Optical Amplification Technologies for Space Division Multiplexing

Hirotaka Ono

Abstract

Technologies that enable simultaneous optical amplification of spatially multiplexed optical signals are essential for a long-haul space division multiplexing (SDM) transmission system that employs a multi-core fiber and/or few-mode fiber. This article introduces optical amplification technologies that make it possible to construct a multi-core erbium-doped fiber amplifier (EDFA) and a few-mode EDFA for SDM transmission.

Keywords: multi-core fiber amplifier, few-mode fiber amplifier, erbium-doped fiber

1. Introduction

An optical amplifier is necessary for a long-haul space division multiplexing (SDM) transmission system that employs a multi-core fiber and/or a few-mode fiber as a transmission line. SDM optical amplifiers utilize an erbium-doped fiber (EDF) as the amplification medium in the same way as the optical amplifiers used in the current single-core and single-mode fiber transmission system. An important function of SDM optical amplifiers is simultaneous amplification of spatially multiplexed optical signals. Two kinds of optical amplifiers have mainly been studied in recent years in order to realize such a function. One is a multi-core erbium-doped fiber amplifier (MC-EDFA), which employs a multi-core EDF that has multiple erbium cores within a single fiber. The other is a few-mode erbium-doped fiber amplifier (FM-EDFA), which utilizes a few-mode EDF that is a kind of multi-mode fiber. A few-mode EDF supports several propagation modes used for signal transmission and restricts unusable higher-order modes.

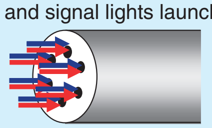
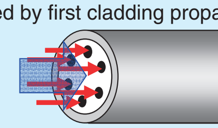
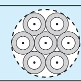
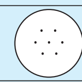
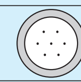
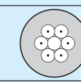
2. MC-EDFA

Table 1 categorizes MC-EDFAs in terms of pumping schemes and active fibers. There are two kinds of pumping schemes, namely core pumping and cladding pumping.

An MC-EDFA employing core pumping can employ optical components that are used for a conventional single-core EDFA. It provides high pumping efficiency and can also support conventional high-speed control to suppress the transient power caused by a change in the input signal power. The challenges to be met include integrating the optical components to reduce the total amplifier size, cost, and power consumption. Cladding pumping has the potential to achieve both low power consumption and downsizing by using an uncooled multi-mode pump laser diode (LD). Challenges include improving the pumping efficiency, developing optical components for launching the pump and multiple signal lights simultaneously, and devising a technique for adjusting the gain of several cores to achieve a pump power with high-speed control.

Four kinds of active fibers have already been reported for multi-core amplification: a bundle of reduced-cladding EDFs, a multi-core EDF with a single cladding, a multi-core EDF with a double cladding, and a multi-element EDF. The bundle and multi-element EDFs can utilize conventional mature fiber fabrication techniques, and the lengths of different EDFs can be adjusted to achieve a uniform gain. A drawback is the necessity of downsizing the cross-section of the amplification medium. The benefit of multi-core EDFs with single and double cladding lies

Table 1. Categorization of MC-EDFA in terms of pumping scheme and active fiber.

<table>
<tr><td rowspan="2">Pumping scheme</td><td colspan="2">Core pumping</td><td colspan="2">Cladding pumping</td></tr>
<tr><td colspan="2">Multiplexed pump and signal lights launched into core
</td><td colspan="2">All cores pumped by first cladding propagating pump light
</td></tr>
<tr><td>Benefit</td><td colspan="2">High pump efficiency and applicability of components and high-speed control used in conventional single-core EDFA</td><td colspan="2">Possibility of reducing size, power consumption, and cost by employing uncooled multi-mode pump laser diode (LD).</td></tr>
<tr><td>Challenge</td><td colspan="2">Reducing size, cost, and power consumption</td><td colspan="2">Improving pumping efficiency, developing pump/signal combiner, and achieving high-speed control</td></tr>
<tr><td>Fiber</td><td>Single-core EDF</td><td>Multi-core EDF</td><td>Multi-core EDF</td><td>Single-core EDF</td></tr>
<tr><td rowspan="2">Structure</td><td>Bundle</td><td>Single cladding</td><td>Double cladding</td><td>Multi-element</td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td>Benefit</td><td>Applicability of conventional fabrication technology and adjustability of EDF length</td><td colspan="2">Size and cost reduced by manufacturing several cores in one fiber fabrication operation</td><td>Applicability of conventional fabrication technology</td></tr>
<tr><td rowspan="2">Challenge</td><td colspan="4">Reducing cladding diameter and suppressing crosstalk</td></tr>
<tr><td>Developing fiber bundling technique</td><td colspan="3">Achieving uniform gain and noise figure between cores</td></tr>
</table>

