Pulse Compression and Super-Continuum Generation using Cascaded Higher-Order Solitons

J. Nathan Kutz
Department of Applied Mathematics
University of Washington
Seattle, WA 98195-2420
kutz@amath.washington.edu

Qian Li and P. K. A. Wai
Photonics Research Centre, Department of Electronic and Information Engineering
The Hong Kong Polytechnic University
Hung Hom, Hong Kong

Abstract—**Non-adiabatic pulse compression of cascaded higher-order optical solitons is investigated. We demonstrate high degree compression of pulses with soliton order *N*=2, 3, 4 and 5 in two or three nonlinear fibers with different second-order dispersion coefficients. Each fiber length is shorter than half of its soliton period. This compression technique has significant advantages over the widely reported adiabatic and higher-order soliton compression.**

Keywords-component; pulse compression, super-continuum, solitons

I. Introduction

The ability to robustly and routinely produce ultrashort pulses has led to transformative technologies in such diverse areas as telecommunications, photonics, and biological imaging. Ultrashort optical pulse sources are critical components for applications in which femtosecond or picosecond time resolution, high peak powers, and/or large optical bandwidths are required. Ultrashort pulses are usually generated with mode-locked lasers. However, mode-locked lasers can be complex and costly, and the ultrashort pulses emitted from high-energy mode-locked laser sources are often chirped, and/or limited to fairly low output powers. As an alternative, various pulse compression schemes have been proposed to generate ultrashort pulses with high energy content. Pulse compressors based on nonlinear fiber optics can be classified into two broad categories: grating-fiber and soliton-effect compressors [1]. In a grating-fiber compressor, the input pulse is firstly propagated in the normal-dispersion fiber which imposes a nearly linear, positive chirp on the pulse through a combination of self-phase modulation (SPM) and group velocity dispersion (GVD), and then compressed externally using a grating pair. The grating pair provides the anomalous GVD for compression of positively chirped pulses. Grating-fiber compressors are useful for compressing pulses in the visible and near-infrared regions while soliton-effect compressors work typically in the range from 1.3 to 1.6 m [1]. For grating-fiber compressors, the compression factor can be estimated by $F_c \approx N/1.6,$ where N is the soliton order. Although in theory the compression factor can be increased by increasing the peak power of the incident pulse, it is limited in practice since the peak power should be kept below the Raman threshold to avoid the transfer of pulse energy to the Raman pulse. For the soliton-effect compression, two commonly considered techniques are the higher-order soliton compression scheme and the adiabatic pulse compression method. Unfortunately, each method suffers from significant technological drawbacks: the former from the generation of a large pedestal/background structure that contains a large portion of the pulse energy [2], and the latter from a limit on the compression factor and excessively long dispersion decreasing fiber segments [3]. In this paper, a hybrid technique is proposed that takes advantage of the strength of both compression techniques while avoiding their drawbacks. Specifically, we theoretically study the cascaded *N*-soliton for non-adiabatic pulse compression in two or three nonlinear fibers with different constant anomalous dispersion coefficients. Very large compression factors can be achieved with the generation of a relatively small pedestal, making the technique competitive with current pulse compression technologies.

II. Governing Equations

Optical pulses are typically modeled by reducing Maxwell's equations to the nonlinear Schrödinger (NLS) equation [2],

$$i\frac{\partial A}{\partial z} - \frac{\beta_2}{2}\frac{\partial^2 A}{\partial t^2} + \gamma |A|^2 A = 0, \tag{1}$$

where A is the slowly varying amplitude of the pulse envelope, z is the distance, t is the time in the pulses' frame of reference, β_2 is the second-order dispersion coefficient, and γ is the nonlinear coefficient. The soliton order N is defined as

$$N = \sqrt{L_D / L_N}, \tag{2}$$

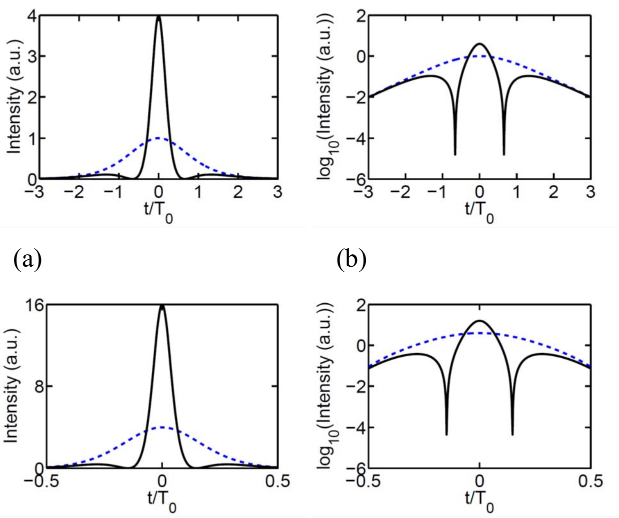
where L_D and L_N are the dispersion length and nonlinear length respectively. The fundamental soliton arises for L_D=L_N. For all higher-order solitons (N>1), $|A|^2$ is periodic with the period

