2017 IEEE International Conference on Telecommunications and Photonics (ICTP)
26-28 December, 2017, Dhaka, Bangladesh

A 63fs Soliton Pulse Generation by Compression of Higher Order Soliton in Linear Dispersion Decreasing Fiber

Shah Md. Salimullah[#], Mohammad Faisal[*], Md. Saddam Hossain[#], Md. Monir Ahamed[#], Md. Shakhawath Hossain[#]

[#]Department of Electrical and Electronic Engineering, Bangladesh Army International University of Science and Technology (BAIUST), Comilla.

[*]Department of Electrical and Electronic Engineering, Bangladesh University of Engineering and Technology (BUET), Dhaka-1205.

[#]saikateee07@gmail.com,[*]mdfaisal@eee.buet.ac.bd

***Abstract*— A 2.05 m long linear dispersion decreasing fiber (LDDF) has been proposed for higher-order ultrashort soliton compression for nm-pm range soliton generation. We have obtained numerically ultrashort soliton of 63 fs after compression in LDDF. The spatial dimension has been found as 523.5 pm. Nonlinear Schrödinger equation (NLSE) has been solved using split-step Fourier (SSF) method for numerical analysis of ultrashort soliton propagation and compression. Such compressed pulse may have extensive applications in cancer cell treatment for creating smaller beam spot.**

***Keywords*— Liner dispersion decreasing fiber, split-step Fourier method, optical soliton**

I. Introduction

Soliton pulse has become a subject of tremendous investigation. Ultrashort optical pulses with soliton nature possess vast applications in different fields like nonlinear optics, high speed communications [1], material science and processing (e.g., femtosecond laser ablation), attosecond physics etc. In recent years femtosecond pulse has become multifunctional surgery means for surgery by refraction [2], inner ear surgery [3], dental [4, 5], cardiovascular surgery [6] and so forth. At the same time, ultrashort soliton has become prominent in removal of tissue as well as cancer cell treatment [7, 8]. Side effects associated with radiation therapy [9] in treatment of cancer occur because of high doses of radiation (which has spatial dispersion in mm range) used to destroy cancer cells. As spatial dispersion of radiation is in mm range it affects healthy tissues and cells located near the treatment area. However, the ultrashort soliton maintains spatial dimension (nm or pm range [10]) lower than that of cancer cell, hence it may causes no side effect other than removing the specific affected tissue. To get this ultrashort pulse, compression is one of the techniques [11-16].

Although soliton of width 115 fs [17] and 100 fs [18] has been obtained using compression technique in DDF, however, the impact of the higher-order effects upon such pulse are not considered in those studies. At the same time most works use long length of DDF. In our study, higher-order effects like third-order dispersion (TOD), intrapulse Raman scattering (IRS) and self-steepening (SS) have been considered. The pulse width has been calculated as 63 fs after compression in our proposed LDDF with length of 2.05 m.

In this paper considering higher-order linear and nonlinear effects we have analyzed the soliton compression in LDDF according to nonlinear Schrödinger equation (NLSE). Sect. 2 describes basic physics of ultrashort soliton propagation. Compression of ultrashort fundamental soliton has been explored with the designed dispersion profile of LDDF in Sect. 3. Sect. 4 comprises LDDF based higher-order soliton compression up to 5th order.

II. Theoretical Analysis

Ultrashort (pulse width ⩽1ps) optical pulse propagation through single-mode fiber can be given by the generalized NLSE considering higher-order effects as [19]

$$\frac{\partial E}{\partial z}+\frac{\alpha E}{2}+\frac{i\beta_2}{2}\frac{\partial^2 E}{\partial T^2}-\frac{\beta_3}{6}\frac{\partial^3 E}{\partial T^3}=i\gamma\left(E|E|^2+\frac{i}{\omega_0}\frac{\partial}{\partial T}E|E|^2-T_R E\frac{\partial |E|^2}{\partial T}\right) \tag{1}$$

where E stands for the complex envelop of the optical pulse, z describes the pulse propagation distance, T is for time, α gives the coefficient of fiber loss, β_2 and β_3 explains the second-order dispersion and TOD respectively. T_R is the time related to Raman gain, the factor $1/\omega_0$ stands for the self-steepening effect and γ is the nonlinearity. The normalized amplitude U can be given as

$$E(z,\tau)=P_0\left(\sqrt{\exp(-0.5\alpha z)}\right)U(z,\tau) \tag{2}$$

Where incident pulse peak power is given by P_0. In Eq. (2) fiber loss is denoted by the exponential factor. Hence the Eq. (1) takes the form

$$\frac{\partial U}{\partial z}+i\frac{\beta_2}{2L_D}\frac{\partial^2 U}{\partial \tau^2}-\frac{\beta_3}{6L'_D}\frac{\partial^3 U}{\partial \tau^3}=i\frac{e^{-\alpha z}}{L_{NL}}\left(U|U|^2+is\frac{\partial}{\partial \tau}U|U|^2-\tau_R U\frac{\partial |U|^2}{\partial \tau}\right) \tag{3}$$

