Evaluation of the Signal Amplified by CC-MC-EDFA under Inter-core Crosstalk Using a Scalable SDM/TDM Translation Method

Hitoshi Takeshita*, Manabu Arikawa, Keiichi Matsumoto, Kohei Hosokawa and Emmanuel Le Taillandier de Gabory

System Platform Research Laboratories, NEC Corporation, 1753 Shimonumabe Nakahara-ku, Kawasaki, Japan, *h-takeshita@nec.com

Abstract *We propose using SDM/TDM translation method to signals amplified by CC-MC-EDFA in a scalable manner to the number of MCF core. We confirmed identical signal quality of the CC-4C-EDFA among 4 cores even if $\pm$0.65dB output optical power fluctuated due to inter-core crosstalk appears.*

Introduction

Recently, parallel transmission using Space Division Multiplexing (SDM) technologies has been attracting attention [1]-[3]. Among them, multicore fibre transmission system shows an advantage in terms of installation space saving and implementation simplicity such as delay equalization among parallel channels. Especially, Coupled Core (CC) MCF transmission system is promising regarding to the transmission signal reachability over equivalent Uncoupled Core (UC) MCF, as inter-core crosstalk is compensated in DSP, and over multi-Single Core Fibre (SCF) transmission system, in virtue of reduced fibre nonlinearities[4]. As CC-MC-EDFA would be preferable for lowest loss system integration, this type of as optical amplifier has been recently researched [5]-[8].

As a major difference with conventional Single Core (SC) EDFA and UC-MC-EDFA, the output power per core of CC-MC-EDFA can fluctuate by 10 dB [5]-[6] due to inter-core crosstalk. Therefore, amplification performance characterization of the CC-MC-EDFA becomes difficult with standard techniques; furthermore, concerns arise on transmission system design due to power fluctuations. Thus, we have proposed an optical gain monitoring method and confirmed experimentally that the output power and optical gain of CC-MC-EDFA can be monitored within 0.65 dB of standard deviation for signals with baudrate higher than 6GBd [5].

For actual characterization, measurement of amplified signal quality, such as Q-value or Error Vector Magnitude (EVM) will be necessary, notably with Multiple-Input Multiple-Output (MIMO). One of the problem of the MIMO receiver used for EDFA characterization purpose, is its feasibility in cost effective manner when the MIMO dimension, *i.e.* the number of coupled SDM channels, increases. Indeed, the feasibility of 12 SDM channels transmission by a single CC-MCF has been confirmed [8] and requirements around 1000 spatial channels are being discussed [9] to support the communication traffic growth within the next decade. Therefore, for the CC-MC-EDFA, signal quality evaluation should be scalable with the MIMO dimension.

In this paper, we experimentally investigated the influence of the output optical power fluctuation of a core pumped CC-4-core (4C)-EDFA prototype [5]-[6] on EVM measured by an offline MIMO Coherent receiver (Co-Rx). As a scalable MIMO Co-Rx for the number of core, we used a translation from SDM optical signal into Time Domain Multiplexing (TDM) optical signal [10]. We have confirmed that the SDM/TDM MIMO Co-Rx is useful for the signal quality evaluation of the CC-4C-EDFA output even if its output optical power fluctuates due to inter-core crosstalk. Then, we have clarified the fluctuation does not degrade the evaluation result and it does not affect the signal quality uniformity among cores.

CC-MC-EDFA output signal quality evaluation by using the SDM/TDM translation

Fig.1 shows an experimental set-up for EVM measurement. According to our previous results[5], we prepared a transmitter of 32 GBd Polarization Multiplexed (PM) QPSK output with centre wavelength of 1550.918 nm to reduce

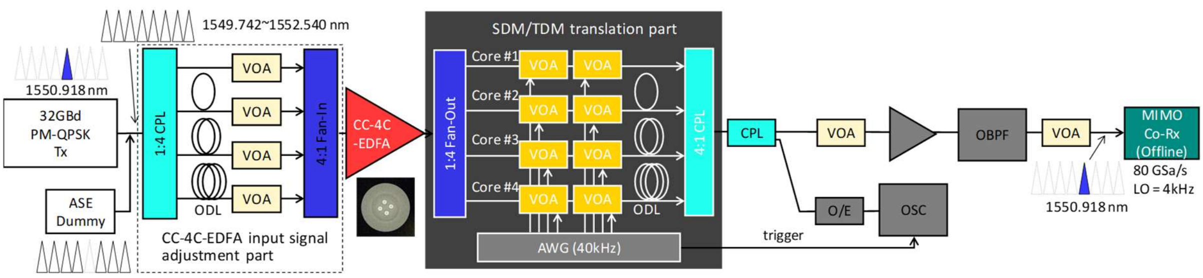


Fig. 1: Experimental set-up

output fluctuations among cores below ±0.65 dB of standard deviation for 1 hour measurement. The transmitted symbol sequence was 2^{15} length of Pseudo Random Bit Sequences (PRBS) to avoid any correlations within the transmitted sequence. By wavelength multiplexing with non-modulated ASE dummy light spectrally shaped as modulated channels, we realized 8 Wavelength Division Multiplexed (WDM) optical signal within the ITU-T 50 GHz grid, from 1549.742 to 1552.540 nm. The 8 WDM optical signal was split by 1:4 optical coupler and inputted into the each core of the CC-4C-EDFA. The core pitch and mode field diameter of the CC-4C-EDF of the EDFA was 20 μm and 5.6 μm respectively. The EDF length was 11.5 m.

