All-optical soliton self-switching in a fiber coupler with saturating nonlinearity via phase control

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Abstract: A numerical study of phase controlled soliton self-switching in a fiber coupler with saturating nonlinearity is reported. It has been observed that it is crucial to control the saturation parameter in order to achieve useful transmission characteristics. The influence of perturbative effects, like cross-phase modulation, third-order dispersion, Raman effect, and self steepening effect, are also included.

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Nonlinear directional couplers have been studied extensively in the context of all-optical soliton switching after the pioneering work of Jensen [1], Maier [2] and Trillo *et al.* [3]. Since the work of Trillo *et al.* [3] there has been a great deal of activity in studying various aspects of soliton switching in NLDCs [4-17]. Jensen and Maier showed that one can switch a continuous signal from one core to the other by varying the input power of the signal. The idea when applied to pulse switching led to pulse distortion and breakup, resulting in inefficient switching. Trillo *et al.* [3] showed that pulse break up could be avoided, if one used soliton pulse as a signal. Switching of soliton can also be achieved by controlling the phase of the input signal [4]. Recently a thorough study of this aspect of switching is carried out in details by Sarma and Kumar [5], however their study restricted completely to the case of Kerr nonlinearity only. It has been observed that fibers made of silica glass doped with semi-conductor or organic crystallites do not exhibit Kerr nonlinearity [6, 8-10]. For such fibers nonlinear addition to the refractive index saturates even at moderate powers and the corresponding nonlinearity coefficient n_2 has values several orders of magnitude higher than for pure silica glass [18]. In this work we are addressing this important issue of saturation nonlinearity and discuss soliton self-switching in a fiber coupler made of silica glass doped with semi-conductor or organic crystallites. This study may also be applicable to highly nonlinear dual-core holey fiber coupler [10].

We consider a homogeneous and isotropic nonlinear directional coupler made of silica glass doped with semi-conductor or organic crystallites. The pulse evolution equation, known as the coupled nonlinear Schrödinger equations (CNLSE), inside the coupler is derived in the framework of the coupled mode formalism [18], using the standard slowly varying envelope approximation.

$$i\frac{\partial A_1}{\partial z}-\frac{\beta_2}{2}\frac{\partial^2 A_1}{\partial T^2}-i\frac{\beta_3}{6}\frac{\partial^3 A_1}{\partial T^3}+\left(\gamma|A_1|^2+\chi|A_2|^2\right)A_1+\frac{i}{\omega_0}\frac{\partial}{\partial T}\left(|A_1|^2A_1\right)-T_RA_1\frac{\partial|A_1|^2}{\partial T}+C_0A_2=0 \quad (1)$$

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where A_1 and A_2 are the slowly varying pulse envelopes in core1 and core2, respectively. Here, $\gamma \approx \gamma_0(1-b_s|A|^2)$, $\gamma_0 = n_2\omega \; / c\, A_{eff}$ is the nonlinear parameter, where n_2 is the nonlinear Kerr-coefficient, c is the speed of light in free space and A_{eff} is the effective core area. Also, b_s is the saturation parameter governing the power level at which the nonlinearity begins to saturate. (For detailed discussion on the saturation of the nonlinearity, refer to the references [19, 20]) β_2 and β_3 are the 2nd and 3rd order dispersion coefficients, respectively. The sixth and the seventh terms in equations (1) and (2) take into account the self-steepening and the intrapulse Raman scattering, respectively. T_R is the Raman response time. C_0 is the coupling constant. Using the well-known soliton units [18],

$$U_1 = \frac{A_1}{\sqrt{P_0}}, U_2 = \frac{A_2}{\sqrt{P_0}}, \xi = \frac{z}{L_D}, \tau = \frac{t}{T_0} \tag{3}$$

where T_0 is the width of the incident pulse, $L_D = T_0^2/|\beta_2|$ is the dispersion length, P_0 is the *input* pulse peak power. Equations (1) and (2) can be written in the following normalized form:

$$i\frac{\partial u_1}{\partial \xi} + \frac{1}{2}\frac{\partial^2 u_1}{\partial \tau^2} - i\delta_3\frac{\partial^3 u_1}{\partial \tau^3} + (|u_1|^2 + \chi|u_2|^2)u_1 - s|u_1|^4 u_1 + is_1\frac{\partial}{\partial \tau}(|u_1|^2 u_1) - \tau_R u_1\frac{\partial |u_1|^2}{\partial \tau} + \kappa_0 u_2 = 0, \tag{4}$$

