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Apodized chirped fibre Bragg gratings for dispersion compensation in a 10 Gbit/s IM-DD semiconductor laser system

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Abstract

Different fibre Bragg grating dispersion compensation schemes are studied for a directly modulated 1550 nm single-mode semiconductor laser signal through a standard nonlinear fibre link. The laser diode is simulated by its stochastic rate equations, while the nonlinear Schrödinger equation is used to simulate the propagation. The optimum length for dispersion compensation after transmission through 100 km SSM fibre is studied. Pulses with a FWHM of the order of 65 ps with any linewidth-enhancement factor are reconstructed using pre-compensation or post-compensation with an apodized 5.75 cm chirped fibre Bragg grating. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

In the course of the last years optical transmission at 1550 nm has become wide-spread, since the introduction of erbium-doped fibre amplifiers (EDFAs) has brought the idea of high capacity optical networks operating around this wavelength. The ultimate transmission limitations in systems operating at 1550 nm are laser chirp, chromatic dispersion, fibre nonlinearities and noise from the EDFAs [1]. Much effort has been invested in obtaining dispersion compensation schemes for standard fibres already installed. Three techniques stand out over the rest, attracting the most attention: dispersion-compensating fibre (DCF) [2], optical phase conjugation (OPC) [3] and fibre Bragg gratings [4–6]. Despite the advantage that it can compensate over the complete erbium bandwidth, DCF length (and thus, applicability) is limited due to its high germanium content and small core diameter, which lead to high optical nonlinearity and losses, while OPC is associated to a net shift of the central frequency of the signal, producing a significant waste of bandwidth. On the other hand, fibre gratings have attained a prominent role in optical communications, not only as dispersion compensation devices, but being susceptible of an amazing number of applications, including raw bandpass filtering, gain flattening in EDFAs, temperature and pressure sensing, frequency stabilization in lasers, soliton generation and pumping in fibre amplifiers [7–11]. Their crescent position is permanently supported by increasing precision and facilities in their manufacture, and by this time gratings as long as 1 m [12] have been obtained.

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The eye-opening of intensity modulated (IM) signals after propagation is critically dependent on the combined effects of group velocity dispersion (GVD), self-phase modulation (SPM) due to the Kerr effect and the laser chirp. This is well known for long-haul systems with direct detection (DD) [13]. Keeping this in mind, we have described pulse propagation by the nonlinear Schrödinger equation (NLSE). This equation takes into account both the effects of GVD and the nonlinearity of the fibre (SPM). In a general case like ours, numerics become necessary to solve the NLSE. We have chosen the split-step Fourier method. In modeling the optical pulses we have used the stochastic rate equations for the laser diode. This approach [13] is by far more realistic than the usual Gaussian [14] or super-Gaussian model [15,16]. Light pulses generated by directly-modulated semiconductor lasers present a modulation-induced frequency chirp [17], which increases their spectral content. Large frequency chirps play a decisive role in the eye-opening degradation of the pulses after propagation, since they interact with chromatic dispersion and SPM, distorting pulses beyond recognition. The aim of this paper is to study the chirp and dispersion compensation effects of different apodized chirped fibre Bragg gratings placed inside the fibre link, as well as to analyze the convenience of pre- and post-compensation schemes in our configuration.

2. Theoretical model

We assume that our optical source produces a biased IM signal with a NRZ format, which is numerically obtained from the noise driven rate equations [18,19], integrated for a slowly varying amplitude of the electric field E and carrier number N inside the laser cavity for a distributed feedback single-mode semiconductor laser (DFB SMSL), which read

$$\frac{\mathrm{d}E}{\mathrm{d}t}=\frac{1-\mathrm{i}\alpha}{2}\left(\frac{g(N-N_0)}{\sqrt{1+s|E|^2}}-\gamma_\mathrm{p}\right)\times E(t)+\sqrt{2\beta N}\xi(t) \quad (1)$$

$$\frac{\mathrm{d}N}{\mathrm{d}t}=\frac{I(t)}{e}-\gamma_\mathrm{e}N-\frac{g(N-N_0)}{\sqrt{1+s|E|^2}}|E|^2 \quad (2)$$

