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Post Deadline session.

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

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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 devices, with both core- and cladding-pumped[2] embodiments demonstrated and found to give excellent performance in a number of transmission experiments. Just recently initial results on a 19-core[3] amplifier have been reported using a core pumped configuration and a 12-core[4] amplifier using a cladding-pumped configuration, which represents the highest core-density multicore erbium doped fiber amplifier (MC-EDFA) reported 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 pump coupling approach. Here, the pump radiation can is readily 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 relatively low absorption of Er-ions in a silica glass host, which can lead to substantially compromised amplifier performance: particularly 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 need for a large diameter cladding (generally, 200~250μm) as required to reduce inter core cross-talk as the core count is increased. Alternatively, a Ytterbium (Yb) sensitized core can be employed which has much stronger pump absorption and which is able to efficiently transfer this across to the Erbium (Er)-ions via a well-established energy exchange mechanism.

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 were each spliced together using a standard fusion splicing process thereby demonstrating the ease of integrating these components. An average gain of >17dB and noise figure of <7dB have been demonstrated for an input signal of -5dBm in the wavelength range1544-1564nm. The amplifier was subsequently successfully used in transmission experiment confirming the viability of using the 32c-MC-EYDFA in a 111.6 km 32-core DSDM transmission line.

## 32-core multicore Er/Yb doped fiber

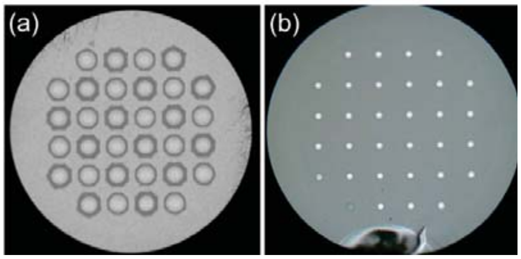


**Fig. 1** Microscope image of (a) passive 32c-MCF and a core pitch matched (b) 32c-MC-EYDF.

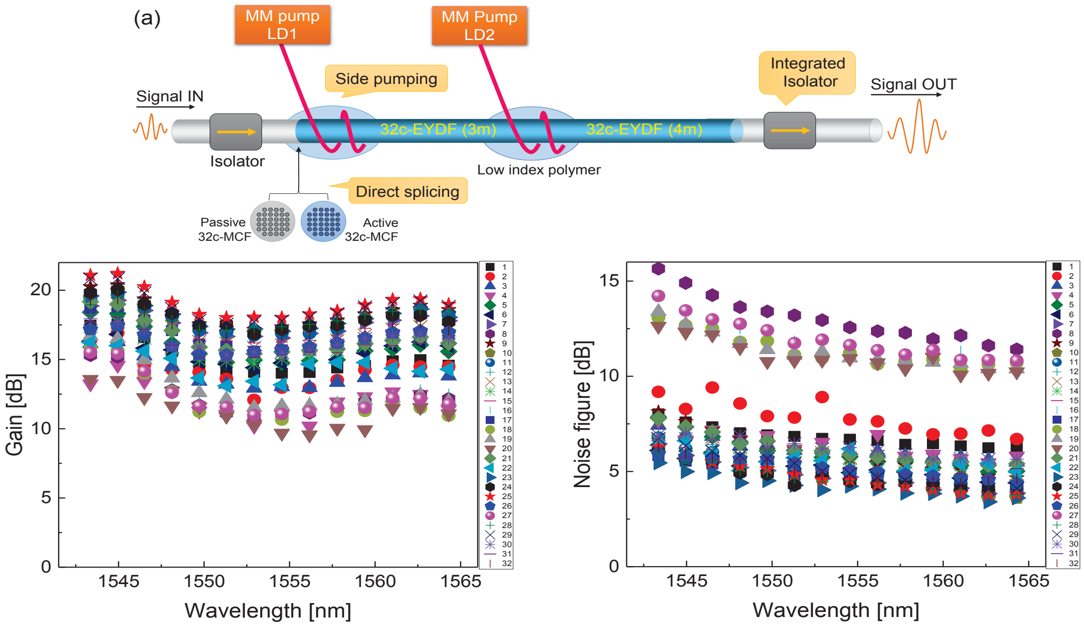


**Fig. 2** (a) Schematic of a fully integrated 32c-MC-EYDFA and (b) measured gain and (c) NF of the amplifier.

The 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 applications and therefore a large volume of glass (i.e. from the cladding) needed to be etched away to achieve the required core pitch (Λ=28.8μm) in the final fiber. Figure 1(a) and (b) show the microscope images of the passive 32c-MCF (fabricated by Fujikura)$^5$ and active 32c-MC-EYDF, respectively. The passive 32c-MCF, had a heterogeneous core arrangement (specifically two kinds of core refractive index profiles were used) and incorporated trench index rings in order to reduce the neighboring channel crosstalk. For the active 32c-MC-EYDF fabrication, however, a 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 just a few meters to a few tens of meters, such that crosstalk in this fiber is less of an issue.

