Nonlinear Optics, 2000, Vol. 25, pp. 407–412
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Compression of Self-trapped Pulses in Kerr-type Planar Waveguides

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Abstract

The compressors of optical pulses based on a Kerr-type planar waveguide enable one to obtain large compression, assuming that dispersion of the pulse is anomalous. However, the compression is localized in the waveguide (i.e. the distance of propagation on which the width of the pulse is nearly constant and equal to the minimal width, which can be obtained during the propagation of the pulse down the waveguide, is very small). We demonstrate how this can be avoided by introducing a subsidiary pulse, whose dispersion is normal. Based on the numerical solutions of two coupled (2+1)- and (1+1)-dimensional nonlinear Schrödinger equations (NSEs), which model the proposed configuration, we shows that the best parameters of compression can be achieved in the case of vanishing dispersion of the subsidiary pulse, when the self-trapped solutions arise.

Keywords: planar Kerr waveguides, pulse compression.

Currently, there is a large demand for generation of short optical pulses which are useful for a variety of applications such as the measurement of ultrafast physical processes, optoelectronics sampling, generation of ultrafast X-ray radiation and ultrahigh-order harmonics. They can also be used to design spectroscopic and imaging devices for investigations of atomic or molecular systems, including diagnostic and therapeutic tools for microbiology and medicine. Moreover, generation of short optical pulses is of great interest for laser satellite communication, ultrahigh-bit-rate and long distance optical communication, ultrafast optical storage and data process-

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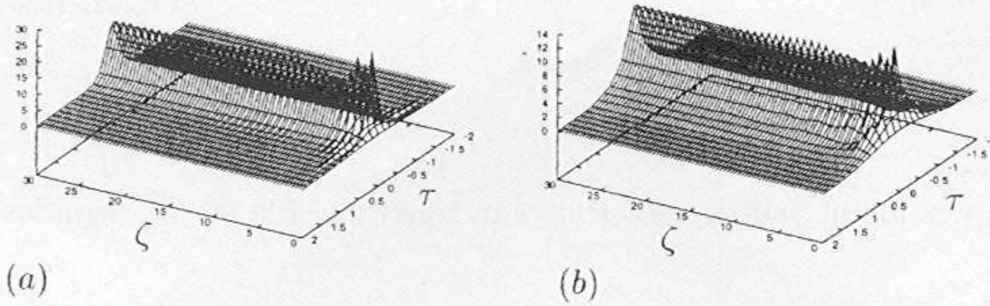

Figure 1: The evolution of the temporal cross-section of the signal pulse (a) co-propagating with the auxiliary pulse (b) (the evolution of the spatial cross-section is very similar), $\kappa_1 = 1.0, \sigma = -1, \kappa_2 = 2.0$.

ing. In the future, short pulses may play a crucial role in a development of all-optical computers. In addition, in some applications, e.g. for nanostructuring, it is essential that pulses are localized not only in time, but also in space. A compressor meeting this requirement can be based, for example, on a Kerr-type bulk medium [1] or a planar waveguide [2, 3] in which a dispersive pulse, with anomalous or normal dispersion, propagates.

This paper is devoted to the study of the compression mechanism of the pulse with anomalous dispersion, propagating together with a subsidiary pulse whose dispersion is neglected due to its large duration. Although, in the configuration under discussion, a simultaneous spatio-temporal compression of pulses can occur, we will consider only the temporal aspect of the compression.

The temporal compression can be characterized by three parameters. The first one, the maximal compression factor, is defined as follows:

$$c_{max} := \frac{w_\tau(0)}{w_{\tau min}(\zeta_{min})}, \quad \delta << 1,$$

where $w_\tau(0)$ is the initial temporal width of the pulse, and $w_{\tau min}$ is the minimal temporal width, which can be achieved during the propagation of the pulse down the waveguide. From the above definition it follows that the minimal temporal width of the pulse takes place at a propagation distance ζ_{min}, which is referred to as the optimal length of the compression. Finally, we define the compression length as the interval of the propagation distance,

$$\Delta\zeta := \{\zeta : w_\tau(\zeta) - \delta w_{\tau min} < w_{\tau min}\},$$

within which the evolution of the pulse does not change significantly, i.e. its temporal width is approximately constant and equals to the minimal width.

