Cladding-Pumped YDFA for Data Transmission in the 1071-1097 nm Range

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Abstract *We report a broadband ytterbium doped fibre amplifier designed for long-wavelength operation. Our amplifier utilizes a simple, single-stage cladding-pumped configuration and is capable of a gain of more than 25 dB over a wide bandwidth of 26 nm (~6.6 THz), in 1071-1097 nm. ©2023 The Author(s)*

Introduction

The demand for increased capacity in optical fibre communication systems has steadily grown, leading to the exploration of new optical fibre and amplifier technologies to expand the usable optical communication window. While the conventional communication window at 1.55 µm provides the lowest propagation loss in silica fibres, other communication windows such as the O, E, and S bands have also been investigated [1-3]. Recently, significant progress has been made in hollow core fibre (HCF) fabrication, enabling a low propagation loss around 1 µm (~0.3 dB/km, as shown in Fig. 1) [4]. This progress has further stimulated interest in exploring the 1 µm transmission window, which can take advantage of additional components and potentially wider usable frequency bandwidth available at this relatively shorter wavelength compared to the C-band.

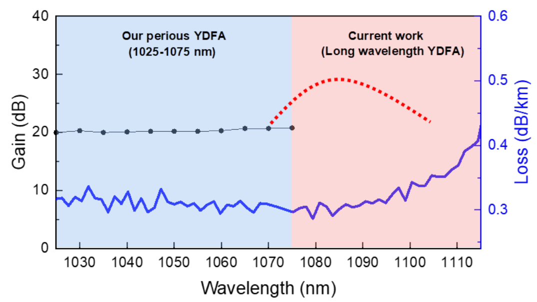

Fig. 1: Propagation loss of HCF at 1 µm and YDFA performance in this window.

To this end we have recently demonstrated a broadband gain-flattened YDFA with a bandwidth of 50 nm in the 1025-1075 nm range (~13.7 THz) [5, 6], as illustrated by the black circles in Fig. 1. This is a substantial improvement in bandwidth compared to a C-band erbium-doped fibre amplifier (EDFA) (~4.4 THz), surpassing the EDFA by a factor of approximately 3.1. However, there is still considerable potential for further improvement by extending the gain bandwidth to longer wavelengths, which can be achieved by using approaches similar to those used in L-band EDFAs, including use of longer gain fibres, increased pump powers, pump wavelength optimisation and multistage designs. Despite this potential, the efficiency of long wavelength band YDFA (beyond 1075 nm) is limited by the low emission cross-section of ytterbium doped fibres (YDFs) [7]. This necessitates use of a high-power pump laser diode (>1 W), and the pump wavelength typically needs to operate away from the high absorption peak at 976 nm to balance the gain distribution over a longer length of gain fibre. In this regard, cladding-pumping offers a more attractive solution for long-wavelength band Yb-amplifiers as it uses readily available, low-cost multimode (MM) pump diodes with high output power and provides higher power conversion efficiency (PCE) compared to core-pumping. This is due to the reduced pump brightness in the core and hence lower level of population inversion along the amplifier length. This is favourable for amplifying signals at longer wavelengths and ultimately results in higher gain and higher PCE than core pumped approaches for longer wavelength amplification [8, 9]. This pump scheme is cost-effective and compatible with a wide range of commercially available pump wavelengths (e.g., 915 nm and 940 nm) and avoids the use of fibre Bragg grating for pump wavelength stabilization due to the relatively flat absorption of YDFs from ~910 nm to ~950 nm.

In this paper, we present a 915 nm MM diode, forward cladding-pumped, long-wavelength YDFA providing good amplifier performance with a simple configuration and low-cost pumping. We achieved more than 25 dB gain across a 10 dB bandwidth of 26 nm (~6.6 THz), with a noise figure (NF) less than 6.5 dB. Simulation results predict that a bandwidth of 43 nm (~10.8 THz) could be achieved in the 1072-1115 nm range.

