Coupled-Core EDFA Compatible with FMF Transmission

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Abstract: We report a 6-core coupled-core fiber amplifier compatible with 6-mode FMF. The coupled-core amplifier not only reduces mode dependent gain but also introduces strong random mode mixing, thus easing mode dependent impairments in FMF transmission systems.
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1. Introduction

Spatial division multiplexing (SDM) has been extensively investigated as a promising solution to increase the transmission capacity of a single fiber. SDM can upscale the capacity per fiber proportional to the number the modes in a few mode fiber (FMF), realizing such operation in long haul transmission systems requires the development of amplifiers that are compatible with FMFs. So far, transmission over FMFs has been shown for more than 15 modes [1]. FMF transmission the main limitations are differential mode group delay (DMGD) and mode dependent loss or gain. Another promising approach to overcome the capacity limitation imposed by single mode fiber systems is the use of coupled-core transmission fibers. In these fibers, the strong random mixing between cores reduces the buildup of nonlinear interactions [2-5]. Moreover, linear impairments are also reduced as the mixing ensures that every input signal propagates nearly equally on all cores which homogenizes any loss or delay differences between cores.

From an amplifier perspective, couple-core fibers are attractive as they can be designed to provide low mode dependent gain levels, as well as, strong random mixing between all supported modes. As such, quite recently, coupled-core fiber amplifiers have been considered in a number of studies, demonstrating their potential for SDM applications [7-8]. On the other hand, all coupled-core amplifiers investigated to date are unsuited for FMF links. The question naturally arises as to whether one can implement a coupled-core amplifier which can be integrated into a FMF transmission system. Here, we report for the first time a coupled-core amplifying fiber concept compatible with FMFs. Our 6 coupled-core EDF can be coupled with low-loss to a 6-mode FMF by a slight adiabatic taper. Thus, allowing efficient mode conversion from a FMF to a couple-core fiber scheme. Moreover, we demonstrate mode dependent gain of less than 2 dB, gain over 20 dB and noise figure below 7 dB across the full c-band for all modes.

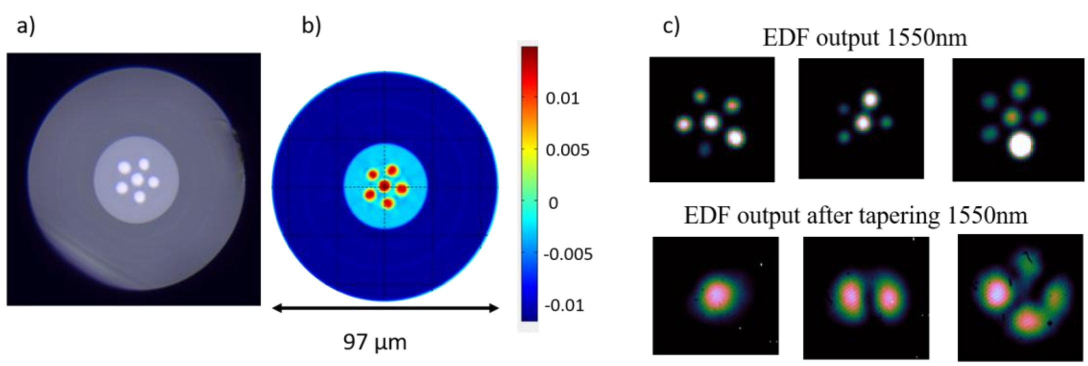

Fig. 1 (a) Cross-section image of the fabricated 6-core coupled-core EDF. (b) Measured refractive index profile. (c) Near-field intensity profiles at the output of the coupled-core fiber (top) and at the output of the tapered coupled-core fiber (bottom).

