OPTOELECTRONICS LETTERS Vol.10 No.5, 1 September 2014

A novel two-stage spectral compression structure employing a logarithmic DIF interconnected with an HNLF-NOLM[*]

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(Received 27 June 2014)

A novel two-stage spectral compression structure which employs a logarithmic dispersion increasing fiber (DIF) interconnected with a highly nonlinear linear fiber-nonlinear optical loop mirror (HNLF-NOLM) is proposed and demonstrated by numerical simulation. The numerical simulation is implemented by solving the generalized nonlinear Schrödinger equation using split-step Fourier method, where the soliton number is in the range of $0.5\leq N\leq 1.4$. The results show that the spectra are well-compressed and low-pedestal, and the maximum spectral compression ratio (SCR) can reach 10.93 when N=1.4.

Document code: A **Article ID:** 1673-1905(2014)05-0329-3

DOI 10.1007/s11801-014-4124-5

All-optical analog-to-digital conversion (ADC) has been investigated as a vital technology to overcome the bottleneck existing in the traditional electronic ADC[1-3]. Recently, tremendous growth in optical communication and digital signal processing has encouraged the research on the all-optical ADC with high speed and high resolution[1]. The process of all-optical ADC includes sampling, quantization and coding. In the last several decades, some schemes have been proposed for the photonic quantization process[4-6], and one of them is the soliton-self-frequency shift (SSFS)[6]. In an all-optical ADC based on Raman self-frequency shift quantization scheme, the resolution can be effectively enhanced by compressing the spectrum after SSFS[1]. The basis of the spectral compression in an optical fiber is the compensation between the initial negative chirp of an optical pulse and the positive chirp introduced by the self phase modulation (SPM) effect. The spectral compression, which is a common technology in the passive picosecond pulse shaping[7], can be achieved through transmitting an initially highly negative-chirped optical pulse through an optical fiber[8,9]. It can also be realized by transmitting a transform-limited optical pulse (or an optical pulse with a low chirp) through an anomalous dispersion fiber[10,11].

In this paper, a novel two-stage all-optical low-pedestal spectral compression scheme using a logarithmic dispersion increasing fiber (DIF) cascaded with a highly nonlinear linear fiber-nonlinear optical loop mirror (HNLF-NOLM) is proposed and demonstrated. The first DIF achieves the spectral compression, while the NOLM consisting of an HNLF, i.e., HNLF-NOLM, is proposed for pedestal suppression due to the chirp-related intensity filtering effect of NOLM, providing an extra spectral compression simultaneously. The nonlinear propagation of the chirp-free femtosecond pulse centered at 1 550 nm in the two-stage structure is solved by the split-step Fourier method under the condition that the soliton number (N) is equal to 0.5, 1 and 1.4, respectively. The simulation results show that the spectrum, which is compressed by the DIF, can be re-compressed when pulses propagate through the HNLF-NOLM. The spectral compression ratio (SCR) is defined as the ratio of the full-width at half maximum (FWHM) of the input spectrum to that of the compressed one. It is found that the SCR increases with the power of the pulses increasing, and the maximum SCR is 10.93 when N=1.4.

The scheme of the two-stage spectral compression is shown in Fig.1, which includes DIF for the first stage of spectral compression and HNLF-NOLM for the second one. The spectral compression principle is analyzed as follows. DIF is used to provide the first-stage spectral compression. The soliton order N is given by

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[*] This work has been supported by the National Basic Research Program of China (No.2012CB315701), and the National Natural Science Foundation of China (No.61205109).

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$$N^2 = \frac{T_{\mathrm{FWHM}}^2 \gamma P_0}{3.11|\beta_2|}, \tag{1}$$

where T_{FWHM} is the temporal pulse width at FWHM, γ is the nonlinear coefficient, P_0 is the peak power, and β_2 is the second-order dispersion coefficient. As a fundamental soliton propagating along a fiber, if $|\beta_2|$ is continuously increased along the transmission length, the value of T_{FWHM} is keeping growing, which leads to the temporal shape broadening. Therefore, the pulse spectrum is gradually compressed to preserve the fundamental soliton condition.

