2R Regeneration of Time-Interleaved Multiwavelength Signals Based on Higher Order Four-Wave Mixing in a Fiber

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Abstract ? All-optical 2R regeneration of two-wavelength time-interleaved signals is demonstrated using higher order four-wave mixing in a fiber. In this regeneration scheme, a single fiber and a pump are shared by the two channels. The results show that interchannel crosstalk can be avoided when pulses in the two channels are time separated by more than 3 times their pulsewidth. A possible power monitoring to determine suitable time-interleaving condition is also discussed.

Keywords: *Four-wave mixing (FWM), nonlinear optics, optical crosstalk, optical fiber communication, optical signal processing.*

Regeneration is a solution to refine the shape of optical signal that had been corrupted by noise and other causes. Fiber nonlinearity in various forms, which has an ultrashort response time, can be used to realize all-optical regeneration function of high-speed signals. Saturation of four-wave mixing (FWM) leads to an ultrafast limiter suppressing marklevel noise on signal pulses [1], [2]. When higher order FWM products are used, space-level noise is also suppressed, by which a 2R regeneration function is obtained [3], [4]. Considering its use in wavelength-division-multiplexing (WDM) systems, a regenerator capable of processing multiwavelength channels in a single nonlinear element is highly desired [5] –[7]

When signals are formatted in a return-to-zero (RZ) shape and its duty ratio is smaller than ~50%, signals in different wavelength channels are expected to be simultaneously regenerated without mutual interaction if they are suitably time-interleaved [8]. The time interleaving scheme works because the temporal extent of pump depletion and generation of higher order FWM products that are responsible for the regeneration will be limited in the vicinity of the input signal pulses.

In this letter, it is demonstrated that ON–OFF keyed (OOK) short RZ pulses in two different wavelength channels can be regenerated using second-higher-order FWM in a single highly nonlinear fiber (HNLF) by proper time interleaving. It is also shown that the power of a spectral component in a certain wavelength range after the HNLF may be used as a monitor signal for adaptive control of time-interleaving of signals in different channels.

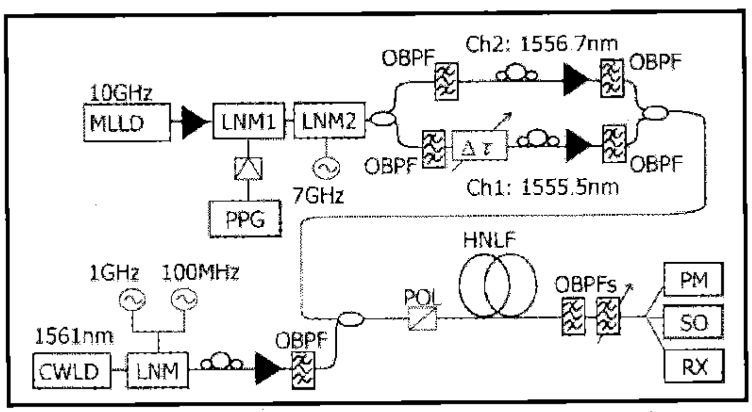

Fig. 1. Experimental setup of two-channel regeneration. CWLD: continuouswave laser diode, PM: power meter, PPG: pulse pattern generator, RX: receiver, SO: sampling oscilloscope.

MULTIWAVELENGTH REGENERATION

The experimental setup of the two-channel regeneration is illustrated in Fig. 1. A 10-GHz pulse train from a mode-locked semiconductor laser diode (MLLD) whose pulse and spectral widths are 2 ps and 2 nm, respectively, is amplitude-modulated using $LiNbO_3$ modulators (LNMs), where $2^{31}-1$ length PRBS is applied to LNM1 for data modulation and a 7-GHz asynchronous RF tone is applied to LNM2 for modulation of pulse amplitude simulating noise on the mark level. The noise addition scheme is used because of its ease in controlling the amplitude fluctuation. The more general case of noise loading by the addition of amplified spontaneous emission (ASE) to the signal will be studied in a subsequent experiment. The modulated signal is sliced into two channels, i.e. 1555.5 nm (Ch1) and 1556.7 nm (Ch2), using optical bandpass filters (OBPFs). Channels are decorrelated and time interleaved using a variable delay line. The pulsewidths are 5.8 and 5.7 ps for Ch1 and Ch2, respectively. The signals together with a continuouswave (CW) pump are injected to an HNLF through a polarizer (POL) for polarization alignment. Power and wavelength of the pump are 70 mW and 1561 nm, respectively. The CW pump is phase-modulated with RF tones of 1 GHz and 100 MHz for suppression of stimulated Brillouin scattering. The HNLF has zero-dispersion wavelength, dispersion slope, nonlinearity, loss, and a length of 1556 nm, 0.026 ps/nm^2/km, ~12 $W^{-1}.km^{-1}$, 0.78 dB/km, and 1500 m, respectively. After the HNLF, cascaded OBPFs are inserted to extract the signal. In this experiment, higher order products at wavelengths $2\lambda_s$ - λ_p are extracted as the output signal, where λ_s (s = 1 or 2) and λ_p are the input signal and pump wavelengths. For this choice of output signal, the output power initially increases quadratically and then saturates as the input power increases, with which noise on the mark level is suppressed while buildup of space-level noise is avoided [3], [4]. The first OBPF (3.2 nm width) is used to extract the two signal components, Ch1 (1550.0 nm) and Ch2 (1552.4 nm), and the second OBPF is used for the selection of one of the two signal components. The output pulsewidths are 5.5 and 5.7 ps for Ch1 and Ch2, respectively.

