



32-core erbium/ytterbium-doped multicore fiber amplifier for next generation space-division multiplexed transmission system

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Abstract: We present a high-core-count 32-core multicore erbium/ytterbium-doped fiber amplifier (32c-MC-EYDFA) in a cladding pumped configuration. A side pumping technique is employed for ease of pump coupling in this monolithic all-fiber amplifier. A minimum gain of >17 dB and an average noise figure (NF) of 6.5 dB is obtained over all cores in the wavelength range 1534 nm–1561 nm for –4 dBm input signal power. The core-to-core variation for both amplifier gain and NF is measured to be <2 dB. The 32c-MC-EYDFA was then tested in a repeated multicore fiber (MCF) loop system and transmission over distances >1850 km was successfully demonstrated. We also compare the total power consumption of our MC-EYDFAs with that of 32 conventional single core erbium doped fiber amplifiers (EDFAs) to illustrate the potential power saving benefits.

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1. Introduction

Multicore fiber (MCF) technology has attracted significant interest as a potential candidate for the implementation of space-division multiplexing (SDM) in next generation optical communication systems [1, 2]. Over the last few years, there have been many impressive and significant advances in passive MCF optical components, amplifiers and transmission

experiments. For example, one of the most critical components for MCF technology, namely fan-in/fan-out couplers, have already been commercially developed with insertion losses as low as 1dB/pair thereby enabling this technology to be more flexible, compatible and comparable to standard single mode fiber (SSMF) based systems [3]. Also, high-core-count MCFs have also been developed [4–7] and to-date record spatial multiplicities of 37 and 114 have been demonstrated using a 37-core MCF with isolated single mode cores [4] and 19 core MCF with 6-moded cores [5] respectively. Transmission capacities of 2.15 Pb/s and 1-Pb/s have also been demonstrated in an unamplified transmission link using a 31 km length of homogenous 22-core MCF [8], and over a total length of 205.6 km heterogeneous 32-core MCF, respectively [9].

Another critical component for the technology, multicore fiber amplifiers, have also undergone significant parallel development. Initially, 7-core multicore Erbium-doped fiber amplifiers (7c-MC-EDFAs) were demonstrated in core-pumped configurations, demonstrating integration of the active Er-doped fiber [10]. Following this MC-EDFAs with up to 19 cores [11] have been demonstrated, further exploiting spatial multiplexing (e.g. by enabling isolator and partial pump sharing amongst the cores). However, a cladding pumped architecture is mandatory to really unlock reduced capital and operational expenditure. In cladding pumped MC-EDFAs, one (or two) high power, but relatively low brightness multimode pump laser diodes (LDs) are used to provide simultaneous amplification in all cores as compared to core-pumped MC-EDFAs, where multiple single mode LDs are used for the direct pumping of individual cores. This represents a clear demonstration of component sharing as required to reduce both cost and complexity, which can be further enhanced by integrating other passive optical components such as MCF isolators and filters [12]. Moreover, in cladding pumped MC-EDFAs, the multimode pump radiation can be delivered to the active MCF using a side pumping technique [13], which greatly simplifies the pump/signal combiner module. However, the pump absorption decreases due to the lower overlap between the pump and dopant area, which results in the need for a longer length of active fiber to fully absorb the pump radiation and an unwanted shift of the amplification window to longer wavelengths due to signal reabsorption effects. The reduced absorption can be improved by increasing the pump and signal overlap through modification of the fiber-cladding region and confining the pump light to a restricted region around the cores [14]. However, with higher multiplicity fibers there remains little scope for reducing the size of the pump waveguide and the preferred method is to enhance the pump absorption by using Yb-sensitized cores (i.e., to use an Er/Yb co-doped MCF). This provides for up to one order of magnitude higher absorption than possible using erbium-only doped cores. The Yb-ions efficiently absorb the pump radiation (at 975 nm) and transfer the energy to the Er-ions. This is common practice in cladding-pump fibers, and multicore Er/Ytterbium (Yb)-doped fiber amplifiers (MC-EYDFAs) with up to 12 cores have been demonstrated [15, 16]. Another advantage of Yb-sensitization is that the Er/Yb-doped fiber in a phosphosilicate glass host results in a relatively flat absorption spectrum to the blue edge of the absorption peak (i.e. 915 nm to 970 nm) which enables the use of passively cooled pump LDs which can be exploited to further reduce the overall power consumption. It is to be noted however that one drawback of using the EYDFA approach is that the phosphorous codoping required for efficient energy transfer from ytterbium to erbium ions modifies the emission/absorption cross sections of erbium relative to the case of an aluminosilicate core composition as used in conventional core-pumped EDFAs [17]. This, coupled with the relatively modest pump intensities associated with cladding pumping, compromises performance at the short wavelength edge of the C-band at wavelengths around 1535nm.

