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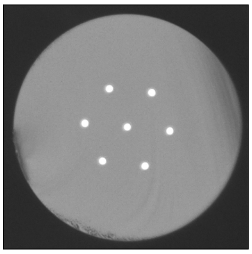

Optical Amplifiers Using Multicore Erbium Doped Optical Fibers

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Three types of individual core pump multicore erbium-doped optical fiber amplifiers with different core coupling have been demonstrated. These amplifiers showed better power consumption efficiency, such as 24% for a coupled 4-core optical fiber amplifier. Crosstalk is an important parameter in uncoupled multicore optical fiber transmission. The crosstalk of the uncoupled 4-core optical fiber amplifier is -43 dB, which is comparable to the lowest crosstalk in previously reported multicore optical fiber amplifiers. The mode-dependent loss, an important parameter in coupled multicore optical fiber transmission, corresponds to the core-dependent gain of uncoupled multicore optical fiber amplifiers and weakly coupled optical fiber amplifiers. The core-dependent gain of the weakly coupled 7-core optical amplifier is 0.52 dB, which is comparable to the smallest mode-dependent loss in previously reported multicore optical fiber amplifiers.

Keywords: optical space-division multiplexing, multicore fiber, multicore erbium-doped fiber amplifier

1. Introduction

Rapidly increasing data traffic is driving research on space-division multiplexing in optical fiber communications. Multicore fibers (MCFs) have two or more cores in a single optical fiber and can be classified into coupled and uncoupled MCFs based on the strength in the optically core coupling. In uncoupled MCFs, since intentional core coupling is forbidden, signal processing similar to one used in conventional communication systems can be applied in receivers. However, the core density in uncoupled MCF cannot be increased. In coupled MCFs, since intentional core coupling is allowed, the core density can be increased. However, multi-input multi-output (MIMO) processing is required to demultiplex original transmitted signals from mixed signals at the receiver.

Recent long-haul transmission experiments demonstrated that coupled MCFs overcame the problem of single-core fibers in channel capacity.(1),(2) These experiments used single-core (SC) erbium-doped fiber amplifiers (EDFAs). Multicore (MC) EDFAs based on MCF technology promises additional improvements in transmission quality because losses with fan-in and fan-out devices*1 to connect a transmission MCF and several SC-EDFAs and adjustment of delay time for each SC-EDFA are not required.

MC-EDFAs can be classified into core pumping*2 or cladding pumping.*3 In cladding-pumped MC-EDFAs, since the increasing number of cores can improve the power consumption efficiency, the simples pumping system and high efficiency pump lasers are driving the researches.(3)-(7) Although the core-pumped MC-EDFA has advantages such as high power efficiency(8)-(11) and the ability to adjust gain for individual cores, there have been fewer research reports on this scheme type than on the cladding-pumped MC-EDFA. One likely reason for this is that no definite advantage has been identified with the core-pumped MC-EDFA in comparison with the use of several SC-EDFAs, with the ultimate power efficiency of the core-pumped MC-EDFA being at a similar level to that of an SC-EDFA.

Nevertheless, in coupled MCF transmission, a very small delay difference between cores is a definite advantage. Hence, the core-pumped MC-EDFA is particularly advantageous if the number of cores is small. This report describes three types of core-pumped MC-EDFAs differing in the strength of the core coupling, which were built as prototypes by Sumitomo Electric Industries, Ltd.

2. Core-Pumped MC-EDFAs and Their Characterization

A core-pumped MC-EDFA consists of a main block, an input isolator, and a gain flattening filter, as shown in Fig. 1. The main block comprises an MC-EDF connected by a bridge MCF, pump lasers whose number is equal to the number of cores, a fan-in device for pumping, a pump combiner, and an output isolator. The input isolator and gain flattening filter are connected to the main block by a bridge or transmission MCF according to the specific purpose. The pump laser uses a single-mode laser diode oscillating at a wavelength of 976 nm. The MC-EDF and the bridge MCF have the same core arrangement as the transmission MCF in order to directly connect the MC-EDFA to the transmission MCF.

