for file. 647 PTL

HIGH SENSITIVITY TWO-STAGE ERBIUM-DOPED FIBRE PRE-AMPLIFIER AT 10Gbit/s

R I Laming[1], A H Gnauck[2], C R Giles[2], M N Zervas[1] & D N Payne[1]

[1]Optoelectronics Research Centre, The University, Southampton, S09 5NH, UK.
[2]AT&T Bell Laboratories, Crawford Hill Laboratory, Holmdel, NJ 07733-0400

Abstract

We have demonstrated an optical preamplifier with a record sensitivity of -38.8 dBm (102 photons/bit) at 10Gbit/s. When employed in a practical link without an input isolator the sensitivity is only slightly degraded to -37.6dBm (135 photons/bit) by input coupling losses and feedback due to Rayleigh backscattering in the transmission fibre.

Introduction

The erbium-doped fibre amplifier (EDFA) will find widespread application in future telecommunications networks. In particular, when employed as an optical pre-amplifier the EDFA can greatly improve receiver sensitivity and provide increased system span, bit-rate or margin, as well as allowing the upgrade of existing links. Previous investigations of high-speed (10Gbit/s) optical pre-amplifiers[1,2] have been limited to sensitivities of -36dBm (193 photons/bit) and -34.6dBm (268 photons/bit) respectively by a combination of high input coupling and insertion losses, insufficient optical gain to overcome the receiver noise, intersymbol interference (ISI) and insufficient optical filtering.

In this paper we investigate the use of a new composite amplifier with an integral isolator[3-5]. The position of the optical isolator has been optimised to suppress the backward-travelling ASE effectively. The resultant amplifier gives a gain as high as 51dB and and a noise figure (NF) of 3.1dB for only 50mW of pump power at 980nm[4,5]. This high gain allows the potential both to use a 50Ω receiver, thus reducing ISI, and to improve the optical filtering (narrower optical bandwidth, accompanied inevitably by increased insertion loss). In addition, since an isolator is incorporated within the amplifier, an isolator at the input is not essential, thus reducing input coupling and insertion losses[6,7]. At a data rate of 10Gbit/s the sensitivity at the input to the amplifier fibre is -38.8dBm (102 photons/bit) and including the input coupling losses from dispersion-shifted fibre (DSF) via a WDM coupler the sensitivity is -38.4dBm (112 photons/bit).

Moving the isolator from the input position to within the amplifier decreases its apparent loss but reduces its effectiveness in suppressing excess noise caused by feedback of the remnant backward ASE due to Rayleigh backscatter in the incoming transmission fibre. The reduction in sensitivity due to these reflections from a long length of transmission fibre is also investigated and it is found that the composite amplifier can be further optimised to minimise this penalty. A sensitivity of -37.6dBm (135 photons/bit) corresponding to a 0.8dB penalty was achieved. It is predicted that this penalty can be reduced to 0.15dB with an improved isolator in the composite EDFA. Nevertheless, this is a considerable improvement over previous results[1,2].

Experiment

The experimental setup is shown in Figure 1. At the transmitter, a 1536nm wavelength DFB laser is externally-modulated using a $LiNbO_3$ Mach-Zehnder amplitude modulator[8] with 11GHz bandwidth. The modulation signal is a non-return-to-zero (NRZ) pseudo-random sequence of length 2^{15}-1. The bias point of the modulator is set manually to give maximum extinction ratio (dc extinction ratio 30dB). There follows a variable optical attenuator and a 3dB optical coupler which is used to monitor the pre-amplifier input power on an optical power meter. An optional 45km length of DSF was fusion spliced onto the amplifier input. This is sufficient for full-amplitude Rayleigh backscatter to build up and provide an estimated equivalent reflector of -28dB at the amplifier input, thus simulating a practical transmission application.

