Recent Trends and Future Prospects regarding Multi-core Optical-Fiber-Amplification Technology

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1. Introduction

Single-core erbium-doped fiber amplifiers (EDFAs) are widely used as standard optical fiber amplifiers in optical-fiber communication systems. A multi-core (MC) EDFA is expected to be smaller and consume less power than a single-core EDFA. It can be miniaturized because multi-core optical devices such as MC-EDFs, isolators, and wavelength-division-multiplexing (WDM) filters are almost the same size and have about the same number of components as conventional single-core devices. The mounting volume of a MC-EDFA is almost the same as that of a single-core EDFA, so the volume per core is reduced by approximately the number of cores. The core-pumped 4-core EDFA has been improved in terms of reducing mounting volume and achieving amplification characteristics equivalent to those of a single-core EDFA.

It is expected that only cladding-pumped MC-EDFAs will achieve low power consumption. The reason for that expectation is that the electrical-optical conversion efficiency of a multi-mode laser diode (MM-LD), which is the pump optical source of a cladding-pumped MC-EDFA, is approximately 1.5 times that of a single-mode LD, which is the pump optical source of a core-pumped MC-EDFA. However, the absorption efficiency of the erbium-doped core in regard to the cladding-pump light is extremely low, so improving the efficiency has been attempted. Recently, power consumption per core of a coupled-12-core EDFA (operating in the C-band) reached a lower level than that of a single-core EDFA[1] and power consumption per core of an uncoupled 19-core EDFA (operating in the L-band) reached the same level as that of a single-core EDFA[2].

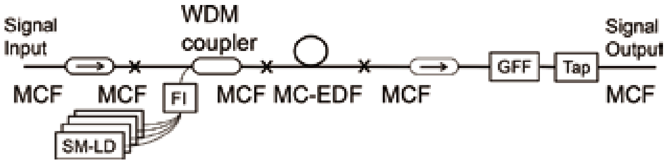
The latest trends and directions of future development of the core-pumped MC-EDFA, which is expected to enable miniaturization, and the cladding-pumped MC-EDFA, which is expected to enable low power consumption, are introduced in this report.

2. Core-pumped MC-EDFA

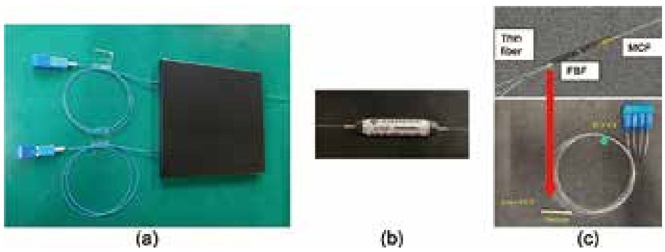
An typical configuration of a core-pumped MC-EDFA is shown in Figure 1. The MC-EDFA is configured so that the input and output fibers are spliced with multi-core fibers (MCF) by a fusion-splicer[3, 4]. Since the number of pump optical sources is the same as the number of cores, power consumption of the MC-EDFA is the same as that of a single-core EDFA. The optical system is configured in the same way as a single-core EDFA, except that MCFs propagate the signal light and the optical device has multi-cores, so the mounting volume is also the same as that of a single-core EDFA. The volume per core is therefore reduced by increasing the number of cores.

A photo of the exterior of the 124 × 135 × 10 (mm^3) housing that houses the optical system (excluding the GFF and tap shown in Figure 1) is shown in Figure 2(a). Two input/output 4-core fibers and four pump input fibers are connected to the housing. The dimensions of the 4-core isolator are f5.5 × 27 mm[5] [Figure 2(b)] and those of the fiber-bundled 4-core fan-in (FI) are 3 × 3.5 × 45 mm^3 [Figure 2(c)][6, 7]. It is clear that the dimensions of 4-core EDFA and optical devices are almost identical to those of the single-core EDFA and optical devices for single cores. A fusion splicer with an automatic-alignment function was used to connect the MCFs. Average splicing losses for two-electrode and three-electrode discharges are 0.07 dB and 0.02 dB, respectively, which are comparable to those for single-core fibers[8-10]. The fusion time, including alignment, for a 4-core fiber with a marker is short (90 s). Although the noise figure (NF) is about 1 to 2 dB larger than that of a single-core EDFA, the gain is the same with a core-to-core gain difference of less than 1 dB. By reducing insertion loss of optical devices, etc., it will be possible to reduce the NF close to that of a single-core EDFA.

