Demonstration of C+L 8.7-THz 7-Core Multicore EDFA with a Single Pump Laser Diode Using Pump Recycling Technology

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Abstract *An L-band 4.1-THz 7-core signal has been successfully amplified by using recycled pump light from C-band 4.6-THz 7-core cladding-pumped multicore EDFA. 4.8 % of power conversion efficiency with a single pump laser diode for C+L-band cladding-pumping was obtained twice large as for C-band.*

Introduction

Spatial division multiplexing (SDM) is a promising way to meet the demand for increased communication capacity over the next decade [1-4]. Transmission above 1 Pbps over a single fibre has been achieved by using SDM in combination with conventional wavelength division multiplexing (WDM) [5][6]. Recent efforts have focused on expanding the transmission bandwidth of single core fibre (SCF) as much as possible [7][8], namely, multiband transmission. Transmission above 14 THz bandwidth has already been reported for the S/C/L/U-band [7]. Optical amplification technology is indispensable in both the SDM and WDM domains to achieve such a huge capacity.

We are focusing on amplification technology in the SDM domain and have been researching ways to achieve an efficient multicore erbium-doped fibre amplifier (MC-EDFA) using cladding pumping [9-13]. While a core-pumped MC-EDFA requires the same number of pump laser diodes (LDs) as transmission cores, a cladding-pumped MC-EDFA [9-21] can amplify many transmission cores collectively by using a single uncooled and highly efficient multimode pump LD. However, its power conversion efficiency (PCE) for C-band signal amplification is lower than that of a conventional single-core EDFA (SC-EDFA) due to low pump light density in the inner cladding of the double-cladding multicore erbium-doped fibre (DC-MC-EDF) [17]. This lower efficiency problem must be overcome to enable practical use. One possible solution is to use pump recycling technology [9][18]. However, the reported improvement is insufficient to achieve PCE equivalent to that of a core-pumped MC- or SC-EDFA.

Considering the recent trend toward multiband transmission [5-8], we have improved the PCE of a cladding-pumped MC-EDFA for C-band signal amplification by using recycled pump light from C-band amplification as the pump light source (LS) for L-band amplification instead of re-amplification of the C-band signal, as was done in our previous work [9-11]. We have achieved multiband (C + L) multicore (7 + 7) amplification with only a single pump LD and have shown that PCE was doubled to 4.8 %.

Configuration and operation principle

The configuration of a prototype multiband multicore EDFA using pump recycling technology is shown in Fig. 1. Both a 7-core C-band signal and a 7-core L-band signal can be amplified using only a single multimode uncooled pump LD. C-band signal light is input into and output from each core of a C-band multicore collective gain block by way of a fan-in (FI) device and a fan-out (FO) device, respectively. The insertion loss is 1.3 dB for the FI/FO pair. The C-band signal is combined with 976-nm pump light by a spatial pump combiner (SPC) which composed of lens optics with a dichroic mirror.

The insertion loss is 0.6 dB for signal light and 0.2 dB for pump light. Here, The C-band signal

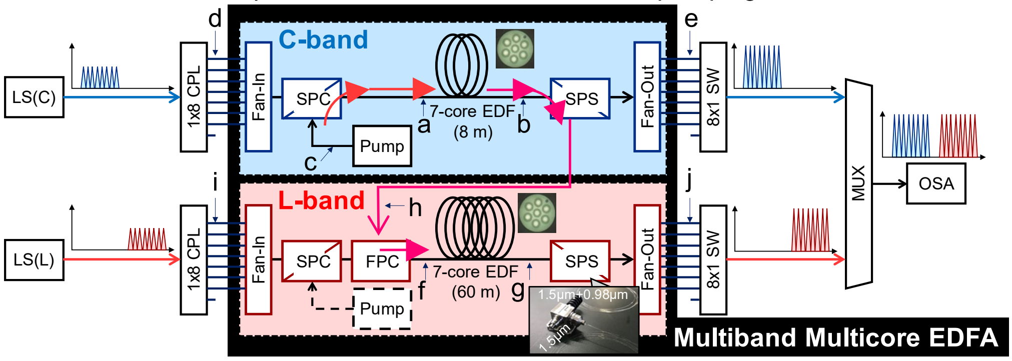

Fig. 1: Configuration of cladding pumped multiband multicore EDFA with a single pump laser diode.

