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Few-mode erbium-doped fiber amplifier based on a multi-inclusions core optical fiber

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Abstract: In this work, we demonstrate and evaluate a new design of micro-structured core erbium-doped few-mode fiber to be used as optical amplifier in the context of mode-division multiplexing. This concept is proposed so as to better control the distribution of the Er³⁺ ions in the core area, thus permitting to adjust the overall differential modal gains between the different signal modes. The design presented here consists of 19 erbium-doped inclusions embedded in a pedestal geometry guiding 10 modes in the C-band. It has been optimized numerically so as to reach the equalized amplification of all the signal modes. The fiber has been realized and combined with custom-made dual-wavelength mode multiplexers based on multi-plane light conversion to shape the signal and pump beams. Amplification properties have finally been evaluated experimentally.

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1. Introduction

Mode Division Multiplexing (MDM) appears as a smart solution to push forward the performances of optical fiber networks by the use of the Higher Order Modes (HOM) of an optical fiber as additional signal channels. Using this approach, it seems possible to scale up the fiber capacity by the number of modes and get access to per-fiber capacity larger than 100 Tbit/s, a number generally cited as the capacity limit of standard Single-Mode Fibers (SMF) [1,2]. Regarding the Few-Mode Fiber (FMF) used as the transmission fiber, two main approaches are possible, namely weakly or strongly coupled fiber designs that will impact the propagation conditions and the Digital Signal Processing (DSP) complexity at the receiver side. Whatever the approach, optical amplifiers are necessary to address long-haul transmission domain and few-mode erbium-doped fiber amplifiers (FM-EDFA) have demonstrated promising performances in this context [3–5]. However, such amplifiers are still today considered as a bottleneck for the performance rise and a challenge lies in the gain equalization of the different spatial (modes) and spectral (wavelengths) channels spanning over the totality of the C-band. In addition, the power consumption of these amplifiers should be optimized in order to have a better energetic performance than its equivalent in classic single-mode erbium-doped fiber amplifiers (SM-EDFA). In other words, a 10-mode FM-EDFA must deliver the required gain for all its modes using less energy than 10 parallel SM-EDFA, so as to reduce the operational expenditure of the data transmission systems. The capital expenditure could also be reduced due to the fact that an FM-EDFA needs less optical components than parallel SM-EDFA. So as to address the question of the electrical-to-optical efficiency, both core-pumped or cladding-pumped systems have been analyzed and experimentally proposed.

In the case of core-pumping [6], a clever erbium distribution (when compared to a simple homogeneous core doping) associated to an adapted pump beam shaping is generally mandatory whereas, in the case of cladding-pumping, ytterbium co-doping and high power multimode laser diode are necessary [7,8]. Although the cladding pumping presents the advantage of a more homogeneous distribution of the population inversion in the core section that facilitates modal gain equalization, the real energetic benefit of a cladding pumping configuration compatible with a full C-band operation (i.e. ytterbium-free glass composition) seems not straightforward. As an example, our group suggested that as long as a number of spatial paths smaller than 20-30 is targeted, a core-pumped configuration is potentially more efficient [4]. As has been previously mentioned, a core-pumping configuration requires adjusting both the transverse distribution of the pump beam and the distribution of Er^{3+} ions in the core so as to be able to balance the gain between the different modes. However, when a conventional fabrication technique (e.g. Modified Chemical Vapor Deposition (MCVD) combined with solution doping, widely used to manufacture single-mode erbium-doped fibers) is used for preform manufacturing, such a tailoring of the erbium distribution is not an easy task. In order to offer new degrees of freedom in the management of erbium distribution, our group proposed few years ago to adopt a micro-structured core design to be able to exploit simple pumping configuration for amplification with good performances in particular with regard to Differential Modal Gain (DMG). The aim of this approach was to efficiently couple the pump power in the amplification medium, a *sine qua non* condition to preserve a good Power Conversion Efficiency (PCE). In the present work, this concept has been revisited and the performances improved in order to eliminate some drawbacks that have been put in evidence after the first proof of concept. This paper is then organized as follows: the new fiber geometry will be presented in the first section, in regard to the manufacturing considerations that led to its advent. The general guiding properties of the fiber will also be exposed and discussed. In a second section, this fiber design is applied to the optical amplification of 10 different spatial modes. The results of a numerical study permitted to identify a relevant geometry that has then been realized and tested in an amplifier configuration using specifically designed multiplexers (MUX and DEMUX). Crosstalk and gain performances are finally presented and discussed.

