High-quality pulse compression in a novel architecture based on a single-mode fiber cascading a nonlinear optical loop mirror*

XU Yong-zhao (徐永钊), **SONG Jian-xun** (宋建勋), **ZHANG Geng** (张耿), **LIU Min-xia** (刘敏霞)**, **and LING Dong-xiong** (凌东雄)

School of Electronic Engineering, Dongguan University of Technology, Dongguan 523808, China

(Received 25 April 2016)

A novel all-fiber low-pedestal pulse compression scheme is proposed and investigated. The scheme is based on an anomalously dispersive single-mode fiber (SMF) cascading a nonlinear optical loop mirror (NOLM) with another anomalously dispersive SMF in the loop. Numerical results show that excellent pulse compression and pedestal reduction can be achieved by using the proposed scheme.

Document code: A **Article ID:** 1673-1905(2016)04-0290-4

DOI 10.1007/s11801-016-6103-5

Optical pulse compression has attracted more and more attention in recent years due to its broad applications, such as optical transmission, ultrafast optics and high-energy field. During the past two decades, a variety of schemes of pulse compression have been proposed and demonstrated[1-7]. There are two well-known techniques to achieve ultra-short pulses, namely, adiabatic pulse compression and higher-order soliton compression[8]. The former typically utilizes dispersion decreasing fiber (DDF) as the transmission waveguide and can provide pulse compression with much lower pedestal[9]. However, it usually requires large lengths of DDF. Moreover, the compression factor is restricted by the dispersion-decreasing ratio and the maximum compression factor is typically limited to about 20[10]. The higher-order soliton compression can have a large degree of compression, but the compressed pulses suffer from significant pedestal generation, leading to nonlinear interaction between neighboring solitons.

To achieve high degree pulse compression while avoiding the technological drawbacks of the two compression techniques, recently, Li et al[11,12] proposed a cascaded higher-order soliton compression scheme. Unfortunately, the compressed pulses obtained intrinsically entail an undesired pedestal component. Presently, a widely adopted technique for pedestal suppression is to utilize a nonlinear optical loop mirror (NOLM). Furthermore, by properly designing the NOLM, both pulse compression and pedestal suppression can be realized in the same loop[13].

In this paper, a novel pulse compression scheme with pedestal suppression using NOLM is proposed. The NOLM is adopted after an anomalously dispersive SMF to realize the low-pedestal pulse compression, in which the fiber in the loop achieves the pulse compression and the NOLM architecture realizes the pedestal suppression. The compression scheme combines the advantages of cascaded higher-order soliton compression technique and NOLM, through which very large compression factors can be achieved with the generation of a relatively small pedestal.

The configuration of the proposed all-fiber pulse compression scheme is shown in Fig.1, which is based on an anomalously dispersive SMF (fiber 1) cascading an NOLM. The NOLM is composed of another anomalously dispersive SMF (fiber 2) and an optical coupler with a power-coupling ratio of α:1$-\alpha$ ($\alpha\neq$0.5). The configuration employs fiber 1 as the first compression stage and the NOLM as the second one. Specifically, the initial pulse u_1 is launched into fiber 1 and reaches the maximal compression after passing through the fiber. The compressed pulse u_2 output from fiber 1 is launched into port 1 of the NOLM for the second stage compression. The NOLM is unbalanced by using a coupler that launches unequal amounts of power in the counter-propagating direction. As shown in Fig.1, the input pulse is split into clockwise pulse u_{2cw} and counter-clockwise pulse u_{2ccw}. The pulse u_2 is split at the coupler according to[14]

$$u_{2cw}(0,t)=\sqrt{\alpha}u_2(0,t), \quad (1)$$

$$u_{2ccw}(0,t)=\mathrm{i}\sqrt{1-\alpha}u_2(0,t), \quad (2)$$

* This work has been supported by the National Natural Science Foundation of China (No.61501118), and the Guangdong Natural Science Fund (No.2014A030310262).