Table 1
Laser diode parameters used in the stochastic rate equations

Parameter	Value
Differential gain	3×10^{-8} ps^{-1}
Inverse photon lifetime	0.5 ps^{-1}
Inverse carrier lifetime	5×10^{-4} ps^{-1}
Threshold current	13.35 mA
Spontaneous emission factor	5×10^{-9} ps^{-1}
Carrier gain at transparency	1.5×10^{8}
Gain saturation	5×10^{-7} (adim.)
Linewidth enhancement factor	$2-8$ (adim.)

where $\xi(t)$ is a white Gaussian process taking into account spontaneous emission, g is the differential gain, γ_p the inverse photon lifetime, γ_e the inverse carrier lifetime, I the injected current, β the spontaneous emission rate, N_0 the carrier number at transparency, s the inverse saturation factor and α the linewidth enhancement factor. Typical values for these parameters can be found in Table 1.

We study pulse degradation over up to 100 km of SSM fibre taking into account GVD, laser chirp and SPM for a modulation of 10 Gb/s in the NRZ scheme. We consider different linewidth enhancement factors within a 2 to 5 range. The SMSL wavelength is 1550 nm and pseudo-random word modulation (PRWM) is used in the NRZ scheme. The propagation is governed by the generalized nonlinear Schrödinger equation [14], written

$$\mathrm{i}\frac{\partial E}{\partial z}=-\frac{\mathrm{i}}{2}\gamma E+\tfrac{1}{2}\beta_2\frac{\partial^2E}{\partial T^2}-\Gamma|E|^2E \quad (3)$$

where z is the propagation distance, T is the time in a reference frame moving at the group velocity, $E(z,T)$ is the complex slowly varying amplitude of the electric field, Γ is the nonlinear parameter that takes account of the optical Kerr effect, γ is the fibre loss and β_2 is the dispersion parameter. Typical values for these parameters can be found in Table 2. The split-step Fourier method is used to solve this equation.

The fibre grating is simulated making use of its coupled mode equations [20], which read

$$\frac{\mathrm{d}R}{\mathrm{d}z}+\mathrm{i}\delta R=-\mathrm{i}\kappa(z)S\exp\left(-F\left(\frac{z}{L}\right)^2\right) \quad (4)$$

$$\frac{\mathrm{d}S}{\mathrm{d}z}-\mathrm{i}\delta S=\mathrm{i}\kappa(z)R\exp\left(F\left(\frac{z}{L}\right)^2\right) \quad (5)$$

Table 2
Parameters used in the nonlinear Schrödinger equation

Parameter	Value
Nonlinear parameter Γ	2×10^{-3} km^{-1} mW^{-1}
Fibre loss	0.2 dB km^{-1}
Dispersion parameter	-16 ps^2 km^{-1}

where R and S are the progressive and regressive waves respectively inside the grating, $\kappa(z)$ is the coupling coefficient that varies according to the chosen apodization function, F is the grating chirp parameter, L is the grating length and δ is the frequency deviation with respect to the Bragg frequency at the center of the grating, which is chosen to be of 1550 nm at $z=0$. The variation of the grating period with z is commonly referred to as the grating 'chirp'. A linear chirp for the grating is needed in order to compensate for second order dispersion effects, since it will produce a linear time delay in the spectral profile of the filtered signal. This linear grating chirp leads to the quadratic dependence with z inside the exponential.

The system works in an anomalous dispersion regime. In such a regime, the laser frequency chirp leads to a continuous broadening and distortion of the pulses with the distance.

The coupled mode equations are solved using a fourth order Runge–Kutta numerical method. A 16th order Gaussian profile for the apodization function is chosen in order to improve the performance of the grating by eliminating any secondary lobes in its reflectivity function.