$$i\frac{\partial u_2}{\partial \xi} + \frac{1}{2}\frac{\partial^2 u_2}{\partial \tau^2} - i\delta_3\frac{\partial^3 u_2}{\partial \tau^3} + (|u_2|^2 + \chi|u_1|^2)u_2 - s|u_1|^4 u_1 + is_1\frac{\partial}{\partial \tau}(|u_2|^2 u_2) - \tau_R u_2\frac{\partial |u_2|^2}{\partial \tau} + \kappa_0 u_1 = 0. \tag{5}$$

where $u_1 = NU_1$ and $u_2 = NU_2$. N is known as the order of the soliton. The parameters N, δ_3, s_1, τ_R and κ_0 are defined as

$$N^2 = \frac{L_D}{L_{NL}} = \frac{\gamma P_0 T_0^{\;2}}{|\beta_2|}\;,\quad \delta_3 = \frac{\beta_3}{6|\beta_2|T_0}, s_1 = \frac{1}{\omega_0 T_0}\;,\quad \tau_R = \frac{T_R}{T_0}\;, \kappa_0 = C_0 L_D$$

where the nonlinear length is given by $L_{NL} = (1/\gamma P_0)$. Thus, κ_0, δ_3, s_1 and τ_R, respectively, are, the normalized linear coupling coefficient, TOD coefficient, self-steepening coefficient, and Raman co-efficient. s is a dimensionless parameter, $s = b_s|\beta_2|/\gamma_0 T_0^2$ called the normalized saturation parameter [10]. The above system of CNLSEs is the basic system of equations in this work.

We solve the set of Eqs. (4) and (5) numerically by the split-step Fourier method for the linear dispersive part and by the fourth-order Runge-Kutta method, for the nonlinear part with auto-control of the step size for a given accuracy of the results.

We calculate the transmission coefficient T, representing the fractional output energy or equivalently output fractional power in the first core after propagation of one coupling length of the coupler by the soliton pulse, according to the formula

$$T = \frac{\int_{-\infty}^{\infty} |u_1(\xi,\tau)|^2 d\tau}{\int_{-\infty}^{\infty} \left(|u_1(\xi,\tau)|^2 + |u_2(\xi,\tau)|^2\right) d\tau} \tag{6}$$

The initial conditions for our numerical integration are [4]

$$u_1 = u_0 \sec h(\tau),$$
$$u_2 = \frac{u_0}{\sqrt{f}} \sec h(\tau) \exp(i\phi), \quad (7)$$

where $u_0 = \sqrt{4\kappa_0 p_0 / 1-\chi}$, p_0 is the input peak power of the soliton.

The initial conditions correspond to the case when a soliton of a given pulse duration is launched into the first core while a weak signal of the same pulse duration, having a peak power ratio f and an initial relative phase of ϕ, is launched in the second core. In this context, it should be noted that in this work we adhere to the usual notion of switching in which a signal launched into the input core emerges from the same core at the output, after traversing one coupling length inside the coupler. The results are presented in the form of plots of T as a function of the relative phase ϕ of the control pulse. We are taking $f = 5$ and $P_0 = 2.0$ for our study as suggested by the work of Trillo and Wabnitz [4]. The normalized saturation parameter is taken to be $s = 0.1$ following the work of [10]. In this work calculations are done for $\kappa_0 = 0.1$.

In order to see the effect of cross-phase modulation on the transmission characteristics of the coupler, in Fig. 1 we plot transmission versus phase for different values of the XPM parameter. It is observed from Fig. 1 that the transmission characteristic of the coupler is enhanced with increase in the XPM parameter.

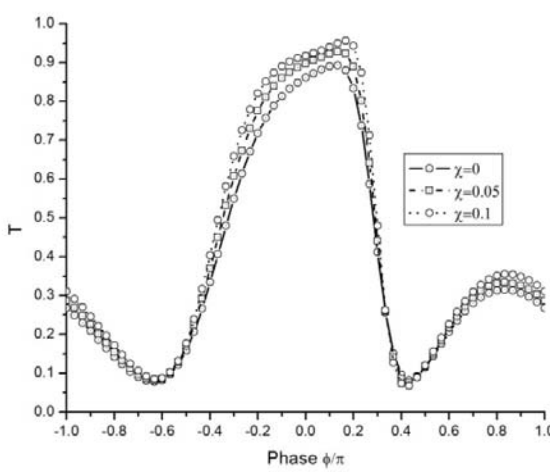

Fig. 1. Transmission vs. phase for different χ

For example it may be observed that, for $\phi = 0.17\pi$, the transmission corresponds to 87%, 92% and 96% for χ =0, 0.05 and 0.1 respectively. It should be noted that the cross-phase modulation parameter is very small in practice for a fiber coupler, it cannot be increased indefinitely [21]. The effect of third-order dispersion, the Raman and the self-steepening one can also be studied in the similar way. In Figs. 2-4 we depict the transmission coefficient a function of the phase of the control pulse in the presence of third-order dispersion, the Raman effect and the self-steepening effect respectively.

