Optical solitons in a dispersion-flattened fiber with linear and quadratic intensity-dependent refractive-index changes

Chi-Feng Chen and Sien Chi

Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu, Taiwan 30050, China

Received January 21, 1998; revised manuscript received April 20, 1998

Optical-soliton propagation in a dispersion-flattened fiber is investigated, of which third-order dispersion is nil and fourth-order dispersion exists with linear and quadratic intensity-dependent refractive-index changes. For four possible sign combinations of the second-order dispersion and the Kerr-effect terms, we found that there are two types of bright-soliton solutions and two types of dark-soliton solutions. The magnitude of the fourth-order dispersion parameter is related to the quadratic intensity-dependent nonlinearity coefficient, and their signs are opposite. The peak power and the period of the soliton are determined by the magnitude of the fourth-order dispersion parameter. We numerically show that the bright-soliton solution in anomalous second-order dispersion and the positive Kerr coefficient regime is stable and becomes quasi stable when the Raman effect is considered. © 1998 Optical Society of America [S0740-3224(98)01308-3]

OCIS codes: 060.4370, 060.5530.

1. INTRODUCTION

The optical soliton in an optical fiber owing to the balance of the anomalous second-order dispersion and self-phase modulation has been studied both theoretically and experimentally. It can propagate[1–4] undistorted over a long distance and remains unaffected after collision with other solitons. It has potential applications in optical fiber communications, pulse compressions, and all-optical switchings. The behavior of the soliton is commonly described by the nonlinear Schrödinger equation as long as the pulse width exceeds roughly 1 ps. It is necessary to include the higher-order linear and nonlinear terms, such as third-order dispersion, fourth-order dispersion, the self-frequency shift, and the self-steepening terms for shorter pulses.[5–16]

The higher-order dispersion effects have been extensively investigated in the negative second-order dispersion regime.[5–11] It is shown that the third-order dispersion can induce radiation at the blue frequency component and that the amplitude of the radiation is small and can be obtained by the perturbation method.[5,6] If the carrier frequency of the soliton is chosen at the minimum of the second-order dispersion, where the third-order dispersion is zero, or the pulse propagation is considered in a dispersion-flattened fiber of which third-order dispersion is nil, the fourth-order dispersion will play an important role. In the regime of negative fourth-order dispersion the propagation of the solitonlike solution is radiationless, and this solution has been shown stable up to a threshold value of the third-order dispersion parameter[7,8]; a new type of stationary stable solitonlike solution with oscillating tails has been found[9]; the dynamics and interactions of bright-solitonlike solutions with oscillating tails have been investigated.[10] In the regime of positive fourth-order dispersion an unstable equilibrium pulse solution for a bright optical soliton has been found, and the width of the soliton is determined by the magnitude of the fourth-order dispersion parameter.[11]

On the other hand, the soliton propagation in the nonlinear medium with an intensity-dependent refractive-index change has also been studied.[17–20] It has been found that a saturable nonlinear medium can support two localized solitons with the same pulse width but different peak intensities,[17–19] which are called bistable solitons.[20] The modulational instability in a doped glass fiber has been theoretically analyzed by considering the saturable nonlinearity and the third- and fourth-order dispersions.[21]

In this paper we shall investigate the soliton propagation in a dispersion-flattened fiber of which third-order dispersion is nil and fourth-order dispersion exists with a linear and quadratic intensity-dependent refraction-index change. The refraction-index change of such fiber has the form $\Delta n(|A|^2) = n_2|A|^2 + n_4|A|^4$. For four possible sign combinations of the second-order dispersion and the Kerr coefficient we can obtain two types of bright-soliton solutions and two types of dark-soliton solutions. For some cases, bistable soliton solutions exist, which are the undistorted pulses with the same duration but different peak powers. We numerically show that the bright-soliton solution in anomalous second-order dispersion and the positive Kerr coefficient regime is stable and becomes quasi stable when the Raman effect is considered.

