Characterisation and modelling of praseodymium doped fibre amplifiers

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A 1300 nm praseodymium doped fibre amplifier (PDFA) was set-up using commercially available praseodymium doped fibre modules and an ytterbium doped fibre laser operating at 1030 nm. CW measurements were performed to characterize the amplifier behaviour, mainly focussing on different doped fibre lengths and pump source configurations. The experimental data was used to validate a spatially and spectrally resolved amplifier model. The simulated data is in close agreement with the measured values. The influence of the applied pumping scheme (co-, and counter-directional) on the gain and noise (amplified spontaneous emission, ASE) is discussed.

Introduction

As the currently most favourite 1.5 μm window faces its capacity limits, the opening of a new window is highly desirable to accommodate the exponentially growth in demand for transmission bandwidth (Internet). Recently praseodymium doped fibre amplifiers (PDFAs), based on fluoride glasses and operating at 1.3 μm, have become commercially available. Our current research in PDFAs is focussed on increasing the gain efficiency of the device in order to reduce the high optical pump powers needed and the dynamic system performance of these amplifiers [1,2].

An amplifier model can be used to study amplifier operation and optimise the design of PDFAs. A spatially and spectrally resolved four-level model has been used to study the properties of a praseodymium doped fibre amplifier based on commercially available modules. The model inputs are fibre geometry and material properties (absorption and emission data, which can be obtained form bulk glass samples). In this study, such amplifier model is used in the characterisation of an experimental PDFA.

Model for the praseodymium doped fibre amplifier

The governing equations for the spatially and spectrally resolved amplifier model used in this study were taken from Karasek [3]. The model is based on the steady state rate equation for the population of the metastable level of Pr, as well as the propagation equations for pump and signal power, and amplified spontaneous emission.

The transitions included in the model are pump ground state absorption, signal ground state absorption, signal emission, signal excited state absorption and spontaneous emission (see figure 2). In the simulations the numerical solver developed by van Osch [4] was used. The cross section data and fibre geometry provided by the manufacturer of the Pr-doped modules were taken as input data.

Experimental set-up

The experimental set-up for co propagating pump configuration is shown in figure 1. The CW signals are generated by a combination of tuneable laser source and an optical attenuator. An ytterbium fibre laser operating at 1030 nm is used as pump source. The signal and pump powers are combined in a 1030/1300 WDM, which is connected to Pr-doped fibre modules. Each Pr-doped fibre module contains 7 m, 1000 ppm Pr doped In-based fluoride fibre between the two silica fibre pigtails.

At the PDFA output the amplified signal, including amplified spontaneous emission (ASE) noise was observed. All signal powers were measured using an optical spectrum analyser (OSA). The applied pump power was monitored using a power meter directly connected to the second WDM output.

Also the behaviour of the amplifier in counter-propagating pump configuration was investigated

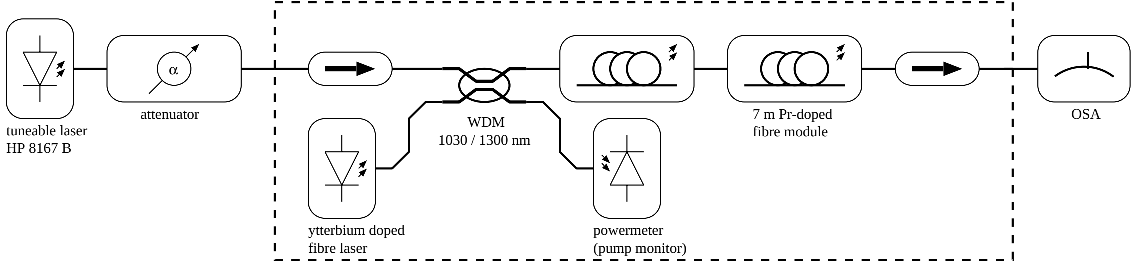

Figure 1. Experimental set-up. PDFA co-propagating pumping scheme incorporating 2 x 7m active fibre

Experimental validation of the amplifier model

The data obtained from the amplifier model can be validated with experimental data. As the model only considers the active fibre section, the experimental data must be compensated for all power losses at both active fibre input and output. In the current set-up proper compensation for coupling losses, mode mismatches (due to different fibre types), and component losses is difficult. At the signal wavelength the compensation introduces an uncertainty of around 0.7 dB for the amplifier input and 0.4 dB for the output (co-propagating pump scheme). For the pump power an inaccuracy of 0.4 dB is expected. When applying 300 mW, this can introduce a worst-case deviation of 50 mW.

