32-core Inline Multicore Fiber Amplifier for Dense Space Division Multiplexed Transmission System

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Abstract *We present a high-core-count SDM amplifier, i.e. 32-core multicore-fiber amplifier, in a cladding-pumped configuration. An average gain of 17dB and NF of 7dB is obtained for -5dBm input signal power in the wavelength range 1544nm-1564nm.*

Introduction

The possibility of using multicore amplifiers to simultaneously amplify multiple spatial channels propagating in a multicore fiber (MCF) has been the topic of considerable research interest in recent years[1]. Most research initially focused on 7-core, with both core- and cladding-pumped embodiments[2] and found to give excellent performance in a number of experiments. Just recently initial results on a 19-core[3] have been reported using a core pumped configuration and a 12-core[4] using a cladding pumped configuration, which represents the highest core-density multicore erbium doped fiber amplifier (MC-EDFA) to date. Among these, the cladding-pumped scheme looks the most promising in terms of providing cost, energy and space saving benefits, and represents the preferred route for MCF amplifier development. The cladding-pumped configuration also offers a convenient route towards a fully integrated MCF amplifier system by adopting a side-coupling approach. Here, the pump radiation can easily be coupled into the active fiber through a fully-fiberized pump coupler and the MCF amplifier can be directly spliced to the MCF transmission fibers. However, cladding pumped MCFs with a conventional Er-doped core would require long lengths of active fiber due to the low absorption of Er-ions in a silica glass host, which can lead to compromised amplifier performance in particular at the short wavelength edge of the C-band. In order to increase the pump absorption, the core-to-cladding area ratio could be engineered but there is not too much room for improvement in a MCF amplifier due to the large diameter of the cladding (generally, 200~250μm) necessitates to maintain a minimum core-to-core pitch so as to avoid excessive cross-talk. Alternatively, Ytterbium (Yb) sensitized core could be employed for much stronger pump absorption enabling Yb to absorb the pump energy and transfer it to the Erbium (Er)-ions.

In this paper, we report a 32-core multicore Er/Yb-doped fiber (32c-MC-EYDF) and a fully integrated MCF amplifier using a cladding-pumped configuration. The 32c-MC-EYDF, 32c-MCF isolators and the passive MCF have been spliced together through standard fusion splicing thereby demonstrating the ease of integrating these components. An averaged gain of >17dB and noise figure of <7dB have been demonstrated for an input signal of -5dBm in the wavelength range of 1544-1564nm. The amplifier was subsequently used for transmission experiment which confirmed the feasibility of the 32c-MC-EYDFA in a 111.6 km 32-core DSDM transmission line.

32-core multicore Er/Yb doped fiber

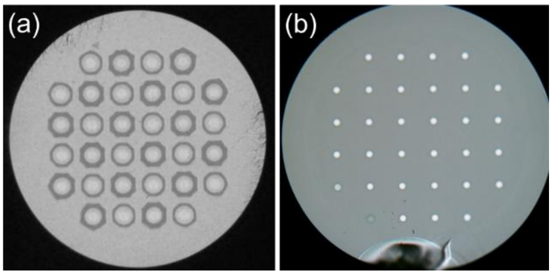


Fig. 1 Microscope image of (a) passive 32c-MCF and a core pitch matched (b) 32c-MC-EYDF.

An active 32c-MC-EYDF was fabricated using an Er/Yb-doped preform with a step-index core (Δn=0.016). This preform was originally developed for the conventional single mode fiber application and therefore a large amount of glass volume (i.e. cladding area) needed to be etched away to achieve the required core pitch (Λ=28.8μm). Figure 1(a) and (b) show the microscope images of the passive 32c-MCF (fabricated by Fujikura)[5] and active 32c-MC-EYDF, respectively. In passive 32c-MCF, heterogeneous core arrangement (e.g. two kinds of core refractive index profile) was incorporated with a trench index ring in order to reduce the neighboring channel crosstalk. For active 32c-MC-EYDF fabrication, however, simple homogeneous step-index core arrangement (i.e. similar refractive index profile) was used for ease of fabrication. In general, amplifier fiber length is in the range of few meters to few tens of meters, and it is not expected to contribute significant crosstalk to the system. The outer diameter and core-pitch of the resultant 32c-MC-EYDF was 242μm and 28.85μm, respectively, which were well matched to that of the passive 32c-MCF from Fujikura. The smaller diameter and higher NA cores in 32c-MC-EYDF resulted in a large MFD mismatch with the passive 32c-MCF, and the butt-coupling loss was estimated to be about 1.3dB. The detail fiber specifications are summarized in Table 1.