Recently, we demonstrated a cladding pumped 32-core MC-EYDFA (32c-MC-EYDFA) with a square core arrangement precisely matched to the geometry of a previously developed passive 32-core MCF (32c-MCF) transmission fiber [18]. The 32c-MC-EYDFA and 32c-MCF was directly spliced together to form an inline amplified space-division multiplexed

(SDM) transmission setup using standard fusion splicing, and successful transmission of 16-QAM signal was demonstrated in a 111.6 km of MCF. The active fiber was pumped at the absorption peak of 975nm and provided an average gain of >17 dB. However, the core-to-core gain variation was about 5dB and six cores exhibited somewhat worse performance relative to the others. We later established that this was mainly due to core-to-core loss variation originating in part from various passive components used in the setup, (i.e. the 111.6 km transmission MCF, MCF isolators, fan-in/fan-out couplers and associated splices) and in part due to core-to-core variations in dopant concentration whose impact was particularly felt due to the fact that the amplifier was pumped at the 975 nm absorption peak. Here, we present an improved 32c-MC-EYDFA providing significantly reduced core-to-core variation (<2 dB) in both gain and noise figure (NF). This was obtained in part by better amplifier construction, but also by tuning the pump wavelength to 965 nm away from the peak absorption wavelength in order to reduce the variation in core-to-core absorption and to ensure a more uniform population inversion along the length of the amplifier. The gain and NF performance of each core was measured in the wavelength range 1534 nm-1561 nm. A gain of >17 dB was obtained across this waveband. Due to its superior performance, the amplifier was then tested in a recirculating loop experiment and transmission over distance >1850 km with QPSK signals and ~720 km with 16-QAM signals was successfully achieved. We have also estimated the power consumption benefits of our cladding pumped MCF amplifier relative to multiple parallel single mode EDFAs.

2. 32-core multicore Er/Yb doped fiber

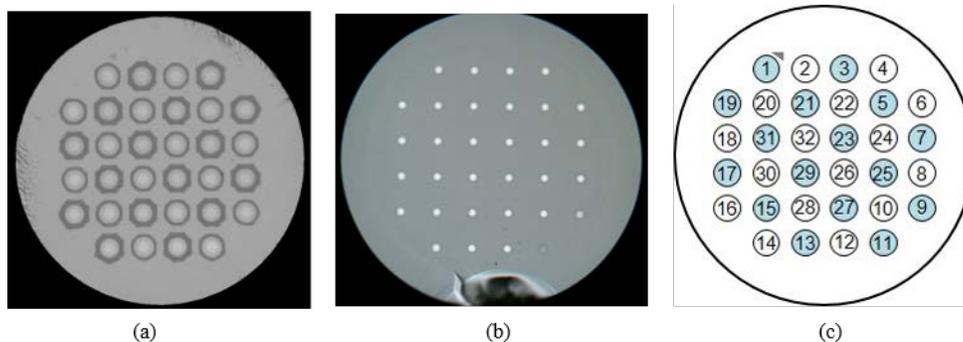


Fig. 1. Microscope image of (a) passive 32c-MCF and a core pitch matched (b) 32c-MC-EYDF, and (c) Schematic with Core indexing in 32c-MCF.