Simulations

Firstly, we employed a commercial fibre amplifier simulator (Optisystem) to evaluate the gain and NF performance of cladding-pumped YDFAs of various fibre lengths. A single-channel tunable laser source (TLS) with an input power of -20 dBm and a wavelength range of 1060-1120 nm was assumed in the simulations. We also accounted for the insertion losses of 1 dB for each isolator and 0.5 dB for the pump/signal combiner. The optimum pump wavelength to obtain the highest gain from the cladding-pumped YDFA was first determined through simulation. It was observed that a pump wavelength of 915 nm can achieve the best gain uniformity over the required fibre length - resulting in the net highest gain. Therefore, 915 nm was used as the pump wavelength in all follow-on simulations. In simulations, we consider the double-clad YDF has a telecom-type fibre geometry that is practical and compatible with standard SM fibre components at 1 µm. The fibre core/clad diameter is 6/125 µm with a core NA of 0.12. We assumed the YDF has a dopant concentration of 3200 ppm and typical transition cross-sections in [7]. Forward pump powers (0.8, 1, and 1.4 W) were used for fibre lengths of 20, 40, and 60 m, respectively (we determined these pump powers as optimal for these respective lengths). The calculated gain and NF spectra are depicted by the the red, blue, and green lines in Fig. 2. As the fibre length increases, the gain peak shifts towards longer wavelengths due to signal reabsorption at shorter wavelengths. The gain bandwidth is also dependent on fibre length. The 20-m-long YDF provides the broadest amplification bandwidth, with >25 dB gain for signal wavelengths up to 1105 nm. However, the gain rapidly decreases for wavelength beyond 1105 nm, and longer fibre lengths are necessary to achieve >25 dB gain at these wavelengths. With a 60 m fibre length, a 43-nm-wide bandwidth extending from 1072 to 1115 nm can be achieved with >25 dB gain. The calculated NF is less than 6 dB for all fibre lengths, and the NF of a 60 m YDF is predicted to be less than 4.7 dB in the 1072-1115 nm wavelength range.

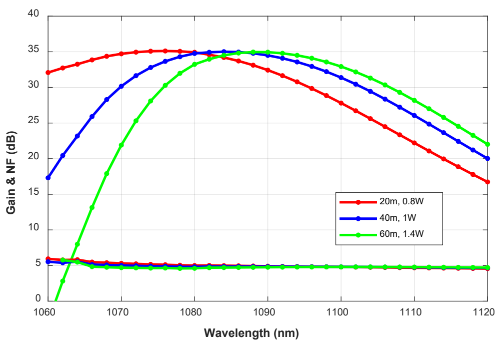

Fig. 2: Simulated gain and NF spectra of long-wavelength YDFA at 1060-1120 nm with different fibre lengths.

Experiments

To begin to confirm our simulation predictions, we have undertaken some preliminary experiments. We first conducted measurement of the forward amplified spontaneous emission (ASE) spectra using various lengths of YDF to assist in optimisation of the cladding-pumped YDFA for long wavelength operation. The YDF employed in this configuration is a double-clad fibre manufactured by nLIGHT, with a core diameter of 6 µm and a core NA of 0.12. It features an octagonal-shaped inner-cladding with a diameter of approximately 125 µm and a cladding NA of 0.48 to increase the MM pump light absorption. The pump absorption at 920 nm is 0.55 dB/m in the inner cladding. The results, shown in Fig. 3, indicate that as the YDF length increased from 20 m to 60 m, the ASE peak shifted from 1075 to 1085 nm and the ASE spectral intensity at longer wavelengths increased. The ASE spectrum had a 10 dB bandwidth of 37 nm, 35 nm, 33 nm for YDF lengths of 20 m, 40 m, and 60 m, respectively. These results suggest that increasing the fibre length further should enhance the gain at signals above 1100 nm, but this would also decrease the 10-dB bandwidth of the YDFA. For longer wavelength operation, longer fibre lengths are necessary, which require higher pump power. Optimal pump powers of 0.8 W, 1 W, and 1.4 W were used for YDF lengths of 20 m, 40 m, and 60 m, respectively. In terms of the 10-dB bandwidth prediction, the results obtained from the ASE measurement showed a nearly 80% agreement with our simulations.

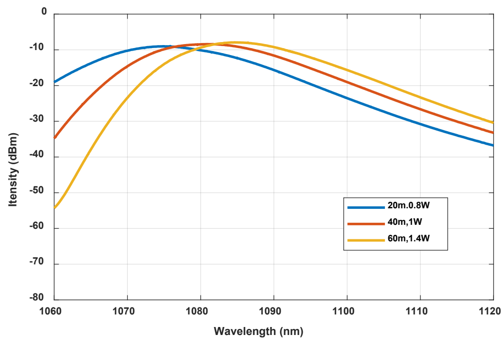

Fig. 3: Measured ASE spectra at different YDF lengths.