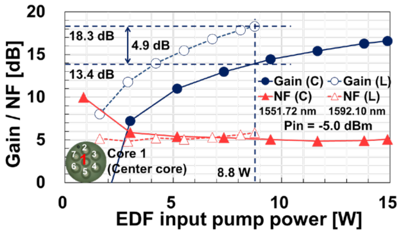

Fig. 2: Individual Gain / NF of C / L-band

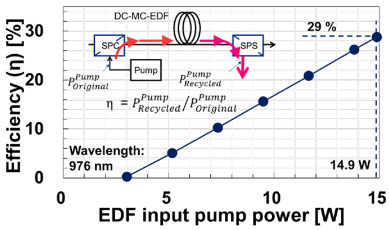

Fig. 3: Recycling efficiency for C-band

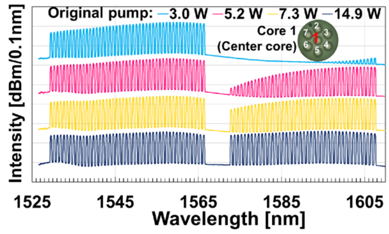

Fig. 4: Pump power dependance

light propagates through each core of the 7-core EDF, which is 8-m long, and pump light propagates through the inner cladding of the EDF. A spatial pump splitter (SPS) is used to separate the remaining pump light from the output of the 7-core EDF and introduce the recycled pump light into the fibre pump combiner (FPC) inside the L-band gain block. The SPS is configured with inverted SPC inputs and outputs.

The insertion loss of the FPC is 0.5 dB for signal light and 0.2 dB for pump light. If the intensity of the recycled pump light is insufficient to pump the L-band signal, another pump LD can be used in this prototype. The use of an SPC/SPS pair is effective for obtaining a gain as large as possible [10][11]. So, it is actually better to use an SPC instead of an FPC. The use of the FPC in this prototype is simply in case the recycled pump light is insufficient.

The L-band signal light propagates with the pump light through a 60-m long 7-core EDF with pump light. The length was optimized to obtain a gain as large as possible and gain characteristics in the wavelength domain as flat as possible. The L-band signal light as well as the C-band signal light for each core is output from FO. The recycled pump light form the SPS of the L-band gain block can be used for re-amplification of the L-band signal light by re-injecting it into the FPC, which can have the multiple pump input ports.

As described above, pump recycling technology enables collective amplification of both C- and L-band signal light of 7-core MCF with only a single pump LD. Doubled PCE in total is expected for C- and L-band amplification with cladding pumping technology.

Evaluation of gain and noise figure

To evaluate the feasibility of multiband collective amplification with only a single LD, we fabricated the prototype illustrated in Fig.1 and evaluated the gain and noise figure (NF) characteristics. Fig. 2 shows the relationship between the pump light intensity originating from the pump LD and gain and NF when the gain blocks of the C- and L-bands were pumped separately by the LD. The L-band gain was around 4.9 dB higher than that of the C-band at a fixed pump power. The input was a continuous wave signal of 1551.72 nm for the C-band and 1592.10 nm for the L-band. The optical power for both was −5 dBm. These results indicate that the PCE for the L-band is more than twice as large as that for the C-band.

Since the recycled pump power is always smaller than the original pump power injected by the pump LD, it is reasonable that recycled pump power be used as the pump light source for L-band amplification. Fig. 3 shows the measured pump recycling efficiency for the C-band. Pump recycling efficiency η is defined as

$$\eta = P^{pump}_{recycled} / P^{pump}_{original} \qquad (1)$$

where $P^{pump}_{original}$ is measured at point c in Fig.1 and $P^{pump}_{recycled}$ is measured at point h. For this prototype, η was linearly proportional to the pump power injected into the 7-core EDF and was measured to be 29 % at 14.9 W of injected pump power.

Next, we connected the output multimode fibre of the SPS inside the C-band gain block with the input multimode fibre port of the FPC inside the L-band gain block. We then amplified both the C- and L-band 7-core signal lights using only the pump LD inside the C-band gain block. Fig. 4 shows the output optical spectrum observed with an optical spectrum analyzer (OSA) when the pump power injected into the 8-m long 7-core EDF was changed.

An ITU-T standards compliant 100-GHz interval WDM signal, which with a bandwidth of 33 GHz and shaped from an amplified spontaneous emission light source was used as the signal light. It's centre wavelength for the C-band was from 1529.55 nm to 1566.31 nm (47 channels); for the L-band it was from 1572.89 nm to 1607.47 nm (42 channels). The total signal bandwidth was 8.7 THz. When the original pump power was increased from 3.0 W to 14.9 W, amplification of the L-band signal was observed. At 14.9 W, the recycled pump power was 4.3 W at point h in Fig. 1, as shown in Fig. 3. Therefore, the pump power injected into the 60-m long 7-core EDF for L-band amplification was reduced to 4.1 W due to the insertion loss of the FPC.

