Amplification and noise properties of an erbium-doped multicore fiber amplifier

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Abstract: A multicore erbium-doped fiber (MC-EDF) amplifier for simultaneous amplification in the 7-cores has been developed, and the gain and noise properties of individual cores have been studied. The pump and signal radiation were coupled to individual cores of MC-EDF using two tapered fiber bundled (TFB) couplers with low insertion loss. For a pump power of 146 mW, the average gain achieved in the MC-EDF fiber was 30 dB, and noise figure was less than 4 dB. The net useful gain from the multicore-amplifier, after taking into consideration of all the passive losses, was about 23-27 dB. Pump induced ASE noise transfer between the neighboring channel was negligible.

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1. Introduction

To meet the demand for larger bandwidth by ever-increasing number of internet users, various multiplexing schemes for transmission of data such as, optical time division multiplexing (OTDM), wavelength division multiplexing (WDM), polarization division multiplexing (PDM), as well as multi-level modulation formats have been developed. Transmission at a rate of 69.1 Tb/s over a distance of 240 km has been demonstrated based on such schemes [1]. Recently, there has been significant effort [2, 3] made to explore another domain for data multiplexing, namely, space division multiplexing (SDM), in optical fiber to increase the bit rate even further. SDM in optical fibers can be achieved either by incorporating multiple cores [4] in a single strand of fiber, or by accommodating multiple fiber modes in the core with a larger V-number (>2.405) [5–7]. To this end, multicore fiber (MCF) with 7 cores has recently been developed, with low loss and cross talk [8–11]. By multiplexing in space, wavelength and polarization, QPSK data has been successfully transmitted over a record length of 76.8 km at 56-Tb/s [12] and record high bit-rate of 109 Tb/s over 16.8 km [13].

The 7-cores have optical properties similar to that of conventional SMF fiber and have transmission loss within the range of 0.18-0.23 dB/km [12, 13]. For testing the performance of MCF as long haul transmission links, one will need compact multi-core erbium-doped fiber amplifier (MC-EDFA) to amplify independently the signals carried by each core. To compensate for the transmission loss occurred in these MCFs over a span of 80 km, optical amplifiers with a 15-18 dB of gain would be required. Besides high gain and low noise figure as offered by common single core EDFAs, MC-EDFA should also have low noise due to pump from neighboring cores.

In this paper, we report for the first time to our knowledge, the gain and noise properties of a 7-core MC-EDFA. The coupling of signal and pump light to individual core of MC-EDF was achieved through two low-loss specially designed all-fiber couplers. For a pump power of 146 mW, the average small-signal gain in the fiber was 30 dB, while the noise figure was below 4 dB. The useful gain from the multicore-amplifier, after all the passive loss, was typically about 23-27 dB, well above that required to compensate for the loss incurred over a span of 40-50 km. Pump induced cross-talk between the neighboring channels was negligible.

2. Multicore erbium-doped fiber (MC-EDF)

Figure 1 shows the cross-section of a 7-core MC-EDF, made from commercially available erbium-doped core rods. The cores are arranged in a hexagonal array with a 40.9 µm pitch. The core diameter and numerical aperture are equal to 3.2 um and 0.23, respectively. The fiber had a cladding diameter of 148 µm and acrylate coating with a diameter 250 µm. The mode field diameter at 1550 nm was estimated to be about 6 µm. The erbium-doped core has an attenuation coefficient of ~2.3 dB/m at 1550 nm, the Er³⁺ concentration in which was estimated to be 6x10²⁴/m³.

![Fig. 1. Microscopic image of the cross section of a MC-EDF.](image-url)
3. Experimental setup

Coupling of light to the individual cores of the MC-EDF was achieved through two compact tapered fiber bundle (TFB) couplers [11]. The TFBs were fabricated by tapering (taper ratio: ~3) a bundle of 7 specially designed fibers to achieve a core-to-core pitch at the tapered end matching the MC-EDF. This allowed use of a conventional PM fusion splicer. In the TFBs reported in [11] for interfacing MCF to single mode fiber, the mode field diameter was kept constant before and after tapering. Since high performance EDF has smaller MFD, the TFBs were designed to allow adiabatic conversion of mode field diameter from 9.04 to 6.1 µm. The 7-input fibers (at the un-tapered end) of TFBs have a MFD (LP01) of 9.04 µm and could be spliced to SMF fibers with minimal loss. We have chosen a core-to-core spacing of 40.9 µm for the MC-EDF that allowed matching with both the pitch and MFD of the tapered end of the TFB.

