High Spatial Density 6-Mode 7-Core Fibre Amplifier for C-band Operation

S. Jain*[(1)], T. Sakamoto[(2)], Y. Jung[(1)], I. A. Davidson[(1)], P. Barua[(1)], J. R. Hayes[(1)], K. Shibahara[(3)], T. Mizuno[(3)], Y. Miyamoto[(3)], K. Nakajima[(2)], and D. J. Richardson [(1)]

[(1)] Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ, U.K,
[(2)] NTT Access Network Service Systems Laboratories, NTT Corporation 1-7-1, Hanabatake, Tsukuba, Ibaraki, Japan
[(3)] NTT Network Innovation Laboratories, NTT Corporation 1-1, Hikari-no-oka, Yokosuka, Kanagawa, Japan
*Corresponding Authors Email: sj3g11@orc.soton.ac.uk

Abstract *We present a C-band 6-mode 7-core fibre amplifier for space-division-multiplexed transmission supporting a record 42 spatial channels. An average gain of 18-dB and NF of 5.4-dB is obtained with an average differential-modal-gain of 3.4-dB.*

Introduction

Space division multiplexing (SDM) has emerged over the last decade as a potential longer-term solution to overcome the “capacity crunch” faced by single mode silica fibre systems as they are engineered and operated ever closer to their fundamental data-carrying limits[1]. Various SDM fibres have been actively investigated but few-mode multicore fibres (FM-MCFs) are receiving particular attention in recent times as a means to achieve high spatial density SDM transmission systems. In order to support longer transmission distances matching optical amplifiers are needed to simultaneously amplify all the spatial channels in a single device. Ideally such amplifiers would be cladding pumped to allow the sharing of high-power low-brightness multimode laser diode pumps and inline fibre components such as pump couplers, isolators and gain-flattening filters among the spatial channels to exploit the cost reduction benefits offered by SDM technology. Initial work on cladding pumped FM-MCF amplifiers started with the realization of a 3-mode 6-core fibre amplifier supporting 18 spatial channels which incorporated an annular ring geometry to reduce the cross-sectional area of the pump waveguide as a means to achieve relatively high-brightness pumping (and resultant high-inversion levels) and reasonably good performance was achieved[2]. More recently, we have reported an L-band 6-mode 7-core fibre (6M-7CF) amplifier supporting 42 spatial channels, setting a new record for channel count in an erbium based optical amplifier, whilst at the same time demonstrating the potential energy/component sharing benefits which accrue with increasing channel count[3].

In this paper, we show that the same high spatial channel density Er-doped fiber used in our previous L-band 6M-7CF amplifier can also be used to achieve good C-band performance (albeit with a somewhat compromised efficiency). We achieve this by reducing the fibre length, using higher brightness pumping and successfully managing the relatively high level of unabsorbed pump light that ensues. The average gain and NF (over wavelength and mode) is 18 dB and 5.4 dB, respectively with an average differential modal gain of 3.4 dB.

6M-7CF amplifier configuration

Fig. 1(a) shows a schematic of the proposed in-line C-band 6M-7CF amplifier supporting 42 spatial channels and the associated characterization setup. The amplifier (orange-boxed area) consists of a 2.1 m length of gain fibre (i.e. a double clad erbium-doped 6M-7CF) which is directly spliced to its matched passive multicore fibre counterpart[4].

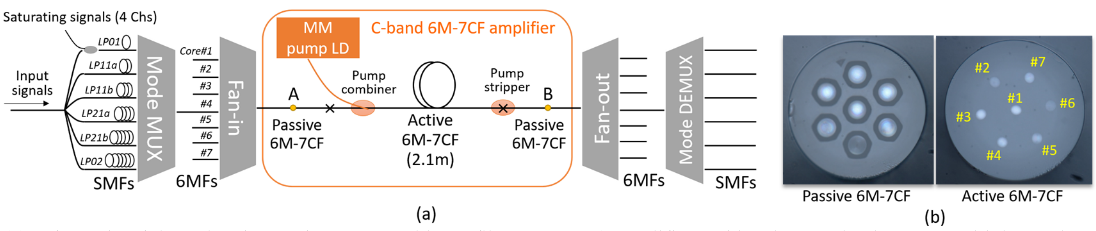

Fig. 1. (a) Schematic of the C-band 6-mode 7-core multicore fibre (6M-7CF) amplifier and its characterization setup with input signal (-25 dBm/mode/core) and saturating signals (-4 dBm/core) launched into the core under test; input and output signal powers are monitored and defined at the points *A* and *B*, respectively. (b) Cross-sectional microscope images of the passive and active 6M-7CF.