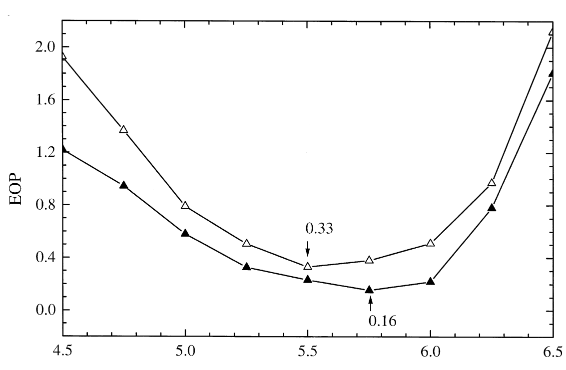

Fig. 1. Evolution of the eye-opening penalty with the grating length. Obvious differences arise between the cases of pre- (hollow triangles) and post-compensation (black triangles). The minimum EOP for the post-compensation case is 0.16, while 0.33 is achieved with pre-compensation.

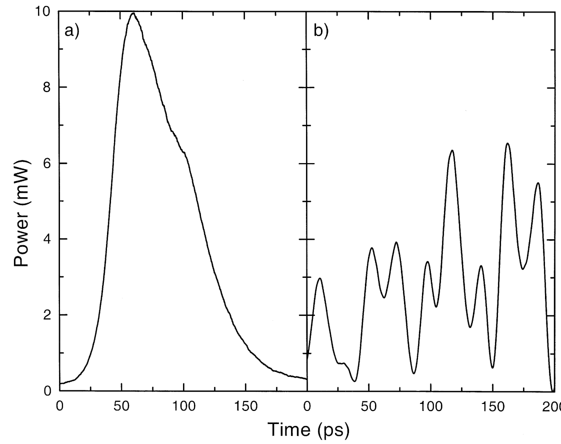

Fig. 2. (a) Isolated pulse with $\alpha=5$ at the laser output. (b) The same pulse after 100 km propagation.

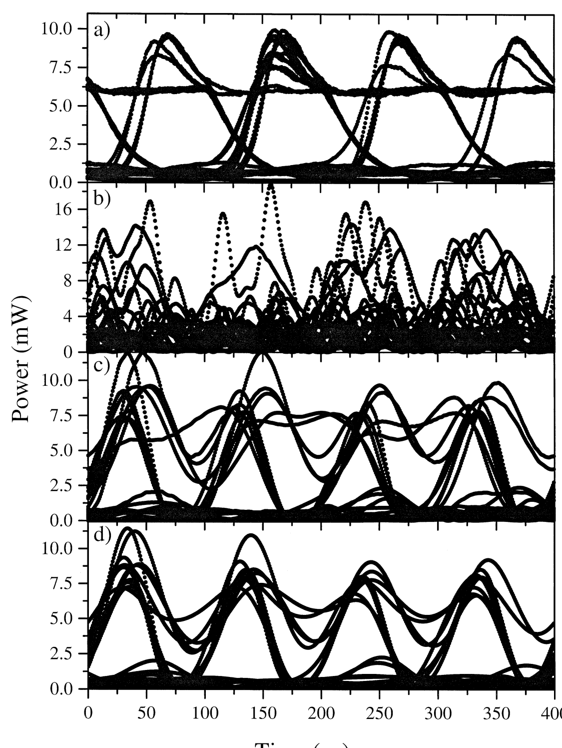

Fig. 3. Comparative eye-opening diagrams for a chirped signal with $\alpha=5$. (a) Laser output. (b) After 100 km without compensation. (c) After 100 km with pre-compensation. (d) After 100 km with post-compensation.

Table 3
Characteristics of the optimal fibre Bragg grating

Parameter	Value
Grating length (L)	5.750 cm
Coupling coefficient (κ)	1.639 cm^{-1}
Chirp parameter (F)	65
Period at the grating center (Λ_0)	5.32×10^{-5} cm
Maximum $\Delta(n)$	5.52×10^{-5}
Apodization function	$\exp\left(-16\left(\frac{z}{L}\right)^2\right)$

A good parameter to monitor the performance of an optical communication system is the eye opening penalty (EOP). The EOP is defined as $10\log(a/b)$, a being the maximal eye opening measured before the fibre link, and b its analogue after propagation. A high value of the EOP implies great degradation of the signal, and a low EOP is indicative of a good communication channel. Negative EOPs imply eye openings greater at the output of the fibre link than at the input, a fact that usually indicates pulse compression.