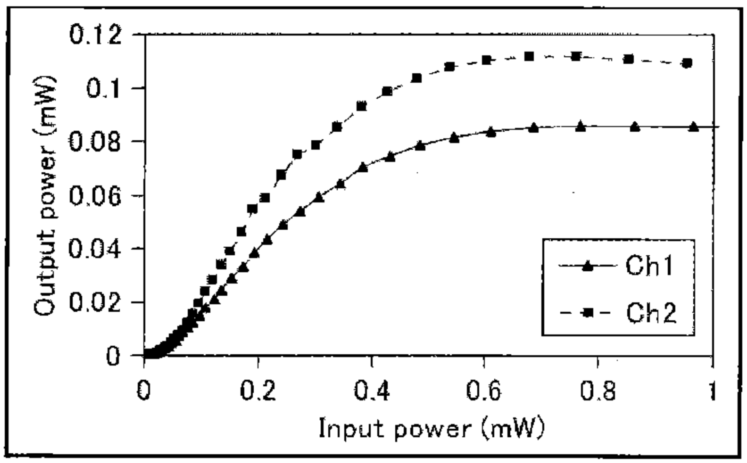

Fig. 2. Output power as a function of input power for Ch1 (solid curve and triangle points) and Ch2 (dashed curve and square points). Input power and output power are time-averaged powers.

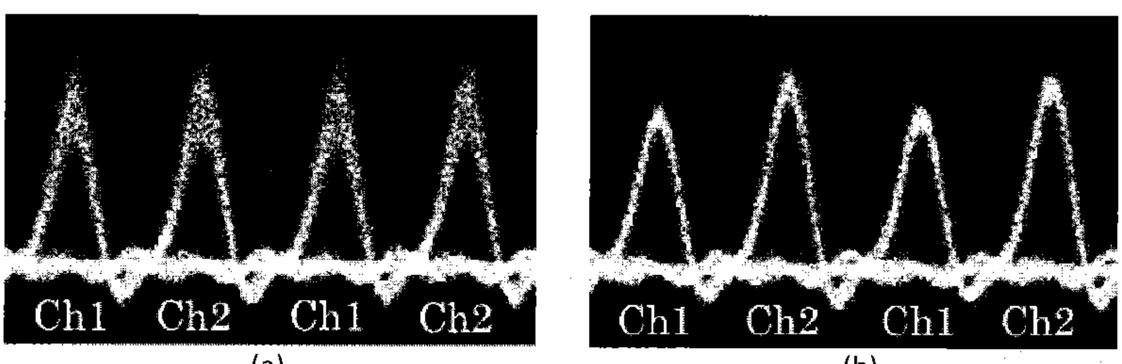

Fig. 3. (a) Input and (b) output pulse waveforms when time separation $\Delta\tau$ is 50 ps. Bandwidth of the sampling oscilloscope is 30 GHz. Horizontal axes: 20 ps/div.

Power transfer curves for Ch1 and Ch2 are shown in Fig. 2. In this measurement, the amplitude modulation simulating marklevelnoise is not applied. Strong saturation of output power at input power around 0.5 mW is observed for both wavelength channels. The output power grows quadratically as a function of the input power until the input power is about 0.1 mW for both channels. This property indicates that amplitude fluctuation and small input noise can be suppressed when input signal power is around the saturation regime. Although the power transfer curves in Fig. 2 were measured in the absence of the other channel, the behavior does not change appreciably also when both channels are launched simultaneously if they are correctly time-interleaved.