The active 32c-MC-EYDF was fabricated using an Er/Yb-doped preform with a step-index core ($\Delta n = 0.016$). This preform was originally developed for conventional single mode fiber applications and therefore a large volume of glass (i.e. from the cladding) was needed to be etched away from the starting preform in order to achieve the required core to cladding ratio and core pitch ($\Lambda = 28.8 \mu\text{m}$) in the final fiber. Figure 1(a) and 1(b) show the microscope images of the passive 32c-MCF (fabricated by Fujikura) [7] and active 32c-MC-EYDF, respectively. Figure 1(c) shows a schematic of the 32c-MCF with the associated core numbering. The passive 32c-MCF, had a heterogeneous core arrangement (specifically two kinds of core refractive index profiles were used) and incorporated an index trench in order to reduce the neighboring channel crosstalk. The MFDs associated with the two core designs were matched. For the active 32c-MC-EYDF fabrication, however, a simple homogeneous step-index core arrangement was used for ease of fabrication. In general, the fiber length used within a cladding pumped amplifier is in the range of just a few meters to a few tens of meters, such that crosstalk in this fiber is much less of an issue. The crosstalk was estimated (through simulations) to be about 70dB for a 10m fiber. The strong absorption and spontaneous emission of the amplifier prevented us from directly measuring the crosstalk

amongst the cores of the amplifier. However, the total crosstalk of an in-line amplified system (incorporating one 32-c EYDFA, 111.6 km of 32-c transmission fibre and 2 passive to active splices) was measured and found to be <30 dB [19]. The outer diameter and core-pitch of the resultant 32c-MC-EYDF was $242 \mu\text{m}$ and $28.85 \mu\text{m}$, respectively, values that were very well matched to those of the passive 32c-MCF. The smaller diameter and higher NA cores in the 32c-MC-EYDF unavoidably resulted in a large core MFD mismatch with the passive 32c-MCF. The butt-coupling loss was estimated to be about 1.3 dB. The detailed fiber specifications are summarized in Table 1.

Table 1. Specifications of 32c-MCF and 32c-MC-EYDF

	32c-MCF	32c-MC-EYDF
Avg. Core Pitch [μm]	28.8	28.85
Max./Min. [μm]	29.4/28.4	29.15/28.45
SD. [μm]	0.2	0.16
Cladding [μm]	241.2	242
MFD [μm]	9.9	5.6
Loss/abs.	0.235dB/km @1550nm	4dB/m @965nm 12dB/m @975nm

3. Experimental setup

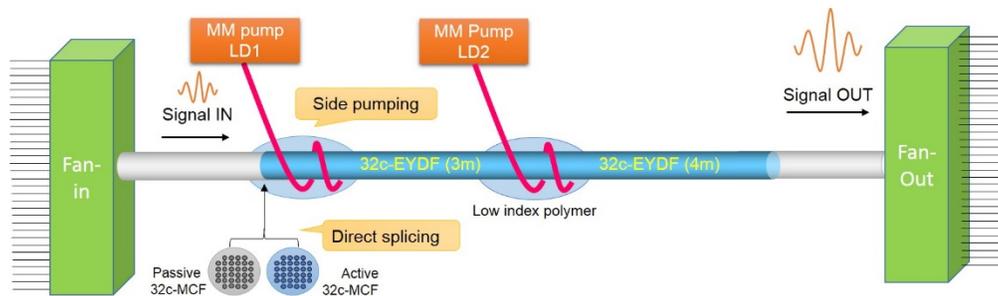


Fig. 2. Schematic of experimental setup for gain and noise figure measurement of 32c-MC-EYDFA.

Figure 2 shows a schematic of the fully integrated 32c-MC-EYDFA. The multimode (MM) pump LDs were coupled into the MC-EYDF via side coupling in a co-directional pumping arrangement. A 7 m long 32c-MC-EYDF was used for the measurement. The 32c-MC-EYDF was directly spliced at both ends to the passive MCF tail of the fan-in/fan-out couplers using a standard Fujikura FSM-100P + fusion splicer. To fabricate the side pump couplers, a commercially available $105/125 \mu\text{m}$ pump delivery fiber was first tapered to $15 \mu\text{m}$, and then coiled around the active fiber. A pump coupling efficiency of $>60\%$ was achieved. Due to the high core count (32-cores), the pump light is quickly absorbed by the doped cores, and the population inversion level reduces rapidly along the fiber length. Consequently, we employed two side-couplers in our experiment; one at the beginning and the other in the middle of the active fiber to better balance the population inversion level along the device length. Moreover, as opposed to our earlier work [18] a pump wavelength of 965 nm was chosen (at the short wavelength edge of the absorption peak) to further minimize the optical performance variation arising from any core-to-core variation in dopant concentration. The fiber cladding absorption at the pump wavelength of 965 nm was measured to be about 4 dB/m as compared to 12 dB/m absorption at 975 nm. The chosen pump wavelength also helped in reducing the variation in inversion along the fiber length and also has the advantage that there is a reduced requirement for diode cooling as the pump absorption is relatively