Gain, noise figure, and power consumption efficiency are important characteristics of an MC-EDFA. Other important characteristics are crosstalk and mode-dependent loss and gain (MDL),*4 which were introduced along with the development of multicore fibers. Crosstalk and MDL correspond to the non-diagonal element and the condition number, respectively, of the transfer matrix of the MC-EDFA. MDL should preferably be low because it is difficult to estimate the input from the output for transfer matrixes with a large condition number.

The MDL of an MC-EDFA can be measured either by swept-wavelength interferometry(12),(13) or a MIMO process.(11) Swept-wavelength interferometry is suitable for characteristics evaluation of discrete MC-EDFAs due to the small amount of equipment required. However, it is difficult to isolate the effects of fan-in and fan-out devices with this method. By contrast, a MIMO process used in circulating transmission experiments can isolate the effects of fan-in and fan-out devices if the circulating system is suitably configured; however, this method requires a large measurement system.

There are few reports on coupled MC-EDFAs and their MDL. With uncoupled MC-EDFAs and weakly coupled MC-EDFAs, MDL can be approximated by core-dependent loss and gain (CDL) defined by the ratio between the maximum gain and the minimum gain across cores because the transfer matrixes of these amplifiers are diagonally dominant. For these reasons, in this report, CDL is used as an alternative parameter to MDL.

Figure 2 illustrates a measurement system used to obtain gain and noise figure spectra. The MC-EDFAs described in this report assume a direct connection to a transmission MCF. Consequently, signal fan-in and fan-out devices are included in the measurement system.

Twenty-four wavelength-division multiplexing (WDM) signals between the wavelengths of 1527 nm to 1564 nm with 200 GHz spacing are adjusted to control wavelength-to-wavelength power fluctuation to be 1 dBpp or less. After being split, the signals are launched into a variable optical attenuator through delay lines differing in length by 100 m increments. The signals input to the MC-EDFA are adjusted by the variable optical attenuator to ensure a uniform level across individual cores, with compensation for the CDL of the fan-in device taken into account. The signal output from the MC-EDFA is split by a signal fan-out device. The optical output spectrum of each core of the MC-EDFA is measured by an optical spectrum analyzer while switching connections by an optical switch. Gain and noise figure spectra are derived, compensating the CDL of the signal fan-out device.

