# The characters of dense dispersion managed soliton in optical fiber transmission systems

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The properties of ultra-short dense dispersion-managed soliton (DDMS) in optical fiber links are investigated. They show some excellent characters, such as, reducing pulse's breathing extent greatly, facing fewer mutual interactions and tolerating larger local dispersion. In general, DDMS is more stable than a conventional dispersion-managed soliton in high-capacity systems. Excessively dense dispersion compensation is more suitable for systems with weak nonlinear effect.

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Dispersion-managed soliton (DMS) plays an important role in soliton-based fiber optic communication systems because it offers the following significant advantages: possessing higher pulse energy than conventional solitons in a uniform fiber with the same pulse-width and path-averaged dispersion, strongly reducing four-wave-mixing effect between wavelength division multiplexed signals, being less influenced by Gordon-Haus timing jitter induced by the noise of amplifier. The effectiveness of dispersion management at 10, 20, and 40 Gb/s has been demonstrated in several laboratory experiments[1−3] on various dispersion maps. However, a system with high bit rates of 100 Gb/s and above in a single channel requires denser pulse packing and, consequently, shorter soliton-widths. Under this condition, some new factors certainly degrade the performance of system, such as, higher-order dispersion, polarization-mode dispersion (PMD), interaction between neighboring optical pulse and so on. Recently, some researches demonstrate that after second-order dispersion is compensated, third-order dispersion compensation[4] and PMD compensation[5] are indispensable for high-speed optical communication systems. In conventional dispersion management technique, where the dispersion compensation period $L_c$ is longer or equal to the amplifier spacing $L_a$, significant adjacent pulses overlap and interaction worsen the performance of high-capacity systems. In order to reduce the interaction of neighboring pulses, short-scale dispersion compensation technology ($L_a > L_c$) receives attractive attention[6−8] and shows some excellent advantages.

Current fiber technology makes short-period dispersion management become realizable, as a fiber with alternating sign dispersion can be manufactured in a continuous draw without splicing. Even dispersion map periods as short as 1 km can be readily achieved and higher-order dispersion compensation can be incorporated in the fiber design. So, fiber manufacture technology has already offered the feasibility of realizing high-capacity communication.

Some theoretical results show that DMS can stably propagate not only in net anomalous dispersion region, but also in mean-zero dispersion and net normal dispersion region[9]. In this paper, we fabricate a fiber using zero-path-averaged dispersion about second- and third-order dispersion with opposite signs of dispersion. Because chirped signal is proved to be one optimal kind of optical signals code for high-bit-rate DM transmission[10,11], we make a short pulse quasi-stable transmit in dispersion-managed fibers by optimizing optical pulse initial frequency chirp. By means of numerical analyzing propagation of optical pulse, we find that denser dispersion management brings less breathing of optical pulse. As a result, the overlap and interaction between adjacent pulses are reduced greatly. Thus the space between neighboring pulses can be shorten evidently and the transmission capacity can be increased greatly. Furthermore, DDMS can tolerate higher local dispersion. This is very useful in wavelength division multiplexed systems to avoid employment of lower dispersion fiber which will bring the effect of four-wave mixing effect among different channel signals. On the other hand, we find that under the same pulse-width and local dispersion, DDMS needs lower power than conventional DMS. DDMS is very suitable for optical transmission systems with weak Kerr nonlinearity.

Short pulse propagation in a fiber is governed by the nonlinear Schrödinger equations[12]

$$i\frac{\partial A}{\partial z} - \frac{1}{2}\beta_2(z)\frac{\partial^2 A}{\partial T^2} + \frac{i}{6}\beta_3(z)\frac{\partial^3 A}{\partial T^3} + \gamma|A|^2 A = \frac{i}{2}(-\Gamma A + gA) + \tau_R A\frac{\partial |A|^2}{\partial T^2}, \quad (1)$$

