump powers of only 5.8mW, consistent with a population inversion factor close to unity.

INTRODUCTION.

The erbium-doped fibre amplifier[1] is extremely attractive for high bit-rate trunk lines[2], multichannel distribution networks[3] and subcarrier-multiplexed video transmission systems[4] operating in the 1.5μm region. The amplifier offers high net gain[5], low noise[6-10], high speed response[11] and immunity to crosstalk and distortion[12].

The noise characteristics of erbium-doped fibre amplifiers have been the subject of much attention recently[6-10]. Erbium is a three-level system and consequently the amplifier noise figure (NF = Power SNR_{in}/Power SNR_{out}) and spontaneous emission factor n_{sp} depend on the gain medium population inversion[6-9] ($(N_2-N_1)/N_2$). The noise figure is thus likely to be sensitive to fibre parameters and pump power, wavelength and direction. Previous theoretical work has predicted a NF of only 0.2dB above the 3dB signal-spontaneous beat-noise quantum limit for an amplifier pumped with 100mW at 514nm. Additionally, low-noise amplifiers have been demonstrated employing pump powers of 100mW at 665nm[6] and ~200mW at 528nm[7]. More recently a NF of around 5dB has been reported for an erbium-doped fibre amplifier pumped in-band at 1.49μm with ~50mW of pump power[10]. This latter NF is some 2dB higher than expected and this is believed to be caused by the proximity of the pump and signal wavelengths which results in an incomplete population inversion.

In this paper we present measurements of NF and spontaneous emission factor, n_{sp} for an optimised erbium-doped fibre amplifier in which the population inversion has been maximised by careful choice of pump wavelength and control of dopant profile. In this way the resulting gain is maximised and NF and n_{sp} minimised. We demonstrate a minimum NF of 2.9 ±0.4dB for input signals in the range -35dBm to -15dBm and pump powers greater than only 5.8mW. In addition, n_{sp} was found to be 0.99 ±0.09 for input signals less than -15dBm and pump powers larger than 5.8mW. These results confirm that the operation of erbium-doped fibre amplifiers close to the 3dB signal-spontaneous beat noise quantum-limit is readily obtainable with the pump powers available from semiconductor lasers[5] emitting at 980nm.

EXPERIMENT

The experimental configuration for the measurement of gain, NF and n_{sp} is shown in Figure 1. The amplifier consisted of 11 metres of erbium-doped germano-silicate fibre with ends terminated so as to provide negligible feedback. The fibre was characterised by an NA of 0.2 and λ_{cutoff} at 965nm. Further, the erbium was localised to the central region of the core to increase the overlap between pump field and dopant, so maximising the population inversion.

Pump light was provided by an Ar^+-pumped Ti-sapphire laser operating at 980nm and the signal beam by a DFB laser operating at 1.535μm. These two beams were multiplexed with a dichroic fibre coupler and copropagated through the amplifier. The amplified signal was optically filtered to remove residual pump light and detected with an InGaAs detector. Care was taken to ensure that η, the product of the optical coupling efficiency to the detector (76%) and the detector responsivity (0.97A/W), was maximised. The signal laser output was sinusoidally modulated with a small (~3% rms) intensity modulation. RF spectral analysis of the detector output thus provides a measure of both amplifier noise and amplified signal level, from which the output SNR and amplifier gain G can be obtained. These were recorded along with the ASE spectra for input signals P in the range

-47dBm to -8dBm. Assuming Poisson statistics for the input SNR, the amplifier NF and n_{sp} could be determined from these data.

THEORY

The amplified signal and unpolarised amplified-spontaneous-emission (ASE) give rise to a mean detector current i_m given by;

$$i_m = \eta\{GP+2n_{sp}h\nu(G-1)\Delta\nu_{ASE}\} \tag{1}$$

and an rms noise current $<i_n>$ with single-sided spectral density

$$<i_n{}^2> = 2e\eta[GP+2n_{sp}h\nu(G-1)\Delta\nu_{ASE}]+ 4\eta^2[n_{sp}GPh\nu(G-1)+(n_{sp}(G-1)h\nu)^2\Delta\nu_{sp-sp}] \tag{2}$$

Here the terms in the brackets refer to amplified signal and ASE shot noises, signal-spontaneous and spontaneous-spontaneous beat noises respectively. With e the electron charge, h Planck's constant and ν the optical frequency. Both $\Delta\nu_{ASE}$ and $\Delta\nu_{sp-sp}$ relate to the linewidth of the ASE and are defined by

$$\Delta\nu_{ASE} = \frac{\int P(\nu)d\nu}{\hat{P}} \tag{3}$$

and

$$\Delta\nu_{sp-sp} = \frac{\int P^2(\nu)d\nu}{\hat{P}^2} \tag{4}$$

where $P(\nu)$ is the power spectral density of the ASE and $\hat{P}$ its peak value.