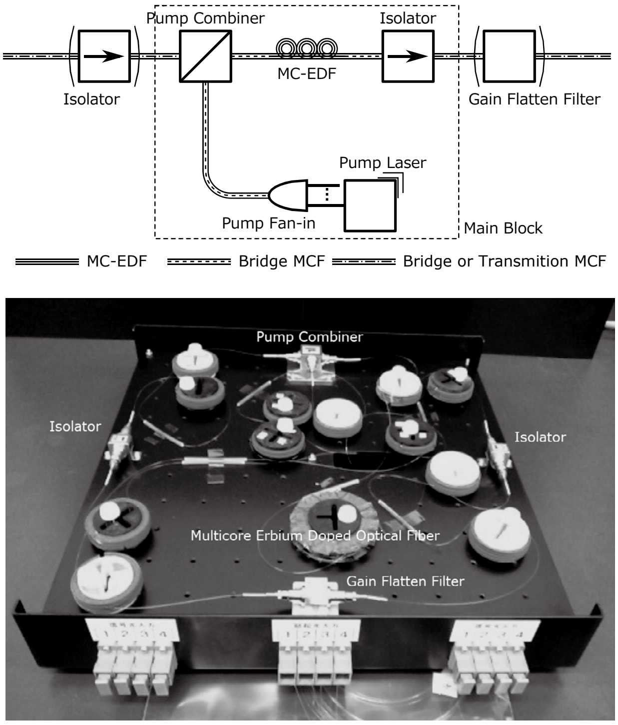

Fig. 1. Configuration of core-pumped EDFA

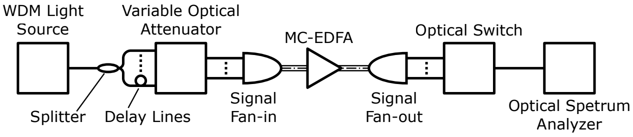

Fig. 2. Gain and noise figure measurement system for MC-EDFAs

Unless otherwise noted, gain refers to the average gain across all cores and all wavelengths, which is the ratio of the total output to the total input across all cores and all wavelengths of wavelength-division multiplexing signals; the noise figure is the maximum across all cores and all wavelengths; CDL means the ratio between the maximum gain and the minimum gain among cores for each wavelength; power efficiency means the minimum value among cores of the ratio of the difference between the output signal power and the input signal power to the input pumping light power.

2-1 Uncoupled four-core EDFA

The prototype uncoupled 4C-EDFA comprised an isolator upstream and a gain flatten filter downstream from the main block. The input and output are terminated by transmission 4CFs. The uncoupled 4C-EDF, bridge 4CF, and transmission 4CF comprised in the uncoupled 4C-EDFA had a 45 µm square lattice core arrangement, as shown in Fig. 3. The length of the EDF was 19 m.

The gain was 14.7 dB; the CDL was 1.8 dB; the noise figure was 7.2 dB; the power efficiency was 7.7% (18% with the gain flatten filter excluded); the crosstalk was −43 dB.

Figure 4 shows gain and noise figure spectra. The input was −12.3 dBm per core per wavelength for all of the four cores (1.5 dBm/core). The pumping light power was controlled for each core so as to minimize CDL and wavelength-dependent loss and gain in the same single core.

The poor flattening performance, despite the presence of the gain flatten filter, was caused by varying angles of incidence of optical signals to the multilayer film filter.

Figure 5 presents an example of crosstalk measurement. In this example, inter-core crosstalk was measured based on the output signal spectrum of each core measured by inputting optical signals differing in wavelength to individual cores, that is, at 0.5 nm intervals centered at 1,547 nm.

2-2 Coupled four-core EDFA

The prototype coupled 4C-EDFA had the simplest configuration, consisting only of a main block. The input and output were terminated by bridge 4CFs. The coupled 4C-EDF and bridge 4CF comprised in the coupled 4C-EDFA had a 20 µm square lattice core arrangement, as shown in Fig. 6. The length of the EDF was 14 m. The gain was 18.8 dB; the CDL was 2.5 dB; the noise figure was 7.3 dB; the power efficiency was 24%.

Figure 7 shows gain and noise figure spectra. The input optical signal was −16.8 dBm per core per wavelength for all of the four cores (−3 dBm/core). The pumping light power was controlled for each core so as to