2. PROPAGATION EQUATION

The propagation equation for solitons in a dispersion-flattened fiber of which third-order dispersion is nil ($\beta_3 = 0$) and fourth-order dispersion exists with an intensity-dependent nonlinearity is

$$\frac{\partial}{\partial z} A = -i \frac{\beta_2}{2} \frac{\partial^2 A}{\partial T^2} + i \frac{\beta_4}{24} \frac{\partial^4 A}{\partial T^4} + i \frac{\omega_0}{c} \Delta n(|A|^2) A, \tag{1}$$

where $A(z, T)$ is the slowly varying amplitude of the field strength, z is the distance coordinate in the direction of propagation, T is measured in a frame of reference moving with the pulse at the group velocity β_1^{-1} ($T = t - \beta_1 z$), β_2 is the second-order dispersion parameter, β_4 is the fourth-order dispersion parameter, c is the velocity of light in vacuum, ω_0 is the angular frequency of the carrier wave, and $\Delta n(|A|^2)$ is the nonlinear refractive-index change. In the ordinary case, $\Delta n(|A|^2) = n_2|A|^2$, we have the well-known nonlinear Schrödinger equation with a Kerr-type nonlinearity. In this paper we consider another type of nonlinear refractive-index change,[17,18]

$$\Delta n(|A|^2) = n_2|A|^2 + n_4|A|^4. \tag{2}$$

Substituting Eq. (2) into Eq. (1) and introducing dimensionless soliton units

$$\xi = \frac{z}{L_D}, \quad \tau = \frac{T}{T_0}, \quad u = \frac{N}{\sqrt{P_0}} A, \quad \beta = \frac{\beta_4}{24|\beta_2| {T_0}^2},$$

where $L_D = {T_0}^2/|\beta_2|$ is dispersion length, $T_0 = T_w/1.763$ and T_W is the initial pulse full width at half-maximum, $N = (\omega_0 L_D P_0 |n_2|/c)^{1/2}$ is the soliton order, and P_0 is peak power of the incident pulse, we obtain

$$\frac{\partial}{\partial \xi} u = -\frac{i}{2} S_{\beta_2} \frac{\partial^2 u}{\partial \tau^2} + i\beta \frac{\partial^4 u}{\partial \tau^4} + iS_{n_2}|u|^2 u + i\alpha |u|^4 u, \tag{3}$$

where $S_{\beta_2} = \text{sgn}(\beta_2)$, $S_{n_2} = \text{sgn}(n_2)$, and $\alpha = n_4 P_0/|n_2|$.

3. SOLUTIONS AND DISCUSSION

We shall find the soliton solutions of Eq. (3) for four possible sign combinations of S_{β_2} and S_{n_2}.

A. $S_{\beta_2} < 0$ and $S_{n_2} > 0$

In this case a soliton is in the anomalous second-order dispersion ($\beta_2 < 0$) and the positive nonlinear coefficient n_2 regime, and Eq. (3) can be rewritten as

$$\frac{\partial}{\partial \xi} u = \frac{i}{2} \frac{\partial^2 u}{\partial \tau^2} + i\beta \frac{\partial^4 u}{\partial \tau^4} + i|u|^2 u + i\alpha |u|^4 u. \tag{4}$$

The bright optical soliton solution of Eq. (4) can be written as

$$u(\xi, \tau) = A_0 r \,\text{sech}(r\tau) \exp(i\delta_0 r^2 \xi/2). \tag{5}$$

Substituting Eq. (5) into Eq. (4), we obtain the following relations for the soliton parameters:

$$\delta_0 = 1 + 2\beta r^2, \tag{6a}$$

$$A_0 = (1 + 20\beta r^2)^{1/2}, \tag{6b}$$

$$\alpha = -\frac{24\beta}{A_0^4}. \tag{6c}$$

To fulfill Eq. (6c), the signs of α and β must be opposite. When $\alpha > 0$, we must take $\beta < 0$. As a result, we get from Eqs. (6a) and (6b) that $\delta_0 < 1$, $A_0 < 1$, and $\beta > -1/20r^2$. From Eqs. (6b) and (6c), we obtain

$$\beta = \frac{-(12/\alpha + 20r^2) + \sqrt{(12/\alpha)(12/\alpha + 40r^2)}}{400r^4}.$$

