Optical 3R Regeneration for 10 Synchronous Channels Using Self-Phase Modulation in a Bidirectional Fiber Configuration

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Abstract
We propose an all-optical 3R regenerator for 10 synchronous WDM channels based on self-phase modulation combined with synchronous modulation in bidirectional fiber configuration. Our simulation results show signal quality improvement of up to 2.5 dB.

Introduction
The single-channel fiber-based optical 2R regeneration exploiting the self-phase modulation (SPM) induced spectral broadening in highly nonlinear fiber (HNLF) followed by offset filtering (aslo know as the Mamyshev technique) has attracted much attention in the past few years because of its simplicity and robustness [1-3]. However, the direct extension of this kind of regenerator for multi-channel applications is very challenging due to the severe nonlinear inter-channel crosstalks, i.e., cross-phase modulation (XPM) and four-wave mixing (FWM). To date, a few schemes have been proposed to mitigate those nonlinear interactions among different channels such that the multiwavelength opeartion of the Mamyshev regenerator can be made practical. Those approaches can be mainly divided into two types. The first type relies on a suitable design of the fiber dispersion map which can induce fast walk-off time between different channels, by using large channel spacing of 600 GHz, to weaken the nonlinear crosstalks [4-6], while the second type makes use of the bidirectional propagation in a polarization maintaining HNLF with the polarization control [7]. In this paper, we propose a new scheme in which the nonlinear inter-channel effects are effectively mitigated by inducing proper timing walk-off on the different wavelength-division-multiplexed (WDM) channels, and the number of supported channels in the regeneration is increased by applying a bidirectional fiber configuration. Bit-synchronous WDM channels are required in the scheme that is applicable in the high-speed point-to-point long-haul transmissions with proper dispersion management.

All-optical 3R regeneration is demonstrated for ten synchronous 10-Gb/s WDM channels with only 1.6-nm channel spacing based on SPM together with synchronous modulation. The numerical simulation results confirm the feasibility of the proposed regenerator and show the signal quality improvement of up to 2.5 dB.

Design and architecture of the proposed regenerator
Fig. 1 shows the architecture of the proposed fiber-based

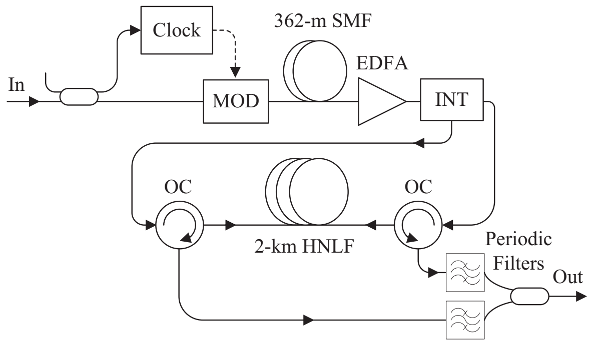

Fig. 1. The architecture of the proposed multi-channel 3R regenerator consisting of a synchronous amplitude modulator in a bidirectional fiber configuration. MOD: amplitude modulator; INT: interleaver; OC: optical circulator.

multi-channel 3R regenerator. Ten RZ-OOK WDM channels at 10 Gb/s with duty cycle of 33% are launched into the regenerator. They are at the wavelength from 1534.6 nm to 1549 nm with 1.6-nm spacing and assumed to be aligned in bit slot and polarization at the input. A synchronous amplitude modulator, which is driven by the electrical clock pulses extracted from the incoming signals, is used to apply pulse carving simultaneously on all the WDM signals such that both the pulsewidth and the timing jitter of the incoming signals can be reduced if the extracted clock pulses are sufficiently narrow and with low jitter. The pulsewidth of the signals after pulse carving is controlled to be around 13 ps. Note that this can be obtained by cascading one or more amplitude modulators if necessary. In order to achieve a ten-channel regeneration, we need to handle five of them in one propagation direction in the HNLF. As a result, a piece of 362-m long standard single mode fiber, which acts as a dispersive element, is employed to induce 20-ps timing walk-off between every two WDM channels spaced by 3.2 nm. A criterion that the pulsewidth to the timing walk-off ratio should be less than 2/3 is adopted, which is found to provide sufficient mitigation of the nonlinear inter-channel effects and therefore this leads to the pulsewidth of the signals after the synchronous modulation to be 13 ps. Note that the increase of the signals' pulsewidth induced by the 362-m SMF is small (less then 0.13 ps). A following erbium-doped fiber amplifier (EDFA) is used for amplification and the signals are then wavelength-interleaved into two groups by an interleaver, of which the channel spacing is 3.2 nm. The odd and even channels are launched into the HNLF from the two sides for spectral broadening. The HNLF has the nonlinear coefficient, the zero dispersion wavelength and the dispersion slope of 10.5 $W^{-1} \cdot km^{-1}$, 1550 nm and 0.019 ps/($nm^2 \cdot km$), respectively. Both the dispersion and the dispersion slope are sufficiently small so the WDM signals will not experience further significant pulse broadening and walk-off in the HNLF. Finally, both sides of the signals are simultaneously filtered with 0.64-nm offset via using two periodic filters with 0.4-nm passband and 3.2-nm free spectral range. Then the filtered signals are combined for the output. It is noted the output signal wavelengths are shifted. We can use even number of regenerators if the wavelength-preserving inline regeneration is needed.