3. Grating performance

Given a fixed distance of propagation, a fibre Bragg grating exists which compensates for dispersion in a nearly exact manner by introducing a linear differential time delay in the spectral components of the signal, with contrary sign and similar magnitude to that induced by dispersion. In such a case, interaction between laser chirp, GVD and SPM totals to nearly zero, and great pulse reconstruction is achieved. We can adjust the optimal values for our fibre Bragg grating by means of minimizing the EOP of the signal. After some tests, we found that $\kappa L = 3\pi$ and $F = 65$ are proper parameters in order to obtain a high reflectivity and a nearly linear slope for the time delay of the fibre grating. With these param-

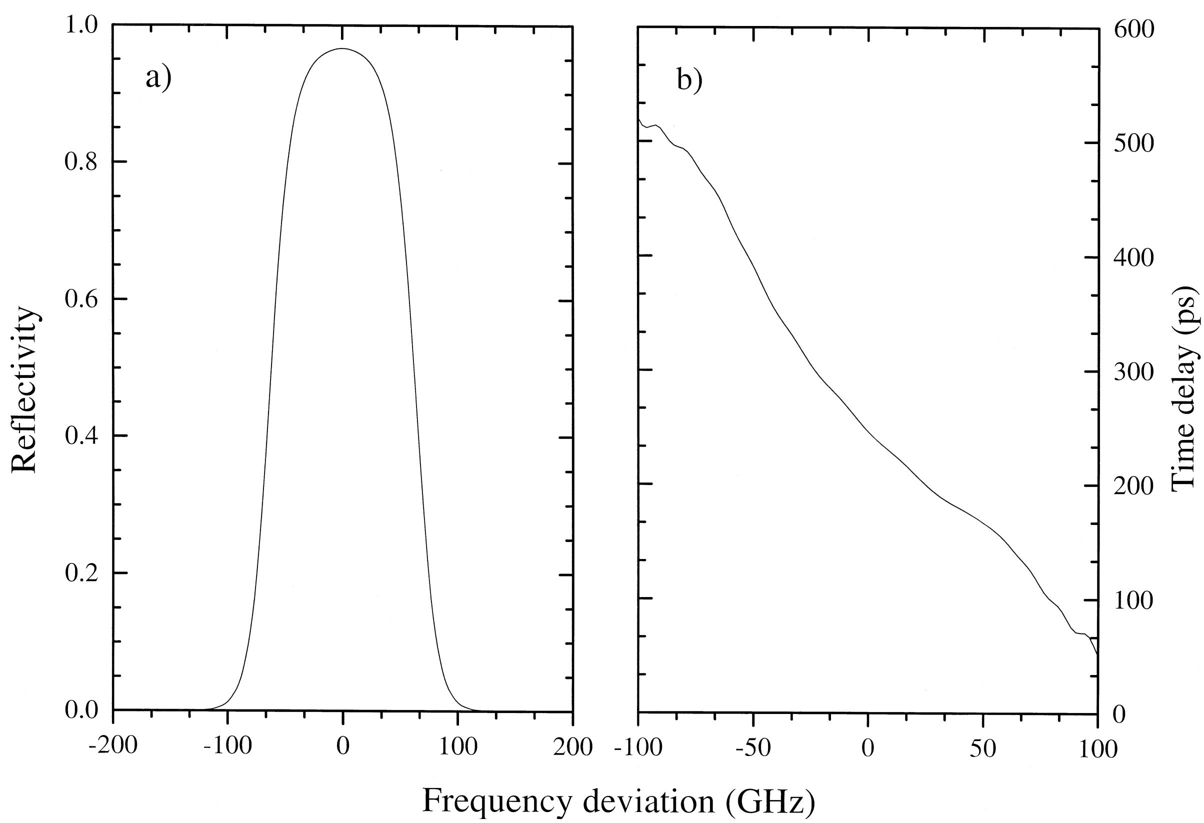

Fig. 4. Reflectivity (a) and time delay (b) of the 5.75 cm fibre Bragg grating.