where $A$ is the slowly varying amplitude of the pulse envelope and $T$ is measured in a frame of reference moving with the pulse at the group velocity $v_g$ ($T = t - z/v_g$). $\beta_2(z)$, $\beta_3(z)$ and $\gamma$ stand for second-, third- order dispersion parameters and nonlinear parameter responsible for self-phase modulation, respectively. $\Gamma$ and $g$ account for the fiber loss and gain produced by the amplifier, respectively, and $\tau_R$ is relevant to soliton Raman self-frequency shift coefficient induced by SRS. For the case of lumped amplifiers periodically inserted at $z = nz_a$ for $n = 1, 2, 3, \cdots, N$, the gain $g(z)$ is given by

$$g(z)A(z) = \sum_{n=1}^{N} a_n\delta(z - nz_a)A(z - 0).$$

It compensates all loss of fiber in an amplified period distance. Split step Fourier-transform method[12] is used to describe the evolution of optical pulse.

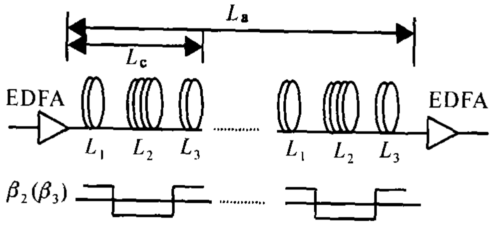


Fig. 1. DDMS fiber system.

We construct a dense dispersion-managed optical fiber transmission system shown in Fig. 1. There are three different non-zero dispersion-shifted fiber (NZDSF) sections in a symmetrical dispersion compensation cell. The length of middle section is twice as long as the first or the third ones, and its dispersion is opposite to the other sections for both second- and third-order dispersion. According to above demand, the net dispersion is zero-path-averaged in every dispersion-managed cell. Due to the effect of fiber loss, the optical signals must be amplified after propagating several dispersion compensation cells. In our system, a lumped erbium-doped fiber amplification compensates all loss during an amplification period distance. A Gaussian optical pulse $A(0,t) = \sqrt{P_0}\exp[-(1+iC)t^2/2T_0^2]$ with $T_0 = 1$ ps ($T_{\mathrm{FWHM}} = 1.665$ ps) is employed as input signal. The following optical fiber system parameters are used: an amplifier spacing, $L_a = 40$ km; loss, 0.22 dB/km at the operating wavelength near 1.55 $\mu$m; $\gamma$, 1.27 km$^{-1}$W$^{-1}$; the absolute value of second- and third-order dispersion parameters in each section fiber, $|\beta_2| = 0.5$ ps$^2$/km, $|\beta_3| = 0.1$ ps$^3$/km, respectively; the peak power of $P_0$, 1 mW; $\tau_R$, 3 fs. In order to describe the dense degree of the dispersion management, the parameter of $n = L_a/L_c$ is introduced, which means the number of dispersion compensation cells per amplifier spacing of $L_a$. We vary the parameter $n$ by changing the length of dispersion compensation cell and keep the amplifier spacing constant.

In order to understand some significant characters about DDMS, we investigate single soliton's breathing process and interaction between two neighboring pulses (5 ps code space, corresponding to 200 Gb/s transmission rate) under different dense degrees with $n = 2$ and 10. Figure 2 shows that the evolution of the pulse-width across $L_a$ is highly regular, with a breathing ratio of approximately above 6 : 1 at $n = 2$ (breathing ratio is the ratio between the maximum and minimum pulse-widths), but less than 1.2 : 1 at $n = 10$. We can also learn from the contour maps, the interaction between neighboring pulses can be reduced greatly when dispersion-management degree become larger. The interaction can hardly be observed for $n = 10$. Under the same local dispersion parameters and system power, denser dispersion-managed soliton exhibits excellent performance in high capacity transmission system.

