Study on compensating methods of transmission system at 40 Gb/s in photonic crystal fiber

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Two compensating methods about solitons transmition systems at 40 Gb/s in a photonic crystal fiber are investigated. The maximum transmission distance of the system is calculated numerically by sliding filters and synchronic modulation technology. The maximum transmission distance increases evidently which occasionally is three times longer than before. The results show that the actions of high order dispersion, polarization mode dispersion, and high order nonlinearity are weakened by the two methods. The compensating effect of synchronic modulation technology is better than that of the other one. The capability of the compensated system is ameliorated, which is shown by eye patterns.

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In the anomalous-dispersion regimes of the fiber, optical soliton effects can be generated because of the interaction between the dispersion and the nonlinear effects. Zero dispersion spot of photonic crystal fiber (PCF) is moved to the visible light region which the traditional fiber cannot reach, so the wave band of optical soliton effects is expanded greatly[1−4]. In 2000, Wadsworth *et al.* reported that the soliton effects have been observed in the PCF at zero-dispersion wavelength of 740 nm by adopting ultrashort pulse with the center wavelength of 850 nm and pulse width of 200 fs[5]. Solitons pulse width, which is lower than 100 fs and adjustable in the range of 1.3 − 1.6 μm, could be generated when femtosecond pulse with 1.3-μm wave length and 200-fs width was input[6]. Using four sections of 31-km fibers (each constituted of a 25-km-long PCF and a 6-km-long dispersion-compensating fiber (DCF)), at 1550 nm and 10-Gb/s velocity, Kurokawa *et al.* demostrated the transmission of solitons with no additional energy loss and original width of 20.6 ps. the soliton pulse width was only increased 9.2 ps after transmission[7]. Recently, Hasegawa *et al.* studied the soliton transmission system at l0 Gb/s in the PCF[8]. The solitons were formed easily because initial power was 2 mW into the PCF of strong nonlinearity. Mecozzi *et al.* analyzed timing jitter and stability in soliton transmission with sliding filter in traditional single mode fiber[9,10]. Kulota *et al.* studied soliton transmission control with synchronic modulation technology in time[11]. Wang *et al.* investigated that the polarization mode dispersion (PMD) was compensated with sliding filters and synchronic modulation technology in single mode fiber[12,13]. The investigation of solitons transmission which controls three-order dispersion (TOD), PMD, and high-order nonlinearity with sliding filter and synchronic modulation technology has unannounced in PCF of strong nonlinearity.

There are two methods in this letter to compensate transmission in order to improve the transmitting performance of the system. Sliding filters and synchronic modulation technology are discussed for compensating TOD, PMD, and high-order nonlinearity. To appraise the compensation effect of sliding filters and synchronic modulation technology, the maximum transmission distance and eye patterns of solitons transmission system are calculated numerically.

In the solitons transmission system, the solitons center or the average frequency would be shifted with distance for the effects of TOD, PMD, and high-order nonlinearity. If the central frequency of filters connected in turns along the line could be shifted synchronously, the dispersive wave accumulated near the central frequency of filter formerly would depart from solitons and fall into outside of band pass of the latter connected filters, leading to be restrained. Consequently, the system was guaranteed to be stable.

To overcome the effects of the TOD, PMD, and high-order nonlinearity, the sliding filter was added at 60 km along the transmission line. The system transmission normalized equations could be obtained with ultrashort pulse transmission equations in the single mode fiber and sliding filter model[14,15]:

