# Short pulse propagation in dense dispersion compensated systems

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The short Hermite-Gaussian optical pulse transmission over 1440 km in a dense dispersion compensated system is investigated based on numerical simulation. In the simulation, compensation is made not only for the group-velocity dispersion but also for the third order dispersion. It is demonstrated that the pulse with reasonably lower power can propagate steadily in net zero, positive and negative dispersion system.

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Dispersion managed communication systems have become increasing important recently, as a result of their excellent performance characteristics, such as simplicity, easiness of upgrading installed fiber lines, large capacity, and long distance. Many research papers focus on such systems in experiments and theories[1−6]. Recent experimental, numerical and analytical studies have demonstrated that periodic dispersion compensation can be used to significantly improve the performance of soliton transmission systems[7].

In conventional dispersion managed soliton (DMS) systems, the dispersion managed (DM) period $z_p$ is the same as or longer than the amplifier spacing $z_a$, thus the pulse width oscillates with significant magnitude and the interaction with neighboring pulses is strong. This interaction limits the transmission capacity. Thus, there exists a major limitation on transmission rate per channel in such systems caused by interaction between neighboring pulses. Dispersion management that is too strong could lead to systems performance even worse than conventional soliton systems. To overcome this limitation, a dense dispersion managed soliton (DDMS) system is recently proposed[7,8]. In this system, there are $n$ ($n > 1$) DM periods existing within one amplifier spacing. Because the periodicity is so small, the interaction between neighboring pulses becomes smaller, and the pulse approaches to an ideal soliton. An importance of solitons in DDMS was that it could reduce power, compared with conventional DMS. In conventional soliton systems of high power and short pulse width, communication could not be achieved[9].

As to DM communication systems, Turitsyn *et al.* developed a systematic method to describe the dynamic of the self-similar core and no-similar oscillatory tail of the DM pulse using an orthogonal set of chirped Hermite-Gauss (H-G) function[4,10]. In this paper, to accurately describe the communication of the oscillatory tails of pulse in DDMS, the pulse is represented in terms of the complete basis of the chirped H-G orthogonal functions. In previous research, H-G pulse in DM system was studied with only the group-velocity dispersion (GVD) effect. Since the width of pulse represented in this paper is short, we not only consider GVD effect on H-G pulse, but also make compensation for the third order dispersion (TOD) in DDMS systems. As we know, the optical pulse width becomes very narrow, the effects of TOD can not be neglected[11]. It is well known that TOD of fibers influences negatively transmission performance. Such effects are creation of asymmetry of the profile of DM pulse and generation of continuum radiation[12,13].

In this paper, we give a numerical simulation of stationary propagation of the DDM pulse that is presented as an infinite sum of certain H-G harmonics. We will investigate its transmission over 1440 km, and demonstrate that the pulse can achieve stable transmission in zero, positive and negative net dispersion, while not only the GVD but also the TOD is compensated.

The evolution of a pulse propagated in an optical fiber with loss and weak kerr nonlinear is described by nonlinear Schrödinger equation

$$i\frac{\partial u}{\partial z} - \frac{1}{2}\beta_2(z)\frac{\partial^2 u}{\partial \tau^2} + \frac{i}{6}\beta_3(z)\frac{\partial^3 \Phi}{\partial \tau^3} + \gamma|u|^2 u + \frac{i}{2}\alpha u = 0, \quad (1)$$

where $z$ is the propagation distance, $\tau$ is the time in the group-velocity frame, $\beta_2$ is the GVD, $\beta_3$ is the TOD, $\gamma$ is the Kerr nonlinear coefficient, and $\alpha$ is the loss coefficient.

We write $\beta_2$, $\beta_3$ as functions of $z$ to account for the change of these parameters from fiber to fiber.

As far as the optical fiber concerned, if $P_0$ is the input power, the transmission power of the fiber is $P_T = P_0 \exp(-\alpha L)$, where $\alpha$ is the loss coefficient, namely loss coefficient of the optical fiber, and $L$ is the length of the optical fiber. So the loss coefficient is $\alpha = -\frac{1}{L}\ln\left(\frac{P_T}{P_0}\right)$.

Let $u = \exp(-\alpha z/2)\psi$, we can obtain

$$i\frac{\partial \psi}{\partial z} - \frac{1}{2}\beta_2(z)\frac{\partial^2 \psi}{\partial \tau^2} + \frac{1}{6}\beta_3(z) i\frac{\partial^3 \psi}{\partial \tau^3} - \gamma'(z)|\psi|^2\psi = 0, \quad (2)$$

here, $\gamma'(z) = \gamma\exp(-\alpha z)$.

