High Spatial-Density, Cladding-Pumped 6-Mode 7-Core Fiber Amplifier for C-band Operation

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Abstract: We present a C-band 6-mode 7-core fiber amplifier in an all-fiberized cladding-pumped configuration for space division multiplexed transmission supporting a record 42 spatial channels. With optimized fiber components (e.g. passively cooled pump laser diode, pump coupler, pump stripper), high power multimode pump light is coupled to the active fiber without any noticeable thermal degradation and an average gain of 18 dB and noise figure of 5.4 dB are obtained with an average differential modal gain of 3.4 dB.

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1. Introduction

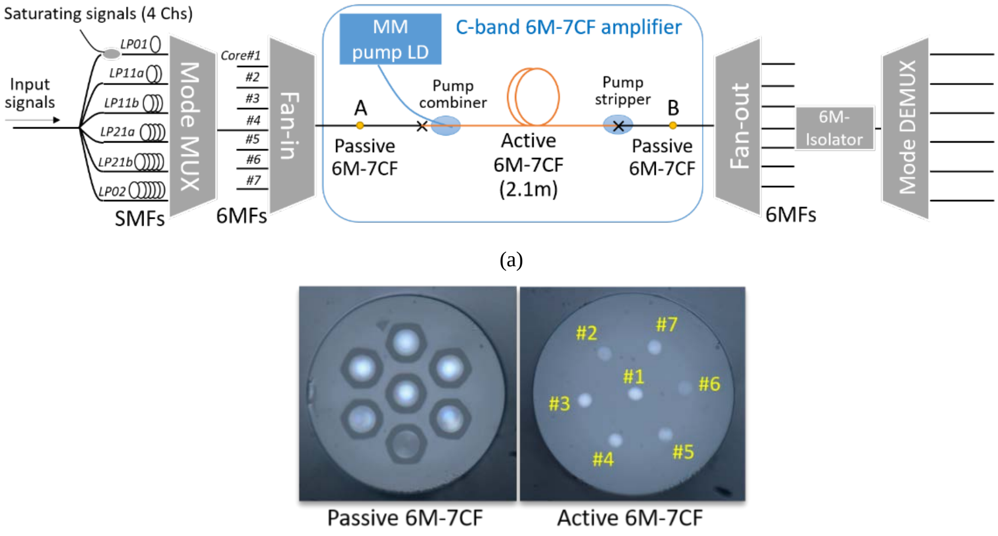
Space division multiplexing (SDM) [1-4] has emerged over the last decade as a potential long-term solution to overcome the “capacity crunch” faced by single mode silica fiber systems as they are engineered and operated ever closer to their fundamental data-carrying limits. Various SDM fiber approaches have been actively investigated but few-mode multicore fibers (FM-MCFs) have received particular attention in recent times as a means to achieve high spatial density SDM transmission systems. Here, spatial channel multiplicity can be readily scaled by mode count per core × core count in a fiber. To date more than 100 spatial channel transmission has successfully been realized with several different FM-FCFs designs such as a 3-mode 36-core fiber [5], 6-mode 19-core fiber [6] and 10-mode 12-core fiber [7] and a record fiber capacity of >10 Pb/s using both the C- and L-bands has been demonstrated [8], which represents a ~100-fold increase in data carrying capacity relative to the maximum currently attainable in an optimally engineered transmission system based on single mode fiber. However, it should be noted that the maximum transmission distance was limited to a few tens of kilometers due to the lack of a compatible inline fiber amplifier. In order to support longer transmission distances, therefore, matching optical amplifiers are needed to simultaneously amplify all the spatial channels in a single device. Ideally such amplifiers would be of a cladding pumped configuration to allow the sharing of high-power low-brightness pump light generated by multimode laser diode pumps and of inline fiber components such as pump couplers, isolators and gain-flattening filters among the spatial channels in order 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 fiber amplifier supporting 18 spatial channels [9] 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. More recently, we have reported an L-band 6-mode 7-core fiber (6M-7CF) amplifier supporting 42 spatial channels [10], setting a new record for channel count in an erbium based optical fiber amplifier, whilst at the same time demonstrating the potential energy/component sharing benefits which accrue with increasing channel count. Table 1 summarizes the latest high spatial density SDM amplifiers reported so far including few mode fiber (FMF) and single-mode multicore fiber (SM-MCF) amplifiers.