Simulation results and discussions

The regenerative performance of the proposed regenerator is investigated by numerical simulation. The input signals to the regenerator are degraded by timing jitter and amplitude fluctuations on both the mark and the space levels. The corresponding eye diagram is shown in Fig. 2(a). In the regeneration, the timing jitter is expected to be reduced by the synchronous modulation. And, those amplitude fluctuations on the space levels are suppressed by the offset filtering as their power are not high enough to generate sufficient spectral broading and hence are rejected by the filter, while the fluctuations on the mark levels is reduced since the pulses with larger power will experience larger loss and this can result in a self-regulating effect on the mark levels. The gain of the EDFA is optimized to give the best regeneration on the signals. Fig. 2(b) gives the eye diagram of the regenerated signals without proper timing walk-off between different channels and we can see that the eye is totally closed due to severe nonlinear inter-channel crosstalks. However, with the proper timing walk-off introduced, the crosstalks due to nonlinear interaction among channels are significantly mitigated and the eyes are widely open, as shown in Fig. 2(c) and (d) for the best and the worst channel after regeneration respectively.

Effective extinction ratio improvement is obtained by the successful reduction of the amplitude fluctuations on both the mark and the space levels. The results of the bit-error rate (BER) measurement is given in Fig. 3. We can see that the regenerative performance for the five-channel operation (unidirectional only) and the ten-channel operation (bidirectional) are close which means the noise caused by the Rayleigh back-scattering is limited and the use of the bidirectional fiber configuration induces almost no performance degradation. In addition, the regenerator itself is confirmed to cause little additional penalty to the un-degraded input signals. We also see no significant variation of the regenerative performance among different channels and the receiver sensitivity improvement at BER of 10^{-9} in the ten-channel operation is observed to be up to 2.5 dB for the best channel.

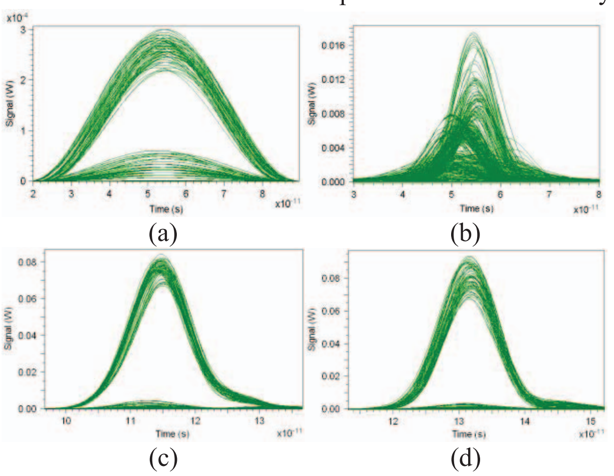

Fig. 2. (a) Degraded input signal. (b) Regenerated signal without proper timing walk-off among channels. (c) and (d) are the best and the worst channel respectively of the regenerated signals with proper timing walk-off introduced.

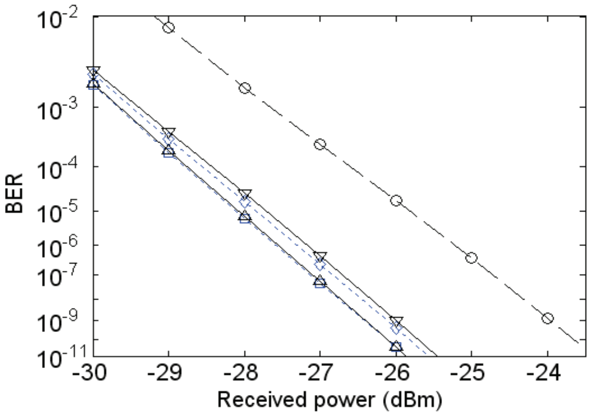

Fig. 3. BER measurement of the proposed multi-channel 3R regenerator by numerical simulations. The line with circle makers: degraded input signal. The line with squares and diamonds: the best and the worst channel respectively in the 5-channel operation (unidirectional only). The line with up- and down-triangles markers: the best and the worst channel in 10-channel operation (bidirectional).

Conclusions

The regenerative performance of the proposed multi-channel 3R regenerator is investigated and confirmed by numerical simulation. The severe inter-channel nonlinearities in HNLF are successfully mitigated by introducing proper timing walk-off among different channels and the use of the synchronous modulation and the bidirectional fiber configuration enables the scheme to achieve simultaneous 10-channel 3R regeneration with channel spacing of only 1.6 nm. The improvement of the signals' quality is observed to be up to 2.5 dB. This work is supported in part by GRF 411007.

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