Fig. 3 shows the comparison of the input and output pulse waveforms when the two channels are simultaneously launched to the regenerator. The mark levels of the input signals are intentionally fluctuated. The pulses in the two channels are time-interleaved with separation of 50 ps. It is clearly shown that the noise on the mark level is strongly removed by the regeneration. In addition, it is also shown that the extinction ratio is not degraded by the regeneration process using the second-higher-order product of FWM. The corresponding bit-error rates (BERs) of each channel before and after the regeneration are shown in Fig. 4. The receiver sensitivity of both channels is improved about 2.5 dB by the regeneration. The two-channel regeneration works well when there is no time overlapping between the channels. Crosstalk appears when the time-interleaving is not ideal. Fig. 5 shows receiver sensitivity of Ch2 (received signal power at which BER is 10^{-9}) versus the time separation between Ch1 and Ch2 $\Delta\tau$. Note that the $\Delta\tau$ is positive (negative) when Ch1 is leading (lagging). For the time separation between channels less than 12 ps, BER below 10^{-9} cannot be obtained. The plot indicates that the time separation larger than about 15 ps, which is more than about three times the pulsewidth, is needed for power penalty to be less than 1 dB.

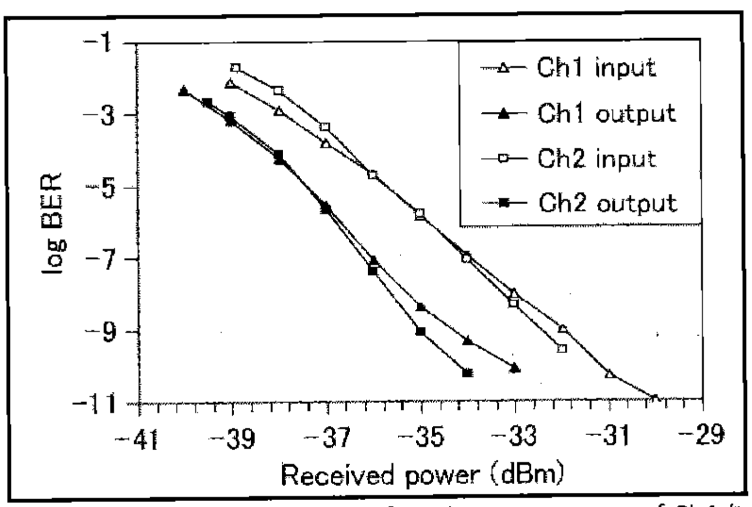

Fig. 4. BER measurements before and after the regenerator of Ch1 (triangles) and Ch2 (squares). Time separation between the two channels is 50 ps.

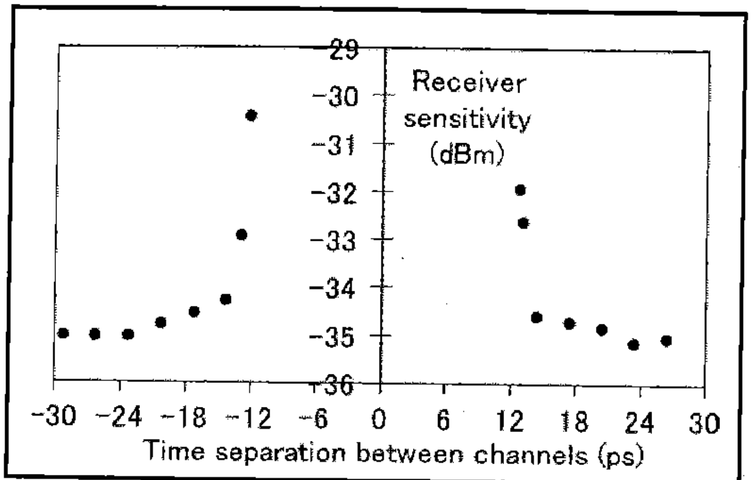

Fig. 5. Receiver sensitivity at BER = 10^{-9} of Ch2 versus time separation between channels.

For this regenerator to be placed after transmission in real systems, adaptive time interleaving is mandatory. One straightforward method for the time interleaving is to demux and mux the channels with a tunable time delay given to one of the channels between the demux and mux stages. A slow light technique might be used as the channel selective time delay without demultiplexing [9]. In both cases, monitoring is necessary to verify that the correct time interleaving is achieved. Fig. 6 illustrates spectra measured at the output of the HNLF when (a) the inputsignal pulses are time-interleaved and (b) they are overlapped.

When the input signal pulses are overlapped, additional FWM products involving the two spectral components appear. The power of the spectral component after the HNLF at the shaded portion in Fig. 6, for example, may be used as a monitor signal in such an adaptive timing control.