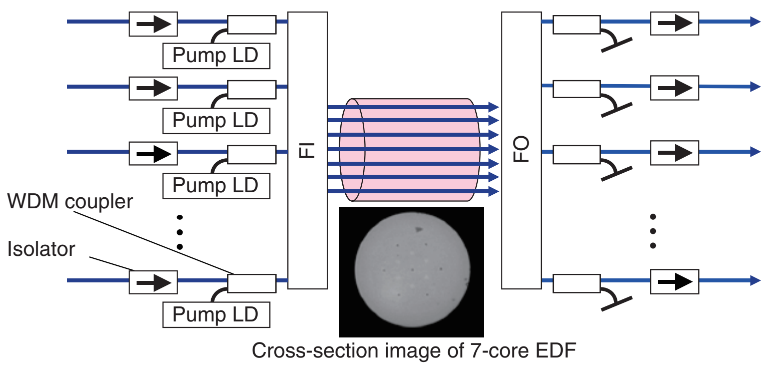
in the reduced cost, which is achieved by manufacturing several cores in one fiber fabrication operation. Another benefit of multi-core EDFs is that their cladding diameter is small compared with bundled and multi-element EDFs. Finding a way to achieve a uniform amplification characteristic for all the cores is a challenge for both multi-core and multi-element EDFs, and finding a way to suppress crosstalk is a common challenge for all active fibers.

2.1 Core-pumped MC-EDFA

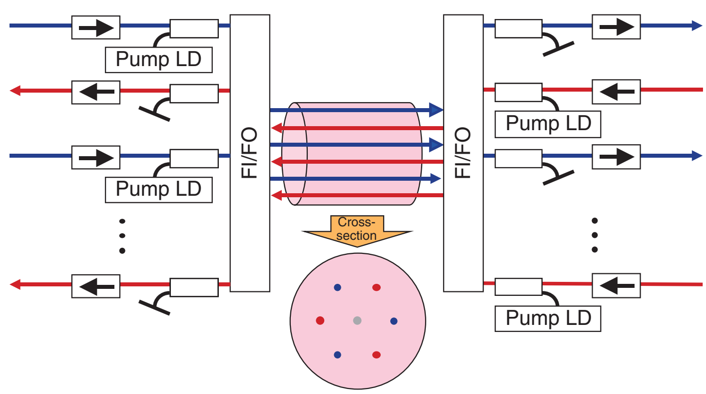
A typical configuration of a core-pumped MC-EDFA is shown in **Fig. 1(a)**. Both the pump and signal lights are multiplexed with a wavelength division multiplexing (WDM) coupler and launched into an erbium-doped core through a fan-in (FI), and the amplified signals are output through a fan-out (FO). In this amplifier configuration, since the FI and FO can reverse the propagation direction of the signal lights, the propagation of the signal light in each core can be set in any direction. Setting the signal lights in two adjacent cores to propagate in opposite directions reduces the intercore crosstalk [1]. An MC-EDFA was constructed for long-haul transmission through 12-core fiber by employing this method. Its configuration is shown in **Fig. 1(b)**. This MC-EDFA utilizes the outer cores of a dual 7-core EDF. As shown in **Fig. 1(c)**, a gain of over 11.4 dB and a noise figure of less than 6.5 dB were achieved across the entire C-band when the signal lights of all the cores propagated in the same direction. The MC-EDFA was applied to SDM transmission with a capacity-distance product of 1 Ebit/s, and the results suggest its feasibility [2]. A bundle of reduced-cladding EDFs can also be used in this kind of SDM optical amplifier [3].

