# WDM signal regeneration using a single all-optical device

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**Abstract:** Using the principle of quasi-continuous filtering in a non-linear fibre, we propose an optical device for the simultaneous regeneration of sevaral channels at 40 Gbit/s. Simulations predict an improvement of the signal quality for four channels by more than 6.8 dB.



**OCIS codes:** (060.4510) Optical communications; (190.4370) Nonlinear optics, fibers.

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## 1. Introduction

Optical regeneration is a key technology for next generation optical networks. Regenerators based on self-phase modulation (SPM) in fibre [1-4] are advantageous because of their

#83650 - $15.00 USD Received 4 Jun 2007; revised 19 Jul 2007; accepted 23 Jul 2007; published 24 Aug 2007

simplicity and of their ability to simultaneously process several wavelengths [5, 6]. To the best of our knowledge, performance of optical regenerators based on this principle, as defined by the improvement of the quality factor of the signal, are typically lower than 2 or 3 dB at 10 and 40 Gbit/s [5, 6]. In this paper, we present a performance analysis of a 40 Gbit/s regenerator based on quasi-continuous filtering (QCF). This regenerator simultaneously regenerates four 40 Gbit/s channels, offering remarkable quality factor enhancements in excess of 6.8 dB. We further analyze the tolerance of the regenerator to variations in key design parameters, illustrating that acceptable performance is achieved for a wide variety of configurations.

## 2. Optical regeneration device

The regeneration device is schemed on Fig. 1. The device is constituted by several sections of highly non-linear fibre (HNLF), separated by filtering elements, which are slightly offset one from another. A piece of linear fibre is used at the end in order to compensate for the pulse broadening along the HNLF. The principle of the device is the following: as a signal is launched into a HNLF piece, spectral broadening occurs due to SPM inducing non-linear chirp, which interacts with HNLF fibre dispersion and results in pulse reshaping, as for soliton systems. It is therefore preferable, as for the latter, to use positive dispersion HNLF to balance the non-linear induced pulse broadening. Furthermore, distributed filtering along the device enables to stabilize the pulse width, reducing the standard deviation of the "ones" [7].

In order to enable WDM operation, distributed optical filtering is used along the device. Firstly, it constrains the spectral width, allowing the possibility of WDM operation with moderate channel spacing. Secondly, it enables to reduce, up to a certain amount, the accumulation of timing jitter induced by interchannel cross-phase modulation (XPM) [7, 8]. Due to the small total offset of the regenerator, optical noise and ghost pulses are transmitted by the device as the total frequency shift in this device is smaller than the signal bandwidth. However, a regeneration of the "zeros" is expected if using a cascade of regenerators so that the total frequency shift becomes greater than the spectral bandwidth of the signal [6].

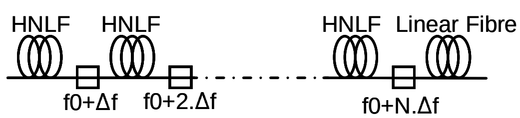


Fig. 1. Schematic diagram of the regenerator comprising N sections. Blocks represent optical filters with centre frequencies offset from each other by Δf, followed by a piece of linear fibre.

### *2.1 Performance analysis*

Simulations were made using VPI Transmission Maker v7.0. We considered four WDM signals at 40 Gbit/s with 8 ps Gaussian pulse width, spaced by 600 GHz. Each signal was independently modulated considering PRBS sequences of 512 bits. At the receiver, optical filtering with 78 GHz bandwidth was used in order to demultiplex the fours channels before detection. Optical signal was then converted into electrical signal using a PIN photodiode and an electrical filter with 28 GHz bandwidth was used before estimation of the quality factor as displayed in Fig. 2.

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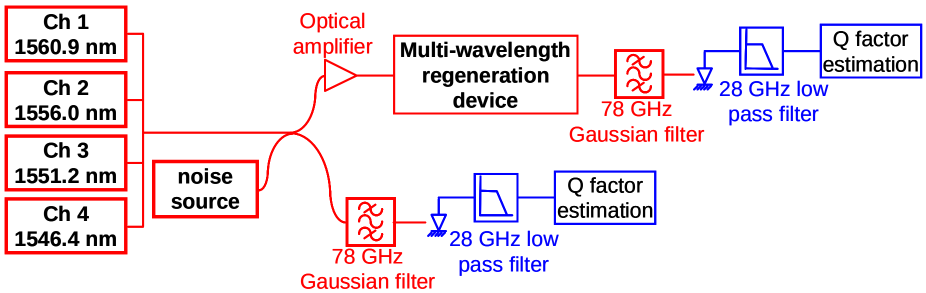


Fig. 2. Simulation setup for the estimation of the regenerator performance.