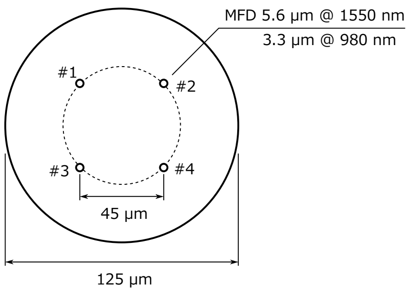

Fig. 3. Cross section of uncoupled 4C-EDF

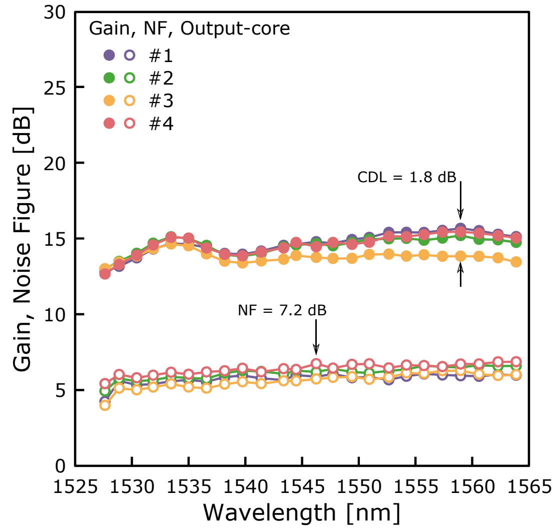

Fig. 4. Gain and noise figure spectra of uncoupled 4C-EDFA

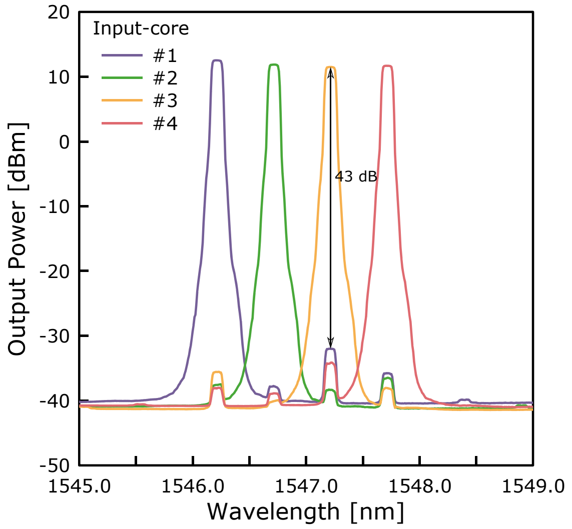

Fig. 5. Crosstalk of uncoupled 4C-EDFA

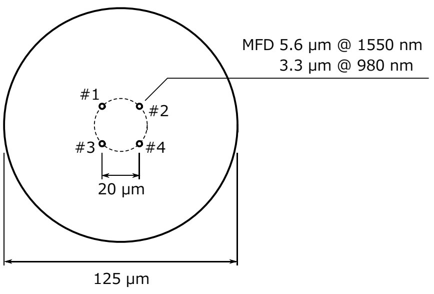

Fig. 6. Cross section of coupled 4C-EDF

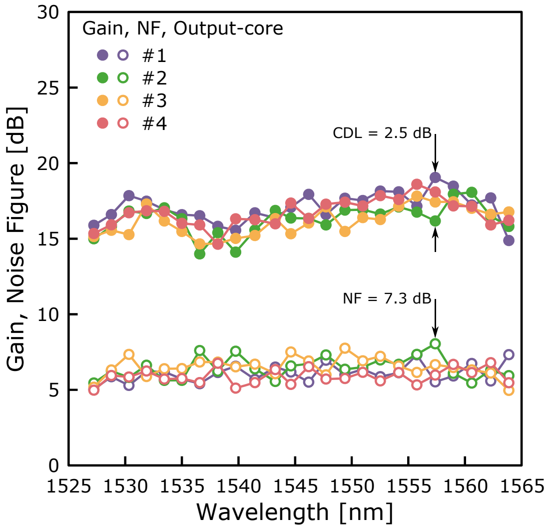

Fig. 7. Gain and noise figure spectra of coupled 4C-EDFA

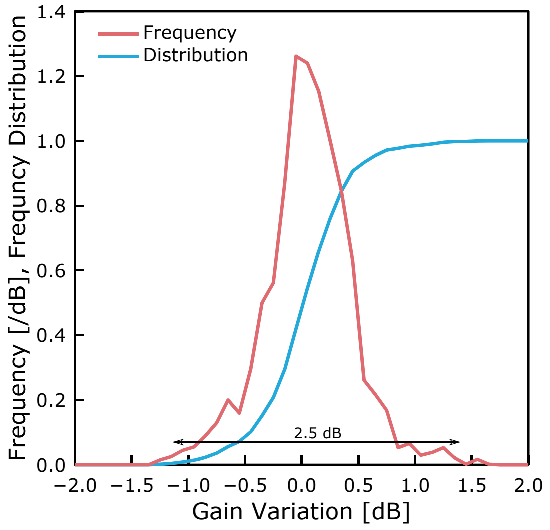

Fig. 8. Distribution of gain variation from the average gain among cores at one wavelength of coupled 4C-EDFA

make gain uniform across cores with the pump power of the best core being 22 dBm. Incidentally, spectral variations between wavelengths are due to optical signal interference resulting from strong core coupling in the coupled 4C-EDFA and in the signal fan-in and fan-out devices.

