



Analysis and experiment of all-optical time-interleaved multi-channel regeneration based on higher-order four-wave mixing in a fiber

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ABSTRACT

Simultaneous all-optical multi-channel regeneration based on second-order four-wave mixing (FWM) in a single highly nonlinear fiber (HNLF) is studied. Interchannel crosstalk, especially cross gain saturation and generation of interchannel FWM, is avoided by properly time-interleaved channels. Preliminary experiment of $2 \text{ ch} \times 10 \text{ Gbit/s}$ operation shows simultaneous noise reduction of the two channels and good agreement with numerical analysis. Numerical investigation on $2 \text{ ch} \times 40 \text{ Gbit/s}$ operation using the same parameters as the experiment shows that the regeneration can improve qualities of both channels. For more number of channels and higher speed of operation, several parameters need to be adjusted to avoid interchannel crosstalks. Time synchronization techniques for the input channels are also discussed.

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1. Introduction

Four-wave mixing (FWM) in fibers relies on Kerr nonlinearity of fiber glasses that has very short response time. This leads to applications of ultra-fast all-optical signal processing. One of the promising signal processing using FWM in fibers is signal regeneration. Parametric amplifiers operating in saturation regime can be used as phase-preserving amplitude limiter that can improve phase-shift keying (PSK) signal transmission [1–3]. For suppression of noise both in mark and space levels of on-off keying (OOK) signals, a number of regeneration methods have been proposed, such as those using higher-order FWM product as the output [4–6], pump-modulated FWM [7–9], and 2-stage FWM processes [10,11]. However, all of these studies only concern single channel operation.

All-optical multi-wavelength channel regeneration based on FWM in a single fiber is quite challenging to realize. For the multi-wavelength regeneration, nonlinear interchannel crosstalks, mainly from FWM and cross-phase modulation (XPM) between different channels need to be avoided while efficient FWM between individual signals and pump is required. Most of the reported fiber-based multi-wavelength all-optical regeneration use dispersion management of nonlinear medium to suppress the interchannel crosstalks [12–14]. However, the method of dispersion management is not suitable to be used in the FWM-based regeneration because the high local dispersion violates the phase matching condition. It is also noted that the reduction of XPM-induced

interchannel interaction by the dispersion management is still not satisfactory in that the channel separation cannot be small enough [12]. In Ref. [13], polarization orthogonalization between adjacent channels is used in addition to fiber dispersion management for suppression of the XPM effect. Ref. [14] applies periodic-group-delay devices as the dispersion compensators to ensure fast bit walk-off between different channels, thus, suppressed the interchannel XPM and also FWM. To operate at spectral efficiency up to 0.4 bit/s/Hz , they use carrier-suppressed return-to-zero pulses to have phase shift of π within adjacent bits, 1:4 de-interleaver and 4:1 interleaver to allow four times greater channel spacing, and additional amplitude filtering to reduce spectral distortion. Another method to avoid interchannel crosstalk in multi-wavelength regeneration is bidirectional configuration [15,16]. However, the number of channels that can be regenerated in a single fiber is limited to two [15], or can be extended to four channels by combining a polarization multiplexing scheme in the bidirectional architecture [16].

Interchannel crosstalk mitigation by properly time-interleaved channels is another method for multi-wavelength channel regeneration. This method has been used in a regeneration based on a dispersion-imbalanced nonlinear optical loop mirror [17]. Although the time interleaving method cannot regenerate asynchronous multi-wavelength channels and requires adaptive time synchronization for practical applications, it can regenerate a number of channels, six in the scheme demonstrated in [17], in a single nonlinear medium. The time-interleaving method is possible for FWM-based regeneration because FWM process in fibers is ultrafast, as mentioned above, and temporal extent of pump depletion that is responsible for the regeneration is limited in the vicinity of the input pulses. Thus, interaction between multi-wavelength pulses separated in time by more than several picoseconds is negligibly small. We have applied

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the time-interleaving method in the two-channel regeneration based on higher-order FWM in a single highly nonlinear fiber (HNLF). A preliminary experiment has shown that $2 \text{ ch} \times 10 \text{ Gbit/s}$ regeneration works well [18]. Here, we numerically study the time-interleaving multi-channel regeneration to investigate if this scheme can be applied to higher-speed signals with channel number more than two.

In this paper, we first perform numerical simulation to confirm the experimental results of the two-channel signal regeneration using the second higher-order FWM product in a highly nonlinear fiber [18]. Then, we study the performance of 40 Gbit/s/ch operation. Problems in adding a channel and ways to solve them are discussed. We also discuss the issue of time synchronization between input channels that should be achieved in practical usage of the regenerator in transmission systems.