Therefore, when the values of α and r are given, we have only one set of β, A_0, and δ_0. On the other hand, when $\alpha < 0$, we must take $\beta > 0$ and obtain $\delta_0 > 1$ and $A_0 > 1$. When the condition $0 > \alpha > -3/10r^2$ is satisfied, we obtain

$$\beta = \frac{-(12/\alpha + 20r^2) \pm \sqrt{(12/\alpha)(12/\alpha + 40r^2)}}{400r^4};$$

that is, there are two sets of β, A_0, and δ_0 when the values of α and r are given. This is the case of a bistable soliton solution. When the value of α is equal to $-3/10r^2$, we obtain $\beta = 1/20r^2$, $A_0 = \sqrt{2}$, and $\delta_0 = 1.1$. For $\alpha < -3/10r^2$, no solution is found. Figures 1, 2, and 3 show β, and amplitude that is equal to $A_0 r$, and δ_0, as functions of α, respectively.

B. $S_{\beta_2} > 0$ and $S_{n_2} < 0$

In this case a soliton is in the normal second-order dispersion ($\beta_2 > 0$) and the negative nonlinear coefficient n_2 regime, and Eq. (3) can be rewritten as

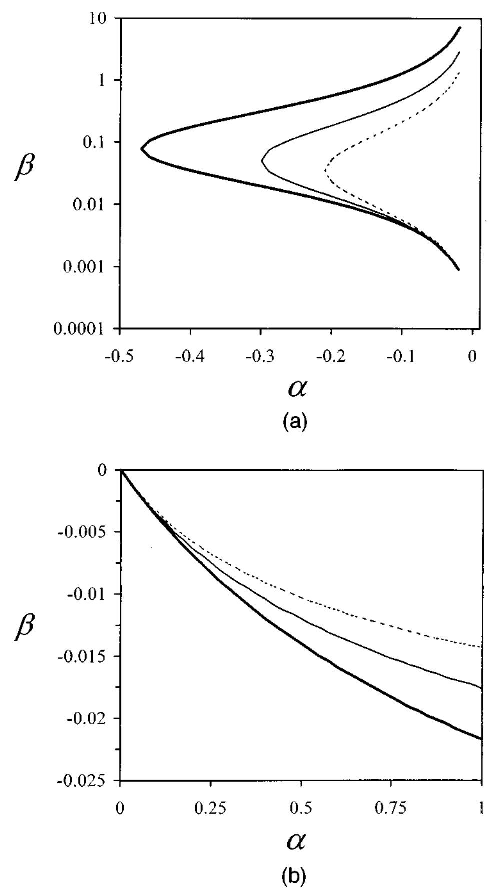

Fig. 1. β as a function of (a) $\alpha < 0$ and (b) $\alpha > 0$ for case A with $r = 0.8$ (thick solid curve), $r = 1$ (solid curve), and $r = 1.2$ (dashed curve).

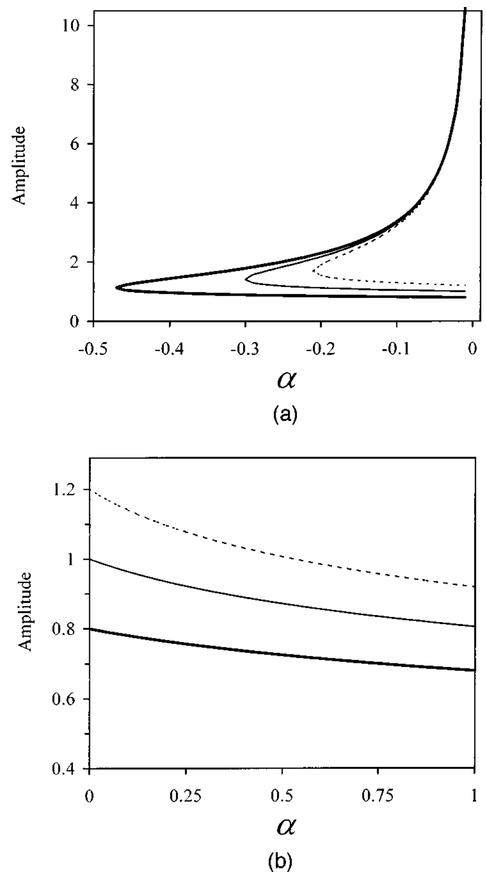

Fig. 2. Amplitude as a function of (a) $\alpha < 0$ and (b) $\alpha > 0$ for case A with $r = 0.8$ (thick solid curve), $r = 1$ (solid curve), and $r = 1.2$ (dashed curve).