** E-mail: liumxdgut@qq.com

where $u_{2cw}(0,t)$ and $u_{2ccw}(0,t)$ are the field amplitudes right after the coupler. For the clockwise pulse u_{2cw}, the dispersion of fiber 2 is properly set so that the clockwise pulse u_{2cw} is compressed again as a new higher-order soliton. The length of fiber 2 is chosen so that the clockwise propagating pulse is maximally compressed after passing through the fiber. After traveling around the loop, the counter-propagating pulses recombine at the coupler and the transmitted pulse u_T is output from port 2. The transmitted pulse u_T is the final compressed pulse which is given by

$$u_T = \sqrt{\alpha} u_{2cw}(L,t) + i\sqrt{1-\alpha} u_{2ccw}(L,t), \quad (3)$$

where L is the length of the fiber loop. Since the phase shift difference between the two counter-propagating pulses is intensity dependent, only the central part of the pulse is intense enough to experience switching. The power dependence of switching condition leads to pedestal suppression after recombination.

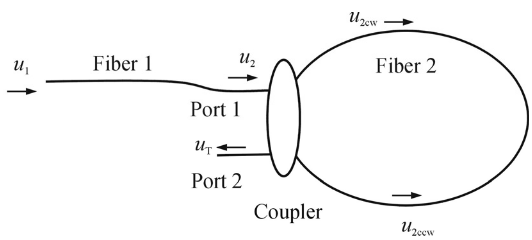


Fig.1 Schematic of the cascaded pulse compression scheme

The model used in this work to simulate the propagation of pulses in cascades of fibers is based on the generalized nonlinear Schrödinger equation (GNSE)[15]

$$\frac{\partial u}{\partial z} + i\frac{\beta_2}{2}\frac{\partial^2 u}{\partial t^2} - i\gamma |u|^2 u = 0, \quad (4)$$

where u is the slowly varying envelope of the optical field, z is the propagation distance, and t is the time in the moving reference frame. The parameters β_2 and γ are the second order dispersion coefficient and Kerr nonlinearity coefficient, respectively. In this paper, the contributions of the higher-order dispersion terms and higher-order nonlinear effects are neglected, for simplicity, although they should be taken into account for propagation of ultrashort high peak power pulses with duration less than 1 ps. Fiber loss here is neglected too.

For the proposed cascaded compression scheme, the initial pulse is assumed to be a hyperbolic secant pulse $N_1\mathrm{sech}(t/T_0)$, where T_0 is the pulse width parameter related to the full width at half-maximum (*FWHM*) by $T_{FWHM} \approx 1.763T_0$, and N_1 is the soliton order in the first fiber. The output of the first fiber is launched into the NOLM with a different set of dispersion coefficients, and the soliton order of the clockwise pulse u_{2cw} in the second fiber is N_2. Consequently, we have

$$N_1^2 = \frac{\gamma P_{01} T_{01}^2}{|\beta_{21}|}, N_2^2 = \frac{\gamma P_{02} T_{02}^2}{|\beta_{22}|}, \quad (5)$$

where $T_{01,02}$, $P_{01,02}$ are the pulse width parameter and peak power of the pulses input to the first and second fibers, respectively. β_{21} and β_{22} are the second order dispersion coefficients in the first and second fibers, respectively. Since the input pulse of the second fiber is not an exact hyperbolic secant shape, N_2 is decided by the pulse fitting with a sech^2 pulse which has the same peak power and *FWHM* intensity. Here, we assume that the nonlinear coefficient γ is the same for the two fibers (γ=2.5W^{-1}·km^{-1}), and $N_1=N_2=N$.

We perform numerical simulations for the power-coupling coefficient α in the range of $0.6 \leq \alpha \leq 0.9$. The T_{FWHM} of the initial pulses and β_{21} are set to be 30 ps and −20 ps^2·km^{-1}, respectively.

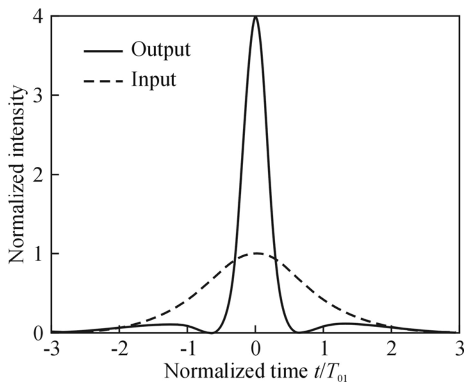
Tab.1 shows the calculated results for four typical power-coupling coefficients of α=0.6, 0.7, 0.8 and 0.9. For each α and each N, the fiber parameters of the first and second fibers are appropriately chosen so that the compressions are maximized in both the first fiber and NOLM. We note that for each N, both compression factor and pedestal energy increase with the increase of α, but the pedestal energy is more sensitive to the change of α. For example, for N=2, increasing α from 0.6 to 0.9, the pedestal energy increases from 3.5% to 12.6%, yet the compression factor only increases from 17.3 to 19.1. For N=5, increasing α from 0.6 to 0.9, the pedestal energy increases from 15.6% to 70.5%, yet the compression factor increases from 238.6 to 289.1. By choosing the value of α in the vicinity of 0.6, the two-stage pulse compression with an NOLM can achieve significant pedestal suppression without much compression factor decrease.