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

	32c-MCF	32c-MC-EYDF
Avg. Pitch	28.8	28.85
Max./Min.	29.4/28.4	29.15/28.45
SD.	0.2	0.16
Cladding[μm]	241.2	242
MFD[μm]	9.9	5.6
Loss/abs.	0.235dB/km @1550nm	19dB/m @975nm

Fully integrated 32c-MC-EYDFA

Figure 2(a) shows a schematic of the fully integrated 32c-MC-EYDFA. The multimode (MM) pump laser was coupled into the MC-EYDF via side coupling in a co-directional pumping arrangement. To make the side coupler a 125μm pump delivery fiber was tapered to 15μm and then coiled around the active fiber and more than 60% of pump coupling efficiency was readily achieved. Due to high core counts (32-cores), the pump light was quickly absorbed by the cores and population inversion level was drastically reduced along the fiber length. In our experiment, two side-couplers were employed, one at the beginning and another in the middle of the active fiber to balance the population inversion level along the device length. We also developed an integrated 32c-MCF isolator using a micro-lens based fiber collimator assembly[6]. Two such 32c-MCF isolators were placed at both input and output ends of the 32c-MC-EYDFA and a pair of fan-in/fan-out device were incorporated to measure the gain/NF of our amplifier.

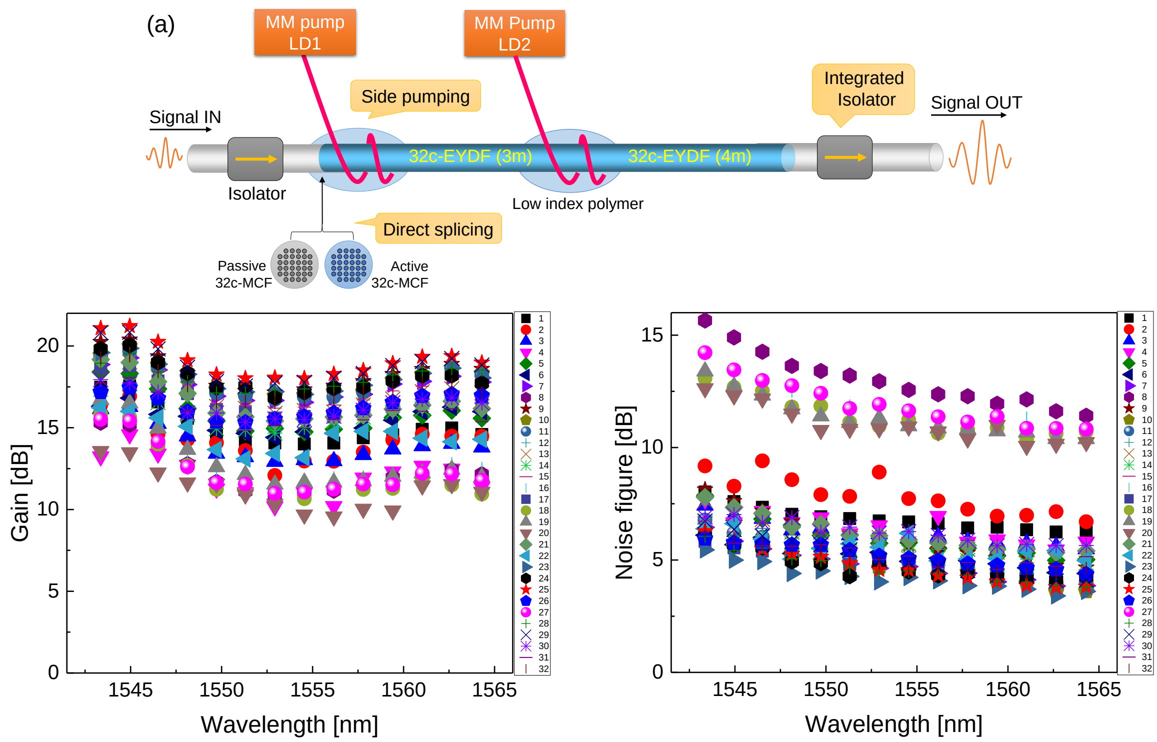
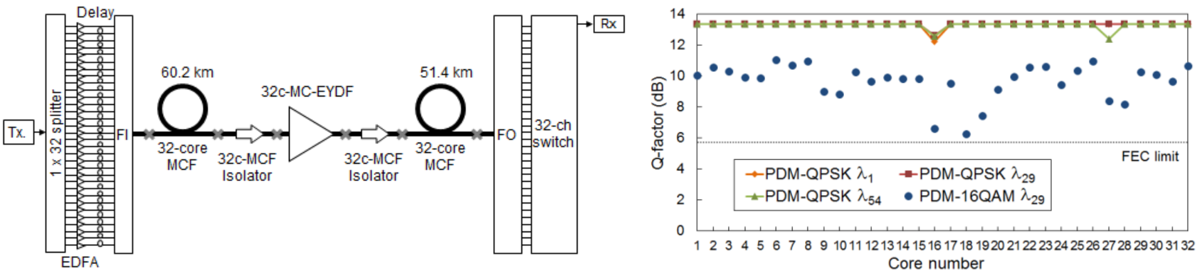