We define the regenerator improvement as the difference between estimated signal qualities after the regenerator and in back-to-back. Following successive optimisation of the regenerator parameters, an optimum configuration was found to be 5 sections of 200 metres of HNLF (D= 40 ps/nm/km; $\gamma$ = 13 $W^{-1}.km^{-1}$ and $\alpha$ = 0.6 $dB.km^{-1}$). Because of this high dispersion value, we expect dispersion slope impact to be minimal and therefore, we do not consider it throughout this study. Each section is followed by a WDM filter with 200 GHz bandwidth and periodicity of 600 GHz, equal to the channel spacing. Each filter is offset from the previous one by 2 GHz. Launched power into the device was optimised to 20 dBm per channel. We did not consider SBS in our simulations as we independently verified its impact to be minimal for a 1km fibre length (less than 2 dB additional loss only for 20 dBm input power) due to the high bandwidth of the 40 Gbit/s signals. Furthermore, special HNLFs are currently developed showing enhanced SBS threshold [9]. Filter insertion loss is not considered in this part but will be investigated in the next chapter. Total dispersion in the linear fibre piece was optimised to – 6.5 ps/nm. In order to estimate the performance of this regenerator, the optical signal to noise ratio (OSNR) is varied at the input of the device. Figure 3 shows the regenerator performance as a function of the OSNR in back-to-back for the four WDM channels as well as the eye diagrams of channel 3, before and after regeneration, for an OSNR of 20 dB. As shown, we obtain an improvement of the signal quality up to 6.8 dB for the worst of the four channels.

Regeneration may also be used for a single channel input. In this case, the regenerator improvement increases due to the reduction of XPM induced timing jitter and was evaluated to be 9.8 dB.

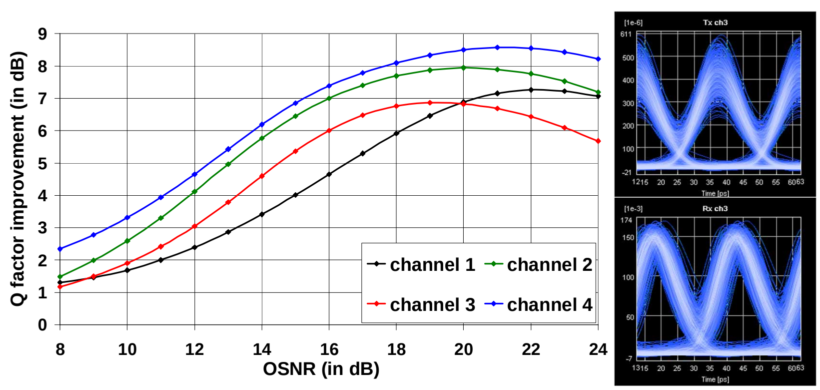


Fig. 3. Quality improvement for each of the four channels in the case of WDM regeneration as a function of the input signal OSNR. Eye diagram of worst channel (channel 3) in back-to-back (top right) and after regeneration (bottom right) for an input OSNR of 20 dB.

It is well known that the quality factor is not necessary a good indicator of a regenerator performance. We therefore refined the analysis of the improvement brought by the regenerator

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by estimating the histogram of the receiver voltage. For this particular purpose, simulations were performed considering $2^{15}$ bits; typical histograms as shown in Fig. 4 are obtained for back-to-back and after regeneration of a single channel with an OSNR of 18 dB.

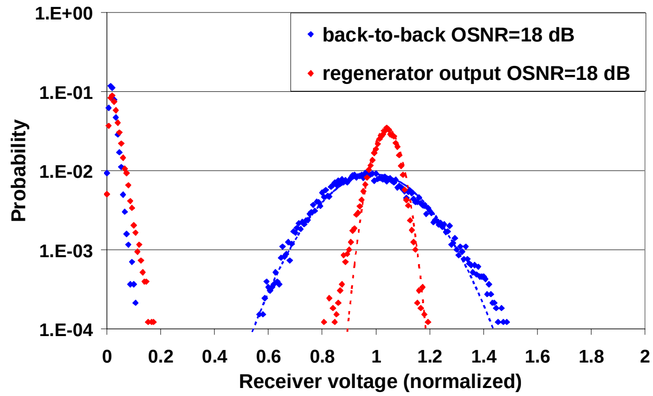


Fig. 4. Receiver voltage histograms at the input and output of the regenerator.