A fiber coupled high power multimode laser diode is directly coupled to the input end of the active fibre via a pump combiner, and a pump stripper is used to remove the residual pump light at the end of the active fibre. This cladding pumped configuration can offer a cost-effective means to simultaneously amplify all the spatial channels but also to provide substantially better device robustness and stability in a compact all-fiberized format. Fig. 1(b) shows the cross-sectional microscope images of the passive and active 6M-7CFs. Our active fibre was fabricated in-house by the stack-and-draw technique and the core pitch distance was ~44 μm, closely matched to that of the counterpart passive transmission fibre (44.4 μm), facilitating easy fusion splicing. The cladding absorption of the fibre was measured to be about 0.62 dB/m at the absorption peak of 978 nm. It should be noted that the same active fibre and a similar amplifier configuration were used as in our previous L-band amplifier but a much shorter fibre length and higher pump power is required to achieve effective C-band operation. In our experiment, a wavelength stabilized multimode pump laser diode operating at 975 nm (IPG Photonics, PLD-975-70-WS) was used as a pump source and a fused side coupler was used to provide efficient (~95 %) pump coupling with a high maximum power handling capability (~50 W). In order to reduce the overall energy consumption of our amplifier, the pump laser diode was passively air-cooled without a thermo-electric cooler (TEC) using a heat sink and low power consumption fans through forced convection, as shown in the inset of Fig. 2(a). Above the threshold current, the pump power increases linearly as a function of drive current with a slope efficiency of 5.1 W/A (red square line) and no thermal rollover was observed at an even high injection current of 6 A (providing ~28 W), which provides an indirect but important confirmation of the good heat dissipation provided by our passive cooling system. We also monitored the case temperature of the pump LD using a thermistor and the results are shown in Fig. 2(a) (blue square line). The case temperature increases linearly with the applied current with a slope of 4.2 ^{o}C/A due to self-heating but it remains less than 35 ^{o}C (within the operating temperature range) at 28 W pump power. Moreover, we tested the long-term stability of our passive cooling with constant pump power of 20 W (this pump power will be used for in the following amplifier experiments) and the results from 0 to ~50 minutes after turn on are shown in Fig. 2(b). Due to the relatively slow nature of the passive cooling, it takes ~15 minutes to settle down to a steady level but only a few degrees of temperature overshoot was observed and the case temperature was thereafter well maintained at 30 ^{o}C. We also tested the power handling of our pump stripper, which is fabricated by applying a high refractive index UV-curable resin at the end of active fibre, and we confirmed that it can handle ~20 W of residual pump light with the temperature of the pump stripper section remaining below 60 ^{0}C (a safe temperature for long term operation). Note that we ensured that all of the passive fibre components used in our experiment (i.e. passively cooled pump laser diode, pump coupler, pump stripper) are able to reliably handle pump power of at least 20 W without any noticeable thermal degradation.

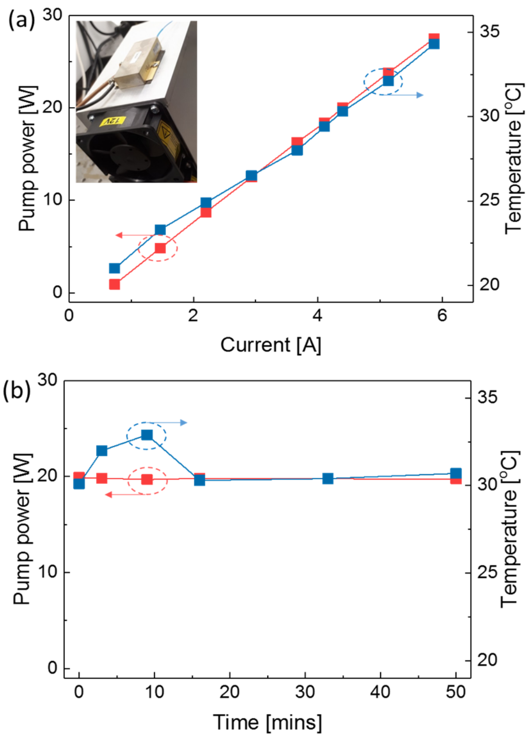

Fig. 2. (a) Case temperature variation of the pump LD as a function of drive current and (b) long-term stability of the passive cooled pump LD at 20W pump power.

With these optimized fibre components, high power pump light (>20 W) was successfully coupled to our active fibre and the fibre length was optimized to achieve good C-band operation. To perform this optimization a central core of the fibre was directly spliced to standard single mode fibres at both ends and the amplified spontaneous emission (ASE) spectrum was monitored whilst gradually shortening the length of the fibre. As shown in Fig. 3, the forward-propagating ASE spectrum strongly depends on the length of active fibre and the ASE peak is shifted to shorter wavelengths for a short fibre length. A reasonably flat C-band emission is achieved with a ~2.5 m length of EDF, while L-band ASE can be obtained for ~15 m of EDF.