■ **Figure 1: Typical configuration of core-pumped MC-EDFA: Arrow: isolator; cross: fusion points; GFF: gain-equalizing filter; FI: fan-in**



■ **Figure 2: (a) Appearance of a core-pumped 4-core EDFA, (b) 4-core isolator, and (c) fiber-bundle fan-in (FI)**



3. Cladding-pumped MC-EDFA

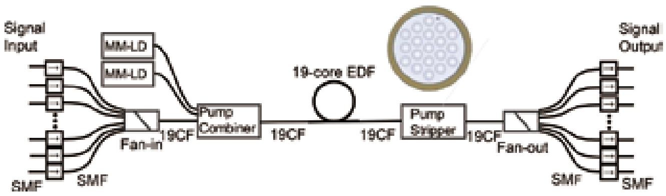
A typical configuration of a cladding-pumped MC-EDFA is shown in Figure 3[2]. To propagate the pumping light in the cladding, a "double-cladding" structure is formed by coating the outside of the glass cladding with a low-refractive-index resin, as shown in the cross-sectional photo of the 19-core EDF shown in Figure 3. The difference between the cladding-pumped MC-EDFA and the core-pumped configuration is that the output light of the MM-LDs is injected into the inner cladding of the MC (19-core)-EDF by using the pump combiner, and the residual pump light from the MC (19-core) fiber is extracted by the pump stripper. If the single-core isolators installed outside the FIFO are replaced with multi-core isolators, the mounting volume is reduced. Amplification characteristics of a C-band cladding-pumped 19-core EDFA are shown in Figure 4[11]. The amplification characteristics are identical to that of a single-core EDFA, and the gain difference between the cores is less than 1 dB. Note that the NF of the C-band cladding-pumped 19-core EDFA is about 1 dB larger than that of the single-core EDFA due to the insertion loss of the optical device.

An issue with cladding-pumped MC-EDFAs is their low efficiency of cladding pumping. The large inner-cladding diameter of MC-EDF cable makes it difficult to calculate light-propagation efficiency and optimize the MC-EDF. We have therefore experimentally identified ways to increase cladding-pumping efficiency[12]. Since the output power of the amplified light is proportional to cladding-pumping power density, the first way is to reduce cladding diameter[13]. The second way is to increase core diameter. Increasing core diameter is considered to improve the probability that the cladding-pumped light collides with the core. The third way is to increase the number of cores[14]. When core characteristics and core density are the same, gain is higher when the number of cores is greater. This way is considered to be highly effective in scattering cladding pump light.

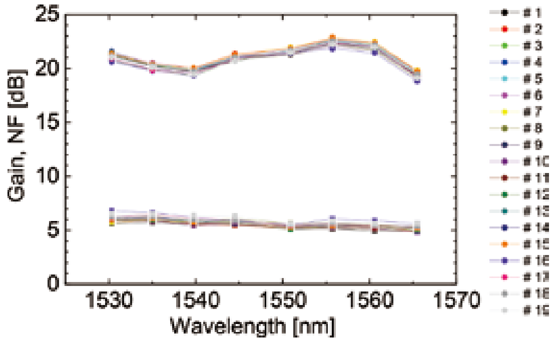
By applying all three ways, we fabricated a 19-core EDFA with cladding diameter of 166 μm, core-to-core distance of 30 μm, and mode-field diameter of 7 μm. When EDF length was set to 8 m, the input optical signal was amplified in the C-band; in particular, under pump power of 28 W and input of –5 dBm/core, output was 17.5 dBm/core[4], which is, however, below the 20 dBm/core required for practical use. On the other hand, when EDF length is set to 50 m, the input signal is amplified in the L-band, and under input of 7.5 dBm/core and pump power of 28 W, output power was increased to 24.3 dBm/core[4].

Output power and power consumption of the developed 19-core EDFA (under cladding pump power of 11.2 W) were respectively 20 dBm/core and 1.2 W/core, which is equivalent to that of a single-core EDFA. We believe that the increased EDF length of the EDFA (50 m) compensates for its low cladding-pumping efficiency.

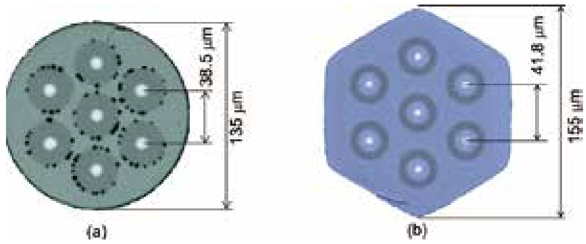
■ Figure 3: Typical configuration of cladding-pumped MC-EDFA. MCF: double-clad fibers; arrow: isolators



■ Figure 4: Typical amplification characteristics of cladding-pumped 19-core EDFA. Input signal power: -5 dBm/core; pump power: 35 W[11]



■ Figure 5: (a) 7-core EDFA with air holes inserted in the cladding[15] and (b) 7-core EDFA with hexagonal cladding[16]



Recently, a 12-core EDFA with smaller cladding diameter (90 μm) and higher core density finally demonstrated lower power consumption than that of a single-core EDFA, even in the C-band, where the EDF length is short[1]. Core-to-core distance of this 12-core EDFA is reduced to 15.5 μm, so it operates as a coupled MC-EDFA. The remaining challenge is to improve gain under C-band operation of uncoupled MC-EDFAs, which require core-to-core distance of, for example, 30 μm or more.

Furthermore, it has been confirmed that inserting air bubbles (as "Mie scatterers") in the cladding[15] and changing the cladding shape from circular to hexagonal[16], for example, are effective means to improve cladding-pump efficiency. Such means would help reduce power consumption of cladding-excited MC-EDFAs.

4. Conclusion

The latest trends and future directions of technologies concerning core-pumped MC-EDFAs and cladding-pumped MC-EDFAs, which are expected to be smaller and achieve lower power consumption, respectively, were introduced.

References

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