Increasing the local second-order dispersion of each section in every cell, $|\beta_2| = 2$ ps$^2$/km is used, and other parameters are similar to the former. As shown in Fig. 3, DDMS's breathing ratio approximately becomes 2.4 : 1 for $n = 10$. Though optical pulse experiences larger breathing in a cell, the interaction between neighboring optical pulses is still very small. As a result, good transmitting performance is kept. For a system of 200 Gb/s, it is necessary to use a pulse interval of only 5 ps. In order to look into the long distance transmitting properties of

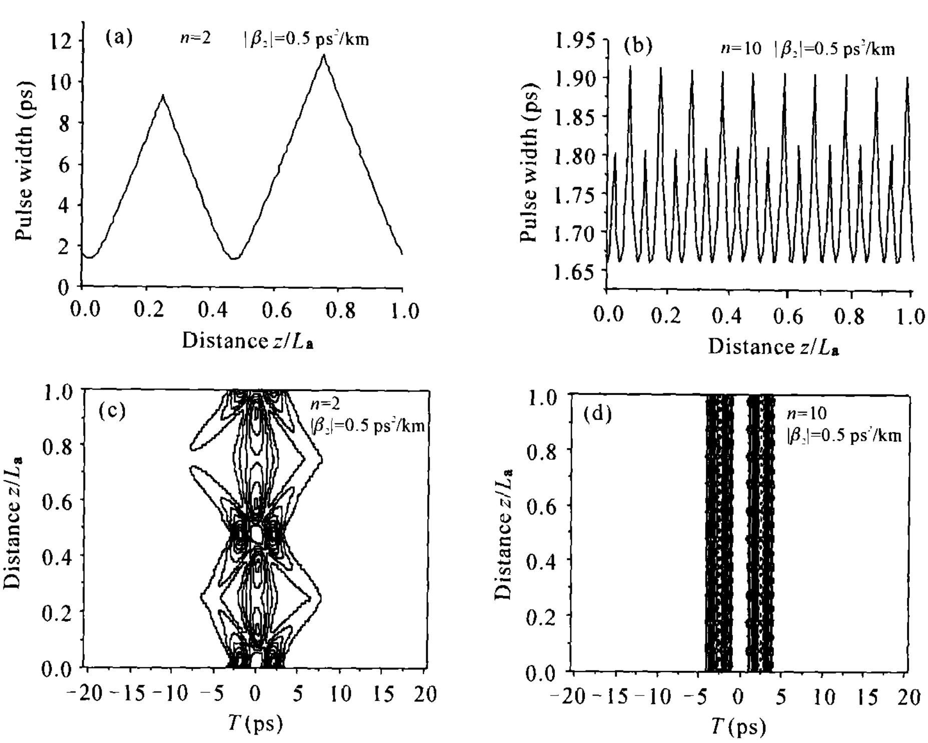


Fig. 2. Evolution of the DDMS's full width at half-maximum (a, b) and contour maps (c, d) of a pair solitons along the first cell under different dispersion-managed ratios $n = 2$ (a, c) and 10 (b, d). Amplification distance, 40 km; dispersion-compensation periods, 20 and 4 km respectively; the absolute value of second- and third-order local dispersion, 0.5 ps$^2$/km and 0.1 ps$^3$/km.

high-bit rate system, we use a 64-bit pseudorandom bit sequence in numerical simulation. The four-bit-wide "eye diagram" (unfiltered) after transmitting over 2000 km with $|\beta_2| = 2$ ps$^2$/km is shown in Fig. 4. From the eye diagram, we can see that, good property of system is still maintained under higher local dispersion. After using denser dispersion-managed map, the system can tolerate larger local dispersion parameter and keep excellent transmission performance.

