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# Efficient erbium-doped fibre amplifiers incorporating an optical isolator.

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## ABSTRACT

A composite-EDFA configuration which incorporates an optical isolator has been investigated theoretically and experimentally. The isolator prevents the build-up of the backward-ASE and results in an amplifier with high gain and near-quantum-limited noise figure (NF). The optimum position of the isolator has been calculated as a function of the pump power so that minimum NF and maximum gain are achieved simultaneously. It is shown that under practical pump powers, the optimised composite EDFA exhibits a gain improvement of about 5dB and a NF reduction in excess of 1.5dB when compared with an optimised conventional EDFA. Finally, a high-gain composite EDFA has been experimentally demonstrated which exhibits a gain of 51dB and NF of 3.1dB for only 45mW of pump power.

## I. Introduction.

Erbium-doped Fibre Amplifiers [1] are proving to be components of tremendous importance in a number of optoelectronic applications. This is due to their compatibility with the fibre network, low insertion loss, polarisation insensitivity, high gain levels and near quantum-limited noise performance. In the field of optical communications, EDFAs are expected to be extensively used as pre-, line- and power amplifiers guaranteeing multichannel amplification with insignificant cross-talk, multigigabit transmission rates accompanied by low bit-error rates.

In a well designed system, the maximum gain efficiency should be achieved, i.e. the maximum attainable gain for the lowest pump power. However, in the ordinary EDFA the optimum gain efficiency is always accompanied by a compromise in noise figure to a value well above the quantum limit [2]. This is due to the fact that in an amplifier exhibiting large gain (and associated amplified spontaneous emission (ASE)), the backwards-travelling ASE is comparable to the pump power at the amplifier input and readily saturates the gain, thus reducing the population inversion and increasing the noise figure. In this regime, increasing the pump power always improves the population inversion and decreases the noise figure [3], but at the expense of gain efficiency and pump diode reliability.

In this paper, we present the full analysis as well as experimental results of a composite EDFA configuration which overcomes this problem and results both in amplifiers with increased gain efficiency compared with the basic configuration, as well as a reduced, near quantum-limited noise figure [4-6]. A fibre isolator has been incorporated within the erbium-doped section of the amplifier so that the backward-travelling ASE is extinguished and thus prevented from building-up. The forward-travelling signals (pump, signal and forward-travelling ASE), on the other hand, are transmitted by the isolator and suffer only minor insertion losses. The effect of the extinction ratio and insertion loss of the isolator on the gain efficiency and noise figure is explained and the optimum position of the isolator calculated. Methods of by-passing the optical isolator and thus reducing the pump losses caused by the isolator insertion will also be discussed. The reduced pump requirements under fully optimised conditions are particularly stressed. The advantages of the composite (EDF+Isolator) amplifier are highlighted and applications were the use of this configuration is beneficial are given.

## II. Theoretical model.

In the present analysis, a three-level model is employed, suitable for modelling co-directional pumping with 980nm, which utilizes the effective overlap integral approximation [7]. The forward- and backward-ASE are treated as quasi-monochromatic waves with an equivalent bandwidth $\Delta\nu=600GHz$

(4.5nm) centered at the signal wavelength (1536nm). The aim of this work is to investigate highly efficient amplifier configurations with high total gain and narrow ASE spectrum and, hence, the use of the equivalent-bandwidth approximation is justifiable.

A step-index fibre profile and the corresponding $LP_{01}$ fundamental signal and pump modes were assumed. The effect of the various approximations was estimated by comparing the results of our model with the results of an exact model [8] The discrepancy in the optimum- efficiency calculation between the two models was less than 3.5%. The noise figure was then calculated by using the relation [9] $NF=(2n_{sp}(G\text{-}1)+1)/G$, where $n_{sp}=P_{ASE(+)}/2h\nu\Delta\nu$ is the spontaneous emission factor, $P_{ASE(+)}$ is the forward-travelling ASE for both orthogonal polarisations at the output of the amplifier, $G$ is the net gain, $h$ is Planck's constant and $\nu$ is the signal frequency. Additional parameters employed in the model refer to germano-silicate fiber. They were determined experimentally [10] and are listed in Appendix A.

