EXPERIMENTAL DEMONSTRATION OF THE CORE UNIFORMITY OF TURBO CLADDING PUMPING WITH A 7-CORE MULTICORE ERBIUM DOPED FIBER AMPLIFIER

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Abstract: Space-Division Multiplexing (SDM) is being actively researched for next generation submarine systems as candidate technology to increase capacity within cost and power limited system constraints. We demonstrated Turbo Cladding Pumping (TCP) scheme, where the residual cladding pump is recycled through a pump splitter and re-injected into the Multi-Core Erbium Doped Fiber (MC-EDF) with side coupling. We demonstrated in detail a gain uniformity within ±0.6dB among the 7 cores of cladding pumped Multi-Core Erbium Doped Fiber Amplifier (MC-EDFA). Furthermore, we show a 2 dB improvement of optical gain and a 32 % reduction of power consumption for the cladding pumped 7-core MC-EDFA using our proposed TCP scheme.

1. INTRODUCTION

Currently, the total amount of the global IP communication traffic in a year is reaching 4.8 ZByte and has been increasing at CAGR of 26 % [1]. Therefore, the capacity of optical transmission systems need to be increased in order to accommodate such a huge traffic. So far, numerous reported research and development works were conducted in order to expand the capacity of optical transmission systems using Single Core Single Mode optical Fiber (SC-SMF). However, the realizable capacity of the SC-SMF based optical transmission systems are approaching to the nonlinear Shannon limit [2]. Space Division Multiplexing (SDM) technology using Multi Core Fiber (MCF) is promising candidate to solve the problem of capacity expansion and has been research lots in these days [3-4].

Among systems with foreseen capacity issues, submarine optical transmission systems will reach their practical limit first because of the huge traffic they carry and of their intrinsic limits, among which electric power supply [5] becomes now a clear capacity limitation. In this regard, SDM technology can contribute not only directly to higher capacity but also indirectly through more efficient electric power usage. Indeed, Multicore erbium doped fiber amplifier (MC-EDFA) is one of the key components to realize SDM transmission systems. One of the benefit of MC-EDFA with cladding pumping is collective amplification of several spatial channels filled with WDM optical signals collectively. Cladding pumping [6] has potential to reduce significantly the power consumption of amplification of spatially multiplexed optical signals. However, the efficiency of cladding pumping still needs to be improved for amplification signals in the C band [7] to keep the reachability of the SDM optical signals. In this perspective, technologies for recycling the remaining cladding pump have recently been reported, namely Turbo Cladding Pumping (TCP) [8] and Cladding Pump Recycling [9].

In this paper, we detail the evaluation results of optical gain deviation between cores of our prototype 7-core MC-EDFA with cladding pumping; we show a sufficient uniformity among cores of ±0.6 dB. We also demonstrate the TCP scheme; we show an improvement of optical gain of 2 dB and reduction of power consumption of 32 % in the same conditions as evaluation of the gain deviation.

2. UNIFORMITY OF OPTICAL GAIN AND NOISE FIGURE AMONG CORES FOR A 7-CORE MC-EDFA

In the case of a SDM system, the whole system will be limited by the SDM channel with the worst characteristics. Specifically, for 7-core MC-EDFA, the gain and Noise Figure (NF) characteristics need to be uniform.

In order to evaluate the uniformity of gain and NF, we used our 7-core MC-EDFA with the experimental setup of Figure 1. 8 Wavelength Division Multiplexed (WDM) CW light sources ranging from 1530.34 nm to 1565.49 nm and with identical optical powers were used. The 8-WDM CW lights were split and input into each port of Fan In

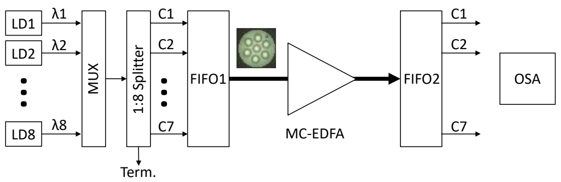

Figure 1: Experimental set-up of optical gain and NF evaluation for 7-core MC-EDFA

Fan Out (FIFO) device to produce 7SDM/8WDM optical signal as shown in Figure 1. The excessive loss of the multiplexing 1:8 splitter was less than 0.1 dB; its influence on wavelength and core dependence of optical gain characteristics of the 7-core MC-EDFA was negligible. The total optical power input into the fan in (FIFO1) was 0 dBm. The 7-SDM/ 8WDM optical signals were amplified collectively in spatial and wavelength domains by the MC-EDFA. Cladding pumping was performed with a single uncooled multimode pump laser diode was used emitting 18.5 W at 0.98 µm wavelength. The length of the MC-EDF was optimized at 8 m. The amplified 7SDM/8WDM optical signals were spatially demultiplexed by the fan out (FIFO2). The spectra of input and output lights were measured with an Optical Spectrum Analyzer (OSA) individually in turn for each core. According to the measurements, optical gain and NF was calculated core by core.