insensitive to temperature fluctuation around this wavelength [20]. The fan-in/fan-out coupler pair used were first characterized (average insertion loss ~ 2 dB and core-to-core loss variation $\sim \pm 0.5$ dB) and then spliced to opposite ends of the amplifier. The performance of each core was tested individually by launching 10 WDM channels to the core under test. The channel wavelength range spanned 1534.3 nm- 1560.25 nm, providing a total input power of -4 dBm. As a precautionary measure a dummy channel, which was first pre-amplified and then split using a 1x32 splitter, was loaded into the remaining cores to prevent any spurious lasing arising from back reflections off the fiber end-facets in the fan-in/fan-out couplers as may occur if any of the cores are unseeded.

4. Results and discussion

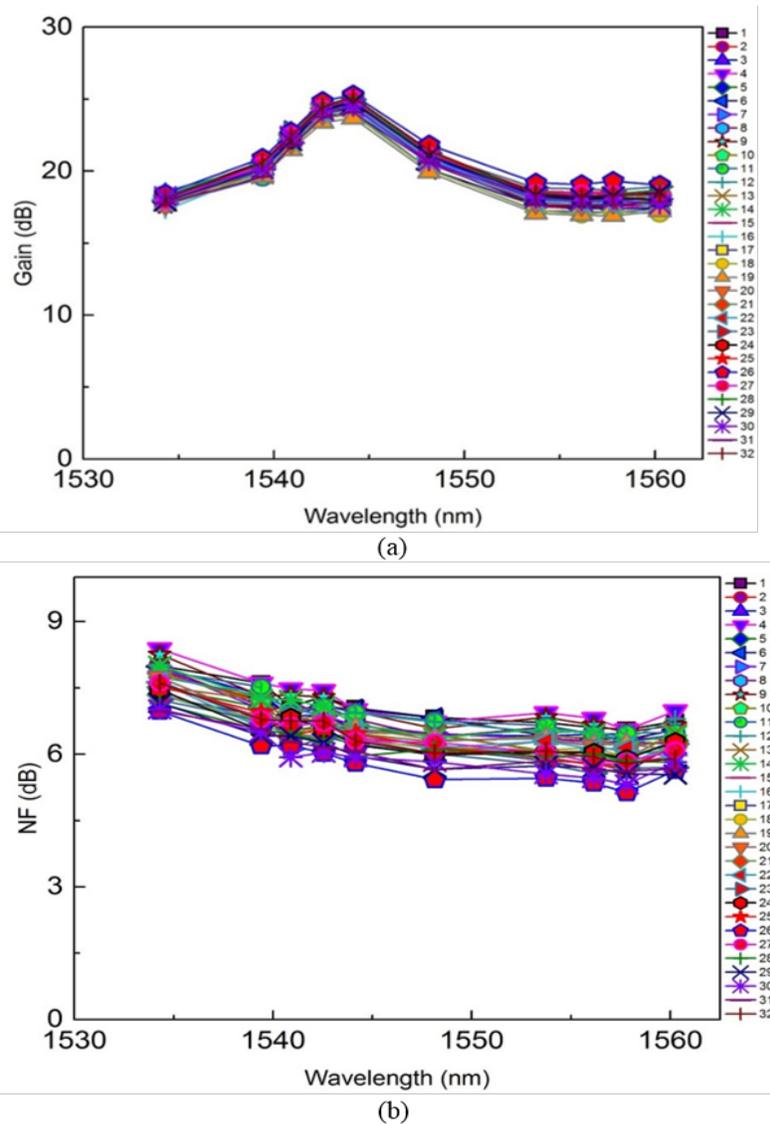


Fig. 3. (a) Gain, and (b) NF performance of the 32c-MC-EYDA for an input signal power of -4 dBm.

