Power efficient all-fiberized 12-core erbium/ytterbium doped optical amplifier

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Abstract: 20dB gain in C-band with only 5.3W of pump is achieved with an all-fiberized 12-core Er/Yb doped fiber amplifier. This result is a first step towards SDM transmission including power efficient amplifiers and ROADM. **OCIS codes:** 230.2285, 060.2280

1. Introduction

Space Division Multiplexing (SDM) is viewed as a viable solution to face the upcoming capacity crunch in optical networks [1]. Since the beginning of 2010s, there has been a lot of work to develop passive multicore fibers (MCF) for long-haul transmission applications. One of the key issues studied in parallel is the availability of power efficient amplification schemes, including active MCFs and fan-in/fan-out solutions [2-6]. This work describes the characteristics of a 12-core Er/Yb-doped fiber (12c-EYDF) amplifier prototype, that includes two 12+1 combiners directly spliced to the active MCF. In high capacity cables, optical fibers are most often arranged by 12 in so-called micro-modules. This configuration is the driving factor in the number of cores chosen to target realistic terrestrial amplifier specifications: 20dB of gain for an input power per core of 0dBm in the C-band.

2. Fabrication and characterization of a 12-core Er/Yb-doped MCF

The 12c-EYDF is fabricated by iXblue and Photonics Bretagne using the stack-and-draw process which originally developed for photonic crystal fibers, offers versality in the preform design. Accuracy and stability of core-to-core distances are crucial to reduce splicing losses between MCF and bundles. Accordingly, the preform design is derived from air-clad fibers [7] and based on a circular arrangement of doped preforms around a central rod, with all the cores lying on a single circle. Core size is fixed to ~6µm owing the fact that we do not expect non-linear effects in the targeted range of output power. Core contents in erbium and ytterbium strongly impact amplifier properties. A numerical model [8-9] developed by TELECOM Paris is used to optimize respective dopant concentration necessary to meet the targeted amplifier requirements. Calculations are performed for a single core in the configuration of a 940nm counter-propagating pump, uniformly distributed in 1/12th of the 12c-EYDF cladding area. As indicated in figure 1, erbium core absorption of ~36dB/m at 1536nm and [Yb]/[Er] atomic ratio of ~20 are good targets to meet amplifier requirements.

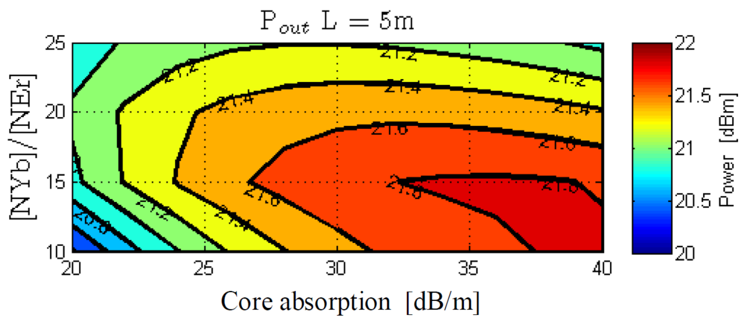

Fig. 1. Calculation of dopants concentration impact on overall gain for an injected power of 600mW and 5m fiber length

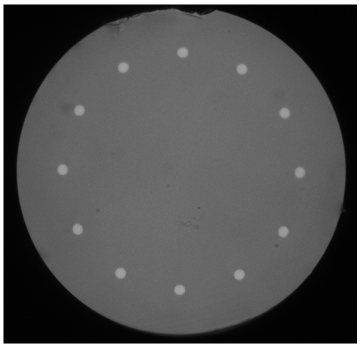

Fig. 2. Optical microscopy picture of the 12c-EYDF (Φ_{clad} = 187.5µm)

Based on those calculations, Er/Yb-doped preforms have been fabricated by MCVD process using conventional solution doping process. Drawing is preformed to obtain a 35.0µm core-to-core distance, the silica clad diameter is equal to 187.5µm. A dual primary low index/secondary high index coating is used to get a numerical aperture of 0.48 for the multimode clad. The 12c-EYDF cross-section is shown on figure 2. Core-to-core spacing is found to be 35.0±0.3µm using a calibrated optical microscope. This result highlights the tight geometrical tolerance obtained on the cores positioning. Erbium and ytterbium absorptions have been measured by the cut-back method using a broad-band source launched into to the multimode clad. Total rare-earth clad absorptions are estimated to be 3.7dB/m and 0.53dB/m, respectively at 914nm and 1534nm.