$$z_0 = \frac{\pi}{2} L_D. \tag{3}$$

As a higher-order soliton pulse propagates along the fiber, it first contracts to a fraction of its initial width, splits into a multi-humped pulse, and then merges again, in a symmetric fashion, to recover the original shape at the end of soliton period z=z_0. In the conventional higher-order soliton compression, the fiber length is chosen so that the soliton pulse is at its highest peak during the evolution, which corresponds to the minimum pulse width. This gives the maximum compression factor possible in the higher-order soliton compression schemes. Indeed, the compressed pulse is much narrower than the initial pulse. However, the pulse is now accompanied by a potentially large pedestal. Specifically, the larger the soliton order, the larger the generated pedestal. For high-quality pulse compression, the pedestal must be minimized in order to suppress the deleterious interaction between the pedestal and compressed spike that occurs upon further propagation. The interaction leads to a host of undesirable periodic pulse reshaping effects that are detrimental for optical communication applications.

III. N=2 SOLITON COMPRESSOR

The key idea of this paper is to consider switching the dispersion of the fiber at the maximal compression point so that the localized compressed pulse structure is now ready to be compressed again as a new higher-order soliton in the next fiber segment. Specifically, consider an N=2 soliton. At a propagation distance of z/z_0=0.5, the pulse has been compressed and its peak intensity increased by a factor of four. The idea is to now make this new compressed pulse an N=2 soliton in a new fiber segment and compress the pulse again so that the intensity is again increased by another factor of four. All that is required in this process is to determine the length of the fiber and the dispersion of the next fiber segment. Cascading higher-order solitons this way is a promising compression technology provided the pedestal can be kept relatively small.



(c) (d)

Fig. 3. (Color online) Pulse shapes where compression is maximized in both the first and second fiber for N=2. The dashed curve and solid curve in (a) & (b) represent the input pulse and output pulse of the first fiber in (a) linear and (b) logarithmic scales. The dashed curve and solid curve in (c) & (d) represent the input pulse and output pulse of the second fiber in (c) linear and (d) logarithmic scales.

For the proposed 2-stage N-soliton compression, the initial pulse is a chirp-free hyperbolic secant pulse $N_1\mathrm{sech}(\tau)$, where τ is the normalized time, N_1 is the soliton order in the first fiber. The output of the first fiber is launched into a second fiber with a different dispersion coefficient, and the soliton order in the second fiber is N_2. Consequently, we have

$$N_1^2 = T_{01}^2\gamma P_1/|\beta_{21}|,\ \ N_2^2 = T_{02}^2\gamma P_2/|\beta_{22}|, \tag{4}$$

where $T_{01,02}, P_{1,2}, \beta_{21,22}$ are the initial pulse width parameter, peak power and second-order dispersion in the first and second fiber, respectively. Since the input of the second fiber is not an exact hyperbolic secant shape, T_{02} is decided by the pulse fitting with a sech^2 pulse having the same peak power and full-width at half maximum intensity (FWHM). Here, we assume the nonlinear coefficient γ is same for the first and second fiber. Figure 1(a) and (b) show the pulse shapes where compression is maximized in the first fiber when N=2. The dashed curve and solid curve represent the input pulse and output pulse of the first fiber. The intensity enhancement by a factor of four is clearly illustrated. Figure 1(c) and (d) show the pulse shapes where compression is maximized in the second fiber using a fiber dispersion corresponding to an N=2 fitted input soliton. This example illustrates the key concepts.

IV. CONCLUSIONS

Cascaded higher-order soliton compression can achieve a very large compression factor using two or three nonlinear fibers with different constant anomalous dispersion coefficients. Each fiber length is shorter than half of its soliton period. The 2-stage fifth-order soliton compression gives a compression factor of 284 and corresponding pedestal of 71%. The 3-stage second-order soliton compression gives a compression factor of 87 and corresponding pedestal of 27%. The 3-stage third-order soliton compression gives a compression factor of 600 and corresponding pedestal of 59%. These results are highly favorable when compared to the standard techniques previously used, thus suggesting that the cascaded higher-order soliton compression technique is a promising technology that is easy to implement with current technological components.

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