Analytical design of 160 Gb/s dispersion-managed soliton systems compensated by chirped fiber gratings

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Abstract
We present an efficient and easy analytical method for designing grating compensated dispersion-managed systems. We also report a good transmission performance over 7,400 km of an analytically designed 160 Gb/s system.

Recently, dispersion management has emerged as an important technology in high speed optical communication systems. Among the many different dispersion compensating methods, the use of chirped fiber gratings (CFGs) is an effective one because of its compact size, high bandwidth times dispersion figure of merit, the capability to compensate higher order dispersion, low insertion loss, and the absence of non-linear effects. It has been shown that solitons exist in dispersion-managed (DM) fiber transmission systems utilizing ideal CFGs for dispersion compensation and the transmission speed can be up to 100 Gb/s [1].

The first step in setting up any DM fiber systems using chirped fiber gratings (CFGs) for dispersion compensation is to design the transmission lines in terms of the fiber, grating, and pulse parameters [1]. Up to date, there is no completely analytical method to find soliton solutions for CFG compensated DM soliton systems. We can however obtain the numerical soliton solutions by the commonly used numerical averaging method [2]. It is difficult, to use this method to obtain a stable solution for the desired pulse width and energy simultaneously. System engineers, however, are interested to design DM soliton systems for a given bit rate (hence the pulse width) and initial pulse energy. We can use the averaging algorithm to perform a massive study in map design. The process however, can be time consuming.

In this work, we present an efficient analytical method to design the dispersion map for a given pulse (energy and width) and fiber (dispersion and nonlinearity) parameters in any DM soliton systems compensated by CFGs. We study numerically the performance of a 160 Gb/s system designed using the proposed analytical method with launching a 32-bit pseudo-random Gaussian-shaped sequence and all the important higher-order effects.

One of the major defects in CFGs for dispersion compensation is the group delay ripples (GDR) which is formed during the grating manufacturing process. We assume that the pulse bandwidth is much larger than the ripple period of GDR in gratings, so that we can neglect the effect of GDR [3]. For the analytical design, we consider a dispersion map that consists of a segment of fiber with the CFG placed at the middle of the fiber. Using Gaussian ansatz in the variational analysis of the nonlinear Schrödinger equation [4], we obtain the map length in a lossless system as

\[ L = 2G - \left[ \gamma \beta E_0 \ln(4\alpha_3 x_3 - 2\sqrt{2} \gamma E_0)/c \right], \]

where \( G = \left[ \sqrt{G} + \gamma \beta E_0 \ln(2\sqrt{2} \gamma E_0 + 4\alpha_3 x_3 - 2\sqrt{2} \gamma E_0)/c \right], \)

\( R = 2\alpha_3 x_3 - 2\sqrt{2} \gamma E_0 x_3 - 4\beta^2. \)

The parameter \( \beta \) is the fiber dispersion, \( \gamma \) is Kerr coefficient and \( c = 2\beta^2 x_3^2 - 2\beta \gamma E_0 x_3 - 2\frac{x_3}{x_3 - 1/2} \). Here \( E_0, x_3 - 1, \) and \( x_3 \) are respectively the energy, minimum, and maximum width (at the input of gratings) of the pulse. The required grating dispersion is

\[ g = 2x_3^4 x_4^2 + x_3^4 / (4 + x_3^4 x_4^2), \]

where

\[ x_3 = \sqrt[3]{\alpha_3 - \frac{1}{2}} / x_3. \]

The method for designing the lossless DM fiber systems can be utilized in the lossy DM soliton systems. For high speed communications, short dispersion maps (map length less than amplification span) are needed. To get the map lengths for different dispersion maps within an amplification span, we follow these steps [4]:

1. Calculate the fiber length and grating dispersion of each section using the desired pulse and fiber parameters as a lossless system. The input energy of each section is that after all the previous sections.

2. Adjust the average dispersion of each section by modifying the grating dispersion such that the ratio between the energy and the average dispersion of the respective section are the same.

3. Average all the dispersion map lengths and gr-
ing dispersions respectively, within an amplifier span to obtain the final map length and grating dispersion.

We apply the analytical method to design a 160 Gb/s transmission system. We consider a fiber dispersion of 1 ps/km/nm, nonlinearity of 2 km−1W−1, loss of 0.2 dB/km, input width of 1.25 ps, and Gaussian energy of 0.038 pJ. We choose the map strength to be 1.65 for minimum pulse interaction which corresponds to a maximum FWHM of 1.9 ps. Using these input parameters, we calculate the lossless dispersion map length L as 1.02 km. The final map length and grating dispersion are calculated as 1 km and −1 ps/nm, respectively [4]. The amplifier spacing is 40 km. To illustrate the effectiveness of our method for the lossy DM soliton system, we use direct numerical simulations to find the periodic DM soliton solutions and compare the simulated results with the analytical results. Figure 1 shows the Gaussian ansatz (solid curve) and the numerical solution (dashed curve) after the amplifier location in the system. The pulse width of the stable solution after amplifier location is 1.28 ps. It shows that our analytical design is very useful for designing grating compensated DM soliton systems with a given pulse (energy and width) and fiber (dispersion and nonlinearity) parameters.

We use 50 sets of random sequence to model amplifier noise with noise figure 4.5 dB. For high speed transmission, we include the third-order dispersion of 0.1 ps³/km in the fiber and −0.1 ps³ in the gratings since the grating can compensate the third-order dispersion [5]. We also include the intrapulse Raman scattering with the response time of 3 fs. An upshifted filter is placed after each amplifier to reduce the effects of third-order dispersion and intrapulse Raman scattering [6]. The initial pulses are Gaussian in shape. Figure 2(a) shows the intensity (solid) and timing (dashed) Q-factors along the propagation distance. The value $Q = 6$ (dotted line) corresponds to a bit-error ratio of $10^{-9}$. The eye diagram at which $Q = 6$ is shown in Fig. 2(b). The figures show an excellent performance over transoceanic distance using the analytically designed grating compensated DM soliton systems. Moreover, it demonstrates the utility of our analytical design in high-speed long-haul CFG compensated optical fiber transmission systems.

In summary, we have presented an efficient method for designing grating compensated DM soliton systems. We have also shown that this analytical method can be applied for 160 Gb/s data transmission.

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References