2.2 Cladding-pumped MC-EDFA

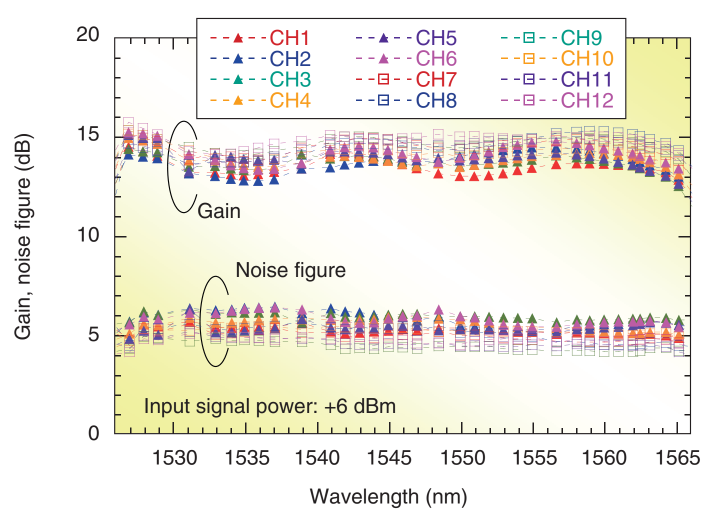
The configuration of a cladding-pumped MC-EDFA is shown in **Fig. 2(a)**. To improve pumping efficiency, we employed double-clad multi-core erbium/ytterbium-doped fiber (DCMC-EYDF). In this fiber, the pump absorption is sensitized by transferring energy from the ytterbium to erbium ions and suppressing the clustering of erbium ions, which results in improved pumping efficiency. Twelve erbium/ytterbium-doped cores were arranged in a hexagon as shown in the figure. The core pitch is 37.2 µm, and the first and second claddings and the coating diameters are 216, 284, and 356 µm, respectively. The pump source was a 976-nm multi-mode LD with a 125-µm-diameter multi-mode fiber pigtail. A schematic of the pump combiner is also shown in Fig. 2(a). The pump combiner consists of a multi-mode fiber with a tapered section and the double-clad 12-core fiber, whose cross-sectional design was the same as that of the DCMC-EYDF. A short section of the double-clad 12-core fiber was stripped of its low refractive-index



(a) Configuration for propagation in the same direction



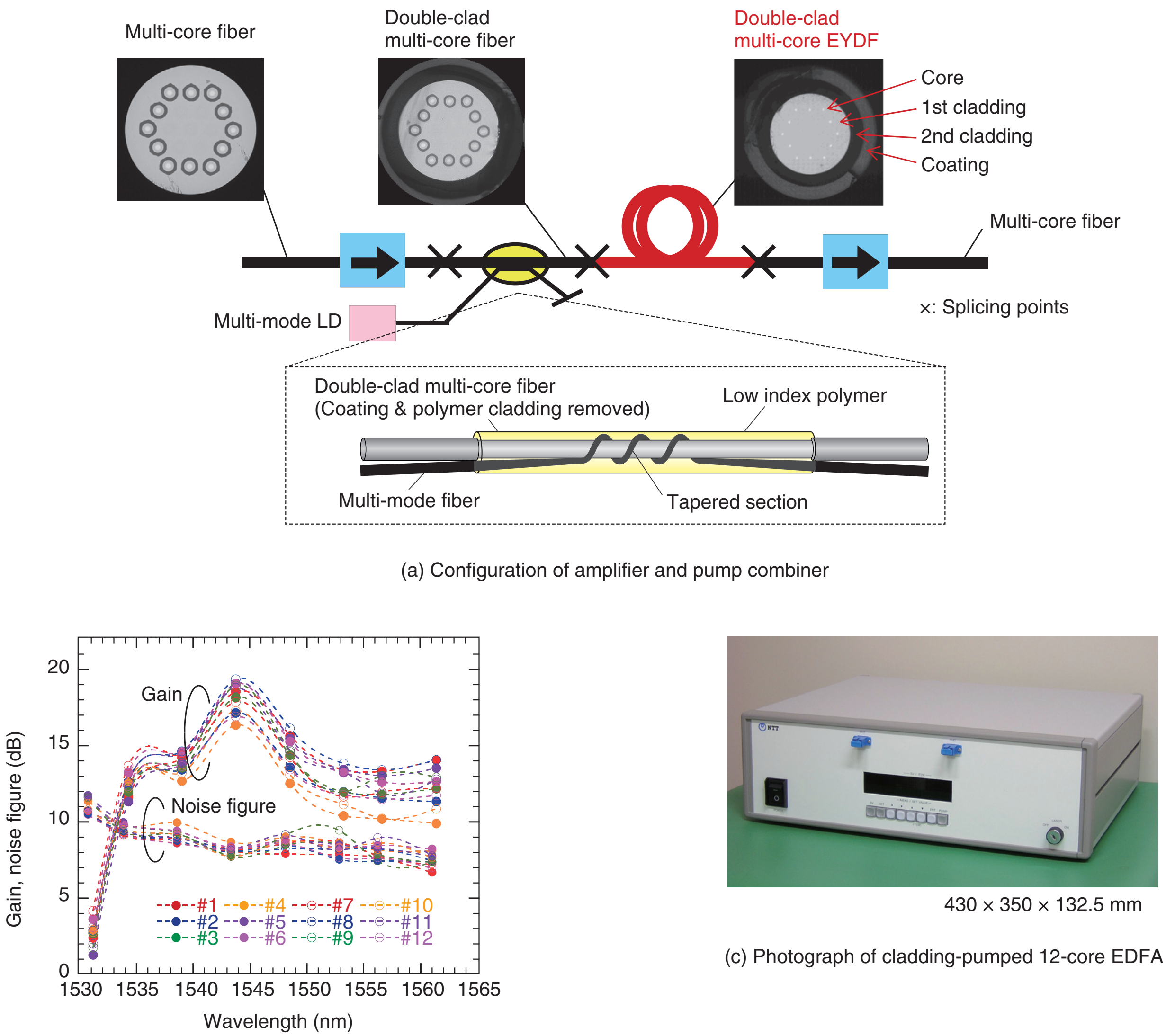
(b) Configuration for propagation-direction interleaving