Table 1. Recently reported high spatial density SDM amplifiers

Amplifier fiber types	Spatial multiplicity	Pump scheme	References
FMF	10	Cladding	[21]
SM-MCF	19	Core	[12]
SM-MCF	32	Cladding	[16]
FM-MCF	18	Core	[11]
FM-MCF	18	Cladding	[9]
FM-MCF (L-band)	48	Cladding	[10]

In this paper, we show that the same high spatial channel density erbium-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) [13]. We achieve this by reducing the fiber length, using higher brightness pumping and successfully managing the relatively high level of unabsorbed pump light that ensues. The average gain and noise figure (over wavelength and mode) is 18 dB and 5.4 dB, respectively with an average differential modal gain of 3.4 dB.

2. 6M-7CF amplifier configuration

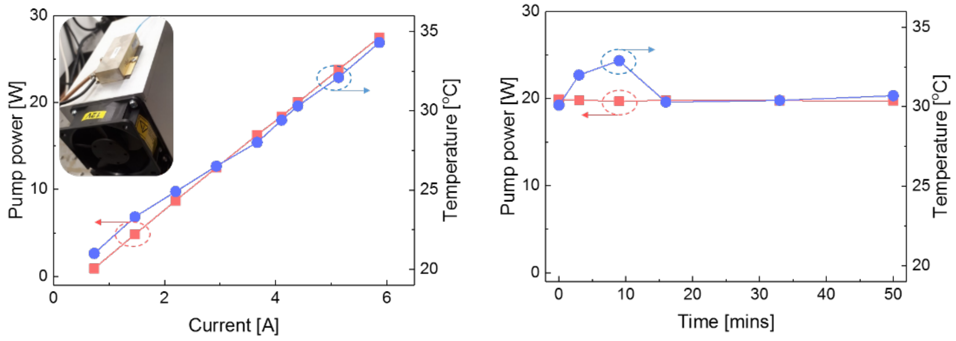


(a)

(b)

Fig. 1. (a) Schematic of the C-band 6-mode 7-core fiber (6M-7CF) amplifier and associated characterization setup with an 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 points A and B, respectively. (b) Cross-sectional microscope images of the passive and active 6M-7CF.

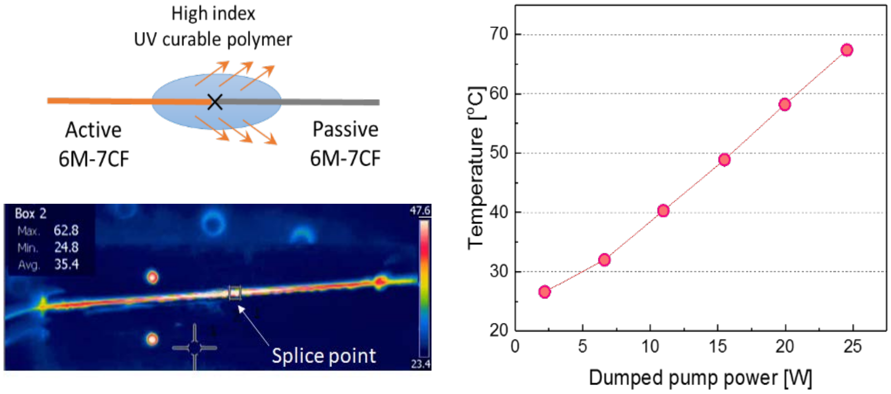
Fig. 1(a) shows a schematic of the proposed in-line C-band 6M-7CF amplifier supporting 42 spatial channels and the associated characterization setup. The amplifier consists of a 2.1 m length of gain fiber (i.e. a double clad erbium-doped 6M-7CF) which is directly spliced to matched passive multicore fiber counterpart [14]. The average splice loss between the active and passive fiber was ~0.2 dB for LP_{01}, 1.6 dB for LP_{11} and 1.8 dB for the LP_{21} & LP_{02} modes, respectively. A fiber coupled high power multimode laser diode is directly coupled to the input end of the active fiber via a pump combiner and a pump stripper is used to remove the residual pump light at the end of the active fiber. This cladding pumped configuration can offer a cost-effective means to simultaneously amplify all of 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 fiber 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 fiber (44.4 µm), facilitating easy fusion splicing. The core diameter of the fiber was 12.5 µm and the refractive index difference between core and cladding was ~1.4% to ensure reliable 6 spatial mode operation. The overall fiber diameter was 175.5 µm. The cladding absorption of the fiber was measured to be about 0.62 dB/m at the absorption peak of 978 nm. It should be noted that the same active fiber and a similar amplifier configuration were used as in our previous L-band amplifier [10] but a much shorter fiber 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 [15, 16] 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 higher injection current of 6 A (providing ~28 W of pump power), 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 circle 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 stated safe operating temperature range) at 28 W pump power. Moreover, we tested the long-term stability of our passive cooling at a 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. The pump spectrum was also observed using an OSA and it remained stable over this operating range.