2. Proposed design

2.1. General concept

As has been recalled in the introduction, our group previously demonstrated that the use of a micro-structured core in a Photonic Crystal Fiber (PCF) geometry gives access to a wide range of possibilities for efficiently addressing the amplification of up to 10 modes in a single FMF [9]. In the design proposed back in 2013, besides the need to accurately match the refractive index of the different elements that were constituting the 19-cell core, a quite large volume of glass was necessary to synthesize the fiber by the so-called Stack and Draw method. More precisely, considering that the central part of the stack was made of millimeter-sized rods, it was not possible to use only one MCVD preform because erbium-doped region is about 2 nm in diameter when the solution doping approach is used. This explains why Sol-Gel-made erbium-doped rods had been adopted at that time, the glass volume being more than 5 times larger in this case. However, it is well-known that MCVD process gives access to a wider range of glass compositions and erbium concentrations, which explains why we tried to identify an alternative fiber design that could permit to exploit glass materials easily accessible by such a technique. The basic idea of the new approach is to realize a micro-structured core made of several high-index erbium-doped inclusions, with a refractive index n_2 and a diameter d_2 . These inclusions are arranged in a triangular symmetry with a pitch equal to $d_1 > d_2$, and are embedded in a medium-refractive index pedestal structure with an hexagonal shape, having a background refractive index $n_1 < n_2$. This large pedestal structure constitutes the core of the fiber. The core zone is finally surrounded

by a pure silica cladding with refractive index $n_0 < n_1$. The elementary cell of the core is hence made of an erbium-doped rod concentrically surrounded by a pedestal, such a structure being easily manufactured by MCVD. Moreover, a single preform provides, in this case, enough raw materials to draw all the necessary millimeter-sized inclusions. Figure 1 illustrates the proposed theoretical fiber design and the key opto-geometrical parameters that are conditioning the guidance properties. Depending on the values used for these parameters, various possibilities in terms of guiding properties are accessible and discussed hereafter.

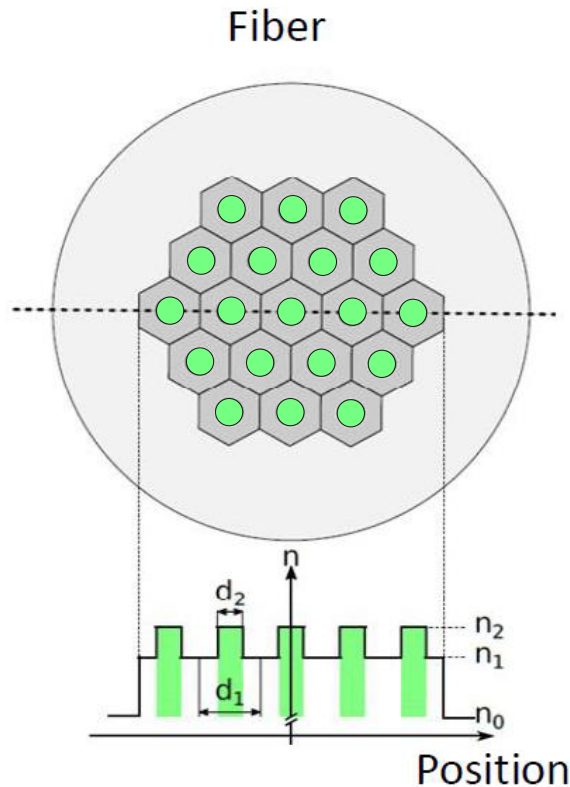


Fig. 1. Illustration of the concept of micro-structured core FMF. The high-index erbium-doped inclusions are represented in green, having a refractive index of n_2 and a diameter of d_2 . These inclusions are located in a pedestal structure with a refractive index of n_1 surrounded by a pure silica cladding with a refractive index of n_0 .