$$-\frac{\partial}{\partial \xi} u = \frac{i}{2} \frac{\partial^2 u}{\partial \tau^2} - i\beta \frac{\partial^4 u}{\partial \tau^4} + i|u|^2 u - i\alpha |u|^4 u. \quad (7)$$

The bright optical soliton solution can be written as

$$u(\xi, \tau) = A_0 r \operatorname{sech}(r\tau)\exp(-i\delta_0 r^2 \xi/2). \quad (8)$$

Substituting Eq. (8) into Eq. (7), we obtain the following relations for the soliton parameters:

$$\delta_0 = 1 - 2\beta r^2, \quad (9a)$$

$$A_0 = (1 - 20\beta r^2)^{1/2}, \quad (9b)$$

$$\alpha = -\frac{24\beta}{A_0^4}. \quad (9c)$$

Equations (9c) and (6c) are identical, and the signs of α and β must be opposite. When $\alpha > 0$ and $\beta < 0$, we gain $\delta_0 > 1$ and $A_0 > 1$. When the condition $0 < \alpha < 3/10r^2$ is satisfied, from Eqs. (9b) and (9c), we obtain

$$\beta = \frac{-(12/\alpha - 20r^2) \pm \sqrt{(12/\alpha)(12/\alpha - 40r^2)}}{400r^4};$$

that is, there are two sets of β, A_0, and δ_0 when the values of α and r are given. This is also the case of a bistable soliton solution. When $\alpha = 3/10r^2$, we obtain $\beta = -1/20r^2$, $A_0 = \sqrt{2}$, and $\delta_0 = 1.1$. For $\alpha > 3/10r^2$, no solution is found. In addition, when $\alpha < 0$ and $\beta > 0$, we obtain $\delta_0 < 1$, $A_0 < 1$, and $\beta < 1/20r^2$. From Eqs. (9b) and (9c) we obtain

$$\beta = \frac{-(12/\alpha - 20r^2) - \sqrt{(12/\alpha)(12/\alpha - 40r^2)}}{400r^4}.$$

Thus we have only one set of β, A_0, and δ_0 when the values of α and r are given.

C. $S_{\beta_2} > 0$ and $S_{n_2} > 0$

In this case a soliton is in the normal second-order dispersion ($\beta_2 > 0$) and the positive nonlinear coefficient n_2 regime, and Eq. (3) can be rewritten as

$$\frac{\partial}{\partial \xi} u = -\frac{i}{2} \frac{\partial^2 u}{\partial \tau^2} + i\beta \frac{\partial^4 u}{\partial \tau^4} + i|u|^2 u + i\alpha |u|^4 u. \quad (10)$$

The dark optical soliton solution can be written as

$$u(\xi, \tau) = A_0 r \tanh(r\tau)\exp(i\delta_0 r^2 \xi). \quad (11)$$

Substituting Eq. (12) into Eq. (11), we obtain the following relations for the soliton parameters:

$$\delta_0 = 1 + 16\beta r^2, \quad (12a)$$

$$A_0 = (1 + 40\beta r^2)^{1/2}, \quad (12b)$$

$$\alpha = -\frac{24\beta}{A_0^4}. \quad (12c)$$

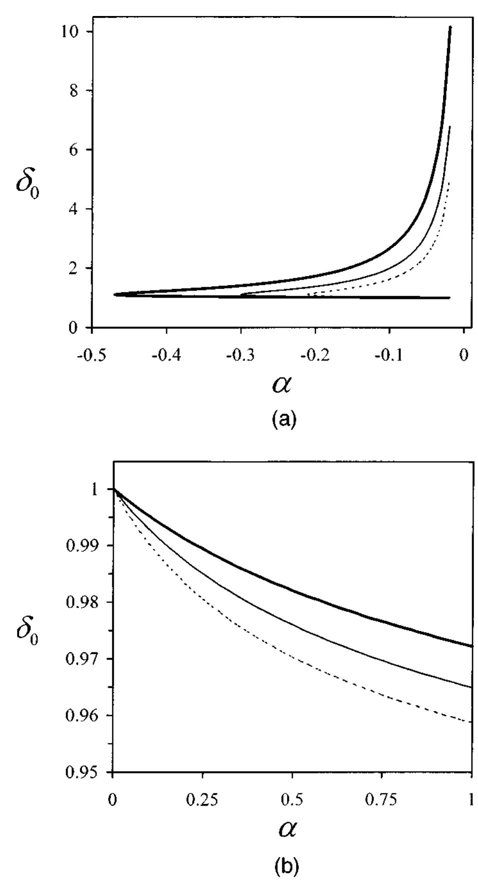

Fig. 3. δ_0 as a function of (a) $\alpha < 0$ and (b) $\alpha > 0$ for case A with $r = 0.8$ (thick solid curve), $r = 1$ (solid curve), and $r = 1.2$ (dashed curve).

When $\alpha > 0$, we must have $\beta < 0$. From Eqs. (12a) and (12b), we obtain $\delta_0 < 1$, $A_0 < 1$, and $\beta > -1/40r^2$. Using Eqs. (12b) and (12c), we obtain

$$\beta = \frac{-(12/\alpha + 40r^2) + \sqrt{(12/\alpha)(12/\alpha + 80r^2)}}{1600r^4}.$$

Hence, when the values of α and r are given, we have only one set of β, A_0, and δ_0. Additionally, when $\alpha < 0$ and $\beta > 0$, we obtain $\delta_0 > 1$ and $A_0 > 1$. When the condition $0 > \alpha > -3/20r^2$ is fulfilled, we obtain

$$\beta = \frac{-(12/\alpha + 40r^2) \pm \sqrt{(12/\alpha)(12/\alpha + 80r^2)}}{1600r^4};$$

that is, there are two sets of β, A_0, and δ_0 when the values of α and r are given. Similarly, this is the case of a bistable soliton solution. When $\alpha = -3/20r^2$, we obtain $\beta = 1/40r^2$, $A_0 = \sqrt{2}$, $\delta_0 = 1.1$. No solution is found for $\alpha < -3/20r^2$.

D. $S_{\beta_2} < 0$ and $S_{n_2} < 0$

In this case a soliton is in the anomalous second-order dispersion ($\beta_2 < 0$) and the negative nonlinear coefficient n_2 regime, and Eq. (3) can be rewritten as

$$-\frac{\partial}{\partial \xi} u = -\frac{i}{2}\frac{\partial^2 u}{\partial \tau^2} - i\beta \frac{\partial^4 u}{\partial \tau^4} + i|u|^2 u - i\alpha |u|^4 u. \quad (13)$$

The dark optical soliton solution can be written as

$$u(\xi, \tau) = A_0 r \tanh(r\tau)\exp(-i\delta_0 r^2 \xi). \quad (14)$$

Substituting Eq. (14) into Eq. (13), we obtain the following relations for the soliton parameters:

$$\delta_0 = 1 - 16\beta r^2, \quad (15a)$$

$$A_0 = (1 - 40\beta r^2)^{1/2}, \quad (15b)$$

$$\alpha = -\frac{24\beta}{A_0^4}. \quad (15c)$$

When $\alpha > 0$ and $\beta < 0$, we have $\delta_0 > 1$ and $A_0 > 1$. When the condition $0 < \alpha < 3/20r^2$ is fulfilled, we obtain

$$\beta = \frac{-(12/\alpha - 40r^2) \pm \sqrt{(12/\alpha)(12/\alpha - 80r^2)}}{1600r^4};$$

that is, there are two sets of β, A_0, and δ_0 when the values of α and r are given. This is also the case of a bistable soliton solution. When $\alpha = 3/20r^2$, we obtain $\beta = -1/40r^2$, $A_0 = \sqrt{2}$, and $\delta_0 = 1.1$. On the other hand, $\alpha < 0$ and $\beta > 0$, we obtain $\delta_0 < 1$, $A_0 < 1$, and

$$\beta = \frac{-(12/\alpha - 40r^2) - \sqrt{(12/\alpha)(12/\alpha - 80r^2)}}{1600r^4}.$$

Hence, when the values of α and r are given, we have only one set of β, A_0, and δ_0.