The output signal to noise ratio is thus given by

$$SNR_{out} = (\eta GP)^2/<i_n{}^2>B_e \tag{5}$$

where B_e is the electronic receiver bandwidth.

Comparison with the input signal to noise power ratio,

$$SNR_{in} = P/2h\nu B_e \qquad (6)$$

gives the amplifier NF,

$$NF = 10Log_{10}(SNR_{in}/SNR_{out}) \qquad (7)$$

It is clear from equation 2 that if the detector coupling coefficient, η is maximised and if the gain is high (G>10dB) then the output noise is signal-spontaneous and spontaneous-spontaneous beat-noise dominated. In this case the measured NF will be an accurate measure of the absolute[13] amplifier NF (obtained with unit quantum efficiency detection, i.e. η=e/hν). In addition, it is clear from equations (2) and (5) that if the SNR_{out}, the coupling coefficient η, the amplifier gain G and the effective ASE linewidths, $\Delta\nu_{ASE}$ and $\Delta\nu_{sp-sp}$ are known for each input signal level P, then n_{sp} can be determined.

RESULTS AND DISCUSSION

Figure 2(a,b) shows the measured NF and amplifier gain for input signals in the range -47dBm to -8dBm and launched pump powers of 5.8mW, 7.4mW and 12mW. It can be seen that over the range of input signals between -35dBm and -15dBm the amplifier is operating with its lowest NF. The mean value of the noise figure in this region was found to be 2.9dB with a standard deviation of 0.4dB. Additionally, it can be seen from Figure 2(b) that for the same range of input signals the gain was greater than 12dB which ensures that the measured NF was within 0.1dB of the absolute amplifier NF. Thus, these results confirm that the erbium-doped fibre amplifier can be operated at, or very near to the 3dB signal-spontaneous quantum limit.

Decreasing the input signal below -35dBm results in a sharp increase in NF owing to an increase in the relative importance of the spontaneous-spontaneous beat noise. The effective ASE linewidths, $\Delta\nu_{ASE}$ and $\Delta\nu_{sp-sp}$, were evaluated numerically from the ASE spectra. Under small-signal operation $\Delta\nu_{sp-sp}$ was found to range between the equivalent of 3.7nm and 2.9nm for pump powers of 5.8mW and 12mW. Whilst for the same range of pump powers $\Delta\nu_{ASE}$ ranged between the equivalent of 8nm and 5.5nm. Increasing the input signal beyond -15dBm results in a ~1dB increase in NF which is caused by the amplifier (which has been optimised for small signal operation) being driven into saturation. In this case, the amplified output signal becomes comparable to the pump power and depletes the amplifier inversion, resulting in an increase in NF.

It should be noted that the measurements at higher signal input powers were complicated by the additional relative-intensity noise (RIN) of the signal laser which measured -146dB/$\sqrt{Hz}$ in the frequency regime of interest. However, this was taken into account for input signals greater than approximately -20dBm and the NF presented here is the true NF which would be measured for an input source with Poisson statistics. The actual NF measured in the presence of the additional noise due to the input signal was somewhat lower.

Figure 3 shows the spontaneous emission factor n_{sp} determined from the previous data. From the figure it can be seen that for input signals below -15dBm n_{sp} had a mean value of 0.99, with standard deviation 0.09. This shows that erbium-doped fibre amplifiers could be operated at the quantum limit for all input signals less than -35dBm, provided the ASE is spectrally filtered to reduce the spontaneous-spontaneous beat-noise. However, in this fibre with increased signals above -15dB, the spontaneous emission factor n_{sp} increased markedly up to a value of 2.

