Extending L-Band Gain to 1628 nm Using Phospho-Alumino-Silicate Erbium-Doped Fibre Pumped by 1480 nm Laser Diodes

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Abstract *We demonstrate phospho-alumino-silicate erbium-doped fibres for an extended L-band amplification to 1628nm, achieving 13.3dB gain and 8.6dB NF at 1628nm, and >20dB gain with <6.9dB NF from 1580-1625nm. At 1625nm, the gain coefficient and the saturated output power were 0.024dB/mW and 15dBm, respectively. ©2023 The Author(s)*

Introduction
There is an increasing demand from the telecom industry for the use of optical fibre amplifiers operating in the extended L-band after exhausting the C-band and common L-band of the conventional erbium-doped fibre amplifiers (EDFAs). Beyond 1610 nm, the gain limitation of EDFA is mainly contributed by the signal-induced excited-state absorption (ESA), determining the upper operating wavelength of the amplifier [1]. Also, a much longer device length is required to balance the population inversion and amplified spontaneous emission (ASE) to favour the L-band amplification [2]. It, however, induces higher propagation loss, lower efficiency, and nonlinearities [3].

With a strong glass composition dependency, the spectroscopic characteristics of the EDFs determine the amplification capacity in the desired waveband. It was reported that the tellurite and antimony-silicate glass EDFs red-shifted the ESA to extend the L-band gain [1,4]. Bismuth and erbium co-doped high (50 mol%) germane-silicate fibres were investigated for C+L+U-band amplification [5]. However, the above non-silica glass fibres are often challenging to satisfy the commercial telecommunication applications, e.g., the splicing and handling problems. Therefore, phospho-alumino-silicate glass fibres are preferable to develop L-band EDFAs, with improved Er ion solubility in the glass matrix, broadened emission spectrum, and red-shifted ESA [6-9]. A double-pass EDFA using phospho-silicate EDF was demonstrated from 1565-1625 nm [10]. Er/Yb/P- and Er/Yb/P/Al- co-doped silica fibres were reported to extend the gain to 1625 nm [11,12]. Single- and multi-mode hybrid pumped EDFA based on the Yb/Er phospho-silicate glass was proposed to cover from 1575-1626 nm [13].

In this paper, we report for the first time, to the best of our knowledge, phospho-alumino-silicate EDFs for extending the L-band gain to 1628 nm, using a single-stage, single-pass amplifier configuration by pumping at 1480 nm. The gain and noise figure (NF) characteristics from 1580-1628 nm were studied at different pump powers and signal powers. By engineering the glass compositions, EDFs with a P-to-Al mass ratio of ~1.8 were found to be a good candidate for extended L-band amplification. The EDFA was demonstrated using 85 m of 'EDF-a' to achieve 13.3 dB gain with 8.6 dB NF at 1628 nm, with negligible gain variations with the input signal power. From 1580-1625 nm, >20 dB gain with <6.9 dB NF was obtained. With a higher Er concentration, 'EDF-b' exhibited a reduced device length of 40 m but a lower gain, with no degradation on the NF or gain flatness.

L-band EDFA Using 1480 nm Laser Diodes
Several Er-doped phospho-alumino-silicate preforms were fabricated in-house by the modified chemical vapour deposition (MCVD) and solution doping method. Then, the preforms were drawn into fibres for the characterisations on the extended L-band amplification. Two fibres were selected to demonstrate the L-band EDFAs, with a core/cladding diameter of ~9.7/125 μm for EDF-a and ~10.2/135 μm for EDF-b. The numerical aperture (NA) was 0.11 and 0.10 for EDF-a and EDF-b, respectively. Two fibres had a similar P-to-Al mass ratio in the core, which was ~1.8 for EDF-a and ~1.7 for EDF-b measured from an electron probe analyser (EPMA). The small-signal absorption at 1480 nm pump wavelength was 5.8 dB/m for EDF-a and 9.8 dB/m for EDF-b. EDF-b was designed with more Er incorporation, thus having an unsaturable absorption at 1480 nm of 0.48 dB/m, which was ~4.9% of the total small-signal absorption [14].

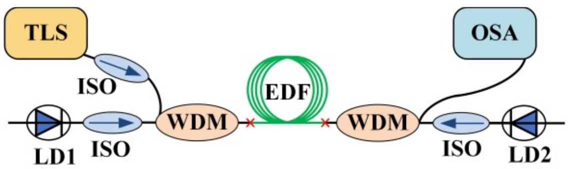

Fig. 1: Schematic of the L-band EDFA experimental setup.