Where L_D and L'_D explains second-order and third-order dispersive length respectively and L_{NL} explains nonlinear length defined as

978-1-5386-3374-8/17/$31.00 ©2017 IEEE

$$L_{NL} = \frac{1}{\gamma P_0}, L_D = \frac{T_0^{\ 2}}{|\beta_2|}, L'_D = \frac{T_0^{\ 3}}{|\beta_3|} \tag{4}$$

In Eq. (3) self-steepening effect and intrapulse Raman scattering are followed by the factor s and τ_R respectively, and are given by

$$\tau_R = \frac{T_R}{T_0}, s = \frac{\lambda}{2\pi c T_0} \tag{5}$$

Where T_0 defines the input pulse width. Although the two effects are quite negligible for picoseconds pulses but for ultrashort pulses (pulse width T_0<1 ps) should be considered. Considering normalized amplitude (U), distance (Z) and time (τ) the Eq. (3) can be written as

$$\frac{\partial U}{\partial Z} + i\frac{1}{2}\frac{\partial^2 U}{\partial \tau^2} - i\frac{1}{6}\frac{\partial^3 U}{\partial \tau^3} = iN^2 e^{-\alpha z}\left(U|U|^2 + \frac{is}{\omega_0}\frac{\partial}{\partial \tau}U|U|^2 - \tau_R U\frac{\partial |U|^2}{\partial \tau} \right) \tag{6}$$

Here $U = \frac{A}{\sqrt{P_0}}, \tau = \frac{T}{T_0}, Z = \frac{z}{L_D}$ (7)

For soliton pulse, T_0 is as follows

$$T_0 = \frac{T_{FWHM}}{1.763} \tag{8}$$

Here N stands for the soliton order and is expressed as

$$N^2 = \frac{L_D}{L_{NL}} = \frac{\gamma P_0 T_0^{\ 2}}{|\beta_2|} \tag{9}$$

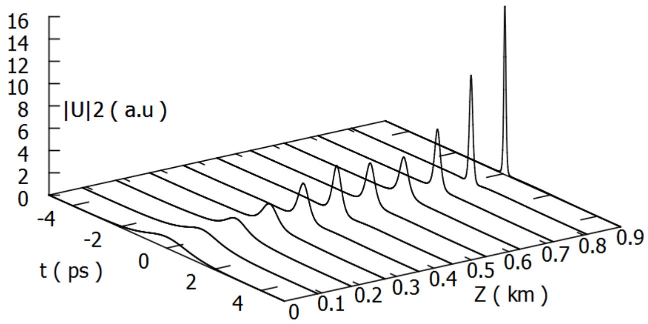
We have observed compression of ultrashort fundamental and higher-order soliton and explored our analysis solving Eq. (3) using SSF method. The time-bandwidth product for sech pulse is always 0.32. With temporal and spectral evolution of both fundamental and higher-order ultrashort soliton, the time-bandwidth product has also been checked.

III. Fundamental Soliton Dynamics in LDDF

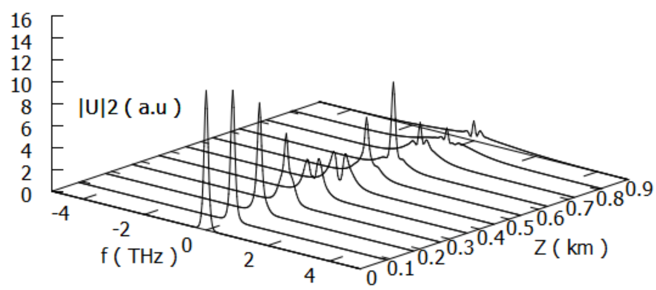
Soliton dynamics has been investigated for N = 1 using NLSE. Compression of fundamental soliton has been observed in LDDF. We have observed the temporal and spectral evolution of compressed soliton in an LDDF with following dispersion profile [20]:

$$\beta_{2n} = \beta_{2p}\left(1 + \frac{z}{\beta L} - \frac{z}{L}\right) \tag{10}$$