## III. Composite amplifier.

### *3a. Description and principle of operation.*

The proposed amplifier configuration is shown in Figure 1(a). A commercially-available fibre isolator is incorporated into the erbium-doped segment of the EDFA. The active length now comprises two erbium-doped fibre lengths (EDF#1 and EDF#2) with the isolator spliced in between. A wavelength-division-multiplexing (WDM) coupler is used to launch both the pump and signal into the input section (EDF#1), whereupon it is transmitted via the isolator to EDF#2. The amplifier is pumped in the forward direction, ie. the pump and signal co-propagate. The isolator is designed to transmit the signal, forward ASE and pump wavelengths with low loss (typical values : pump loss < 0.5dB, signal loss < 2.0dB). In Figure 1(b), there is shown an alternative configuration in which the pump power by-passes the isolator in order to eliminate the effect of its loss. Two low-loss WDM fibre couplers (typical loss < 0.1 dB) are utilised to extract the residual pump power (WDM#2) and re-launch it into the erbium-doped fibre (WDM#3).

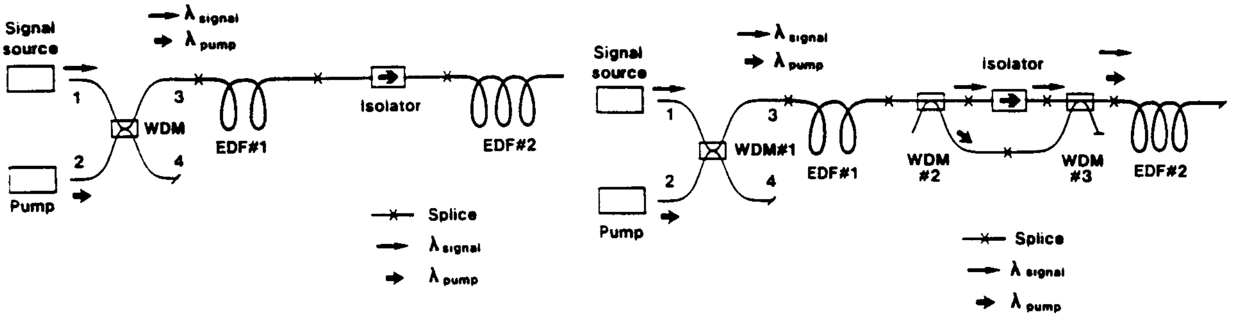

**FIGURE 1:** (*a*) Proposed composite EDFA configuration and (*b*) modified configuration with the pump power by-passing the isolator.

The principle of operation of the proposed configuration is illustrated in Figures 2(a) and (b), where the computed power distribution of the pump, signal, forward and backward ASE along the EDFA length (normalised to the total EDFA length) without and with the isolator are shown. The curves are for a highly-efficient amplifier design operating in the small-signal regime (see Table I). From Figure 2(a), it can be seen that in the case without the isolator the backward ASE grows to a high value (+8 dBm) towards the input end of the amplifier and, therefore, significantly depletes the gain-medium population inversion. In fact, at the input end of the EDFA the pump power is primarily used to amplify the backward-travelling ASE which considerably exceeds the signal. The effect of introducing the isolator is shown in Figure 2(b). The backward ASE at the isolator insertion point suffers a reduction equal to the isolator extinction ratio (ER) and must rebuild from a low value. As a result, the backward ASE is significantly reduced at the input end of the composite EDFA and its effect on the pump depletion much reduced, as evidenced by the fact that the same pump power as in Fig. 2(a) produces a higher signal output power. The pump power retains a high level over a longer EDFA length thus achieving better population inversion over this length. Effectively, a larger proportion of pump photons are transformed into useful signal photons, resulting in higher gain and lower noise figure.

