Numerical Investigation of a Novel Two-stage Spectral Compression Structure Employing a Logarithmic DIF Cascading with a HNLF-NOLM

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Abstract— A novel all-optical spectral compression structure is proposed, which employs a logarithmic dispersion increasing fiber cascading with a highly nonlinear linear fiber-nonlinear optical loop mirror. Numerical simulation is carried out by solving the generalized nonlinear Schrödinger equation using split-step Fouier 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 the maximal spectral compression ratio can reach 10.93 with a little of pedestal when $N = 1.4$.

1. INTRODUCTION

All-optical analog-to-digital conversion (ADC) has been investigated as a vital technology to overcome the "electronic bottleneck" existed in the traditional electronic ADC. Recent 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 the all-optical ADC includes sampling, quantization and coding. In the last several decades, several groups have proposed some schemes for the photonic quantization process [2–4], and one of them is the soliton-self-frequency shift (SSFS) [4]. The main method to improve the resolution of SSFS is to compress the spectral width after SSFS. Up to date, the general scheme is that the pre-negative-chip pulses suffer self-phase modulation (SPM) in fiber [5], the other ones include the schemes of transmitting through dispersion increasing fiber (DIF) [6] and anomalous dispersion fiber [7, 8].

In this paper, a novel two-stage all-optical spectral compression scheme using a logarithmic DIF cascading with a highly nonlinear linear fiber-nonlinear optical loop mirror [9] (HNLF-NOLM) is proposed. The nonlinear propagation of the chirp-free femtosecond pulse at 1550 nm is solved by the split-step Fourier method in the range of $0.5 \leq N \leq 1.4$. 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 FWHM (full-width at half maximum) of the input spectrum to that of the compressed one. It is found that the SCR increases with the power of the pulses, and the maximal SCR is 10.93 when $N = 1.4$.

2. OPERATION PRINCIPLE

The scheme of the two-stage spectral compression is shown in Figure 1, which includes DIF for the first stage of spectral compression, and HNLF-NOLM for the second one. The sub-picosecond pulse, whose peak power satisfies the range of $0.5 \leq N \leq 1.4$, is injected into the DIF to generate spectral compression and some negative chirp. Then the pulse enters the HNLF-NOLM. Firstly the negative chirp of the pulse is enhanced in the single mode fiber (SSMF); and then the pulse is divided into the clockwise and counter-clockwise ones in the 2×2 optical power coupler (coupling

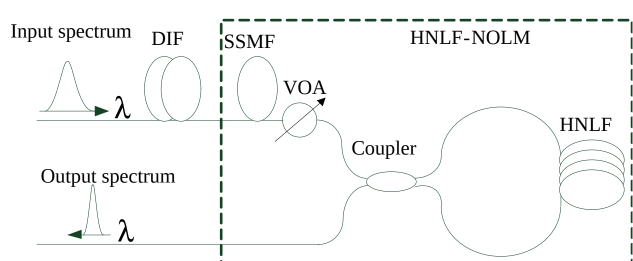

Figure 1: Schematic diagram of the two-stage spectral compression.

ratio is $\alpha : 1-\alpha$, where $\alpha \neq 0.5$) of the HNLF-NOLM, where the spectra of the both pulses are compressed because of the offset between the negative chirp in the pulses and the positive chirp generated by SPM effect in HNLF. When the pulses meet each other again in the coupler, their phase is different because of the SPM effect for different peak power of the pulses in the HNLF. As a result, the two pulses' pedestal can be decreased by interference only if the pulse which enters the NOLM possesses an appropriate power, at the same time, the spectrum of the output pulse is compressed effectively.

