All-optical Regeneration of Time-interleaved Multi-wavelength Signals Based on Higher-Order Four-wave Mixing

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Abstract ? Dual-channel all-optical 2R regeneration based on higher-order four-wave mixing in a nonlinear fiber is presented. A single fiber and a pump are shared by the time-interleaved two wavelength channels.

INTRODUCTION

Optical 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 the regeneration function for high-speed signals. Saturation of four-wave mixing (FWM) leads to an ultrafast limiter suppressing amplitude noise on signal pulses [1], [2]. When higher-order FWM products are used, space-level noise is also suppressed, by which 2R regeneration function is obtained [3]-[5].

When signals are formatted in a return-to-zero (RZ) shape and its duty ratio is smaller than ~50%, signals in different wavelength channels is expected to be simultaneously regenerated without mutual interaction if they are suitably time-interleaved [6]. 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 is limited in the vicinity of the input signal pulses.

In this paper we demonstrate that on-off keyed (OOK) short RZ pulses in two different wavelength channels can be simultaneously regenerated by the use of second-higher order FWM in a highly nonlinear fiber (HNLF). We also show that power of a spectral component in a certain wavelength range after the HNLF may be used as a monitor signal for adaptive control of temporal alignment of signals in different channels.

MULTI-WAVELENGTH REGENERATION

The experimental setup of 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 1.5 ps and 3 nm, respectively, is amplitude-modulated using $LiNbO_3$ modulators (LNMs), where 2^{11}-1 length PRBS is applied to LNM1 for data modulation and a 1.9 GHz asynchronous RF tone is applied to LNM2 for modulation of pulse amplitude simulating noise on the mark level. The bias voltage to LNM1 is not optimum giving finite extinction ratio (ER). 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 pulse widths are 5.6 ps and 6.0 ps for ch1 and ch2, respectively. The signals together with a continuous-wave (CW) pump are injected to a HNLF through a polarizer (POL) for polarization alignment. Power and wavelength of the pump are 100 mW and 1561 nm, respectively. The CW pump is phase-modulated with RF tones with 1 GHz and 100 MHz for suppression of stimulated Brillouin scattering. The HNLF has zero-dispersion wavelength, dispersion slope, nonlinearity, loss, and length of 1556 nm, 0.026 ps/nm2/km, ~12 W-1 km-1, 0.78 dB/km, and 1500 m, respectively. Fig. 2 shows wavelengths of various components involved in the FWM interaction. In this experiment, second-higher-order products at wavelength 2?i – ?p are extracted as the output signal, where ?i (i=1 or 2) and ?p are the 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. After the HNLF in Fig. 1, cascaded OBPFs are inserted to extract the signal. The first OBPF (3.2 nm width) is used to extract the two signal components and the second OBPF is used for the selection of one of the two signal components.

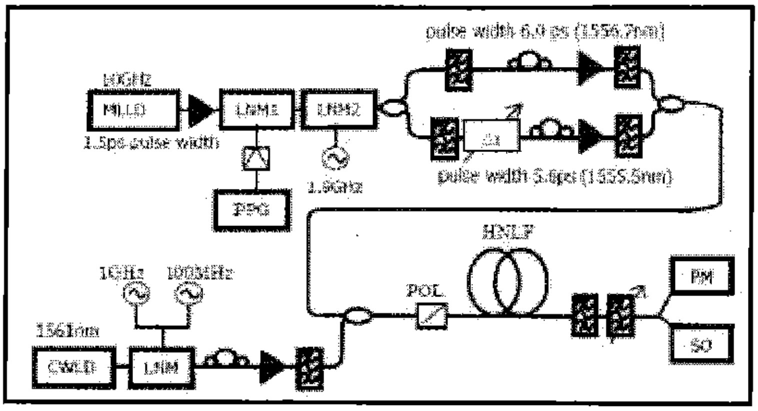


Fig. 1. Experimental setup of two-channel regeneration. CWLD: continuous-wave laser diode, PM: power meter, SO: sampling oscilloscope, PPG: pulse pattern generator.