The composite EDFA consisted of an input WDM coupler and two lengths (25m and 60m) of erbium-doped fibre separated by a polarisation-independent isolator to suppress the backward-travelling ASE. Since the isolator has a very high loss at the pump wavelength, two WDM couplers with insertion losses at the pump/signal wavelengths of 0.11dB/0.31dB and 0.16dB/0.31dB were included to provide a low-loss by-pass for the pump. The resultant losses between the two sections of amplifier fibre were ~ 0.6dB at the pump wavelength and ~ 2.1dB at the signal wavelength. The isolation in the reverse direction was ~ 37dB at the amplifier gain peak of 1536nm. The silica-germania erbium-doped fibre is characterised by a NA of 0.24, a λ_{cutoff} at 920nm and an absorption coefficient of 0.95dB/m at 1536nm. The total input loss typically measured 0.4dB including the WDM coupler insertion loss (0.17dB) and the loss due to two splices. The position of the isolator was optimised for maximum gain and minimum NF[3]. The amplifier was pumped by a pigtailed 980nm diode which coupled 40mW of power for a 140mA drive current. For an input signal power of around -40dBm the amplifier internal gain was approximately 46dB and NF $\sim$ 3.1dB.

The amplifier output was optically filtered with a Fabry-Perot filter of 20GHz passband and finesse of 100. Two optical isolators were included to suppress feedback into the EDFA from the Fabry-Perot and between the Fabry-Perot and pin-diode. The transmission loss of this combination was high ($\sim$9dB), but was tolerable because of the high amplifier gain.

The receiver consisted of a pin-diode followed by hybrid GaAs FET amplifiers, giving a bandwidth of 8GHz. In the case of transmission experiments a phase-locked loop was used to recover the clock from the received NRZ signal. Without optical pre-amplification, the receiver sensitivity was -12.5dBm at 10Gbit/s, using the full 8GHz electrical bandwidth (Figure 2).

Results

Bit-error rate (BER) curves for the optical pre-amplifier are shown in Figure 2. In the case of the back-to-back measurement (no DSF) the sensitivity at 10^{-9} BER is -38.4dBm (112 photons/bit). This corresponds to a sensitivity of -38.8dBm (102 photons/bit) at the EDFA input and is, to our knowledge, the highest sensitivity reported to date at this bit-rate. For this condition the receiver electrical noise was negligible. Analysis shows that the results are consistent with the amplifier NF, the electrical and optical bandwidths and possible signal distortion due to the optical filter[9,10]. The received eye pattern at this sensitivity is shown in Figure 3. It is clear from the increased noise during the mark period that the predominant noise source at the receiver is signal-spontaneous beat noise.

Referring back to Figure 2 it is seen that with a 45km section of DSF spliced directly to the amplifier input (sufficient to provide a real input reflector of ~-28dB) the pre-amplifier sensitivity is degraded by 1.15dB to -37.25dBm (146 photons/bit). By reducing the length and thus the gain of the first stage EDFA to ~20m, a reduction in noise penalty to only ~0.8dB at a BER of 10^{-9} is observed. Thus a pre-amplifier sensitivity of -37.6dBm (135 photons/bit) for a 10^{-9} BER is demonstrated at 10Gbit/s. Reducing the first stage length further (15m and 10m) results in a BER degradation due to a NF increase since the first stage gain is now reduced and the insertion loss of the isolator becomes detrimental.

Figure 4 shows calculated gain and NF for our composite EDFA as a function of the first stage fibre length (and hence gain) assuming an input reflector of -28dB due to Rayleigh backscatter in the DSF. In this case an isolator extinction ratio of 37dB and 2.1dB loss due to its insertion were assumed. It can be seen that for the 25m length, the amplifier noise figure is degraded by ~0.6dB to 3.8dB due to the input reflector. Reducing the 1st stage fibre length to approximately 17m can reduce the NF to ~3.55dB (a ~0.35dB penalty) with only a small penalty in gain, in qualitative agreement with the BER data. Employing an improved isolator with 50dB extinction ratio and 1.0dB loss in the composite EDFA should result in a penalty as low as 0.15dB, effectively alleviating the requirement for an input isolator and giving a further improvement in sensitivity.