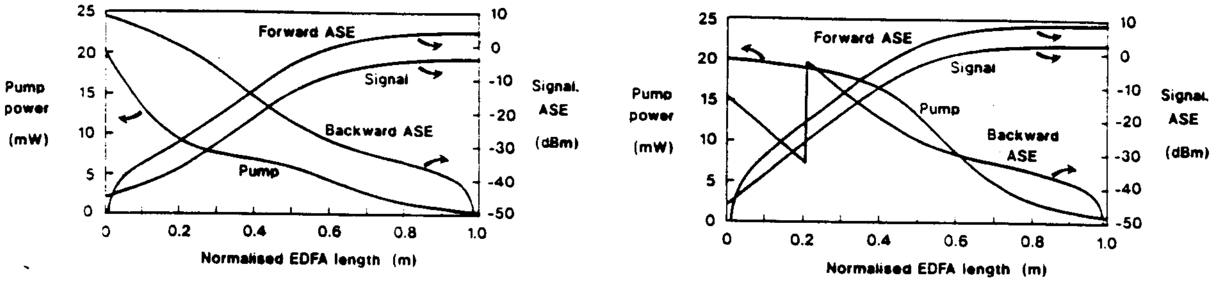

**FIGURE 2:** Signal, pump, forward- and backward-ASE power distribution along fibre length (*a*) without isolator (conventional EDFA), (*b*) with isolator (composite EDFA).

### *3b. Optimum Isolator Position - Optimum range.*

The relative position of the isolator within the amplifier affects the power build-up of all four interdependent waves (signal, pump, forward and backward ASE) and, therefore, has an impact on the gain and noise figure improvement. In Figures 3(a) and (b), typical theoretical predictions of the gain and noise figure are shown, respectively, as a function of the isolator position along the EDFA length (normalised to the optimum total amplifier length), as well as for various isolator extinction ratios (ERs).

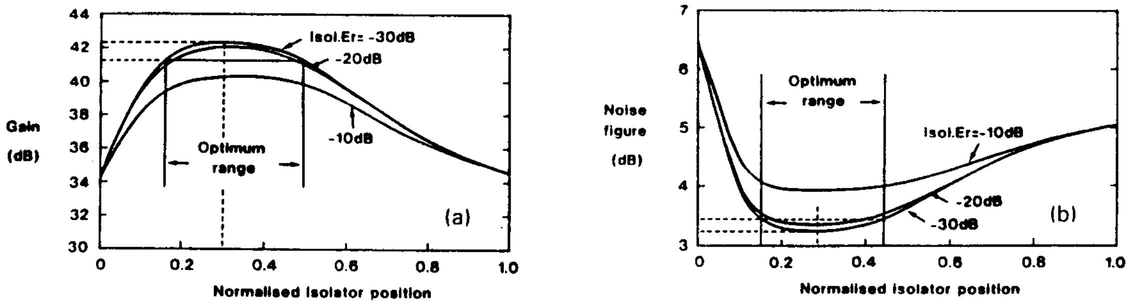

**FIGURE 3:** Gain and noise performance of composite EDFA versus the isolator position, (*a*) Gain, (*b*) NF.

The isolator has a detrimental effect on the gain and noise performance of the composite EDFA when placed towards either end of the fibre length due to its insertion losses. The effect is more pronounced at the input end since both the signal and the pump are attenuated before entering the fibre. In addition, the backward-ASE is fully built-up before exiting the EDFA. At the output end, the deterioration in the performance is less pronounced. Again, the build-up of the backward ASE is unaffected by the presence of the isolator but, in this case, only the signal loss is significant reducing the gain by the same amount. The NF remains unaffected as both the signal and forward ASE suffer approximately the same losses. At this point, the pump loss is of no importance whatsoever. Away from these extremes, a significant improvement of the composite amplifier performance is predicted. Increasing the isolator ER improves considerably the composite-EDFA performance. However, for ERs greater than 30dB the improvement is minor and is not shown in Figures 3(a) and (b). For the parameters shown in Table I and isolator ER of 30dB, the calculated gain increase is ~ 8 dB and the corresponding noise figure decrease ~3.2 dB. The *optimum position* is determined as the position of the isolator where the noise figure attains its lowest value. The optimum isolator position is at about 0.3 of the total EDFA length from the signal-input end.

