Characterisation and modelling of the noise figure (NF) of a praseodymium doped fibre amplifier (PDFA)

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An experimental assessment of the gain and noise characteristics of a praseodymium doped fibre amplifier (PDFA) is presented. The experimental data was used to validate a spatially and spectrally resolved amplifier model. The influence of the applied pumping scheme (co-, counter- or bi-directional) obtained from the Amplified Spontaneous Emission (ASE) spectrum on the internal gain and noise figure is shown. The wavelength dependence of both gain and noise figure are well predicted by the amplifier model.
Furthermore, the application of the bi-directional pumped PDFA as an optical preamplifier in the receiver is evaluated. The receiver sensitivity improvement is 15 dB. The noise figure directly derived from the system experiments is 9 dB.

Introduction

Recently, Praseodymium Doped Fibre Amplifiers (PDFAs), operating at 1.3 μm, have become commercially available. An amplifier model can be used to study amplifier operation and optimise the design of PDFAs [1]. The governing equations for the spatially and spectrally resolved amplifier model used in this study were taken from Karasek [2]. In the simulations the numerical solver developed by van Osch [3] was used. The amplifier noise analysis presented here is based on the work of Olsson [4]. The cross-section data and fibre geometry provided by the manufacturer of the Pr-doped fibe modules were taken as input data. In this study, the experimentally determined gain and noise characteristics are compared with results obtained from an amplifier model.

Device characterisation

The performance of the PDFA is described by its gain G and noise figure F, which is defined as the ratio between the beat-noise limited input Signal-to-Noise Ratio (SNR_{in}) and the signal-spontaneous beat-noise limited output Signal-to-Noise Ratio (SNR_{out}).

$$F = \frac{SNR_{in}}{SNR_{out}} = \frac{2}{h\nu RB}\frac{P_{sp}}{G} \tag{1}$$

A tuneable laser source and a variable attenuator were used to generate the test signals. The interpolation-substraction technique was used to determine the gain (G) and the Amplified Spontaneous Emission (ASE) power (P_{sp}) at the optical frequency (ν) from Optical Spectrum Analyser (OSA) data with Resolution Bandwidth (RB).
The noise figure of the PDFA, used as a pre-amplifier in a direct detection system, is given by

$$F = \frac{SNR_{in}}{SNR_{out}} = \left[\frac{\alpha\eta}{\eta_{in}^2}\left(\frac{\eta_{in}GP_s + P_{sp}}{G^2P_s\eta_{out}} + \frac{2\eta_{in}P_{sp}}{Gh\nu B_o} + \frac{(B_o - \frac{1}{2}B_e)P_s^2}{G^2P_sh\nu B_o^2}\right)\right] \tag{2}$$

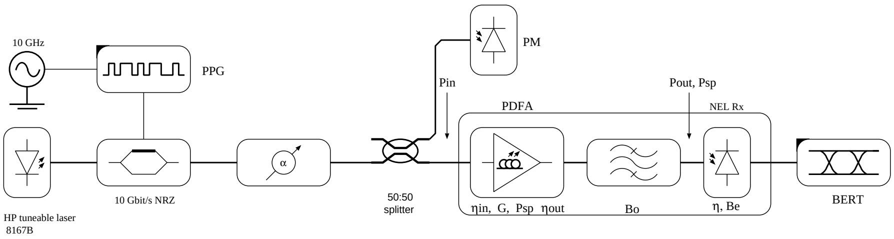

Figure 1: Set-up for PDFA pre-amplified receiver sensitivity determination.

where the SNR_{in} is the signal-to-noise ratio at the input of the PDFA and SNR_{out} is the signal-to-noise ratio at the amplifier output. In order to reduce the spontaneous noise contributions, both optical and electrical filtering is applied at the receiver. The electrical bandwidth and the optical bandwidth of the (pre-amplified) receiver are B_e and B_o respectively. The noise figure is calculated using a signal without the presence of spontaneous emission originating from the source (shot noise limited). In equation 2, the contributions of shot noise, signal-spontaneous beat noise and spontaneous-spontaneous beat noise are taken into account according to [4].

