Real-Time Optical Gain Monitoring for Coupled Core Multi-Core EDFA with Strong Inter-Core Crosstalk

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Abstract: We have successfully confirmed the feasibility of real-time optical gain spectrum monitoring of CC-MC-EDFA with the standard deviation within 0.65 dB even if the optical power per core fluctuate due to the inter-core crosstalk.

1. Introduction

Space Division Multiplexing (SDM) technology using Multi Core Fiber (MCF) is one of the promising candidates to continue increasing capacity of optical transmission systems; thus it has been actively researched recently, aiming at practical use [1-3]. Among systems using MCF, Coupled Core (CC) MCF transmission system has shown an advantage over equivalent Uncoupled Core (UC) MCF and multi-Single Core Fiber (SCF) transmission system in term of the longer reachability [3]. Although SCF Erbium Doped Fiber Amplifier (EDFA) or UC-MC-EDFA may be used in CC-MCF based repeated long-haul transmission systems, such as submarine optical cable systems, using CC-MC-EDFA is promising in terms of the implementation simplicity and installation space saving as it can share the same fiber geometry and present high core density [4].

According to a recent trend [5], the behavior of the SCF transmission system including SC-EDFA is expected to be reported by telemetry to the system operator in real time. The same expectation will also apply to CC-MC-EDFA, as shown in Fig. 1, for CC-MCF transmission systems in the future. Therefore the problem of monitoring does not only apply as factory characterization before shipment but also as in-service online operation: the output total optical power per core of CC-MC-EDFA should be monitored for the optical gain control and telemetry, even if the output power stochastically fluctuates due to the strong inter-core crosstalk of CC-MCF or CC-MC-EDF. The monitoring speed should be sufficiently fast to observe the variation of output optical power considering with the EDF response time of millisecond order. However, contrary to parallel SC-EDFA or UC-MC-EDFA [6] the orthogonal SDM signal base is no longer obvious for CC-MC-EDFA as super-modes vary. One solution is to use Multi-In Multi-Out (MIMO) evaluation [7] but it requires signal transmission, making characterization time consuming and telemetry unrealistic. As a simple alternative, an averaging method on core characteristics has researched so far considering with the inter-core crosstalk [8]. The method can clarify optical gain and noise figure of CC-MC-EDFA in the presence of temporal variation of optical gain exceeding 10 dB due to the inter-core crosstalk. However, such a method takes time to perform sufficient average to obtain the desired precision.

In this paper, we study the feasibility of simple real-time optical gain spectrum monitoring of CC-MC-EDFA considering strong inter-core crosstalk. Even if transmitted signals have strong correlation, optical gain spectrum monitoring of all cores within 35 msec with the standard deviation less than 0.65 dB has been demonstrated. Its performance has realized by inserting optical delay among the modulated optical input into the each core of CC-MC-EDFA and collective acquisition in wavelength region using an arrayed photodiode.

2. Real-time in-service optical gain monitoring for coupled core multi-core EDFA

The knowledge of the optical gain spectrum per core of each CC-MC-EDFA placed in the transmission system is very important to equalize the optical power per wavelength channel received by the transponder. It has been reported that in CC-MCF, when the signal light modulated at more than 10 GBd, the optical power variation due to the inter-core