As is illustrated by the numerical results presented in Fig. 2, one can see that, depending on the relative size of the erbium-doped inclusions, d_2 , with regard to the wavelength, λ , the fiber can authorize different guiding regimes. For example, in the case of $\lambda \ll d_2$, light is strongly confined in the high index erbium-doped regions that can be viewed as individual cores. However, the distance between them is small enough to generate coupling: supermodes are then formed and the fiber can be considered as a multicore coupled-core fiber (here defined as coupling regime #1, Fig. 2(b)). In the case of $\lambda \gg d_2$, the fiber behaves similarly to a step-index FMF for which the large hexagonal core presents a refractive index given by the geometrical average of the composite medium that constitutes the 19-cell area. In this case, light cannot resolve structural details of the core, as can be seen in Fig. 2(d) (coupling regime #3). Such a situation is quite similar to the one reported for multifilament core SMF [10]. In between these two extrema (see Fig. 2(c)), there exists an operating point (coupling regime #2), labelled as $\lambda \simeq d_2$, for which the fiber behaves as an FMF with light confinement occurring in the whole pedestal region and extra-confinement in

the high-index inclusions, as is illustrated by Fig. 2(e) at the pump wavelength in the case of the fundamental mode. These over-intensities will help to increase the mode/dopant overlap integrals, hence offering the potential for better PCE values.

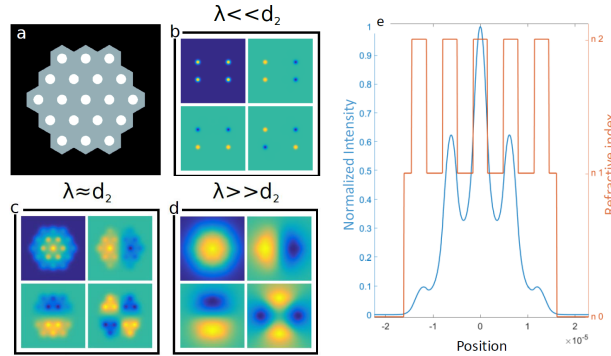


Fig. 2. (a) 2D Refractive index profile of the proposed fiber design (refractive index n_2 in white, n_1 in grey and n_0 in black). Numerical results for the distribution of the electric field of the first four guided modes as a function of the relative dimension of the wavelength in regard to the core micro-structure when (b) $\lambda \ll d_2$, (c) $\lambda \approx d_2$ and (d) $\lambda \gg d_2$. Calculations are performed at the pump wavelength. (e) 1D refractive index profile of the fiber along the horizontal direction superimposed to the normalized intensity profile of the LP_{01} mode at 980 nm guided in the coupling regime #2.

2.2. Model and global guiding properties

Starting from the generic design presented in the previous section and scaled to the guidance of 10 spatial modes in the C-band in coupling regime #2, optical amplification has been modeled with the help of the optimization procedure presented in Ref. [11] in order to determine the modal distribution of the pump beam that minimizes the gain excursion. The opto-geometrical parameters of the fiber considered here are $d_1=6 \mu\text{m}$, $d_2=2.5 \mu\text{m}$, $n_2-n_0=8 \times 10^{-3}$, $n_1-n_0=4.4 \times 10^{-3}$. These values have been chosen both by taking into account the manufacturing constraints of the fiber and the efficient guidance of 10 spatial modes at the signal wavelength guided under the coupling regime #2 described in Fig. 2(c). Note that the overlap integral between the guided modes obtained in this case and those of a perfectly circular step index fiber can be large: more than 94 % for all the modes at 1550 nm in the case of our fiber and a step index fiber with a core diameter of $24 \mu\text{m}$ and a numerical aperture of 0.12.