Further improvements in sensitivity should also be possible by reducing the output losses and improved optical and electrical filtering.

Conclusions We have demonstrated a new high-sensitivity optical pre-amplifier at 10Gbit/s employing a composite EDFA. At the input to the amplifier a record sensitivity of -38.8dBm (102 photons/bit) is achieved, although input coupling losses degrade this slightly to -38.4dBm. Operation of the optical pre-amplifier without an input isolator is demonstrated, and a sensitivity of -37.6dBm (135 photons/bit) obtained, corresponding to a 0.8dB penalty caused by feedback due to Rayleigh backscattering in the 45km length of DSF transmission fibre. It is predicted that this penalty can be reduced to 0.15dB with an improved isolator in the composite EDFA. The best previously reported result at 10Gbit/s was 193 photons/bit[1].

Acknowledgments The authors wish to thank York Fibers for fabricating the doped fibre. One of the authors (RIL) acknowledges the Royal Society for the provision of a University Research Fellowship. The ORC is a SERC-funded Interdisciplinary Research Centre.

References

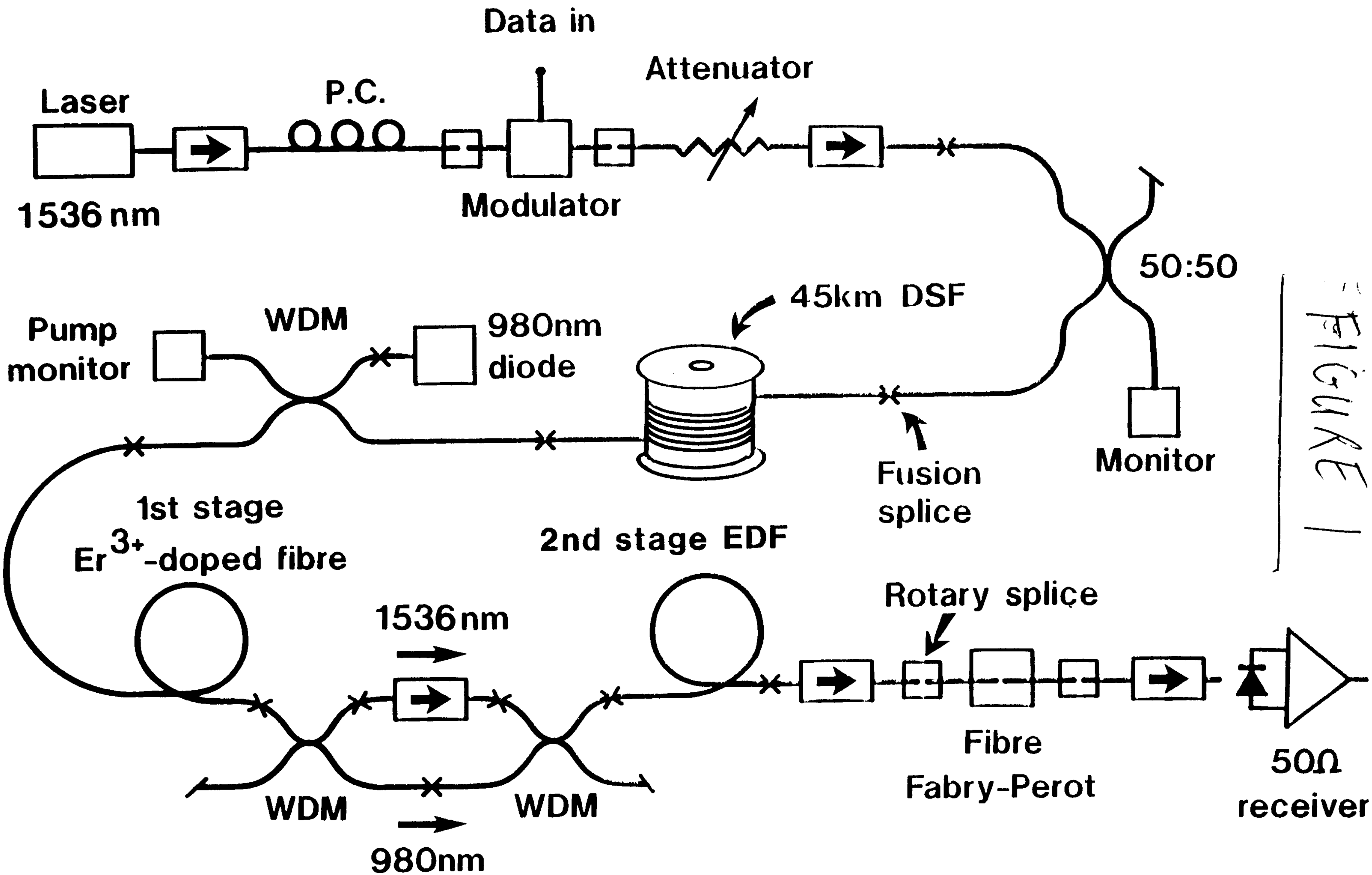
1. A.H. Gnauck & C.R. Giles, "2.5 and 10 Gb/s transmission experiments using a 137 photon/bit erbium-fiber preamplifier receiver", IEEE Photonics Technology Letters, Vol. 4, pp. 80-82, 1992.
2. T. Saito, Y. Sunohara, K. Fukagai, S. Ishikawa, N. Henmi, S. Fujita and Y. Aoki, "High receiver sensitivity at 10 Gb/s using an Er-doped fiber preamplifier pumped with a 0.98μm laser-diode", OFC'91, San Diego, CA, 1991, PD14.