However, from Figures 3(a) and (b) it is clear that there exist a range of positions (~ ±0.15 of total EDFA length) around the optimum, hereafter called *optimum range*, where the noise figure deviates slightly (by ~ 0.17 dB) from its optimum (minimum) value. Within the optimum range the gain performance is optimised as well. The gain level varies only by ~ 1dB. Thus, the isolator can be placed anywhere within the optimum range with only a minor sacrifice of the absolute optimum performance.

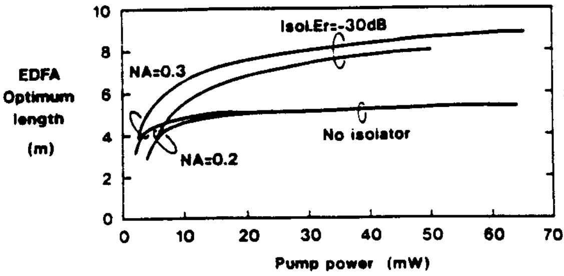

**FIGURE 4:** Optimum EDFA length versus pump power.

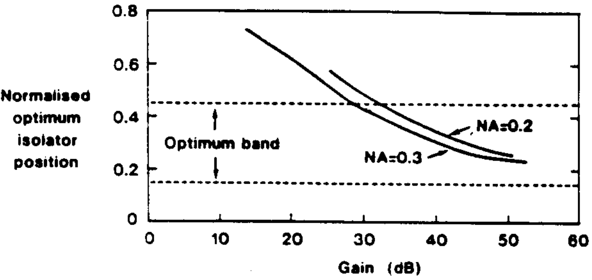

**FIGURE 5:** Normalised optimum isolator position versus Gain.

Under the same pumping conditions, the optimum length ($L_{opt}$) of the composite amplifier (EDFA + Isolator), i.e. the length that gives the maximum gain for a given pump power, is longer than in the case of an amplifier without isolator. In Figure 4, the optimum EDF length is plotted against the pump power, for the case with (composite) and without (conventional) isolator, for the typical values of the EDF fibre and the isolator, shown in Table I. For a fibre NA of 0.3 and pump powers greater than 20mW, an increase of the optimum amplifier length by ~70% is predicted. This is due to the fact that the reduction of the backward ASE renders a large number of pump photons available for absorption. Therefore, a longer fibre length is required for the interaction with the active medium and the energy transfer to signal photons to take place.

The optimum composite-amplifier length and, therefore, the optimum isolator position depend on the input pump power. In Figure 5, the optimum isolator position (normalised to the optimum lengths shown in Figure 4) is plotted as a function of the calculated amplifier gain level. The gain is varied by increasing the input pump power. The optimum range ($\pm 0.15\ L_{opt}$), corresponding to a normalised optimum isolator position of ~0.3, is also shown. It is clear that the optimum isolator position remains well within the optimum band ($0.30 \pm 0.15\ L_{opt}$) and,therefore, the composite EDFA remains always optimised for gains greater than 30 dB. For gain levels below 30 dB, the optimum position of the isolator is found to vary significantly both with the fibre parameters (i.e NA) and the gain level. For gains below 30dB, the optimum isolator position is moved towards the back end of the amplifier. However, as we show later in conjunction with Figures 6 and 7, there is no significant advantage to incorporating an isolator in the amplifier when the gain requirements are relatively low (below about 30 dB for the particular isolator characteristics used here). This gain limit is determined primarily by the extra pump and signal loss introduced by the isolator and varies with the fibre NA (see Figure 8).

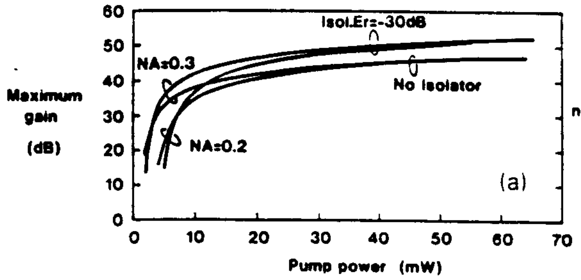

**FIGURE 6:** Maximum net gain versus Pump power, at optimum EDFA length with the isolator at optimum position.

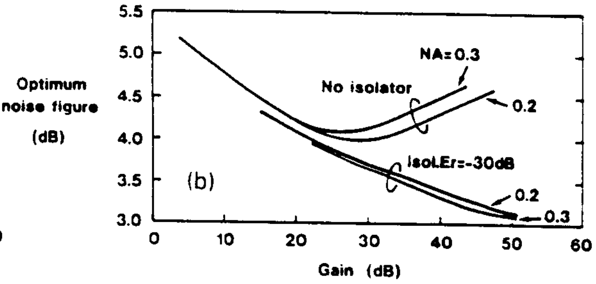

**FIGURE 7:** Noise Figure versus Maximum gain, at optimum EDFA length with the isolator at optimum position (parameters as in Fig.7),

