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Pulse–pulse interaction in dispersion-managed fiber systems with nonlinear amplifiers

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Abstract

The pulse–pulse interaction in a dispersion-managed fiber system is studied for the case when a nonlinear gain and spectral filtering are included into the dispersion-gain map. In this system, the pulse of any shape converges quickly to a dispersion-managed soliton. Using the technique of interaction plane, we have found stable bound states of two pulses. The effects we have studied may significantly reduce the chances of pulse coalescence in specially designed optical transmission lines. © 2002 Published by Elsevier Science B.V.

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Recent developments in lightwave transmission systems [1] are stimulated by increasing demands in communication. Dispersion-managed optical transmission systems may greatly improve the transmission capacity of fiber links [2–5]. Periodic variations of dispersion bring the pulse back almost to its original shape after each period [6]. Solitons in such links may exist even when the average dispersion is zero or positive [7,8]. The performance obtained with this technique is beyond the most optimistic expectations. A properly designed pulse periodically resumes its shape for hundreds of periods.

However, there are a few major problems related to dispersion-managed systems. Firstly, there is the problem of initial pulse preparation. It is well known that a dispersion-managed system without gain and loss allows stable pulse propagation. The shape of the stable pulse is close to a Gaussian [9,10], thus allowing an analytical description [11–13]. If initial condition is chosen to be slightly different from the stable pulse, it oscillates chaotically around the stable shape. This chaotic behavior can be a source of noise in the fiber transmission system [14].

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The pulse–pulse interaction in the link is another problem which has not been completely solved [15,16]. Periodic breathing of pulse width in dispersion-managed link leads to a significant overlap between adjacent pulses. This overlap may lead to their fusion causing the loss of information bits. Thirdly, if we are dealing with all optical fiber systems with optical amplifiers periodically located in the line we cannot consider the system to be conservative. We have to take into account periodic changes in gain and loss [17,18]. Clearly, dynamics of dissipative systems is qualitatively different from the dynamics of conservative systems.

These problems can be solved if nonlinear gain and spectral filtering are explicitly introduced into the system. This might require additional elements to be introduced into the system. For example, nonlinear gain (or loss) can be introduced using saturable absorbers very much like in the passively mode-locked laser systems [20–22]. These elements also have nonlinear saturation. Spectral filtering has already been used in experiments [23]. Once introduced, these effects may appreciably improve the quality of the transmission line. The presence of periodic gain and loss converts the pulse to a dissipative soliton which can be viewed as an attractor or the 'mode' of this system. In this instance, the actual shape of the initial pulse does not play a major role, as it will always converge to the 'mode' of the link. Another remarkable feature of such an approach can be better pulse-to-pulse performance. Indeed, we find in this work, that the proper choice of parameters prevents the neighboring solitons from merging. It happens that there is an equilibrium distance, ρ, between the pulses such that, when closer than ρ, the pulses repel each other, while when further apart than ρ they attract. This means that the two pulses never merge together and each can successfully carry a separate bit of information.

To some approximation, the equations describing the pulse propagation in dispersion-managed system become integrable [19]. However, when gain and loss effects are taken into account, the problem can only be solved numerically. We start with the general pulse-propagation equation, which, after both distributed gain and dispersion have been included, takes the form

$$\begin{aligned} &\mathrm{i}\psi_z + \frac{\sigma(z)}{2}\psi_{tt} + |\psi|^2\psi \\ &\quad = \mathrm{i}\delta(z)\psi + \mathrm{i}\epsilon(z)|\psi|^2\psi + \mathrm{i}\beta(z)\psi_{tt} \\ &\qquad + \mathrm{i}\mu(z)|\psi|^4\psi - \nu(z)|\psi|^4\psi, \end{aligned} \tag{1}$$

where z is the propagation distance, t is the retarded time, ψ is the normalized envelope of the optical field, $\sigma(z)$ is the renormalized dispersion, $\delta(z)$ is the linear gain (usually negative, thus indicating loss), $\beta(z)$ is the spectral filtering, $\epsilon(z)$ is the nonlinear gain or loss, $\mu(z)$ represents the saturation of the nonlinear gain, and $\nu(z)$ the saturation of the nonlinearity. We suppose that all z-dependent coefficients except δ and σ are zero in the fiber with negative dispersion and finite in the positive dispersion part (see the numbers in Fig. 1). Linear loss $\delta(z)$ is negative everywhere to prevent the noise generation.