The compressor based on a planar waveguide with Kerr-type nonlinearity and a single pulse has been studied in the literature [3, 2]. It was shown that anomalous dispersion of the pulse results in a large compression factor, c_{max}; moreover, spatio-temporal splitting of the pulse, which can occur in the case of normal dispersion, is eliminated. In order to optimize such a compressor (i.e. to obtain c_{max} and $\Delta\zeta$ as large as possible) the values of the parameters describing the system should be just below the threshold of catastrophic self-focusing [4]. When this condition is satisfied the compression length can be quite large, $\Delta\zeta \approx 1$, which allow for a trivial adjustment of the compressor length. However, in this configuration, the maximal compression factor is rather small, $c_{max} \approx 1.5$. Besides, meeting the optimization condition would be, as a matter of fact, quite difficult in practice. This can be explained as follows: for a given medium which constitutes the basic element of the compressor (with a fixed value of the group velocity dispersion and the nonlinear refraction index), and for a fixed wavelength of the pulse, the only free parameter of the system is the energy of the pulse. It means that such a compressor cannot be considered as a universal device, for its operation is limited to pulses with energy belonging to a narrow interval of values (i.e. just below the threshold of catastrophic self-focusing).

In order to improve the operation of the above described compressor we consider that a subsidiary pulse is introduced to the system. Such a configuration was studied in [4], where it was assumed that the subsidiary pulse propagates in normal dispersion regime. It was shown that the optimization of the compressor can be achieved either when (i) the values of the parameters describing the configuration are just below the threshold of catastrophic self-focusing or when (ii) the dispersion of the auxiliary pulse vanishes. In the case (i) the maximal compression factor and the compression length can be, respectively, $2.5 \div 3$ times larger and $1.5 \div 5$ times smaller than the corresponding values in the configuration with a single pulse. However, the compression length in this case is rather large. We will

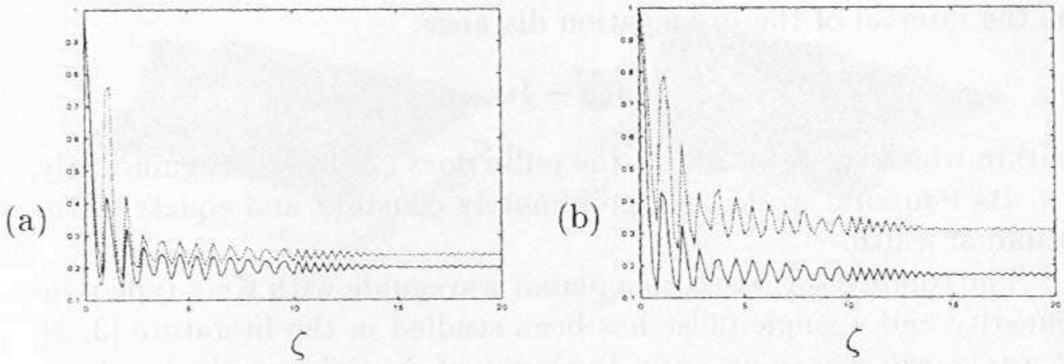

Figure 2: The dependence of the temporal, w_τ, (the dotted lines) and spatial, w_ξ, (the continuous lines) widths of the signal pulse, (a) co-propagating with the auxiliary pulse, (b), $\kappa_1 = 1.0, \sigma = -1, \kappa_2 = 2.0$.

try to answer to the question whether or not it is possible to remove the latter disadvantage. We will concentrate basically on the case (ii), i.e. vanishing dispersion of the subsidiary pulse.

The configuration with a subsidiary pulse, as described above, can be modeled by a system of two coupled (2+1)- and the (1+1)-dimensional NSEs:

$$i\frac{\partial}{\partial\zeta}\Psi_1 + \frac{1}{2}\frac{\partial^2}{\partial\xi^2}\Psi_1 + \frac{1}{2}\sigma_1\frac{\partial^2}{\partial\tau^2}\Psi_1 + (|\Psi_1|^2 + 2|\Psi_2|^2)\Psi_1 = 0, \quad (1a)$$

$$i\frac{\partial}{\partial\zeta}\Psi_2 + \frac{1}{2}\frac{\partial^2}{\partial\xi^2}\Psi_2 + (|\Psi_2|^2 + 2|\Psi_1|^2)\Psi_2 = 0, \quad (1b)$$