$$\begin{aligned}
&\mathrm{i}\left[\frac{\partial u}{\partial \xi}+\sigma\frac{\partial u}{\partial \tau}\right]+\frac{1}{2}\frac{\partial^2 u}{\partial \tau^2}-\frac{\mathrm{i}}{6}\delta\frac{\partial^3 u}{\partial \tau^3}+\left[|u|^2+\frac{2}{3}|v|^2\right]u+\mathrm{i}\Gamma u+\mathrm{i}s\frac{\partial}{\partial \tau}(|u|^2u)-\tau_{\mathrm{R}}u\frac{\partial}{\partial \tau}\Big(|u|^2\Big)=\mathrm{i}gu-\mathrm{i}\beta\Big(\mathrm{i}\frac{\partial}{\partial \tau}-\varepsilon\xi\Big)^2u,\\
&\mathrm{i}\left[\frac{\partial v}{\partial \xi}-\delta\frac{\partial v}{\partial \tau}\right]+\frac{1}{2}\frac{\partial^2 v}{\partial \tau^2}-\frac{\mathrm{i}}{b}\delta\frac{\partial^3 v}{\partial \tau^3}+\left[|v|^2+\frac{2}{3}|u|^2\right]v+\mathrm{i}\Gamma v+\mathrm{i}s\frac{\partial}{\partial \tau}\Big(|v|^2v\Big)-\tau_{\mathrm{R}}v\frac{\partial}{\partial \tau}\Big(|v|^2\Big)=\mathrm{i}gv-\mathrm{i}\beta\Big(\mathrm{i}\frac{\partial}{\partial \tau}-\varepsilon\xi\Big)^2v,
\end{aligned} \tag{1}$$

where g is the gain coefficient compensating the added loss produced by sliding filters, β is the intensity of the filter, and ε is the shift-velocity of the filter's central frequency. When $\varepsilon < \frac{2\sqrt{6}}{9}\beta, g = \frac{\beta}{3} + \frac{9\varepsilon^2}{16\beta}$. The parameters of sliding filters are $\beta = 0.3$ and $\varepsilon = 0.1$, respectively, and the input pulse is soliton. The right part of Eq. (1) is mathematical model of sliding filters. The maximum transmission distance of compensating system varying with parameters would be calculated next.

In the calculation, parameters of the PCF are set as follows, nonlinear-index coefficient $n_2 = 3.0\times10^{-20}$ m^2/W, effective core area $A_{\text{eff}} = 3.14$ μm^2, wavelength $\lambda =$ 800 nm, TOD coefficient $\beta_3 = 0.082385$ ps^3/km, nonlinearity coefficient $\gamma = 75$ w$^{-1}\cdot$ km^{-1}, self-steepening coefficient $s = 0.2$, Raman scattering coefficient $\tau_{\text{R}} =$ 0.0244, and initial pulse width is 100 fs.

Then the PMD coefficient D_{p} is equal to 0.5 ps/$\sqrt{\text{km}}$ and sliding filters are connected at 60 km, the results calculated numerically are shown in Fig. 1. When group-velocity dispersion (GVD) parameter D is equal to 0.5 ps/(km·nm), the transmission distance is added more than 10 km by sliding filters. Until D is added to the range from 1.0 to 1.5 ps/(km·nm), the compensation effects of sliding filters plays a more important role in propagation, and the system propagation distance is added by approximate 30 km. When D is larger than 2 ps/(km·nm), the system transmission distance is added more than 40 km with sliding filters. Consequently, the larger the GVD is, the better the compensation effect of sliding filtersis. It is obvious that the system transmission performance could be much better improved using sliding filters to compensate.

If the GVD coefficient D is equal to 1.6 ps/(km·nm) and sliding filters are connected at 60 km, the calculated results of the maximum transmission distance varying with the PMD are shown in Fig. 2.

With the increasing value of the PMD, the maximum transmission distance would be increased from 30 to 40 km by the compensation of sliding filters. Thus, the compensation effect of sliding filters is better.

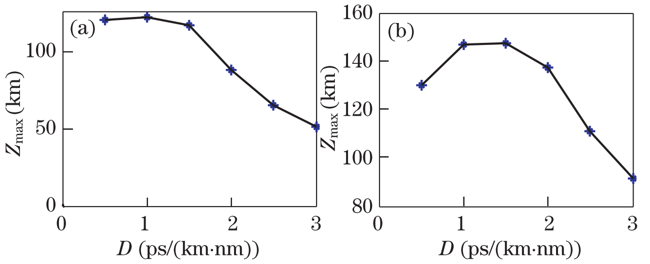

Fig. 1. Maximum transmission distance of the system Z_{max} versus the dispersion D (a) before and (b) after compensated by the sliding filter.