Considering that the suited mode profiles could be generated using Multi-Plane Light Conversion (MPLC) technology [12], we left the possibility to the algorithm to converge towards a pump mode profile made of a reduced number of modes chosen among the 20 modes that are guided at the pump wavelength (980 nm). This optimization targeted the best compromise between the highest average gain value delivered by the amplifier and the lowest gain excursion between the different signal modes. Four signal wavelengths (1530 nm, 1540 nm, 1550 nm and 1560 nm) representative of the main spectral features of the gain curve of EDFA have been considered for this optimization. The result of the optimization procedure are presented in Fig. 3 and Table 1, whereas all the parameters used for the modeling are listed in Table 2. One can see that low DMG value is predicted with a maximum value of 1.1 dB at 1560 nm, whereas gain excursion is 2.4 dB. An average gain value that is about 19.2 dB can be reached with a quite reasonable pump power budget of 300 mW distributed over four modes.

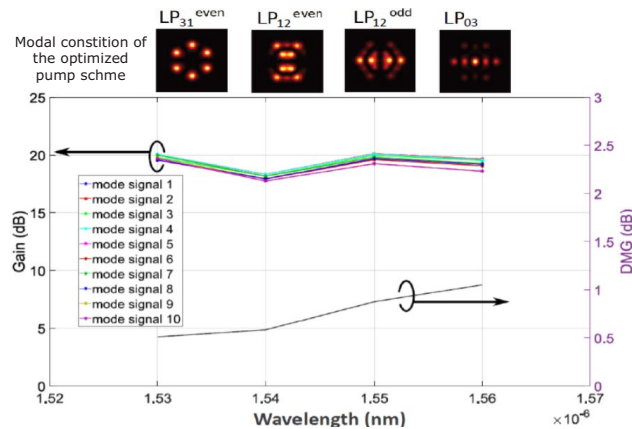


Fig. 3. Numerical results for the modal gain and differential modal gain (DMG) provided over the C-band by the 10-mode FM-EDFA in the configuration deduced from the optimization procedure, together with the pump modes used to form the optimized pumping pattern.

Table 1. Predicted amplification properties of the micro-structured core erbium-doped FMF using optimal pump scheme.

Average gain	19.2 dB
ΔG	2.4 dB
DMG (C-band)	0.5 - 0.6 - 0.9 - 1.1 dB
Number of pump modes	4
Pump modes	LP_{31}^{odd} - LP_{12}^{even} - LP_{12}^{odd} - LP_{03}
Pump modes percentage	23 - 26 - 36 - 15

Table 2. The parameters used to optimize the micro-structured core erbium-doped FMF.

Pump power	300 mW
Signal power	$12 \mu\text{W}/\text{mode}/\lambda$
Fiber length	1.68 m
Erbium concentration	$10^{26} \text{ ion}/\text{m}^3$

2.3. Fabrication

On the basis of this prediction, a fiber has been manufactured. The core material is obtained from a preform synthesized by MCVD. More precisely, 10 germanium-doped layers have been deposited on the inner surface of a pure silica tube and covered by a germanium-doped porous layer that has then been soaked with an alcoholic solution containing erbium and aluminum salts. This layer has then been dried and sintered into a transparent glass before the collapsing of the preform. The refractive index profile of this preform and its erbium ions distribution are presented in Fig. 4(a). After chemical etching of almost all the pure silica cladding, the preform has been drawn into several millimeter-sized rods that have then been assembled with pure silica elements, sleeved into a tube and then drawn into a cane and then into an all-solid fiber after a second oversleeving. The 2D refractive index profile of the fabricated fiber is presented in Fig. 4(b) and the scanning electron microscope (SEM) image of the core region of the final fiber is presented in Fig. 4(c). One can note that it respects very well the theoretical design (see

Fig. 2(a) for reference). The core dimension is close to $24\ \mu\text{m}$, the diameter of the high-index erbium-doped inclusions is about $2.5\ \mu\text{m}$ and the distance between two adjacent inclusions is about $6\ \mu\text{m}$.

