Effectiveness of nonlinear optical loop mirrors in chirped fiber gratings compensated dispersion-managed transmission systems

Y. H. C. Kwan,† K. Nakkeeran, and P. K. A. Wai
Photons Research Centre and Department of Electronic and Information Engineering, The Hong Kong Polytechnic University, Hung Hom, Hong Kong

P. Tchofo Dinda
Laboratoire de Physique de l’Université de Bourgogne, B.P. 47 870, Dijon, France
†Phone: +852 2766-4094, fax: +852 2362-8439, email: canny@eie.polyu.edu.hk

Abstract: We show that nonlinear optical loop mirrors can dramatically suppress the side peaks induced by the group delay ripples in chirped fiber gratings compensated dispersion-managed systems and significantly improve the system performance.

© 2005 Optical Society of America

OCIS codes: (190.4360) Nonlinear optics, devices; (050.2770) Gratings; (190.5530) Pulse propagation and solitons

1. Introduction

It is now well perceived that nonlinear optical loop mirrors (NOLMs) are a very useful lumped device for various applications, such as short pulse generation, optical switching, or transmission control in communication systems [1]. The NOLMs are specially attractive because of the relative simplicity of their configuration, and their size, which can be shortened using highly nonlinear fibers. This device has been shown to be highly efficient in transmission control operations such as the 2R re-generation (reshaping and re-amplification) in RZ dispersion-managed (DM) transmission systems using dispersion compensating fibers (DCFs) [2]–[5]. In general, a length of 18–20 km of DCFs is needed to compensate 100 km of single-mode fiber.

Another well-known dispersion compensator is the chirped fiber gratings (CFGs), which are particularly attractive because of their compact size (typically < 1 m long) and their ability to compensate higher order dispersion simultaneously. The major problem in using CFGs is the group delay ripples (GDR) which is formed during grating manufacturing processes. The GDR introduce side peaks (peaks besides the main peak) in the pulse profile as shown in Fig. 1(a). When these side peaks overlap with neighboring pulses, they lead to inter-symbol interference (ISI) and degrade the transmission system performance. In linear systems, the amplitude of these side peaks grows linearly with the number of CFGs along the propagation distance [6]. We have shown that soliton transmission, unlike in linear systems, can substantially suppress the growth of these side peaks [7]. But the side peaks, however, may still exist in many types optical transmission systems.

In this work, we propose to use nonlinear optical loop mirrors as an intensity filter to suppress the side peaks resulting from the GDR in CFGs. First we model the GDR by sinusoidal function and then we use real grating profile to study the effectiveness of NOLMs to suppress the side peaks. We demonstrate auto-soliton formation in a DM system in which the dispersion is compensated by CFGs with GDR and an NOLM is placed at every amplifier location. In addition, we study the effectiveness of NOLMs when the ripple period in CFGs randomly varies along the transmission line, which includes the amplifier noise in a 40 Gb/s DM system [8]. We show that the propagation can reach transoceanic distance when NOLMs are used to suppress both the amplifier noise and the side-peaks introduced from GDR.

2. System modeling

The pulse propagating in an optical fiber under the influence of the Kerr nonlinearity and varying dispersion is governed by the nonlinear Schrödinger equation. The gratings are located at the middle of the fiber segments. In the simulation, we will first model the GDR by a sinusoidal function and assume that the grating bandwidth is wider than the signal bandwidth [7]. Then to show the practical feasibility of NOLMs under real GDR, we will use the grating reflectivity and delay spectra from a chirped fiber grating produced by Redfern Optical Components as shown in Figs. 1(b) and 1(c), respectively.
3. Simulation results