Where β_{2n}, β_{2p} are the changing group velocity dispersion (GVD) and starting GVD respectively. Here $\beta = \beta_{2p}/\beta_{2L}$, β_{2L} = final GVD and L is the total fiber length. We have explored fundamental soliton compression in LDDF with parameters as full width half maximum (FWHM) pulse width, T_{FWHM} = 2ps (initial pulse is chirp free), peak power, P_0 = 1.6W, β_{2P} = –10 ps^2 /km, β_{2L} = –1 ps^2/km, β_3 = 0.029 ps^3/km, γ = 5, s = 0.29, and τ_R = 0.02. Although the GVD is decreasing along the length of DDF, TOD has been considered constant. The time-bandwidth product of the soliton pulse has been checked as 0.32 that means adiabatic compression has been happened during the propagation. Fig.1 (a) gives the temporal evolution whereas Fig.1 (b) shows the spectral evolution of ultrashort fundamental soliton compression in LDDF.



(a)



(b)

Fig. 1: Compression of fundamental soliton in LDDF, (a) Temporal Evolution and (b) Spectral Evolution.

Higher-order effects are not observed since pulse width is more than 1ps. The 2ps pulse has been compressed up to 200fs using LDDF with 0.9 km length. Fig. 2 shows pulse width (FWHM) vs. distance curve for fundamental soliton in LDDF. In LDDF, dispersion decreases with distance, so nonlinearity dominates gradually and consequently the pulse width decreases. With decrease of pulse width, the peak power increases, so we have to take care of that power to keep it below the capacity of fiber.

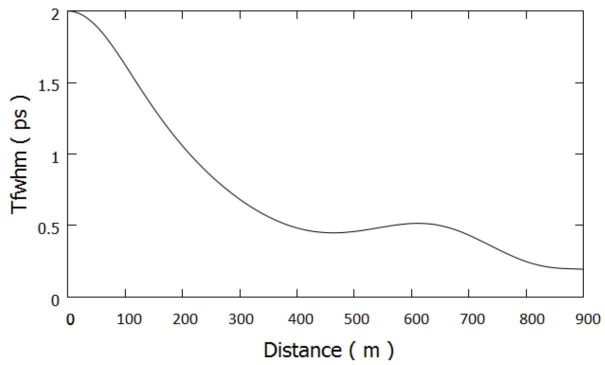
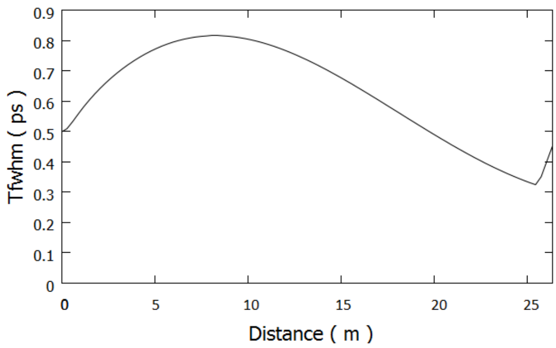


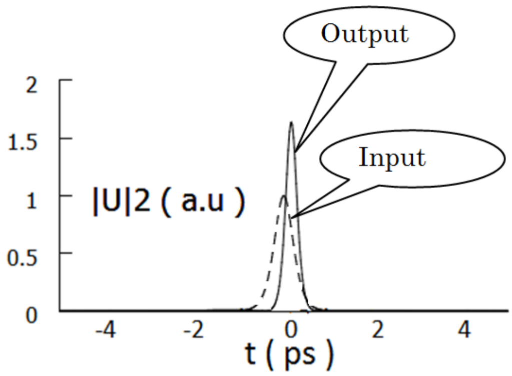
Fig. 2: Pulse width (FWHM) vs. distance curve for fundamental soliton in LDDF.