4. NUMERICAL RESULTS

The type of nonlinear refractive-index change $\Delta n(|A|^2) = n_2|A|^2 + n_4|A|^4$ may be attributed to various processes. To obtain a large effect of the quadratic intensity-dependent term, we must have a smaller value of n_2 and a larger value of n_4. The optical fiber doped with two appropriate materials can satisfy such requirements. One dopand should have a positive sign $n_2{}^{(a)} > 0$ and a high saturation intensity $I_{\text{sat}}^{(a)}$, and the other dopand should have a negative sign $n_2{}^{(b)} < 0$ with nearly the same magnitude, $|n_2{}^{(a)} - |n_2{}^{(b)}|| < 0.1|n_2{}^{(b)}|$, and a low saturation intensity $I_{\text{sat}}^{(b)}$ such that $I_{\text{sat}}^{(b)} \ll I_{\text{sat}}^{(a)}$ or vice versa. The nonlinear refractive-index change can be written as

$$\Delta n(|A|^2) = n_2{}^{(a)}|A|^2 - |n_2{}^{(b)}| \frac{|A|^2}{1 + |A|^2/I_{\text{sat}}^{(b)}} \quad (16a)$$

or

$$\Delta n(|A|^2) = n_2{}^{(a)} \frac{|A|^2}{1 + |A|^2/I_{\text{sat}}^{(a)}} - |n_2{}^{(b)}||A|^2, \quad (16b)$$

which can be approximately expressed by $\Delta n(|A|^2) = n_2|A|^2 + n_4|A|^4$ with $n_2 = n_2{}^{(a)} - |n_2{}^{(b)}|$, $n_4 = |n_2{}^{(b)}|/I_{\text{sat}}^{(b)}$, or $n_4 = -n_2{}^{(a)}/I_{\text{sat}}^{(a)}$. We obtain

$$\alpha = \frac{|n_2{}^{(b)}|P_0}{|n_2{}^{(a)} - |n_2{}^{(b)}||I_{\text{sat}}^{(b)}}$$

or

$$\alpha = \frac{-n_2{}^{(a)}P_0}{|n_2{}^{(a)} - |n_2{}^{(b)}||I_{\text{sat}}^{(a)}}.$$

Here we consider case A and take $\alpha = 0.2$ and $r = 1$. Then we obtain $\beta = -0.064$, $A_0 = 0.934$, and $\delta_0 = 0.987$. In a typical fiber the parameters used to numerically solve Eqs. (3) are soliton wavelength $\lambda = 1.55\ \mu\text{m}$, $\beta_2 = -0.5\ \text{fs}^2/\text{mm}$, $\beta_3 = 0\ \text{fs}^3/\text{mm}$, $\beta_4 = -550\ \text{fs}^4/\text{mm}$, $n_2 = 2.3 \times 10^{-20}\ \text{m}^2/\text{W}$, and the soliton pulse width $T_W = 150$ fs. The effective fiber cross section is $50\ \mu\text{m}^2$. The dispersion length L_D is 14.5 m. The initial condition is $u(\xi = 0, \tau) = A_i\ \text{sech}(\tau)$, where A_i is initial amplitude. Figure 4 shows the pulse shapes of the modified soliton, $A_i = 0.934$, and the conventional soliton, $A_i = 1$, at $\xi = 30L_D$. For input modified soliton, it

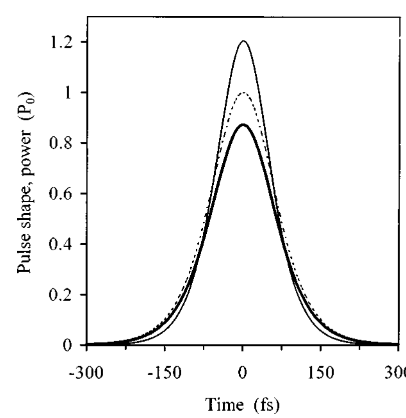

Fig. 4. Pulse shapes of the modified soliton (solid curve), $A_i = 0.934$, and the conventional soliton (thick solid curve), $A_i = 1$, at $\xi = 30L_D$. The dashed curve shows the initial conventional soliton.