Tab.1 Compression factor, pedestal (%) and fiber design for different α

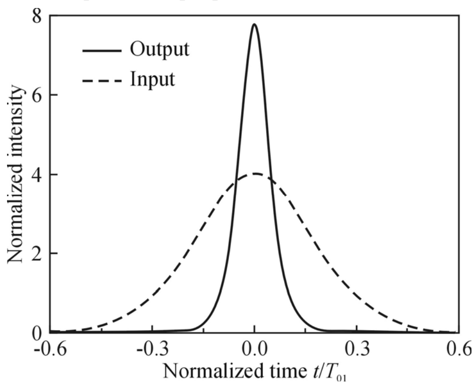
Parameters	N=2				N=3			
α	0.6	0.7	0.8	0.9	0.6	0.7	0.8	0.9
Compression factor	17.3	17.6	18.4	19.1	60.1	63.2	67.3	70.0
Pedestal(%)	3.5	4.1	7.3	12.6	4.8	13.1	26.6	38.0
β_{22}/β_{21}	0.122	0.142	0.163	0.183	0.053	0.062	0.071	0.080
L_1/z_{01}	0.500				0.237			
L_2/z_{02}	0.487				0.235			
Parameters	N=4				N=5			
α	0.6	0.7	0.8	0.9	0.6	0.7	0.8	0.9
Compression factor	132.8	145.4	156.5	160.6	238.6	270.1	289.1	289.1
Pedestal(%)	8.3	29.6	49.4	58.4	15.6	49.5	66.4	70.5
β_{22}/β_{21}	0.030	0.035	0.040	0.045	0.019	0.022	0.025	0.029
L_1/z_{01}	0.150				0.108			
L_2/z_{02}	0.150				0.108			

The details of the fiber design in the two-stage higher-order soliton compression with an NOLM are also explicitly presented in Tab.1, where L_1 and L_2 are the lengths of the first and second fibers, respectively, and z_{01} and z_{02} are the soliton periods in the first and second fibers, respectively. It can be noticed that the dispersion coefficient of the second fiber is always smaller than that of the first fiber. For each N, with the increase of α, the ratio of the dispersion coefficients in the second and first fibers, β_{22}/β_{21}, becomes larger, however L_1/z_{01} and L_2/z_{02} remain unchanged. L_1/z_{01} and L_2/z_{02} only depend on N. With the increase of N, both L_1/z_{01} and L_2/z_{02} become smaller.

Figs.2—5 show the compressed pulses in the case of α=0.6. Fig.2(a) shows the pulse shape where compression is maximized in the first fiber when N=2. The most notable feature of the compressed pulse is that it contains a broad pedestal. The figure clearly illustrates that the peak intensity of the compressed pulse is four times higher than that of the initial pulse. Fig.2(b) shows the final compressed pulse output from the NOLM when compression of the clockwise pulse is maximized in the loop using a fiber dispersion corresponding to N=2. It is evident that the pedestal has almost disappeared. The peak intensity (which is normalized to the peak intensity of the initial pulse) of the final compressed pulse is nearly eight times higher than that of the initial pulse and the final compression factor is 17.3. In Ref.[11], the conventional two-stage second-order soliton compression achieved a compression factor of 19.7, but the corresponding pedestal energy was as high as 18.8%.