With the coupled 4C-EDFA, gain variation—observed with one wavelength—from the average gain across cores exhibits a distribution as shown in Fig. 8 due to optical signal interference. With respect to the mode, the top 5% lie on the gain side ranging from 0.6 dB to 1.6 dB, while the bottom 5% are located on the loss side ranging from −0.6 dB to −1.3 dB; the mean ±25% are distributed within the range −0.25 dB to 0.2 dB. This distribution conforms to the fact that the CDL is 2.5 dB. Noise figure distributions exhibit a reverse trend compared with gain distributions; therefore, the mode is probably approximately 6 dB even at 1,557 nm where the noise figure peaked at 7.3 dB during the spectral measurement shown in Fig. 7.

2-3 Weakly coupled seven-core EDFA

The prototype weakly coupled 7C-EDFA had an isolator upstream from the main block. The input and output were terminated by bridge 7CF. The coupled 7C-EDF and the bridge 7CF comprised in the weakly coupled 7C-EDFA had their cores arranged into a 23.5 µm hexagonal close-packed lattice, as shown in Fig. 9. The length of the EDF was 15 m. The gain was 18.4 dB; the CDL was 0.52 dB; the noise figure was 6.8 dB; the power efficiency was 22%.

The inter-core crosstalk was −18 dB, which followed the diagonal dominance conditions for a transfer matrix. While with the coupled 4C-EDFA, a signal input into one core is output roughly equally split among the four cores, with the weakly coupled 7C-EDFA, the signal is output almost exclusively from the core that received the signal.

Figure 10 plots gain and noise figure spectra. The input was −16.8 dBm per core per wavelength for all of the seven cores (−3 dBm/core). The pumping light power was controlled for each core so as to make gain uniform across cores with the pumping light power of the central core being 22 dBm.

In the weakly coupled 7C-EDFA, gain variation—observed with one wavelength—from the average gain across cores more or less exhibits a distribution as shown in Fig. 11 although the optical signal interference is well controlled. With respect to the mode, the top 5% are on the gain side ranging from 0.2 dB to 0.5 dB, while the bottom 5% are found on the loss side ranging from −2.6 dB to −0.5 dB; the mean ±25% are distributed within the ±0.1 dB range. This distribution conforms to the fact that the CDL is 0.52 dB.

Figure 12 shows an example of crosstalk measurement. In this example, inter-core crosstalk was measured based on the output signal spectrum of each core measured by inputting, to individual cores, optical signals differing in wavelength, namely 1,550 nm and ±0.5 nm, ±0.7 nm, and ±0.9 nm from 1,550 nm.

While with the coupled 4C-EDFA it is difficult to adjust gain between cores due to substantial optical signal fluctuation caused by interference, with the weakly coupled