(c) Gain and noise figure of MC-EDFA with propagation-direction interleaving configuration for 12-core fiber transmission

Fig. 1. Core-pumped MC-EDFA.

second cladding and coating, and the stripped section was rounded to form an optical contact with the tapered multi-mode fiber. The optical contact section was recoated with a low index polymer. This pump



(a) Configuration of amplifier and pump combiner

(b) Gain and noise figure

(c) Photograph of cladding-pumped 12-core EDFA

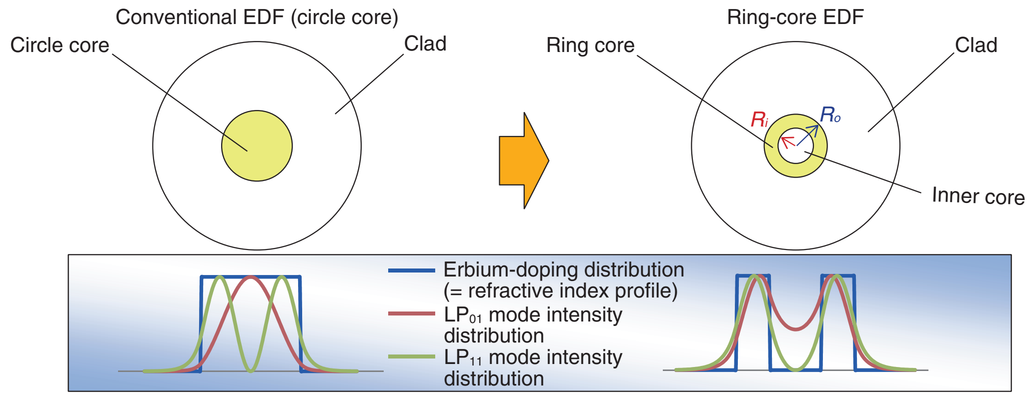
Fig. 2. Cladding-pumped MC-EDFA.

combiner was fusion-spliced to the DCMC-EYDF, which enables the pump light to couple to the first cladding of the DCMC-EYDF. Twelve-core isolators were located at the input and output ends of the amplifier to avoid laser oscillation.

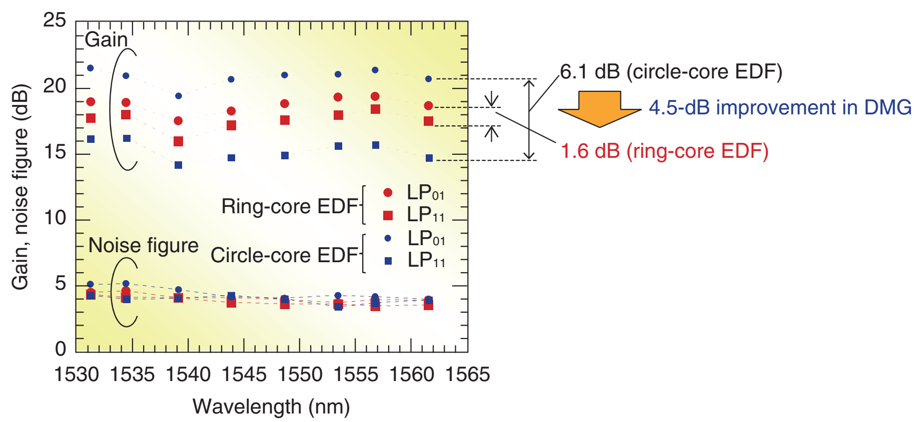
The gain and noise figure of the cladding-pumped MC-EDFA are shown in **Fig. 2(b)**, and a photo of the device is shown in **Fig. 2(c)**. The input signal was an 8-channel WDM signal with a power of −14 dBm/ch, and the pump power was 3.4 W. The optical amplifier exhibited over 10-dB gain and less than an 8.7-dB noise figure for all 12 cores at wavelengths longer than 1534 nm. In this case, the electrical power consumption was about 10 W, while the sum of that of 12 conventional EDFAs was estimated to be 20 W at an ambient temperature of 65°C. This suggests that the cladding-pumped MC-EDFA successfully reduced the power consumption by about half that of the conventional optical amplifier.