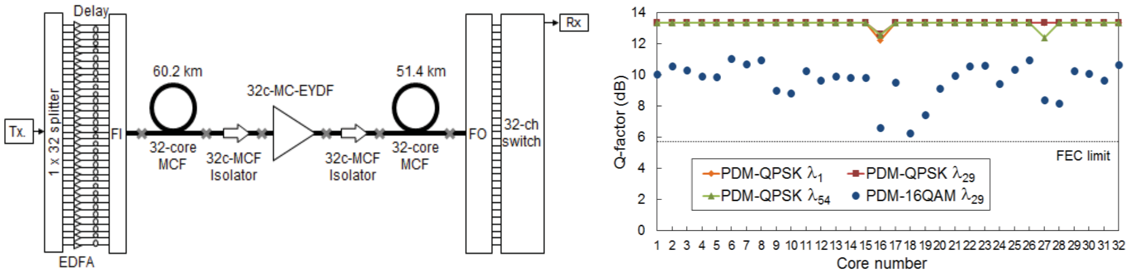
**Table 1.** Specifications of 32c-MCF and 32c-MC-EYDF

| | 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<br>@1550nm | 19dB/m<br>@975nm |

The outer diameter and core-pitch of the resultant 32c-MC-EYDF was 242μm and 28.85μm, respectively, values that were very well matched to those of the passive 32c-MCF. The smaller diameter and higher NA cores (required to achieve efficient amplifier performance) in the 32c-MC-EYDF unavoidably resulted in a large core MFD mismatch with the passive 32c-MCF with the butt-coupling loss estimated to be about 1.3dB. The detailed fiber specifications are summarized in Table 1.

### 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 couplers a 125μm pump delivery fiber was tapered to 15μm and then coiled around the active fiber and more than 60% pump coupling efficiency was readily achieved. Due to the high core count (32-cores), the pump light was quickly absorbed by the doped cores and the population inversion level rapidly reduced along the fiber length. Consequently, in our experiment, two side-couplers were employed, one at the beginning and another in the middle of the active fiber to better 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 spliced at both input and output ends of the 32c-MC-EYDFA and a pair of fan-in/fan-out (FI/FO) devices were incorporated to measure the gain/NF of the amplifier. To characterize the 32c-MC-EYDFA, 14 CW channels in the wavelength range 1544nm-1564nm were launched through the (FI).



(a) (b)

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

The total input signal power at input of FI was +8dBm (-5dBm at input of active fiber; average FI+MCF, 60km, loss was 13dB). The corresponding output was 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 were measured and the results are plotted in Fig. 2(b) and 2(c), respectively. The majority of the cores exhibited quite similar performance with an average gain of >17dB, a NF of <7dB and with a core-to-core variation of 5-6dB. This gain 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 splicing imperfections. The inner cores had comparatively less loss variation in the passive components and thus these cores showed more uniform gain and NF performance. It is to be noted however that a few cores (6 cores to be exact) exhibit somewhat worse performance than the others. We are in the process of understanding the exact origin of this compromised performance. Nevertheless appreciable gain was achieved for each core, sufficient to allow for high capacity data transmission as successfully illustrated in Fig. 3(b)

## Inline amplified 32c-MCF Transmission

Figure 3(a) shows the transmission experiment 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 delayed relative to each other by 0, $\Delta t$, $2\Delta t$, … , and $31\Delta t$ with a unit time delay $\Delta t$ of 20 ns. The optical powers were set at +17 dBm/core at the input of the transmission line. The 32-core 111.6km 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 test was selected by a 32-channel matrix switch, filtered by tuneable optical filters, and input to a coherent receiver. The signal 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

We have reported the highest core-count (32 core) multicore amplifier yet demonstrated. Our 32-core MC-EYDFA is in a fully fiberized format and provides an average gain of >17dB and average NF of <7dB with a core-to-core variation of ~5dB for the majority of cores. We also successfully confirmed operation of our amplifier in a fully-integrated 111.6 km 32 MCF transmission line. Reductions in core-to-core performance variation are to be anticipated as improvements in passive and active fibres, components and splicing recipes are made.

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## References

[1] D. J. Richardson et al., Nat. Photonics **7**, 354 (2013).
[2] K. Abedin et al., Opt. Exp. **39**, 993 (2014).
[3] J. Sakaguchi et al., Opt. Exp. **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, Dusseldorf (2016).
[7] Y. Sasaki et al., Proc. ECOC, W2.B2, Dusseldorf(2016).