eters fixed, we studied the EOP evolution with the grating length. Some differences appear between the post-compensation (grating placed at the end of the fibre link) and pre-compensation (grating placed just before the fibre input) cases, yielding post-compensation slightly better results in general. The minimum EOP is found in a post-compensation regime with a grating length of 5.75 cm, and its value is 0.16 (see Fig. 1), while the optimal length in pre-compensation is near 5.5 cm, where an EOP of 0.33 is achieved. The differences between both cases will be discussed later. It is worth noting that none of these optimal gratings has an exactly linear time delay profile, since the dispersion suffered by the pulses is not completely linear due to SPM and the nonlinear chirp of the laser signal.

As an illustration of the combined effects of laser chirp, fibre dispersion and SPM, an isolated pulse with $\alpha = 5$ is shown at the laser output in Fig. 2a. The same pulse is shown in Fig. 2b after 100 km propagation without dispersion compensation. As it arises from this figure, the destruction of the original signal by the combined effects of laser chirp, GVD and SPM is complete. An amplification factor has been applied to compensate for the losses due to propagation. The performance of the apodized chirped fibre Bragg grating can be evaluated through comparison between the eye opening diagrams of a grating-filtered signal and an unfiltered signal. Fig. 3a and Fig. 3b show the eye-opening diagrams corresponding to the same situations described in Fig. 2a and Fig. 2b. High power fluctuations appear in Fig. 3b due to signal distortion. This distortion is highly dependent on the initial frequency chirp [21]. Fig. 3c shows the eye-opening diagram of a pre-compensated signal after 100 km propagation. In this case the grating of 5.75 cm length was placed just before the fibre link (pre-compensation). The characteristics of this grating are summarized in Table 3, and its reflectivity and time delay are depicted in Fig. 4.

The eye-opening diagram in Fig. 3d corresponds to the case of post-compensation with the same grating. As it might be expected, some differences appear between Fig. 3c and Fig. 3d, and even though pre-compensation yields good eye-openings, post-compensated pulses appear less distorted, show clearer eyes and better EOPs.

The difference between the grating performances in the pre- and post-compensation schemes can be explained on the basis of the different propagation conditions in both cases. Dispersion is highly dependent on pulse width and profile both in time and frequencies. Nonlinear effects (SPM), which are partially balanced by GVD in an anomalous dispersion regime [14,22], depend on the power spectrum of the signal. Pre-compensation affects the initial signal before propagation and transforms it, giving it a high normal dispersion-induced broadening and also filtering it in frequencies. But if we change the initial characteristics of the pulses, they will be affected in a different manner by the various linear and nonlinear effects during propagation.

Thus, a grating that compensates in a nearly exact manner for dispersion in post-compensation will not have the optimal profile to compensate for the different dispersion effects that the pulse will suffer in the pre-compensation case. These effects are, anyway,