Fig. 5 shows the gain and NF of each core in the 7-core MCF in the wavelength domain when the original pump power was 14.9 W. The optical power input into both the C- and L-band gain blocks was + 2.5 dBm. Fig. 6 shows the gain and

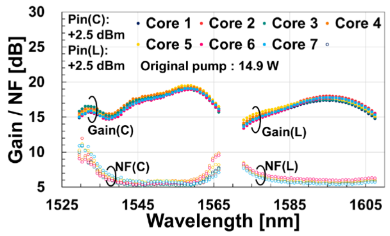

Fig. 5: Core to core deviation

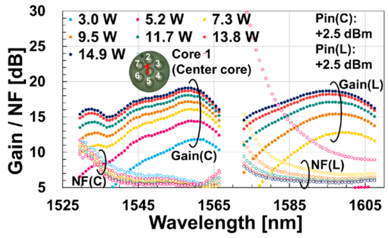

Fig. 6: Pump power dependence

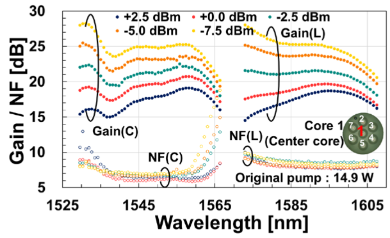

Fig. 7: Input power dependence

NF of the centre core (Core 1) of the 7-core MCF when for six values of the original pump power at a fixed input signal power of +2.5 dBm for both the C- and L-bands. An L-band signal appeared when the original pump power was greater than 7.3 W, which corresponds to the 0.7-W pump power for the L-band signal. The flatness of the gain and NF improved proportionally with an increase in the original pump power.

The input power dependence of the gain and NF for Core 1 at 14.9-W original pump power is plotted in Fig. 7. Though the average gain and NF in the wavelength domain were degraded with an increase in the input optical power, the flatness improved.

The results presented in Figs. 5 to 7 shows that the gain and NF of the C- and L-band signals followed the same trend. The evaluation results are summarized in Table 1. The finding that the gain and NF of the L-band signal were equivalent to those of the C-band one demonstrates that the recycled pump light from the C-band gain block is sufficient as the pump light source for the L-band gain block.

Tab. 1: Statistics of evaluation results

Pump: 14.9 W, Pin: +2.5 dBm			C	L	C+L
Bandwidth [THz]			4.6	4.1	8.7
Gain	Max [dB]		19.1	18.7	19.1
	Min [dB]		15.0	14.5	14.6
	P2P [dB]		4.1	4.2	4.6
	Average [dB]		17.2	17.3	17.3
	Deviation	Wavelength	1.3	1.2	1.2
		Core	0.8	1.2	1.2
NF	Max [dB]		9.7	8.0	9.7
	Min [dB]		5.2	5.7	5.2
	P2P [dB]		4.5	2.4	4.5
	Average [dB]		6.3	6.1	6.2
	Deviation	Wavelength	1.3	0.5	1.2
		Core	2.5	0.5	2.5

Evaluation of power conversion efficiency

Next, we calculated the PCE of the prototype. PCE is defined as

$$PCE = (P_{out}^{FO} - P_{in}^{FI}) \times N_{core} / (P_{pump}^{Original}) \quad (2)$$

where P_{out}^{FO} and P_{in}^{FI} are, respectively, the sum of the input (d, i in Fig. 1) and output (e, j in Fig. 1) optical signal powers of the C- and L-band gain blocks. $P_{pump}^{Original}$ is the pump optical power (c in Fig.1) for the C-band gain block. N_{core} is the total number of cores used for signal amplification.

Fig. 8 shows that the total PCE for C- and L-band amplification was independently of the input optical power and the amplified core, as expected. The maximum PCE was doubled from 2.4 % to 4.8 % at +2.5 dBm of input power for signal light under the experimental conditions of this study. From Eq. (2), the PCE can be further improved if pump recycling is achieved using EDFs with larger number of cores [19].

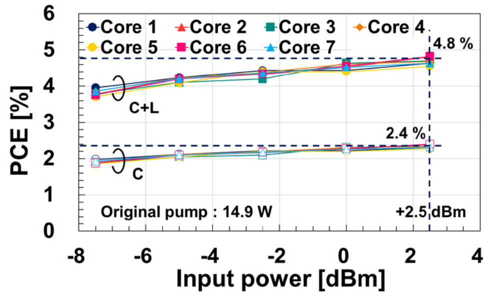

Fig. 8: Pump to signal power conversion efficiency

Conclusions

Our proposed configuration of a cladding pumped multiband multicore EDFA with only a single pump laser diode is aimed at improving the power conversion efficiency (PCE) of cladding pumped MC-EDFAs The key technology is pump recycling. Use of recycled pump light from C-band amplification as the pump light source for L-band amplification enables the pump laser diode for L-band amplification to be eliminated. Evaluation of the gain and noise figure (NF) demonstrated that recycled pump light can be used as well as pump light originating from a pump laser diode and thereby obtain gain and NF for L-band that is equivalent to that of the C-band. Evaluation of the pump-to-signal PCE revealed that a PCE of 2.4 % for only the C-band can be doubled to 4.8 % for the C- and L-bands, as expected.

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