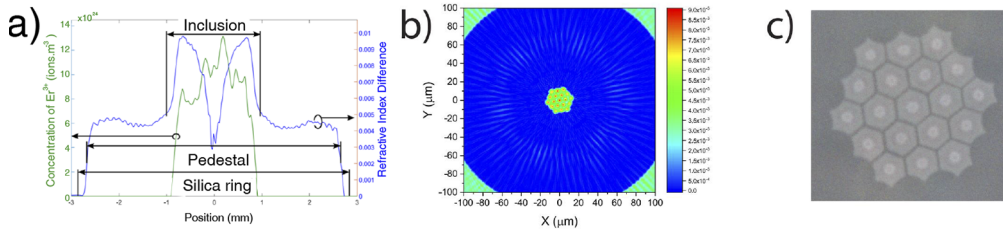


Fig. 4. (a) Refractive index profile of the preform fabricated by the MCVD method (in blue) as well as the Er^{3+} distribution (in green), (b) 2D refractive index profile and (c) SEM image of the core region of the fabricated fiber. On images (b) and (c), each bright inclusion is $d_2 = 2.5\ \mu\text{m}$ in diameter.

2.4. Experimental characterizations

At first, the guiding properties of the fiber were investigated. The attenuation curve and the Er^{3+} -related absorption of the fiber have been measured by the cut-back method using a broadband light source and an optical spectrum analyzer (OSA)(Yokogawa 6370B). These measurements were done by splicing the micro-structured core erbium-doped FMF to a single-mode fiber, which favors the excitation of LP_{0n} modes. The results are presented in Fig. 5 for which different fiber lengths have been used. As can be seen in Fig. 5(b), the intensity of the ${}^4\text{I}_{15/2} \rightarrow {}^4\text{I}_{13/2}$ absorption band is about 2.2 dB/m whereas a relatively high level of background losses around 0.12 dB/m is deduced from a measurement performed on a 50 m-long piece of fiber (Fig. 5(a)). We should mention that these loss properties could be improved, adopting cleaning and dehydrating procedures of the stack before drawing. The fiber has then been equipped with mode multiplexing/demultiplexing systems based on the MPLC technology developed by the company Cailabs, so as to permit the individual probe of the different modal channels. Figure 5(c) provides a visual comparison between the numerically calculated mode intensities of the fiber (upper row) and a view of the guided modes recorded using a filtered Amplified Stimulated Emission (ASE) source imaged with a camera (Hamamatsu C10633-23) (lower row). The guided modes obtained experimentally match well the numerically calculated modes, especially for the first five groups of modes. We should mention that this MPLC technology was built to be compatible with Polarization Division Multiplexing (PDM): the variation of the polarization state in the system has no effects on its performance.

A 24 m-long piece of the fiber equipped with mode MUX and DEMUX has then been tested. This quite long fiber length, compared to the one for the ideal fiber showcased in Table 2, is due to a lower erbium concentration level in the manufactured preform. We emphasize that each mode multiplexer contains a single phase plate designed for both signal and pump wavelengths. This permits injecting the pump on an SMF ("Channel 11" in Fig. 6) in parallel with the 10 signal SMF, the mode multiplexer converts the pump input into the optimal pump mode in the same way as for the signal inputs. At first, in order to quantify the crosstalk, each mode is successively injected with the same input power at the wavelength of $1610 \pm 10\ \text{nm}$ (ASE source filtered in this wavelength window), thus minimizing the impact of erbium absorption while staying in the wavelength range of the MUX and DEMUX. At the output DEMUX, the power of each mode is successively measured (Agilent 81624B), and the crosstalk performances of the whole system (MUX + FM-EDF + DEMUX) are reported in Table 3. An average crosstalk value of about