3. M.N. Zervas, R.I. Laming & D.N. Payne, "Efficient erbium-doped fibre amplifier with an integral isolator", Proc. 3rd Top. Meet. on Optical Amplifiers & Their Applications, Santa Fe, FB2, June 1992. & O. Lumholt, K. Schusler, A. Bjarklev, S. Dahl-Peterson, J.H. Povslen, T. Rasmussen & K. Rottwitt, "Efficiency improvements of EDFAs by insertion of an isolator within the active fibre", CLEO 92, CWO8, 1992.
4. R.I. Laming, M.N. Zervas & D.N. Payne, "54dB gain quantum-noise-limited erbium-doped fibre amplifier", ECOC 92, Berlin.
5. R.I. Laming, M.N. Zervas & D.N. Payne, "Erbium-doped fibre amplifier with 54dB gain and 3.1dB noise figure", submitted to IEEE Photonics Technology Letters.
6. N. Henmi, Y. Aoki, S. Fujita, Y. Sunohara & M. Shikada, "Rayleigh scattering influence on performance of 10 Gb/s optical receiver with Er-doped optical fibre preamplifier", IEEE Photon. Technology Letter, Vol.2, pp.227-278, 1990.
7. C.G. Joergensen, B. Mikkelsen, O. Frolich, T. Durhuus, K.E. Stubkjaer, C. F. Pedersen, K. Schusler, C.C. Larsen, J.A. Berk, "Refined amplifier design for unrepeatered 2.5 Gbit/s transmission over 59 dB of fibre loss", Proceedings of Optical Amplifiers and Their Applications, Sante Fe, New Mexico, June 24-26, Paper FC3, 1992.
8. S.K. Korotky, J.J. Veselka, C.T. Kemmerer, W.J. Minford, D.T. Moser, J.E. Watson, C.A. Mattoe & P.L. Stoddard, "High-speed low-power optical modulator with adjustable chirp parameter", Top. Meet. Integrated Photonics Research, Monterey, CA, 1991, paper TuG2.
9. Y. Aoki, "Properties of Raman amplifiers and their applicability to digital optical communications system", Journal of Lightwave Technology, Vol. LT-6, pp. 1225-1239, 1988.

10. Y.E. Dallal & S. Shamai, "Analytical techniques assessing the performance of optical amplifiers", Proceedings of Optical Amplifier and Their Applications, Sante Fe, New Mexico, June 24-26, Paper ThC5, 1992.

