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Improved multisoliton compressor

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A fiber optic laser pulse compressor, consisting of two fibers, one with positive and the other with negative dispersion of group velocities for the same wavelength, was investigated. This compressor combines the positive sides of the known fiber grating compressor and multisoliton compressor and can be viewed as modified and improved variant of the multisoliton compressor. A numerical model was made to examine the parameters of the proposed compressor and determine the conditions at which the highest compression degree is obtained. The optimal length of the additionally added fiber with positive dispersion which gives maximum compression was determined. A comparative analysis was made between the classic multisoliton compressor and the proposed scheme with improvements. The proposed method is suitable for pulse compression within the spectral range 1.3 − 1.5 μm, where fibers with positive as well as with negative dispersion can be produced using one and the same material.

Keywords: Laser pulse compression, Optical fibers

INTRODUCTION

Compression of optical pulses is one of the important areas of laser physics because the generation of super-short optical pulses allows to study the super-fast processes in chemistry, physics, biology and so on. Fiber-optical methods for laser pulse compression are one of the most powerful techniques because the optical fibers have the ability to maintain high energy densities at very long distances [1].

The compression of optical pulses in all types of compressors is done as follows. First, the pulses are spectrally broadened and then compressed to temporary lengths determined by their spectral bandwidth.

Within the spectral range of positive dispersion of the group velocity in quartz fibers the so-called fiber-grating compressor is usually used [1,2]. In this type of compressor the input pulse first passes through an optical fiber with positive group velocity dispersion where it is spectrally broadened due to the self-phase modulation [3]. After that the pulse is compressed up to the time duration determined by its spectral bandwidth in a pair of gratings which works as an optical line with negative dispersion.

Within the spectral range of negative dispersion of the group velocity the method” multisoliton compression” is used [1,4]. The compression is performed due to the mutual influence of the self-phase modulation and of the negative dispersion of the fiber. This type of compressor consists only of a piece of fiber with negative dispersion whit appropriate length. As it is well known, in this case the pulse periodically changes its shape and its duration. So if we take a fiber with an appropriate length the output pulse will be much shorter than the input pulse.

The main advantage of this method is its simplicity. The disadvantage is the appearance of a broad pedestal, where most of the energy is concentrated. The reason for this is the simultaneous flow of the processes of the spectral broadening of the pulses due to the Kerr non-linearity and the compression of the pulse due to the negative dispersion. Thus, it is impossible to obtain a linear chirp all over the optical pulse but only within its central part and as a result only a small part of the full energy remains within the compressed pulse and the other goes to the pedestal.

Such a combination of both techniques was first applied in [5] and then improved in [6,7].

Recent progress in technology and performance of fibers, especially of fibers with a shifted dispersion allows producing a fiber with positive as well as with negative dispersion at some fixed wavelength, for example for $\lambda = 1.4 \mu m$. It is possible because fibers dispersion is the sum of the material and the waveguide dispersion. On the other hand, waveguide dispersion depends on the refractive index profile. It means that the change of dispersion may be done by changing the refractive index profile of the fiber.

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For the first time the idea to use a fiber with negative dispersion after a fiber with positive dispersion in order to compensate the dispersion pulse broadening in optical communication lines is proposed in [8]. Now it is broadly used and is known as ”dispersion management” .

In our previous work [9.10] we have proposed a new type of compressor which consists of successively connected fiber with positive dispersion and fiber with negative dispersion (Figure 1). In the first fiber with positive dispersion we expect a spectral broadening of the pulses due to self-phase modulation and a temporal broadening due to the positive dispersion. We also hope to improve the linearity of the frequency chirp. In this sense the first fiber is intended to help the process of multisoliton compression performed in the second fiber with negative dispersion and to improve the compression rate and the quality of the received pulses.

The present work is aimed to investigate the parameters of the proposed compressor - the length of the used fibers and the dispersion module ratio which gives the maximum increase of the compression degree.

Numerical model

Analysis of the nonlinear dynamics of the pulse propagation in single mode optical fibers is performed by the standard split-step Fourier method [11,12] in numerical solving of the nonlinear Schrödinger equation [1]. In the numerical model we assume that the transition between both fibers is realized without any changes of the transverse size of the radiation and the optical connector is of sufficient quality as a result of which the optical losses of the transition from one to the other fiber can be neglected. Because the lengths of the used fibers do not exceed a few tens of meters we also neglect the optical losses in both fibers.

