European Conference on Optical Communication (ECOC) 2022 © Optica Publishing Group 2022

Extending L-Band Gain to 1625 nm Using Er^{3+}:Yb^{3+} Co-Doped Silica Fibre Pumped by 1480 nm Laser Diodes

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Abstract *We report a high-concentration Er-Yb co-doped phospho-alumino-silicate fibre providing 18.4±3.9dB multi-channel gain with 5.8dB average NF from 1570-1616nm. At 1616nm, the gain was 19.3dB at 20°C and 25.3dB at -60°C, with a -0.065dB/°C temperature-dependent-gain coefficient. Also, a 10dB single-channel small-signal gain was obtained at 1625nm. ©2022 The Author(s)*

Introduction

The erbium (Er)-doped fibre amplifier (EDFA) was developed in the L-band for a wider data transmission bandwidth in the second lowest-loss wavelength band of optical fibre communication, with a challenge of overcoming the signal excited-state absorption (SESA) effect at wavelengths beyond 1610 nm. One effective and direct way is investigating novel co-dopants in the erbium-doped fibre (EDF) to suppress the SESA for extending the bandwidth in the L-band [1,2]. It was reported that phosphorus (P) co-doped silica EDF redshifted the L-band gain profile [3-5]. Another attractive development was the high Er^{3+} concentration in EDF, contributing to a reduced fibre length of the amplifier, thus decreasing the non-linearity and the amplified spontaneous emission (ASE) level. However, a highly doped EDF has a higher possibility of the Er ion clustering, leading to the concentration quenching and up-conversion processes [6]. Several effective co-dopants were required to improve the Er ion solubility with less clustering effect, such as aluminium (Al), lanthanum (La), and ytterbium (Yb) [7,8]. However, there are very few reports concerning the Yb-sensitized highly Er-doped L-band EDFA extending to a longer wavelength of 1625 nm.

In this paper, we report in-house fabricated Yb-sensitized high-Er doped phospho-alumino-silicate fibre (EYDF) suffering less from the Er concentration quenching and SESA. The gain and noise figure (NF) characteristics were studied using single- and multi-channel input signal sources. An 18.4±3.9 dB multi-channel gain was obtained from 1570 to 1616 nm, with a 19.3 dB gain at 1616 nm at room temperature (RT, ~20 °C). The temperature-dependent gain performance was studied from -60 to 80 °C, reaching 25.3 dB gain at 1616 nm at -60 °C. At 1625 nm, a 10 dB single-channel small-signal gain was obtained at RT. Also, the gain coefficient and the gain saturation were studied.

L-band Yb-sensitised EDFA using 1480 nm pump diodes

Er-doped preforms were fabricated using the modified chemical vapour deposition (MCVD) and solution doping technique, where a P-SiO2 soot layer was soaked in solutions containing Er, Yb, and Al chlorides. By engineering the co-doping level of Yb, P, and Al, one highly Er-doped preform was fabricated and drawn into a fibre with an index difference (Δn) between the core and cladding of 0.015 and with an LP_{11} cutoff wavelength of 1091 nm. The inset of Fig. 1 shows the small-signal absorption coefficient spectrum measured using the white light source (WLS) and the cutback method. The Er absorption peak appeared at 1535.2 nm with a high absorption coefficient of 77 dB/m. The small-signal absorption at the wavelength of 1480 nm was 21.6 dB/m. Then, the absorption coefficient variation as a function of the launched power at 1480 nm was measured using the 1480 nm laser diode (LD) and the cutback method of a short piece of fibre. As shown in Fig 1, the absorption coefficient decreased and flattened out when the launched power was high enough to saturate the fibre. The unsaturable loss (UL) was ~11%,

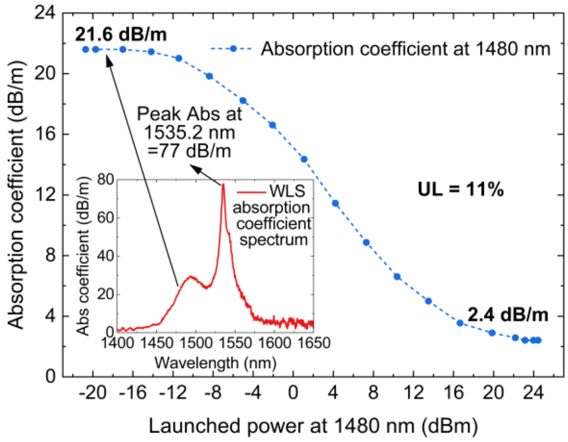

Fig. 1: The absorption coefficient variation with the launched power at 1480 nm, where the inset shows the small-signal absorption coefficient spectrum measured by the WLS.