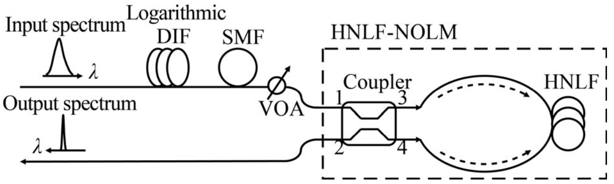


Fig.1 Schematic diagram of the proposed two-stage spectral compression scheme

After the first spectral compression in the DIF, negative chirp is induced to the sub-picosecond fundamental soliton pulse and enhanced by the single mode fiber (SMF). Then the pulse is injected into the HNLF-NOLM, and divided into the clockwise and counter-clockwise ones in the 2×2 optical power coupler (with coupling ratio of α:1–α, where $\alpha \neq 0.5$) of the HNLF-NOLM. HNLF-NOLM provides a further spectral narrowing for the forestage shaped spectrum. Consequently, the two-stage spectral compressor can achieve a higher spectral compression ratio and a low-pedestal spectrum simultaneously.

Besides, the undesired pedestal is generated after pulse propagation in DIF. The origin of the spectral pedestal is the unmatched compensation of the SPM-induced nonlinear chirp mainly distributed at the leading and trailing edges of the optical pulse, which has a lower power in the time domain compared with the pulse center (the area of matched chirp compensation). It is well-known that the leading and trailing edges of the optical pulse with a lower power (i.e., a smaller nonlinear phase shift) are reflected by NOLM[12]. Therefore, the spectrum pedestal can be efficiently filtered out by NOLM architecture in its transmission mode, which is called chirp-related spectrum filtering effect in this paper.

In the simulation, the input pulse FWHM width is 200 fs with the central wavelength of 1 550 nm. The dispersion of the DIF increases with the transmission distance of z which is given by

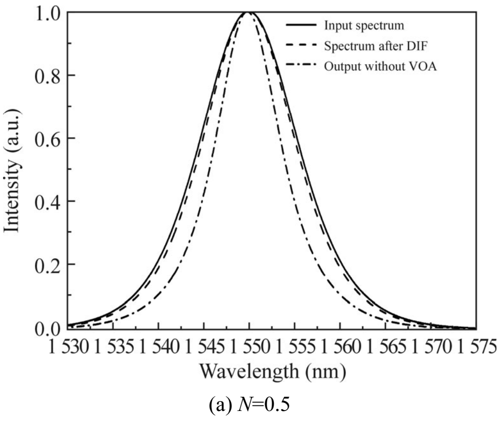
$$\beta_2(z) = -\ln[\mathrm{e} + \frac{z}{L}(\mathrm{e}^{-\beta_2(L)} - \mathrm{e})], \tag{2}$$

where L is the length of DIF, and $\beta_2(z)$ and $\beta_2(L)$ are the group velocity dispersion (GVD) parameters of the fiber at z and L, respectively. The parameters of the DIF are shown in Tab.1. A 20 m-long SMF with the dispersion of 15 ps/(nm·km) is connected with the DIF. In the HNLF-NOLM, the coupler ratio is 60:40, and the loss, dispersion, dispersion slope and nonlinearity coefficient of the HNLF are 0.939 dB/km, 2.187 ps/(nm·km), 0.022 ps/(nm^2·km) and 27 W^{-1}km^{-1}, respectively. The generalized nonlinear Schrödinger equation which describes the propagation of the pulses in the fibers is solved numerically using split-step Fourier method. In our simulation, the peak powers of the input pulses are 10 W, 40 W and 80 W, corresponding to N=0.5, 1.0 and 1.4, respectively, and different SCRs are obtained by controlling the variable optical attenuator (VOA), which is located between SMF and coupler.