IV. Higher Order Soliton Dynamics in LDDF

Here we will see the compression of higher-order soliton in LDDF. Using LDDF the compression of second order soliton has been shown in Fig. 3 (a) with parameters used as T_{FWHM} = 500fs (initial pulse is chirp free), P_0 = 100W, $\beta_{2P} = -10$ ps^2/km, $\beta_{2L} = -1$ ps^2/km, $\beta_3 = 0.029$ ps^3/km, $\gamma = 5$, s = 0.29, $\tau_R = 0.02$, N = 2. What we have observed is that broadening of pulse is happened within first 10m of LDDF and then compression occurs in next 15m. The pulse width increases from 500fs to 800fs in first 10m and then decreases from 800fs to 340fs in next 15m through LDDF. This is because initially dispersive effect dominates and hence pulse broadening occurs (first 10m of LDDF in Fig. 3 (a)). With increase in fiber length dispersion decreases and nonlinear effect dominates here and we get pulse compression (next 15m of LDDF). The input and output pulse shape has been shown in Fig. 3 (b).

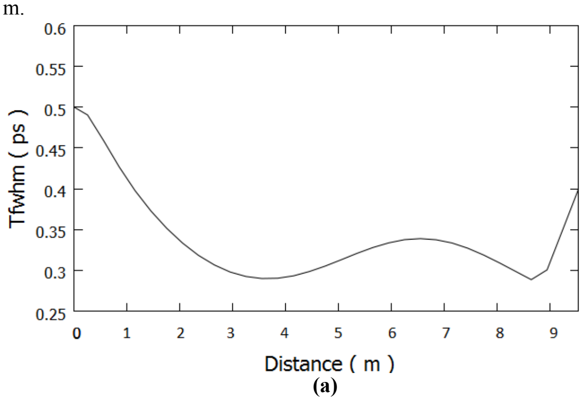


(a)

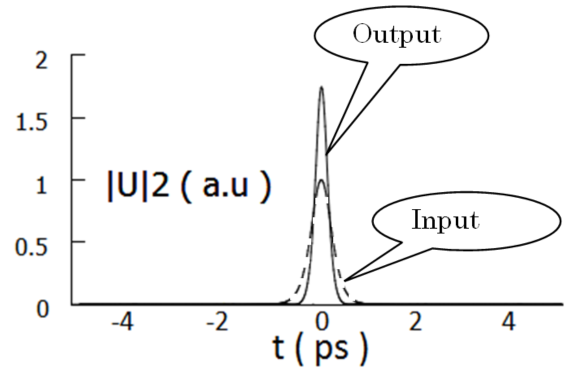


(b)

Fig. 3: (a) Pulse width (FWHM) vs. distance curve for second - order soliton in LDDF, (b) Input pulse and compressed output pulse after propagation of 25 m.



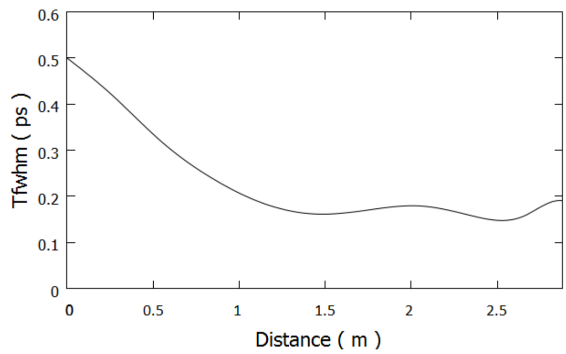
(a)



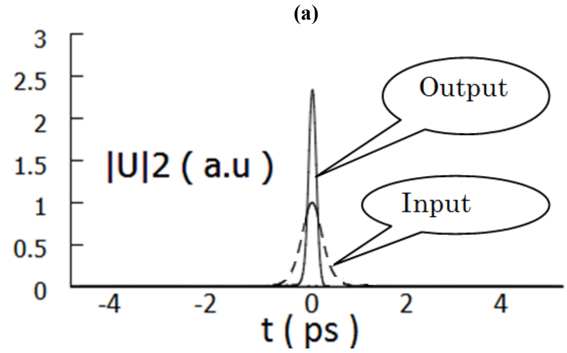
(b)

Fig. 4: (a) Pulse width (FWHM) vs. distance curve for third - order soliton in LDDF, (b) Input pulse and compressed output pulse after propagation of 8.5 m.

Fig. 4 shows the third-order soliton compression in LDDF. A smooth curve has been observed in LDDF that indicates compression of third-order soliton into 300fs from 500fs which is clear from Fig. 4 (a). The input/output pulse shape after compression has been shown in Fig. 4 (b).