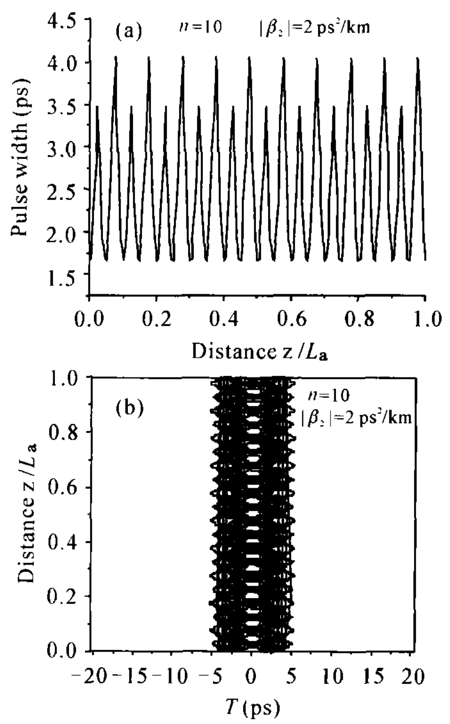


Fig. 3. Evolution of the DDMS's full width at half-maximun (a) and intensity contour map (b) along first cell at $n = 10$ and with higher local second-order dispersion ($|\beta_2| = 2$ ps$^2$/km).

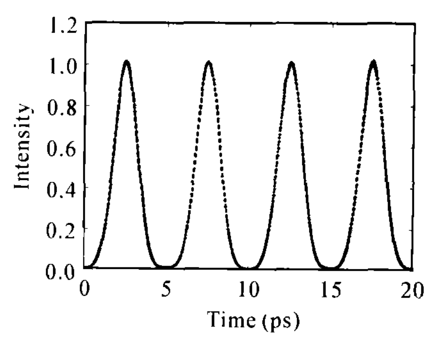


Fig. 4. Eye diagram (unfiltered) after transmitting over 2000 km with $|\beta_2| = 2$ ps$^2$/km and denser dispersion management for $n = 10$.

The above study is based on the low system power ($P_0 = 1$ mW). In this paper, system with high power are also investigated. Optical pulse with different initial frequency chirp can keep stable transmission at $n = 2$ when the system power vary from 1 mW to 10 mW. However, the property of propagating will become worse at $P_0 = 2$ or 4 mW, and can hardly stably propagate at $P_0 = 10$ mW for $n = 10$. Hence, we can conclude that the excessively dense dispersion-managed fiber is very advantageous to systems with weak nonlinear or to quasi-linear system.

In conclusion, we have investigated the performance of the chirped short pulse transmitting in zero-path- averaged dense dispersion-managed optical fiber. DDMS shows some excellent characters: depressing breathing extent, reducing overlap and interaction between adjacent optical pulses, and tolerating larger local dispersion. However, in general, DDMS can stably propagate under weak nonlinear or quasi-linear condition. The influence of polarization-mode dispersion in high-bit rate transmission system will be considered in our future research work.

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## References

1. J. M. Jacob and G. M. Carter, Electron. Lett. **33,** 1128 (1997).
2. G. M. Carter, R. M. Mu, V. S. Grigoryan, C. R. Menyuk, P. Sinha, T. F. Carruthers, M. L. Dennis, and I. N. Duling III, Electron. Lett. **35,** 233 (1999).
3. S. B. Alleston, P. Harper, I. S. Penketh, I. Bennion, N. J. Doran, and A. D. Ellis, Electron. Lett. **35,** 823 (1999).
4. S. Wabnitz and F. Neddam, Opt. Commun. **183,** 395 (2000).
5. C. K. Madsen, Opt. Lett. **25,** 878 (2000).
6. A. H. Liang, H. Toda, and A. Hasegawa, Opt. Lett. **24,** 799 (1999).
7. T. Hirooka, T. Nakada, and A. Hasegawa, IEEE Trans. on Photon. Technol. Lett. **12,** 633 (2000).
8. J. Chen, H. Kim, and Y. C. Chung, IEEE Photon. Technol. Lett. **13,** 663 (2001).
9. J. N. Kutz and S. G. Evangelides, Opt. Lett. **23,** 685 (1998).
10. A. Hodzic, B. Konrad, and K. Peternann, IEEE Photon. Technol. Lett. **14,** 152 (2002).
11. R.-M. Mu and C. R. Menyuk, IEEE Photon. Technol. Lett. **13,** 797 (2001).
12. G. P. Agrawal, *Nonlinear Fiber Optics* (the second edition) (Academic press, Inc., San Diego, 1995).