The amplifier NF and n_{sp} are governed by the population inversion. In the small-signal case the inversion at a point in the fibre is:

$$(N_2-N_1)/N_2 \approx (P_p-P_{th})/P_p, \qquad (8)$$

where P_p is the local pump power and P_{th} is the pump threshold, i.e. that power required to bleach an infinitesimally small section of fibre. Thus, by minimising P_{th}, the inversion can be maximised and n_{sp} minimised for a given pump power. In this experiment the strong absorption cross-section at 980nm and the optimised dopant profile resulted in a pump threshold of only 500μW and this contributed to the excellent results for NF and n_{sp}.

The amplifier NF measured as a function of pump power and for a constant input signal P of 1μW is shown in Figure 4. It can be seen that for pump powers greater than ~5.5mW the NF is close to the 3dB signal-spontaneous beat-noise limit. Reducing the pump power below 5mW results in a marked increase in NF owing to a marked reduction in amplifier gain and an increase in n_{sp} as the amplifier inversion is reduced.

CONCLUSIONS

A noise figure of 2.9 ±0.4dB has been measured in a high gain erbium-doped fibre amplifier for input signals in the range -35dBm to -15dBm and for pump powers of only >5.8mW. Additionally, the spontaneous emission factor n_{sp} has been measured to be 0.99 ±0.09 for input signals less than -15dBm. These low figures are attributable to the optimised fibre design and the use of a pump wavelength of 980nm at which erbium operates as a true three-level system. These two factors contribute to the very low (~500μW) pump threshold seen in fibre which permits nearly complete inversion to be achieved for the low pump powers employed.

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REFERENCES

1). R.J. Mears, L. Reekie, I.M. Jauncey and D.N. Payne, "Low noise erbium-doped fiber amplifier operating at 1.54μm," Electronic Letters, Vol. 23, No. 19, p. 1026, 1987.

2). N. Edagawa, Y. Yoshida, H. Taga, S. Yamamoto, K. Mochizuki and H. Wakabayashi, "904km, 1.2Gbit/s non-regenerative optical transmission experiment using 12 Er-doped fibre amplifiers", ECOC'89, Postdeadline paper PDA-8, 1989.

3). R. Welter, R.I. Laming, W.B. Sessa, R.S. Vodhanel, M.W. Maeda and R.E. Wagner, "Performance of erbium-doped fibre amplifier in 16-channel coherent broadcast network", Electronics Letters, Vol. 25, pp. 1333-1335, 1989.

4). W.I. Way, M.M. Choy, A. Yi-Yan, M. Andrejco, M. Saifi and Chinlon Lin, "Multi-channel AM-VSB television signal transmission using an erbium-doped optical fiber power amplifier", Seventh International Conference on Integrated Optics and Optical Fibre Communication, Kobe, Japan, Postdeadline paper 20PDA-10, 1989.

5). R.S. Vodhanel, R.I. Laming, V. Shah, L. Curtis, D.P. Bour, W.L. Barnes, J.D. Minelly, E.J. Tarbox and F.J. Favire, "Highly Efficient 978nm Diode-pumped Erbium-doped Fiber Amplifier with 24dB Gain", Electronics Letters, Vol. 25, pp. 1386-1387, 1989.

6). R.I. Laming, P.R. Morkel, D.N. Payne & L. Reekie: "Noise in erbium-doped fibre amplifiers", Proc. 14th European Conference on Optical Communications, Brighton, IEE 292 (Part 1), pp. 54-57, 1988.

7). M.J. Pettitt, R.A. Baker and A. Hadjifotiou,
"System performance of optical fiber preamplifier",
Electronic Letters, Vol. 23, No. 5, p. 216, 1987.

8). R. Olshansky,
"Noise figure for erbium-doped optical fiber amplifiers",
Electronics Letters, Vol. 24, No. 22, p. 1363, 1988.

9). P.R. Morkel & R.I. Laming,
"Theoretical modelling of erbium-doped fibre amplifiers with excited state absorption",
Optics Letters, Vol. 14, No. 19, pp. 1062-1064, 1989.

10). C.R. Giles, E. Desurvire, J.L. Zyskind and J.R. Simpson,
"Noise performance of erbium-doped fiber amplifier pumped at 1.49μm, and application to signal preamplification at 1.8 Gbits/s",
IEEE Photonics Technology Letters, Vol. 1, No. 11, 1989.