The cladding pumping was also adopted in an SDM optical amplifier for a dense SDM (DSDM) transmission. A 32-core EDFA that employed a DCMC-EYDF was used in a DSDM transmission experiment as an optical amplifier repeater [4].

The gain and noise figure of the cladding-pumped MC-EDFA with a DCMC-EYDF degraded in the



(a) Constriction of EDF cross-section and comparison between erbium-doping and intensity distribution



(b) Gain and noise figure of FM-EDFA employing ring-core EDF

Fig. 3. FM-EDFA.

shorter wavelength region because of the strong absorption of the erbium ions in the EDF. Further study is necessary to improve the uniformity of the gain and the noise characteristics if we are to use the entire C-band for amplification.

3. FM-EDFA

One issue with FM-EDFAs is the differential modal gain (DMG) needed to minimize the differences between the signal-to-noise ratios of all the transmitted signals and thus maintain signal quality. To reduce the DMG in FM-EDFAs, it is important to reduce the difference between two overlap integrals, namely that for the excited erbium ion area and the intensity distribution of the fundamental mode signal and that for the excited erbium ion area and the intensity profile of higher-order signals. For this purpose, the doping of erbium ions with a ring profile and the use of a reconfigurable pump mode have been reported [5, 6]. Disadvantages of these techniques are that the former complicates the EDF fabrication process, and the latter introduces an additional loss for the pump power.

Another approach was taken in an NTT study, which involves employing a ring-core erbium-doped fiber (RC-EDF) with a ring-shaped index profile. As shown in **Fig. 3(a)**, the optical signals of LP_{01} and LP_{11} modes at the RC-EDF have a similar intensity distribution, in which the overlap integral for both the LP_{01} and LP_{11} mode signals have similar values, resulting in a reduction of the DMG. Our approach has advantages over other approaches in that it maintains a simple fabrication process with uniform erbium doping and eliminates the need for lossy additional pump adjustment. The FM-EDFA with an

RC-EDF whose parameters were optimized successfully exhibited a small DMG of 1.6 dB, which is 4.5 dB smaller than that for an FM-EDFA with a conventional circular core (**Fig. 3(b)**). The FM-EDFA with the RC-EDF was also used for a long-haul mode-division-multiplexing transmission as an optical amplifier repeater, which confirmed its feasibility [7].

4. Future work

In upcoming research, we will investigate advanced amplification technologies for gain and output control in SDM optical amplifiers.

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Hirotaka Ono

Senior Research Engineer, Photonics-Electronics Convergence Laboratory, NTT Device Technology Laboratories.

He received a B.S., M.S., and Ph.D. in applied physics from Tohoku University, Miyagi, in 1993, 1995, and 2004. He joined NTT in 1995. He was also a Visiting Research Fellow with the Optoelectronics Research Centre (ORC), University of Southampton, UK, from 2005 to 2006. He has been engaged in research on optical fiber amplifiers, including L- and S-band erbium-doped fiber amplifiers. He has also undertaken research on highly nonlinear fiber devices, photonic crystal fibers, and wavelength-division-multiplexing transmission systems. He is now working on research of multi-core and few-mode fiber and waveguide devices, including optical amplifiers, and space-division-multiplexing systems. He received the OECC'97 Best Paper Award, Electronics Letters Premium in 1997, and Young Engineers Award from the Institute of Electronic, Information and Communication Engineers (IEICE) in 2003. He is a senior member of the Institute of Electrical and Electronics Engineers (IEEE), The Optical Society (OSA) and IEICE, and a member of the Japan Society of Applied Physics (JSAP).