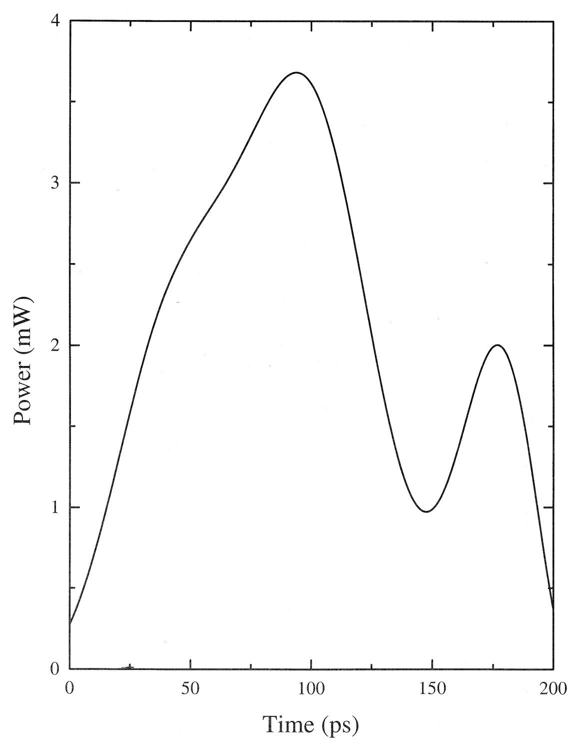

Fig. 5. Isolated chirped pulse with $\alpha = 5$ after pre-compensation with the 5.75 cm fibre Bragg grating

only slightly different in magnitude, and good reconstruction is obtained in both cases with any one of the two optimal lengths for the grating.

Attending to the minimum EOPs obtained using both schemes, it seems clear that post-compensation offers a slightly better global result (Fig. 1). We will see that this is mainly due to the interaction between pulses, for which the nonlinearities are responsible. A pre-compensated pulse exhibits two main differences with the original one. The signal has been given a high contrary dispersion-induced frequency chirp and is initially broadened in the time domain, due to the equivalent of 100 km normal dispersion through a standard fibre link the signal has suffered in its propagation through the fibre grating. A sample pre-compensated pulse with $\alpha = 5$ is shown in Fig. 5.

Dispersion-induced broadening (in this case, we should say compression, since under our conditions and for a 100 km propagation distance the signal is compressed due to the interplay between the grating-induced positive chirp and the anomalous dispersion regime of propagation) and dispersion-induced chirp are lower for broadened pulses [11]. Though the nonlinear effects are also lowered by the initial broadening (since power is lower in a broadened signal) the interaction between pulses is increased due to the initial overlapping between the broadened pulses. The anomalous GVD-induced chirp has been reduced, and so has been its lessening effect on the nonlinearities, which are responsible for pulse interaction. The main effect of pulse interaction is a slight variation of the distance between pulses that increases the EOP of the pre-compensated signal.

Both in pre- and post-compensation, and since the signal is initially chirped, the pulses suffer some compression in the minimum EOP gratings, as observed experimentally by Kawase et al. [23] for isolated chirped pulses. As an illustration, Fig. 6 shows the pulse from Fig. 2b reconstructed by means of the previously stated fibre grating in post-com-

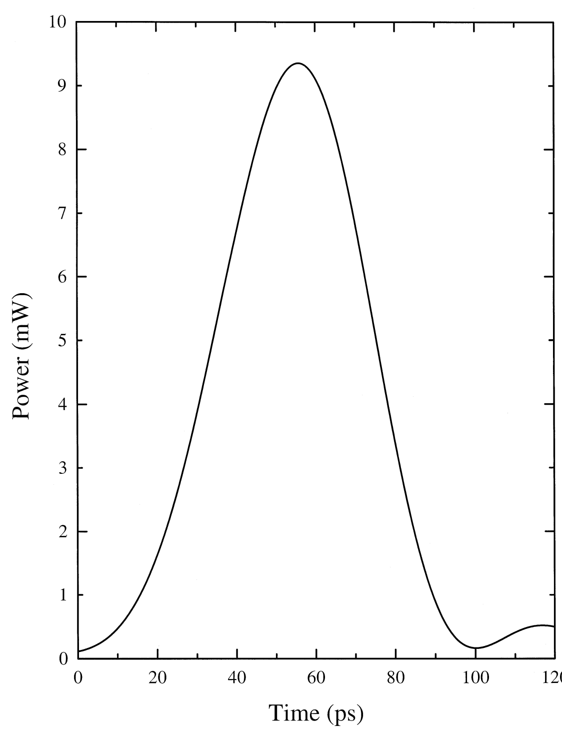

Fig. 6. Isolated chirped pulse with $\alpha = 5$ after propagation through 100 km of SSM fibre with post-compensation.

pensation. This pulse is narrower than the original pulse in Fig. 2a, though not much higher, since some power loss has occurred in the filtering process, and our amplification factor takes into account only fibre losses.