At the CC-4C-EDFA input signal adjustment part in Fig.1, using Variable Optical Attenuators (VOAs) and Optical fibre Delay Line (ODL), the inputted optical power into the CC-4C-EDFA was equalized and de-correlated among cores. As the temporal decorrelation (more than 5 nsec) of the crosstalk interferers was wider than the MIMO equalizer tap length (1.89 nsec), it did not affect the evaluation results. Each core of the CC-4C-EDFA was equally pumped by controlling output power of pump Laser Diodes (LDs).

The CC-4C-EDFA output was inputted into the SDM/TDM offline MIMO Co-Rx using a 1:4 Fan-Out (FO) device. Fig.2. shows details of the SDM/TDM translation. Each of 4 inputs was doubly gated using VOAs to realise high power extinction ratio. Insufficient power extinction ratio degrades signal quality evaluation results. All of VOA gates were synchronously driven by an Arbitrary Waveform Generator (AWG). By the gating, each of 4 SDM optical signals was converted to optical packet trains and delayed using ODLs of different lengths core by core. Then, they were multiplexed in time domain using a 4:1 optical coupler.

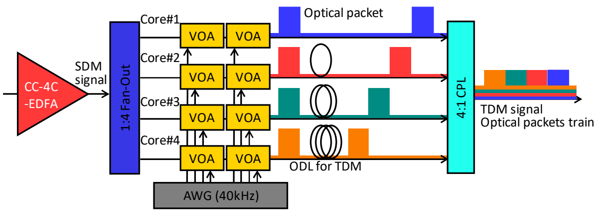


Fig. 2: Details of SDM/TDM translation part in Fig.1.

Using an Optical Band Pass Filter (OBPF), only the modulated channel at 1550.92 nm was inputted into the unique Co-Rx with offline MIMO function. Sampling rate of the offline Co-Rx was 80 GSa/s and linewidth of its local oscillator was 4 kHz. As mentioned above, all of 4-core output from the CC-4C-EDFA was received by only single Co-Rx with MIMO function of Decision Directed Least Mean Square (DDLMS) based algorithm. The MIMO equalizer was the same used in a standard reception with 4 receiver; it consisted of 8 x 8 FIR filters of 121 samples with 2-symbol period tap length [11].

Design details of the SDM/TDM translation

When TDM translation is used, each of the 4-core outputs of CC-MC-EDFA cannot be received simultaneously by using 4 Co-RXs. As optical phase noise of the local oscillator varies in time, the received time lag causes signal quality difference among 4-core due to the SDM/TDM translation, when the receive time lag becomes too large to ignore these variations. It degrades signal quality evaluation results. Therefore the design of the TDM translation cycle is very important as well as the selection of the narrow linewidth local oscillator. Our design was as followings. According to the symbol sequence length of PRBS 2^{15}, the minimum time delay between each optical packet becomes 1 μsec, *i.e.* 200 m of ODL length. Considering with the optical phase noise temporal variation speed and ease of ODL length adjustment, we determined the optical packet length as 5 μsec for our 4-core CC-MC-EDFA evaluation, which represents a total length of 20 μsec. Since the bandwidth of VOAs is not infinite, an additional 5 μsec was used as buffer to ensure flat amplitude response during reception. Therefore, the SDM/TDM translation cycle became 25 μsec. It requires 2 Mpts memory of the Co-Rx to process offline signal reception.

The required memory is important as SDM/TDM translation design is scalable to the signal quality evaluation for the SDM signal of 1000-core CC-MCF with just one single MIMO Co-Rx when the transmitted signal condition is unchanged. Indeed the required memory for such high core number, 2 Gpt, is already available on latest

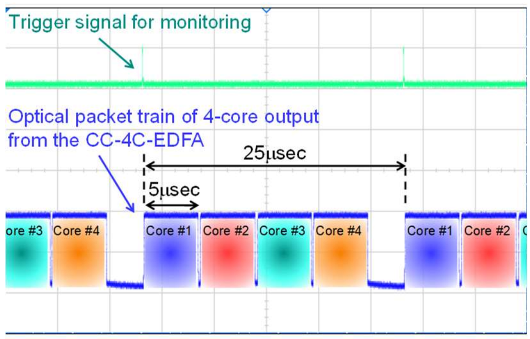
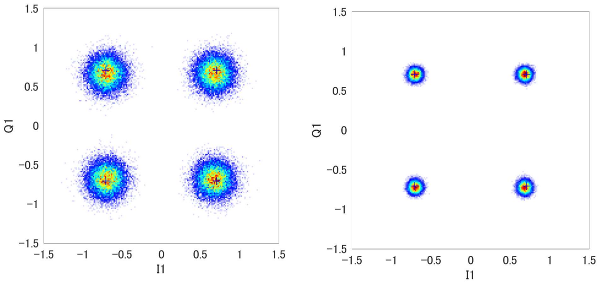


Fig. 3: TDM 4-core packet train.

oscilloscopes [12]. Fig. 3 shows the translated 4-core optical packet train monitored by a low speed oscilloscope (OSC).