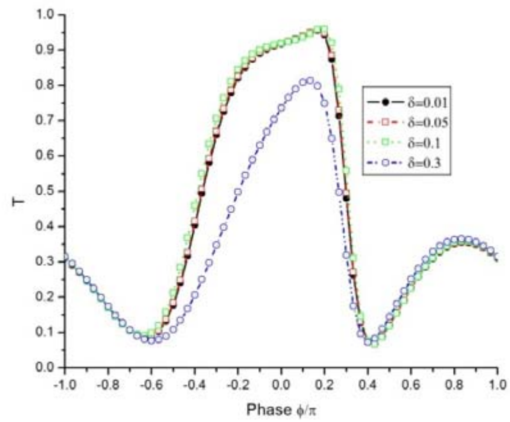

Fig. 2. Transmission vs. phase for different TOD coefficient

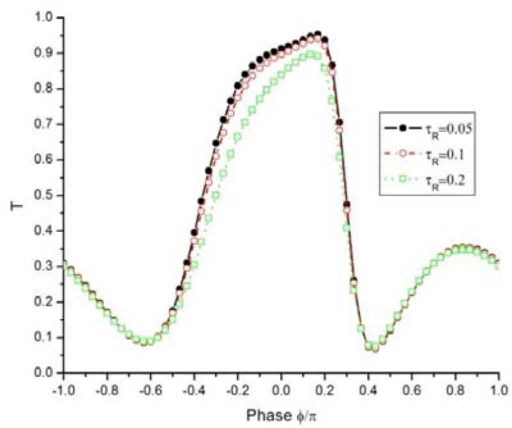

Fig. 3. Transmission vs. phase for different Raman coefficient

It can be easily observed from these figures that the transmission characteristics of the coupler get deteriorated with increase in the TOD and Raman coefficient. However the presence of self-steepening effect has no influence on the switching characteristics of the coupler. In order to find the role of the normalized saturation parameter on the switching characteristics of the coupler distinctly, in Fig. 5, we plot the transmission as a function of the saturation parameter in the simultaneous presence of all the perturbative effects. We have taken the following optimum parameters for our computation: $\chi = 0.1, \delta = 0.05; \tau_R = 0.1; s_1 = 0.1$ and $\phi = 0.17\pi$. It can be observed from Fig. 5 that as long as we keep the normalized saturation parameter below 0.15 we get fairly good transmission characteristics. This parameter may be controlled either by choosing the pulse width of the soliton judiciously or by taking the appropriate doping material.

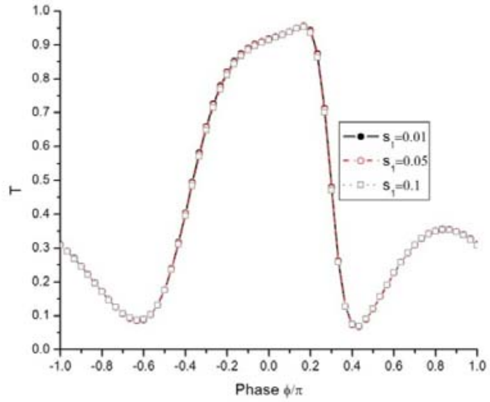

Fig. 4. Transmission vs. phase for different self-steepening coefficient.

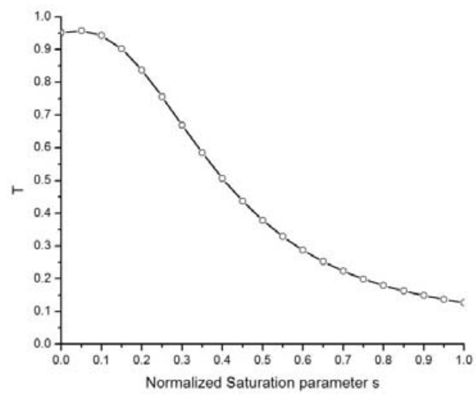

Fig. 5. Transmission vs. saturation parameter.