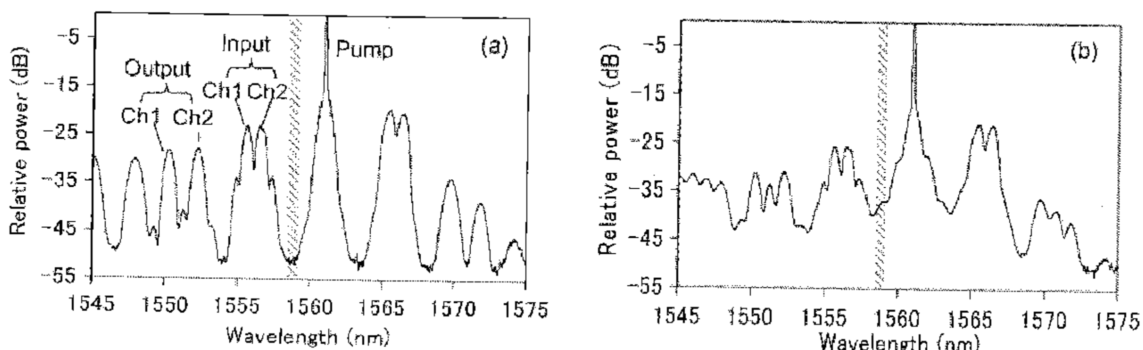

Fig. 6. Output spectra when pulses are (a) time-interleaved and (b) overlapped. Shaded portion shows the position of power level that possible for time-interleaved monitoring.

Fig. 7 shows the power measured at the shaded portion afterpassing through a 0.6-nm bandwidth OBPF. It is shown that the power is high when the channels are overlapped and decreased as the time separation between the channels is increased. For the time separation of more than 15 ps, the power is almost unchanged, showing that almost no generation of interchannel FWM products at that wavelength. The time delay before the HNLF can be controlled so as to minimize the power extracted by the OBPF.

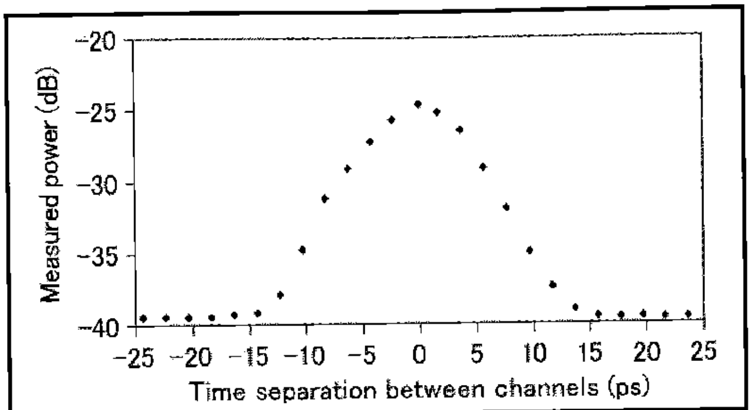

Fig. 7. Power level at the shaded portion in Fig. 6 as a function of time separation between channels.

DISCUSSION AND CONCLUSION

All-optical 2R regeneration of two-channel signals is achieved by using higher order FWM in a single HNLF. The experimental results show that crosstalk between channels can be avoided by time-interleaving before entering the fiber. When the time separation is more than ~15 ps, which is ~3 times the signal pulsewidth, interchannel interaction is greatly suppressed. A possible power monitoring method to determine a suitable time-interleaved condition is also discussed.

In this experiment, we used short pulses (duty ratio of ~6%) for the input signals. This is not a fundamental requirement for 10-Gb/s operation but was determined by the experimental equipment. From numerical simulation of this regeneration system, the width of the pump depletion in the saturation regime is roughly proportional to the input signal pulsewidth. Considering that the minimum pulse separation for 5.8-ps input pulses is ~14 ps according to Fig. 5, the maximum input pulsewidth will be about 5.8 X 50/14 = 20 ps for 10 Gb/s X 2 ch operation. For this regeneration scheme to be practical, it should be able to process still wider pulses. One method for this aim would be to place a pulse compression stage prior to the regenerator although such an arrangement will be highly complicated. The usable pulsewidth will be furthermore determined by the number of channels simultaneously processed by the regenerator.

In this 2R regeneration scheme, the output signal wavelengths are different from those of the input signals. Wavelength separation between the channels is also changed. These feature inconsistent to requirements in real system application will be resolved by the use of an additional wavelength conversion stage and use of different FWM orders for different output channels.

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