Energy Enhancement of Dispersion Managed Soliton Transmission System Using Mostly Normal Dispersion Fiber

Sien Chi, Jeng-Cherng Dung, and Shy-Chaung Lin

***Abstract*—The dispersion managed soliton transmission system using mostly normal dispersion fiber is investigated. It is shown that, with the same net anomalous dispersion, the optimum energy enhancement is larger for the system using mostly normal dispersion fiber than the system using mostly anomalous dispersion fiber. The allowed transmission distance for the system using mostly normal dispersion fiber is longer than those using mostly anomalous dispersion fiber.**

***Index Terms*— Dispersion management, energy enhancement, optical soliton.**

THE DISPERSION management has become an important technique for optical soliton transmission because the soliton interactions and Gordon–Haus timing jitters can be greatly reduced by using the dispersion management. In a dispersion managed transmission system, the soliton generally propagates in the anomalous dispersion regime of a long dispersion-shifted fiber (DSF) and then the accumulated dispersion is compensated by a much shorter dispersion compensation fiber (DCF) [1], [2]. Recently, in order to sufficiently utilize the huge bandwidth of the DSF, the wavelength of the signal in a soliton dispersion managed transmission has been extended to the normal dispersion regime of the DSF [3], [4]. It is found that the soliton can maintain a stable pulse variation even more than 90% of the fiber is in the normal dispersion regime as long as the net dispersion is anomalous. In this letter, we will investigate the energy enhancement of the soliton in a dispersion managed transmission system using the mostly normal dispersion fiber and compare it with the system using the mostly anomalous dispersion fiber.

We consider a system using the mostly normal dispersion fiber as shown in Fig. 1(a), where the soliton propagates in normal dispersion regime of a long DSF and a much shorter standard single-mode fiber (SMF) periodically; this system is called Scheme A. A system using the mostly anomalous dispersion fiber is shown in Fig. 1(b), where the soliton propagates in anomalous dispersion regime of a long DSF and a much shorter DCF periodically; this system is called Scheme B. We numerically simulate the soliton propagation in both systems. We have found that, with the same net anomalous dispersion, the optimum energy enhancement is larger for the system using mostly normal dispersion fiber than the system using mostly anomalous dispersion fiber. The allowed transmission distance for the system using mostly normal dispersion fiber is longer than those using mostly anomalous dispersion fiber.

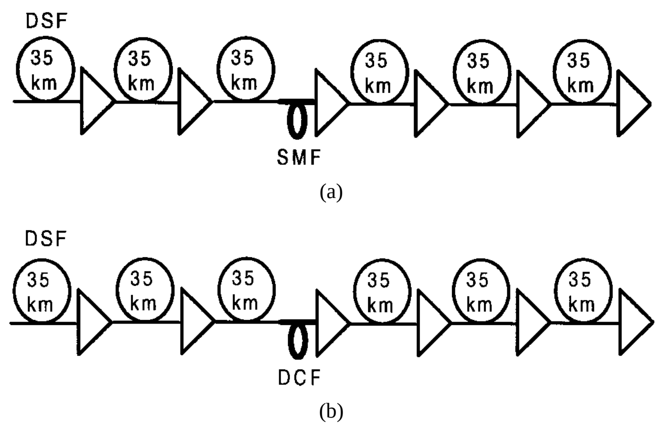

Fig. 1. The schematic diagram of a dispersion management unit cell for the (a) Scheme A having mostly normal dispersion fiber and (b) Scheme B having mostly anomalous dispersion fiber.