To study the amplification properties we used an experimental setup as shown in Fig. 2. Single frequency laser radiation from an external cavity laser diode operating in the range of 1520-1580 nm was used as a signal, which was combined with pump radiation at 980 nm using WDM couplers. In order to avoid spurious back-reflection and suppress ASE noise, isolators were connected at both the input and output ports, and pump radiation was allowed to propagate in the forward direction. In our measurements we number central core as #0 and the outer cores from #1 to #6, in sequence.

![Experimental setup](image)

Power of the amplified output and amplified spontaneous emission (ASE) noise under different input wavelengths and power levels were measured using an optical spectrum analyzer. Passive loss in the isolators and the WDM were measured over a range of 1520-1580 nm, while the loss between the input and output ports of the TFB-MCF-TFB assembly was measured at 1310 nm, where erbium has low absorption loss. The signal and noise power level at all other locations in the amplifier could thus be easily estimated. The gross gain ($G_{PQ}$) provided by the EDF and the net gain in the amplifier ($G_{AD}$), after the passive losses, were determined using the Eq. 1a and 1b.

$$G_{PQ} = \frac{P_{Q}}{P_{P}} \quad (1a)$$

$$G_{AD} = \frac{P_{D}}{P_{A}} \quad (1b)$$

Here, $P_{A}$, $P_{D}$, $P_{P}$ and $P_{Q}$ are signal power measured at points A, D, P, and Q. The noise figure of the amplifier system was computed for all the channels, using the following well known equation [14].

$$NF (dB) = 10.\log \left( \frac{P_{ASE-Q}}{h \nu B_o G_{PQ}} + \frac{1}{G_{PQ}} \frac{P_{SSE-P}}{h \nu B_o} \right) \quad (2)$$

Here, $P_{ASE-Q}$ represents the amplified spontaneous emission noise at the output of the ED-MCF measured over a bandwidth of $B_o$, $P_{SSE-P}$ is the signal spontaneous emission noise at the input (point P) of the MC-EDF.
In addition to measuring the gain and noise figure of the amplifier, we also investigated whether there was transfer of signal and ASE from one core to the other. We launched signal with and without pump in each core of the MC-EDF, one at a time, and monitored the power in the other cores to determine cross-talk.

4. Experimental results

Figure 3 shows the loss and cross-talk properties in the TFB-MCEDF-TFB module measured at 1310 nm. The numbers in the horizontal axis represents the core in which light was launched, and the vertical axis shows the attenuation in the signal, measured at seven outputs of the second TFB. Thus attenuation between the corresponding cores represents the insertion loss. The difference (in dB) in attenuations between corresponding and different cores can be considered as a measure of cross-talk. The loss between an input and corresponding output core of the gain assembly remained within 2.5-4.9 dB. The crosstalk averaged over six cores varied between 30.2 and 36.6 dB for the seven channels. A similar measurement was performed at the signal wavelength of 1546 nm (input power: 0.36 dBm), yielding an average absorption of 33.7 dB in the 15 m long MC-EDF.

![Fig. 3. Loss between the various cores at the input and output of the TFB-MCEDF-TFB module. #0: Central core, #1 - #6: outer corresponding cores.](image1)

![Fig. 4. Gross gain $G_{PQ}$ and NF measured for different cores of the EDMCF.](image2)
Figure 4 shows the gain $G_{PQ}$ and NF versus wavelength plotted for the seven cores, when the pump power was 146 mW. The input signal power level was maintained at $-15$ dBm. Thanks to the efficient coupling of the pump into the different cores, a maximum gain of 32 dB could be obtained from the amplifier. The gross gain $G_{PQ}$ depends on the amount of power launched into each cores and varies with the coupling loss in the TFB-MCEDF located at the input end of the amplifier. This results in a 4-dB gain variation. Since gain (in dB units) varies linearly with the pump power, a ±2-dB gain variation (4-dB total) around average gain of 30 dB can be caused by a pump power variation of about 6% (2/30), i.e. about 0.3 dB. The losses in the individual channel for the TFB-MCEDF-TFB assembly shown in Fig. 3 represent the sum of the unequal coupling losses at the input and output ends, which are different for all the cores. Even though the aggregate loss is higher (e.g. for core 6), if the losses at the input end is sufficiently small, the net gain can be found to be larger.