The pulse can be represented in terms of the complete basis of the chirped H-G orthogonal function. In this paper it is assumed to be H-G pulse

$$\psi = \sqrt{p}\sum_{0}^{N} a_n(z)\mathrm{e}^{i\delta_n(z)}H_n(x)\mathrm{e}^{-\frac{x^2}{2}}, \quad (3)$$

where $x = \frac{\sqrt{2}\tau}{T_0}$, $a_n(z)$ and $\delta_n(z)$ are the coefficient and phase of $n$ order of H-G optical pulse, respectively, $H_n(x)$ is Hermite polynomial, $T_0$ is the pulse width, and $p$ is related to the peak power $p_0$ of pulse.

Because the effect of TOD can be become quite appreciable especially as the width of pulse become shorter and shorter. We need not only compensate the GVD but also compensate the TOD. This can be achieved by choice of fiber sections whose dispersion slopes compensate one another. To the second dispersion, we choose the value of path-averaged second dispersion to be zero, abnormal or normal.

Let us examine a transmission line composed of periodic alternating fiber sections and lump amplifiers, where one amplifier spacing constitutes of $n$ DM periods. The nonlinearity in both segments is, at first, assumed the same. Parameters of the GVD and TOD are listed in Table 1. The dispersion compensation length is 12 km. The amplifier spacing is 120 km and it consists of 10 DM periods. We simulated H-G optical pulse transmission about 1440 km, which consists of 12 amplifier spans. The pulse width of H-G pulse $T_0$ = 1.8 ps, the Kerr nonlinear coefficient and the loss coefficient of fiber are $\gamma$ = 1.27 W/km and $\alpha$ = 0.046/km, respectively. The result of numerical simulation of H-G optical pulse propagation in DDM systems is shown in Figs. 1 − 4 when net dispersion is zero.

Figure 1 shows that the evolution of the coefficient and the phase of H-G optical pulse along the fiber link, and the peak power is $p_0$ = 1.45 mW. It can be seen that variations of the coefficients and the phase of the H-G optical pulse along the fiber link are rapid. The rapid oscillations are due to dispersion. We can see that these coefficients and phases of H-G optical pulse have nearly the same values at beginning and ending point of each compensation line. Not only in zero net dispersion but also in negative net dispersion and positive net dispersion, H-G optical pulse can propagate steadily. The concrete parameters are shown in Table 1. In negative net dispersion, the peak power of pulse $p_0$ = 1.69 mW is higher than that in the zero net dispersion, and the net dispersion is exactly blanched by the weaker nonlinearity. At positive net dispersion, the peak power $p_0$ = 1.20 mW is the lowest. After all, the peak power at DDMS systems can be smaller.

**Table 1. Three Kinds of Combination About the GVD and TOD in Three Segments of a Dispersion Compensation Period**

| | $L_1$ (3 km) | | $L_2$ (6 km) | | $L_3$ (3 km) | |
|---|---|---|---|---|---|---|
| | $\beta_2$ (ps$^2$/km) | $\beta_3$ (ps$^3$/km) | $\beta_2$ (ps$^2$/km) | $\beta_3$ (ps$^3$/km) | $\beta_2$ (ps$^2$/km) | $\beta_3$ (ps$^3$/km) |
| (a) | −16 | −0.12 | 16 | 0.12 | −16 | −0.12 |
| (b) | −16.05 | −0.12 | 16 | 0.12 | −16.05 | −0.12 |
| (c) | −16 | −0.12 | 16.05 | 0.12 | −16 | −0.12 |