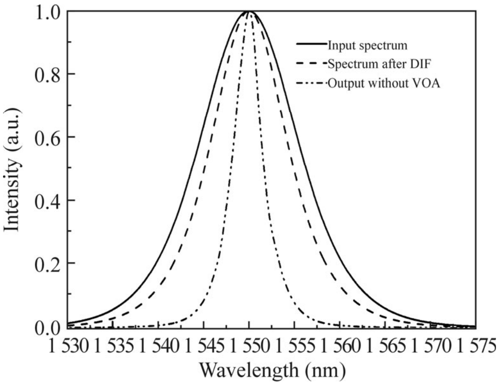
Tab.1 Parameters of DIF

Loss α (m^{-1})	GVD parameter β_2 (ps^2/km)	TOD parameter β_3 (ps^3/km)	Length (m)	Nonlinearity coefficient γ (W^{-1}km^{-1})
0.002	-1—-11	0.02	100	1.96

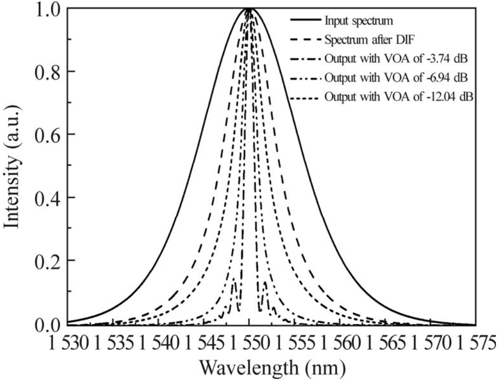
Fig.2 illustrates the simulation results of the two-stage spectral compression scheme at N=0.5, 1.0 and 1.4, respectively. Through the DIF, the spectra of the pulses are compressed from 12.6 nm to 11.96 nm, 9.86 nm and 6.66 nm, respectively, corresponding to the SCRs of 1.05, 1.28 and 1.89, respectively. This working principle is the reverse operation of the well-adopted soliton temporal compression (spectral broadening) in a dispersion decreasing fiber[13]. In the case of N=0.5, as shown in Fig.2(a), the minimum spectral width of the output is 8.56 nm which corresponds to the total SCR of 1.47. Fig.2(b) and (c) represent the variations of the spectra when the attenuation of VOA changes. It is obviously found that the spectra become narrower with increasing the power injected into the HNLF-NOLM. This behavior can be understood by noting that the initial chirp of the pulses launched into the HNLF-NOLM and the chirp due to the SPM effect are of opposite signs over the central portion of the pulses, and the pulses become less and less chirped with increasing the power launched into the HNLF-NOLM. Moreover, the minimum spectral widths of 3.66 nm (total SCR of 3.44) and 1.15 nm (total SCR



(a) N=0.5



(b) N=1.0



(c) N=1.4

Fig.2 Spectral evolutions of the two-stage spectral compression structure with the input peak powers of 10 W, 40 W and 80 W, corresponding to *N*=0.5, 1.0 and 1.4, respectively

of 10.93) are obtained at N=1.0 and 1.4, respectively. However, a pedestal appears clearly, as shown in Fig.2(c) when the attenuation of VOA is 3.74 dB for the insufficient compensation of the nonlinear chirp near the pulse edges. Comparing Fig.2(a)–(c), the greater N is, the narrower the minimum spectral width gets in the range of $0.5 \leq N \leq 1.4$. Besides, because the Raman term of the generalized nonlinear Schrödinger equation has little effect in the case of $N \leq 1.4$, there is almost no Raman soliton self-frequency shift which is vital to the resolution improvement of the all-optical quantization based on SSFS.

A novel two-stage spectral compression structure employing a logarithmic DIF cascaded with an HNLF-NOLM is proposed and demonstrated. The numerical results show that the designed scheme works well on the spectral compression in the range of $0.5 \leq N \leq 1.4$ at 1 550 nm. When the higher peak power of the pulse is launched into the HNLF-NOLM, the narrower spectral width is obtained. With a small center-wavelength shift, the maximum spectral compression ratio can reach 10.93 when the pulse peak power is equal to 80 W.

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