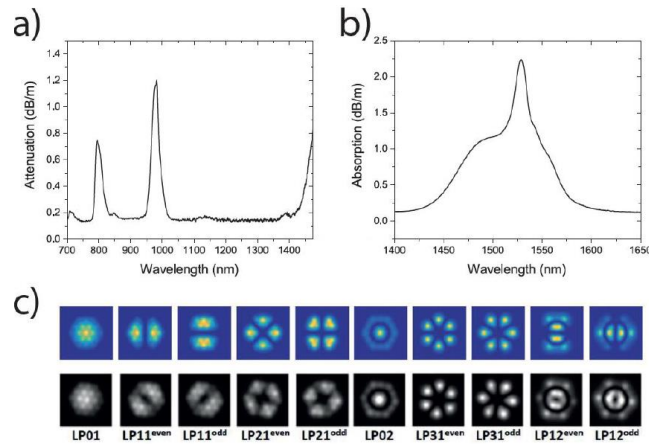


Fig. 5. (a) Attenuation curve measured on the micro-structured core erbium-doped FMF, (b) Er^{3+} related absorption band around 1530 nm and, (c) comparison between the numerically calculated modes (upper row) and a view of the guided modes recorded using an ASE source filtered around 1550 nm (lower row).

-16.3 dB is measured whereas the best and worst values are respectively -27.8 dB and -5.6 dB. Hence, the crosstalk values are fairly acceptable overall for this first demonstration, especially for the first five mode groups. However, some HOM, in particular the LP_{12} mode group, present a much higher level of crosstalk than the rest (especially for the odd LP_{12} that couples to LP_{02} and LP_{21} modes). Looking at Fig. 5(c), this can be attributed to a lower quality mode matching between the calculated modes of the digitized index profile of the manufactured fiber (in which it has been considered that the elementary inclusions were all identical) and the real modes of the fiber itself presented in Fig. 4(c) (when compared to the other mode groups). Non-perfect orientation of the fiber in comparison to that of the modes could also contribute to the observed discrepancies.

Table 3. The global crosstalk performances of the amplification system (MUX + FM-EDF + DEMUX). Values are given in dB.

IN \ OUT	LP_{01}	$\text{LP}_{11}^{\text{even}}$	$\text{LP}_{11}^{\text{odd}}$	$\text{LP}_{21}^{\text{even}}$	$\text{LP}_{21}^{\text{odd}}$	LP_{02}	$\text{LP}_{31}^{\text{even}}$	$\text{LP}_{31}^{\text{odd}}$	$\text{LP}_{12}^{\text{even}}$	$\text{LP}_{12}^{\text{odd}}$
LP_{01}		-12.4	-10.7	-13.3	-21.8	-15.8	-23.3	-19.4	-17.8	-17.5
$\text{LP}_{11}^{\text{even}}$	-11.3			-15.0	-15.0	-13.5	-14.6	-16.7	-18.6	-12.5
$\text{LP}_{11}^{\text{odd}}$	-11.7			-14.2	-12.4	-10.5	-15.8	-17.4	-16.5	-11.7
$\text{LP}_{21}^{\text{even}}$	-17.6	-13.8	-16.8			-15.2	-9.6	-10.9	-17.5	-7.1
$\text{LP}_{21}^{\text{odd}}$	-19.1	-14.1	-14.0			-14.5	-11.5	-13.2	-11.1	-8.2
LP_{02}	-16.9	-17.6	-13.1	-13.8	-14.7		-17.3	-21.1	-10.8	-5.6
$\text{LP}_{31}^{\text{even}}$	-26.1	-19.8	-21.8	-13.1	-15.1	-16.1			-18.9	-17.6
$\text{LP}_{31}^{\text{odd}}$	-25.9	-24.2	-27.4	-10.1	-17.1	-24.8			-17.9	-11.7
$\text{LP}_{12}^{\text{even}}$	-25.9	-20.3	-22.2	-17.3	-17.8	-9.5	-22.8	-20.0		
$\text{LP}_{12}^{\text{odd}}$	-27.8	-20.5	-20.3	-15.0	-14.2	-15.7	-22.7	-15.0		

