All-Optical Fiber Compressor

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Abstract: A simple all-optical fiber compressor, based on an idea of dispersion management using a fiber of positive dispersion in the first part and of negative dispersion in the second one at the working wavelength, is investigated. The method allows a combination of the advantages of the classic fiber-grating and of the multisoliton compression. It is possible to improve substantially the quality of the compressed pulse compared to the multisoliton compression. The compression factor could be increased up to 2-2.5 times when the fraction of the input pulse energy appearing within the compressed pulse enhances more than 2 times. Thus, the peak power of the compressed pulse is able to increase about 5 times and the quality of the obtained pulses should be comparable with those obtained by the fiber-grating compressor.

Key words: Laser pulse compression, optical fiber, dispersion of light

1. INTRODUCTION

Fiber-optical methods are one of the most powerful techniques for laser pulse compression. So-called "fiber-grating compressor" is used within the spectral range of positive dispersion of the group velocity in quartz fibers. The input pulses are first spectrally broadened when passing through an optical waveguide with a positive velocity dispersion of the quartz fiber, as a result of the self-phase modulation. After that, the pulse is compressed up to the time duration determined by its spectral bandwidth by pair gratings which consist of an optical line of negative dispersion. The method is quite efficient [1,2] and it allows obtaining of pulses without a pedestal because of the possibility to realize linear chirp practically over the entire pulse duration.

The method of "multisoliton compression" [1,3] is used within the range of negative dispersion of the group velocity and the compression is performed due to the mutual influence of the self-phase modulation and of the negative dispersion of the fiber. The disadvantage of this method is the appearance of a broad pedestal, where most of the energy is concentrated. The reason for that is that the chirp is linear only within the central part of the pulse and as a result only a small part of the full energy remains within the compressed pulse and the other goes to the pedestal. Contemporary progress in technology and performances of fibers, especially of fibers with a shifted dispersion allows
the production a fiber of positive as well as of negative dispersion at the same fixed wavelength (for example $\lambda = 1.4 \mu m$) [1].

Such a combination of both techniques was first applied in [4] and then improved in [5,6], where the pulse is first compressed by a fiber-grating compressor in an up-shifted fiber and after that the same is additionally compressed by the multisoliton compression in a dispersion down-shifted fiber. This technique allows a higher degree of compression (up to 5000 times) but it is complicated for realization and the obtained pulses are of very bad quality. Recently, the idea of using an optical waveguide of positive as well as of negative dispersion is broadly applicable in order to realize the so-called "dispersion management" in optical communication lines, i.e. a compensation of the dispersion pulse broadening is possible [7].

In this paper we consequently apply fibers of positive and negative dispersion in order to compress the pulses of energy exceeding essentially that of the fundamental soliton. As a matter of fact, this is a combination of both methods: the fiber grating compressor and the 0 multisoliton compression. Thus, the compression degree increases up to 2-3 times and the pulse quality improves substantially.

2. MODEL

Analysis of the nonlinear dynamics of the pulse propagation in single mode optical fibers is performed by the standard split-step Fourier method in numerical solving of the nonlinear Schrödinger equation [8]. It is taken into account that the dispersion for both fibers differs by its module and not only by the sign. Normalization is made concerning the initial pulse parameters and the dispersion module of the second fiber which is of negative dispersion. As a results, we will write the equation for an evolution of temporal and of frequency pulse parameters in the first fiber:

$$i \frac{du}{d\xi} - \beta^4 \frac{1}{2} \frac{d^2 u}{d\tau^2} + |u|^2 u = 0$$  \hspace{1cm} (1)

Also, for the second optical waveguide we have

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

where

$$u = \sqrt{\frac{\gamma \tau_0^2}{\beta_2^2}} A, \quad L = \frac{\tau_0^2}{\beta_2^2}, \quad \tau = \frac{t - z/v_g}{\tau_0}, \quad \beta^* = \left| \frac{\beta_2^+}{\beta_2^-} \right|$$  \hspace{1cm} (3)

Here $A$ is the slowly varying amplitude of the pulse envelope, $\gamma$ is the coefficient of nonlinearity, $\tau_0$ is the initial pulse width, $\beta_2^+$, $\beta_2^-$ are 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 multisoliton compression or the method proposed in this paper. We neglect the optical losses in both fibers. Besides, we assume that the transition between both fibers is realized without any changes of the transverse size of the radiation. The initial pulse shape is assumed to be Our research is done till $N < 15$. Such an expression of the shape allows us to compare our obtained results with those from multisoliton compression studied by other authors. We should note, that the pulse shape $\sec h(\tau)$ and the integer $N$ are not obvious for the proposed method, since such a technique allows a pulse compression of arbitrary shape The expressions by $\sec h(\tau)$ and the $N$ integer are used only because of comparison of our results obtained by the proposed method with those following the method of multisoliton compression.