### *3c. Comparison with conventional EDFA.*

The advantages of the optimised composite EDFA amplifier over the conventional one are shown schematically in Figures 6 and 7 where the maximum attainable gain and the accompanying noise figures have been plotted against the pump power and gain, respectively. The two regimes of operation can now be clearly identified. In the low-pump, moderate-gain regime the maximum gain improvement is relatively small and below a certain pump level (in this case corresponding to a gain of ~ 30 dB) there is a deterioration in the gain of the composite amplifier, i.e. incorporating an isolator produces a detrimental effect because of its insertion loss. Apart from a small improvement in the noise performance (as it has already been mentioned, see Figs. 7) there is no significant advantage in using the proposed composite configuration in low-gain applications. The "cross-over" pump power below which no advantage occurs varies with the fibre parameters. In Figure 8, the gain limit above which the use of the proposed composite amplifier configuration is advantageous is plotted against the fibre NA. Above this limit, the maximum attainable gain increases considerably (>5dB) and is accompanied by a dramatic reduction of the noise figure (>1.5 dB) to levels close to the 3-dB quantum limit. Note that if the isolator has no insertion loss there is never a deliterious effect in incorporating it, although the improvements may be minimal. A method of minimising the insertion loss is to by-pass the isolator at the pump wavelength, using WDM couplers, as shown in Figure 1(b). From Figures 6 and 7, it is clear that with the proposed configuration a high gain and quantum-limited noise performance of EDFA amplifiers can be simultaneously achieved. Such a combination of properties is impossible with the conventional EDFA amplifier [2].

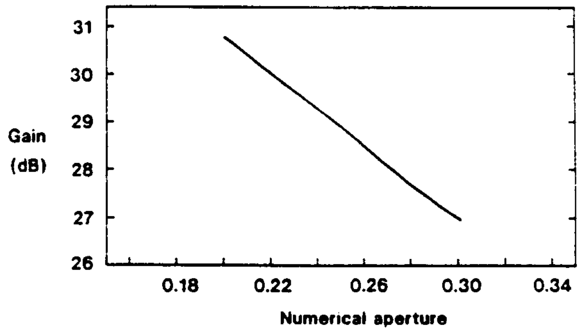

**FIGURE 8:** "Cross-over" gain as a function of the fibre numerical aperture.

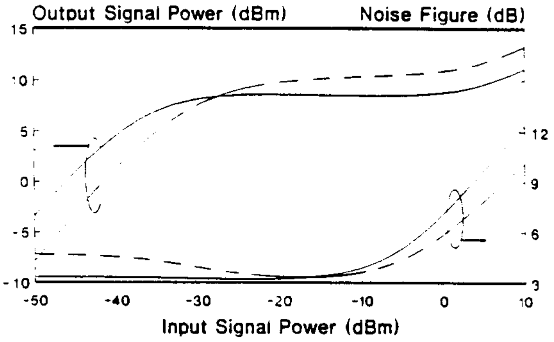

**FIGURE 9:** Input-output characteristics and NF of the composite (solid line) and ordinary (broken line) EDFA of optimum length with pump power of 20mW and fibre NA of 0.3. The rest of the parameters are listed in Table I

