# FIFO-less Core-pumped Multicore Erbium-doped Fiber Amplifier with Hybrid Passive Components


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***Abstract*—We demonstrate a FIFO-less core-pumped multicore erbium-doped fiber amplifier (MC-EDFA) based on hybrid passive components for the first time. The passive element possesses the combination functions of an isolator, a wavelength-division multiplexer, and a pump fan-in device. By virtue of two-stage configuration, the average gain and the maximum noise figure of the MC-EDFA are 16.5 dB and 6.5 dB over a bandwidth of 6 THz. The core-to-core gain variation is less than 1 dB. The output power per core is boosted to 22.5 dBm while the inter-core crosstalk is below -46 dB.**



***Keywords—space-division multiplexing, multicore fiber, erbium-doped fiber amplifier***


## I. Introduction

Space-division multiplexing (SDM) has attracted immense attention over the past decade as a potential technology for scaling up the transmission capacity of fiber-optic communication systems to accommodate ever-increasing internet traffic demands in backbone networks. SDM of optical signals can be implemented through mode-division multiplexing by virtue of few-mode fibers (FMFs) or core-division multiplexing using multicore fibers (MCFs), as well as combinations thereof [1]. According to the strength of coupling between adjacent cores, MCFs can be categorized as either randomly-coupled (RC) MCFs or weakly-coupled (WC) ones. Although RC MCFs and FMFs are promising candidates for improving the spatial density, novel complex digital signal processing techniques become necessary to recover optical signals that undergo linear and nonlinear impairments after the transmission through the fibers. In contrast, WC MCFs, compatible with current single-mode transmitters and receivers, have the potential to be practically deployed in submarine and terrestrial systems in the near future.

For the long-haul transmission over WC MCFs, WC multicore erbium-doped fiber amplifiers (MC-EDFAs) are essential to compensate for the link loss and permit propagation of optical signals carried by all spatial channels over thousands of kilometers. To date, core pumping using individual single-mode laser diodes (LDs) and cladding pumping through a single high-power multi-mode LD have been proposed and demonstrated in WC MC-EDFAs [2]. In comparison with core pumping, the latter suffers from a lower pump conversion efficiency (PCE) and a higher noise figure (NF) arising from the insufficient pump absorption by the gain medium. Furthermore, the core-pumping scheme allows flexibility to control the output power of each core independently. Previously reported core-pumped WC MC-EDFAs utilized fan-in/fan-out (FIFO) devices and conventional wavelength-division multiplexers (WDMs) to combine the optical signals and the pump lights and couple them into the individual cores [3]. However, the insertion loss and the inter-core crosstalk of FIFO degrade the transmission performance of WC MCF systems, while the compensation of the inter-core skew induced by FIFO is required. Very recently, a FIFO-less WC MC-EDFA with 4-cascaded side-polished pump combiners was demonstrated and each pump combiner was connected to a single-core pump LD [4]. This scheme avoids the issue of the inter-core skew, and it would be more suitable for practical applications if the number of passive components can be further reduced.

In this paper, we report on a FIFO-less two-stage MC-EDFA based on the core-pumping scheme. The compact structure is constructed by adopting 4-core hybrid passive components. The gain and NF of the MC-EDFA for all the cores are presented. The output power and the inter-core crosstalk are measured.

## II. Amplifier Configuration and Characterization

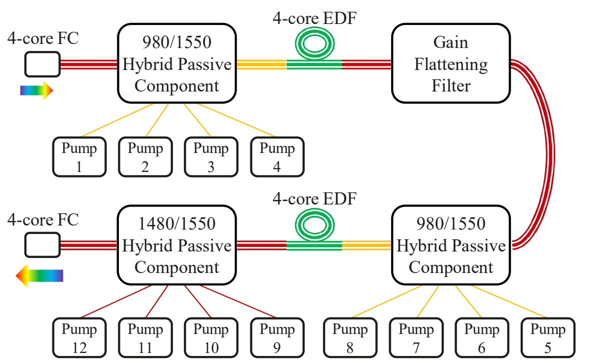


Fig. 1. Schematic of the FIFO-less core-pumped MC-EDFA. FC: fiber connector; EDF: erbium-doped fiber.

