High Spatial Density 6-Mode 7-Core Multicore L-Band Fiber Amplifier

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Abstract: We present high spatial density SDM amplifier (i.e. 6-mode, 7-core multicore fiber amplifier) supporting 42 spatial channels. More than 17 dB average gain is obtained in the L-band with less than 5.4 dB differential modal gain.

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1. Introduction

Few-mode multicore fibers (FM-MCFs) have attracted considerable attention in the research community as a means to increase the information capacity of space division multiplexed (SDM) transmission systems [1], with spatial channel multiplicities >100 already successfully demonstrated [2-4]. In order to realize long distance SDM transmission, the matching amplifiers, i.e. few-mode multicore fiber amplifiers, need to be developed. Recently, there have been two reports of such FM-MCF amplifiers. The first demonstration was of a 3-mode 6-core fiber amplifier supporting 18 spatial channels in a cladding pumped configuration [5] and the other was of a 3-mode 7-core fiber amplifier supporting 21 spatial channels in a core pumped implementation [6]. The spatial multiplicities achieved to date whilst impressive are still relatively modest compared to what has been achieved in the transmission fibers themselves, and substantial improvements in both multiplicity and performance should be possible and are worthy of further study.

In this paper, we design, construct and characterize a 6-mode, 7-core multicore fiber amplifier supporting 42 spatial channels, which represents the highest spatial density SDM amplifier reported to date. An erbium-doped fiber was designed/fabricated to match with the previously fabricated passive transmission fiber [7] and a fully fiberized amplifier was realized in a cladding-pumped configuration.

2. Amplifier configuration and optical performance

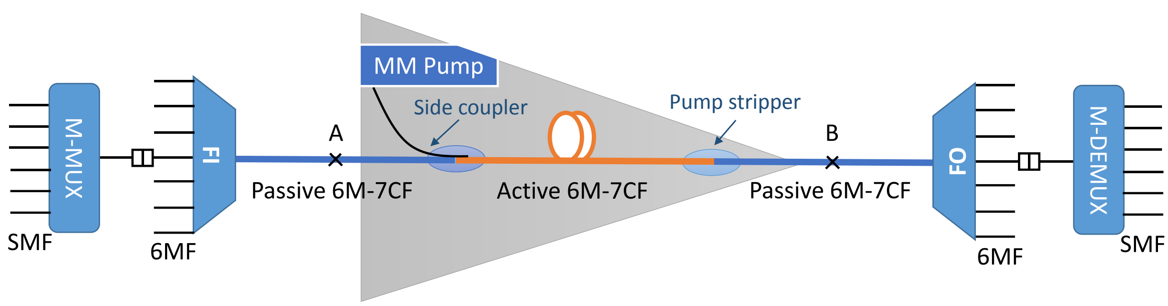
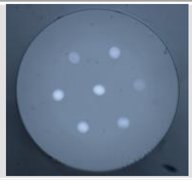


Fig. 1. Schematic of the proposed 6-mode 7-core multicore fiber (6M-7CF) amplifier. FI(FO): fan-in(fan-out) device, M-(DE)MUX: mode multiplexer/demultiplexer, MM Pump: multimode pump laser diode.

Figure 1 shows a schematic of the fabricated 6-mode 7-core multicore fiber (6M-7CF) amplifier supporting 42 spatial channels (i.e. 7-core fiber, each core of which operated on 6 spatial modes). The amplifier is composed of a length of double-clad erbium-doped 6M-7CF gain fiber and is pumped by a multimode pump laser diode (λ=975 nm, volume Bragg grating stabilized). A serial arrangement of multicore fan-in/fan-out devices and mode (de)multiplexers is used at each end of the amplifier to connect the multiple spatial channels from the erbium-doped 6M-7CF to multiple single mode input and output fibers. In order to realize a cost-effective SDM amplifier a cladding pumped approach was used in our amplifier and an in-house all-fiber tapered side coupler (incorporated directly onto the 6M-7CF) was used to couple multimode pump light into the inner cladding of the active fiber (coupling efficiency~ 60%). A pump stripper (based on appropriate application and passive cooling of a high refractive index UV-curable acrylate polymer) was introduced at the other end of the gain fiber to dump the residual unabsorbed pump light.

