Simultaneous all-optical 2R regeneration of 4x10 Gbit/s Wavelength Division Multiplexed channels

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Abstract *We demonstrate all-optical regeneration of four WDM channels in a single optical fibre by using polarization multiplexing in a bidirectional configuration. We observe no performance degradation arising from the presence of the multiple channels.*

Introduction

All-optical regeneration is likely to be an important function within future optical communication systems providing a route to optical networks of increased scalability, capacity and flexibility, as well as reduced network management complexity and costs. Optical regeneration is progressively more attractive as transmission speeds increase since this places ever more stringent demands on existing impairment mitigation techniques such as dispersion and PMD compensation. To date most research has focused on single channel regeneration however the possibility of performing simultaneous multi-wavelength all-optical regeneration in a single device would be extremely attractive offering major potential cost benefits.

All-optical signal regeneration has been addressed to date using a variety of nonlinear effects in optical media. One promising class of solutions exploits self-phase modulation (SPM) in highly nonlinear optical fibres (HNLFs). Although such schemes have been extensively studied in the context of single-channel systems, the main challenge associated with their extension to allow multi-wavelength operation lies in the control of deleterious interchannel effects, such as four-wave mixing and cross-phase modulation (CPM). To date, mitigation of these effects has been addressed using some form of chromatic dispersion management in fibre assemblies [1], often accompanied by polarization interleaving [2]. In this paper we report the experimental demonstration of simultaneous 2R regeneration of four 5nm-spaced WDM channels within a single HNLF based on a scheme known as the Mamyshev regenerator, which relies on SPM followed by filtering at an offset wavelength [3]. Efficient mitigation of the deleterious effects of the interchannel nonlinearities is achieved by combining a polarization multiplexing scheme in a bidirectional architecture.

Principle of operation

The proposed configuration is based on the optical regenerator first demonstrated by P. Mamyshev in 1998 [3]. The principle of this regenerator relies on the discrimination between 'ones' and ghost pulses in 'zero' slots through the power-dependence of the spectral broadening induced by SPM. Distinction between the two power levels is achieved through an offset output filter used to eliminate the insufficiently broadened spectrum (that originates from weak ghost pulses) and to offer pulse reshaping capabilities for the 'ones'. Additional amplitude equalization can be provided through a proper selection of the fibre parameters with respect to the input pulse characteristics [3, 4].

Here we process four channels simultaneously within the same highly nonlinear fibre by efficient combination of two simple schemes. A bidirectional propagation scheme is adopted to drastically reduce the CPM contribution by increasing the relative walk-off times between counter-propagating pulses (typically 10ns/m) so that an individual pulse interacts with many counter-propagating pulses during its passage through the fibre. Secondly, we exploit a polarization-maintaining HNLF (PM-HNLF) to process two co-propagating cross-polarized channels. Propagation of the co-propagating signals on orthogonal polarization axes of the PM-HNLF allows for a three-fold reduction in the CPM strength, while the rapid differential group delay between the two polarization axes of the fibre ensures a rapid walk-off time, thereby allowing for an averaging of the CPM effects.

Experimental set-up

The experimental set-up used to demonstrate the simultaneous regeneration of four channels is illustrated in Fig.1.

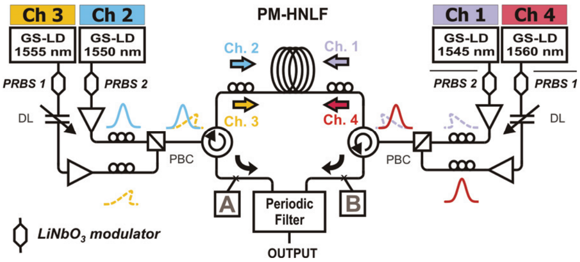

Fig. 1. Experimental set-up and corresponding channels allocation.

Four independent gain-switched DFB laser diode (GS-LD) sources emitted Gaussian pulses at 10GHz, with a FWHM of 7-8ps. The wavelengths of the four lasers were separated by ~5nm and occupied the band between 1545nm and 1560nm. The laser pulses were data-modulated using 2^{31}-1-long PRBSs provided by two independent pattern generators, which ensured that the data for each co-propagating channel-pair were uncorrelated with respect to each other. Optical delay lines (DL) were used to ensure that the pulses of each channel-pair were temporally overlapping at the input of the PM-HNLF (thereby representing the worst-case scenario in terms of inter-channel interference). The polarization states of the incoming signals to the PM-HNLF were combined using polarization beam combiners (PBCs). Two circulators placed on either side of the PM-HNLF, were used to separate the signals propagating in opposite directions within the fibre. The use of non-PM circulators in our system necessitated the inclusion of polarization controllers after the PBCs to ensure that the states of polarization of the incoming signals were aligned to the polarization axes of the PM-HNLF. The presence of the PBC and the circulator accounted for a 4dB insertion loss for each incoming signal before the fibre input.

