Journal of Nonlinear Optical Physics & Materials
Vol. 8, No. 4 (1999) 477–481

SOLITON DYNAMICS IN TWO WAVEGUIDES WITH DISPERSION PROPERTIES OF THE LINEAR COUPLING COEFFICIENT

R. S. KAMBUROVA and M. T. PRIMATAROWA
Institute of Solid State Physics, Bulgarian Academy of Sciences,
Sofia 1784, Bulgaria

Received 6 August 1999

The soliton dynamics in two parallel waveguides is investigated numerically with the dispersion of the linear coupling coefficient taken into account. It is shown that the new terms in the system of coupled nonlinear equations which describe the switching process have an important influence on the soliton propagation for short pulses in directional couplers. In this case, depending on the value of the coupling-coefficient dispersion, an effect of distortion or breakup of the initial pulse can be observed.

All-optical switching devices have been the subject of a current increased interest because they can potentially operate at speeds much higher than those possible with electronic or optoelectronic switches. The directional couplers were proposed as a building block for all optical processing.[1–7] They are designed on the base of dual-core optical fiber consisting of two identical parallel cores. It is known that the energy of the pulses can be transferred back and forth between the cores of the coupler. This process of energy redistribution is called switching. An important idea in the nonlinear switching is to use soliton pulses, which maintain their shape in the presence of weak perturbation, as a result of the balance between dispersion and nonlinear effects. They provide high switching speed as high as the femtosecond range.

The soliton propagation dynamics in directional couplers is described by the system of coupled nonlinear equations. These equations are derived at first for monochromatic continuous waves[8] and then are modified for soliton pulses.[1]

There have been many theoretical and numerical studies[1–7] on the system of two coupled nonlinear equations with linear coupling term. In all of them it is assumed that the distortion of pulses is due only to the group-velocity dispersion which is represented by time-varying terms. Recently, Chiang included dispersion of the linear coupling coefficient[9] and derived a system with two new time-varying terms referred as first-order coupling-coefficient dispersion and second-order coupling-coefficient dispersion.[10] The influence of these new terms was estimated analytically when the nonlinear terms are neglected. It was shown that the coupling-coefficient dispersion can cause pulse distortion or even pulse breakup and in general provides much more significant effects than the group velocity dispersion. In the present paper we investigate numerically the whole set of coupled nonlinear equations of the soliton dynamics.

We consider two parallel nonlinear identical waveguides, which are single-moded when separated. The propagation of pulses in this configuration when linear coupling between the waveguides is present can be described by the following system of modified nonlinear Schrödinger equations:[10]

$$\begin{aligned} &i\left(\frac{\partial a_1}{\partial Z} + R'\frac{\partial a_2}{\partial T}\right) + \frac{1}{2}\frac{\partial^2 a_1}{\partial T^2} + Ra_2 - \frac{R''}{2}\frac{\partial^2 a_2}{\partial T^2} + |a_1|^2 a_1 = 0\,, \\ &i\left(\frac{\partial a_2}{\partial Z} + R'\frac{\partial a_1}{\partial T}\right) + \frac{1}{2}\frac{\partial^2 a_2}{\partial T^2} + Ra_1 - \frac{R''}{2}\frac{\partial^2 a_1}{\partial T^2} + |a_2|^2 a_2 = 0\,. \end{aligned} \tag{1}$$

Here $a_1(Z,T)$ and $a_2(Z,T)$ are the electric field envelopes in the two waveguides and R is the linear coupling coefficient between them. R' and R'' are due to the first-order and the second-order coupling-coefficient dispersion, respectively. Z and T are normalized length and time variables connected with a coordinate system moving at the common group velocity. We assume that the nonlinearity is connected with the Kerr effect.

When R' and R'' are set to zero (1) turns to the well-known system which describes the soliton dynamics in directional couplers.[1–7] In this case we have power transfer back and forth between cores. If a two-core fiber coupler operates in a switching regime the initial pulse is launched into one of the two cores. The switching phenomenon can be characterized by the parameter coupling length $L_c = \pi/2R$. The coupling length is the shortest distance needed for maximum power transfer from one waveguide to the other. The switching depends on the power of the initial pulse and the linear parameter. Our numerical results are shown in Fig. 1 where