Figure captions

Figure 1.	Experimental configuration
Figure 2.	Bit-error-rate curves at 10Gbit/s
Figure 3.	Preamplifier-receiver eye pattern at 10Gbit/s and a bit-error rate of 1×10^{-9}
Figure 4.	Dependence of composite-EDFA NF and gain on the 1^{st}-stage length with a 60m 2^{nd}-stage length. Predictions are for the amplifier employed (isolator extiction ratio 37dB and insertion loss 2.1dB) with and without DSF and for a proposed improved amplifier (isolator extinction ratio 50dB and insertion loss 1.0dB).

FIGURE 1



Data in
Laser
P.C.
Attenuator
1536 nm
Modulator
50:50
45km DSF
WDM
Pump
monitor
980nm
diode
Fusion
splice
Monitor
1st stage
Er3+-doped fibre
2nd stage EDF
Rotary splice
1536nm
Fibre
Fabry-Perot
50Ω
receiver
WDM
WDM
980nm

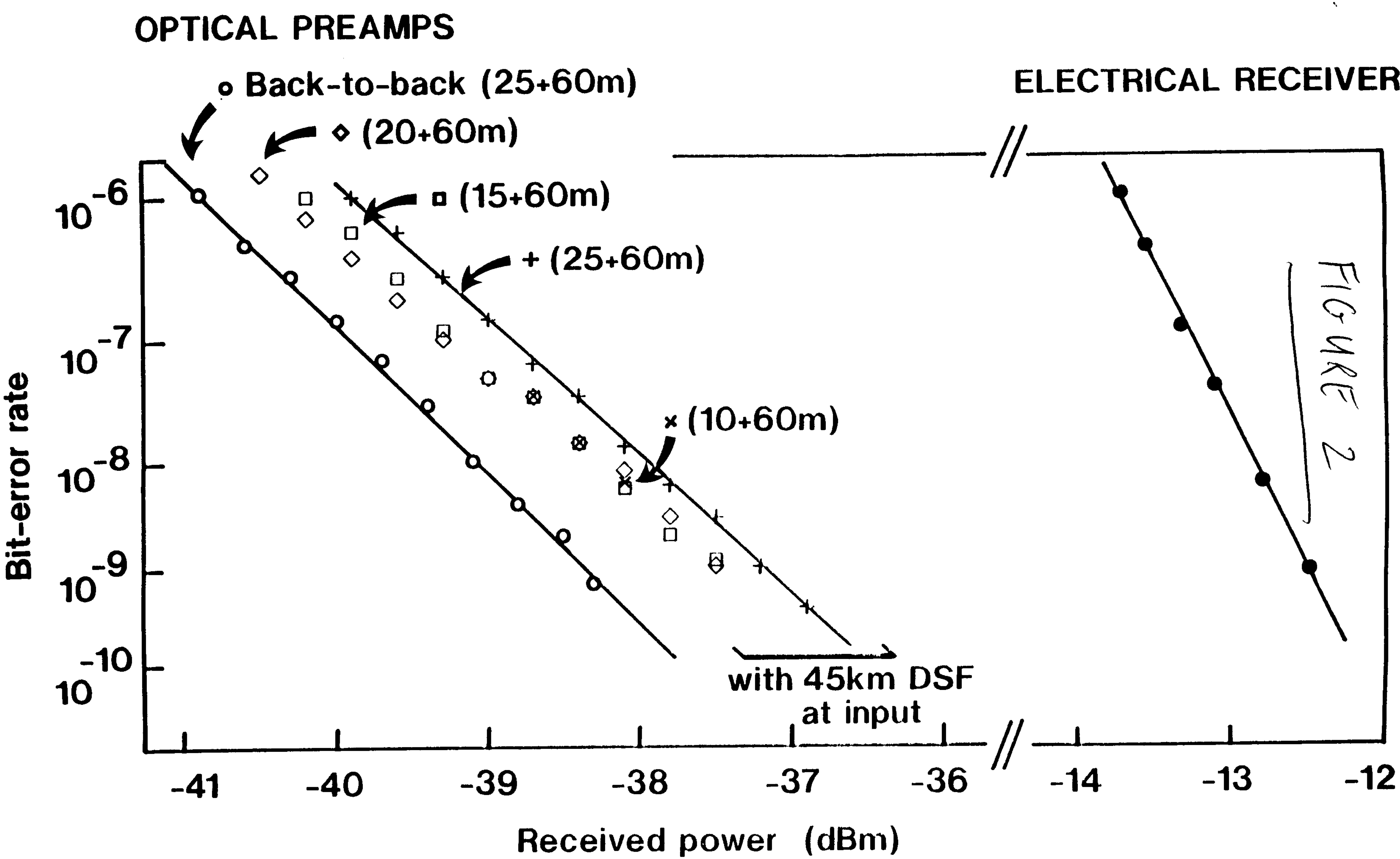

OPTICAL PREAMPS
Back-to-back (25+60m)
(20+60m)
(15+60m)
+ (25+60m)
× (10+60m)
with 45km DSF
at input
ELECTRICAL RECEIVER
FIGURE 2
Bit-error rate
10^-6
10^-7
10^-8
10^-9
10^-10
-41
-40
-39
-38
-37
-36
-14
-13
-12
Received power (dBm)