We use a DM system to demonstrate the suppression of the side peaks formed by the GDR in CFGs. The DM system considered in our study is obtained by an analytical method [9], with map strength of 1.65 that minimizes the pulse-pulse interactions. The dispersion map consists of a fiber segment (length: \( \sim 10.3 \) km; dispersion: 1.62 ps/nm/km; nonlinearity: 2 km\(^{-1}\)W\(^{-1}\); loss coefficient: 0.2 dB/km) and a CFG. The grating dispersion is \( \sim 15.5 \) ps/nm. The GDR is modeled by a sinusoidal function with an amplitude of 5 ps, a period of 0.071 nm, and a phase of \( \pi \). The grating is located at the mid-point of the fibers and the amplifier spacing (of 41.3 km) is four times the map length as shown in Fig. 3(a). An NOLM is placed after each amplifier and the configuration is shown in Fig. 3(b). The NOLM consists of a 50:50 coupler and a dispersion-shifted fiber which has a length of 80 m, zero dispersion, nonlinearity of 4 km\(^{-1}\)W\(^{-1}\), and loss coefficient of 0.3 dB/km. An extra gain is introduced before the loop. The Gaussian filter (with bandwidth 0.88 nm) and the loss element placed after the NOLM (0.4 dB) are used to reshape the pulse and achieve the exact balance between the input and output pulse powers in the NOLMs. The in-loop attenuator is set to 22.4 dB.

Auto-solitons are formed by launching Gaussian pulse into the system. The action of NOLMs quickly stabilizes the pulse. Figure 2(a) shows the pulse shape before (dashed) and after (solid) the NOLMs. Note that the pulse shape before NOLMs is obtained before the extra gain. The pulse peak power and width before and after the NOLMs are almost the same. The results show that the NOLM induces a substantial reduction of the first side peaks (the peaks besides the central peak) by 38.4 dB.

Besides the sinusoidal modeling of the ripples, we report another simulation result which uses a realistic grating spectrum. It includes a limited bandwidth and reflectivity for the ripples. The amplitude of GDR is \( \sim 2 \) ps. We shift the center wavelength of the grating spectrum to 1550 nm and add an extra dispersion of \(-0.6 \) ps/nm for the designed dispersion map. Figure 2(b) shows the stable pulse comparison before (dashed) and after (solid) the NOLMs. The results show a significant pedestal suppression induced by the NOLMs, which is about 96.5 dB at the locations of the first side peaks.

3.1 Tolerance of NOLMs

Since it is impossible to fabricate two gratings with identical ripple period, the variations in the ripple period in CFGs can significantly affect the transmission performance. In this study, we examine the impact
of random variations of ripple period in the CFGs on the system performance using sinusoidal function to model the GDR. To model the practical situation, we change the ripple period in the gratings along the transmission line and include the amplifier noise with a noise figure of 4.5 dB in the system. In order to focus on the effect of ripple period variation, we choose a fixed ripple amplitude of 3 ps. The grating phase is π. The ripple period varies according to a normal distribution with a mean period of 0.06 nm and standard deviation of 0.0056 nm. Thus there is 68% probability that the first side peaks of any pulses will be located within a bit window.

We launch a 128-bit Gaussian-shaped pseudo-random sequence at a speed of 40 Gb/s. We study the DM system, with and without the NOLMs. The $Q$-factors of the system without (dashed) and with (solid) NOLMs are shown in Fig. 3(c). We use 50 sets of random sequence to calculate the $Q$-factors. The value $Q = 6$ (dotted line) corresponds to a bit-error ratio of $10^{-9}$. Since the ripple period changes from one grating to another, we show the eye diagram at 10.3 Mm in the system with NOLM (Fig. 3(d)). The pedestal suppression substantially enhances the system performance, with achievement of excellent transmissions over transoceanic distances, and there, the initial Gaussian pulses converge to the stable solutions under the action of NOLMs. The peak power of the pulses is stabilized. Figure 3(c) shows an excellent improvement in the system performance.

4. Conclusions

In summary, we have shown that using NOLMs in DM systems can substantially reduce the side peaks induced by the GDR in CFGs. The suppression is 38 dB in a sinusoidal form of group delay ripples and 97 dB in a realistic grating profile. The NOLMs can reduce the side peaks even in the presence of amplifier noise and a variation of ripple period in CFGs along the propagation distance. The system can achieve a good transmission performance over transoceanic distance. We believe that the NOLMs can be utilized for pedestal suppression in any systems having CFGs with GDR.

The authors acknowledge the support by the Research Grant Council of the Hong Kong Polytechnic University (Project PolyU5242/03E). P. Tchofo Dinda acknowledges the Hong Kong Polytechnic University for hospitality. We acknowledge Redfern Optical Components for providing the grating data.

References

5. Z. Huang, A. Gray, I. Khrushchev, and I. Bennion, ECOC 2004, Paper Th3.5.5.