3. RESULTS

Several configurations of various ratios of the dispersion module of both fibers $\beta''=1.25$, 1.00, 0.75 and 0.50, are investigated. The quality of the compressed pulse is determined by the compression factor and the quality factor. The compression factor $F_c = T_0/T_{\text{comp}}$, where $T_0$ and $T_{\text{comp}}$ are the full width at half maximum (FWHM) pulse intensity of the initial and of the compressed pulse. The quality factor $Q_c$ is defined as a fraction of the input pulse energy appearing in the compressed pulse. In order to optimize the compression in every version (we fix the pulse energy and the dispersion of the first fiber), we vary the length of the first part which is of positive dispersion and we determine the second length which gives a maximum compression degree. The results of numerical modeling show that we can approximate the optimal length of the first part of the fiber as $z_{\text{opt}} = 0.46 L_D / N$. At such a 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 optical length of the fiber usable in the "fiber grating compressor" which gives $z_{\text{opt}} = 2.5 L_D / N$. Probably this is connected with a 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. We also
studied the variation of the optimal length of the second fiber when the first fiber length is optimized and this allows achievement of the most qualitative compression.

The results show that when fixing the number of solitons \( N \), the second fiber length \( z_D \) depends weakly on the ratio of both fiber dispersions. For example at \( N = 10 \), the \( z_{2, \text{opt}} / z_D = 9.7 - 9.7 \) when \( \beta^* \) changes from 1.25 to 0.5. We can explain such a weak dependence as follows. If \( L = z_{\text{opt}} \) in the first fiber and the energy (the number \( N \) of solitons) is fixed, then the pulses obtain one and the same frequency broadening which does not depend on the dispersion. This determines the same dynamics of propagation through the fiber of negative dispersion, and as a result its optimal length depends weakly on the dispersion of the first fiber.

![Figure 1. Compression dynamics for the 10-soliton pulse following the here proposed method (a) and the multisoliton compression (b).](image)

Advantages of the studied method are shown by comparison of the compression dynamics for the 10-soliton pulse at \( \beta_2 = 1.25 \) (Fig. 1a) with the compression dynamics of the 10-soliton pulse for the multisoliton compression (Fig. 1b). 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 of negative dispersion, it compresses much more with great quality compared to the case of multisoliton compression. The improving of the compression degree and the introducing of more energy within the compressed pulse leads to a substantial increase of the peak power, which in particular is nearly five times greater when compared to the multisoliton compression.

Results for dependence of the $F_c$ compression degree versus the soliton number and the dispersion ratio module for both pieces of fibers, are given in Fig. 2a. Enhancement of the compression degree is achieved more than 2 times compared to the multisoliton compression (curve 5 in Fig. 2a). As an example for 10-soliton pulse, the compression degree is: 74 at $\beta^* = 1.25$, 78 at $\beta^* = 1.00$ and 88 at $\beta^* = 0.75$, when the multisoliton compression gives only 38. We should also note the increase of the compression degree with the growth of the soliton number and with the $\beta^*$ reduction. Anomalous behavior takes place at high values of $N$. We can obtain a sharp reduction of the

![Figure 2. a) Compression factor $F_c$ and b) Quality factor $Q_c$ versus the soliton number](image)

compression degree with the increase of the pulse energy. Such a reduction appears, as earlier, as smaller in value for $\beta^*$. The explanation is connected with the fact that for small values of $\beta^*$ and $N$, the model is close to
the model of the fiber-grating compressor because of stronger impact of the
dispersion than that of the nonlinearity. For fixed $\beta^*$ at the high soliton num-
ber, the nonlinearity becomes essential and its influence is comparable with
that of the dispersion, then, the model is closer to the model of multisoliton
compression. Nevertheless, we think that the clarification of this problem
needs some further studies.

Results for a variation of the quality factor $Q_c$ depending on the soliton
number and the ratio of dispersion modules of both pieces of fibers, are given
in Fig. 3. We obtain substantial increase of the pulse energy compared with
the multisoliton compression (curve 5 in Fig. 3) and the results are improved
with the soliton number increase and with the growth of the dispersion module
in the second fiber. As an example, the energy of the compressed pulse is
only 30% of the input pulse energy for the pure multisoliton compression at
$N = 10$, while our method gives 53% for the compressed pulse energy at
$\beta^* = 1.25$, 56% for $\beta^* = 1.00$, 64% at $\beta^* = 0.75$. Thus, about a 2 times
improvement of the compressed pulse quality is demonstrated. The deviation
from this dependence is observed at a great soliton number and at small $\beta^*$
values. Anomalous behavior is obtained exactly at the same values of $N$, when it appears, if taking into account the compression degree. The reason
is the same as for the variation of the compression degree versus $N$ and $\beta^*$
. In order to avoid the anomalous behavior, we should choose the second
fiber of greater dispersion.

4. CONCLUSION

A scheme of optical pulse compression is investigated when it is based
on an idea of the “dispersion management” i.e. on the consequent using of a
fiber of positive and of negative dispersion. This all-optical fiber compressor
combines the advantages of the classic fiber-grating compressor and of mul-
tisoliton compression. Such a scheme allows an improvement of the compo-
sition 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 about a 2.5 times increase of the compression
degree compared with the multisoliton compression and more than double
increase of the percent-content of the compressed pulse energy. As a result,
we achieve a more than about 5 times growth of the peak power of the com-
pressed pulse compared to the classic multisoliton compression. The pro-
posed method is suitable for pulse compression within the spectral range 1.3
– 1.5 µm , where, using one and the same material, we are able to produce
a fiber of positive or negative dispersion only by change of the optical waveguide diameter.

5. REFERENCES