In Figure 9, the input-output characteristics and the NF of the composite amplifier (solid line) are compared with the ones of the ordinary EDFA (broken line). The input pump power is 20 mW and the fibre NA is 0.3. The rest of the parameters are listed in Appendix A. In both cases, the fibre length is optimised to give maximum small-signal gain. It is clearly shown that in the small-signal (unsaturated) regime, where the signal is dominated by the ASE, the composite EDFA provides higher output signal powers and lower NF due to the efficient extinction of the backward ASE. In the large-signal (saturated) regime, however, the strong signal dominates the ASE and there is little benefit in introducing an isolator. In addition, the insertion losses of the isolator become significant and result in lower output signal power and higher NF for the composite EDFA. From the results of Figure 9 it is obvious that the composite EDFA is suitable for use as pre-amplifier providing higher output powers and lower NF than the ordinary counterpart. In addition, the saturation characteristics of the the composite EDFA enable it to be used as an optical limiter with high output power over a dynamic range in excess of 30dB [11]. However, a further optimisation of the isolator position is required to improve and extend the dynamic range of the optical limiter.

## IV. Experimental results.

An optimised composite amplifier was built and its performance measured experimentally. The amplifier fibre was characterised by a germano-silicate core, an NA of 0.24, cutoff wavelength of ~920nm and erbium absorption of 0.95dB/m at 1.536$\mu$m. The composite EDFA comprised two fibre lengths of 25m and 60m, respectively, which were separated by a polarisation-independent isolator to suppress the backward-travelling ASE. This corresponds to an normalised isolator position of 0.29 and lies well within the optimum-position range. The isolator insertion loss at the signal wavelength was 1dB. 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 (Figure 1(b)). The resultant forward insertion losses between the two sections of amplifier fibre were $\sim$0.6dB and $\sim$2.1dB at the pump and signal wavelengths, respectively. The isolation in the reverse direction was greater than 30dB over a 50nm bandwidth centred at 1540nm.

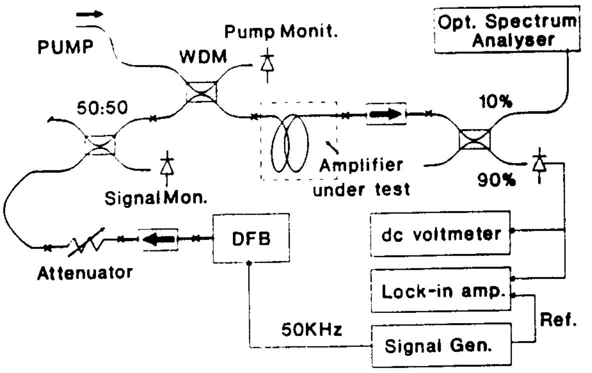

**FIGURE 10:** Experimental set-up for the measurement of gain and noise figure.

The experimental set-up is depicted in Figure 10. Pump light at 980nm from a Ti:sapphire laser and signal light at 1.536$\mu$m from a DFB laser were combined by a WDM coupler and launched into the amplifier. The pump power was monitored at the spare port of the WDM coupler and accurately stabilised via a servo loop. The signal source was modulated at 50kHz to allow accurate discrimination of the amplified signal from the ASE. An attenuator was used to set the average signal input power to a small-signal level to $\sim$-55dBm and one port of a 3dB splitter placed in the signal path was used to monitor it. At the output of the amplifier the signals were passed through an isolator and split with a 90:10 coupler. The 10% port was fed to an optical spectrum analyser and used to determine the ASE spectrum. The output from the 90% port was coupled to a detector where ac and dc measurements gave the amplified signal and ASE, respectively. After the experiment, input and output coupling losses to the amplifier were determined, as well as to the wavelength dependence of the output components. These measurements give the net gain G and ASE spectral density at the signal wavelength, from which the amplifier NF was determined [3] using equations (1) and (2). Care was taken to ensure that backreflections into the amplifier due to splices, launch and other bulk optics were less than -60dB.

Figure 11 shows gain and NF measurements for the composite EDFA. It is shown that gains as high as 54dB with a corresponding NF of 3.1dB can be achieved. The solid line corresponds to the theoretical gain and NF of the composite EDFA. The values of the various parameters used in the model are the same with the experimental ones. An excellent agreement between theory and experiment is observed.