The noise figure (according to equation 2) can also derived directly from system experiments, using the relations between the BER and Q-factor [4]. In Figure 1, the set-up for the experimental assessment of the PDFA as a optical pre-amplifier is shown. The optical receiver (NEL) has a sensitivity of approximately -15 dBm at 10 Gbit/s and provides clock and data regeneration. The electrical bandwidth B_e is 7.5 GHz. Between the PDFA pre-amplifier and the photo detector a bandpass filter B_o has been placed in order to reduce the spontaneous beat-noise components. Sensitivity measurements were performed with a $2^{31}-1$ PRBS, NRZ data pattern. The PDFA was operated in a bi-directional pumping scheme. An optical isolator was applied at the amplifier output. An input isolator, indispensable for optimal system performance, was omitted because of the impact on the noise figure due to the 1.0 dB extra loss.

Results and discussion

In order to compare the gain and noise figure for different amplifier configurations, only the active fibre within the PDFA is considered. Hence, these internal gain and noise figure are independent of input and output losses. In Figure 2 the internal gain and noise figures of the PDFA in different pumping configurations and two lengths (7 m and 14 m) are shown. Figure 2a, c, and e depict the experimentally obtained (internal) gain and noise figure (using equation 1) for a test signal power of -30 dBm. The noise figure increases with increasing signal wavelength due to ground state absorption.
The simulated gain and noise figure (according to equation 2) is shown in Figure 2b, d, and f. In the simulations the electrical bandwidth B_e was 100 MHz and the optical bandwidth B_o was 1 nm or 18.5 GHz. Under these conditions, the noise figure is dominated by signal spontaneous beat noise (second term of equation 2) and can be compared with the experimental noise figure. For all configurations, the trends in wavelength dependence of both gain and noise figure are well predicted by the amplifier model.

Table 1: Receiver sensitivity & noise figure

λ [nm]	B_o [nm]	G [dB]	Sensitivity [dBm]	Preamp Sens. [dBm]	Δ [dB]	F [dB]
1290	1.0	18.4	-14.5	-30.5	16	8.5
1300	1.0	21.1	-15.0	-30.0	15	8.8
1310	1.0	19.9	-15.0	-30.0	15	9.6
1320	1.0	17.2	-15.0	-28.0	13	10.1

The noise figure is strongly dependent on the population inversion within the amplifier. In the experiments, the amplifier was weakly pumped (no complete inversion) and the co-propagating scheme resulted in the lowest noise figure. For small signals, the gain of the amplifier in co-propagating and counter-propagating schemes is comparable.
The 3 dB bandwidth of the bi-directional pumped PDFA (with both input and output isolators) is approximately 40 nm centred around 1305 nm. At 1300 nm, the fibre-to-fibre gain (not shown) is 22 dB and the fibre-to-fibre noise figure (not shown) is approx. 11 dB.

The results of the sensitivity measurements are summarised in Table 1. The small signal gain of the experimental bi-directional pumped PDFA is approximately 20 dB. The sensitivity (at BER = 10^{-9}) of the system with PDFA pre-amplifier (without input isolator) is approximately -30 dBm, which means a 15 dB improvement. A noise figure of 9 dB was directly derived from these system experiments using a 1 nm optical bandpass filter. This noise figure includes signal/pump WDM and coupling losses at the amplifier input.

Conclusions

The influence of the applied pumping scheme (co-, counter- or bi-directional) on the internal gain and noise figure is shown. The wavelength dependence of both gain and noise figure are well predicted by the amplifier model.
The maximum fibre-to-fibre gain of the experimental bidirectional pumped PDFA is approximately 22 dB, the corresponding noise figure is 11 dB. The application of this PDFA as an optical preamplifier in the receiver is evaluated. The receiver sensitivity improvement is 15 dB. The noise figure, directly derived from the system experiments, is 9 dB.