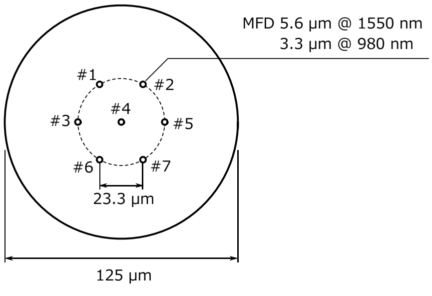

Fig. 9. Cross section of weakly coupled 7C-EDF

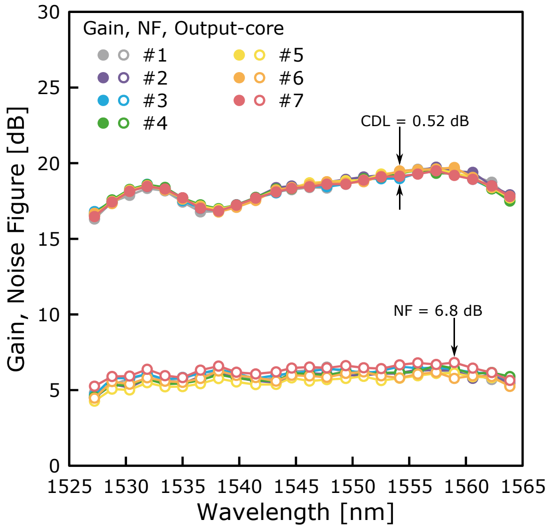

Fig. 10. Gain and noise figure spectra of weakly coupled 7C-EDFA

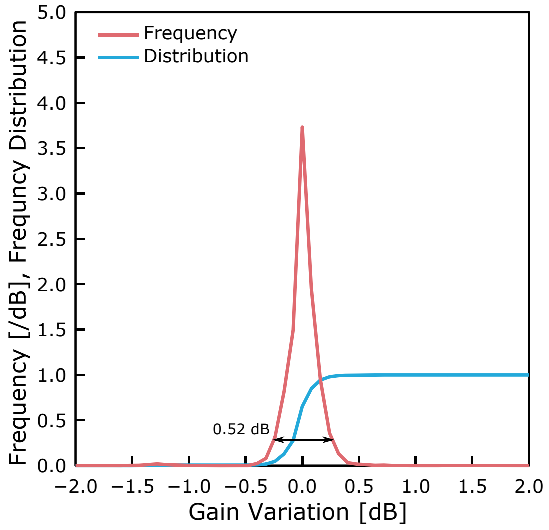

Fig. 11. Distribution of gain variation—observed with one wavelength—from the average gain across cores of weakly coupled 7C-EDFA

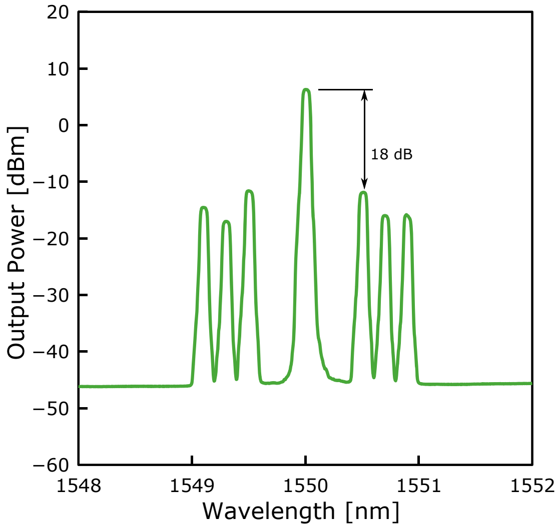

Fig. 12. Crosstalk of weakly coupled 7C-EDFA

7C-EDFA it is easy to adjust gain between cores because its optical signal fluctuation is suppressed. Consequently, it is highly probable that weakly coupled MC-EDFAs are more suitable for coupled MCF transmission in which low MDL is desirable.

3. Discussion

This chapter discusses target values for MC-EDFAs, making a comparison with existing studies reporting on operation in the saturation region because the MC-EDFAs of Sumitomo Electric described above similarly have their operating points in the saturation region.

An MC-EDFA with a flattened gain of 13 dB or more can be used for transmission experiments because the gain is adequate if it compensates for the loss incurred in the relay span. Loss caused by gain flattening is within an approximate range of 3 dB to 6 dB. Thus, without gain flattening, target gain should lie between 16 dB and 19 dB.

Noise figures of 5 dB or less are desirable in practical operation although a noise figure of approximately 8 dB is adequate for transmission experiments. Therefore, improving the noise figure is an important task.

Existing studies report that power efficiency ranges from 10% to 20% for core-pumped MC-EDFAs,(8)–(11) is approximately 2% for cladding-pumped uncoupled MC-EDFAs,(7)–(10) and is 10% for cladding-pumped coupled MC-EDFAs.(11) Compared with these levels, the three examples of Sumitomo Electric are in the highest-level class as an MC-EDFA at approximately 20%. By improving the insertion loss of the pumping system, power efficiency will be likely to reach about 40%, a level comparable to SC-EDFAs.

The cladding-pumped coupled 12C-EDFA is an interesting example of improving power efficiency by increasing the core-to-cladding area ratio.(11) Since a similar core-to-cladding area ratio to the above is not easy to achieve in a four- or seven-core fiber, core pumping is advantageous given a small number of cores.