Figure 3(a) and 3(b) show the gain and NF performance of the 32c-MC-EDFA for an input signal power of -4 dBm. A maximum gain of 25 dB was observed at 1545 nm. The average gain was 20 dB, and the average NF was 6.5 dB (averaged over all cores and wavelengths). A minimum gain of >17 dB was measured across the entire wavelength band extending from 1534 nm-1561 nm (27 nm) in all cores for a pump power of 16 W (8W coupled from each diode). More importantly, the core-to-core gain and NF variation was < 2 dB. The input signal power was chosen so as to obtain similar gain values for shorter and longer wavelengths in the operating band for this length of amplifier fiber. A higher/lower input signal power resulted in a gain tilt towards shorter/longer wavelengths. The amplifier could likely provide similar performance for wavelengths beyond 1565 nm. However, due to the lack of availability of WDM sources at longer wavelengths the performance beyond 1561 nm could not be measured. It should be noted here that the gain in Fig. 3a includes the loss of the fan-in/fan-out pair, and the internal amplifier gain was therefore ~ 2 dB higher.

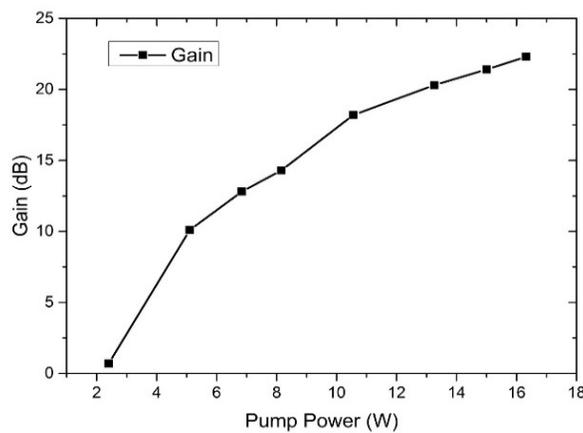


Fig. 4. Gain vs pump power for core 32.

Figure 4 shows the gain variation of a randomly chosen core (specifically core 32, see Fig. 1(c) for the core position) as a function of pump power. An average gain of 22dB was measured for an input signal of -5 dBm with 16W of pump power corresponding to an average output power of ~ 17 dBm per core. Saturation in output power limits the maximum gain that can be extracted from the amplifier. It is envisaged that by optimizing the core design, dopant concentration and the preform fabrication technique it would be possible to further increase the saturated output power and hence the optical efficiency of the amplifier.

Gain dynamics of cladding pumped MC-EYDFA

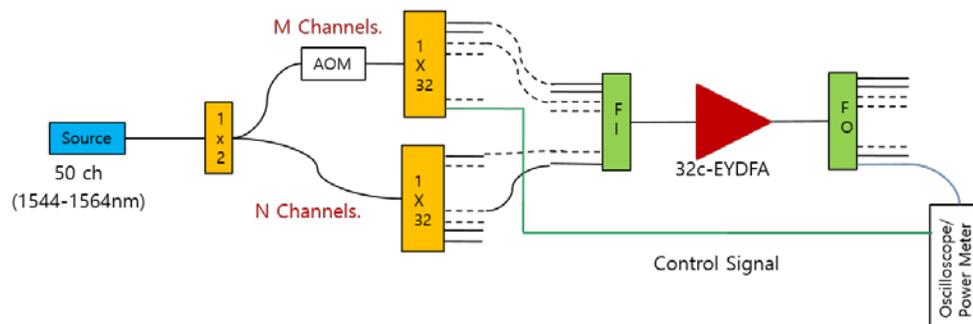


Fig. 5. Schematic setup for measuring transient performance of the 32c-EYDFA.

We also examined the gain dynamics of our cladding pumped 32c-MC-EYDFA. Figure 5 shows the schematic experimental setup for measurement. To emulate the channel add/drop in neighboring cores, a dummy signal was pre-amplified, split into 2 sets (with M and N cores respectively) with M being the number of cores for which the signal is simultaneously switched off, and N being the number of cores in which the signal runs continuously. The output from one of the ports after the top splitter was used to generate a control (trigger) signal to measure the (temporal) characteristics of the CUT whilst the M spatial channels were turned on/off. An electro-optical modulator was inserted before the splitter to simultaneously switch on/off signals in these cores. The output of the CUT and the control signal from the splitter were measured using a photodiode and an oscilloscope. Figure 6 shows the control signal (blue) and the output of the CUT (green, from Core 32), for the worst case scenario when the remaining 31 cores are turned off. The output of the CUT remained constant (13dBm) irrespective of the number of cores being turned on or off. This indicates that the amplifier cores are truly independent of each other and that the output power depends only on the pump power. Obviously intra-core cross wavelength dependent gain, just as for any conventional single mode EDFA operating without active gain control, was observed as expected [21, 22].