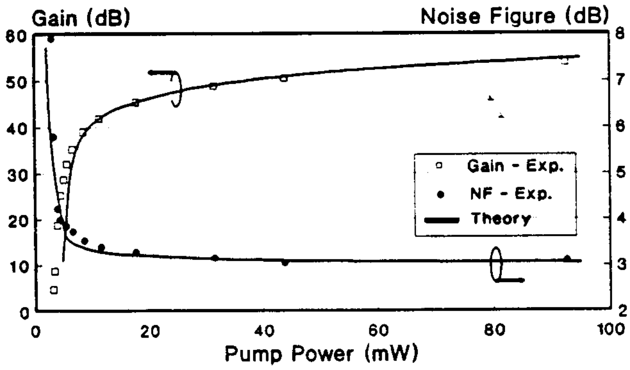

FIGURE 11: Gain and NF measurements for the composite amplifier. First and second stages are 25m and 60m in length respectively. (Solid line: theory).

## V. Discussion.

The results presented so far regarding the gain and NF performance of the composite EDFA amplifier in comparison with the conventional amplifier, can be interpreted in two ways:

a) for the same pump power, a higher gain and lower noise figure are achieved.

b) for the same gain, a lower pump power is required and also results in a lower noise figure. In fact, the pump requirements of the composite amplifier can be reduced by a factor of 2 while, at the same time, the noise is reduced to a value close to its quantum limit (see Figures 6 and 7).

A further advantage of the composite over the conventional EDFA in a practical system which has not been discussed so far is a potential reduction of the insertion loss at the amplifier input and thus an additional improvement of the noise figure by the same amount. When employing high-gain EDFAs in fibre systems as pre-amplifiers, it is usually necessary to incorporate an isolator at the amplifier input to reduce reflections of the backward ASE and its feedback into the amplifier. This reflection is primarily due to Rayleigh backscattering of the backward ASE and for fibre links greater than ~ 40 km can produce an equivalent reflection greater than 0.1% degrading the NF or even resulting in amplifier oscillation. In conventional amplifier designs an isolator is, therefore, included at the input of the amplifier to completely suppress the backward ASE and prevent this feedback. In this location, however, the isolator insertion loss has a deleterious effect on the receiver since it adds to the NF ($NF_{true} = NF_{amp.}$ + Insertion Loss). Relocating the isolator to within the EDFA therefore has the further benefit of removing its insertion loss from the critical amplifier input to a position where it actually improves the NF. The total potential NF improvement can be as high as 2.5dB in a practical EDFA pre-amplifier receiver.

## Conclusions

A composite EDFA configuration has been described which incorporates an optical isolator to suppress the backward ASE. The optimum position and optimum range of the isolator have been calculated and the isolation requirements addressed. The gain and NF characteristics have been estimated and compared with the conventional EDFA. It is shown that the proposed cofiguration can exhibit enhanced gain efficiency accompanied by near-quantum-limited noise performance. The performance degradation in a practical pre-amplifier application is discussed and a design optimisation carried out.

A high-gain composite EDFA has been experimentally demonstrated. The device gives a gain of 51dB and 3.1dB NF for only 45mW of pump power. In contrast, it is shown that it is not possible to simultaneously obtain low noise and high gain from a conventional EDFA using practical pump powers.

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## APPENDIX A

Typical values of the various parameters used in the calculation of the performance characteristics of the proposed composite EDFA.

| | | |
|---|---|---|
| *a)* | *$GeO_2$-$SiO_2$ Fibre parameters.* | |
| | Cut-off wavelength | 870 nm |
| | Signal absorption cross-section | $7.9\times10^{-25}$ m$^2$ |
| | Signal emission cross-section | $6.7\times10^{-25}$ m$^2$ |
| | Pump absorption cross-section | $2.55\times10^{-25}$ m$^2$ |
| | Fluorescence life-time | 12.1 ms |
| | ASE equivalent bandwidth | 4.5 nm |
| | $Er^{+3}$ concentration | $10^{25}$ m$^{-3}$ |
| *b)* | *Isolator parameters.* | |
| | Pump excess loss | 0.5 dB |
| | Signal excess loss | 2.0 dB |
| | Extinction ratio (ER) | 30dB |
| *c)* | Signal wavelength | 1536 nm |
| | Pump wavelength | 980 nm |
| | Input signal power | -45 dBm |

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