For EDF-a, the unsaturable absorption was 0.23 dB/m, which was ~3.9% of the total small-signal absorption. The background loss was measured to be 0.029 dB/m for EDF-a and 0.036 dB/m for EDF-b.

Fig. 1 shows the experimental setup for the L-band EDFA, including a tunable laser source (TLS) operating from 1580 to 1628 nm as the signal source, two fibre pigtailed laser diodes (LDs) at 1480 nm as the pumps, two wavelength division multiplexers (WDMs) to combine or separate the signal and pump wavelengths, and three isolators (ISOs) to protect the components from the back reflections. An optical spectrum analyser (OSA, Yokogawa-AQ6370) was used to measure the input and output spectra using a resolution bandwidth of 0.2 nm. The total launched pump power was 950 mW, with 500 mW from LD1 and 450 mW from LD2. The signal power was set to -25 dBm.

First, we measured the gain and NF spectra for two EDFs, respectively, as Fig. 2 shows. The device length was optimised with respect to the amplification extended to 1628 nm, which was 85 m for EDF-a and 40 m for EDF-b. From 1580-1625 nm, the EDF-a achieved >20 dB gain with <6.9 dB NF. At 1628 nm, the EDF-a had a 13.3 dB gain with 8.6 dB NF. Maximum 31 dB gain with 4.9 dB NF was achieved at 1605 and 1610 nm for EDF-a. With more Er in the core, EDF-b had a shortened device length but the overall gain was ~3 dB lower than EDF-a, mainly due to its higher unsaturable absorption. EDF-b exhibited an 11.3 dB gain and 8.5 dB NF at 1628 nm, with >17 dB gain and <6.8 dB NF from 1580-1625 nm. There is no influence on the NF of EDF-b, and the gain maintains good flatness.

Next, we measured the gain and NF variations with the pump power, as Fig. 3 (a) and (b) show. The gain coefficients were calculated as the slope of the tangent to the gain-to-pump power curve that intersects the origin. As illustrated in

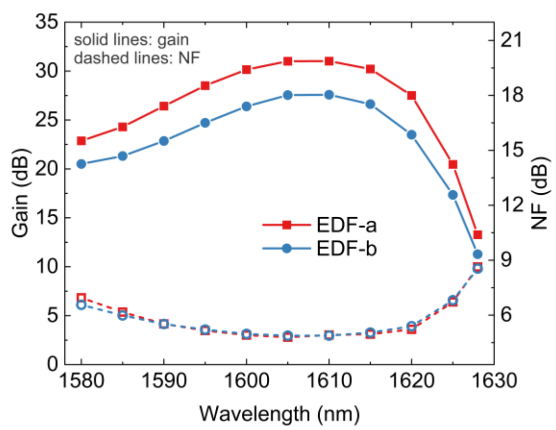

Fig. 2: The gain and NF spectra for 85 m of EDF-a and 40 m of EDF-b, respectively, using 950 mW of the total pump power at 1480 nm and -25 dBm of the input signal power.

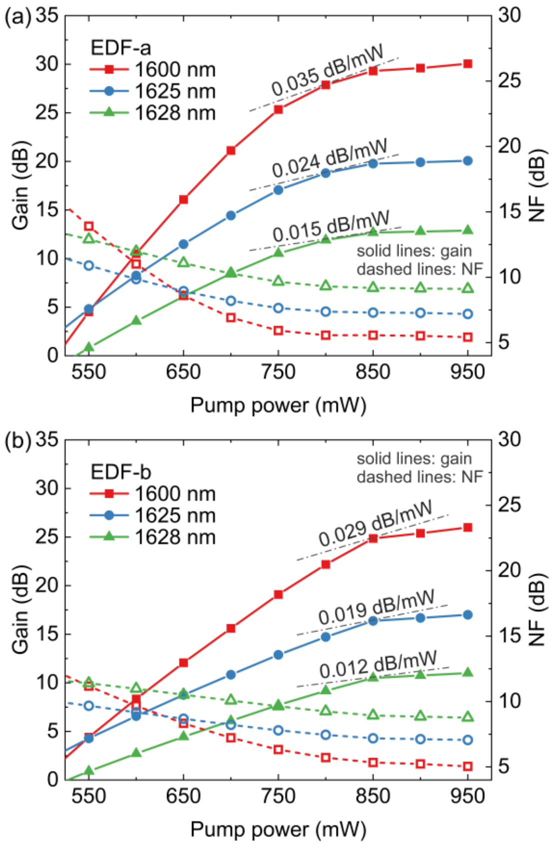

Fig. 3: The gain and NF variations with the pump power at 1600 nm, 1625 nm, 1628 nm for (a) EDF-a and (b) EDF-b.