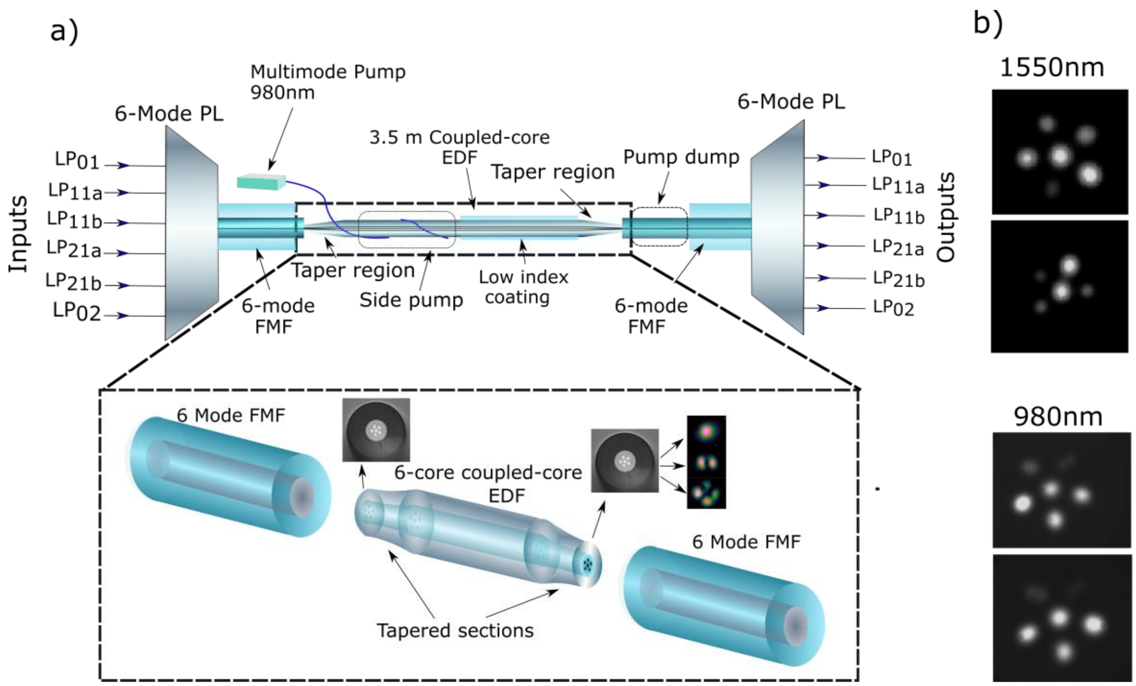

Fig 2. a) Amplifier characterization setup using two PL to launch signal and side pump configuration. b) Mode Profiles of the EDF for signal and pump wavelengths.

2. Coupled-core Amplifier Fiber Design and Fabrication

The coupled core amplifier was designed to minimize both, mode dependent loss and differential group delay when spliced to a 6-mode transmission fiber. The benefit of coupled core amplifier fiber design is because under this regime mode mixing among the cores can be reached. A condition to obtain mode mixing in a multicore fiber has been reported in [7]. This coupled-core approach establishes a regime in which a set of cores, placed at appropriated distance between each other, in a multicore fiber behave like a single-multimoded core with slightly different propagation features.

The multicore EDF was fabricated by inserting six erbium-doped rods into a silica preform with 6 drilled channels. Subsequently, the preform was placed inside a fluorinated tube (Δn of -8.2x10^{-3}). A fiber was then drawn to an outer diameter of 97 μm and a low index polymer coating (NA ~0.4) was applied in order to guide multimode pump light. The outer diameter has a strong impact on the amplifier properties and was designed to provide strong overlap between the pump and the active cores. Figure 1a, shows the cross-section microscope image of the 6 coupled-core EDF. The diameter of inner silica region surrounding the Er-doped cores is 35 μm. The diameter of the Er-doped cores is ~5 μm and the core-to-core distance among the external cores is 7 μm. The distance between the central core and the external cores is 8 μm. We used an Er-doping concentration of 4.5x10^{25} ions/m^{-3}, the refractive index contrast of the Er-doped cores with respect to silica is Δn ~16x10^{-3}. The measured 2D refractive index profile of the fabricated fiber is presented in Fig. 1b, clearly highlighting the F-doped, un-doped silica and Er-doped regions.

3. Experimental Setup

Having considered the linear properties of the coupled-core EDF, it is now important to assess the amplifier performance. In order to do so, we used two 6-mode selective photonic lanterns (PLs) spliced to 5 m of FMF supporting six modes (LP_{01}, LP_{11a}, LP_{11b}, LP_{21a}, $LP_{21b,}$ LP_{02}). The measured transfer matrix (Tx) of the pair of lanterns and 10 m of FMF is depicted in Fig. 3b. We obtained mode dependent loss (MDL) of approximately 3 dB and. Figure 2(a) depicts the experimental setup used to characterize the amplifier. The amplifying fiber is highly coupled for both signal and pump wavelengths, we can adiabatically taper by a small ratio to excite better modes at the FMF output as shown in fig 1 c) after tapering the EDF we can excite some higher order modes (HOMs) as in the FMF. We used a cladding pumped configuration to couple the pump light into the EDF, a coreless fiber is spliced to the pump delivery and tapered down to 20 μm, the coreless fiber is then wrapped 1.5 turns around the EDF so that pump light can couple thanks to the double clad structure of the fiber and the low index coating. The signal is coupled into the amplifying fiber using a 6 mode PL spliced to passive FMF supporting 6 spatial modes. We use only one pump source taking advantage of the strong coupling at the pump wavelength. To characterize the amplifier, we used two 6-mode photonic lanterns (PLs) spliced to 5m of FMF supporting six spatial modes. The transfer matrix of the pair of lanterns is showed in Fig. 3 b) (top), we observe good mode selectivity and a mode dependent loss (MDL) around 3 dB.