Fig. 2 (a) Schematic of a fully integrated 32c-MC-EYDFA and (b) measured internal gain and (c) NF of the amplifier.

To characterize the 32c-MC-EYDFA, 14 continuous wave channels in the wavelength range of 1544nm-1564nm are launched through the fan-in (FI) device with a total input signal power of -5dBm after the 1st isolator, and the corresponding output is monitored at the output of the fan-out (FO) device using an optical spectrum analyzer. At a coupled pump power of 16W, the internal gain and NF of all 32 cores of the amplifier are measured and plotted in Fig. 2(b) and 2(c), respectively. An averaged gain of >17dB and NF of <7dB was achieved. Most of core behaves similarly with a core-to-core variation of <5dB but few of them (core # 8, 16, 18, 19, 20, 27) shows larger gain/NF variations (5-10dB). This gain/NF variation is mainly due to the core-to-core insertion loss variation in the passive MCFs (2-4dB), optical isolators (2.5-3.8dB) and imperfection of splicing. The inner cores had comparatively less loss variation in the passive components and thus showed similar gain and NF performance. The overall amplifier performance can be further improved with the advancement of high performance optical components, passive fibers and better control of splicing technique.



(a) (b)

Fig. 3 (a) Experimental setup of an inline amplified 32c-MCF transmission and (b) measured Q-factors after 111.6 km.

Inline amplified 32c-MCF Transmission

Figure 3(a) shows the transmission experimental setup. 54-ch 50-GHz-spaced 32-Gbaud WDM signals (191.65 to 194.30 THz) were generated at the transmitter. The signal was split into 32, and were relatively delayed by 0, Δt, 2Δt, … , and 31Δt with a unit time delay Δt of 20 ns. The optical powers were set at +17 dBm/core at the input of the transmission line. The 32-core 111.6km dense space-division multiplexed (DSDM) transmission line consisted of a 60.2km single-mode heterogeneous 32c-MCF [6], 32c-MC-EYDFA, 32c-MCF isolators, and a 51.4 km 32c-MCF. Fan-in/fan-out (FI/FO) devices were spliced to the input and output of the 32-core DSDM transmission line. The core under measurement was selected by a 32-channel matrix switch, filtered by tuneable optical filters, and input to a coherent receiver. It was then digitized at 80 GS/s using a 4-ch digital storage oscilloscope, and the stored data was post-processed offline[7].

Figure 3(b) shows the measured Q-factors at the centre, shortest, and longest wavelengths for polarisation-division multiplexed quadrature phase shift keying (PDM-QPSK) signals as a function of the core number after 111.6 km transmission. The figure also shows the Q-factors measured at the centre wavelength for PDM 16 quadrature amplitude modulation (QAM) signals. The measured Q-factors for all 32 cores exceeded the forward error correction (FEC) limit of 5.7 dB with 20 % FEC overhead.

Conclusions

A highest core-density multicore amplifier, 32-core MC-EYDFA, is successfully developed in a fully fiberized format. The amplifier provided an averaged gain of >17dB and NF of <7dB with the core-to-core variation of ~5dB. We also confirmed the feasibility of our amplifier in a 111.6 km MCF transmission line.

Acknowledgement

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References

[1] D. J. Richardson et al., Nat. Photonics **7**, 354 (2013).
[2] K. Abedin et al., Opt. Express **39**, 993 (2014).
[3] J. Sakaguchi et al., Opt. Express **22**, 90 (2014).
[4] H. Ono et al., Proc. ECOC, We4A.4 92013).
[5] T. Mizuno et al., Proc. OFC, Th5C.3, Anaheim (2016).
[6] Y. Jung et al., Proc. ECOC, W2.B4, Düsseldorf (2016).
[7] Y. Sasaki et al., Proc. ECOC, W2.B2, Düsseldorf(2016).