Regarding crosstalk, existing studies present values ranging from −32 dB to −45 dB.(4)–(7),(9) The crosstalk of the uncoupled 4C-EDFA of Sumitomo Electric is −43 dB, being in the highest level class according to existing studies.

Regarding MDL, the cladding-pumped coupled 12C-EDFA exhibits the best value at 0.55 dB.(11) The CDL of the weakly coupled 7C-EDFA of Sumitomo Electric is 0.52 dB, most likely reaching the highest level, even if noting that CDL is underrated as an approximate value of MDL.

At this point, for discussion of target crosstalk and MDL values for MC-EDFAs, it should be appropriate to consider the impact of crosstalk and MDL on bit error rate (BER). With uncoupled MCFs, crosstalk causes BER to increase in one core in such a manner that feeble optical signals leaking from the other cores behave like noise. Moreover, apparent noise power due to crosstalk increases linearly with transmission distance. MDL causes BER to increase by acting as an excess factor when, for example, the quantizing errors of an analog-to-digital converter are converted through a MIMO process to input referred noise. Furthermore, MDL increases exponentially (linearly in dB) with transmission distance.(2),(11) With these characteristics taken into account, dependence of BER on the number of transmission segments in 16-quadrature amplitude modulation (QAM) was calculated, as shown in Fig. 13.

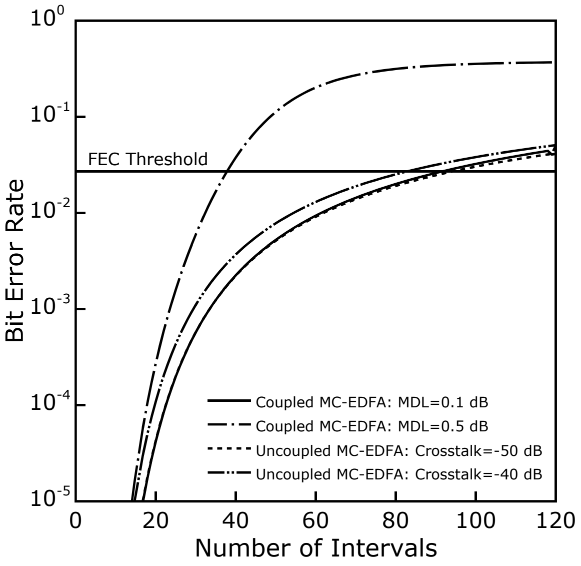

Fig. 13. Dependence of bit error rate on the number of transmission segments in coupled or uncoupled MCF transmission

For uncoupled MCF transmission, if the crosstalk of the MC-EDFA is −40 dB, the number of transmission spans will reach 80; if the crosstalk is −50 dB, the number of transmission spans will increase to 90. This increment is equivalent to an extension of a few hundred kilometers in an actual transmission system. Therefore, with practical use in mind, crosstalk should desirably be −50 dB or less.

For coupled MCF transmission, if MDL is 0.5 dB, the number of transmission segments will reach 35, while if it is 0.1 dB, the number of transmission segments will increase to up to 90. To achieve comparable transmission quality to that of uncoupled MCF transmission (−50 dB in crosstalk), it is desirable to reduce MDL to 0.1 dB or less.

4. Conclusion

Three types of prototype core-pumped MC-EDFAs were constructed differing in core coupling, demonstrating that core pumping is excellent in terms of power efficiency. They exhibited the highest level characteristics in power efficiency, crosstalk, and MDL, as far as comparisons were possible. To make improvements in noise figure and power efficiency from the perspective of practical use, insertion losses incurred by optical components and connecting points need to be reduced. To improve uncoupled MC-EDFAs in terms of crosstalk, it is necessary to reduce crosstalk in optical components. For improved MDL of coupled MC-EDFAs, it is necessary to adjust gain between cores, as well as to reduce the CDL of optical components.