Investigation of the SDM/TDM translation induced signal degradation

When a certain core input is gated on, it is important to completely gate off the other three



(a): Single VOA (Er: 15 dB) Back-to-back **(b):** Double VOA (Er: 30 dB) Back-to-back

Fig. 4: Difference of constellation map

core inputs, which would induce crosstalk. Fig.4 shows an example of the constellation map difference obtained by using the experimental set-up of Fig.1 without the CC-4C-EDFA, in order to evaluate our TDM translation setup. It features the transmitter and receiver with 4 SDM channels in back-to-back (B2B) condition. First, we used VOA of power extinction ratio (PER) of 15 dB. When the first VOA tandemly connected as shown in Fig.1 was used for gating and the second VOA was opened continuously (Fig.4 (a)), EVM was 18.9 %. When the both VOAs were synchronously used for gating (Fig. 4 (b)), EVM was improved to 7.6 %. In addition, no significant difference was observed from the double gated EVM and the one without the SDM/TDM translation (namely without VOAs). This result indicates EVM of transmitted signal were successfully evaluated with the SDM/TDM MIMO Co-Rx even if the CC-4C-EDFA output optical power fluctuates due to inter-core crosstalk within $\pm$0.65 dB of power standard deviation.

Investigation of the signal quality deviation among cores due to inter-core crosstalk

The CC-MC-EDFA output optical power per core fluctuates due to inter-core crosstalk even if both the input and pump power is identical per core [5]-[6]. Next, we investigated EVM deviation among cores when the input and pump power per core was identical. To obtain completely accurate optical gain, complicated MIMO coefficient analysis [7]-[8] would be needed. Here, we used instead a simple conventional optical gain definition, as shown in Eq. (1). In Eq. (1), i represents core number. For example, when G(1) is measured, Pin(i) (i $\neq$ 1) is set to zero.

$$\mathrm{G(i)} = P_{out}(i)/P_{in}(i)\ (i = 1,2,..n) \quad (1)$$

Fig. 5 plots measured result. The total input optical power was fixed at +1 dBm/core. This result shows that the time average optical gain with the simple definition is proportional to pump LD output power. Fig. 6 summarises EVM variation among cores. Only the result for x-polarization is shown because no significant EVM difference was observed between x and y polarization. The EVM variation among cores is 1.19 point at maximum and its standard deviation is 0.32 points. No correlation between the EVM variation and pump LD output power was observed. Though the CC-4C-EDFA output fluctuates $\pm$0.65 dB of the standard deviation, the EVM variation are small enough for actual use. From this result, it is supposed that the MIMO function can balance the optical power fluctuation among cores and suppress the EVM variation among cores.

Conclusions

We proposed using SDM/TDM translation to characterise EVM of the CC-4C-EDFA. The proposed method is scalable to the number of MCF cores. We clarified that 30 dB extinction ratio time gating is essential to prevent signal quality degradation due to the translation. We successfully confirmed that the CC-4C-EDFA output signal quality can be evaluated by using the SDM/TDM MIMO Co-Rx. We showed with it that inter-core crosstalk inducing optical power fluctuations of 0.65 dB of standard deviation did not degrade SDM signals.

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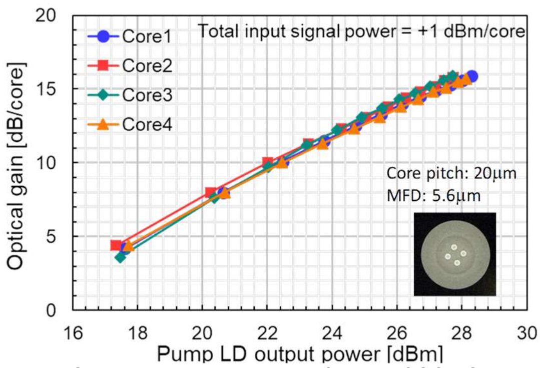

Fig. 5: Optical gain with simple definition of CC-4C-EDFA.

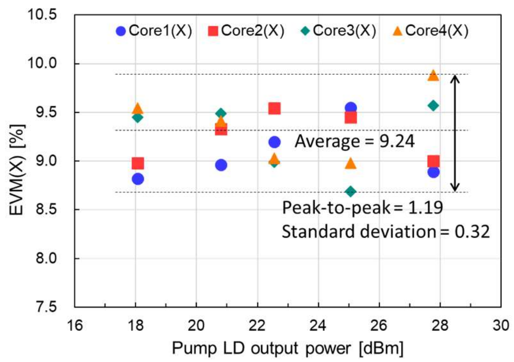

Fig. 6: Difference of x-polarization EVM among cores

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