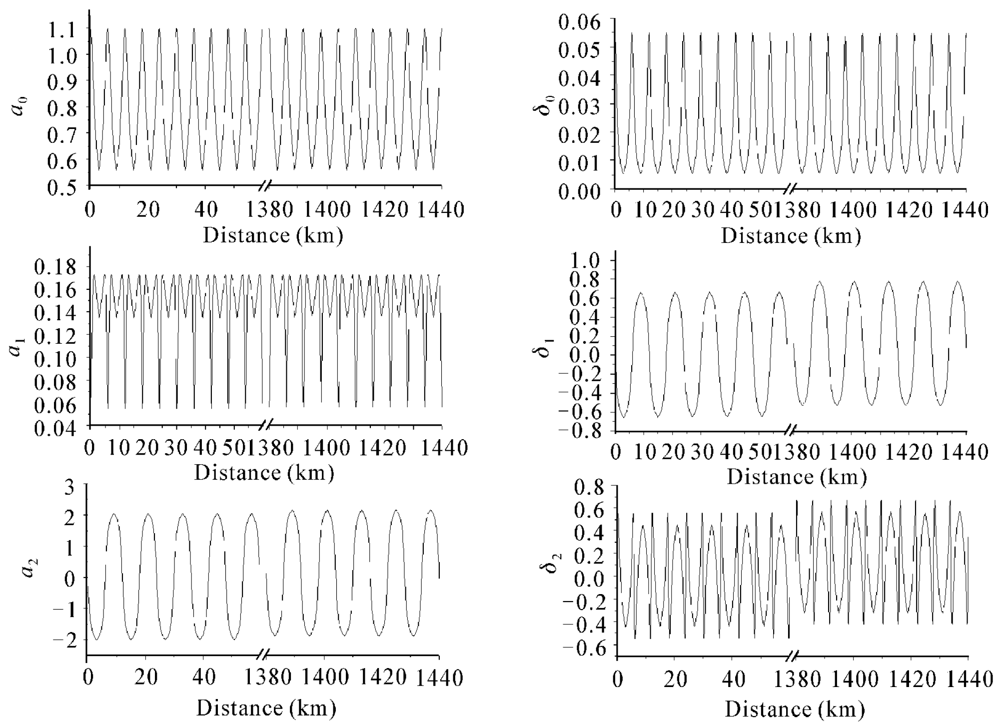


Fig. 1. The evolutions of the coefficient and the phase of H-G optical pulse along the fiber link.

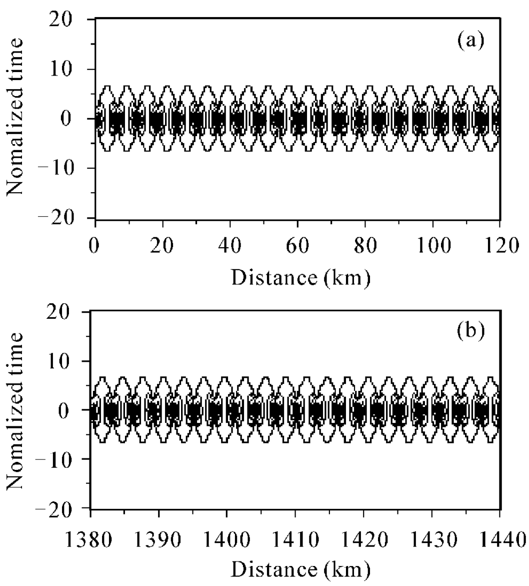


Fig. 2. The contour plot of the peak power of pulse for the first and the last amplify length.

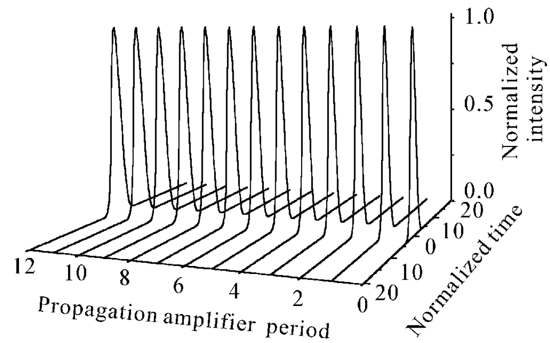


Fig. 3. The shape of H-G optical pulse at end point of every amplify length of fiber link.

Figure 2 shows that the contour plots of the peak power of pulse for the first and the end amplify length. It can be seen that the pulse stretches and compresses as it propagates through one period. The pulse is experienced breathing oscillation of the width during propagation. The result is not surprise because the compensation length $L$ is small and it can be seen that the width has the same value at the beginning and at the end of every compensation units. It can be seen that the pulse stretches and compresses periodically and it propagates steadily. We can see that the pulse can keep its shape well at the end of each amplify spacing. Figure 3 shows that the shape of H-G optical pulse at the end of every amplify spacing of fiber link. It illustrates that the pulse can propagate steadily in these DM fiber systems. Figure 4 shows that the comparison between the input optical pulse and the output pulse after 1440 km propagation. We can see that the pulse width and shape of output pulse are nearly the same as that of the input pulse, but the peak power of the output pulse is lower

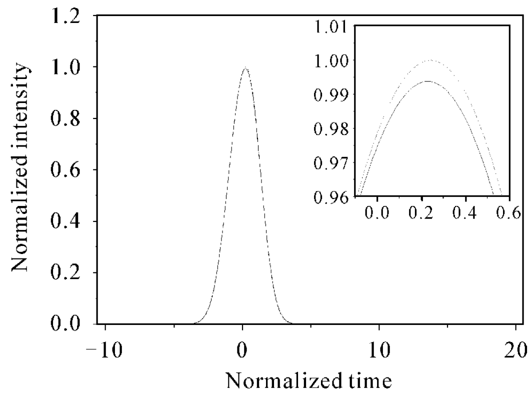


Fig. 4. The comparison between the input pulse and the output pulse at propagation distance 1440 km. The solid line is the output pulse and the dotted line is the input pulse.

than that of the input pulse as the loss exists in the fiber link. Therefore, from these results we can see that in such a dense dispersion compensation system, stable H-G optical pulse can propagate steadily without any distortion.

In conclusion, we have identified that the H-G optical pulse with lower peak power can propagate steadily in DDM systems with net zero, positive and negative dispersion. In the paper, not only is the compensation of the GVD taken into account, but also the compensation of the TOD.

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