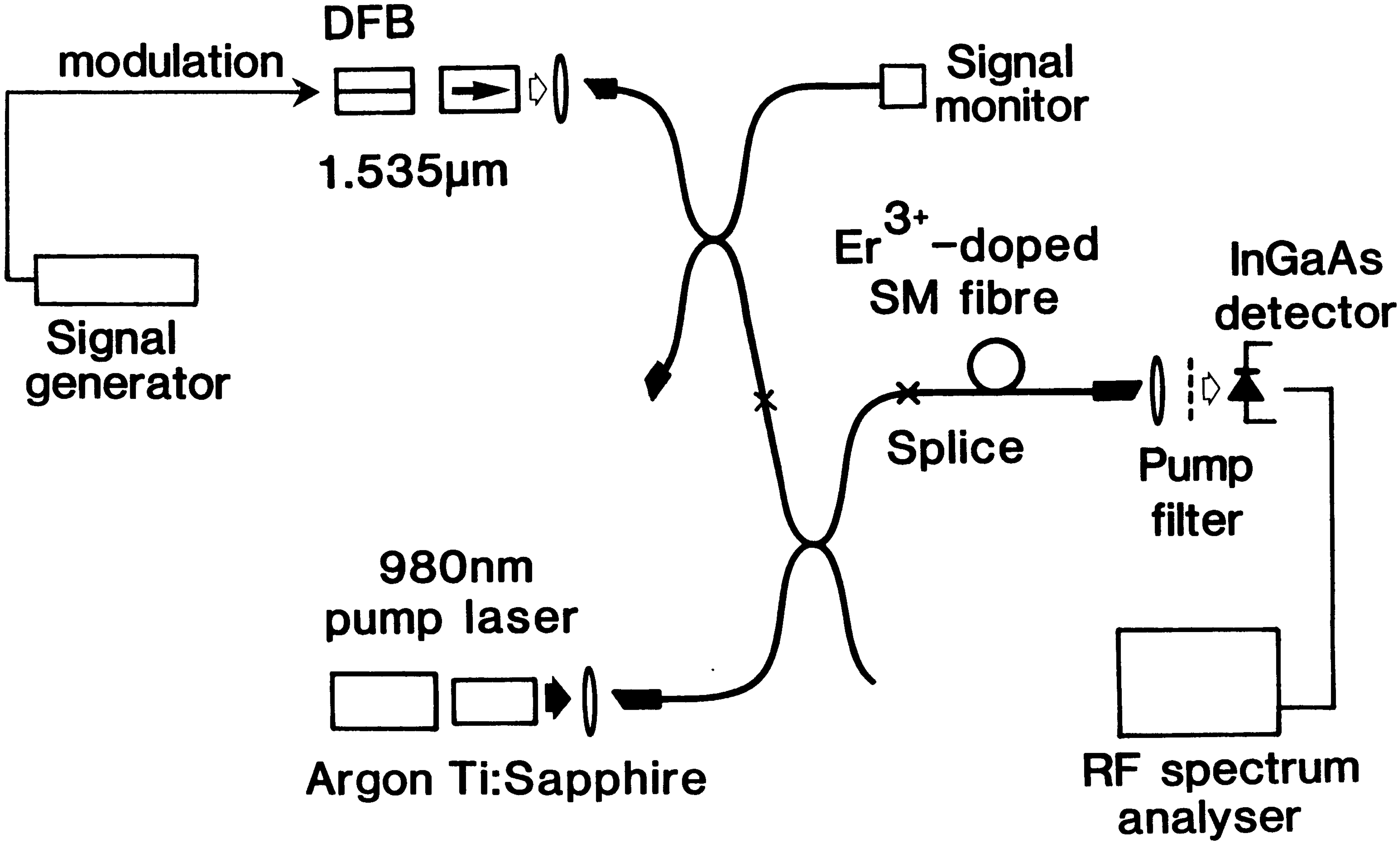
11). R.I. Laming & R.S. Vodhanel,
"0.1-15 GHz AM and FM response of an erbium-doped fibre amplifier",
Electronics Letters, Vol. 25, No. 17, pp. 1129-1130, 1989.

12). R.I. Laming, L. Reekie, P.R. Morkel & D.N. Payne,
"Multichannel crosstalk and pump noise characterisation of an Er^{3+}-doped fibre amplifier pumped at 980nm",
Electronics Letters, Vol. 25, pp. 435-456, 1989.