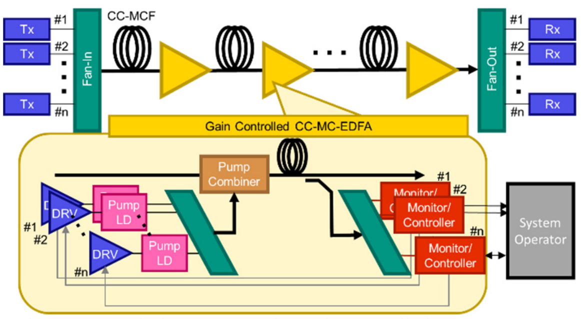

Fig. 1. Transmission system using gain controlled CC-MC-EDFA

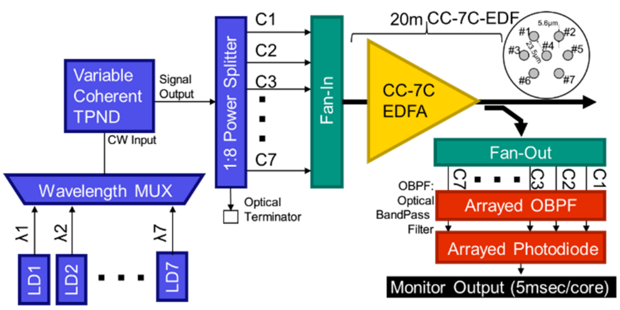

Fig. 2. Experimental set-up using individual core pumped CC-7C- EDFA

crosstalk of MCF is significantly suppressed compared with a single carrier CW light [9]. For higher signal baudrate channels monitoring the input and output optical power per core of CC-MC-EDFA in the same way of the conventional SC-EDFA may provide sufficient precision despite inter-core crosstalk and real-time in-service optical gain monitoring of CC-MC-EDFA may be easily realized. Nevertheless, the reported behavior at low baudrate for MCF hints for the necessity to investigate the case of super-channels or multi-carrier signals amplified by CC-MC-EDFA. This is of particular interest as it was shown that lower baudrate multi-carrier signals show more tolerance to nonlinear impairments [10]. Furthermore, the baudrate of the Orthogonal Frequency Division Multiplexing (OFDM) signal or ultra-high level (1024 or more) QAM signal is often below 10 GBd [11, 12]. In this perspective, the most important system parameter for design of monitor is the signal baudrate of each wavelength. Indeed, the optical power variation could be amplified and become larger than in the case of simple transmission through CC-MCF and, wavelength dependence would remain unclear.

3. Feasibility of the real-time optical gain monitoring for the transmission of single carrier WDM signal

We investigated the variation in the output optical power from a 7-core (7C-) CC-MC-EDFA when the input optical signal conditions for each core were changed. Fig. 2 shows the experimental set-up used for the investigation. We used an individual core pumped CC-7C-EDFA, which gain medium was already reported [8]. We used 7 CW lights with center wavelengths ranging from 1548.49 nm to 1553.76 nm, generated by tunable lasers with linewidth around 250 kHz. We used a baudrate variable coherent transponder to generate multi-carrier 100-Gbps Polarization Multiplexed (PM)-QPSK optical signal, with the tunable lasers. The generated WDM signal was split by using an 1:8 coupler to generate SDM signals. The SDM signals were introduced into the each core of CC-7C-fiber using a Fan-In (FI) device. The optical input power was set to -5 dBm/core at the input of CC-MC-EDFA. 7 pump lights at 0.98 µm wavelength generated by 7 pump laser diodes were spatially multiplexed by using a FI device and combined with signal light core by core by using a pump combiner, which insertion loss is below 0.4 dB. The pumping power was fixed 400 mW by core, and they passed through a 20 m-length CC-7C-EDF. Finally, the 7 SDM signals were spatially demultiplexed using a Fan-Out (FO) device and the optical gain was measured by core. The optical gain of the CC-7C-EDFA was measured for each wavelength repeatedly during 1 hour with a repetition cycle of 5 msec. The baudrate of the input signal was varied from 0 (unmodulated, CW) to 66 GBd. Fig. 3 shows output optical spectrums of the CC-7C-EDFA for CW and 66 GBd signals. Notably, longer wavelength showed higher optical gain since the EDF length was not optimized and no gain flattening filter was placed after the amplifier.

Fig. 4 summarizes the standard deviation (σ) of optical gains measured during 1 hour. For simplicity, we limit the displayed results to the center core but we have verified that other cores exhibit exactly the same tendency. As expected, the standard deviation of the optical gain at each wavelength becomes smaller for higher baudrate signals. It shows a peak at 1551.35 nm for our amplifier independently of the baudrate. It is notably different from the maximum or minimum gain wavelength of Fig. 3. Fig. 5 plots the averaged optical gain spectrum and its difference compared to the gain for signals at 66 GBd. The difference of the averaged optical gain spectrum obtained by using 6 GBd signal from that of 66 GBd signal is within 3.2 % in the measured wavelength range. It reaches 27.5 % for the extreme case of CW light. Therefore, the optical gain spectrum monitoring accuracy becomes higher according to the increase of signal baudrate at each wavelength.

Notably, it took only 35 msec to obtain optical gain spectrum of all cores. Indeed, we could measure all 7 cores in sequenced 5 msec intervals. It is fast enough for transmission system operator to know the optical gain in real-time.

4. Difference in the effects of inter-core crosstalk between superchannel signal and dense WDM signal

To extend the reachability keeping the transmission capacity, superchannel technique is often used [10]. One of the difference of superchannel signals from, for example, ITU-T 50 GHz grid [13] Dense WDM signal is the wavelength interval between adjacent optical carriers as shown in the insets of Fig. 6. As the wavelength interval of adjacent optical carrier of superchannel is so close that optical gain variation due to the inter-core crosstalk of CC-MC-EDFA could affect the total baudrate of all subcarriers instead of the each subcarrier baudrate. Therefore, we further investigated the relationship between the standard deviation of monitored optical gain and the each subcarrier baudrate

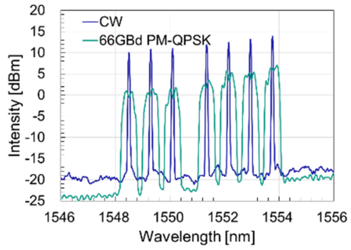

Fig. 3. Gain spectrum (CW)