is numerically shown that the pulse shape remains the same initial pulse shape and its change of the phase is consistent with the analytic result. Therefore the modified soliton is a stable soliton solution of Eq. (4). For the input conventional soliton, the pulse shape changes as it propagates along the fiber. In addition, the Raman effect can be introduced by modifying of the nonlinear term as follows:[21]

$$|u|^2u \rightarrow |u|^2u - \frac{T_R}{T_0}\, u \,\frac{\partial |u|^2}{\partial \tau},$$

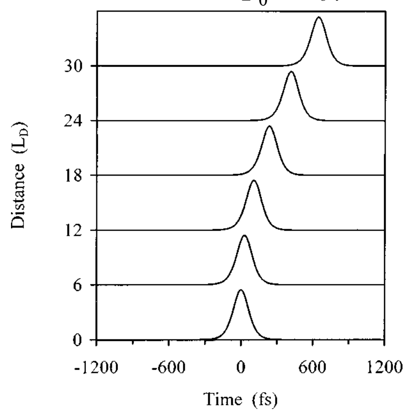

Fig. 5. Power evolution of pulse shapes of the modified soliton, including the Raman effect.

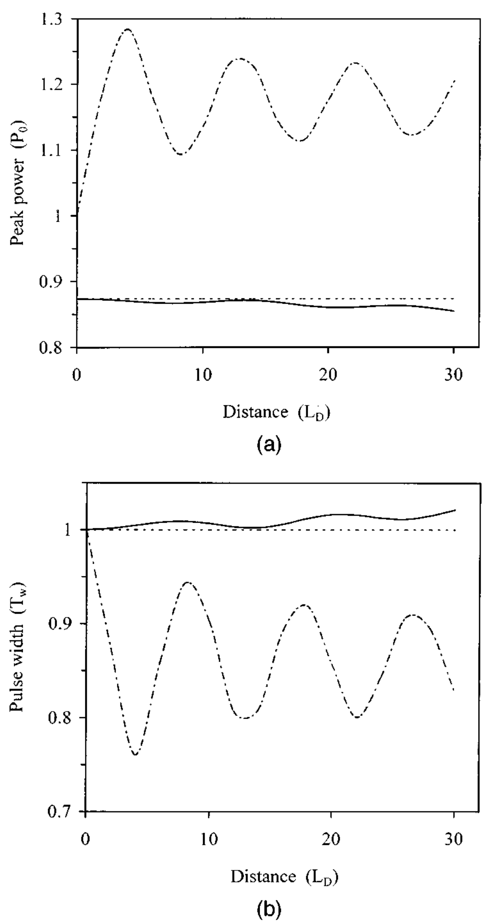

Fig. 6. (a) Peak power and (b) pulse width versus distance for the conventional soliton (dashed-dotted curve) and the modified soliton without (dashed curve) and with (solid curve) the Raman effect.

where the Raman effect contributed by the $|u|^4u$ term is neglected and T_R is the slope of the Raman gain profile at the carrier frequency. Here we take $T_R = 3$ fs. In Fig. 5 we show the power evolution of pulse shapes, including the Raman effect. One can see that the pulse shape is quasi stable and there is a time delay. Figure 6 shows the peak power and pulse width versus distance for the conventional soliton and the modified soliton without and with the Raman effect. For the modified soliton the pulse width and the peak power do not change when the Raman effect is not considered. When the Raman effect is included, the change of the pulse width and peak power is ~2.2% around $30L_D$. However, for the case of the conventional soliton, its pulse width and peak power vary along the fiber.

5. CONCLUSION

In conclusion, we have shown that soliton exists in a dispersion-flattened fiber of which third-order dispersion is nil and fourth-order dispersion exists with linear and quadratic intensity-dependent refractive-index changes. We have obtained four soliton solution forms by four possible sign combinations of the second-order dispersion and the Kerr coefficient. These solution forms include two types of bright soliton solutions and two types of dark soliton solutions. The peak power and the period of the soliton solution are determined by the magnitude of the fourth-order dispersion parameter, which is related to the quadratic intensity-dependent nonlinearity coefficient. It is found that there are bistable solitons in certain ranges. We have numerically shown that a soliton in the anomalous second-order dispersion and positive Kerr coefficient regime is stable and becomes quasi stable when the Raman effect is considered.