Using the setup presented in Fig. 6, the performances of the fiber in optical amplification regime have been analyzed, operating in the small signal configuration. A co+contra-propagating configuration has been used. About 354 mW of total pump power has been effectively injected in the fiber provided by two laser diodes emitting around 980 nm (Lumentum S27-7602-460),

split into 226 mW in co-propagative and 128 mW in contra-propagative directions, to ensure the homogenization of the pump power over the fiber length. So as to measure the optical gain over the C-band for the different modes, a Wavelength-Division Multiplexing (WDM) comb made of 8 wavelengths distributed between 1530 and 1565 nm (CoBrite MX1) has been successively injected into the different modal channels with a power of -15 dBm so that the FM-EDF would be operating in the small signal configuration. This value refers to the power at the input of the EDF. Considering the strong coupling there exists between degenerate non-centered modes (namely mode groups LP_{11} , LP_{21} ··· etc), the gain performances for the odd and the even degeneracy of a given group of mode have been averaged.

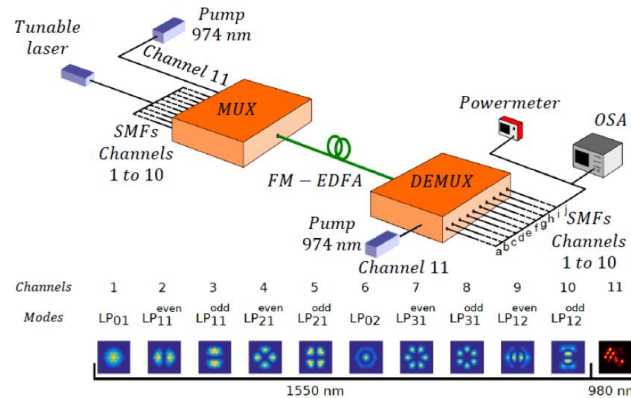


Fig. 6. Experimental setup used to characterize the amplification system (MUX + FM-EDF + DEMUX) and intensity profiles of the modes generated by the MUX at the signal and the pump wavelengths. The pump intensity profile is the result of the combination of modes reported in Table 1 and deduced from the optimization process.

The modal gain performances of the FM-EDF by itself are reported in Fig. 7. One can note that a quite flat gain is measured over the C-band for all the modes individually. The average value over all the modes of the gain fluctuation on the amplification band is 2.9 dB. The mean gain value is 14.9 dB whereas the mean DMG value is about 4.2 dB. The total gain excursion for all the spectral and spatial channels is less 6.9 dB. Such results are quite comparable to those reported by Wada et al. for a core-pumped 10-mode EDFA realized by concatenation of fibers [13]. These values are quite different from the numerical results presented in Table 2. As was previously mentioned for the signal modes, slight mismatches between the calculated and the real modes might also exist for the pump modes. Complementary simulations, not shown in this paper, have indicated that minor changes in the pump modes distributions (especially coupling between LP_{12} odd and even configuration) could increase the gain excursion by some dBs. At the pump wavelength, such a cross-talk will lead to a transverse inversion profile different from the suited one and hence to a degradation of the amplification performances. Moreover, the observed discrepancies are also attributed to losses at the pump wavelength that are larger than expected. These losses are distributed among the background losses of the fiber itself (see Fig. 5(b)) and the insertion losses induced by the MUX, higher than usual for those systems. Typically, the measured losses of a single MUX are around 6 dB when pumped with 300 mW which, added to the losses of the fiber, leads to more than 10 dB cumulated losses. The gain of the amplifier is hence power-limited, which at least explains the gain level smaller than expected. However, we should mention that this is the demonstration of a 10 modes amplifier which is core-pumped and operates using relatively low pump power. Furthermore, this system can be considered as the first all-integrated system to apply the MPLC technology using a single phase plate to shape both beams at the signal and the pump wavelengths.