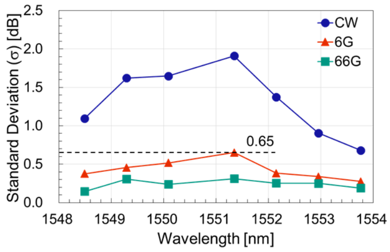

Fig. 4 Gain spectrum (66GBd PM-QPSK)

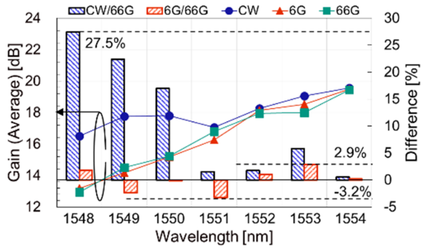

Fig. 5 Difference due to signal baudrate

for different superchannels. We kept the total baudrate constant at 32 GBd and we generated digitally different numbers of identical subcarriers, adjusting their individual baudrate, as plot on Fig. 6. For comparison, we also plot the σ of 4λ-8 GBd DWDM signal as a star symbol; it is close to the 6 GBd case of Fig. 4. However, the standard deviation for 4 subcarriers superchannel signal is half smaller, around 0.3 dB. Furthermore, for superchannels, we confirmed that the σ is independent to the subcarrier baudrate for a constant total signal baudrate. This result shows that the precision of monitoring for superchannel signal is independent of the subcarrier baudrate but that it is dependent to the total baudrate of the whole channel. Notably, a sufficiently low standard deviation below 0.3 dB was obtained for single carrier and superchannels of total baudrates above 32 GBd, which the case of most recent systems.

5. Reduction of the standard deviation of monitoring with additional decorrelation among cores the cores

As shown by low baudrate signals, the inter-core crosstalk becomes larger according to the coherency of optical signals among cores of CC-MCF. Generally, signals are generated independently, which causes low correlation. However, two cases may cause significant correlation among cores: the first one is amplifier characterization using a single signal source split among spatial channels without decorrelation; the second one is intentional correlation among cores in order to obtain higher signal quality at the expense of capacity as in the spatial mode overheard method [14]. To simulate practical use cases, we adjusted the skew among cores by inserting delays between 1:8 splitter and FI device using 1 to 6 km-length SCF per core as shown in the insets of Fig. 7 considering with the pattern length and coherent length determined by transmission signal.

Likewise section 4, the σ of was measured when CW signals were inputted into the CC-7C-EDFA. The linewidth of the CW signals were changed by replacing the light source with various laser diodes. By decorrelating optical signal inputted into the each core of CC-7C-EDFA, σ was significantly decreased as shown in Fig. 7. Even if high coherent CW signal of 1 kHz linewidth, the σ was decreased to less than half. When the PM-QPSK signal which baudrate was more than 6 GBd, the σ decreased to less than 0.2 dB from 0.65 dB. Therefore, unless intentional correlation is intentionally caused among spatial channels our monitoring method exhibits sufficient precision.

5. Conclusion

The feasibility of real-time optical gain monitoring for CC-MC-EDFA has been researched in this paper. The inter-crosstalk induced optical output power variation can be suppressed by using more than 6 GBd optical signal for monitoring. The sufficient standard deviation of less than 0.65 dB within 35 msec monitoring has been confirmed in the case of CC-7C-EDFA using additional decorrelation among cores. The optical gain monitoring performance is enough to use for the telemetry and automatic optical gain control of optical transmission system. We have confirmed our method for single carrier and superchannels as well as for signal transmission with strong inter-core crosstalk.

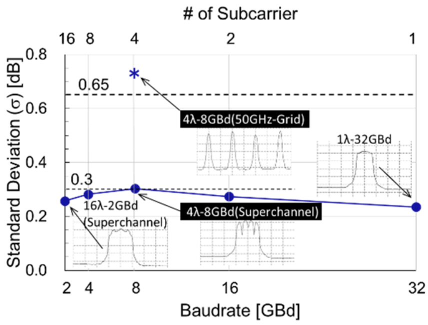

Fig. 6. Difference between 50GHz Grid DWDM and superchannel

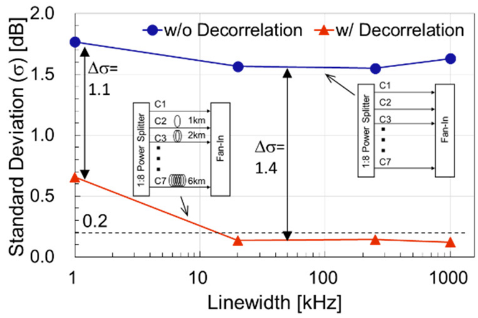

Fig. 7 Effect of the decorrelation (CW signal)

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