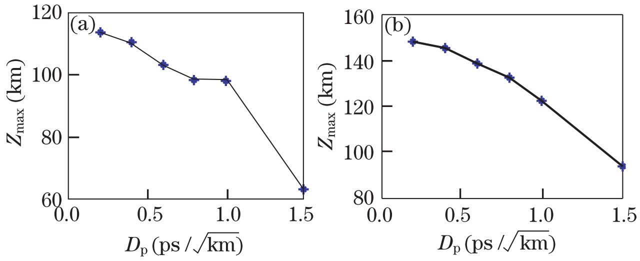

Fig. 2. Maximum transmission distance of the system versus the PMD (a) before and (b) after compensated by the sliding frequency filter.

It is concluded from two cases above that sliding filters have some compensation effects on system performance. Sliding filters are closely related to the spectrum structure of pulse. However, the influence of the PMD on pulses in the frequency domain is represented as pattern noise distributed in all frequency domains, and the TOD and the high order nonlinearity remove only frequency. The filters cannot reduce all noises in the frequency domain, so the increased maximum transmission distance is limited.

The numerical results show that, for sliding filters, compensation effects on the system at 40 Gb/s really exists, making the maximum transmission distance of solitons increase to improve the quality of transmission system.

The system transmission normalized equations could be obtained with ultrashort pulse transmission equations in the single mode fiber and synchronic modulation model[14,15]:

$$\begin{aligned}
&\mathrm{i}\left[\frac{\partial u}{\partial \xi} + \delta\frac{\partial u}{\partial \tau}\right] + \frac{1}{2}\frac{\partial^2 u}{\partial \tau^2} + \left[|u|^2 + \frac{2}{3}|v|^2\right]u + \mathrm{i}\Gamma u + \mathrm{i}s\frac{\partial}{\partial \tau}\left(|u|^2 u\right) - \tau_{\text{R}} u\frac{\partial}{\partial \tau}\left(|u|^2\right) = \mathrm{i}gu + \mathrm{i}\varepsilon\frac{\partial^2 u}{\partial \tau^2} + \mathrm{i}\mu\left[\cos(\Omega_{\text{m}}\tau) - 1\right]u,\\
&\mathrm{i}\left[\frac{\partial v}{\partial \xi} - \delta\frac{\partial v}{\partial \xi}\right] + \frac{1}{2}\frac{\partial^2 v}{\partial \tau^2} + \left[|v|^2 + \frac{2}{3}|u|^2\right]v + \mathrm{i}\Gamma v + \mathrm{i}s\frac{\partial}{\partial \tau}\left(|v|^2 v\right) - \tau_{\text{R}} v\frac{\partial}{\partial \tau}\left(|v|^2\right) = \mathrm{i}gv + \mathrm{i}\varepsilon\frac{\partial^2 v}{\partial \tau^2} + \mathrm{i}\mu\left[\cos(\Omega_m\tau) - 1\right]v,
\end{aligned} \tag{2}$$

where g is the gain parameter and compensates the excess loss produced by synchronic modulation, μ is the synchronic modulation depth, Ω_{m} is modulation angular frequency, and ε is the filter intensity. If $\mu\Omega_{\text{m}}^2 < \frac{8\varepsilon}{\pi^2}$ is satisfied, then $g = \frac{\varepsilon}{3} + \frac{\pi^2\mu\Omega_{\text{m}}^2}{24}$. The left part of Eq. (2) represents the mechanism of the synchronic modulation technology on line.

If the PMD parameter D_{p} is equal to 0.5 ps/$\sqrt{\text{km}}$, the maximum transmission distances of the system are shown in Fig. 3 with and without synchronous modulation at 60 km. The effects of synchronic modulation is not obvious if D is smaller than 0.5 ps/(km·nm). When $D = 1.0$ ps/(km·nm), the maximum transmission distance increases more than 20 km by synchronic modulation. Outsides, if D changes into the range from 2.0 to 3.0 ps/(km·nm), the maximum transmission distance of the system is remarkably increased and the compensation effects of synchronic modulation are correspondingly better. Especially, when $D = 3.0$ ps/(km·nm), synchronic modulation causes the maximum transmission distance of system increased about three times.

When D is equal to 1.6 ps/(km·nm) and the PMD is designed by different values, the numerical results are shown in Fig. 4 after modulated synchronously at 60 km.