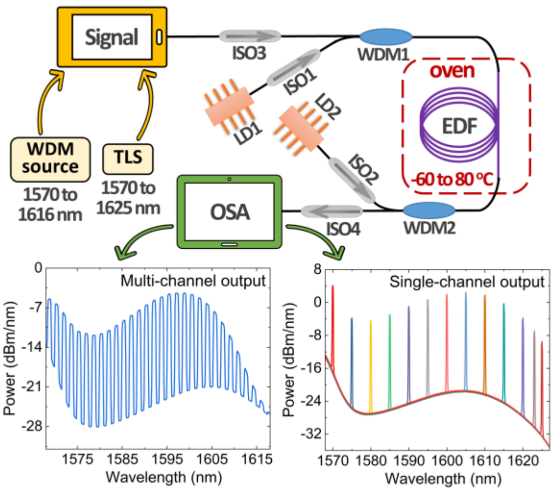

Fig. 2: Schematic of the experimental setup for the L-band EDFA. Multi- and single-channel signal output spectra.

calculated as the fraction of the unsaturable absorption coefficient (2.4 dB/m) to the small-signal absorption coefficient (21.6 dB/m) [9].

The experimental setup of the L-band amplifier was illustrated in Fig. 2. One wavelength division multiplexed (WDM) source was used to provide a 28-channel input signal from 1570 to 1616 nm, with a channel bandwidth of 0.7 nm and a channel spacing of 1.6 nm. The total input signal power was -11 dBm with an average of -25 dBm in each channel. Due to the upper wavelength limit with good flatness and optical signal to noise ratio (OSNR) of the WDM source, we can only reach up to 1616 nm for the multi-channel signal. To evaluate the amplifier performance covering a wider bandwidth in the L-band, a tunable laser source (TLS) was used to provide the single-channel signal from 1570 to 1625 nm. Two LDs provided the bi-directional pumps at 1480 nm, to directly pump Er^{3+} ions to the $^4I_{13/2}$ energy level, which does not overlap with any absorption bands of Yb^{3+} ions. The total available power from the two LDs was 811 mW (forward 404.7 mW and backward 406.3 mW).

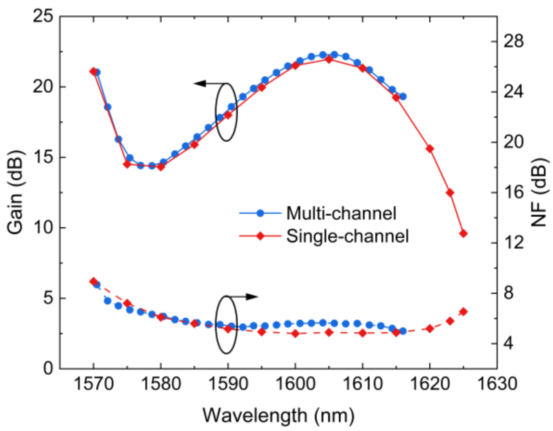

Fig. 3: The gain and NF spectra for 18 m of EYDF using 811 mW of pump power at 1480 nm for the multi-channel and single-channel input signals, respectively.

Isolators (ISOs) were used to avoid back reflections. Two wavelength division multiplexers (WDMs) were used to separate and couple the signal and pumps. The input and output signal spectra were captured by an optical spectrum analyser (OSA: AQ6370, YOKOGAWA). To characterise the temperature performance, an oven was used to control the environmental temperature of the EYDF from -60 to 80 ºC.

We first measured the multi-channel signal gain and NF using the optimised fibre length of 18 m, as shown in Fig. 3. The gain was 18.4±3.9 dB with 5.8 dB average NF from 1570 to 1616 nm. A <6 dB NF over the 34 nm bandwidth from 1582 nm to 1616 nm was obtained, with a higher NF at shorter wavelengths due to the strong C-band ASE effect. At 1616 nm, a gain of 19.3 dB and a NF of 5 dB were achieved. To match the average power in each channel of the multi-channel signal, the single-channel input signal power was set as -25 dBm from 1570 to 1625 nm. As Fig. 3 shows, there exhibited a well-matching gain spectrum overlap between the two signal sources, indicating that our single-channel gain performance can represent the multi-channel