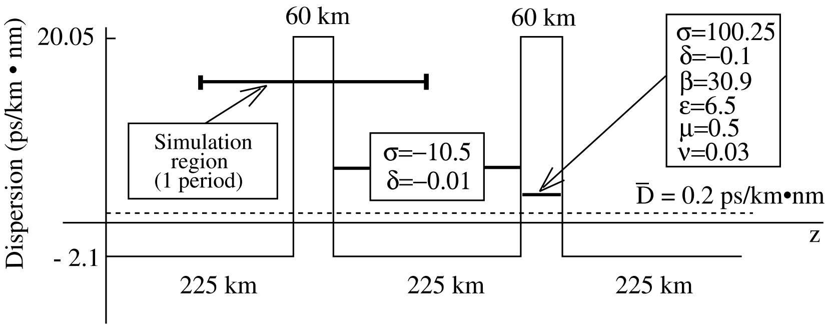

Fig. 1. Dispersion map used in the numerical simulations. This is similar to the dispersion map used in experiments [6]. The values for the parameters on the RHS of Eq. (1) for this numerical simulation are given in rectangular boxes.

As mentioned before, nonlinear saturation does not exist in the present practical transmission lines, as well as nonlinear gain. Like in the laser systems, they must be introduced into the line artificially in the form of saturable absorbers [20–22] or other optical elements. Thus our results predict new phenomena rather than describe the performance of existing transmission lines.

The dispersion map is similar to the one in the work [6] with a slight variation of parameters in order to achieve the best performance (see Fig. 1). The major difference is the addition of periodic gain and loss effects. The values of parameters are shown in two rectangular boxes in Fig. 1. Our numerical simulations show that for this choice of parameters, practically any pulse reasonably close in shape to a dispersion-managed soliton converges very quickly (in around 10–15 periods of the dispersion map) in propagation to a fixed stable shape which then evolves periodically in the link. One period of this evolution is shown in Fig. 2. To represent the profiles, we choose the z-range of evolution shown by the thick solid line in Fig. 1. The final pulse produced by this evolution can be viewed as an attractor for this dynamical system or a nonlinear 'mode' of the system [24].

In order to investigate the interaction between the pulses, we used two of these stable pulses, and located them at a distance from each other which is comparable to the single pulse width. Pulses which are far from each other (at distances larger than two pulse widths) essentially do not interact with each other. If there is a train of such pulses, due to the spectral filtering in the system, all solitons in the train have the same velocity, so jitter can be ignored. Real interaction between the pulses occurs when the distance between the solitons in a pair is close to the soliton width. Maximal interaction occurs when the phase difference between the pulses is $\pi/2$. A bound state appears when, in addition, the solitons are located at some specific distance z_F from each other.

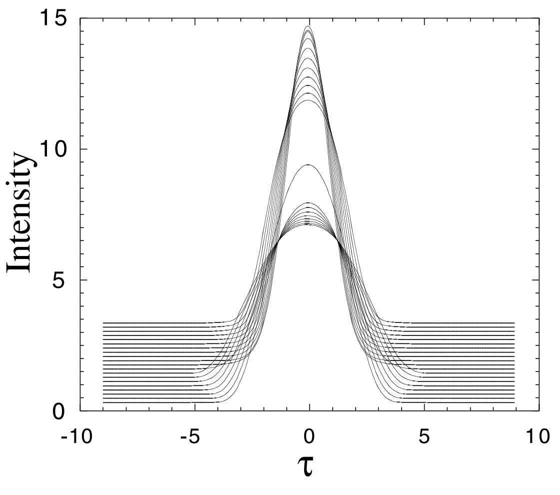

Fig. 2. Single pulse evolution during one period (marked by the solid thick line in Fig. 1) in a dispersion-managed fiber.