2. Regeneration scheme

The regeneration uses the second-order FWM product generated at a frequency $2f_s - f_p$, where f_s and f_p are the input signal and pump frequencies. When the input signal power is small, the generated power at $2f_s - f_p$ is proportional to $P_s^2 P_p$, where P_s and P_p are input signal and pump powers, respectively. This avoids buildup of space-level noise, by which the extinction ratio of the signal is not degraded. When the input signal power is large and the second-order FWM component grows, on the other hand, the output power at $2f_s - f_p$ saturates as the direction of power flow is changed and other higher-order FWM products are newly generated. Thus, the function of 2R regeneration is obtained. The schematic diagram of the regenerator, which is almost the same as a single-pump parametric amplifier, is illustrated in Fig. 1. For multi-channel regeneration, channels are properly time-interleaved before entering the regenerator to avoid nonlinear interchannel crosstalks. The main crosstalks avoided by this scheme are cross-gain saturation (XGS) [19] and FWM between different signal channels. The XGS occurs when pump depletion caused by different signal channels overlaps temporally. When pulses in adjacent channels directly overlap in time, additional unneeded FWM products are generated. For effective regeneration, the polarization of multi-wavelength channels and a continuous-wave pump are aligned before entering the HNLF. After the FWM interaction between the pump and signals takes place in the HNLF, the second-order products are extracted at the output via an optical bandpass filter (OBPF). Insets are eye patterns before and after the regeneration when two 10 Gbit/s amplitude fluctuated signals are simultaneously launched to the regenerator with time separation of 50 ps, details of which will be described in the next section.

3. Comparison of experimental and numerical results

Simulation accuracy is verified by comparing the preliminary experimental results with simulation results for $2 \text{ ch} \times 10 \text{ Gbit/s}$ operation.

Regenerator setup used in this study is the same as the experiment in [18]. Simulation conditions are set to be almost identical to the experiment except for the input signal pattern length, which is 1024 for the simulation, instead of $2^{31} - 1$ for the experiment. The input signals are return-to-zero (RZ) OOK Gaussian shaped pulse trains. Amplitude noise is adopted by modulating the amplitude of the input signal pulses by a 7-GHz RF tone. Input signal wavelengths and pulse width are 1555.5 nm and 5.5 ps for ch.1, and 1556.7 nm and 5.6 ps for ch.2, respectively. The continuous wave pump has wavelength λ_p and power P_p of 1561 nm and 80 mW, respectively. The HNLF has zero-dispersion wavelength λ_0 of 1556 nm, dispersion slope $dD/d\lambda$ of 0.026 ps/nm²/km, loss α of 0.78 dB/km, and length L of 1.5 km. After the HNLF, cascaded OBPFs are inserted to extract the signal. The first OBPF (3.2 nm width) is used to extract the two signal components, ch.1 (1550.0 nm) and ch.2 (1552.4 nm), and the second OBPF is used for the selection of one of the two signal components.

Fig. 2 illustrates average power transfer curves for ch.1 and ch.2 when noise is not applied. The measured transfer curves are shown by symbols while the numerical results are drawn in continuous curves. The numerical simulation is performed by solving nonlinear Schrödinger equation including loss and third-order dispersion terms using the split-step Fourier method. The numerical simulation results agree well with the experiment, where the value of fiber nonlinear coefficient $\gamma = 14 \text{ W}^{-1} \text{ km}^{-1}$ is chosen so that the simulation results best fit the experimental results. The output power grows quadratically as a function of the input power until the input power is about 0.15 mW for both channels. Strong saturation of output power at input power around 0.5 mW is observed for both wavelength channels. This property indicates that amplitude fluctuation and small input noise can be suppressed when input signal power is around the saturation regime. Note that the power transfer curves in Fig. 2 were measured in the absence of the other channel. This is adequate as the behavior does not change appreciably when properly time-interleaved channels are launched simultaneously.

Fig. 3 illustrates the spectra measured at the output of the HNLF when the two channels are simultaneously launched to the regenerator at the optimum input power for the regeneration to occur. The spectral resolution of the spectrum analyzer is 0.1 nm. The input signal pulses are time-interleaved by 50 ps in Fig. 3(a) while they are overlapped in Fig. 3(b). When the input signal pulses are properly time-interleaved, nonlinear interaction between the signals in different channels does not occur. On the other hand, when the input signal pulses are overlapped, additional FWM products involving the two signal channels and the pump appear. This makes the spectral shapes shown in Fig. 3(a) and (b) different. The power of the spectral components at the shaded portion in Fig. 3, for example, can be used as a monitor signal for adaptive time-interleaving control, which will be discussed in Section 5 of this paper in more detail. There is again no much difference between the experimental (solid line) and numerical (dotted line) results.

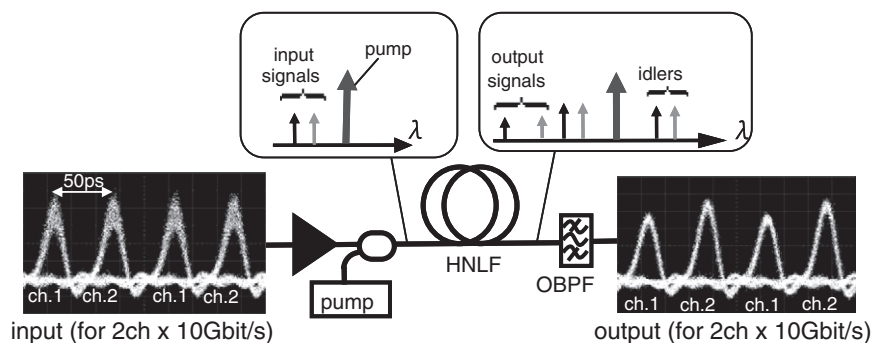


Fig. 1. Schematic diagram of the multi-wavelength regeneration. Insets are input and output pulse waveforms for $2 \text{ ch} \times 10 \text{ Gbit/s}$ operation.

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