The soliton transmission in a SMF can be described by the modified nonlinear Schrödinger equation

$$i\,\frac{\partial U}{\partial z} - \frac{1}{2}\,\beta_2\,\frac{\partial^2 U}{\partial \tau^2} - i\,\frac{1}{6}\,\beta_3\,\frac{\partial^3 U}{\partial \tau^3} + n_2\beta_o|U|^2U - C_rU\,\frac{\partial}{\partial \tau}|U|^2 = -\frac{i}{2}\,\alpha U \tag{1}$$

where $\tau = (t-\beta_1 z)/T_0$ and β_1 is the reciprocal group velocity, β_2 and β_3 represent the second- and third-order dispersion of the fiber, respectively, U is the slowly varying amplitude, n_2 is the Kerr coefficient, C_r is the slope of Raman gain profile, and α is the loss coefficient of the fiber. For the numerical simulation, the coefficients in (1) are taken as $\beta_3 = 0.14$ ps^3/km, $n_2 = 2.6\times10^{-20}$ m^2/W, $C_r = 3.8\times10^{-16}$ (ps $\cdot$ m)/W, and $\alpha = 0.22$ dB/km for the DSF and SMF, and 0.5 dB/km for the DCF. The incident soliton pulse is assumed to be of the form $U(z=0,\tau) = (0\ \exp(-\tau^2/2)$, where η_0 is the initial pulse amplitude. The initial pulsewidth (full width at half maximum) is 10 ps and the amplifier spacing is 35 km. The energy needed to form a soliton in a uniform fiber is proportional to the dispersion. However, in a dispersion managed soliton system, since the rate of self-phase modulation

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TABLE I
CHOICE OF THE CENTRAL WAVELENGTH AND THE SECOND-ORDER DISPERSION OF SIGNALS IN THE SCHEME A AND B

Scheme	λ_0(nm)	β_2 (ps^2/Km) DSF	β_2 (ps^2/Km) SMF/DCF	$\overline{\beta}_2$ (ps^2/Km)	S
A	1550.00	0.4	-21	-0.05	1.89
B	1558.19	-0.5	136	-0.05	1.89

(zero-dispersion wavelength of the DSF = 1553.64 nm)

(SPM) is reduced, more energy is required to balance the path-average dispersion when compared to the equivalent uniform dispersion system [5]–[7]. Furthermore, from the semi-empirical formula describing the energy enhancement of a soliton in dispersion managed transmission system, it is found that the energy enhancement is dependent on the dispersion map strength [8] and the location of the amplifier [9]. In numerical simulations, the second-order dispersions for Scheme A and B are listed in Table I, where the Scheme A and B have the same path-average second-order dispersion $\overline{\beta}_2$ and the dispersion map strength S. The DCF and SMF are viewed as the dispersion compensation elements and the lengths of DCF and SMF are not incorporated into the transmission distances, but the losses in the DCF and SMF are considered. The $\overline{\beta}_2$ is defined in Scheme A as

$$\overline{\beta}_2 = (\beta_2^{\mathrm{DSF}} \times L_{\mathrm{DSF}} + \beta_2^{\mathrm{SMF}} \times L_{\mathrm{SMF}})/(L_{\mathrm{DSF}} + L_{\mathrm{SMF}}) \tag{2}$$

where β_2^{DSF} and β_2^{SMF} are the second-order dispersions for DSF and SMF, respectively, and L_{DSF} and L_{SMF} are the lengths of DSF and SMF, respectively. The dispersion map strength S is defined in the Scheme A as

$$S = \left| \frac{(\beta_2^{\mathrm{DSF}} - \overline{\beta}_2) \cdot L_{\mathrm{DSF}} - (\beta_2^{\mathrm{SMF}} - \overline{\beta}_2) \cdot L_{\mathrm{SMF}}}{\tau_{\min}^2} \right| \tag{3}$$

where $\tau_{\min}$ is the minimum full-width at half maximum of the soliton at the unchirped position in the dispersion cycle. Similar definitions of $\overline{\beta}_2$ and S are used in the Scheme B. In our case, the fiber lengths are 210 km, 4.510 74 km, and 0.694 59 km for L_{DSF}, L_{SMF} and L_{DCF}, respectively. The energy enhancement factor F_{en} is defined as $F_{\mathrm{en}} = E_{\mathrm{sol}}/E_0$ [6], where E_{sol} is the energy of the soliton in a dispersion managed system and E_0 is the energy of the soliton of equal pulsewidth in a uniform fiber system with the same path-average second-order dispersion.