The results of gain and NF evaluation are summarized on Figure 2. Optical gain and NF profiles were almost identical among all cores. The maximum optical gain was 18 dB

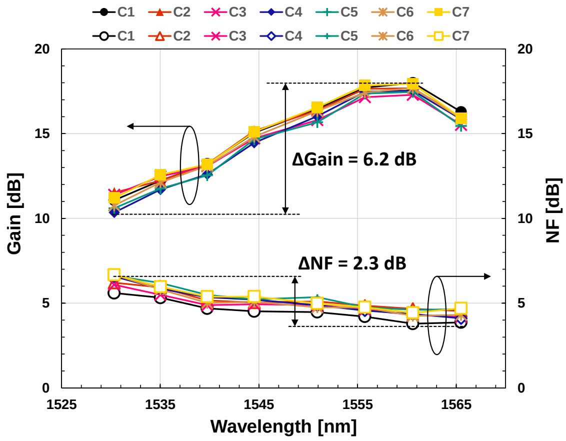

Figure 2: Wavelength dependence of optical gain and NF of the cladding pumped 7-core MC-EDFA prototype. The parameter is core.

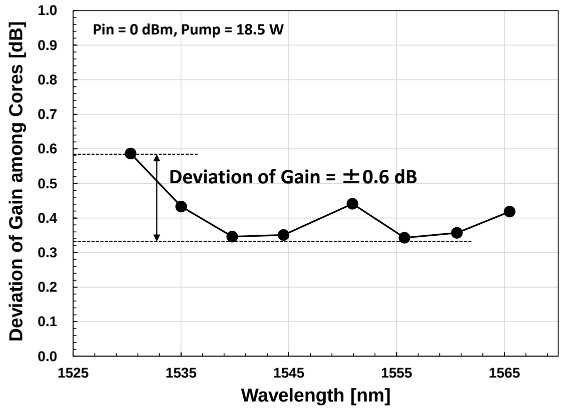

Figure 3: Optical gain deviation among cores.

around 1560.60 nm for core No.1. The variation of optical gain depending on wavelength between 1530.34 nm to 1565.49 nm reached 6.2 dB. The minimum NF was 3.8 dB for a wavelength of 1560.60 nm with core No.1. The variation of NF depending on wavelength was 2.3 dB in the same measurement range.

Figure 3 summarizes the deviation of optical gain among cores. The deviation was larger in short wavelength range, where the gain is weak, but it is still limited to ±0.6 dB at 1530.34 nm. After verification of our experimental setup, we attribute most of the deviation of the optical gain to the accumulation of small optical losses in the experimental setup, such as optical connectors, and to splices in the 7-core MC-EDFA prototype. Most interestingly, the central core, degenerated central ring here denoted as Core No.4, presented characteristics similar to other cores of the outer ring. This highlights the fact that the geometry of the MC-EDFA is not the main source of deviation in characteristics among cores arranged on two rings, for a 7-core MC-EDFA. Again, the deviation of ±0.6 dB among cores is considered to be sufficiently small practically. Noticeably, the spatial deviation is smaller than the spectral deviation, which could advocate for repartition in more SDM channels and fewer WDM channels in SDM/WDM systems.

3. TURBO CLADDING PUMPING SCHEME USING A 7-CORE MC-EDFA PROTOTYPE

In order to improve optical amplification efficiency, residual pump recycling schemes have been recently researched [8-10]. Our proposed TCP scheme is to be classified among them. Figure 4 shows the

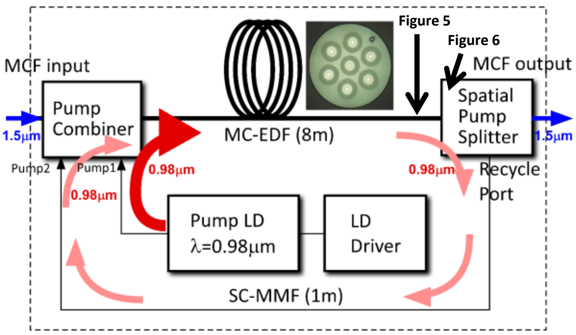

Figure 4: A configuration of Turbo Cladding Pumping scheme by using 7-core MC-EDFA with cladding pumping.