FIGURE 3

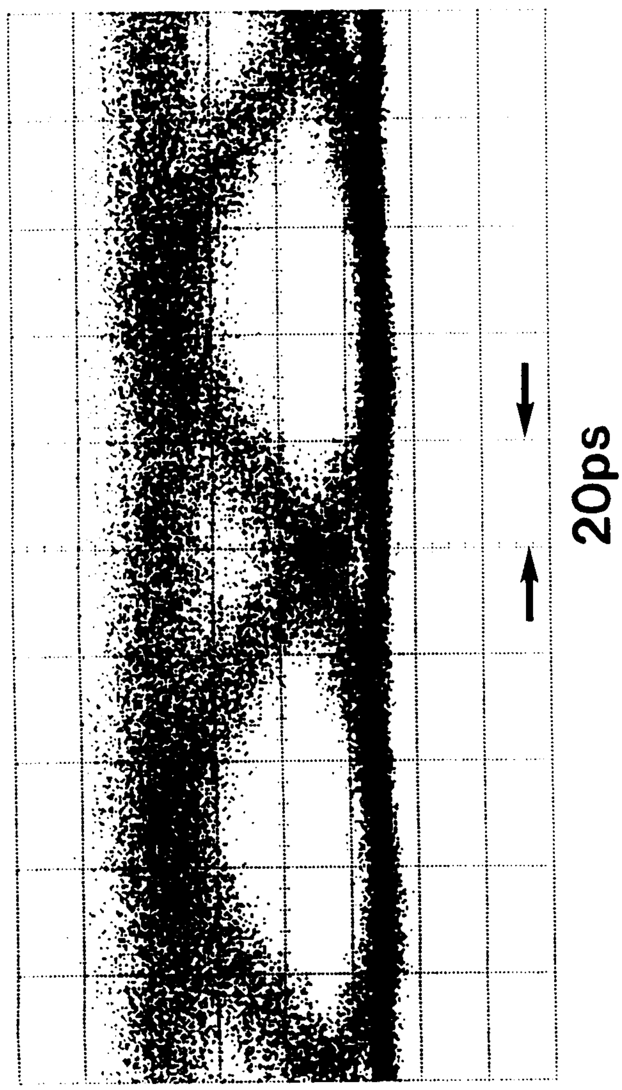
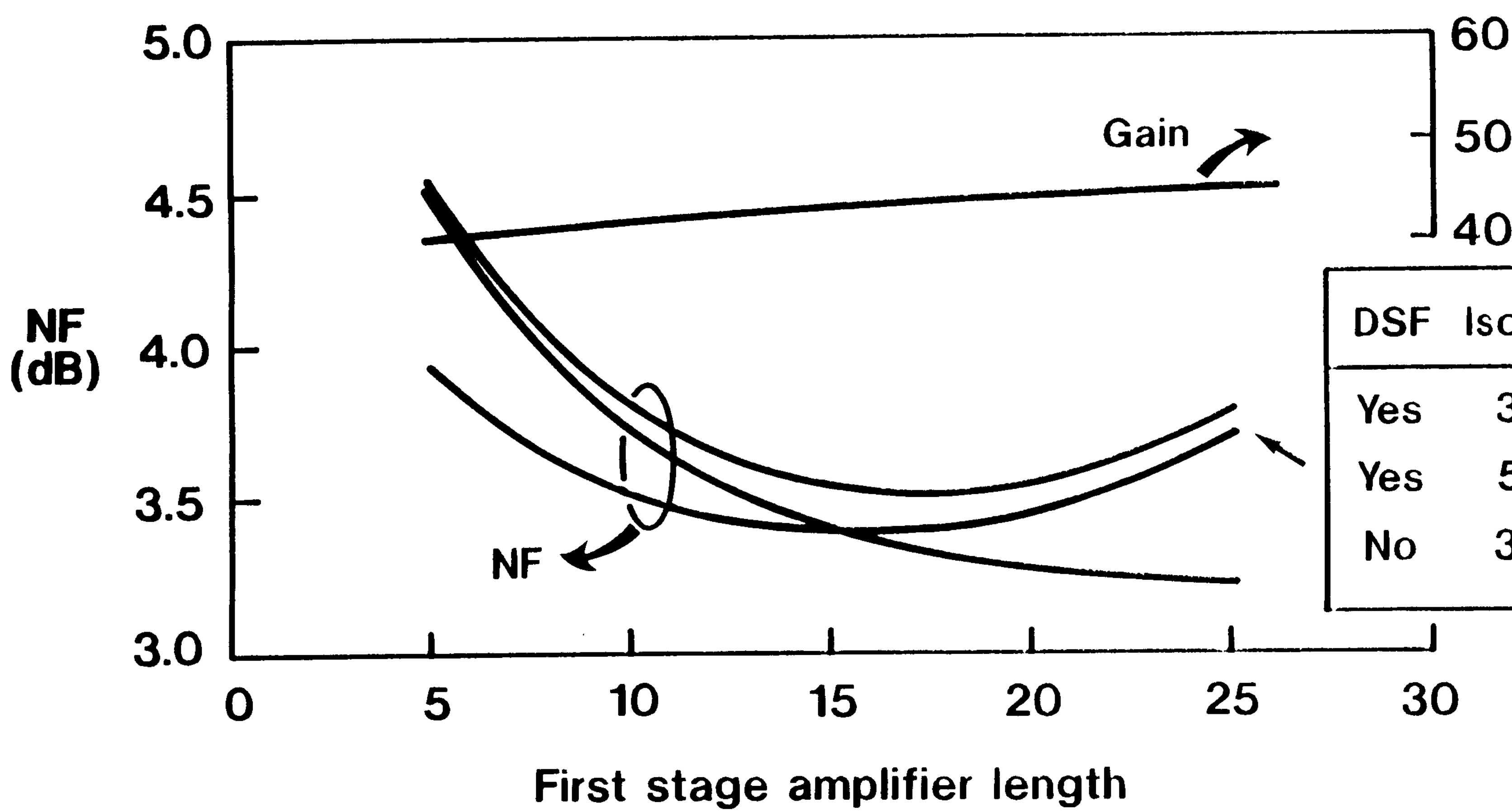


FIGURE 4



DSF	Isolation	Pump loss	Signal loss
Yes	37dB	0.6dB	2.1dB
Yes	50dB	0.6dB	1.0dB
No	37dB	0.6dB	2.1dB

Pump power 40mW @ 980nm

Signal input power -40dBm