The PM-HNLF was 1 km-long and has a chromatic dispersion value of -4.2ps.nm^{-1}km^{-1} at 1550nm on the slow axis, and a nonlinear coefficient of ~20W^{-1}km^{-1}. The differential group delay value was estimated to be ~2.3ps/m. The total loss of the HNLF was 4.2dB (including splicing losses). A periodic filter is ideally required at the output of the system to provide offset filtering of the four channels. In our demonstration a ~0.4nm bandwidth tuneable filter was used instead due to lack of a suitable alternative but which allowed a full individual assessment of each of the channels. The optimum operating conditions for the regeneration process were found using the previously studied design rules for Mamyshev-type regenerators [4]. Following these rules, an offset detuning of -0.8nm and input powers of 20-23dBm (at the input of the PBCs) were predicted to provide the maximum power equalization for each of the channels. (Note that due to lack of sufficiently high power amplifiers for Channels 2 and 4 in our experiment, a spectral detuning of -0.6nm was used for Channel 4, whereas a small power penalty was allowed for Channel 2). Although the wavelength allocation for the forward- and backward-propagating channel pairs was chosen somewhat arbitrarily (15nm spacing in one direction, 5nm in the other), a 10nm spacing per channel-pair could alternatively be considered and would further reduce the interchannel crosstalk in the PM-HNLF.

Experimental results

The FWHM of the output pulses was ~10ps for all of the channels, mainly determined by the bandwidth of the offset filter. In order to characterize the regenerating system, we first measured the power transfer functions (TF – output vs. input powers) for each channel. The interfering channels manifest themselves mainly as crosstalk due to the additional spectral components that fall within the filter bandwidth of the considered channel. These spectral components originate from either the co-propagating signal or from the backscattered contribution of the counter-propagating signal (see Fig.2(a)). The effect of the crosstalk is to slightly decrease the extinction ratio of the regenerated signal as compared to the case of single-channel operation (see Fig.2(b)). However, the figure shows that an extinction ratio in excess of 30dB can still be achieved at the output. Similar results are obtained for the other channels.

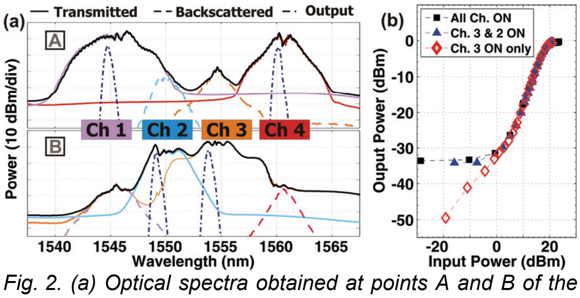

Fig. 2. (a) Optical spectra obtained at points A and B of the experimental set-up of Fig.1, showing the contribution of the various channels. (b) Experimental TF of Channel 3 in the absence or presence of the remaining channels.

We next performed bit-error rate (BER) measurements on the four channels both in the case of single- and multi-channel operation (Fig.3 a-d). We observe that the presence of the multiple channels does not give rise to any additional power penalty, and that the performance of the regenerating system is very close to that obtained under single channel operation. Finally, we degraded one of the channels (Channel 3) artificially, by selecting a sub-optimum bias voltage setting for the corresponding $LiNbO_3$ data modulator. The eye diagrams of the degraded signal at the input and the output of the regenerator are shown in Fig.3(e-f). The corresponding BER measurements in Fig.3(d) confirm that a complete correction of the ~1.8dB power penalty (at BER=10^{-9}) introduced by the signal degradation was achieved at the regenerator output.

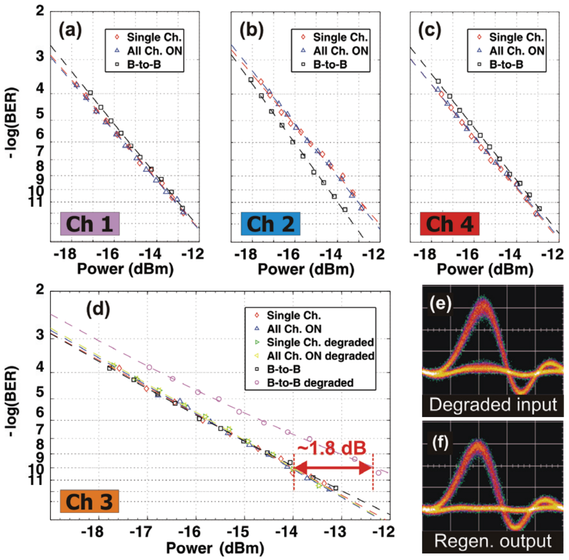

*Fig. 3. BER traces of the four channels when interfering channels are either present (ON) or absent. The graph of Channel 3 also includes the case of the regeneration of a degraded signal. Corresponding eye diagrams of (e) the degraded input and (f) the regenerated output (when all channels are present) are also shown (same scale)***.**

Conclusion

We have demonstrated the simultaneous 2R regeneration of four WDM channels in an architecture that allows two channel pairs to propagate in opposite directions in a PM-HNLF, and uses polarization multiplexing for each of the channel pairs. Through BER and TF measurements, it is shown that no additional power penalties are observed due to the presence of the multiple channels. We believe that these results highlight the potential of HNLF technology for multi-wavelength all-optical signal processing.

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