ACKNOWLEDGMENT

This research is partially supported by the National Science Council, China, under contract NSC 87-2215-E-009-014.

REFERENCES

1. A. Hasegawa and F. Tappert, "Transmission of stationary nonlinear optical pulses in dispersive dielectric fibers," Appl. Phys. Lett. **23**, 142 (1973).
2. L. F. Mollenauer, R. H. Stolen, and J. P. Gordon, "Experimental observation of picosecond pulse narrowing and solitons in optical fibers," Phys. Rev. Lett. **45**, 1095 (1980).
3. A. Hasegawa, *Optical Solitons in Fibers*, Vol. 116 of Springer Tracts in Modern Physics (Springer-Verlag, New York, 1989).
4. G. P. Agrawal, *Nonlinear Fiber Optics*, 2nd ed. (Academic, New York, 1995).
5. P. K. A. Wai, C. R. Menyuk, Y. C. Lee, and H. H. Chen, "Nonlinear pulse propagation in the neighborhood of the zero-dispersion wavelength of monomode optical fibers," Opt. Lett. **11**, 464 (1986).
6. P. K. A. Wai, H. H. Chen, and Y. C. Lee, "Radiations by solitons at the zero group-dispersion wavelength of single-mode optical fibers," Phys. Rev. A **41**, 426 (1990).
7. M. Karisson and A. Hook, "Soliton-like pulses governed by fourth-order dispersion in optical fibers," Opt. Commun. **104**, 303 (1994).
8. M. Piché, J. F. Cormier, and X. Zhu, "Bright optical soliton

in the presence of fourth-order dispersion," Opt. Lett. **21**, 845 (1996).
9. N. N. Akhmediev, A. V. Buryak, and A. Hook, "Radiationless optical soliton with oscillating tails," Opt. Commun. **110**, 540 (1994).
10. N. N. Akhmediev and A. V. Buryak, "Interaction of solitons with oscillating tails," Opt. Commun. **121**, 109 (1995).
11. A. Höök and M. Karlsson, "Ultrashort solitons at the minimum-dispersion wavelength: effects of fourth-order dispersion," Opt. Lett. **18**, 1388 (1993).
12. J. P. Gordon, "Theory of the soliton self-frequency shift," Opt. Lett. **11**, 662 (1986).
13. R. H. Stolen and W. J. Tomlinson, "Raman response function of silica-core fibers," J. Opt. Soc. Am. B **6**, 1159 (1989).
14. E. A. Golovchenko, E. M. Menyuk, A. M. Prokhorov, and V. N. Serkin, "Decay of optical solitons," JETP Lett. **42**, 87 (1985).
15. N. Tzoar and M. Jain, "Self-phase modulation in long-geometry optical waveguides," Phys. Rev. A **23**, 1266 (1981).
16. G. Yang and Y. R. Shen, "Spectral broadening of ultrashort pulses in a nonlinear medium," Opt. Lett. **9**, 510 (1984).
17. S. Gatz and J. Herrmann, "Soliton propagation materials with saturable nonlinearity," J. Opt. Soc. Am. B **8**, 2296 (1991).
18. S. Gatz and J. Herrmann, "Soliton propagation and soliton collision in double-doped fibers with a non-Kerr-like nonlinear refractive index change," Opt. Lett. **17**, 484 (1992).
19. S. Gatz and J. Herrmann, "Soliton collision and soliton fusion in dispersive materials with a linear and quadratic intensity depending refractive index change," IEEE J. Quantum Electron. **28**, 1732 (1992).
20. A. E. Kaplan, "Bistable solitons," Phys. Rev. Lett. **55**, 1291 (1985).
21. J. M. Hickmann, S. B. Cavalcanti, N. M. Borges, E. A. Gouveia, and A. S. Gouveia-Neto, "Modulational instability in semiconductor-doped glass fibers with saturable nonlinearity," Opt. Lett. **18**, 182 (1993).