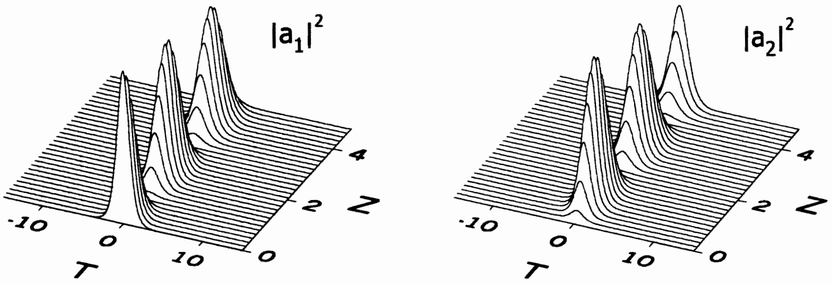

Fig. 1. Stable soliton switching for $R = 2.5$ and $R' = R'' = 0$. T is measured in soliton widths and Z — in coupling lengths L_c.

the initial pulse has the form of the fundamental soliton

$$a_1(Z=0,T)=\text{sech}(T), \qquad a_2(Z=0,T)=0\,. \tag{2}$$

The linear coupling coefficient has the value for which the condition for perfect soliton switching is fulfilled.[3,5,6]

The real pulse consists of continuous waves and as they have slightly different coupling coefficients they will have slightly different coupling lengths. This is the physical origin of the coupling-coefficient dispersion which leads to the distortion of the initial pulse. This effect should be more significant for shorter pulses. To show the role of the first-order coupling-coefficient dispersion R', we neglect R and R'' and investigate the propagation of the initial soliton pulse with the form (2). As can be seen in Fig. 2 the presence of R' leads to a transfer of the energy from the first to the second waveguide until the two parts become equal. Each part breaks into two identical pulses and they walk off with the distance. The shortest distance for which the two components in each waveguide do not overlap is defined as the walk-off length $L_w = 1/2R'$. They possess a quarter of the input power but this quantity is not sufficient to form stable solitons and a broadening of the shape is observed.

Further we shall consider the propagation of the initial pulse for various pulsewidths using values for the constants which are typical for silica fibers at the wavelength 1.5 μm.[9,10] For picosecond pulsewidth the inequality $R'' \ll R' \ll R$ is fulfilled[10] and the R terms are dominant. The influence of R' and R'' terms on the switching process is not significant and a distortion of the pulse shape may be caused only by the group-velocity dispersion. So if the pulses are not short enough the R' and R'' terms can be omitted. Our numerical simulations confirm this assumption. In this case the soliton dynamics remains as in Fig. 1.

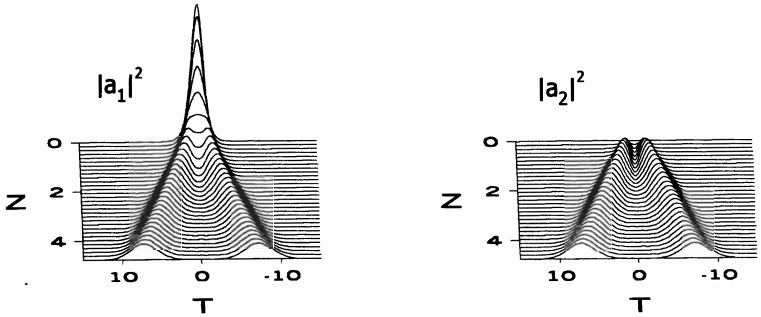

Fig. 2. Evolution of a soliton pulse launched into the first core for $R' = 2.5$ and $R = R'' = 0$. The units for T and Z are the same as in Fig. 1.

For pulsewidths in the range of femtoseconds the values for R' and R'' are comparable with those for R and the corresponding terms should to be taken into account. We have performed numerical simulations for $R = 2.5$ and $R' = 0.125$

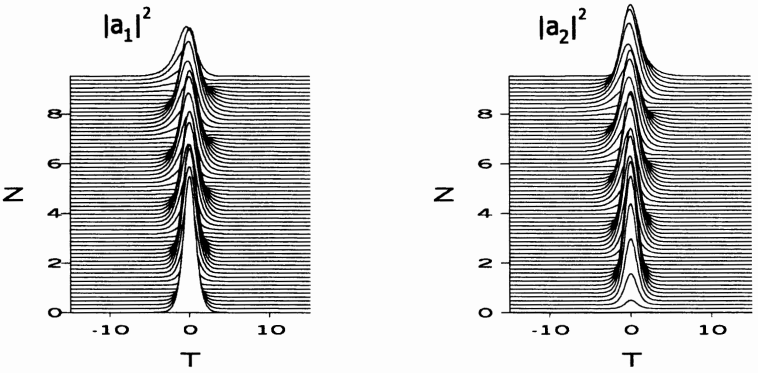

Fig. 3. Stable soliton switching for $R = 2.5$, $R' = 0.125$ and $R'' = 0$. The units for T and Z are the same as in Fig. 1.