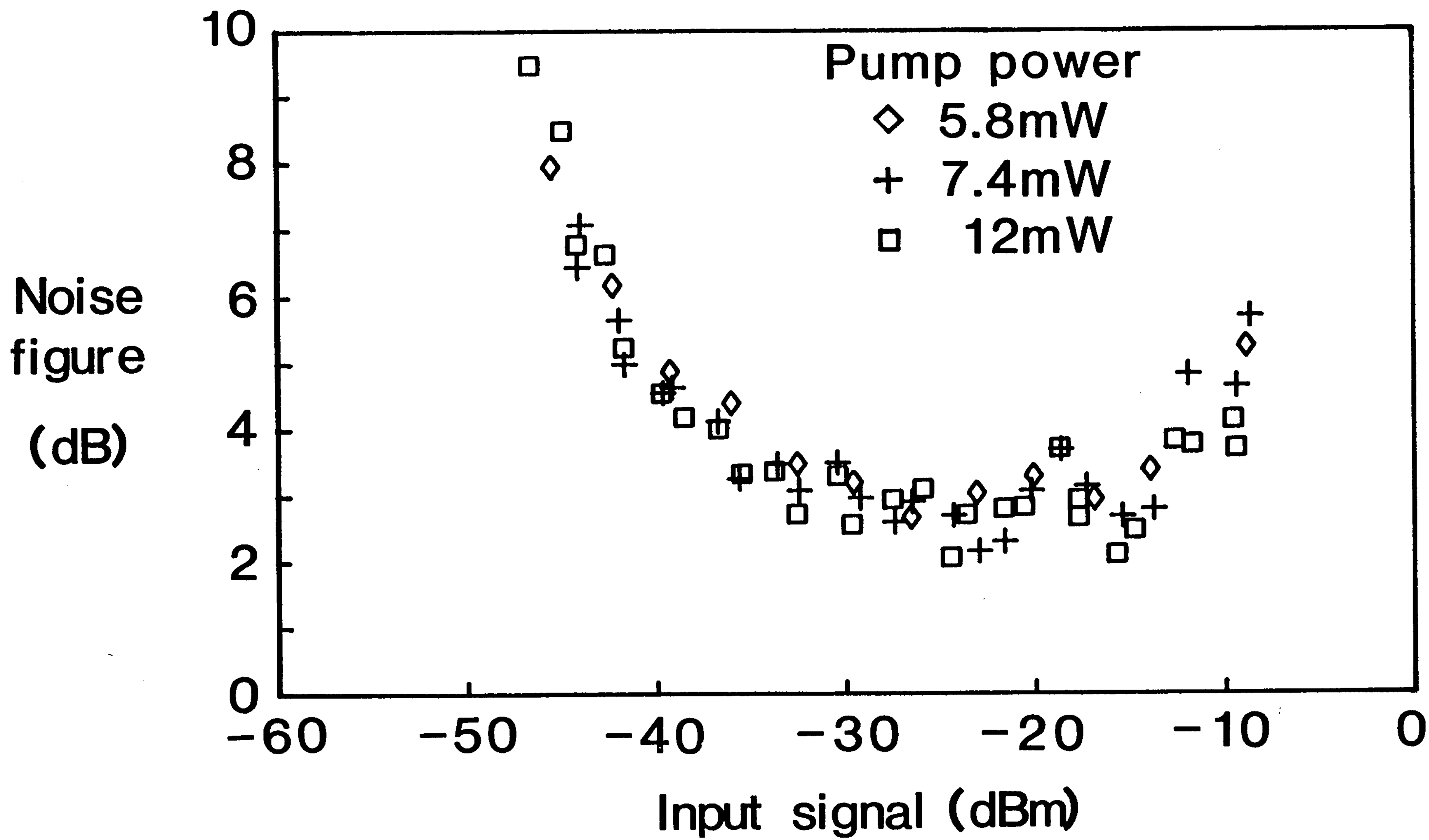
13). Y. Yamamoto.
"Noise and error-rate performance of semiconductor laser amplifiers in PCM-IM optical transmission systems",
IEEE J. Quantum Electronics, QE-16, pp. 1073-1081, 1980.