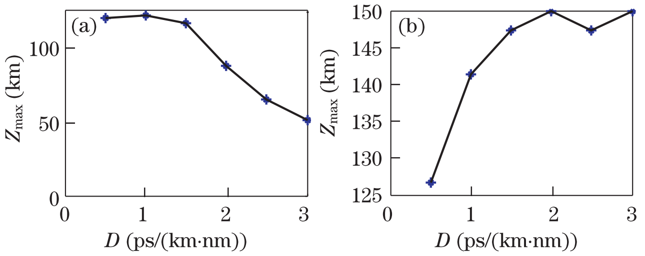

Fig. 3. Maximum transmission distance of the system versus group velocity dispersion (a) before and (b) after the synchronous modulation.

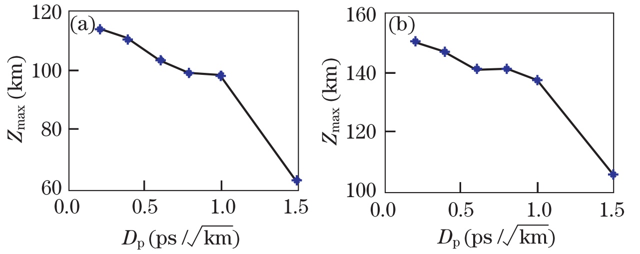

Fig. 4. Maximum transmission distance of system versus the PMD (a) before and (b) after synchronous modulation.

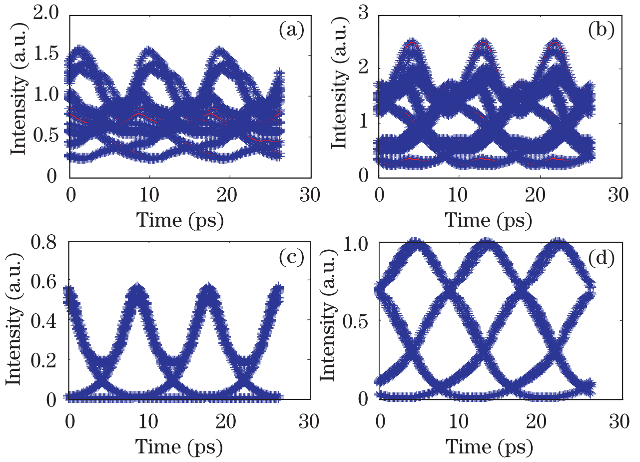

Fig. 5. Eye patterns of soliton pulse in the transmission system (a) is original fiber condition and under the control of various controls of (b) added amplifier, (c) added synchronic modulation, and (d) added sliding filter.

On the condition that D_p is smaller than 1.0 ps/$\sqrt{\text{km}}$, the added values of maximum transmission distance are all more than 40 km. The larger value of PMD leads the better compensation effect and the longer maximum transmission distance.

When the amplifiers or sliding filters or synchronic modulation are connected into the system at 60 km, respectively, the transmitting eye patterns of the system are simulated. If the input pulse is solitons, four cases are calculated (Fig. 5), and they are (a) in the PCF; (b) adding the amplifiers with noise at 60 km; (c) with synchronic modulation at 60 km; (d) with sliding filters at 60 km, respectively. Figure 5 shows that when solitons propagate at 180 km, the eye pattern of system has slurred due to the interaction of the GVD, TOD, PMD, and high-order nonlinear effect. Until added amplifiers, the eye pattern of the system could goggle somewhat, and the open degree is small.

However, using the synchronic modulation in the system, eye pattern is much clearer, indicating that the system performance is much better. If sliding filters are used to control the system, the open degree of the eye pattern also increases and the system performance would be improved correspondingly.

It is obvious that the control effect of synchronic modulation on solitons is the strongest indicating that synchronic modulation on line reduces, not only the effect of the PMD but also the nonlinear interactions among more other dispersions. The compensation method to the system like synchronic modulation is more suitable to the solitons propagation.

In conclusion, if the system is controlled by adding sliding filter and synchronous modulation technology, the system performance is improved, and the biggest transmission distance of the system is increased by 30–50 km, and it will even be increased by three times in some cases. The system transmission performance can be inspected visually from eye pattern, and the results of eye pattern is fully consistent with the biggest calculated transmission distance. In short, the properties of the PCF supports this new type fiber's application to achieve a high-speed solitons communication system, and it has a better prospect in deep-sea communications.

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