We studied these bound states using the interaction plane formalism developed in [25]. Basically, the fact that the pulse parameters are fixed implies that, during the interaction of two of them, only two parameters can change: their separation ρ, and the phase difference between them, ϕ. Thus the phase space here is 2-dimensional, and we may analyze the bound states formed from two solitons, their stability and their global dynamics in this 2-dimensional "interaction plane" [25]. Essentially, the "interaction plane" is a plane of polar co-ordinates with ρ plotted along the radius and ϕ plotted as the polar angle. The possibility of this reduction in the number of degrees of freedom is a unique feature of systems with gain and loss. It does not apply to conservative dispersion-managed systems, where the amplitudes of the solitons can also change, and therefore more sources of instability of the bound states appear.

Fig. 3 shows some trajectories on the interaction plane obtained in our direct numerical simulations of Eq. (1). Initial conditions have been chosen in the form of two stable solitons located at some distance from each other, comparable to the width of each soliton. Any initial condition in this form can be represented as a point in the interaction plane. The value of ρ in further evolution has been calculated as the separation between the maxima of the two pulses and the value of ϕ as the phase difference between the fields at same points. The values of ρ and ϕ oscillate slightly inside each period because of the oscillations of pulse shapes. To remove completely these small effects we have been calculating ρ and ϕ at some point of the period in the dispersion map.

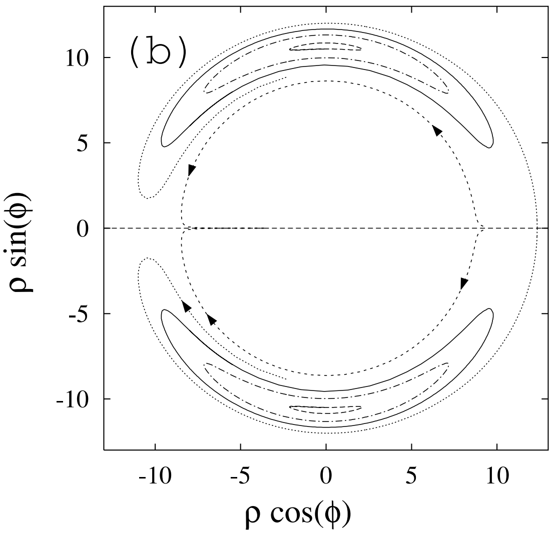

Fig. 3. Trajectories on the interaction plane showing the evolution of ρ and ϕ for a pair of nearest pulses. The trajectories rotate around two singular points, thus showing the existence of two stable foci which correspond to bound states consisting of two pulses.

When the two pulses are located too close to each other, they merge. In fact, there is some critical distance z_{cr} so that if initial point in the interaction plane is located inside the circle of the radius z_{cr}, the trajectory collapses into the center. Trajectories corresponding to such collapse are shown in Fig. 3 using dotted lines. No trajectories corresponding to an interaction exist inside of the circle made by these two lines.

On the other hand, if two pulses are initially separated by a distance which is larger than z_{cr}, the trajectories never go to the center. Instead, they rotate around one of the two fixed points. We can see from this figure that there are, indeed, bound states of two pulses with a phase difference between them of $\pm\pi/2$. When the distance between the pulses and the phase difference between them are not exactly those which correspond to the bound state, these values evolve and the trajectory rotates around one of the foci which corresponds to an exact bound state. Hence, if initially two adjacent pulses in a train are located at a distance which is larger than z_{cr}, then these pulses will never merge, thus ensuring reliable information transmission.

In conclusion, our two main results from this investigation are the following. When the dispersion-managed system has, in addition, spectral filtering and nonlinear gain in the fiber, pulses convert to a dissipative soliton whose properties are qualitatively different from those in conservative systems. In particular:

1. There is no need to prepare pulses for the transmission carefully. Each pulse converges to the shape which can be considered as an attractor or the mode of this nonlinear system.
2. There is a minimal separation between the pulses such that if initially two pulses are located further apart than the critical distance, the two pulses never merge together.

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