Based on our simulation results and the ASE measurement, we have constructed a long-wavelength YDFA in a cladding-pumped configuration. The schematic of the amplifier is shown in Fig. 4, which comprises a length of YDF, a (2+1)×1 pump and signal combiner, and two optical isolators. To forward-pump the YDF, we coupled the pump light from a commercially available 915 nm LD into the YDF via the pump and signal combiner. Isolators were inserted at the amplifier input and output ends to minimize

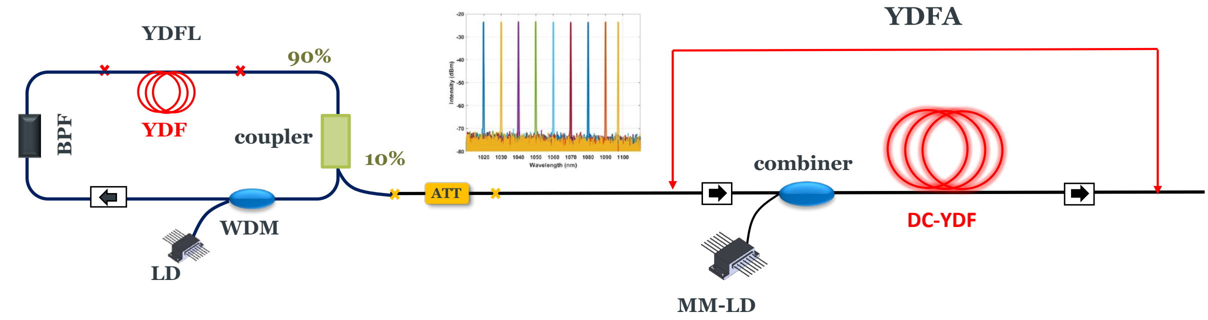

Fig. 4: Schematic of the long-wavelength YDFA in a cladding-pumped configuration.

back reflections and prevent parasitic lasing. Additionally, the residual pump light from the YDF was removed by a high-index-coated cladding-light-stripper positioned before the output isolator.

To characterize the long-wavelength YDFA, an in-house built Yb-doped fibre ring laser was used as the seed source, as no commercial TLS operating beyond 1070 nm was available. The seed laser consisted of a 1-m-long YDF (YB1200-4/125) core-pumped by a single-mode 980-nm pump LD, with an isolator used in the laser cavity to ensure unidirectional propagation of the oscillating laser. The output was tapped out from the cavity through the 10% port of a 90/10 coupler, and the lasing wavelength could be tuned by adjusting the tuneable band pass filter (BPF) inside the cavity. The homemade seed laser provided an operating wavelength range from 1020 to 1097 nm with a high output power optical signal to noise ratio (OSNR) of >40 dB (measured at a resolution of 1 nm), as shown in the inset of Fig. 4. Access to longer lasing wavelengths was currently limited by the operating range of the BPF (up to 1097 nm) used in our experiment. An optical attenuator (ATT) was placed after the seed laser to control the power launched into the YDFA. The output of the cladding-pumped YDFA was characterised using an optical spectrum analyser (OSA) and a power meter.

Fig. 5 shows the measured gain and NF of the long-wavelength YDFAs using various fibre lengths. The experimental data (scatter points) is

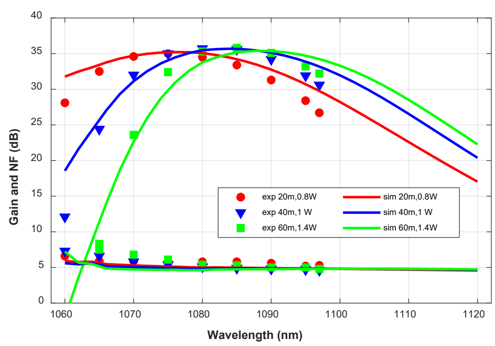

Fig. 5: Measured gain and NF spectra of the YDFA with various fibre lengths.

shown to be in good agreement with the simulation results (solid lines). A clear trend of higher gain at longer wavelengths achieved by increasing the YDF length can be observed. Notably, a 60-m-long YDFA exhibits >25 dB gain for signals from 1071 to 1097 nm, with a NF of <6.5 dB. This 26-nm-wide bandwidth corresponds to ~6.6 THz in the frequency domain, which is almost 1.5 times that of a C-band EDFA (~4.4 THz). Note that the upper limit of the longest characterisation wavelength in our experiments was restricted by the BPF integrated into our seed laser and there is more bandwidth available for exploration beyond this limit. By cascading our previous core-pumped YDFA with this new long-wavelength YDFA, we anticipate that a total amplifier bandwidth in excess of 70 nm (~19.2 THz) should be possible, which is almost twice the bandwidth of C+L band EDFAs (~11.4 THz).

Conclusions

We have characterised and optimized a cladding-pumped YDFA for long-wavelength operation. By using a commercially available 915 nm MM pump LD, we were able to achieve a wide gain bandwidth of 1071 to 1097 nm with a gain of >25 dB and NF of <6.5 dB. Our simulations also suggest that the operable bandwidth can be further extended up to 1115 nm. The demonstrated YDFA bandwidth is ~6.6 THz in frequency domain, which is nearly 1.5 times as wide as that of EDFAs in the C-band. This advancement could open new data transmission windows around 1 μm, potentially expanding the capacity of optical communication networks.

Acknowledgements

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