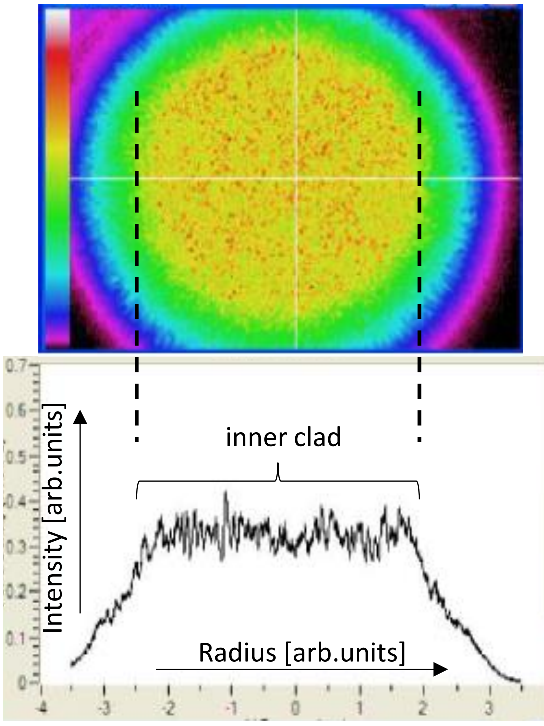

Figure 5: A spatial beam profile of the residual pump light measured at the end of the MC-EDF.

configuration of the TCP scheme by using a 7-core MC-EDFA with cladding pumping. The pump light at 0.98 µm is side coupled [6] into the 8 m-length MC-EDF by using a fiber based pump combiner. The 1.5µm signals and the 0.98 µm pump light propagate together in the same direction in the MC-EDF; while the signals are confined in the 7 cores, the pump lights propagates in the inner cladding including the cores. By using a spatial pump splitter placed at the output of the MC-EDF, the residual pump light is split from signals and outputted into the recycling port of the splitter. Figure 5 shows details of the spatial beam profile for the residual pump

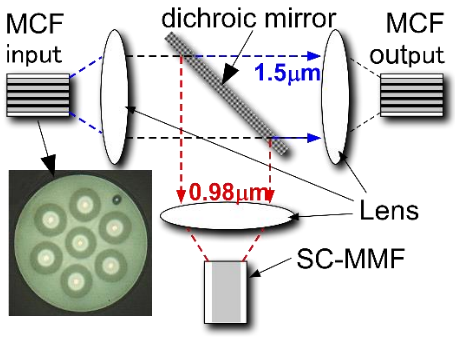

Figure 6: A configuration of spatial pump splitter

outputted from the inner clad of the MC-EDF [9]. Noticeably, the spatial distribution of the pump intensity is uniform in the inner clad of our 7-core MC-EDFA. This result shows the uniformity of optical gain among cores. 1.5 µm signal light and Amplified Spontaneous Emission (ASE), optical noise, are outputted from MCF output port.

Now, we detail the key device of the TCP scheme, *i.e.* the pump splitter, and its characteristics. Figure 6 shows the configuration of our developed spatial pump splitter. The splitter is based on free space optics. 0.98 µm residual pump light is split from 1.5 µm signal light and ASE by using a dichroic mirror and introduced into 1 m-length Single Core Multi Mode Fiber (SC-MMF) which is used as a recycling path. The insertion loss of the spatial pump splitter is less than 0.8 dB. This loss is comparable with the one of pump stripper, which would be required when TCP is not used. Even for an extremely high optical pump power of 18 W input into the pump splitter, the temperature of the pump splitter increases only to 62 °C, 35 °C above room temperature, which remains in range of reliability requirements and of the intrinsic cooling capacity of submarine repeaters. The residual pump from the spatial pump splitter is re-injected into the MC-EDF by way of the pump combiner as shown in Figure 4. The TCP schemes takes advantage of the spatial combining of the multimode pump into the MC-EDF. Indeed, as the pump combining is performed in spatial domain, the simultaneous injection of the original optical pump and of the recycled pump does not suffer the 3 dB loss of a single mode optical coupler with single output, which would be used with single core schemes. Therefore, the 0.98 µm pump optical power injected into the MC-EDF is increased without increasing output optical power of the pump Laser Diode (LD). In this way, optical amplification efficiency can be improved by the TCP scheme. At the constant optical input and optical gain condition, power consumption of LD driver can be reduced.