Fig. 2(a) and (b) shows the pulsewidth variation and self-frequency shift of the signals versus transmission distance at the beginning of every dispersion management unit cell for different F_{en}'s of Scheme A and B, respectively; the solid lines and dotted lines are for the Scheme A and B, respectively. Comparing the pulsewidth variations of Scheme B when $F_{\mathrm{en}} = 2.50$ with other values of F_{en}, we have found $F_{\mathrm{en}} = 2.50$ is the optimum enhancement and the pulsewidths of signals at the beginning of every dispersion management unit cell are very close to the initial pulsewidth. Fig. 3 shows the stable pulsewidth variation in a unit cell with $F_{\mathrm{en}} = 2.50$; the solid lines and dotted lines are for the Scheme A and B, respectively. With the same Fen, we have found that the average pulsewidth of the soliton broadens more in Scheme A than the one in Scheme B. Since the Kerr effect is dependent on the power of signal, the energy enhancement in Scheme A

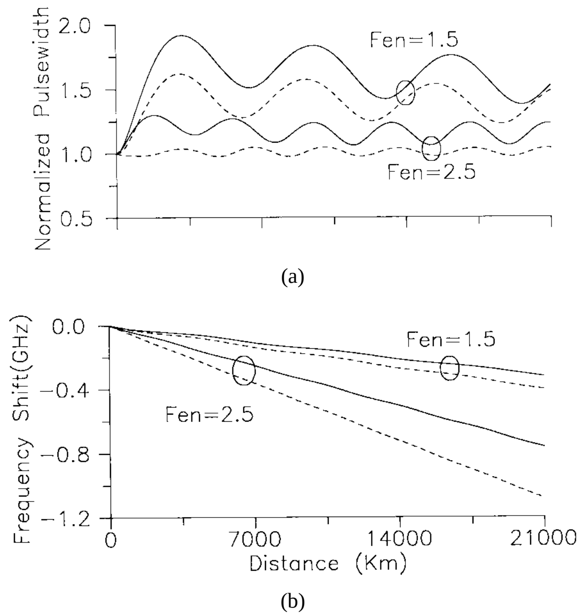

Fig. 2. (a) The pulsewidth variations and (b) the self-frequency shifts of the signal versus transmission distance at the beginning of every dispersion management unit cell, the solid and dotted lines indicate the Scheme A and B, respectively.

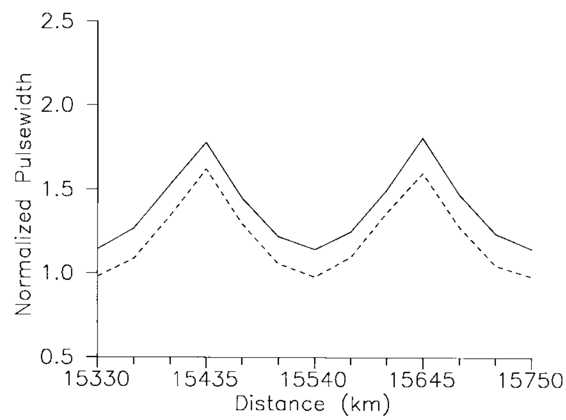

Fig. 3. The pulsewidth variation in a unit cell with $F_{\mathrm{en}} = 2.50$; the solid lines and dotted lines are for the Scheme A and B, respectively.

has to be increased to maintain a stable soliton propagation. Fig. 4 shows the pulsewidth variation and self-frequency shift of the pulse versus transmission distance in Scheme A with $F_{\mathrm{en}} = 3.38$. Comparing the pulsewidth variation of Scheme A when $F_{\mathrm{en}} = 3.38$ with other values of F_{en}, we know that $F_{\mathrm{en}} = 3.38$ is the optimum value in Scheme A. In the mean time, the self-frequency shifts of $F_{\mathrm{en}} = 3.38$ in the Scheme A and $F_{\mathrm{en}} = 2.50$ in the Scheme B are found to be equal. Therefore, the optimum enhancement factors for the Scheme A and B have the same self-frequency shift. We have also found when $F_{\mathrm{en}} = 2.50$ in the Scheme B that the pulsewidth variation quickly become stable. On the otherhand, when $F_{\mathrm{en}} = 3.38$ in the Scheme A, the pulsewidth variation become stable after long propagating distance. During the transient stage, the pulse adjusts itself by shedding some of its energy, and finally the stable pulse emerges. We use the stable pulses for both the Scheme A and Scheme B as the initial pulses and calculate the Q-value by simulating the