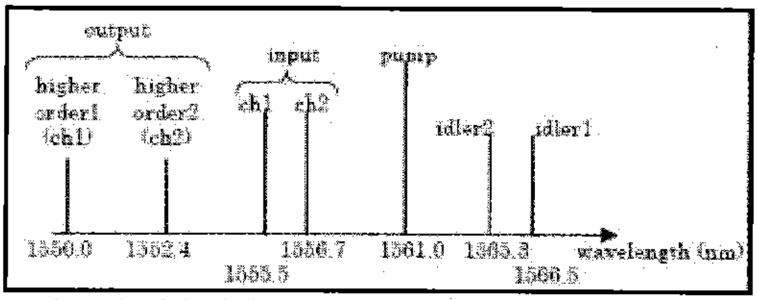


Fig. 2. Wavelength of the light components involved in the FWM interaction

EXPERIMENTAL RESULTS

Power transfer curves for ch1 and ch2 are shown in Fig. 3. In this measurement, the amplitude modulation simulating mark-level noise is not applied. Strong saturation of output power at input power *P*in ~ 0.5 mW is observed for both wavelength channels. The output power grows quadratically as the input power for *P*in less than about 0.15 mW.

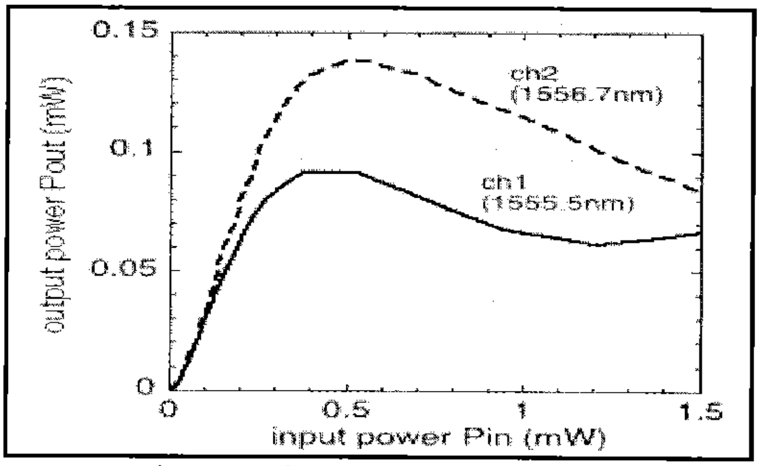
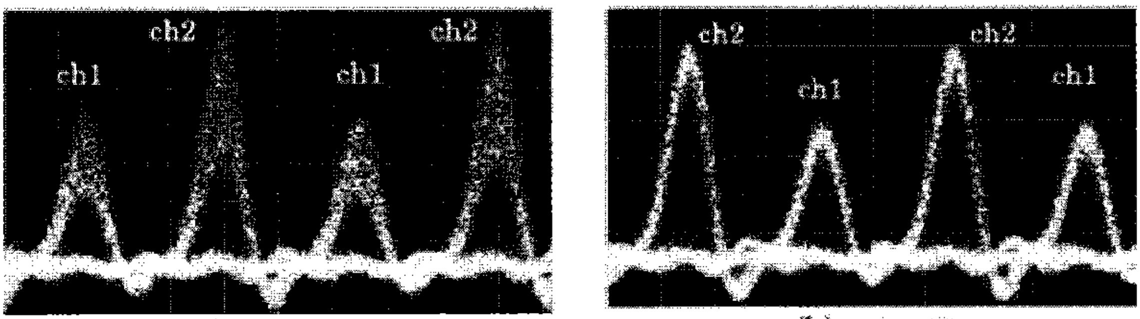


Fig. 3. Output power as a function of input power for ch1 (solid curve) and ch2 (dashed curve). *P*out and *P*in are time-averaged powers. Output wavelengths are 1550.0 nm and 1552.4 nm for ch1 and ch2, respectively.