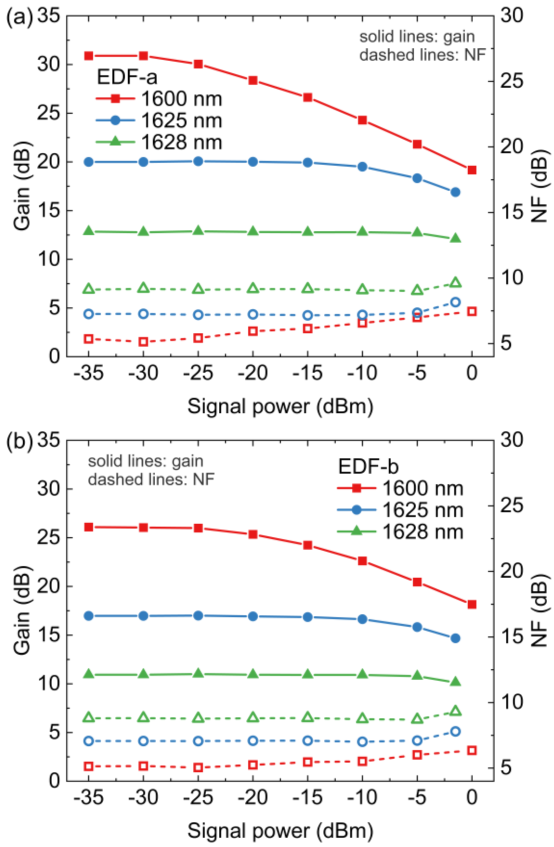

Fig. 4: The gain and NF variations with the signal power at 1600 nm, 1625 nm, 1628 nm for (a) EDF-a and (b) EDF-b.

the graphs, we obtained a lower gain coefficient from EDF-a to EDF-b. For EDF-a, the gain coefficient was 0.035 dB/mW at 1600 nm, 0.024 dB/mW at 1625 nm, and 0.015 dB/mW at 1628 nm. For EDF-b, the gain coefficient was 0.029 dB/mW at 1600 nm, 0.019 dB/mW at 1625 nm, and 0.012 dB/mW at 1628 nm. Then, we measured the gain and NF variations with the signal power, as Fig. 4 (a) and (b) show. The saturated output power was calculated as the output signal power where the gain was 3 dB lower than the small-signal gain. At 1600 nm, the saturated output power was 9 dBm for EDF-a and 11.6 dBm for EDF-b. The corresponding input signal power was -19 dBm for EDF-a and -11.5 dBm for EDF-b. At 1625 nm, the saturated output power was 15 dBm for EDF-a, with -2 dBm input signal power. For EDF-b, the gain drops less with the signal power, which is not starting to saturate at the input signal power of -2 dBm. At 1628 nm, the gain variations with the input signal power were negligible for both EDFs.

Conclusions

In summary, we have demonstrated the use of phospho-alumino-silicate EDF, fabricated using the MCVD-solution doping technique, to extend the L-band amplifier gain to 1628 nm. Using the 1480 nm in-band pumping and -25 dBm input signal power, we achieved 13.3 dB gain with 8.6 dB NF at 1628 nm and >20 dB gain with <6.9 dB NF from 1580-1625 nm using 80 m of EDF (EDF-a). A second EDF, EDF-b, with a higher Er concentration in which the device length has shortened to 40 m, exhibited ~3 dB lower gain with no influence on the NF. In addition, the gain coefficient and the saturated output power were reported in the extended L-band. At 1628 nm, the gain exhibited a negligible variation with the input signal power from -35 to -2 dBm. To the best of our knowledge, for the first time, the EDFA in the extended L-band up to 1628 nm, with the study on the gain and NF, gain coefficient, and gain saturation has been reported. The experimental results indicate the potential of our in-house fabricated phospho-alumino-silicate EDFs in extending the L-band transmission capacity in commercial telecommunication systems.

Acknowledgements

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