It is taken into account that the dispersion for both fibers differs not only by the sign but by its module. As a result, we will write the equation for an evolution of temporal and of frequency pulse parameters in the first fiber:

$$i\frac{du}{d\xi} - \beta^{*}\frac{1}{2}\frac{d^{2}u}{d\tau^{2}} + \left|u^{2}\right|u = 0 \qquad (1)$$

Also for the second optical waveguide we have:

$$i\frac{du}{d\xi} + \frac{1}{2}\frac{d^{2}u}{d\tau^{2}} + \left|u^{2}\right|u = 0 \qquad (2)$$

Normalization is made following the standard approach and concerns the initial pulse parameters and the dispersion module of the second fiber which is with negative dispersion. There

$$u = \sqrt{\frac{\gamma\tau_0^2}{\left|\beta_2^-\right|}}A \qquad L_D = \frac{\tau_0^2}{\left|\beta_2^-\right|} \qquad \tau = \frac{t - z/v_g}{\tau_0}$$

$$\beta^{*} = \frac{\left|\beta_2^+\right|}{\left|\beta_2^=\right|} \qquad (3)$$

Here A is the slowly varying amplitude of the pulse envelope, γ is the coefficient of nonlinearity, τ_0 is the initial pulse width, β_2^+ $\beta_2^=$ are the group velocity dispersion parameters in the first and second fiber respectively, L_D is the dispersion length, v_g is the group velocity.

Such manner of normalization of the equation allows easier comparison of the compression quality for one and the same pulse using either the pure multisoliton compression or the method proposed by us. The initial pulse shape is assumed to be hyperbolic secant $\sec h(\tau)$ with energy corresponding to *N* less than 15 solitons. Such an expression of the shape allows us to compare our obtained results with those from multisoliton compression studied by other authors.

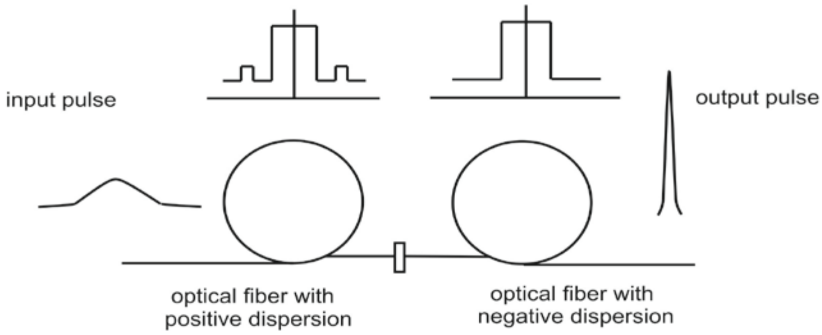

Fig. 1. Improved multisoliton compressor

The qualitative advantage of the studied method compared to multisoliton compression is presented on fig. 2. This figure shows the compression dynamics for the initial pulse with energy corresponding to a 10-soliton pulse.

Curve "a" is the compression dynamics in our optical compressor with dispersion ratio $\beta^* = 1.25$. Optimal compression conditions were selected. Curve "b" is the compression dynamics in a multisoliton compressor.

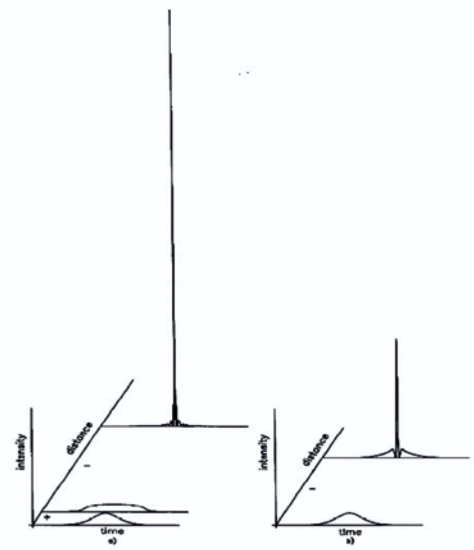

Fig. 2. Compression dynamics for the 10-soliton pulse following the here proposed method (a) and the pure multisoliton compression (b).

In the case of our optical compressor it is evident that the pulse in the first fiber acquires a nearly rectangular shape. This is due to the spectral broadening and to the linearization of the chirp of the whole pulse. When the chirped and spectrally broadened pulse passes through the fiber with negative dispersion, it compresses much more ion and peak power, increased nearly five times compared to the pure multisoliton compression.

RESULTS

The quality of the compression is determined by the compression factor which is defined as a ratio between initial pulse duration and compressed pulse duration $F_c = T_o/T_{comp}$, where T_o and T_{comp} are the full width at half maximum (FWHM) pulse intensities of the initial and of the compressed pulse.