Finally to check the stability of the soliton pulse during its evolution inside the coupler, in Figs. 6 and 7 we plot the spatio-temporal evolution of the pulse in core 1 and 2 respectively. It is easily noticed that the

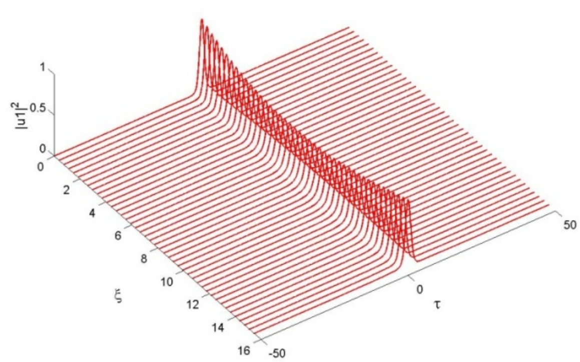

Fig. 6. Spatio-temporal evolution of soliton pulse in core 1 of the coupler.

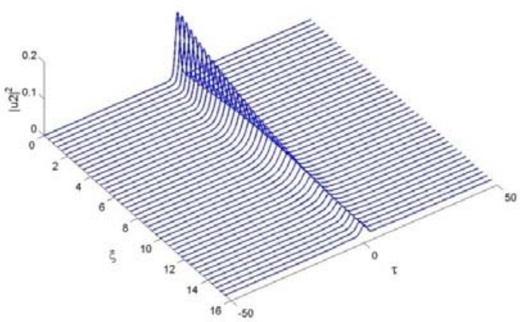

Fig. 7. Spatio-temporal evolution of soliton pulse in core 2 of the coupler.

soliton is preserved and stable inside the coupler during its evolution.

In this work we have carried out a numerical study of phase induced soliton self-switching in a fiber coupler with saturating nonlinearity. It has been observed that it is crucial to control the saturation parameter in order to achieve useful transmission characteristics. The influence of perturbative effects like XPM, TOD, Raman and self steepening is also carried out. It is found that while XPM enhances the switching characteristics, TOD and Raman influences in a negative way. Self-steepening has absolutely no effect on the transmission characteristics of the coupler. It is possible to use this coupler as a useful switching device if the parameters and phase of the control pulse are chosen judiciously.

References

1. S. M. Jensen, *IEEE J. Quantum Electron.* **18**, 1580 (1982).
2. A. A. Maier, *Sov. J. Quantum Electron.* **12**, 1490 (1982).
3. S. Trillo, S. Wabnitz, E. M. Wright, and G. I. Stegeman, *Opt. Lett.* **13**, 672 (1988).
4. S. Trillo and S. Wabnitz, *Opt. Lett.* **16**, 1 (1991).
5. A. K. Sarma and A. Kumar, *Opt. Eng.* **46**, 115005 (2007).
6. H. Hatami-Hanza, P. L. Chu, and G. D. Peng, *Opt. Quantum Electron.* **26**, 365 (1994).
7. I. M. Uzunov, R. Muschall, M. Gölles, Y. S. Kivshar, B. A. Malomed, and F. Lederer, *Phys. Rev. E* **51**, 2527 (1995).
8. B. V. Gisin, R. Driben, and B. A Malomed, *J. Opt. B* **6**, 259 (2004).
9. L. Albuch and B.A. Malomed, *Math. Commun. Simul.* **74**, 312 (2007).
10. A. K.Sarma, *Jpn. J. Appl. Phys. 1* **47**, 5493 (2008).
11. Y. Wang and W. Wang, *J. Lightwave Technol.* **24**, 1041 (2006).
12. A. K. Sarma, *Optik*, *in press.*
13. A. Kumar and A. K. Sarma, *Jpn. J. of Appl. Phys.* **44**, 8498 (2005).
14. I. M. Skinner, G. D. Peng, B. A. Malomed, and P. L. Chu, *Opt. Comm.* **113**, 493 (1995).
15. B. A. Umarov, F. Kh. Abdullaev, and M. K. B. Wahiddin, *Opt. Comm.* **162**, 340 (1999).
16. B. A. Malomed, I. M. Skinner, R. S. Tasgal, *Opt. Comm.* **139**, 247 (1997).
17. P. Shum, K. S. Chiang, and W. A. Gambling, *IEEE J. Quantum Electron.* **35**, 79 (1999).
18. G. P. Agrawal, *Nonlinear Fiber Optics*, 2nd ed., (Academic, New York, 2001).
19. E. Caglioti, S. Trillo, S. Wabnitz, and G. I. Stegeman, *J. Opt. Soc. Am B* **5**, 472 (1988).
20. W. Krolikowski and B. Luther-Davies, *Opt. Lett.* **17**, 1414 (1992).
21. G. P. Agrawal, *Applications of Nonlinear Fiber Optics* (Academic, New York, 2001).