Erbium-Doped Fiber Amplifier with 54 dB Gain and 3.1 dB Noise Figure

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

THE erbium-doped fiber amplifier [1] (EDFA) will be extensively employed in telecommunications networks owing to its compatibility with the fiber 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 980 nm [3], [4]. However, it has also been realized theoretically [5] that there is a tradeoff between noise and gain efficiency. Under conditions of maximum gain efficiency EDFA's are predicted to exhibit NF's well above the 3 dB 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, copropagating scheme, backward-traveling 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 (> 33 dB) and low noise (3 dB) operation for practical pump powers. To date all demonstrations of virtually quantum-noise-limited EDFA's have been obtained for gains less than 30 dB [6]–[8]. In the case of high-sensitivity optical preamplifiers this can be insufficient to overcome the thermal noise of the electrical receiver [7]. Fortunately, it has been realized [9], [10] that these limitations can be overcome by incorporating an isolator within the amplifier to suppress the backward ASE while allowing the pump, ASE, and signal to propagate in the forward direction.

In this letter, we compare experimentally the gain and noise characteristics of conventional codirectionally pumped EDFA's [6], [8] and the new codirectionally pumped composite EDFA incorporating an isolator (Fig. 1). In the case of the conventional amplifier it is shown that for practical pump powers (< 100 mW) a combination of high gain (> 33 dB) and low noise cannot be achieved. However, the composite EDFA is shown to alleviate these problems and, in the high-gain region, gain increases up to 5 dB are obtained for the same pump power and are accompanied by near quantum-limited NF's. These observations are in agreement with theoretical predictions [9].

The experimental configuration is indicated schematically in Fig. 2. Pump light at 980 nm from a Ti:sapphire laser and signal light at 1.536 μm from a DFB laser were combined in a WDM coupler and fed to 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 50 kHz 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 ~ −55 dBm and monitored at one port of a 3 dB splitter placed in the signal path. 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 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], [11]. Care was taken to ensure that backreflections into the amplifier due to the launch and diagnostic optics were less than −60 dB.2

The amplifier fiber was characterized by a germano-silicate core, an NA of 0.24, cutoff wavelength of ~ 920 nm, and erbium absorption of 0.95 dB/m at 1.536 μm. In the case of the conventional EDFA, lengths in the range 30–75 m were evaluated, while for the optimised composite EDFA two fiber lengths were used [9] (25 and 60 m), separated by a polarization-independent isolator (signal insertion loss 1 dB) to suppress the backward-traveling ASE. Since the isolator has a very high loss at the pump
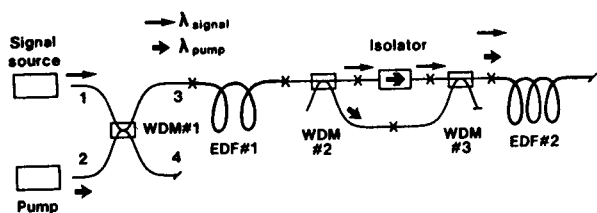
Fig. 1. Schematics of the composite EDFA configuration.

Fig. 2. Experimental configuration.

Fig. 3. (a) Gain and (b) NF measurements for the conventional amplifier as a function of pump power and amplifier lengths in the range 30–75 m. The optimum length for best gain efficiency is 60 m.
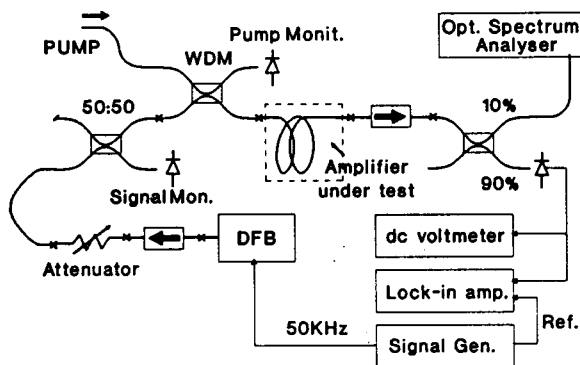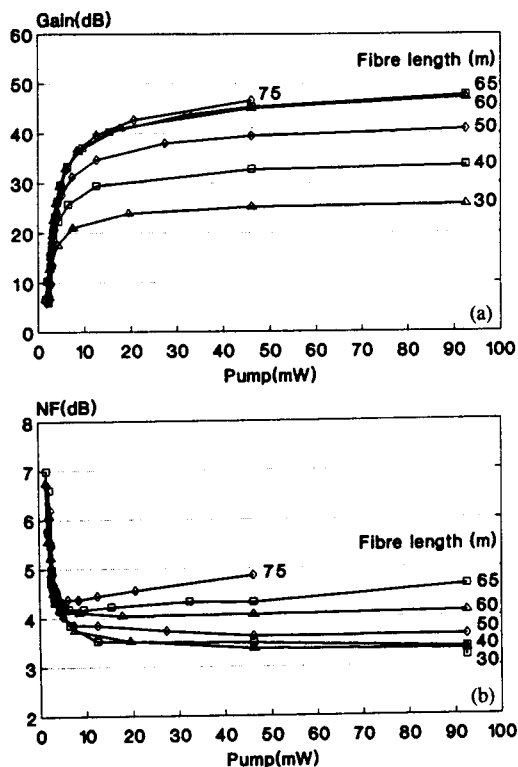
wavelength, two WDM couplers with insertion losses at the pump/signal wavelengths of 0.11/0.31 dB and 0.16/0.31 dB were included to provide a low-loss bypass for the pump (Fig. 1). The resultant forward insertion losses between the two sections of amplifier fiber were ~ 0.6 dB at the pump wavelength and ~ 2.1 dB at the signal wavelength. The isolation in the reverse direction was greater than 30 dB over a 50 nm bandwidth centered at 1540 nm.