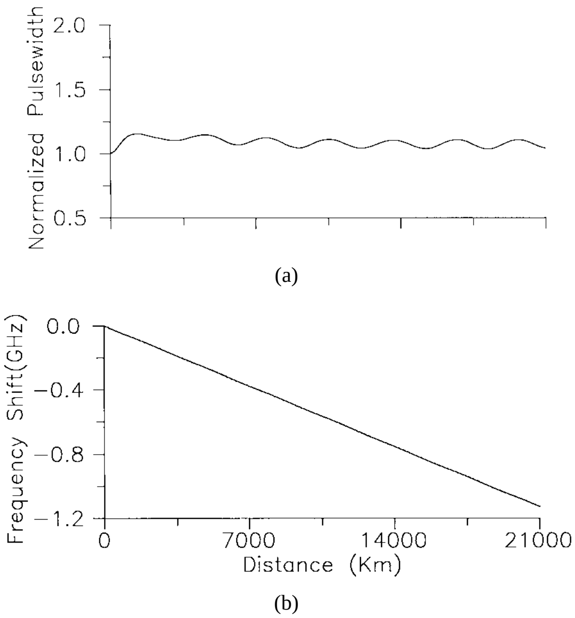

Fig. 4. The pulsewidth variations and self-frequency shifts of the signal versus transmission distance at the every beginning of dispersion management unit cell with $F_{\rm en} = 3.38$ in the Scheme A.

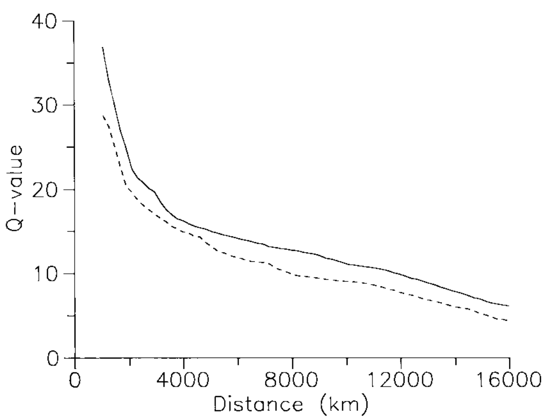

Fig. 5. The Q-value versus transmission distance, the solid line and dotted line indicate the signals with $F_{\rm en} = 3.38$ in the Scheme A and $F_{\rm en} = 2.50$ in the Scheme B, respectively.

transmissions of 1024 pseudorandom bits (512 ONE's and 512 ZERO's), the spontaneous emission factor of an amplifier is assumed to be 1.2, the bit rates are 20 Gb/s. Fig. 5 shows the Q-value versus transmission distance for Scheme A and B, respectively. The solid line and dotted line indicate the signals of average power −2.19 dBm ($F_{\rm en} = 3.38$) and -3.39 dBm ($F_{\rm en} = 2.5$) in Scheme A and B, respectively. A 10^{-9} bit-error rate corresponds to $Q = 6$. The allowed transmission distances with 10^{-9} bit-error rate for Scheme A and B are 16 000 and 14 070 km, respectively. For the same transmission distance, the Scheme A has a higher Q-value because of its higher signal-to-noise ratio.

In conclusion, we have found that the Scheme of the system having mostly normal dispersion of fiber needs a larger energy enhancement of soliton than those of having mostly anomalous dispersion of fiber. It is because the soliton broadens more in the mostly normal dispersion fiber system and needs more energy to balance the path-average dispersion and maintain a stable soliton transmission. The allowed transmission distance for the system using mostly normal dispersion fiber is longer than those using mostly anomalous dispersion fiber.

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