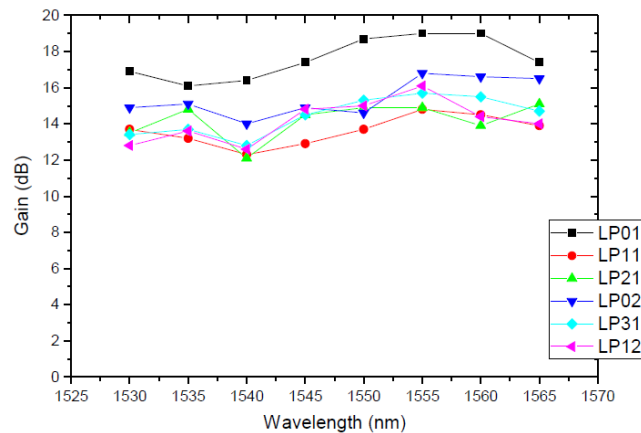


Fig. 7. The modal gain performances of the FM-EDF operating in the small signal configuration.

The PCE is generally considered as a good parameter to compare the energetic performances of two fiber amplifiers. For a pump wavelength centered around 980 nm and a signal wavelength centered around 1550 nm, the maximum theoretical PCE value is given by the ratio of the pump/signal photon energies, known as the quantum defect, which is 63 % in this case. This level is, however, never reached experimentally and the PCE values of SM-EDFA reported in the literature are about 50 % as cited in Ref. [14] whereas the PCE of commercial EDFA is assumed to be below this value and closer to about 30 %. The presented micro-structured fiber presents a PCE value of 22 %, while considering the MUX induced losses, for a mean gain value of 14.9 dB, which is hence not so far from the PCE of SM-EDFA used in Telecom networks. We concede that the value of 22 % only represents the PCE over the fiber alone; while the PCE of the entire amplification system comprising MUX and DEMUX is much lower the excess loss of MUX and DEMUX is at cause. So, while the presented fiber itself performs relatively well, even compared to SMF, currently available multi-mode interfacing components impede amplification systems from exploiting the fiber at its full potential. In order to better illustrate the efficiency comparison between these two fibers, we simulated a single-mode EDF delivering the same mean gain value as the micro-structured EDF and found that it necessitates 15 mW of pump power. Thus, in order to amplify the same number of spatial channels as the micro-structured EDF, 10 SM-EDFA are necessary for a total pump optical power of 150 mW. As aforementioned, the few-mode amplification system presented here can be the subject to several improvements that could boost its efficiency to potentially exceed that of parallel single-mode EDFA. Some ways to improve the performances of the systems consist in the reduction of the fiber losses by adoption of some purification steps during the fiber manufacturing, a better global transmission at the MUX level, specially at the pump wavelength and a better mode matching between the modes generated by the phase plate of the MUX and those of the fiber.

3. Conclusion

In this paper, a new micro-structured core erbium-doped FMF design has been presented. Using 19 sub-cores in a pedestal geometry, we theoretically demonstrated the ability of controlling with great precision the distribution of the Er^{3+} ions inside the core in order to obtain an optimized array delivering equal gain to the 10 guided modes at the signal wavelength. This design was later optimized and realized with a good match with the targeted design. This fiber was combined with customized single phase plate MUX and DEMUX operating at both pump and signal wavelengths.

This permits an all-integrated amplification system which was experimentally tested and offered the validation of the feasibility of such systems based on this technology, with some room to improve its performances. We should mention that this design presents a significant upgrade to our previous micro-structured design: a better and more accessible fabrication process is demonstrated, together with promising cross-talk levels between its modes and a flat gain for all the guided modes over the C-band.

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Disclosures. The authors declare no conflicts of interest.

Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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