Figure 1 shows the schematic diagram of our proposed FIFO-less core-pumped MC-EDFA. It is a typical two-stage configuration, consisting of three 4-core hybrid passive components, a 4-core gain flattening filter (GFF), and two pieces of 4-core erbium-doped fibers (EDFs). The first stage is forward pumped by 980-nm LDs for low noise, while the second one is bi-directionally pumped with 980/1480-nm LDs for high output power. The GFF is inserted between the two stages to alter the gain profile and improve the PCE of the amplifier. Passive fibers and the EDF are designed with the same core layout, benefitting for a low-loss fusion splicing.

The 4-core EDF was fabricated by the drilling method in combination with the modified chemical vapor deposition (MCVD) process and the solution doping technology (SDT). It mainly contains 3 steps, which are briefly described as follows. First, 4 identical preforms were prepared uniformly via the MCVD process and the SDT. The second step was to drill the high-purity quartz casing according to the core distribution. This process allowed error-free control of the core arrangement to ensure the core-pitch accuracy during the drawing process. Finally, these preforms were inserted into the manufactured casing and mounted on the tower for high-temperature drawing to achieve the 4-core EDF. The cross section of the fabricated EDF is depicted in Fig. 2. The cores are arranged in a square lattice with a pitch of 43 μm. The cladding diameter and numerical aperture are equal to 125 μm and 0.22, respectively. The mode field diameter at 1550 nm is about 6.2 μm. The trench-assisted structure is introduced into the EDF to suppress the inter-core crosstalk. The peak absorption coefficient is 6 dB/m at 1530 nm.

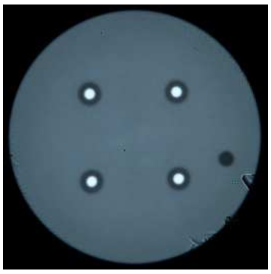

Fig. 2. The cross section of the 4-core EDF.

The 980-nm 4-core hybrid passive component possesses the combination functions of an isolator, a 980/1550-nm WDM, and a 980-nm FI device. The signals from the input MCF are collimated and then reflected by a signal-reflective coating to the WDM. The pump lights emitted from 4 single-mode 980-nm LDs are first collimated and propagated to the WDM. After passing through the WDM, both the signal and pump beams are focused on the facet of the output MCF by a collimator. The isolator is placed between the input port and the WDM to avoid spurious back-reflection light and suppress amplified spontaneous emission (ASE) noise. The maximum insertion loss of the signals and the pump lights were measured to be 1.3 dB and 1 dB, respectively. The inter-core crosstalk is at the level of -50 dB or even lower. As for the 1480-nm 4-core hybrid passive component, the signals injected into the input MCF are collimated and then propagated to the WDM. After that, the signals are reflected by a signal-reflective coating and focused on the output MCF. The incident 1480-nm pump lights are collimated first, then passed through the WDM and focused again on the input MCF. The isolator is placed between the output port and the WDM. The insertion loss of the signals and the pump lights are below 1.3 dB and 1.2 dB, respectively. The inter-core crosstalk is less than -50 dB. The GFF was fabricated based on multiple dielectric films. Due to the variation of incidence angle of signal lights on the films, the actually measured transmission spectra of the GFF among the 4 cores are slightly shifted. All the passive components have a unified package dimension of 54×25×7 mm$^3$, as depicted in Fig. 3.

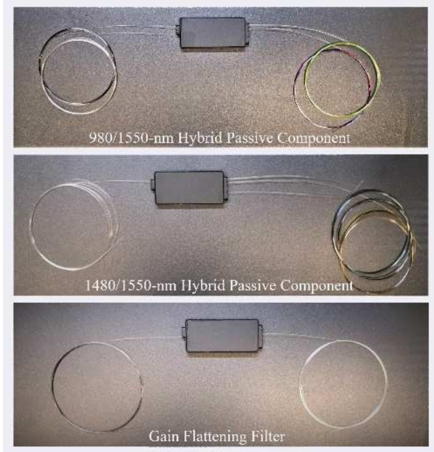


Fig. 3. Prototype image of 4-core passive components.