4. OPTICAL GAIN IMPROVEMENT AND REDUCTION OF POWER CONSUMPTION USING TURBO CLADDING PUMPING SCHEME

Finally, the improvement of optical gain and

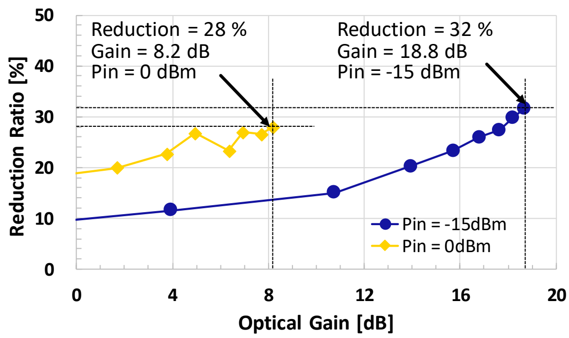

Figure 8: Relationship between optical gain of the TCP 7-core MC-EDFA and its pump LD driver's power consumption reduction ratio.

the reduction of power consumption with turbo cladding pumped 7-core MC-EDFA were evaluated by comparison with conventional cladding pumped 7-core MC-EDFA. As the deviation of optical gain among cores was sufficiently small enough and the spatial distribution of the pump intensity was uniform in the inner clad, the reported data is limited to the one of the center core.

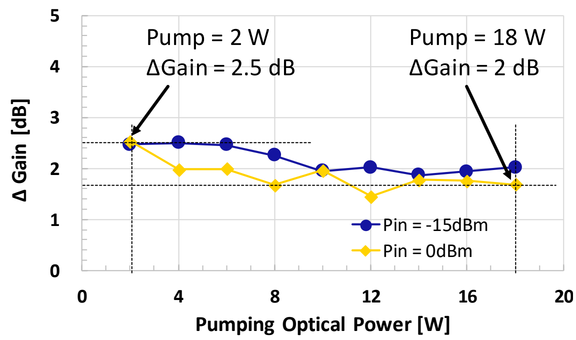

Figure 7: Measured results of optical gain improvement compared with non-TCP 7-core MC-EDFA.

Figure 7 shows results of optical gain improvement (ΔGain) by using TCP scheme. The parameter is total optical power inputted into the center core of 7-core MC-EDFA. ΔGain reaches a maximum of 2.5 dB for a power of 2 W, independently of the total optical input power. Furthermore, ΔGain tends to decrease with the increase of the pumping optical power. We attribute this to the saturation characteristics of optical gain of the cladding pumped MC-EDFA.

Figure 8 shows the relationship between the optical gain of the TCP 7-core MC-EDFA and the reduction ratio of power consumption of uncooled pump LD including its driver. The reduction ratio tends to increase according to the increase of optical gain even if total optical input power is changed. A maximum reduction ratio of 32 % was measured for a total optical input power of -15 dBm into the center core and an optical gain of 18.8 dB. Under this condition, the power consumption of the pump LD and its driver power was reduced by 32 % for the 7-core MC-EDFA by using TCP.

According to the result of Figure 8, the reduction of power consumption with TCP is more advantageous for high optical gain conditions. This can be attributed to the enhancement of optical gain granted by TCP, which is a significant improvement for cladding pumping in the C band, where the optical gain is indeed limited.

5. CONCLUSION

We have confirmed a ±0.6 dB uniformity of optical gain among 7 cores of a cladding pumped 7-core MC-EDFA. The reported flattened spatial distribution of pump light intensity in the radial direction of the MC-EDF is supposed to be the key of this uniformity.

We have demonstrated Turbo Cladding Pumping scheme, where the residual cladding pump is recycled through a pump splitter by using the 7-core MC-EDFA, which optical gain among cores is uniform. We have shown an improvement of 2 dB of optical gain and a reduction of 32 % of power consumption reduction of the cladding pumped 7-core MC-EDFA by using our proposed TCP scheme. In order to maximize the effect of the TCP scheme, 7-core MC-EDFA should be operated under the maximum optical gain condition.

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