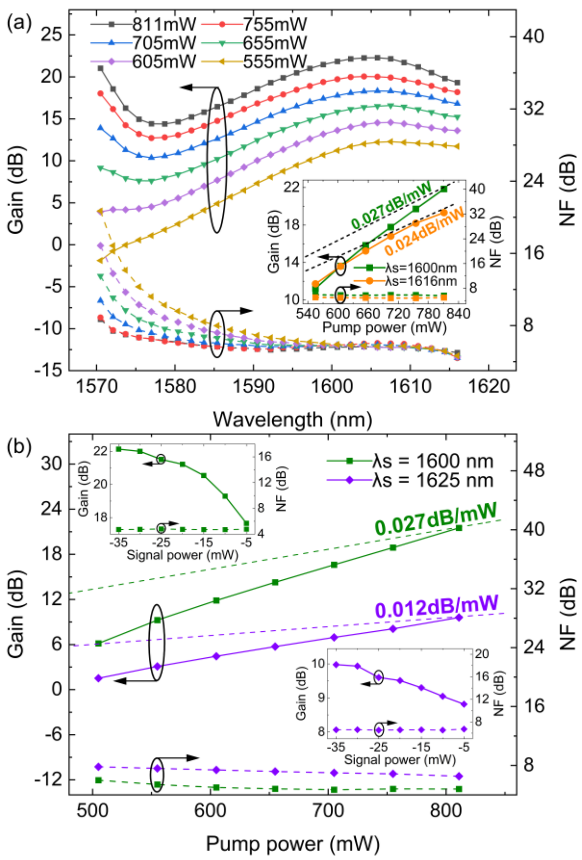

Fig. 4: (a)The multi-channel gain and NF spectra using different pump powers, where the inset shows the gain and NF variation at 1600 and 1616 nm. The slope of the dashed line which intersects the origin was illustrated. (b)The single-channel gain and NF variation with the pump power at 1600 and 1625 nm, where the insets show the gain and NF variation with the TLS signal power at 1600 and 1625nm.

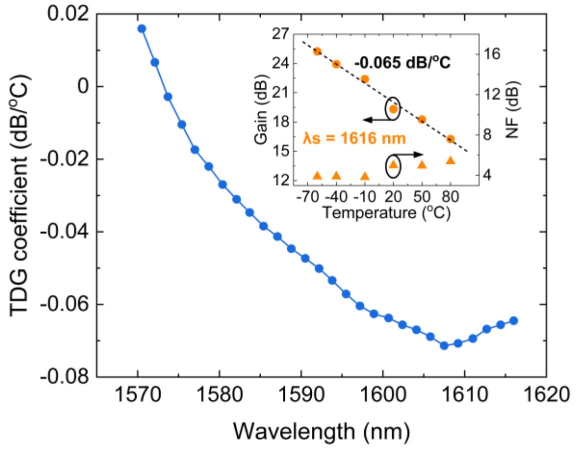

Fig. 5: The temperature-dependent gain coefficient spectrum for the multi-channel signal, where the inset shows the gain and NF variation with the temperature at 1616 nm.

gain performance. A 9.6 dB single-channel gain with a 26.9 dB OSNR was obtained at 1625 nm. In the range from 1580 to 1623 nm, the NF was <6 dB, with a 6.5 dB NF at 1625 nm.

Next, we measured the multi-channel gain and NF variation with the pump power, as shown in Fig. 4(a). The gain coefficient, defined as the highest gain-to-pump power ratio, was 0.024 dB/mW at 1616 nm. At 1600 nm, the gain coefficient was expected to be >0.027 dB/mW, as the current maximum pump power was not high enough to obtain the gain coefficient. Similarly, we measured the single-channel gain and NF with an input signal power of -25 dBm using different pump powers. At 1600 nm, the gain coefficient was >0.027 dB/mW as well. The gain coefficient was >0.012 dB/mW at 1625 nm, as shown in Fig. 4(b). Then, we measured the single-channel gain and NF variation with the TLS input signal power increasing from -35 dBm to -5 dBm. At 1600 nm, the gain increased as the signal power decreased, with a 22.2 dB gain and 4.7 dB NF for a signal power of -35 dBm. The saturation signal power was ~ -10 dBm. At 1625 nm, the gain and NF exhibited a much less variation with the signal power, exhibiting a 10 dB small-signal gain with a 6.5 dB NF.

Furthermore, we measured the temperature dependence of the multi-channel gain and NF from -60 to 80 °C. Fig. 5 shows the temperature-dependent gain (TDG) coefficient defined as the slope of the linear regression fitting curve between the gain and the temperature. Beyond 1573 nm, the gain increased as the temperature decreased. At 1616 nm, the TDG coefficient was -0.065 dB/°C. As a result, a 25.3 dB gain with a 3.9 dB NF was obtained at 1616 nm at -60 °C.

Conclusions

In summary, a high concentration Yb-sensitized Er-doped fibre was fabricated and characterised for L-band amplifier up to 1625 nm using 1480 nm pumps. By tailoring the glass composition, the Er quenching was controlled at an insignificant level and the gain profile was beneficial for the extended L-band operation. At 1616 nm, the gain was 19.3 dB with 5 dB NF at RT and improved to 25.3 dB with 3.9 dB NF at -60 °C. At 1625 nm, a 10 dB single-channel small-signal gain with a 6.5 dB NF was obtained at RT, for the signal power of -35 dBm. To the best of our knowledge, our study reported a higher Er concentration in EYDF for L-band amplifiers covering a longer wavelength up to 1625 nm.

Acknowledgements

The data for this work can be accessed at https://doi.org/10.5258/SOTON/D2202.

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