The noise figure NF over the whole C-band was less than 4 dB, except near 1520 nm where it increases to 6.4 dB. In Eq. (2), which was used to calculate NF, the contribution from the first term was the most dominant. An inaccuracy in estimating $P_{ASE,Q}$ by ± 1dB (which could result from any inaccuracy in the measurement of TFB coupler loss and ASE noise floor) would result in an error in NF approximately by the same amount in dB unit. This explains why NF for some core appears too low compared with 3-dB theoretical value.

![Figure 5: Gross gain $G_{PQ}$ and net gain $G_{AD}$ measured in different cores of the multicore EDF.](image)

Figure 5 plots the gains $G_{PQ}$ and $G_{AD}$ as a function of wavelength for the seven cores of the MC-EDF. The input power level was maintained at $-15$ dBm. The net gain was lower than the gross gain by about 5 dB, which was due to passive losses in the components, and splices. Variation in gain between the channels can be suppressed by further optimization of the TFBs and splicing, and also adjustment of the pump power injected to each of the cores.
To study the gain saturation effect, we measured the gain $G_{PQ}$ for varying signal power levels. Figure 6 shows gain and noise figure NF plotted as a function of output power for core #1. The 3-dB-saturated output power was about 10.3 dBm. Further increase in this output power is expected through pumping bi-directionally or at a higher power level.

In using erbium-doped multicore fiber amplifiers in transmission systems, one concern would be whether there is any accumulation of ASE due to the pump from neighboring erbium-doped cores. To study this we launched 1550 nm signal into the outer core (#1) and monitored the output from that core, while pump was launched into either center core #0 or core #1. The measured optical spectra are shown in Fig. 7. The level of ASE from the pump in core #0 is 25 dB lower than the ASE level for the pump launched into the core #1 and 60 dB lower than the amplified signal power level. If pumps were launched in all cores, as in typical operation, the ASE noise related to pump crosstalk would be strongest in the central core, as ASE is contributed from 6 surrounding cores. Since noise adds incoherently, for the center core it can be increase by as much as 7.7 dB. This, however, would still be 17.3 dB lower than the noise floor due to the pump in the same core.
We also launched a signal with an average power of 0.4 dBm and pump radiation of 146 mW in each of the cores at the input end, and measured the average output power for the various cores at the output end. The results of measurement are shown in Fig. 8. The signal amplification in different cores ranged from 11.2 dB (Channel #4) to 13.5 (channel #1). The leakage to the other cores, which consisted of signal and ASE, was lower than ~20 dB. By using a narrow bandpass filter the cross talk could be further suppressed.

Since the MFD of the erbium doped fiber (6 µm) is considerably smaller than that of passive MCF [11], any mismatch in MFD and pitch between TFB and MC-EDF is expected to result in higher loss and increased cross talk. The cross talk in the gain module is found to be higher than that observed in a previous passive MCF connectorized with TFBs [11]. Further optimization of the fabrication in TFB and splicing is expected to further enhance the gain and suppress the cross-talk between the cores.

5. Conclusion

In conclusion, we have demonstrated for the first time to our knowledge an erbium-doped multicore fiber amplifier for amplifying independent signals carried by 7 cores. Pump and signal were coupled to the individual cores by using all-fiber compact TFB couplers. The low loss coupling of TFB couplers, allowed us obtain net gain around 25 dB (gross gain ~30 dB) with a noise figure smaller than 4 dB and 3-dB saturated output of over 10 dBm. The ASE level from the neighboring channel was below 25 dB.

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