As can be seen, the amplitude jitter on the ones is greatly reduced whereas the “zeros” are not regenerated by the use of a single regenerator, as discussed in previous chapter. We estimate the reduction of the distribution width of the “ones” to nearly 10 dB assuming Gaussian distribution. However, the Gaussian noise distribution is not maintained after regeneration [10], as can be noticed on the tail of the “ones” distribution, which does not fully superimpose with Gaussian-fit dashed lines. Whilst care should be taken in the prediction of the overall performance, such regenerator still seems very advantageous in order to limit the accumulation of distortion due to transmission effects.

### *2.2 Channel spacing*

QCF regeneration is primarily based on SPM effect. At the same time, interchannel non-linear effects occur in the HNLF inducing pulse distortions. We believe that the overall performance of such regeneration is limited by XPM. We confirm this statement by plotting on Fig. 5 the regeneration performance of the 4 channels as a function of the channel spacing, using the optimized regenerator described above. As expected, strong phase matching for channel spacing below 400 GHz negates the benefit of the QCF regenerator. At higher channel spacing, walk-off of more than one bit period per stage occurs, allowing acceptable regenerator performance. However, as observed for long-haul soliton transmission systems, a quasi-phase matched condition is observed for channel spacing around 800 GHz where the XPM contribution of neighboring bits in adjacent sections may add constructively. At this channel spacing, the impact of quasi-phase matched XPM varies strongly with the relative delay of the input signals giving rise to large quality factor fluctuations. Techniques to minimize the impact of XPM in WDM systems are well known and could be used in order to enhance the performance of this device [11].

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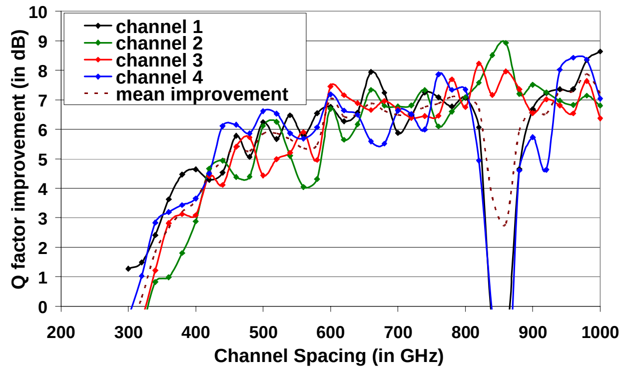


Fig. 5. Regenerator performance of the four channels as a function of the channel spacing.

## 3. Tolerance for the physical parameters of the regenerator

In this chapter, we consider the impact of the variation of the regenerator parameters which may suffer from random fluctuations. These include fibre properties, insertion loss and offset of the optical filters.

### *3.1 Optical fibre*

In terms of HNLF, we already established that the non-linear coefficient and loss may be effectively normalized by appropriate choice of the section length to obtain a given level of non-linear phase shift [6]. Hence, for simplicity, we consider a section of 200 metres of HNLF with a non-linear coefficient $\gamma$=13 $W^{-1}.km^{-1}$ in the following. In a multiwavelength 2R device, phase matching of adjacent channels is critical and determines the efficiency of FWM and XPM. Simulations were performed as above with an input OSNR of 18 dB, a 600 GHz channel spacing, a launched power of 20 dBm per channel and omitting the linear chirp compensation stage for simplicity. Fig. 6 shows the mean regenerator performance averaged over the four channels as a function of the HNLF dispersion and the number of sections.