FIGURE CAPTIONS

Figure 1	Experimental set-up.
Figure 2(a,b)	Measured noise figure and gain of the amplifier as a function of input signal.
Figure 3	Measured amplifier spontaneous emission factor, n_{sp} as a function of input signal.
Figure 4	Measured amplifier noise figure as a function of pump power for a fixed input signal of $1\mu W$.


modulation
DFB
1.535µm
Signal generator
Signal monitor
Er3+-doped SM fibre
InGaAs detector
Splice
Pump filter
980nm pump laser
Argon Ti:Sapphire
RF spectrum analyser

REVISED



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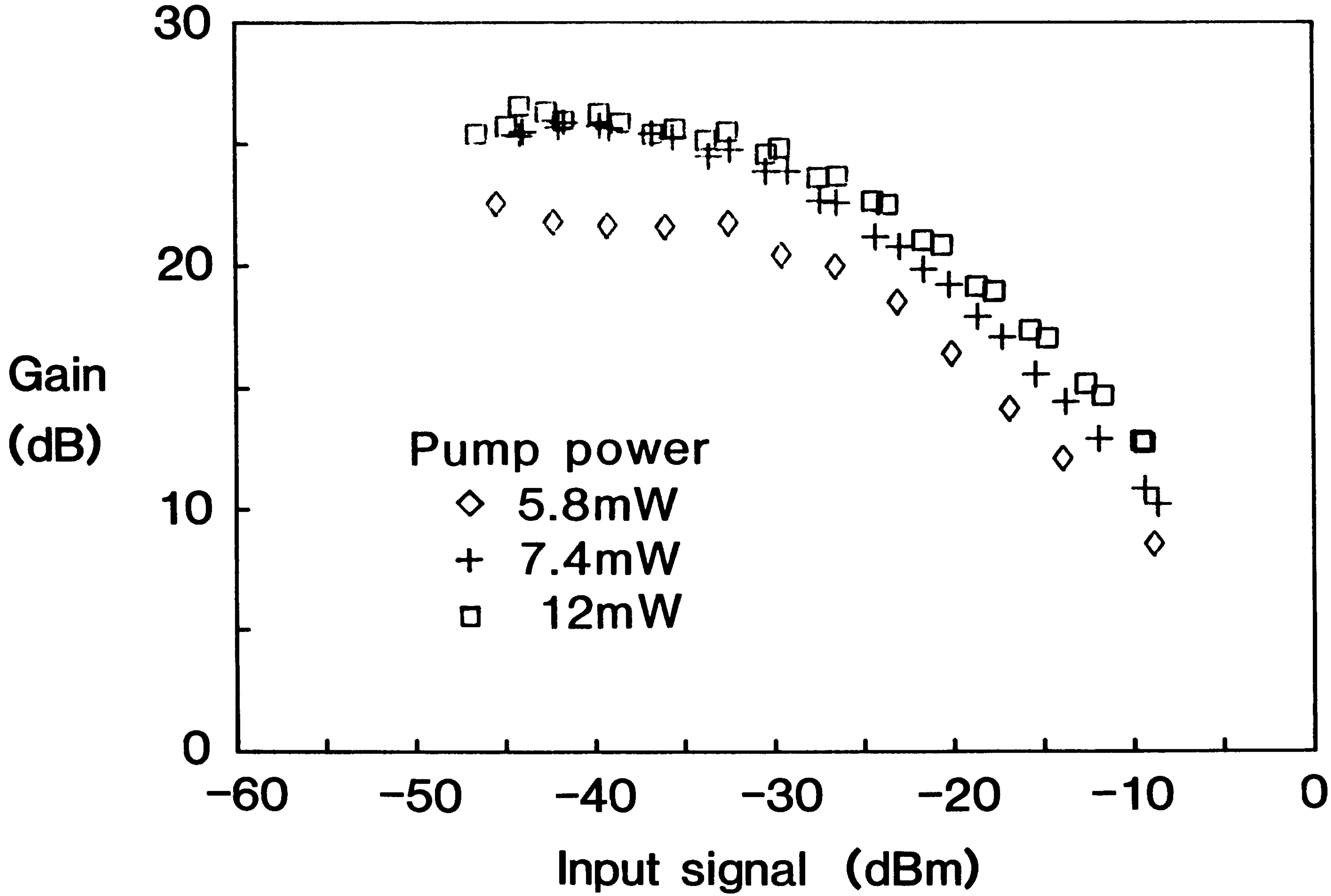
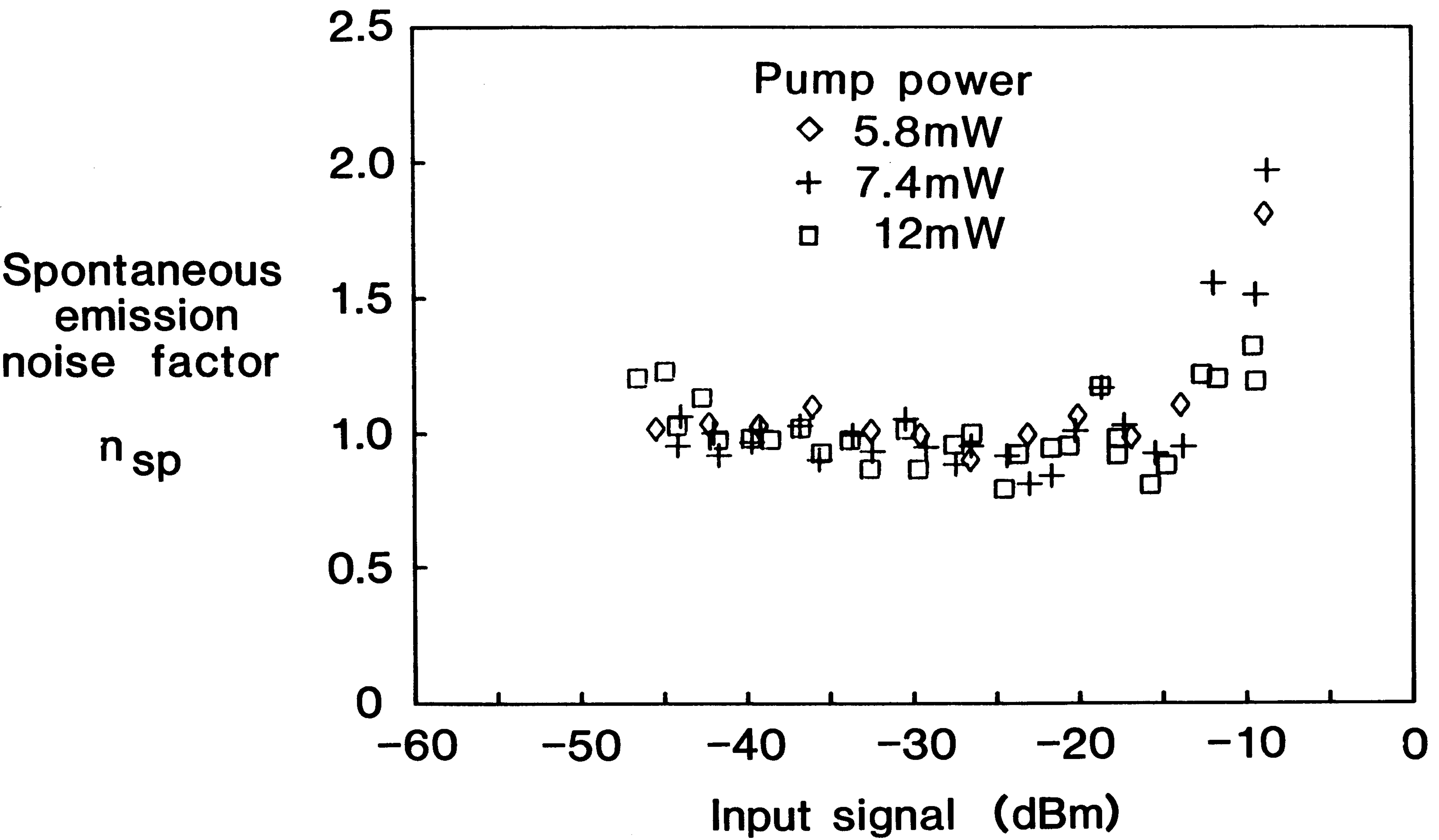


30
20
10
0
Gain
(dB)
Pump power
◇ 5.8mW
+ 7.4mW
□ 12mW
−60
−50
−40
−30
−20
−10
0
Input signal (dBm)