Due to signal ground state absorption, the fibre loss is wavelength dependent. In figure 3 measured and simulated total doped fibre loss are plotted versus signal wavelength (no pump power applied). The coupling of two 7 m Pr-doped fibre modules introduces additional splicing and mode conversion losses. In the simulations these extra losses were not taken into account.

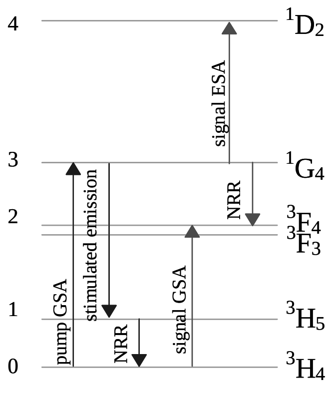

Figure 2. Simplified Energy level diagram for Praseodymium

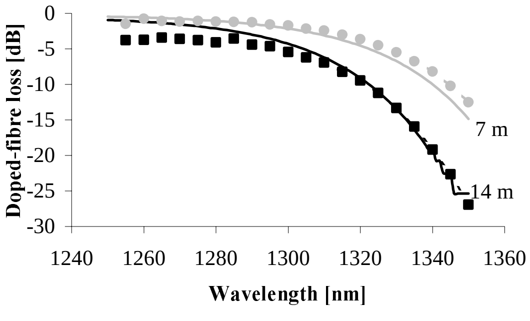

Figure 3. Doped-fibre loss when no pump power is applied with 7 m (grey) and 14 m (black) of fibre and a signal power of –30 dBm. Solid lines represent simulated and dashed lines experimental results

Figure 4 depicts the small signal gain spectrum as a function of applied pump power. At low pump powers, the effect of ground state absorption (at higher wavelengths) becomes more distinct due to poor inversion. In the 14 m case, the applied pump power is not sufficient to overcome the additional losses, resulting in reduced gain. Similar results were obtained for moderate and large (approx. 0 dBm) signal input powers.

At large signal input powers the amplifier gain saturates, see figure 5. The experimental amplifier tends to saturate at lower signal powers than predicted by the amplifier model.

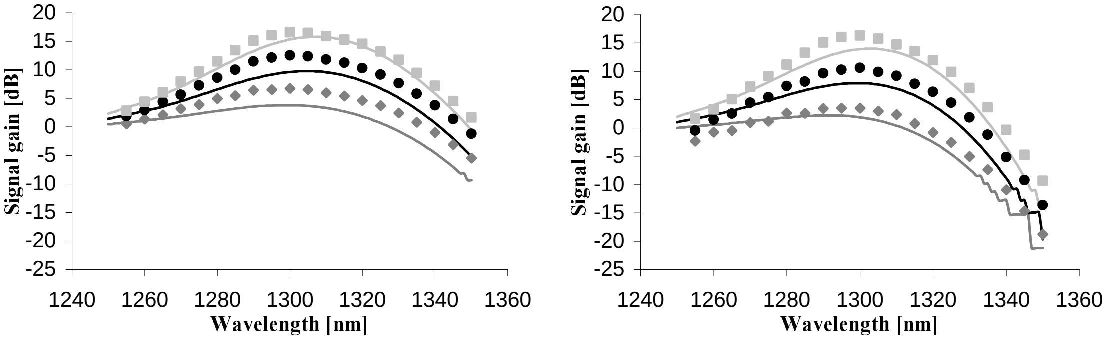

Figure 4: Small signal gain spectrum for co-propagating pump with 100 mW (◆), 200 mW (●) and 300 mW (■) of pump power. Signal power is –40 dBm. Left side is 7 m and right side 14 m of fibre. Solid lines represent simulated and markers experimental values.