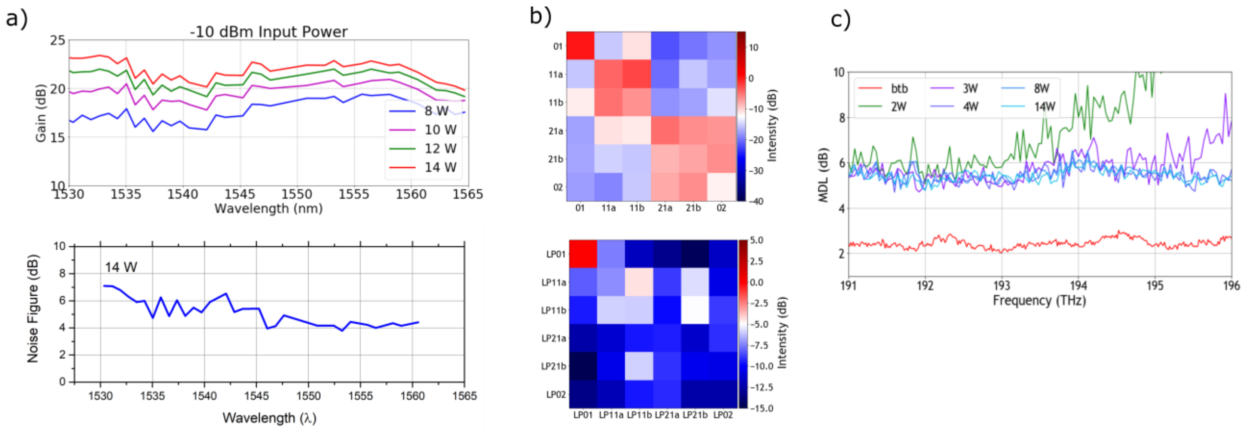

Fig. 3 a) Gain and noise figure measurements for a 3.5 m long EDF b) Transfer matrix of the pair of PL used in the amplifier (top) and including the amplifier fiber (bottom) c) MDL measured for a pair of lanterns back to back and for different pump powers in the amplifier.

Fig. 3 b) (bottom) shows the transfer matrix when the amplifying fiber is spliced in between the FMFs, the matrix is not showing high mode selectivity compare to the case when having two lanterns back to back, when the amplifying fiber is spliced in between the PLs we measured 5 dB MDL for pump powers above 4W, this increase in MDL is due to the mode field mismatch between the amplifying fiber and the FMF, this can be further improved by matching better the 6-core coupled-core EDF to the FMF mode overlap. One of the features of this fiber is that it also provides some mode missing specially into HOMs, this helps to reduce the DMGD in FMFs, by better designing the EDF we can provide mode mixing across the whole transfer matrix.

4. Mode Dependent Gain Measurements

Fig. 3 (b) shows the transfer matrix of the amplifier measured across the entire c-band, we observe strong mixing for modes in groups 2 and 3, so that mode-selective excitation and reception can be erroneous because of the coupling that exists between each mode group. To better measure the amplifier MDG the amplitude and phase transfer matrices (TM) of the amplifier between each input and output pair across all wavelengths need to be characterized. We measure the TM using swept-wavelength interferometer with spatial diversity [6], from this TM, the MDL/MDG can be computed by a eigen-analysis of the TM.

Under cladding pump illumination, we characterize the MDL and observe that for pump values above 4 W the MDL remains constant at around 5 dB showing low MDG for 3 mode groups with a MDG variation below 2 dB with pump levels from 4 to 14 W as shown in Fig 3 c).

In conclusion we have demonstrated for the first time a coupled-core amplifying fiber concept compatible with FMFs, the fiber is a 6-core coupled core EDF that by a slight taper can be spliced to FMFs supporting 6 modes. Strong coupling in the EDF for pump and signal reduces the MDG and provides mode mixing to reduce DMGD in transmission systems and can be scaled to FMF amplifiers supporting more modes.

References

[1] N. K. Fontaine *et al.*, in *OFC, 2015*, Th5C.1

[2] R. Ryf *et al.*, in *ECOC 2016-Post Deadline Paper; 42nd European Conference on Optical Communication; Proceedings of*, VDE, 2016, PDP Th3.C.3.

[3] S. Mumtaz *et al*. *IEEE Photonics Technology Letters*, vol. 24, p. 1574, 2012.

[4] R. Ryf *et al.*, in *2014 European Conference on Optical Communication (ECOC)*, 2014, PDP 3.2.

[5] T. Hayashi *et al.*, in *ECOC 2016; 42nd European Conference on Optical Communication; Proceedings of*, VDE, 2016, W2.B.5.

[6] N. K. Fontaine *et al.*, in *Optical Fiber Communications Conference and Exhibition (OFC)*, 2013, OW1K.2.

[7] N. K. Fontaine *et al.*, in *Optical Fiber Communications Conference and Exhibition (OFC)*, 2017. Th5D.

[8] M. Wada *et al.*, in *Journal of Lightwave Technology*, vol. 36, no. 5, pp. 1220-1225, March1, 1 2018.