Several configurations of various ratios of the dispersion module of both fibers between 1.25 and 0.50 were investigated. To determine the optimal compression conditions, we proceed as follows. We fix the energy of input pulses (soliton number) and the dispersion ratio. Then we vary the length of the first fiber with positive dispersion and for each length determine the optimal length of the second fiber with negative dispersion which gives the best compression degree. Thus, for the most suitable lengths of the two fibers we choose those that give the maximum degree of compression.

Our results show that we can approximate the optimal length of the first fiber by the expression:

$$z_{opt} = 0.46 L_D / N$$

At this length of the fiber with positive dispersion and optimizing the fiber's length with negative dispersion we achieve the highest quality compression.

This result substantially differs from the optimal length of the fiber usable in the "fiber grating compressor" which can be calculated by the expression:

$$z_{opt} = 2.5 L_D / N$$

Probably this is connected with the substantial difference between our proposed method and the fiber grating compressor. As a distinction of the pair diffraction gratings, the fiber of negative dispersion is an essentially nonlinear medium and there is a strong nonlinear impact on the pulse besides the compression.

The results for the dependence of the F_c compression degree *versus* the soliton number and the dispersion ratio module for both pieces of fibers are given in Figure 3. The following dependence is observed for all the studied dispersion ratios β^*. Initially, the compression degree increases linearly with the energy of the input pulses (soliton number). Then, when some critical value is reached, a collapse and a sharp decrease in compression quality occur.

The occurrence of collapse is explained by the fact that in fixed β^* and great pulse energies the phase modulation is so strong that the enrichment of the spectrum is very great. The linearity of the frequency modulation is disturbed and the negative dispersion of the second fiber cannot give qualitative compression.

The soliton number in which the collapse occurs, depending on the dispersion ratio, has a good approximation with the following formula:

$$N = 7.8 + 4.8(\beta^*)^2$$

This indicates that for high performance compression of high energy pulses it is necessary to use a compressor with a big dispersion ratio.

In the linear part, enhancement of the compression degree compared to pure multisoliton compression (curve 5) is slightly dependent on β and is more than 2 times lower. As an example for a 10-soliton pulse, the compression degree is 78 at a dispersion ratio of 0.75 (curve 3) when the multisoliton compression gives only 38.

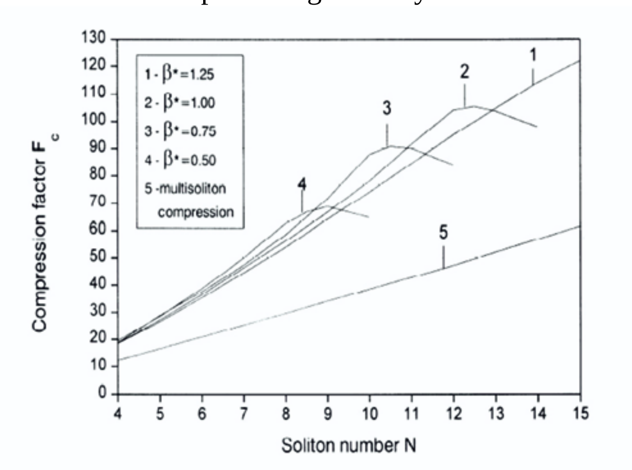

Fig. 3. Compression factor Fc *versus* the soliton number N.

It is interesting to note that the incensement of the compression degree is only about 2 times while, as it was mentioned, the peak energy of compressed pulses increases more than five times. This is most likely due to the decrease of the energy in the pedestal. Therefore it should be expected that simultaneously with increasing the compression degree, the quality of the compressed impulses will be improved, i.e. increasing the energy in the central part of the pulse at the expense of the energy in the pedestal. Determining the optimum conditions for this will be a goal of further research.

CONCLUSION

A scheme of optical pulse compression based on an idea of the "dispersion management" is investigated. This idea consists of the consequent usage of a fiber with positive and fiber with negative dispersion.

This improved optical fiber compressor combines the advantages of the classic fiber-grating compressor and of multisoliton compression. Such scheme allows improving of the compression degree as well as of the quality factor. This improvement depends on the soliton number of the input pulse as well as the dispersion of the used fibers. Thus, we have obtained 2 times increase of the compression degree compared to the multisoliton compression more than 5 times growth of the peak power of the compressed pulse compared to the classic multisoliton compression. The proposed method is suitable for pulse compression within the spectral range $1.3-1.5\ \mu m$ where using one and the same material we are able to produce fibers with positive as well as fibers with negative dispersion.

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