Gain and NF data are plotted in Fig. 3(a) and (b) for the conventional amplifier as a function of pump power and for amplifier lengths in the range 30–75 m. The optimum fiber length was found to be 60 m, at which a maximum gain efficiency of 6.8 dB/mW for a pump power of 3.32 mW and gain of 22.6 dB was measured. At this optimum gain the NF was 4.55 dB. For pump powers greater than a few milliwatts it can be seen that the shortest fiber lengths provide the lowest NF's, at the expense of gain efficiency. In the case of the two shortest lengths (30 and 40 m), the NF decreases asymptotically from ~ 7 to ~ 3.3 dB as the pump power increase from ~ 2 to ~ 93 mW. However, owing to the reduced amplifier length the maximum gain achieved (25–33 dB) and the maximum gain efficiency are low.

For the optimum fiber length (60 m) the NF initially decreases with increasing pump power to a value around ~ 4.1 dB where it appears clamped for the range of practical pump powers employed here. In this case, gains as high as 48 dB can be achieved for ~ 93 mW of pump power. However, even at the optimum length standard models [5], [9] predict the NF to reduce with increasing pump power, with a value of 3.52 dB being anticipated for a pump power of 100 mW. The observed discrepancy

(~ 0.6 dB at 100 mW) arises from effective input and output mirrors of ~ −55 dB due to internal Rayleigh backscattering [12]–[14]. We have measured a scatter coefficient of −62 dB/m at 1.53 μm for a Nd^{3+}-doped fiber of similar composition, NA and λ_{cutoff} which is consistent with this result. Increasing the erbium concentration to allow a reduction in amplifier length would reduce, but not erradicate the effect. Alternatively, a lower NA fiber with reduced backscatter capture fraction could be employed [15]; however, in this case the gain efficiency would be reduced.

For fiber lengths in excess of the optimum the NF is first observed to decrease with increasing pump power and to reach a minimum of ~ 4.2–4.4 dB at the pump power which gives the optimum gain efficiency ($G \sim 25$ dB, pump ~ 5 mW). Further increasing the pump power results in a NF increase, eventually reaching 4.85 dB, although at a gain which exceeds that for the optimum length. This behavior is due to the increased backward ASE in these cases. Thus, it is clear that for the conventional design and practical pump powers a combination of high gain (> 40 dB) and quantum-limited NF cannot be obtained.

Fig. 4 shows similar gain and NF measurements for the composite EDFA. A marked difference is observed. It is now possible to obtain gains as high as 54 dB with a corresponding NF of 3.1 dB. Comparing the two cases, we note that for 45 mW of pump power the 75 m length conventional EDFA gives a high gain of 46.6 dB and NF
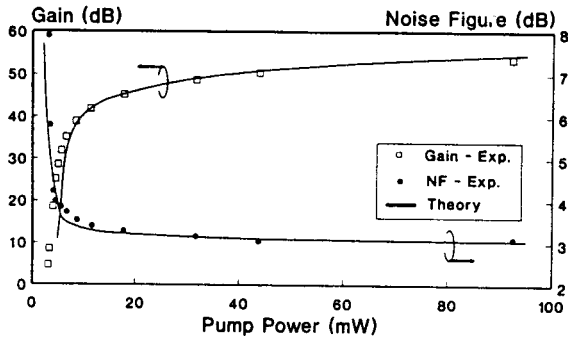
Fig. 4. Gain and NF measurements for the composite amplifier. First and second stages are 25 and 60 m in length, respectively. (Solid line: theory.)
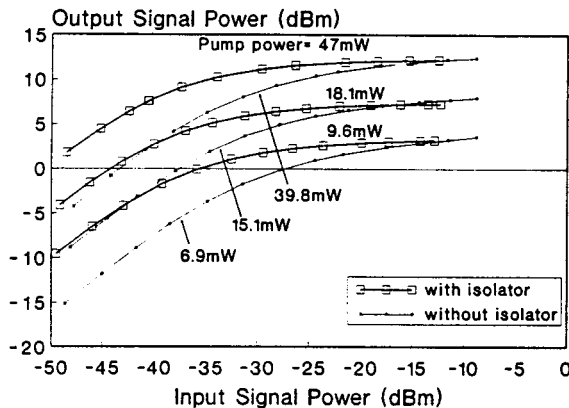

Fig. 5. Comparison of the input/output characteristics of the 60 m-length conventional and (25 m + 60 m)-length composite amplifiers.

of 4.85 dB while to reduce the NF to about 3.36 dB requires a suboptimal length of 30 m resulting in a moderate gain of 25.2 dB and corresponding gain-efficiency reduction. On the other hand, for the same pump power the composite EDFA achieves a combination of 51 dB gain and 3.1 dB NF, which represents a very significant improvement. The solid lines of Fig. 4 are theoretical predictions [9] of the gain and NF employing parameters representative of the experiment and are in excellent agreement with the experimental data.

The input/output characteristics of the 25 m + 60 m length composite amplifier and the 60 m length conventional EDFA are compared for similar pump powers in Fig. 5. 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, although decreased due to saturation, gains in excess of 47 dB can be obtained for input signals as large as −39 dBm, corresponding to 100 photons/bit at 10 Gb/s [16]. This confirms the usefulness of the device as an optical preamplifier at a wide range of bit rates. For higher input signals the device behaves as an optical limiter [17].

In conclusion, a high-gain codirectionally pumped composite EDFA incorporating an isolator has been experimentally demonstrated. The device gives a gain of 51 dB and 3.1 dB NF for only 45 mW 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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