3. Development of combined Bundle/Fan technology

Pump and signals are coupled into the 12c-EYDF using a tapered fiber bundle based combiner co-designed by Photonics Bretagne, iXblue, Lumibird and manufactured by Lumibird. Pump light is launched through a central multimode fiber (core/clad sizes of 195µm/230µm and numerical aperture of 0.22) and signals through the 12 outer fibers (core/clad sizes of 15µm/80µm and numerical aperture of 0.19) designed to match mode field diameter of active cores after down-tapering. Owing to an optimized fusing/tapering process, reproductible core-to-core distances of 35±0.5µm are obtained, leading to a satisfactorily accurate matching to the 12c-EYDF geometry. The combiner cross-section is shown on figure 3. The compact packaging (80mmx5mmx5mm) of the complete assembly can be seen on figure 4.

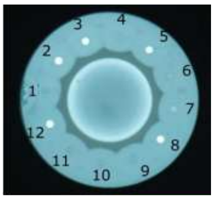

Fig 3. End view of the bundle

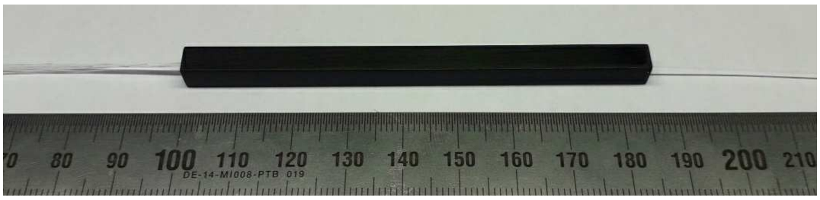

Fig 4. Packaging of the combiner/fan-in spliced to the 12c-EYDF

4. 12c-EYDF amplifier prototype assembly and characterization

The amplifier prototype is designed and manufactured by Lumibird. As described on figure 5, the 12c-EYDF is directly spliced at both ends to two 12+1 combiners. The fiber cleave angle is found to have a critical impact on the coupling loss and should be maintained below 0.1deg. The fan-in and fan-out combiners are first characterized by measuring signal total loss at 1.31µm when spliced to a 5.5m long 12c-EYDF. As seen on figure 6, an average insertion loss of 1.7dB is obtained with ±0.3dB core-to-core variations. This value includes 0.45dB for pigtails and 0.5dB for core attenuation, the latter has been estimated from optical time domain reflectometry measurements over a long length of 12c-EYDF. A 940nm multimode pump laser diode is chosen as it relaxes diode cooling requirements as the pump absorption is relatively temperature insensitive in this wavelength range [10]. 5.3W of optical power is coupled into 5.5m long 12c-EYDF via end-coupling in a counter-directional pumping configuration, with an efficiency >99%. Individual core performance is measured by launching 15 WDM channels spanning from 1535.2nm to 1564.1nm (with 0dBm of signal launched into each core under test). Figure 7 shows minimum, maximum and averaged over all the cores spectral gain curves. Averaged over all the cores and all the wavelengths, gain and optical power conversion efficiency are respectively of 20dB and 23%. Overall core-to-core gain variation ranges from 2.5 to 4.0dB along the full spectrum. Gain flatness around 7dB is typical for an Er/Yb co-doped fiber amplifier [11]. Figure 8 shows that maximal core-to-core power variation is only of 1.4dB. Core-to-core crosstalk is evaluated by injecting signal power in one core and measuring power at the output of one of the two adjacent cores. The measured crosstalk varies from 33 to 42dB from core-to-core, which is sufficient to prevent system performance impairments.

