

**HIGH SENSITIVITY OPTICAL PRE-AMPLIFIER AT 10Gbit/s EMPLOYING A
LOW NOISE COMPOSITE EDFA WITH 46dB GAIN**

R I Laming¹, A H Gnauck², C R Giles², M N Zervas¹ & D N Payne¹

¹Optoelectronics Research Centre, The University, Southampton, S09 5NH, UK.

²AT&T Bell Laboratories, Crawford Hill Laboratory, Holmdel, NJ 07733-0400

Abstract

We have demonstrated an optical preamplifier with a record sensitivity of -38.8dBm (102 photons/bit) at 10Gbit/s. When employed in a practical link the sensitivity is only slightly degraded to -37.6dBm (135 photons/bit) by input coupling losses and feedback due to Rayleigh backscattering.

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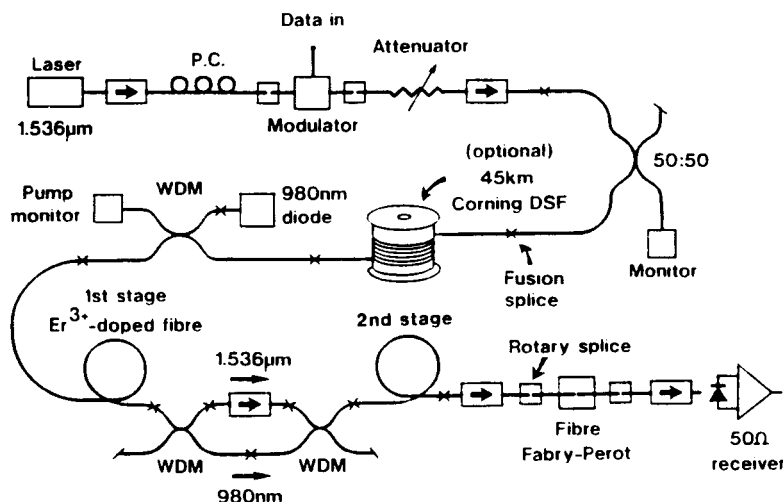
Abstract We have demonstrated an optical preamplifier with a record sensitivity of -38.8 dBm (102 photons/bit) at 10Gbit/s. When employed in a practical link the sensitivity is only slightly degraded to -37.6dBm (135 photons/bit) by input coupling losses and feedback due to Rayleigh backscattering.

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 input losses, insufficient optical gain to overcome the receiver noise, intersymbol interference (ISI) and excess optical bandwidth. In this paper we investigate the use of a new composite amplifier with integral isolator^{3,4}. The amplifier gives a gain as high as 51dB and a noise figure (NF) of 3.1dB for only 50mW of pump power at 980nm⁴. This high gain allows the potential both to use a 50Ω receiver, thus reducing ISI, and to improve the optical filtering (narrower linewidth, but 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 losses. 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 noise due to Rayleigh backscatter feedback. 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 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 1.536μm wavelength DFB laser is externally-modulated using a LiNbO₃ Mach-Zehnder amplitude modulator⁵ with 11GHz bandwidth. The modulation signal is a non-return-to-zero (NRZ) pseudo-random sequence of length 2¹⁵-1. 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 a Hewlett Packard 8152A optical power meter. An optional 45km length of Corning DSF was fusion spliced onto the amplifier input. This is sufficient for full-amplitude Rayleigh

Figure 1.
Experimental
configuration



backscatter to build up and provide an equivalent reflector at the amplifier input, thus simulating a practical transmission application.

The composite EDFA consisted of an input WDM coupler and two lengths 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 ~ 0.6 dB at the pump wavelength and ~ 2.1 dB at the signal wavelength. The isolation in the reverse direction was ~ 37 dB at the amplifier gain peak of $1.536\mu\text{m}$. 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 $1.536\mu\text{m}$. The total input loss typically measured 0.4dB including the WDM coupler insertion loss (0.17dB) and the loss due to two splices. The amplifier was pumped by a pigtailed 980nm diode which coupled 40mW of power for a 140mA drive current. The amplifier internal gain was ~ 46 dB and NF ~ 3.1 dB.

The amplifier output was optically filtered with a Fabry-Perot filter with a 20GHz passband. 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 (~ 9 dB), but was tolerable because of the high amplifier gain.

The receiver consisted of a pin-diode followed by a 50Ω amplifier and hybrid GaAs FET amplifiers, giving a bandwidth of 8GHz. 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 at this bit-rate. 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 ~ -28 dB) 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, a reduction in noise penalty to only 0.5dB at a BER of 10^{-6} and ~ 0.8 dB 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. 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 ~ 0.6 dB to 3.8dB due to the input reflector. Reducing the 1st stage fibre length can reduce the NF to ~ 3.55 dB (a ~ 0.35 dB 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 due to Rayleigh backscattering. 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/bit¹.