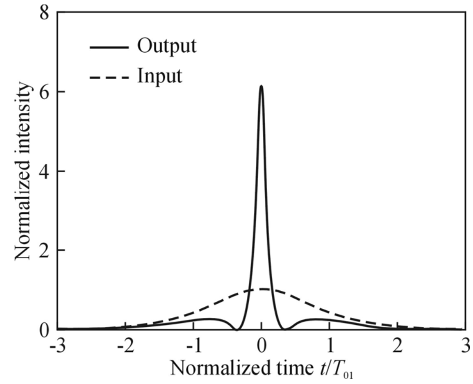


(a) The input and output pulses of the first fiber for N=2

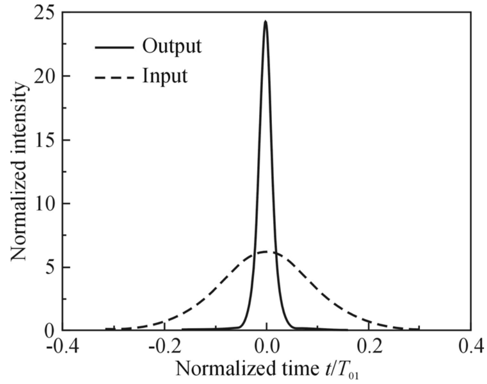


(b) The input and output pulses of the NOLM for N=2 and α=0.6

Fig.2 Pulse shapes where compression is maximized in both the first fiber and NOLM for *N*=2 and α=0.6

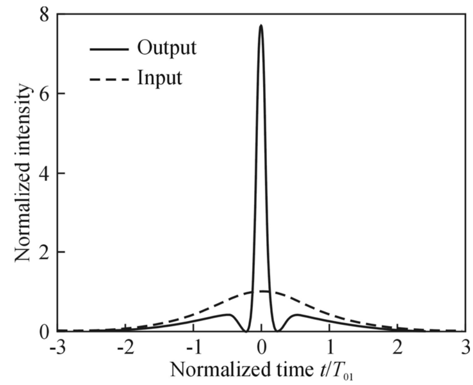


(a) The input and output pulses of the first fiber for N=3

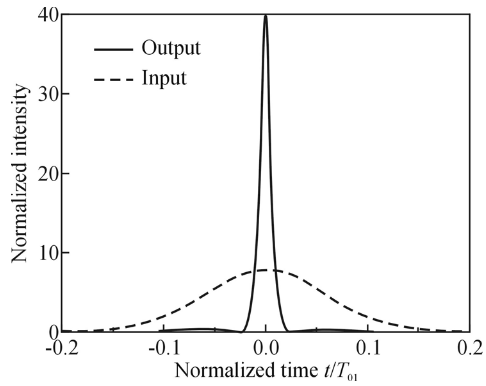


(b) The input and output pulses of the NOLM for N=3 and α=0.6

Fig.3 Pulse shapes where compression is maximized in both the first fiber and NOLM for *N*=3 and α=0.6

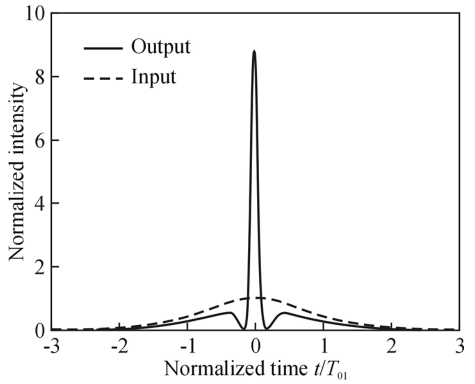


(a) The input and output pulses of the first fiber for N=4

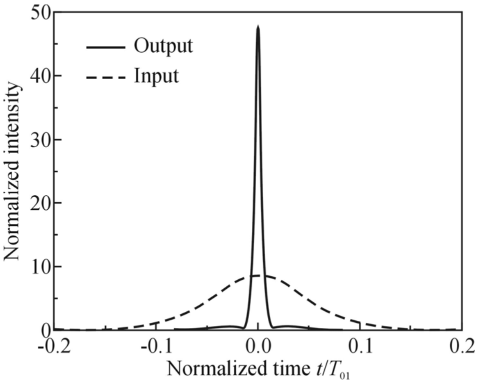


(b) The input and output pulses of the NOLM for N=4 and α=0.6

Fig.4 Pulse shapes where compression is maximized in both the first fiber and NOLM for *N*=4 and α=0.6



(a) The input and output pulses of the first fiber for N=5



(b) The input and output pulses of the NOLM for N=5 and α=0.6

Fig.5 Pulse shapes where compression is maximized in both the first fiber and NOLM for *N*=5 and *α*=0.6

Similarly, Figs.3—5 show the pulse shapes where compression is maximized in both the first fiber and NOLM for N=3, 4 and 5, respectively. The details of the compression factor and pedestal energy are given in Tab.2. For comparison, the results of Ref.[11] (the conventional two-stage higher-order soliton compression without the NOLM) are also shown in the table.

