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54dB Gain Quantum-Noise-Limited Erbium-Doped Fibre Amplifier

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Abstract

It is shown that for practical pump powers (<100mW) a combination of high gain (>33dB) and low noise figure (3dB) cannot simultaneously be achieved with a conventional co-directionally-pumped EDFA. However, using a composite EDFA incorporating an isolator overcomes the problem and we demonstrate an amplifier with 51dB (54dB) gain and 3.1dB NF for only 45mW (93mW) of pump power.

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Introduction

Erbium doped fibre amplifiers (EDFAs[1]) will be extensively employed in telecommunications networks owing to their compatability with the fibre network, low insertion loss, high gain and low noise figure (NF). It has been predicted theoretically[2] and demonstrated experimentally that the highest gain efficiencies are achieved when Er^{3+} is pumped at 980nm[3,4]. However, it has also been realised theoretically[5] that there is a trade-off between noise and gain efficiency. Under conditions of maximum gain efficiency EDFAs are predicted to exhibit NFs well above the 3dB quantum limit and any attempt to reduce the amplifier NF results in a significant gain-efficiency reduction.

The main limitation to the performance of the EDFA is imposed by amplified spontaneous emission (ASE). In a high-gain, co-propagating scheme backward-travelling ASE acquires high intensity, especially at the input end of the amplifier, thus depleting the pump power and reducing the local population inversion of the active medium. This results in a gain efficiency decrease and NF increase. In fact it is not possible with a single-stage amplifier to simultaneously obtain high gain (> 33dB) and low noise (3dB) operation for practical pump powers. To date all demonstrations of virtually quantum-noise-limited EDFAs have been obtained for gains less than 30dB [6,7]. In the case of high sensitivity optical pre-amplifiers this can be insufficient to overcome the thermal noise of the electrical receiver[7]. Fortunately, it has been shown theoretically[8] that these limitations can be overcome by incorporating an isolator within the amplifier to suppress the backward ASE whilst allowing the pump, ASE and signal to propagate in the forward direction.

In this communication we present measurements of the dependence of gain and NF on pump power for conventional, co-directionally pumped EDFA's as indicated schematically in Figure 1a. Several different amplifier lengths around the optimum are investigated. These confirm that in each case for the pump power giving the optimum gain efficiency the NF is around 4dB. In addition, it is found that for the amplifier having optimum length the NF does not fall below ~4.1dB for practical pump powers (< 100mW). Increasing the fibre length results in an increase in NF. Decreasing the length, on the other hand, results in near quantum-limited NF (3.3dB), but at the expense of gain efficiency and maximum gain. However, the new configuration (Figure 1b) is shown to give a gain of 51dB with a 3.1dB NF for a pump power of only 45mW.

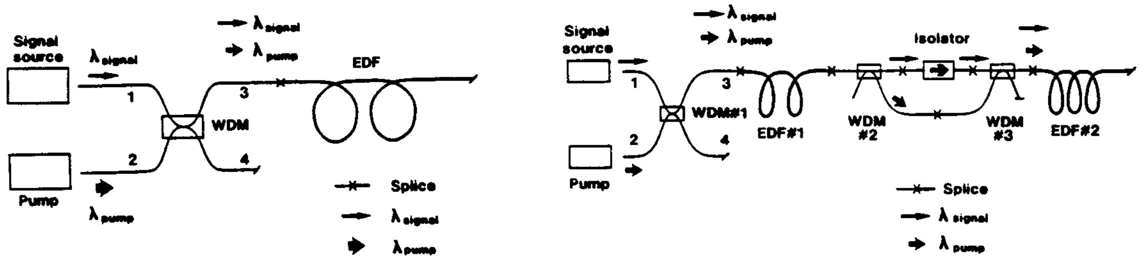

Figure 1 : Schematics of the (a) conventional and (b) new composite EDFA configurations

Experimental

The experimental configuration is indicated schematically in Figure 2. Pump light at 980nm from a Ti:sapphire laser and signal light at 1.536μm from a DFB laser were combined in a WDM coupler and input to the amplifier. The pump power was monitored at the spare port of the WDM 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. The average signal input power was set with the attenuator to a small signal level of ~-55dBm and monitored at one port of the 3dB splitter. 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 and ac and dc measurements gave the amplified signal and ASE. After the experiment, input & output coupling losses to the amplifier were determined, in addition 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.[6]

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 1.536μm. In the case of the conventional EDFA lengths in the range 30-75m were evaluated, whilst for the composite EDFA two fibre lengths were used (25m and 60m), separated by a polarisation-independent isolator (signal insertion loss ldB) 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 (Figure 1(b)). The resultant forward insertion 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 greater than 30dB over a 50nm bandwidth centred at 1540nm.