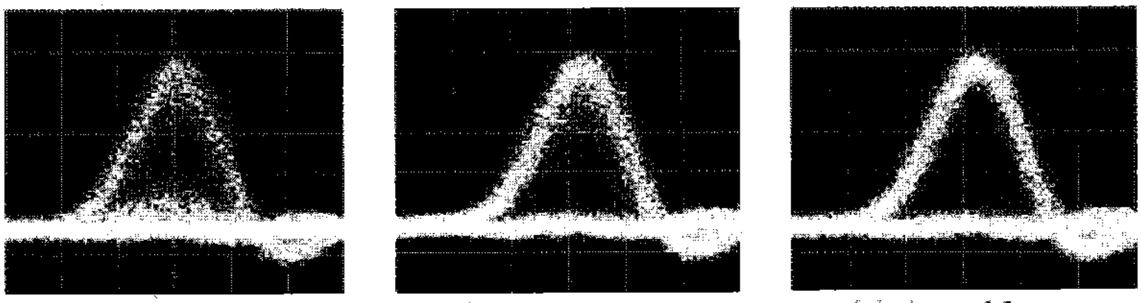
Fig. 4 shows the comparison of the input and output pulse waveforms when mark levels of the input signal are intentionally fluctuated. The pulses in the two channels are time-interleaved with separation of ?t = 50 ps. It is clearly shown that the noise on the mark level is strongly removed by the regenerator. In addition, it is also shown that the ER is not appreciably degraded by the regeneration process using the second-higher-order product of FWM.



(a) input (b) output

Fig. 4. Input and output pulse waveforms. Time separation ?t is 50 ps. Horizontal axes: 20 ps/div.

Fig. 5 shows output eye patterns where only ch2 is extracted. Time separation ?t between ch1 and ch2 is varied. As is seen in Fig. 5 (a) and (b), severe crosstalk appears when pulses in two channels are overlapped. The crosstalk disappears for ?t larger than 11 ps. Fig. 6 shows spectra measured at the output of the HNLF when (a) the pulses are time-interleaved and (b) they are overlapped (?t = 0). When the input signal pulses are overlapped, additional FWM products involving the two signal components appear. For this regenerator to be placed after transmission in real systems, adaptive time interleaving is mandatory. The power of the spectral component after the HNLF at the shaded portion in Fig. 6(b), for example, may be used as a monitor signal in such an adaptive timing control.



(a) $\Delta\tau = 0$ ps (b) $\Delta\tau = 8$ ps (c) $\Delta\tau = 11$ ps

Fig. 5. Output eye patterns of ch2. Time separation?t between ch1 and ch2 are (a) 0 ps, (b) 8 ps, and (c) 11 ps. Horizontal axes: 10 ps/div.

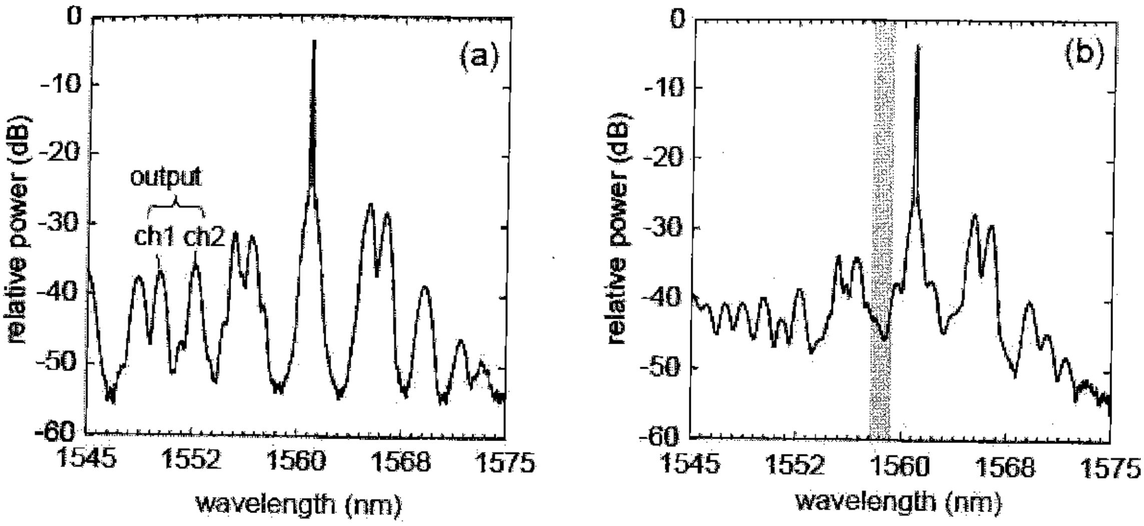


Fig. 6. Output spectra when pulses are (a) time-interleaved, and (b) overlapped.

CONCLUSION

Simultaneous two-channel signals are properly regenerated using higher-order FWM in a single HNLF when the channels are time-interleaved before entering the fiber. A possible way to determine suitable time-interleaved condition in the real system is also discussed.

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

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