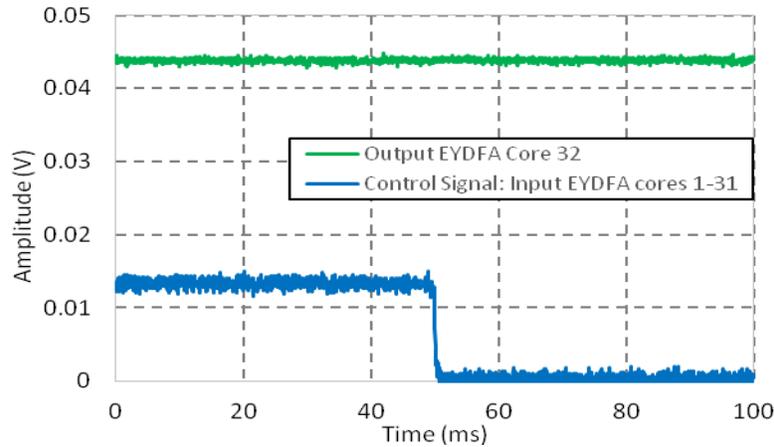


Fig. 6. Output for core 32 (green), and input signal to the remaining cores.

Transmission experiment with our 32c-MC-EYDFA

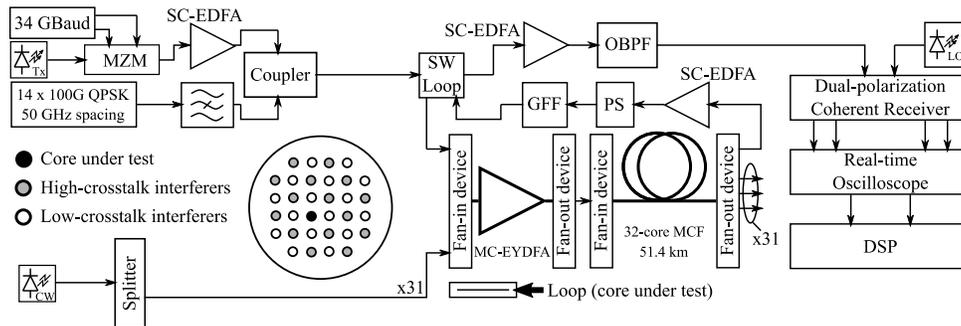


Fig. 7. Experimental setup for amplifier testing.

Figure 7 shows the recirculating SDM transmission setup was used to investigate the amplifier performance (with a low crosstalk scenario) [23]. At the transmitter, 15 WDM channels are set to a 50 GHz grid between 1555 nm and 1561 nm. For the test channel, an m-QAM 34 GBaud signal is generated. The remaining channels, on the other hand, carry de-

correlated 100 Gbit/s QPSK data signals. The combined 15-channel signal is fed to one of the inner core, Core 32, (see inset of Fig. 7). To emulate crosstalk-free conditions in our setup, a single out-of-band unmodulated continuous-wave signal is fed to the remaining 31 cores of the multicore system.

The multicore transmission link in the recirculating loop consists of an integrated MC-EYDFA that pre-compensates the loss of the fiber, a 51.4-km-long length of the 32-core heterogeneous MCF, and two sets of fan-in/fan-out couplers. After the MCF, a single-core EDFA is used to compensate the losses of the additional optical elements in the recirculating loop; polarization scrambler, gain-flattening filter, and the loop switches.

In the experimental setup, only the core under test goes into the recirculating loop; the CW signals traveling in the rest of the cores just go through the multicore components once before being terminated. The launch power into the MC-EYDFA for all cores including the CUT was set to -3 dBm per core.

At the receiver, an optical bandpass filter extracts the test channel. A coherent receiver transforms the signal from the optical to electrical domain, where upon a real-time sampling oscilloscope captures data points to be processed offline. Digital signal processing is performed and the bit-error ratio (BER) is estimated via error-counting.