	Passive 6M-7CF	Active 6M-7CF
Cross-sectional images		
Core pitch	44.4 μm	44 μm
Core dia.	23.6 μm	12.5 μm
Cladding dia.	172 μm	175.5 μm
Δ	Core +0.7%/ trench -0.7%	1.4%

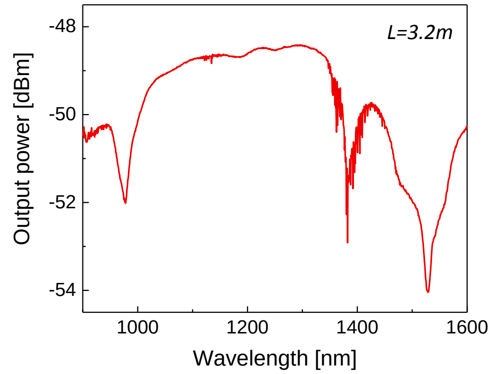


Fig. 2. (a) Specification of the active 6M-7CF and matching passive transmission fiber and (b) transmission spectrum of a 3.2 m-long active fiber (obtained using a white light source).

The active 6M-7CF was fabricated in-house using a stack-and-draw technique from an erbium-doped preform with a step-index, uniformly doped core. Note that, for our active fiber fabrication, a simple homogeneous core arrangement was employed for ease of fiber fabrication. The detailed fiber geometry and specification of the fabricated fiber is summarized in Fig. 2(a). The core pitch of the active fiber was about 44 μm, which was closely matched to that of the passive fiber (44.4 μm). The core diameter was ~12.5 μm to ensure reliable 6 spatial mode operation. However, the higher numerical aperture cores in the active fiber resulted in a large mode field diameter mismatch with the passive fiber and consequently a mode dependent splice loss was observed (~0.2 dB for LP_{01}, 1.6 dB for LP_{11} and 1.8 dB for the LP_{21} & LP_{02} modes, respectively). Figure 2(b) shows the transmission spectrum of a 3.2 m long active fiber. An incoherent white light source (with an incident large beam diameter) was launched into the inner cladding of the active fiber and the small signal cladding absorption spectrum was measured using cut-back approach with the aid of an optical spectrum analyser. The cladding absorption at the absorption peak of 978 nm was measured to be about 0.62 dB/m.

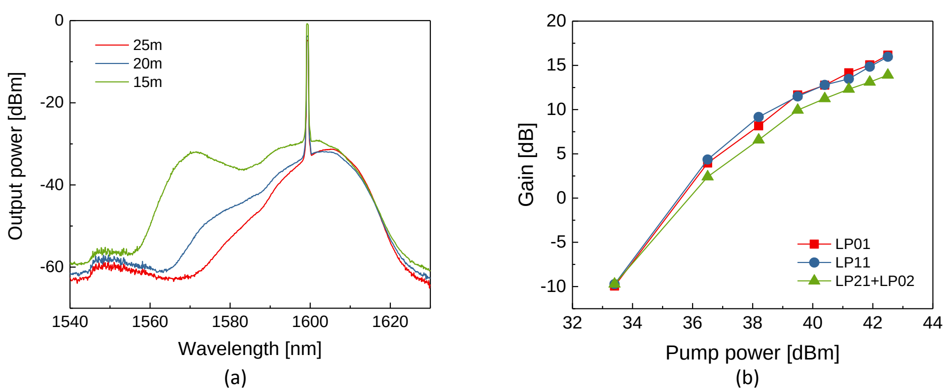


Fig. 3. (a) Shift in ASE spectra with different Er-doped fiber lengths and (b) mode dependent gain performance according to the different pump powers (for the center core).

In order to optimize the active fiber length, the center core (#7) was first monitored to evaluate the gain and amplified spontaneous emission (ASE) spectrum. As shown in Fig. 3(a), the ASE spectrum depends on the length of active fiber and the ASE peak shifts to shorter wavelengths with reduced fiber length at a fixed signal power (0 dBm per mode at 1600 nm) and pump power (40 dBm). With a 15 m length of active fiber, we can achieve good L-band amplifier performance with a good gain flatness. The gain peak tends to shift to short wavelengths region at higher pump powers but was not possible to achieve C-band operation with this fiber due to lower overall population inversion. Using this L-band optimized fiber length, we further investigated the mode dependant amplifier gain performance of the center core at different pump powers. As shown in Fig. 3(b), the averaged modal gain was more than 15 dB and the differential modal gain (DMG) was less than 2.5 dB at 42.5dBm pump power. Note that the characteristics of the LP_{21} and LP_{02} modes were evaluated as a single mode group considering the degeneracy of modes in the passive transmission fiber. As expected in a simple step-index, uniformly doped fiber, the lower order modes (LP_{01} and LP_{11}) have higher gain than the higher order modes (LP_{21} and LP_{02}).