where ζ, τ, ξ denote, respectively, the longitudinal coordinate, the local time, and the transverse spatial coordinate. The subscript $j = 1$ ($j = 2$) corresponds to the pulse referred to as the signal (subsidiary) pulse. The second terms in equations (1)a,b are associated with diffraction, which causes spreading of the pulse in space. The third term in equation (1)a is due to first-order group velocity dispersion, which leads to temporal broadening of the signal pulse; the dispersion-to-diffraction ratio, σ, is positive, since it is assumed that the signal pulse propagates in anomalous dispersion regime. The forth term in (1)a and the third one in (1)b describes self-phase modulation, while the last terms is (1)a,b describe cross-phase modulation - a nonlinear effect through which the phase of one pulse is affected by another pulse and, as a result, leads to a redistribution of energy between pulses. The terms describing four-wave mixing are neglected, i.e. energy transfer between pulses is not taken into account. The terms proportional to the difference in group velocities of the pulses are also omitted.

Based on the numerical simulations of the set of equations (1)a,b we found that when the parameters of the system are properly chosen, i.e. the energy of the signal pulse is below the threshold of catastrophic self-focusing and energy of the auxiliary pulse is above the threshold of soliton generation, there can exist self-trapped solutions to (1)a,b, which propagate down the waveguide with constant shapes, amplitudes and widths. As an example let us examine the following parameters: $\kappa_1 = 1.0, \sigma = -1, \kappa_2 = 2.0$. From Figure 1, where the temporal cross sections of the pulses have been displayed (the evolution of the spatial cross sections are very similar), it is evident that both pulses undergo periodic oscillations. The amplitudes of these oscillations decrease with the propagation distance, ζ. For sufficiently large propagation distance, $\zeta > 15$, the oscillations' amplitudes practically vanish, giving rise to the self-trapped solution. The formation of the self-trapped solution can be explained as follows: the pulse with negligible dispersion, since its dynamics can be modeled by integrable (1+1)-dimensional NSE, creates a waveguide in the medium in which it propagates and the other pulse gets trapped into this waveguide [5]. From Figure 2, which displays the evolution of the temporal and spatial widths of the pulses, it is evident that both widths of the pulses, which constitute such a self-trapped solution, are few times smaller than the initial widths. It means that the formation of the self-trapped solution is accompanied by a spatio-temporal compression. The parameters of the compressor operating in the proposed configuration would be as follows: large maximal compression factor, $c_{max} \approx 5$, large optimal length, $\zeta_{min} \approx 15$, and also large compression length, $\Delta\zeta >> 1$ (the maximal compression factor is more than 3 times larger, and the optimal length of the compressor is at least 10 times bigger than the corresponding values for a compressor with a single anomalous pulse). Note that the optimal length of the compressor is equivalent to the distance of propagation necessary for the formation of self-trapped solutions. The compression length, which is associated with the distance of propagation on which self-trapped solutions maintain their shapes, should be infinitely large, assuming that self-trapped solutions are stable against small perturbations (we hope to analyze this question in a forthcoming publication). Moreover, in such a configuration much smaller energies of signal pulses can be used to obtain the same compression as in the single-pulse case. Besides, the compressor operating in the configuration under discussion, as opposite to the compressor with a single pulse, can be viewed as a universal device. Its operation only slightly depends on initial parameters of the signal pulse: since the compression length is relatively large, it is always possible to chose the length of compressor in such a way that optimally compressed pulses are obtained in the output, irrespective of their initial shapes, amplitudes and widths. To our knowledge, there is only one circumstance which can be considered as a disadvantage of the proposed two-pulse configuration: namely the large optimal length of the compressor, which requires long waveguides and implies technical problems with preparing them. However, we believe that the proposed configuration has potential to be realized in practice. For this purpose AlGaAs structures, which have high nonlinear refraction index and large damage threshold, could be used. In this paper we investigated only the temporal aspect of the compression; however, in the configuration under discussion one obtains pulses which are confined not only in time but also in space. Such pulses, compressed both temporally and spatially, can be beneficial, e.g., for nanostructuring. Note also that the two-pulse configuration proposed in this paper could be used also in optical steering or switching devices.

References

[1] Y. Silberberg, Opt. Lett. **15**, 1282 (1990).

[2] A. T. Ryan, G. P. Agrawal, J. Opt. Soc. Am. B. **12**, 2382 (1995).

[3] M. Pietrzyk, Opt. Q.E. **29**, 579 (1997).

[4] M. E. Pietrzyk, to appear in J. Mod. Opt. (2000)

[5] M. E. Pietrzyk, to appear in Rep. Math. Phys. (2000)