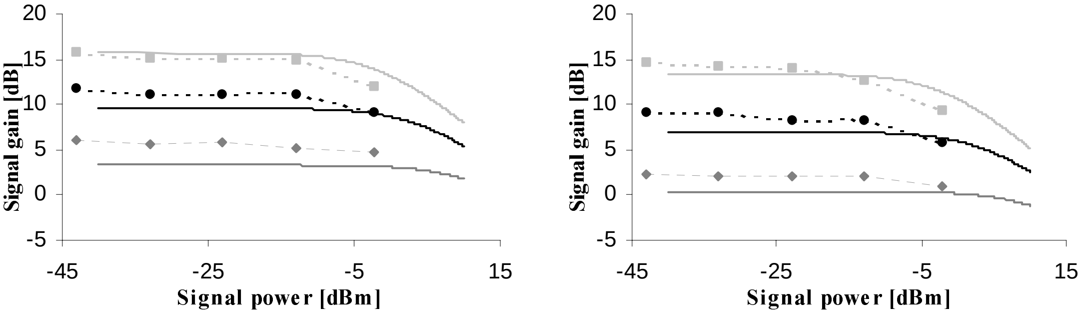

Figure 5: Gain versus signal power for co-propagating pump with 100 mW (◆), 200 mW (●) and 300 mW (■) of pump power. Signal wavelength is 1310 nm. Left side is 7 m and right side 14 m of fibre. Solid lines represent simulated data and markers (connected by dashed lines) represent experimental data.

Effects of pump configuration.

The small signal fibre net gain versus pump power is shown in figure 6. At high pump powers the counter-pumping scheme will lead to slightly higher gain values. The pump power efficiency is approx. 0.09 dB/mW.

The measured wavelength dependent small signal gain (-40 dBm) and the difference between ASE contribution for co- and counter propagating pumping scheme is depicted in figure 7. Due to the increased fibre losses, 300 mW pump power is not sufficient to pump 14 m of fibre, resulting in a decreased gain, particularly at the higher wavelengths. The 3 dB gain bandwidth is over 30 nm centred around 1300 nm for the 7 m amplifier. The differences in the shape of the ASE spectra can be assigned to the effect of incomplete population inversion. When pumping in co-propagating direction there is only complete inversion at the fibre input. Due to the ground state absorption at the fibre's end, this will result in larger losses at higher wavelengths.

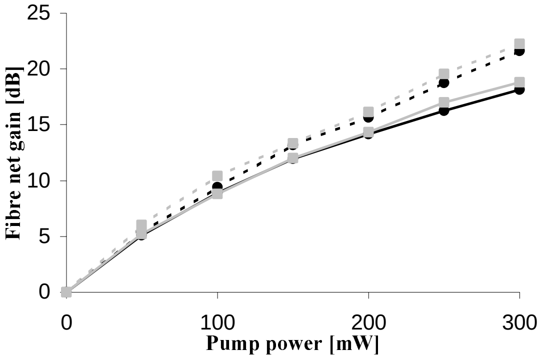

Figure 6: Small signal gain (-40 dBm, 1310 nm) with co- (●) and counter- (■) directional pump power of 300 mW. Solid lines represent 7 m and dashed lines 14 m of doped fibre.

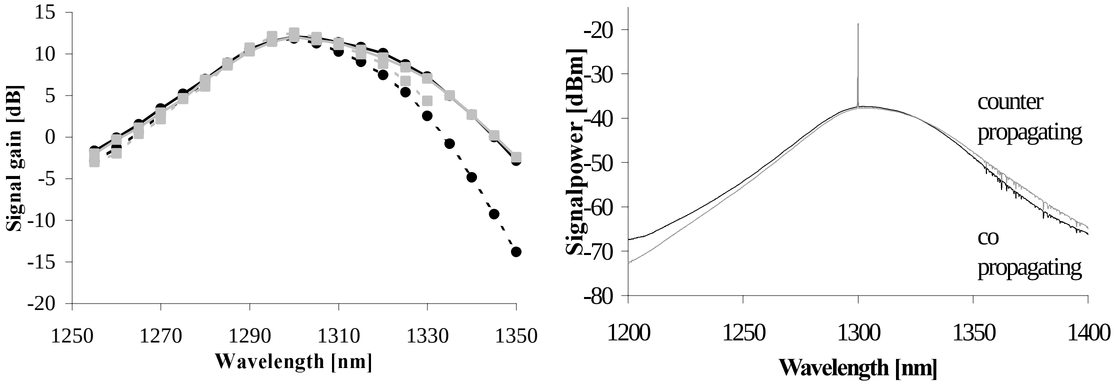

Figure 7. Small signal gain (-40 dBm) with co- (●) and counter- (■) directional pump power of 300 mW. Solid lines represent 7 m and dashed lines 14 m of doped fibre. Typical output spectra for co- and counter propagating pump powers with 7 m of fibre. Signal power –30 dBm at 1300 nm.

Conclusions

CW measurements were performed to characterize the amplifier behaviour, mainly focussing on different doped fibre lengths and pump source configurations. The experimental data was used to validate a spatially and spectrally resolved amplifier model. The simulated data is in agreement with the measured values.

Acknowledgements

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