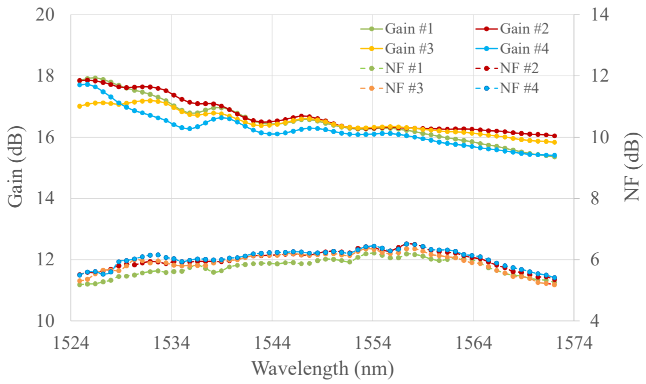


Fig. 4. Gain and NF spectra of the MC-EDFA.

The input and output pigtails of the MC-EDFA described here were terminated by customized LC-type 4-core fiber connectors (FCs), contributing to a direct connection with WC MCF transmission systems. The typical connection loss for a pair of the FCs is 0.3 dB. By utilizing a 60-channel combed ASE with a channel spacing of 100 GHz as an input light, the gain and NF spectra of the MC-EDFA for all the cores were measured, as shown in Fig. 4. The average gain is about 16.5 dB with a designed gain slope of ~2 dB over a bandwidth of 6 THz. The core-to-core gain variation is suppressed to be within 1 dB. The maximum NF is 6.5 dB. Owing to the two-stage amplifier configuration, the output power is boosted to 22.5 dBm.

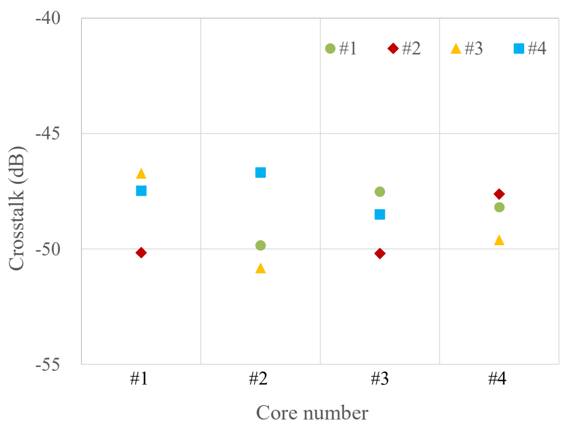


Fig. 5. Inter-core crosstalk of the MC-EDFA.

In order to characterize the inter-core crosstalk of the MC-EDFA, a single-channel signal light centered at 1546 nm was launched into one core of a FI whereas another 1548-nm signal light was injected into one of the remaining 3 cores. The input and output power of the MC-EDFA per core were set to be the same by adjusting two variable optical attenuators and the pump power separately. The output spectra extracted from a FO were recorded by an optical spectrum analyzer and the inter-core crosstalk was defined as the power difference between the two cores at the same wavelength. As shown in Fig. 5, the crosstalk properties for all the core pairs are less than -46 dB. In 2013, a 7-core EDFA with the two-stage configuration was reported [5]. A gain of over 13 dB and a NF of below 5.5 dB in a 5-THz bandwidth were obtained. However, each core of the MC-EDF was pumped through several FIFO devices and discrete single-mode WDMs. Herein, we propose a FIFO-less integrated 4-core EDFA, which significantly reduces the component count and improves the structure compactness. Moreover, WC MC-EDFAs may also be suitable for the RC MCF transmission with the aid of core-pitch adapters, and thus the MC-EDFs and passive components in WC/RC MCF systems could employ a unified WC technology path.

## III. Conclusion

We have experimentally demonstrated a FIFO-less core-pumped MC-EDFA with a 6-THz operation bandwidth for the first time. The MC-EDFA was incorporated with hybrid passive components to effectively decrease the number of discrete elements. The average gain of 16.5 dB and the maximum NF of 6.5 dB were achieved. The core-to-core gain difference was less than 1 dB and the output power per core was scaled up to 22.5 dBm. The inter-core crosstalk below -46 dB was obtained. Our experimental results suggest that the proposed MC-EDFA with high output power and low NF performances can serve as a promising option for the long-haul MCF transmission systems.

## Acknowledgment

We wish to thank Dan Guo from the Central Hardware Engineering Institute of Huawei 2012 Lab for her support.

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