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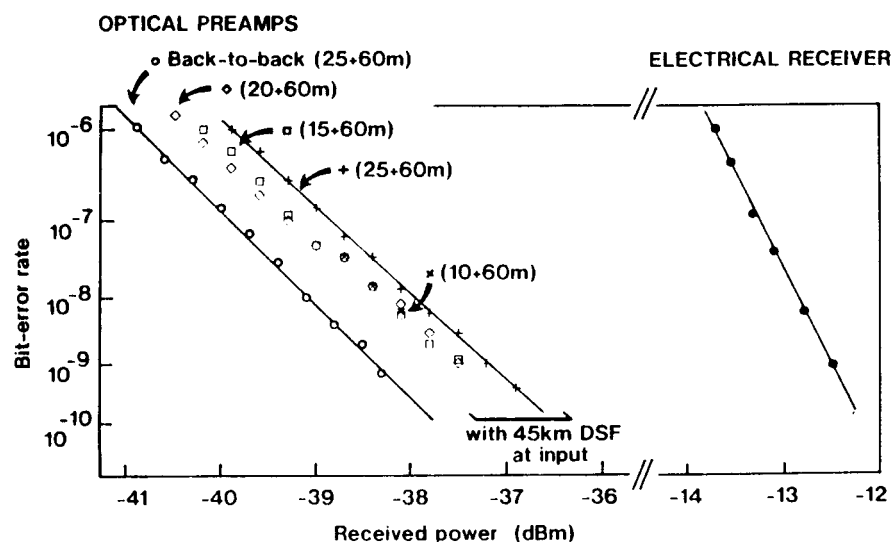


Figure 2. Bit-error-rate curves at 10Gbit/s

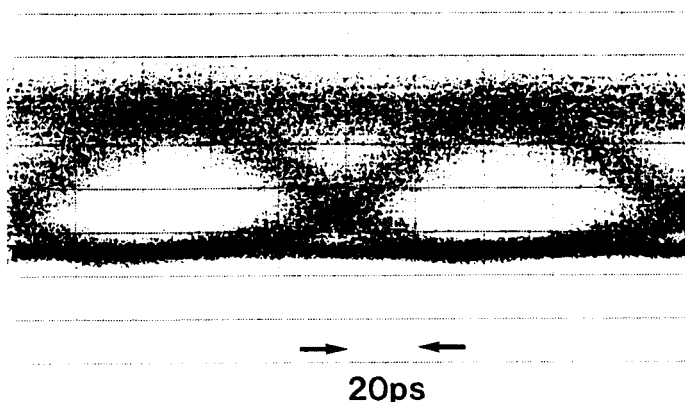


Figure 3. Preamplifier-receiver eye pattern at 10Gbit/s and a bit-error rate of 1×10^{-9}

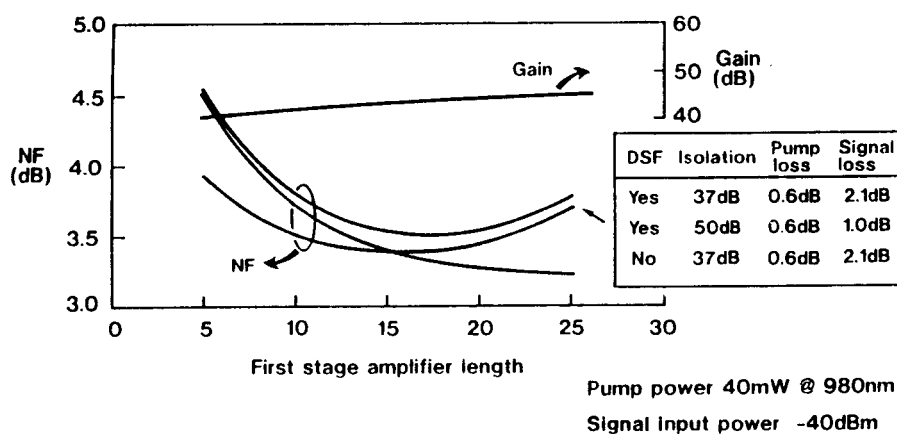


Figure 4. Dependence of composite-EDFA NF and gain on the 1st-stage length with a 60m 2nd-stage length. Predictions are for the amplifier employed (isolator extinction ratio 37dB and insertion loss 2.1dB) with and without DSF and for a new improved amplifier (isolator extinction ratio 50dB and insertion loss 1.0dB).