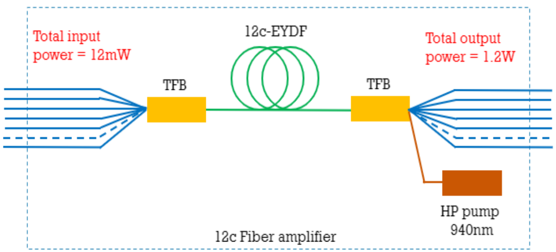

Fig. 5. Amplifier architecture

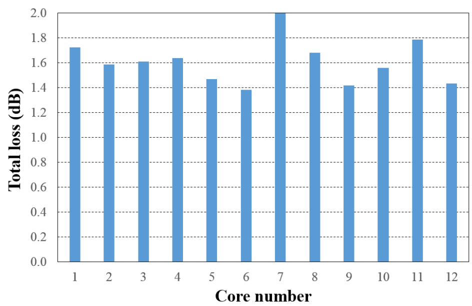

Fig. 6. End-to-end loss measured at 1.31µm for each core (combiner + 12c-EYDF + combiner)

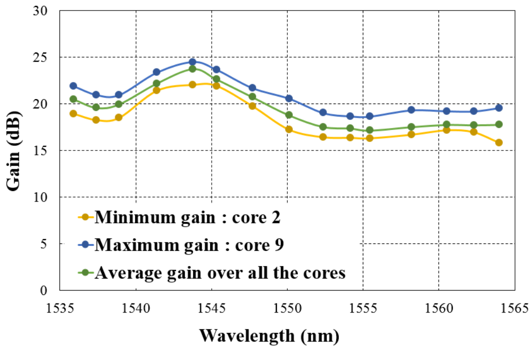

Fig. 7. Gain curves of the 12c-EYDF amplifier

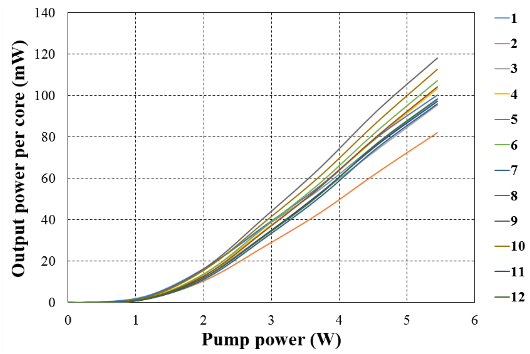

Fig. 8. Output power versus pump power for each core

5. Comparison of power consumption requirements

We compare the total power consumption required for laser diodes operation and cooling in conventional single mode EDFAs and the proposed cladding pumped 12c-EYDFA. In conventional single mode EDFAs, a typical pump diode consumes an average of 1.6W of electrical power for an output pump power of about 400mW, sufficient to provide about 20dBm of saturated output power. To operate at this power level, around 1.8W of electrical power is needed to actively cool the diode and to maintain its temperature (assuming a state-of-the-art low power consumption diode [11]). This would lead to a total power consumption of about 40.8W for 12 amplifiers. In the case of the studied 12c-EYDF, we use a total coupled pump power of 5.3W with a ~99% pump coupling efficiency. On the other hand, optical efficiency of our multimode pump laser diodes is about 50%. Using those figures, the total electrical power consumed in our 12-core EYDFAs is about 10.6W. This comparison highlights that our 12c-EYDFA architecture has the potential to provide significant power saving benefits. Moreover, used low brightness laser diode pumps are much cheaper than single-mode ones [12].

6. Conclusion

An all-fiberized 12c-EYDFA prototype has been assembled and characterized. Thanks to optimized design and fabrication processes, core-to-core spacing of the active fiber and 12+1 combiners matches very accurately. Splicing procedure optimization enables an average splice loss as low as 0.5dB. An average gain of 20dB in the C-band for an input power per core of 1mW is achieved with 5.3W of pump power at 940nm with an optical power conversion of 23%. There is still room for improvement of the amplifier performances by further optimizing cleaving/splicing procedures and combining co- and counter-directional pumping. Based on power consumption comparisons, this prototype demonstrates the benefit of pump mutualization though multicore fiber technology. Estimated power reduction compared to 12 EDFAs reaches a fourfold factor, leading to potential breakthroughs in the domain of specific amplifiers and ROADM suited to SDM transmissions.

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