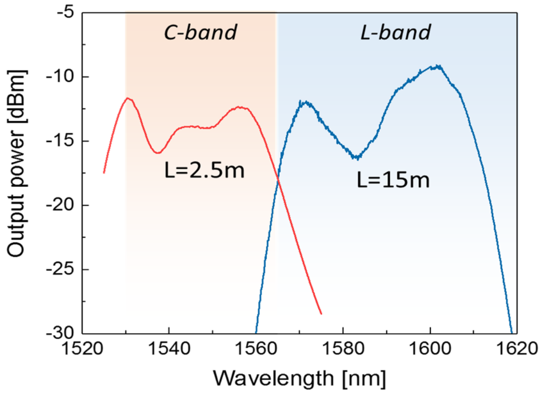

Fig. 3 ASE spectra of a 2.5 m (for C-band) and 15 m length (for L-band) of active fibre.

Characterization of 6M-7CF amplifier

In order to characterize our amplifier, a series of multicore fan-in/fan-out (FIFO) devices and mode coupler pairs (i.e. fibre bundle type and multi-plane light conversion type) were used to couple/decouple the signals into the amplifier as shown in Fig. 1(a). It should be noted that a FIFO and mode-couplers were custom built and still need further optimization in terms of device loss, hence the internal performance of the amplifier was measured. A single wavelength channel (one of 1530nm, 1540nm, 1550nm or 1565 nm) was injected into the core under test with an input signal power of -25 dBm/core/mode at point *A*. In order to characterize the amplifier performance in the saturated regime, 4 additional wavelengths (1532, 1542, 1552 and 1562 nm) were also multiplexed into the monitored core to provide a saturating signal with an input power of -4 dBm/core. The internal gain of the amplifier is defined as the ratio of the output signal power (point *B*) to input signal power (point *A*) and it was obtained by subtracting the insertion losses of the passive components (i.e. fan-out and mode demultiplexer). The gain and NF of all spatial channels were measured, and the results are plotted in Fig. 4(a). All 42 spatial channels were successfully amplified, and the average gain and NF was measured to be ~18 dB and ~5.4 dB respectively with a core-to-core variation of 3.5 dB. Note that reasonably good spectral gain flatness (spectral variation of ~1.5 dB) over the C-band is achieved in our simple cladding pumped configuration at a launched pump power of 20 W. Fig. 4(b) shows the measured differential modal gain (DMG) of the amplifier. The DMG is defined as the maximum difference of the modal gain among the six modes. As expected in a step-index uniformly doped EDF, lower-order spatial modes experience higher gain than higher-order modes and the averaged DMG was measured to be ~3.4 dB.

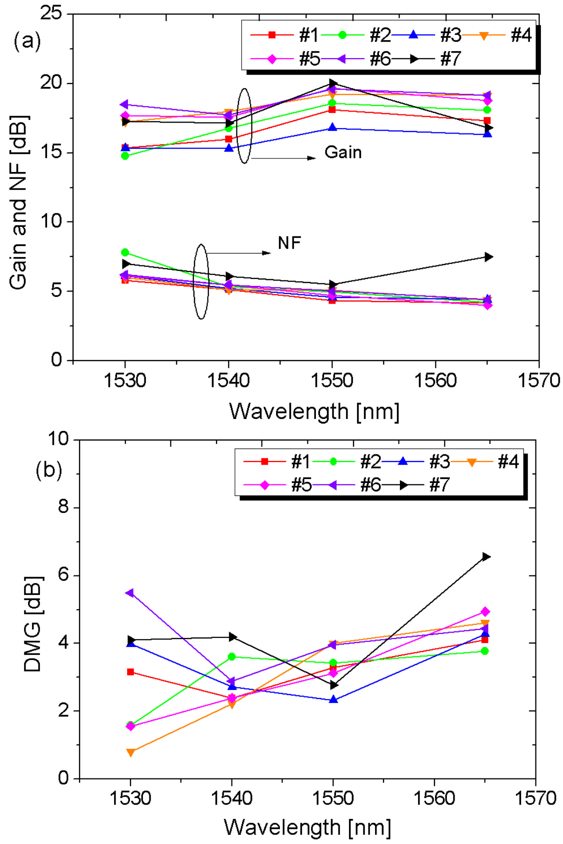

Fig. 4. (a) Average modal Gain/NF and (b) differential modal gain of the 6M-7CF amplifier in the C-band.

Conclusions

In conclusion, a few-mode multicore fibre amplifier with a record high spatial density of 42 has been successfully built and demonstrated in the C-band. The amplifier exhibited an average gain of 18 dB and a NF of 5.5 dB. The core-to-core variation was measured to be ~3.5 dB with an averaged differential modal gain of ~3.4 dB. The amplifier performance can be further improved by reducing the core/cladding area ratio, engineering the core dopant distribution for gain equalisation and optimization of the mode dependent splice loss.

Acknowledgements

The work was supported in part by the UK EPSRC funded “Airguide Photonics” Program Grant (EP/P030181/1).

References

[1] D. J. Richardson et al., *Nat. Photonics* 7, 354 (2013).
[2] H. Chen et. al., *Nat. Photonics* 10, 529 (2016).
[3] Y. Jung et. al., *J. Lightwave Technol.* 38, 2938 (2020).
[4] T. Sakamoto et. al., *J. Lightwave Tech.* 36, 1226 (2018).