Tab.2 Comparison of compression factor and pedestal

Methods	Parameters	N=2	N=3	N=4	N=5
Ours	Compression factor	17.3	60.1	132.8	238.6
	Pedestal (%)	3.5	4.8	8.3	15.6
Ref.[11]	Compression factor	19.7	70.8	158.4	283.9
	Pedestal (%)	18.8	44.8	61.1	71.3

As seen in Tab.2, in our two-stage pulse compression with an NOLM, both the compression factor and the proportion of pedestal energy become larger with the increase of the soliton order N, but the proportion of the pedestal energy is kept at a rather low level. In the case of N=2, the compressed pulse achieves a compression factor of 17.3, and the corresponding pedestal is only 3.5%. In the case of N=5, the compressed pulse achieves a compression factor of 238.6, while the corresponding pedestal is no more than 16%. As reported in Ref.[11], in the conventional two-stage higher-order soliton compression, for a pulse compression factor of 19.7, the pedestal energy has already exceeded 18%. For the conventional two-stage fifth-order soliton compression, although the compressed pulse achieves a compression factor of 283.9, the pedestal energy is as high as 71.3%.

Our compression scheme can also be applied in three-stage or other multi-stage pulse compression. Very large compression factors with the generation of a relatively small pedestal can also be achieved.

In summary, a novel pulse compression and pedestal suppression scheme based on cascaded SMF and NOLM is proposed and investigated. The scheme firstly employs an anomalously dispersive SMF to compress the higher-order soliton, and then an NOLM with another anomalously dispersive SMF in the loop is used to further compress the pulse as a new higher-order soliton and to suppress the pedestal after the pulse compression. The simulation results show that by appropriately choosing the power-coupling ratio and fiber parameters, both large compression factors and low-pedestal compression can be achieved. In comparison with the conventional cascaded higher-order soliton compression technique without the NOLM, comparable compression factors can be attained with much lower pedestal energy. The proposed compression scheme is a superior compression technique, which can be applied in pulse compression for a wider range of pulse widths. It is very attractive in comparison with current compression schemes and techniques.

References

[1] Q. Li, P. K. A. Wai, K. Senthilnathan and K. Nakkeeran, J. Lightw. Technol. **29**, 1293 (2011).
[2] D. Wang, Y. X. Leng and Z. Z. Xu, Opt. Commun. **285**, 2418 (2012).
[3] A. A. Voronin, J. M. Mikhailova, M. Gorjan, Zs. Major and A. M. Zheltikov, Opt. Lett. **38**, 4354 (2013).
[4] C. Lefort, M. Kalashyan, G. Ducourthial, T. Mansuryan, R. P. O'Connor and F. Louradour, J. Opt. Soc. Am. B **31**, 2317 (2014).
[5] H. J. Zheng, S. L. Liu, X. Li and C. Q. Wu, Opt. Laser Technol. **43**, 1321 (2011).
[6] WEI Zhi-hu, WANG Rong, PU Tao, FANG Tao, ZHENG Ji-lin, SUN Guo-dan and ZHEN Fei, Journal of Optoelectronics·Laser **25**, 61(2014). (in Chinese)
[7] A. M. Rubenchik, S. Chekhovskoy, M. P. Fedoruk, O. V. Shtyrina and S. K. Turitsyn, Opt. Lett. **40**, 721 (2015).
[8] G. P. Agrawal, Application of Nonlinear Fiber Optics, 2nd Edition, New York: Academic Press 2001.
[9] A. Mostofi, H. Hatami-Hanza and P. L. Chu, IEEE J. Quantum Electron. **33**, 620 (1997).
[10] M. D. Pelusi and H. F. Liu, IEEE J. Quantum Electron. **33**, 1430 (1997).
[11] Q. Li, J. N. Kutz and P. K. A. Wai, J. Opt. Soc. Am. B **27**, 2180 (2010).
[12] Q. Li, J. N. Kutz and P. K. A. Wai, Opt. Commun. **301**, 29 (2013).
[13] A. Bananej, A. K. Aghaee, A. Madjabadi and M. Vaezzadeh, Optik **125**, 5476 (2014).
[14] N. J. Doran and D. Wood, Opt. Lett. **13**, 56 (1988).
[15] G. P. Agrawal, Nonlinear Fiber Optics, San Diego: Academic Press, 2001.