Spontaneous emission noise factor
n sp
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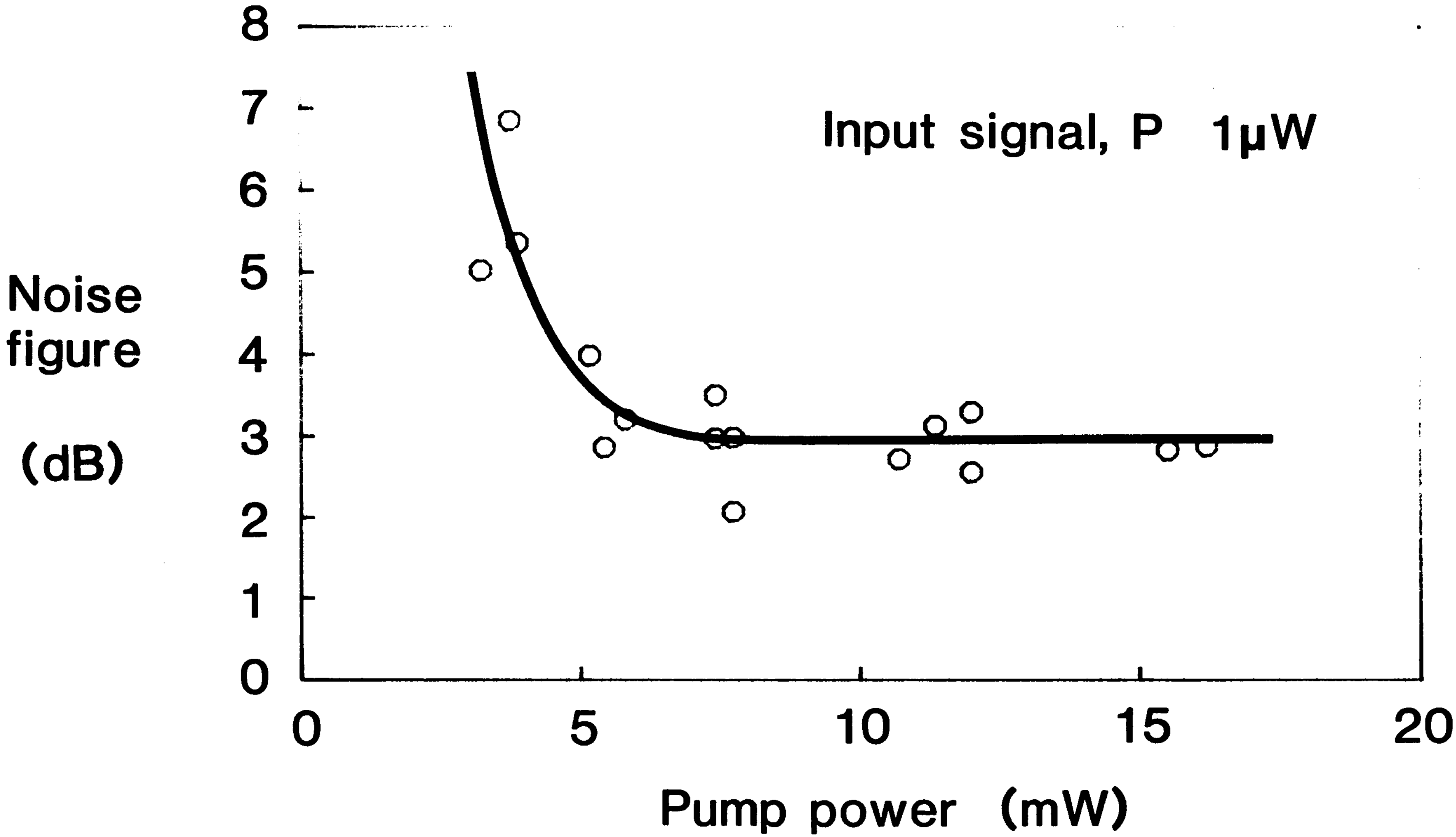
2.0
1.5
1.0
0.5
0
Pump power
5.8mW
7.4mW
12mW
−60
−50
−40
−30
−20
−10
0
Input signal (dBm)


Input signal, P 1μW
Noise
figure
(dB)
8
7
6
5
4
3
2
1
0
0
5
10
15
20
Pump power (mW)