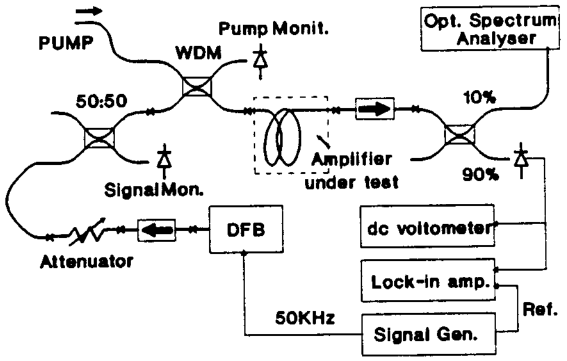

Figure 2 : Experimental configuration

Results

Gain and NF data are plotted in Figures 3(a) and (b) for the conventional amplifier as a function of pump power and amplifier lengths in the range 30 to 75m. The optimum fibre length is found to be 60m, giving a maximum gain efficiency of 6.8dB/mW for a pump power of 3.32mW and gain of 22.6dB. At this optimum gain the NF measured 4.55dB. For pump powers greater than a few mWs it can be seen that the shortest fibre lengths provide the lowest NFs. In the case of the two shortest lengths (30 and 40m) the NF decreases asymtoptically from ~7dB to ~3.3dB with pump power increasing from ~2mW to ~93mW. However, owing to the reduced amplifier length the maximum gain achieved (25-33dB) and the maximum gain efficiency are low. For the optimum fibre length (60m) the NF is again seen to decrease asymtoptically with increasing pump power, although for practical pump powers employed here the minimum NF is ~4.1dB. However, in this case gains as high as 48dB can be achieved for ~93mW of pump power. For fibre lengths in excess of the optimum the NF is first observed to decrease with increasing pump power, to reach a minimum of ~4.2-4.4dB at the pump power which gives the optimum gain efficiency (G~25dB, pump~5mW). Further increasing the pump power results in an NF increase, eventually reaching 4.85dB although at a gain which exceeds that for the optimum length. Thus it is clear that for the conventional design and practical pump powers a combination of high gain (>40dB) and quantum-limited NFs cannot be obtained.

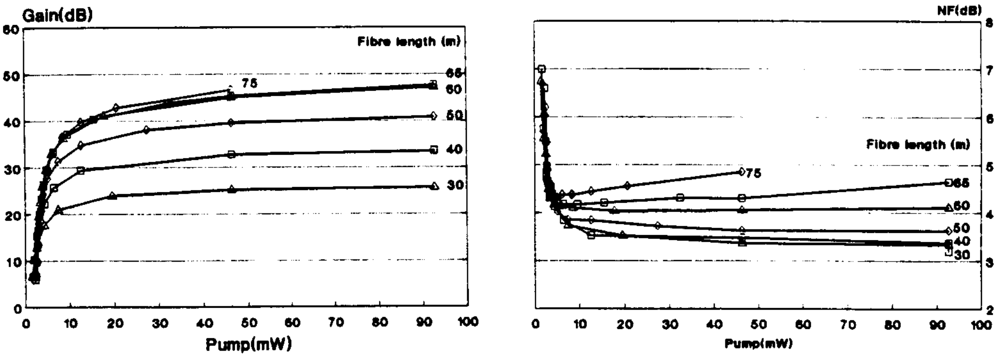

Figure 3 : (a) Gain and (b) NF data for the conventional amplifier as a function of pump power and amplifier lengths in the range 30-75m. The optimum length is 60m.

Figure 4 shows similar gain and NF measurements for the composite EDFA. A marked difference is observed, with gains as high as 54dB and a corresponding NF of 3.1dB. Comparing the two cases, we note that for 45mW of pump power the conventional configuration gives either 46.6dB gain and 4.85dB NF or a 25.2dB gain and 3.36dB NF, whereas the composite EDFA achieves 51dB gain and 3.1dB NF, a very significant improvement.

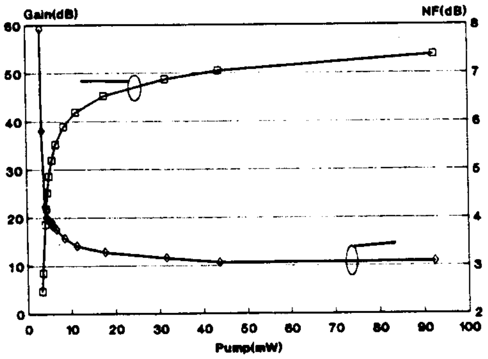

Figure 4 : Gain and NF data for the composite amplifier. First and second stages are 25m and 60m in length respectively.

The input/output characteristics of the composite (60m) and conventional EDFA are compared in Figure 5 where it is seen that no significant decrease in output power arises from the insertion losses of the isolator. Further, it can be seen that for the highest pump power gains in excess of 49dB can be obtained for input signals as large as -39dBm, corresponding to 100 photons/bit at 10Gbits^{-1}. This confirms the usefullness of the device as an optical pre-amplifier at a wide range of bit rates. For higher input signals the device behaves as an optical limiter[9].

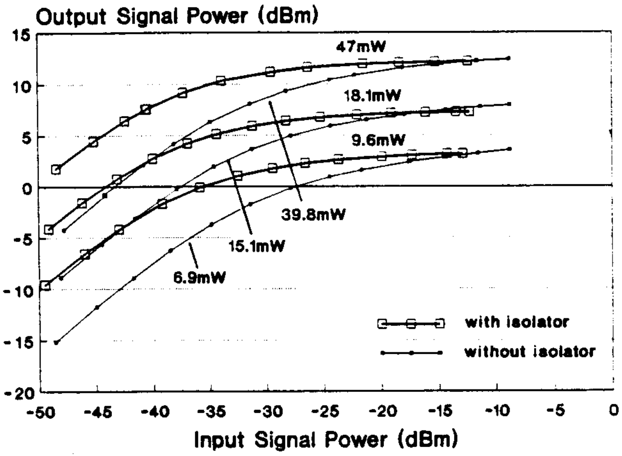

Figure 5 : Comparison of the input/output characteristics of the conventional (60m) and composite (25m+60m) amplifiers.

Conclusions

A high-gain composite EDFA incorporating an isolator has been 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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