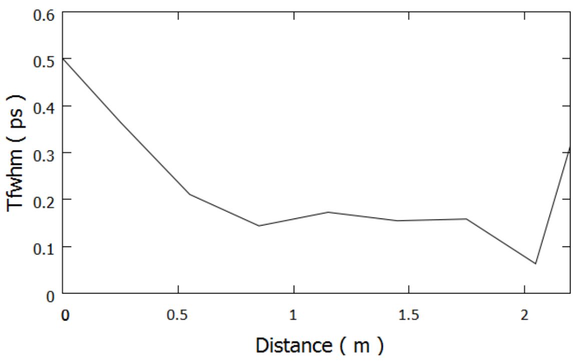
(a)



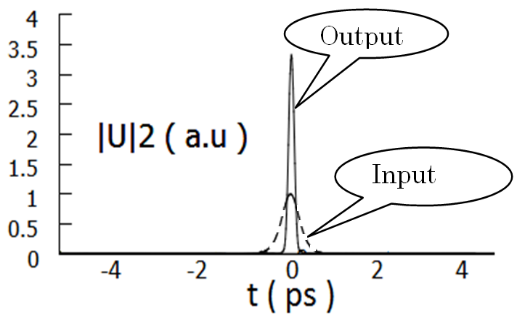
(b)

Fig. 5: (a) Pulse width (FWHM) vs. distance curve for fourth - order soliton in LDDF, (b) Input pulse and compressed output pulse after propagation of 2.5 m.

Let us see fourth-order sub-picosecond soliton compression shown in Fig. 5 for LDDF. We have found a very good compression of 500fs pulse into 150fs in LDDF briefed by Fig. 5 (a). Input pulse and output pulse after compression has been shown in Fig. 5 (b). For fifth-order soliton, the best compression has been found using LDDF where 500fs pulse is compressed to 63fs for 2.05m of fiber as shown in Fig. 6.



(a)



(b)

Fig. 6: (a) Pulse width (FWHM) vs. distance curve for fifth - order soliton in LDDF, (b) Input pulse and output pulse after compression through propagation of 2.05 m.

It is evident that with the more the soliton order increases, pulse width decreases at the end of LDDF. However, the peak power increases with increase of soliton order which could be so high and go beyond the tolerable limit of fiber. Even it may damage the fiber. Furthermore, higher-order dispersive and nonlinear effects will also be enhanced and pulse distortion may occur. The order of soliton and optimum length of LDDF for compression will be regulated by these factors.

V. Result and Discussion

All the data for ultrashort soliton compression in LDDF are given in Table I.

TABLE I
PULSE WIDTH AFTER COMPRESSION AND SPATIAL SOLITON DIMENSION FOR 500FS INPUT PULSE

Soliton order	Pulse width (post-compression) in LDDF	Spatial dimension of soliton in LDDF	Length of LDDF
2nd	340fs	2.72nm	25m
3rd	300fs	2.408nm	9m
4th	150fs	1.2nm	3m
5th	63fs	523.5pm	2.05m

We can summarize the results for ultrashort fundamental and higher-order soliton compression in LDDF as follows. For 2ps input pulse, the compressed soliton FWHM has been found 200fs in LDDF. Second-order soliton compression has been explored with 500fs input pulse width. The compressed pulse width has been found about 340fs in LDDF. Again in fourth-order soliton compression, LDDF causes compression upto 150fs. Finally in fifth-order soliton compression, the best output has been observed in LDDF. The compressed pulse width is as low as 63fs. The spatial dimension has also been calculated which maintains nm range for second, third and fourth order soliton and the last one occupies 523.5pm.

From all of the above comparison and outcomes for ultrashort optical soliton compression for fundamental and higher-order soliton up to fifth order, we can say that LDDF has performed compression with excellence which has been shown in Table I.

VI. Conclusions

Considering higher order dispersive effects i.e. TOD and higher order nonlinear effects i.e. SS and IRS, the compression of ultrashort optical soliton in LDDF has been investigated. LDDF of smaller length has been proposed for higher-order ultrashort soliton compression for formation of soliton in nm-pm range. Employing a small length of 2.05 m LDDF, we have obtained ultrashort soliton of 63 fs after compression. The spatial dimension has been found as 523.5pm.

References

[1] S. M. Salimullah and M. Faisal, "Ultrashort soliton propagation in multi-clad optical fibers with per channel data rate of 1Tb/s," in *Telecommunications and Photonics (ICTP), 2015 IEEE International Conference on*, 2015, pp. 1-5.

[2] S. I. Mian and R. M. Shtein, "Femtosecond laser-assisted corneal surgery," *Current opinion in ophthalmology,* vol. 18, pp. 295-299, 2007.