(a) (b)

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 20 W pump power.

Another important component to build a C-band 6M-7CF amplifier is a robust cladding light stripper to dissipate the unabsorbed residual pump power in the active fiber. Note that the residual pump power of a C-band amplifier is much higher than that of an L-band amplifier in a cladding pumped configuration and a pump stripper with high power handling capability is an important aspect of the overall amplifier performance and stability. In our experiment, we used an in-house developed pump stripper implemented by applying a high refractive index UV-curable resin (n~1.54 at 1550 nm) and by curing it using a UV lamp in an aluminum V-groove assembly placed at the end of the active fiber, as shown in Fig. 3(a, top). Thermally conductive tape was applied to the stripper to help dissipate the heat [17, 18]. To examine the power handling capability, we measured the temperature in the vicinity of the splice to the stripper using an IR thermal camera as the pump power was increased. The highest temperature was always observed at the splice point (see Fig 3(a, bottom)). We measured the maximum temperature at a given dumped pump power by setting a measurement box in the vicinity of the splice point and recording the maximum value within that box (the minimum and average temperature within the box were also measured). The two apparent hot spots either side of the fiber are measurement artifacts associated with the mechanical mounting of the v-groove assembly. For each measurement the pump laser was left running for about 5 minutes to account for any temporal increase due to the heat accumulation. As observed in Fig. 3(b), the measured temperature varies linearly with the dumped pump power and the fabricated pump stripper 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). The cooling efficiency could be further enhanced by mounting the pump stripper on a fan-cooled heat sink. Note that we ensured that all of the passive fiber components used in our experiment (i.e. passively cooled pump laser diode, pump coupler, pump stripper) are able to reliably handle a pump power of at least 20 W without any noticeable thermal degradation.



(a) (b)

Fig. 3. (a) Schematic (top figure) and IR thermal image (bottom figure) of pump stripper. (b) Measured temperature according to the residual pump power at the splice point between active and passive 6M-7CF.

With these optimized fiber components, high power pump light (>20 W) was successfully coupled to our active fiber and the fiber length was optimized to achieve good C-band operation. To perform this optimization a central core of the fiber was directly spliced to standard single mode fibers at both ends and the amplified spontaneous emission (ASE) spectrum was monitored whilst gradually shortening the length of the fiber. As shown in Fig. 4, the forward-propagating ASE spectrum strongly depends on the length of active fiber and the ASE peak is shifted to shorter wavelengths for a short fiber length. A reasonably flat C-band emission is achieved with a ~2.5 m length of erbium doped fiber (EDF), while L-band

ASE can be obtained for a ~15 m length of EDF. The presence of a 1560 nm peak in the ASE spectrum means that the fiber length could be further shortened to improve the gain for C-band amplification, albeit at the expense of reduced amplifier gain.