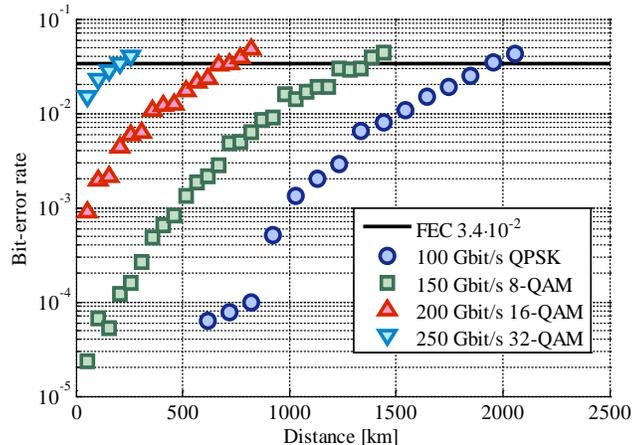


Fig. 8. BER vs distance for different m-QAM modulation formats.

Figure 8 shows the test channel's BER readings for 100 Gbit/s QPSK, 150 Gbit/s 8QAM, 200 Gbit/s 16QAM, and 250 Gbit/s 32QAM signals. We report achieved distances of 1850.4 km (QPSK), 1336.4 km (8-QAM), 719.6 km (16-QAM), and 205.6 km (32-QAM). Soft decision forward error correction (FEC) with a threshold BER of $3.4 \cdot 10^{-2}$ is assumed.

Comparison of power consumption requirements

In Table 2 we compared the total power consumption required for LD operation and cooling in conventional single mode EDFAs and the proposed cladding pumped MC-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. Operating at this power level around 1.8W of electrical power would be needed to actively cool the diode and to maintain its temperature (assuming a state-of-the-art low power consumption diode) [24].

In our 7-core and 32-core MC-EYDFAs we used coupled pump powers of 9W and 16W respectively. The pump coupling efficiency was $\sim 60\%$, and the optical efficiency of our multimode pump LDs is about 50%. Using these values, the total electrical power consumed in our 7-core and 32-core EYDFAs was about 30W and 56W, respectively. In our first 32c-MC-EYDFA, the total power consumption for cooling both diodes was about 20W. In this

demonstration, we used a 965nm LD, where the fiber absorption remains relatively flat with respect to the pump wavelength variation. Due to this, the total cooling power required for our improved 32c-MC-EYDFA was only 9W resulting in a total power reduction factor of 0.60 in our current version of 32c-MC-EYDFA compared to using 32 conventional EDFAs. It should be noted that pump coupling efficiencies of >90% should be readily achievable in an optimized tapered side coupler [25, 26]. Assuming this value using our current setup we should be able to improve the power reduction factor to 0.41. It can be clearly observed that MC-EYDFAs have the potential to provide power saving benefits as the number of cores is increased. Moreover, low brightness LD pumps are much cheaper than single mode LD pumps. This along with components sharing could reduce overall costs.

Table 2. Power consumption of conventional EDFAs and our MC-EYDFA (*: 60% pump coupling efficiency, ** 90% pump coupling efficiency)

Amp. Type	Electrical Power for LD: A [W]	Cooling power: B [W]	Total Power: A + B [W]	Eq. Power of multiple EDFAs: C[W]	Power reduction Factor (A + B)/C
Conventional EDFA	1.6	1.8	3.4	-	1.0
7c-MCF (EYDFA)*	30	15.0	45	23.8 (= 7 x 3.4)	1.89
Initial 32c-MC (EYDFA)*	56	20	76	108.8 (= 32 x 3.4)	0.70
Current 32c-MC (EYDFA)*	56	9	65	108.8	0.60
Expected 32c-MC (EYDFA)**	36	9	45	108.8	0.41

5. Conclusions

We have presented an improved version of a high core-count (32 core) multicore amplifier. In our fully fiberized 32-core MC-EYDFA, >17dB gain was observed in the wavelength range 1534nm-1561nm (27nm), with an average NF of 6.5dB. A core-to-core variation of <2dB in both gain and NF was demonstrated illustrating the excellent consistency amongst cores. The amplifier was also tested in recirculating loop experiments for different modulation format signals and successful transmission over >1850 km distances was demonstrated using QPSK signals. We also showed the potential power consumption benefits as the number of cores are scaled in MC-EYDFAs. The power consumption was further reduced through the use of 965nm wavelength pumping with power reduction factors of 0.41 predicted. We believe that there is significant scope for further optimization of such amplifiers and that as well as being of relevance to MCF SDM systems such technology might also be used to simplify and reduce cost in conventional parallel strand SMF systems.

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