Reduction of intersymbol interference in grating compensated dispersion-managed soliton systems using nonlinear optical loop mirrors

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Abstract
We show the possibility of reduction of intersymbol interference in chirped fiber gratings compensated dispersion-managed soliton systems by the use of nonlinear optical loop mirrors. Our proposed method can achieve transoceanic transmission.

One of the important techniques in optical transmission is dispersion management. Many installed terrestrial transmission systems are not dispersion-managed (DM) and upgrading such systems to DM systems is an economic way to increase system capacity. A simple method to upgrade those systems is to insert lumped dispersion compensators at the amplification sites. Among the proposed dispersion compensating methods, the use of chirped fiber gratings (CFGs) appears as one of the most attractive method because of its compact size, large lumped dispersion, low insertion loss, and zero nonlinear effects. The typical length of CFGs for compensating 100 km of standard single-mode fiber is about 20 cm. It has been shown that solitons exist in DM fiber transmission systems utilizing ideal CFGs for dispersion compensation and the transmission speed can be up to 100 Gb/s [1]. Yamada et al. demonstrated transmission over 2,900 km for return-to-zero (RZ) formatted signals utilizing CFGs as dispersion compensator at 10 Gb/s [2].

However, CFGs have group delay ripples (GDR) which are caused by the imperfections in the grating fabrication process. The GDR introduces side peaks in the pulse profile as illustrated in Fig. 1. The pulse consists of a central peak and multiple side peaks. When the side peaks of a pulse overlap with its neighboring pulses, intersymbol interference (ISI) occurs which significantly degrades the transmission performance. In linear systems, the amplitudes of these side peaks grow linearly with the number of CFGs along the propagation distance [3]. We have shown that the use of DM solitons can suppress the growth of these side peaks [4] but residual side peaks still present and cause ISI.

Different grating fabricating methods were proposed to eliminate the GDR, but GDR remains. Komukai et al. succeeded to reduce the ripple amplitude to 3 ps [5]. Since the GDR remains exist in CFGs, it is important to find an effective way to solve the induced ISI. It has been demonstrated that nonlinear optical loop mirrors (NOLMs) can be utilized for 2R regeneration in DM fiber system compensated by dispersion compensating fibers [6]. We have shown that the DM fiber system compensated by CFGs can be incorporated with NOLMs to further reduce the amplitude of the side peaks [7].

In this work, we investigate the effectiveness of NOLMs in the DM soliton system compensated by CFGs with loss and gain. In Ref. [7], we modeled the GDR by a sinusoidal approximation and considered that the gratings reflectivity is ideal, i.e., lossless. Here, we model the CFG by solving the coupled-mode equations [8] for a more realistic model including the physical grating parameters, such as grating length, apodization profile, etc. In this model, the period and amplitude of GDR are changing along the grating reflectivity spectrum that has power loss. We study the system performance when the first side peaks (the nearest side peaks besides the central peak) are exactly located at the other signal pulses for a condition of maximum ISI. We found that DM systems using NOLMs can significantly increase the transmission distance by nearly 30 times when compared to that without NOLMs.

![Figure 1: Temporal pulse shapes in grating-compensated DM soliton systems with GDR, and without (dashed) and with (solid) NOLMs.](image-url)

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We consider a system with a dispersion map consisting of 40 km of fiber segment with a CFG inserted at the middle of the fiber segment. The dispersion, nonlinearity, and loss coefficient of fibers are 1.06 ps/nm/km, 2 km⁻¹W⁻¹, and 0.2 dB/km, respectively. The average lumped dispersion of the gratings is −39.2 ps/nm. For the coupled-mode equations, the CFG has a length of 2 cm, and we adopt a Gaussian apodization function. The grating reflectivity and delay spectra are shown in Figs. 2(a) and 2(b), respectively. The amplifiers are placed at the end of fiber segment and followed by an NOLM. Thus the amplifier and NOLM spacings are the same as the length of dispersion map, i.e., 40 km. In each NOLM, we use a 50:50 coupler and place an amplifier with a gain of 17 dB at one port of the loop to break the symmetry. The NOLM is constructed from dispersion-shifted fiber with loop length of 1 km and loss coefficient of 0.3 dB/km. A Gaussian filter is placed at the output port of the NOLMs to reshape the pulse and then followed by an attenuator to balance the extra gain in NOLMs.

In the simulation, we obtained stable solutions in the systems and found that the pulse widths are 5.71 ps (without NOLMs) and 5.06 ps (with NOLMs) for the same pulse energy (0.23 pJ) as shown in Fig. 1. We find that the side peaks separation is 100 ps and the amplitude of the side peaks is further reduced by ~65 dB using NOLMs. This reduction is done by the NOLM which acts as a nonlinear intensity filter. Nonlinear optical loop mirror will enhance the pulse peak power and strongly suppress the pedestals, i.e., the low power parts, containing the side peaks simultaneously. To examine the transmission performance of the systems without and with NOLMs, we launch the stable solution as a bit pattern [011110101100100] into the system. We choose a bit separation of 100 ps, which is same as the side peak separation so that the central peak of each pulse exactly overlaps with the first side peaks of neighboring pulse which results in maximum ISI. We obtain the Q-factors (minimum of intensity and timing Q-factors) of the pulses along the transmission distance without (dashed curves and inset) and with (solid) NOLMs and the data is shown in Fig. 3. The value \( Q = 6 \) (dotted line) corresponds to a bit-error-rate of \( 10^{-9} \). The transmission distance in the system with NOLMs (10 Mm) is 30 times longer than that without NOLMs (0.28 Mm). Without the NOLMs, energy exchange between the central and the side peaks of the pulses reduces the intensity Q-factor. We find that the timing Q-factor is dominant over the intensity Q-factor after 1 Mm in the system with NOLMs and it is caused by the asymmetric pulse spectra as shown in Fig. 1. At the locations just after CFGs, the power of the left and right first side peaks are unbalanced and respectively of −21.6 dBm and −27 dBm and it is due to the asymmetric delay spectrum of the grating profile as shown in Fig. 2(b).

In summary, we have shown that the use of NOLMs substantially enhances the system performance in grating-compensated DM soliton systems even the gratings have power loss, limited bandwidth and asymmetric group delay spectrum. The system achieves transoceanic propagation.

The authors acknowledge the support from the Research Grant Council of the Hong Kong Special Administrative Region, China, under Project PolyU5242/03E.

References