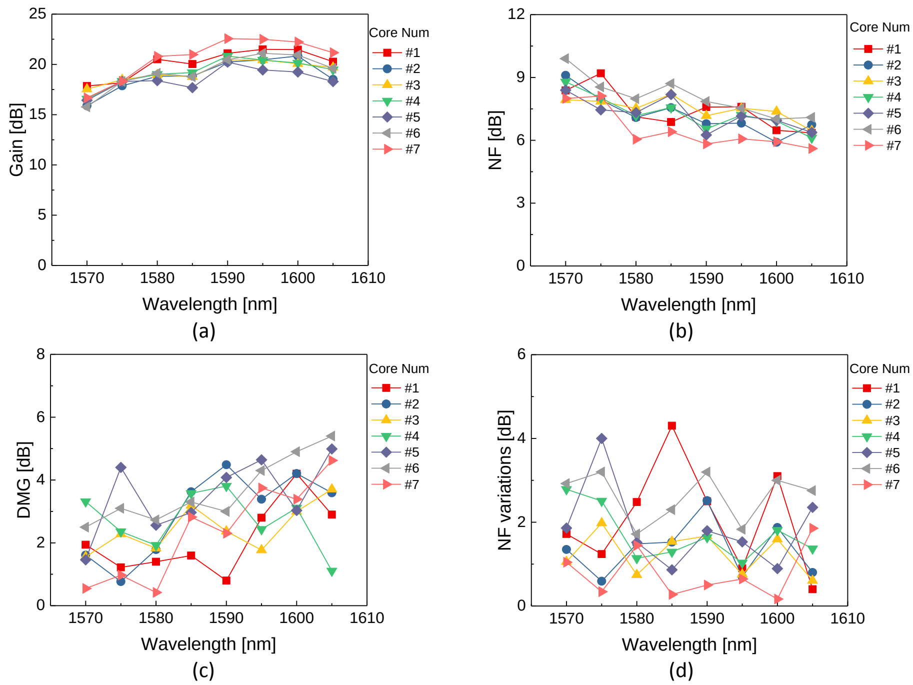


Fig. 4. (a) Average gain and (b) NF performance of the 6M-7CF amplifier. (c) Mode dependent gain and (d) NF variation for each individual core.

After these initial tests, the complete performance of the 6M-7CF amplifier was characterized using multiple wavelength signals (8 WDM channels in the wavelength range 1570-1605 nm). The input signal power was -10 dBm per mode at the input of the active fiber and the injected pump power was ~40 dBm. The gain and noise figure of all spatial channels were measured, and the results are plotted in Fig. 4 (a-d). The majority of the cores exhibited very similar performance with an average gain of >17 dB and a NF of <7 dB with a core-to-core variation of 2-3 dB. We believe that this gain variation is mainly due to the core-to-core insertion loss variation from imperfect fiber splicing. In Fig. 4(b), the NFs at longer wavelengths are about 6-7 dB although these gradually increased at the shorter wavelengths, due mainly to the reduced gain and increased signal re-absorption. We believe that the performance could be further optimized by reducing the active fiber length to enhance the gain at the shorter wavelengths (e.g. ~1570 nm). The differential modal gains (DMGs) and NFs for each individual core were also tested and are plotted in Fig. 4(c, d). The maximum DMG was observed to be ~5.4 dB but it should be noted that this includes two splice points between the passive and active fibers. Each splice currently has a mode dependent splice loss of ~1.6 dB and the intrinsic internal amplifier performance is expected to be significantly better. These results should be considered as provisional and we anticipate further improvements with further splice and fiber amplifier length optimization.

3. Conclusion

A fully fiberized 6-mode 7-core multicore fiber amplifier has successfully been realized in a cladding-pumped configuration. The amplifier provided an average gain of >17 dB and a NF < 7 dB with a core-to-core variation of ~5-6 dB in the L-band. This amplifier is capable of providing simultaneous amplification of 42 spatial channels in a single device (a record multiplicity) and significant cost/energy consumption benefits are ultimately to be expected relative to the use of 42 individual EDFAs.

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4. References

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