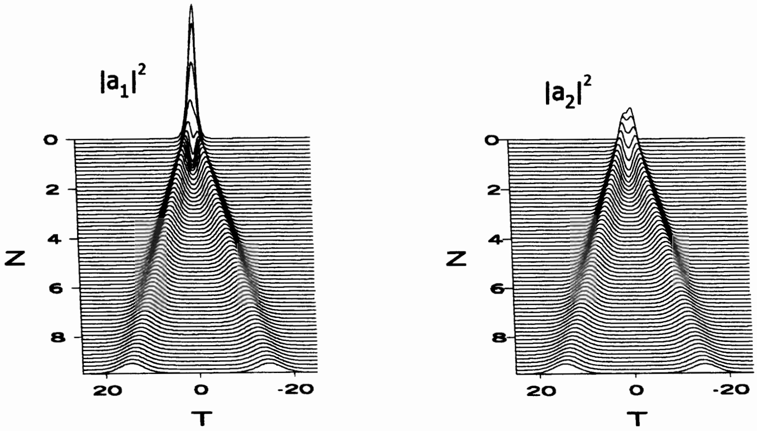

Fig. 4. Soliton propagation for $R = R' = 2.5$ and $R'' = 0$. The units for T and Z are the same as in Fig. 1.

which are relevant for a pulsewidth of $10fs$. In this case the walk-off length is bigger than the coupling length $L_w = 6.4L_c$ and the breaking is not observed (Fig. 3), but the shape of the input pulse changes over a distance longer than L_w.

For $R = R' = 2.5$ which corresponds to a pulsewidth of $0.5fs$ the walk-off length is smaller than the coupling length $L_w = 0.32L_c$. The launched soliton is decomposed within one coupling length into two pulses with identical shapes in each waveguide (Fig. 4). In this case the dispersion of the first-order linear-coupling is predominant. The inclusion of the R'' terms results in the different shape of the two components (Fig. 5).

We would like to point out that for values in the range $0.125 < R' < 2.5$ the linear-coupling dispersion begin to play an important role and leads to much more significant effects than the group-velocity dispersion. In this case the breaking up is not observed but the shape of the initial soliton changes strongly and over a distance of a few L_c it can be fully destroyed.

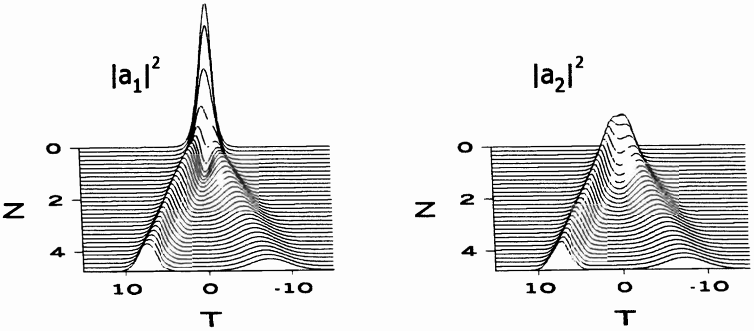

Fig. 5. Time evolution of a soliton for $R = R' = 2.5$ and $R'' = 0.25$. The units for T and Z are the same as in Fig. 1.

We have investigated the soliton switching in a directional coupler consisting of two parallel single-mode waveguides. Our numerical studies of the system of coupled nonlinear Schrödinger equations shows that for short pulses the dispersion of the linear coupling coefficient is predominant and has to be taken into account. In this case, depending on the value of the first-order coupling-coefficient dispersion, an effect of distortion or breakup of the initial pulse can be observed.

Acknowledgments

We are grateful to Dr. K. T. Stoychev for a critical reading of our manuscript. This work is supported in part by the National Science Foundation of Bulgaria under Grant No. F810.

References

1. S. Trillo, S. Wabnitz, E. M. Wright and G. I. Stegeman, *Opt. Lett.* **13**, 672 (1988).
2. F. Kh. Abdullaev, R. M. Abrarov and S. A. Darmanyan, *Opt. Lett.* **14**, 131 (1989).
3. C. Paré and M. Florjańczyk, *Phys. Rev.* **A41**, 6287 (1990).
4. J. M. Soto-Crespo and E. M. Wright, *J. Appl. Phys.* **70**, 7240 (1991).
5. P. L. Chu, G. D. Peng and B. A. Malomed, *Opt. Lett.* **18**, 328 (1993).
6. Y. S. Kivshar, *Opt. Lett.* **18**, 7 (1993).
7. N. Akhmediev and A. Ankiewicz, *Phys. Rev. Lett.* **70**, 2395 (1993).
8. S. M. Jensen, *IEEE J. Quantum Electron.* **18**, 1580 (1982).
9. K. S. Chiang, *Opt. Lett.* **20**, 997 (1995).
10. K. S. Chiang, *IEEE J. Quantum Electron.* **33**, 950 (1997).