Acknowledgements

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References

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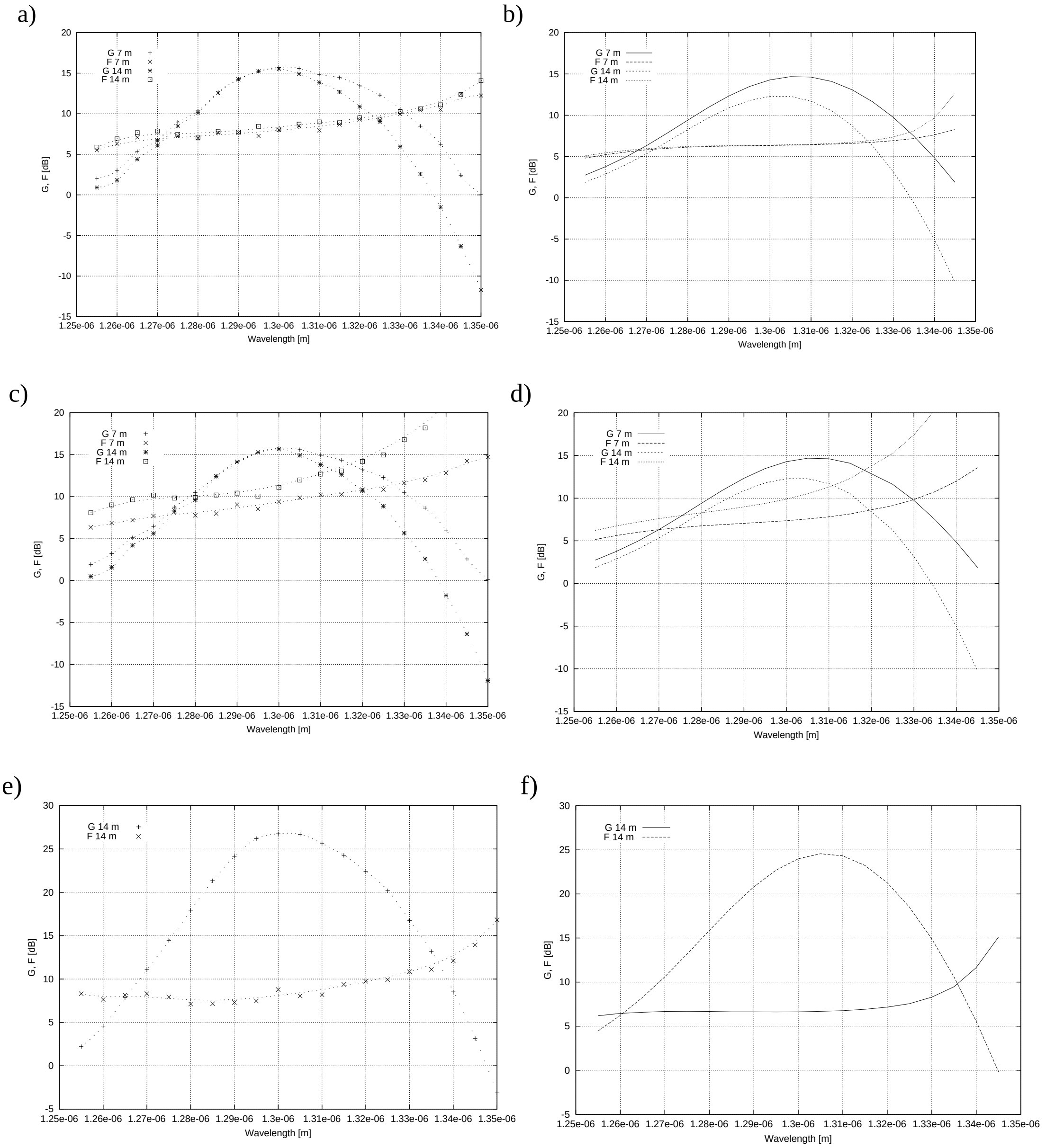

Figure 2: Measured and simulated signal gain (G) and noise figure (F) vs wavelength. a,b: co-propagating pumping scheme, 300 mW pump power; c,d: counter-propagating pumping scheme, 300 mW pump power; d,e: bi-directional pump configuration 500 mW pump power. The test signal power is -30 dBm.