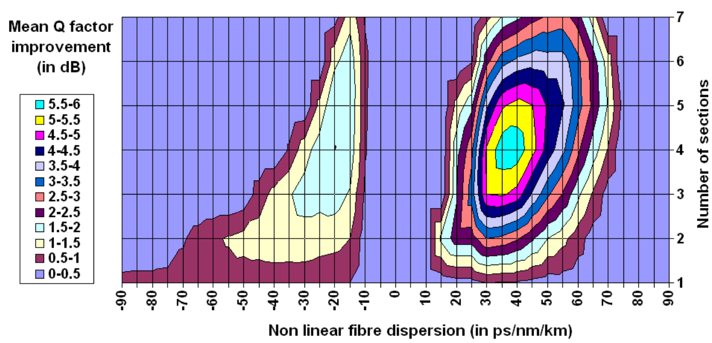


Fig. 6. Impact of non-linear fibre dispersion and number of sections considering 200 m-long sections separated with 200 GHz filters with 2 GHz shift per section.

Using such a design, regeneration may only be obtained if the fibre dispersion is not between -15 and 15 ps/nm/km. For fibre dispersion in this range, XPM is responsible for the apparition of timing jitter leading to strong distortion of the optical pulses. Slight increase of the HNLF dispersion allows for a mitigation of XPM without significantly degrading SPM effect through excessive pulse broadening. We find that for anomalous dispersion fibres, the non-linear chirp compensation enables operation of SPM for higher dispersion. We believe that the greater decrease of XPM encountered allows improved overall 2R performance. For large dispersion values, below -50 ps/nm/km or above +70 ps/nm/km, performance degrades

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due to significant pulse distortion and subsequent reduction of SPM effect. Effective regeneration is obtained for both normal and anomalous dispersion fibres. In both cases, 2R performance improves as number of sections increases, up to 4 or 5 sections. Beyond that point, performance decreases firstly because of the accumulation of XPM induced timing jitter. Secondly, as optical power decreases after the first sections, SPM effect is reduced and does not compensate for HNLF dispersion induced pulse broadening.

We note that a Q factor improvement greater than 5 dB is obtained for fibre dispersion between 30 and 45 ps/nm/km and for 4 or 5 sections. In the following, we will consider the use of a HNLF with a dispersion of 40 ps/nm/km. Current developments for HNLF targets zero-dispersion-wavelength at 1550 nm in order to enhance the non-linearities. By contrast, for WDM regeneration, it is necessary to use dispersion management in order to avoid non-linear interchannel effects [5]. It should be noted that promising developments may lead to the realization of such positive-dispersion HNLF [12, 13].

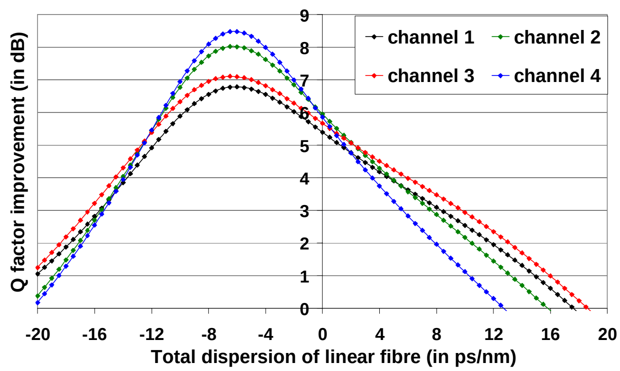


Fig. 7. Impact of the linear fibre total dispersion after 5 sections of 200 m of non-linear fibre (D=40 ps/nm/km) separated with 200 GHz bandwidth.

During propagation in the device, pulse broadening occurs due to the interaction between SPM induced non-linear chirp and fibre dispersion and to the succession of optical filters. The use of a linear fibre after the sections of HNLF enables to compensate for this effect [4]. Considering a regenerator with 5 sections, 2 GHz filter offset pet section, 20 dBm input power per channel and an input OSNR of 20 dB, quality factor improvements of the four channels are shown in Fig. 7 as a function of the total dispersion of the linear fibre. Optimum is found for a value of -6.5 ps/nm.

*3.2 Optical filter*

We here consider the impact of filter parameters likely to vary, namely the frequency shift and insertion loss per stage. Considering a regenerator with HNLF sections separated by 200 GHz bandwidth filters, we omit the linear fibre dispersion at the end of the regenerator for simplicity. We estimate the quality factor improvement averaged over the 4 channels, with an input OSNR of 18 dB, as a function of the frequency shift per section and for 1 to 8 sections of HNLF. As shown in Fig. 8, a performance greater than 5 dB is obtained for 4 and 5 sections and for a filter offset below 5 GHz (40 pm), which is compatible with current technology of fibre-Bragg-grating or thin film filters. For higher filter offset, optical power is strongly reduced by the successive filters, leading to reduced regenerator performance.