[3] B. Schwab, D. Hagner, W. Müller, H. Lubatschowski, T. Lenarz, and R. Heermann, "Bone ablation using ultrashort laser pulses. A new technique for middle ear surgery," *Laryngo-rhino-otologie,* vol. 83, pp. 219-225, 2004.

[4] J. Serbin, T. Bauer, C. Fallnich, A. Kasenbacher, and W. Arnold, "Femtosecond lasers as novel tool in dental surgery," *applied surface science,* vol. 197, pp. 737-740, 2002.

[5] R. F. Lizarelli, M. Costa, E. Carvalho-Filho, F. Nunes, and V. S. Bagnato, "Selective ablation of dental enamel and dentin using femtosecond laser pulses," *Laser Physics Letters,* vol. 5, p. 63, 2007.

[6] H. Lubatschowski, A. Heisterkamp, F. Will, J. Serbin, T. Bauer, C. Fallnich, *et al.*, "Ultrafast laser pulses for medical applications," in *Proc. SPIE*, 2002, pp. 38-49.

[7] I. Amiri, A. Nikoukar, J. Ali, and P. Yupapin, "Ultra-short of pico and femtosecond soliton laser pulse using microring resonator for cancer cells treatment," *Quantum Matter,* vol. 1, pp. 159-165, 2012.

[8] M. Jalil, J. Phelawan, M. Aziz, T. Saktioto, C. Ong, and P. P. Yupapin, "Acne vulgarism treatment using ultra-short laser pulse generated by micro-and nano-ring resonator system," *Artificial cells, nanomedicine, and biotechnology,* vol. 41, pp. 92-97, 2013.

[9] D. P. Dearnaley, V. S. Khoo, A. R. Norman, L. Meyer, A. Nahum, D. Tait, *et al.*, "Comparison of radiation side-effects of conformal and conventional radiotherapy in prostate cancer: a randomised trial," *The Lancet,* vol. 353, pp. 267-272, 1999.

[10] S. M. Salimullah and M. Faisal, "Femtosecond Soliton Formation by Higher-Order Soliton Compression in Linear Dispersion Decreasing Fiber," in *Proceedings of 20th Microoptics Conference (MOC'15)*, Fukuoka, Japan., 2015, pp. paper no. H-11.

[11] T. Murphy, "10-GHz 1.3-ps pulse generation using chirped soliton compression in a Raman gain medium," *IEEE Photonics Technology Letters,* vol. 14, pp. 1424-1426, 2002.

[12] C.-C. Chang, A. Vengsarkar, D. Peckham, and A. Weiner, "Broadband fiber dispersion compensation for sub-100-fs pulses with a compression ratio of 300," *Optics letters,* vol. 21, pp. 1141-1143, 1996.

[13] Q. Li, P. Wai, K. Senthilnathan, and K. Nakkeeran, "Modeling self-similar optical pulse compression in nonlinear fiber Bragg grating using coupled-mode equations," *Journal of Lightwave Technology,* vol. 29, pp. 1293-1305, 2011.

[14] Q. Li, K. Senthilnathan, K. Nakkeeran, and P. Wai, "Nearly chirp- and pedestal-free pulse compression in nonlinear fiber Bragg gratings," *JOSA B,* vol. 26, pp. 432-443, 2009.

[15] S. M. Salimullah, "Analysis of higher-order soliton compression for formation of ultra-short pulses," 2015.

[16] J. H. Lee, T. Kogure, and D. J. Richardson, "Wavelength tunable 10-GHz 3-ps pulse source using a dispersion decreasing fiber-based nonlinear optical loop mirror," *IEEE Journal of selected topics in quantum electronics,* vol. 10, pp. 181-185, 2004.

[17] S. V. Chernikov, D. Richardson, D. Payne, and E. Dianov, "Soliton pulse compression in dispersion-decreasing fiber," *Optics letters,* vol. 18, pp. 476-478, 1993.

[18] P. Wai and W.-h. Cao, "Ultrashort soliton generation through higher-order soliton compression in a nonlinear optical loop mirror constructed from dispersion-decreasing fiber," *JOSA B,* vol. 20, pp. 1346-1355, 2003.

[19] G. Agrawal, *Applications of nonlinear fiber optics*: Academic press, 2001.

[20] D. Chao-Qing and C. Jun-Lang, "Ultrashort optical solitons in the dispersion-decreasing fibers," *Chinese Physics B,* vol. 21, p. 080507, 2012.