Even though the fibre Bragg grating offers nearly exact dispersion compensation, pulse degradation still grows with the linewidth enhancement factor. But if we stay close to the optimal configuration, good results will be obtained no matter how high the value of the linewidth enhancement factor is. As an extreme example, compensation for $\alpha = 8$ is illustrated in Fig. 7. Using the notation from Fig. 3, Fig. 7a shows the eye-opening diagram of the laser signal, Fig. 7b illustrates the degraded eye-opening diagram after 100 km propagation without compensation and Fig. 7c and Fig. 7d depict, respectively, the pre- and post-compensation cases. If we compare the results depicted in Fig. 7 with those appearing in Fig. 3 we can see that, as it could be expected, better results are obtained for $\alpha = 5$, but even for $\alpha = 8$ the fibre Bragg grating yields good eye-openings.

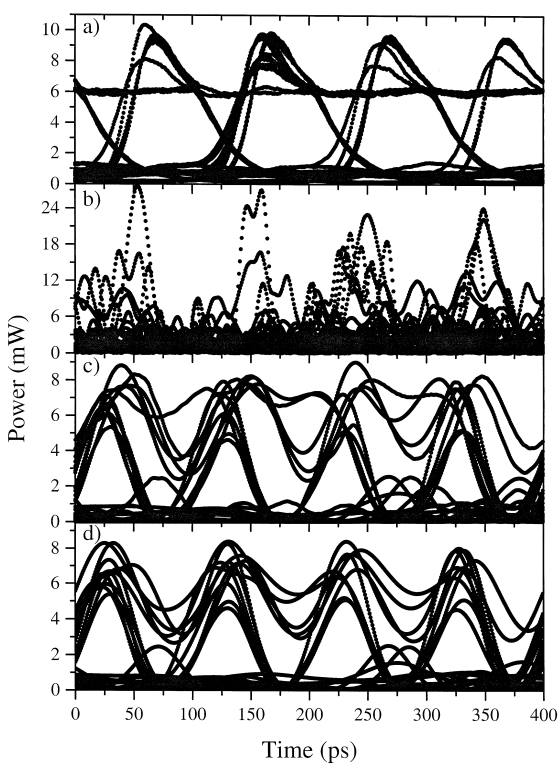

Fig. 7. Comparative eye-opening diagrams for a chirped signal with $\alpha = 8$. (a) Laser output. (b) After 100 km without compensation. (c) After 100 km with pre-compensation. (d) After 100 km with post-compensation.

4. Conclusions

We have numerically studied the performance of an apodized chirped fibre Bragg grating for dispersion compensation in an IM/DD 10 Gbit/s DFB laser system in the NRZ scheme over 100 km of SSM fibre. The fibre grating, either placed before or after the fibre link, reveals itself as a very good compensation device, achieving even better results than other methods previously tested in a similar system, such as optical phase conjugation and dispersion-shifted fibre [24,25]. As it could be expected for chirped pulses, the grating is able to yield some compression in order to increase the EOP.

The grating performance is in good agreement with experimental results [23,26,27]. As seen in the experiment carried out by Kawase et al. [23], the control of the chirp of the optical pulses may not be necessary, which agrees with the good pulse reconstruction that we achieve for both $\alpha = 5$ and $\alpha = 8$ with the same fibre Bragg grating. Our grating characteristics are similar to those of Hill et al. [27], but some differences arise, since our grating is optimized for compensation with a different signal and a slightly longer propagation distance. Williams et al. [26] deal with pulses of 1.8 ps duration at 908.5 nm, and thus no direct comparison may be established between their results and ours, but they point out that a linear time delay should not be the ideal one to compensate for dispersion in a system with SPM, being in good agreement with the time delay profile of our optimal fibre grating.

From our results we conclude that fibre Bragg gratings seem to be a very good option for dispersion compensation in already installed systems that are similar to the one depicted in this numerical study. The same properties of the fibre gratings here employed in dispersion compensation have lead recently to new applications for FBGs in soliton-based communication systems [28,29].

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