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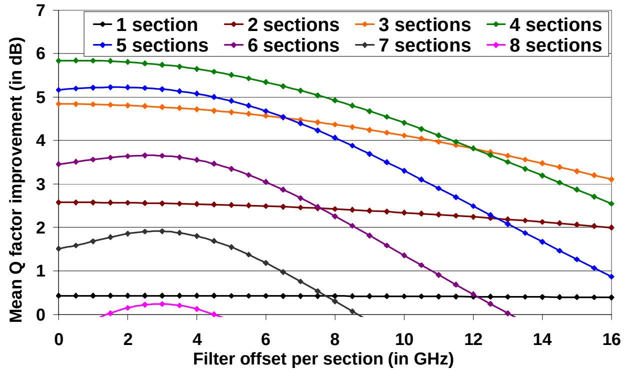


Fig. 8. Impact of the filter offset per section and the number of sections considering 200 m-long sections of HNLF (D=40 ps/nm/km) and 20 dBm input channel power.

As with all devices constructed from HNLF, insertion losses are a key aspect of the device performance [12]. To a certain extent, insertion loss may be lumped as part of the fibre propagation loss and accommodated by appropriate choice of stage length, launched power and non-linear coefficient [4]. To illustrate the sensitivity of the device to variation in insertion loss, we estimate the mean improvement averaged over the four channels as a function of the insertion loss and the input power per channel.

We here consider a regenerator with 5 sections of HNLF and 2 GHz filter offset per section. Figure 9 shows that the quality factor degrades by approximately 0.3 dB per 0.1 dB increase in insertion loss. We expect improved loss tolerance through further optimisation of device parameters considering non-zero insertion loss. For this particular design, we note that a performance greater than 3.5 dB is obtained for a realistic insertion loss below 1 dB. Note that, if photonic crystal fibre as the non linear medium [12, 14], insertion losses may be a limiting factor. However, recent developments suggest the possibility for low splicing losses [14]. We may also anticipate the fabrication of low loss fibre based filters where the evenescent field of a highly nonlinear fibre is accessed by side polishing [15].

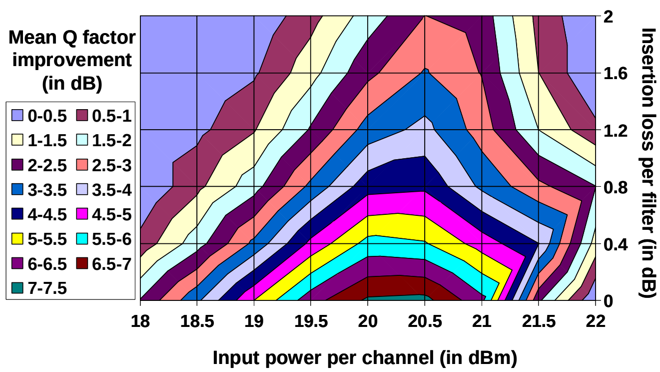


Fig. 9. Impact of the insertion loss per filter and channel input power considering 5 sections of 200 metres of non-linear fibre (D=40 ps/nm/km) separated with 200 GHz filters.

## 5. Conclusion

We have presented the design for a WDM regenerator based on quasi-continuous filtering operating on 4 channels at 40 Gbit/s with 600 GHz channel spacing. An improvement of more than 6.8 dB of the quality factor is obtained in simulations and confirmed by estimating the distribution of the receiver voltage. We have presented an analysis of the tolerance of the different physical parameters of the non-linear fibre and of the optical filters. Such a

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regenerator may be built using either negative or preferably positive dispersion non-linear fibre with a relatively large tolerance concerning the centre frequency of the optical filters along the device. We have shown that this regenerator performance relies on the insertion loss per filter; an average improvement of more than 3.5 dB is obtained for a realistic filter insertion loss of 1 dB. Furthermore, we have demonstrated that, despite the main limitation of interchannel cross-phase modulation, such a regenerator still presents very good performance for smaller channel spacing.

**Acknowledgment**

This work has been supported by the European Commission under TRIUMPH project IST-027638 STP and by Science Foundation Ireland under grants 03/IN.1/I340 and 06/IN/I969.

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