Compared with coupled 4C-EDFAs, weakly coupled 7C-EDFAs are advantageous in reducing MDL because of reduced optical signal interference, which makes it easy to adjust gain between cores. Thus, core-pumped weakly coupled MC-EDFAs are highly likely to be a promising option as an optical amplifier for coupled MCF transmission.

Technical Terms

∗1 Fan-in and fan-out devices: Fan-in and fan-out devices are optical components used to establish optical connections between more than one single-core optical fiber and one multicore optical fiber. Those which are used to launch light into a multicore optical fiber are known as fan-in devices; those which are used to take light from a multicore optical fiber are known as fan-out devices.

∗2 Core pumping: A pumping scheme that launches pumping light into an EDF core as guided light.

∗3 Cladding pumping: A pumping scheme that launches pumping light into the cladding of an EDF; a second cladding made of low-refractive-index plastic or the like is provided to ensure that the pumping light propagates in the cladding.

∗4 Mode-dependent loss and gain: A quantity defined as the ratio of the maximum eigenvalue to the minimum eigenvalue or the maximum singular value to the minimum singular value; it is equal to the condition number defined as the 2-norm of a transfer matrix. Gain is collectively handled with loss because mode-dependent loss and gain is normally defined in such a way that it takes a positive value in terms of dB.

References

(1) R. Ryf, et al., “Long-haul transmission over multi-core fibers with coupled cores,” in Proc. Eur. Conf. Opt. Commun., 2017, Paper M.2.E.1

(2) R. Ryf, et al., “Coupled-core transmission over 7-core fiber,” in Proc. Opt. Fiber Commun. Conf., 2019, Paper Th4B.3

(3) S. Takasaka, et al, “Cladding-Pumped Seven-Core EDFA Using a Multimode Pump Light Coupler” in Proc. Eur. Conf. Opt. Commun., 2013, Paper We4A5

(4) S. Takasaka, et al, “Cladding Pump Recycling in 7-core EDFA,” in Proc. Eur. Conf. Opt. Commun., 2018, Paper We.1E

(5) S. Takasaka etal, “EDF Length Dependence of Amplification Characteristics of Cladding Pumped 19-Core EDFA,” in Proc. Opt. Fiber Commun. Conf., 2018, Paper Th1K.2

(6) S. Takasaka et al, “Cladding Pump Recycling Device for 19-core EDFA,” in Proc. Opt. Fiber Commun. Conf., 2019, Paper Th3D.7

(7) M. Wada, et al. “Full C-band and Power Efficient Coupled-multi-core Fiber Amplifier,” in Proc. Opt. Fiber Commun. Conf., 2020, Paper M4C.3

(8) K. Igarashi, et al, “Seven-Core Fiber with Enlarged Aeff and Full-C-band Seven-Core EDFA for 100-Tbit/s-Class Transoceanic Transmission” in Proc. Eur. Conf. Opt. Commun., 2013, Paper Mo3A2

(9) Y. Tsuchida, et al, “Multicore EDFA for Space Division Multiplexing,” in Proc. Optoelectronics Commun. Conf., 2013, Paper TuS1-1

(10) J. Sakaguchi, et al, “19-core MCF transmission system using EDFA with shared core pumping coupled via free-space optics,” Optics Express vol.22 (2014) 90-95

(11) M. Filipowicz, et al, “Optical Amplifier Based on a 7-core Fiber for Telecommunication Satellite Purpose,” in Proc. Opt. Fiber Commun. Conf., 2017, Paper Th4A.5

(12) J. C. Alvarado-Zacaias, et al. “Characterization of coupled-core fiber amplifiers using swept-wavelength interferometer,” in Proc. Opt. Fiber Commun. Conf., 2019, Paper Th1B.6

(13) M. Maur, et al. “Transfer Matrix Characterization and Mode-Dependent Loss Optimization of Packaged 7-Core Coupled-Core EDFA,” in Proc. Eur. Conf. Opt. Commun., 2021, Paper Tu3a-6

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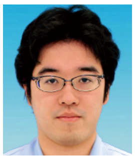

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