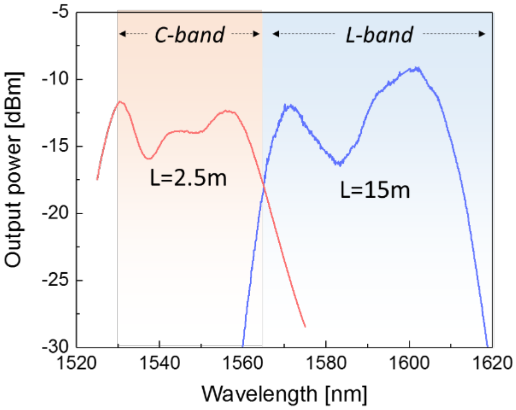
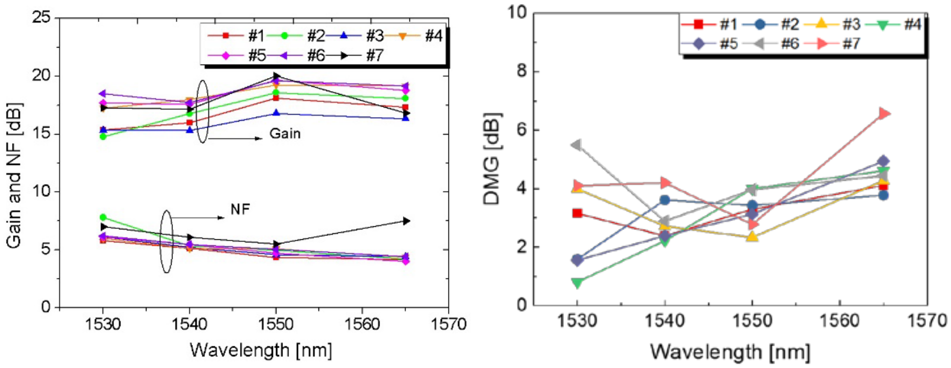


Fig. 4 ASE spectra of a 2.5 m (for C-band) and 15 m length (for L-band) of active fiber.

3. Characterization of 6M-7CF amplifier

In order to characterize our amplifier, a series of multicore fan-in/fan-out (FIFO) devices and mode (de)multiplexers (i.e. fiber bundle type and multi-plane light conversion type) [19, 20] were used to couple/decouple the signals into the amplifier. The insertion losses of FIFO and mode multiplexer/demultiplexer (MUX/DEMUX) was about 1.1 dB and 4.7 dB, respectively. It should be noted that the 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 modes of the core under test with an input signal power of -25 dBm/core/mode at point *A*. The output of the optical signal was split into multiple paths in order to create all spatial mode signals and optical delay lines were used to decorrelate the six optical signals. 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). Note that such an amplifier would directly be integrated as an in-line amplifier and FIFO and (DE)MUX components will not be necessary in real-world applications. Due to the lack of low loss 6M-7CF optical isolators, a 6-mode isolator was used at the output before the DEMUX to prevent potential unwanted reflections. The gain and noise figure (NF) of all spatial channels were measured, and the results are plotted in Fig. 5(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. Figure 5(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 the higher-order modes and the averaged DMG was measured to be ~3.4 dB. The spectral dependence of the DMG is mainly due to the combined effect of the DMG of the amplifier and the mode dependent losses from the various passive fiber optic components and fiber splices, which can be further improved as the device technology advances.



(a) (b)

Fig. 5. (a) Average modal gain/NF and (b) differential modal gain of the 6M-7CF amplifier in the C-band.

4. Conclusions

In conclusion, a few-mode multicore fiber 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 5.4 dB. The core-to-core gain variation was measured to be ~3.5 dB with an averaged differential modal gain of ~3.4 dB. The amplifier performance could be further improved by reducing the core/cladding area ratio, engineering the core dopant distribution for gain equalization and optimization of the mode dependent splice loss.

Funding

Engineering and Physics Science Research Council (“Airguide Photonics” Programme Grant EP/P030181/1 and National Hub in High Value Photonics Manufacturing EP/N00762X/1).

Acknowledgements

Data contained in this paper is openly available from the University of Southampton repository at https://doi.org/10.5258/SOTON/D1853

Disclosures

The authors declare no conflicts of interest.

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