3. SIMULATION

In the simulation, the input pulse width is $T_{\mathrm{FWHM}} = 200\,\mathrm{fs}$ with the central wavelength 1550 nm. The dispersion of the DIF increases with the transmission distance of z which is given by the following

$$\beta_2(z) = -\ln\left(e + \frac{z}{L}\left(e^{-\beta_2(L)} - e\right)\right)\ \mathrm{ps}^2/\mathrm{km} \tag{1}$$

where L is the length of the DIF, $\beta_2(z)$ and $\beta_2(L)$ are the GVD parameter of the fiber at z and L, respectively. The parameters of the DIF are shown in Table 1. A 20 m-long SSMF 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, nonlinearity coefficient of HNLF are 0.939 dB/km, 2.187 ps/nm/km, 0.022 ps/nm^2/km, 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 power of the input pulse of $P_{\mathrm{peak}} = 10\,\mathrm{W}$, 40 W and 80 W (correspond to $N = 0.5$, 1, 1.4 respectively for the DIF) are used, different SCRs are obtained by controlling the variable optical attenuator (VOA), which is located between the SSMF and coupler.

Figures 2, 3 and 4 illustrate the simulating results of the two-stage spectral compression scheme at $N = 0.5$, 1 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, 6.66 nm, respectively, corresponding to the SCR of 1.05, 1.28 and 1.89. This working principle is the reverse operation of the well-adopted soliton temporal compression (spectral broadening) in a dispersion decreasing fiber [10]. In the case of $N = 0.5$, as shown in Figure 2, the minimum spectral width of the output is 8.56 nm which corresponds to the total SCR = 1.47. Figure 3 and Figure 4 represent the variation of the spectra when changing the attenuation of the VOA. 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 width of 3.66 nm (total SCR = 3.44) and 1.15 nm (total SCR = 10.93) are obtained, respectively, at $N = 1$

Table 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

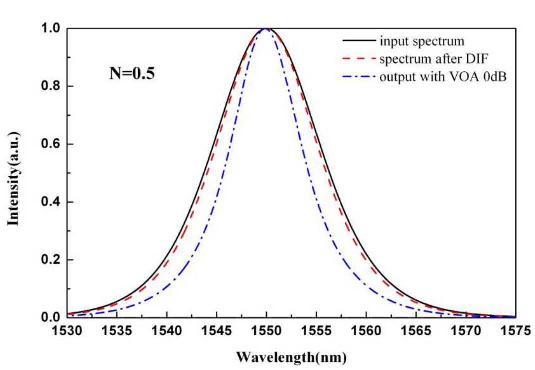

Figure 2: spectra of pulses at $N = 0.5$.

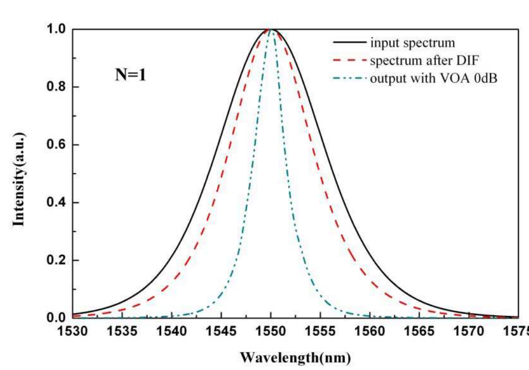

Figure 3: spectra of pulses at $N = 1$.

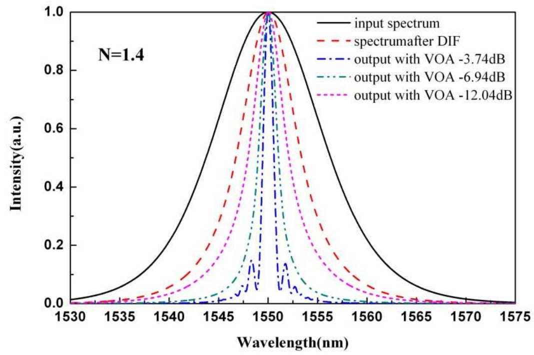

Figure 4: Spectra of pulses at $N = 1.4$.

and $N = 1.4$. However, a pedestal appears clearly, as shown in Figure 4, when the attenuation of the VOA is 3.74 dB for the insufficient compensation of the nonlinear chirp near the pulse edges. Comparing the three figures, 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 GNLS has little effect in the cases 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.

4. CONCLUSION

A novel two-stage spectral compression structure employing a logarithmic DIF cascading with a HNLF-NOLM is proposed. The numerically results show that the designed scheme works well on the spectral compression in the range of $0.5 \leq N \leq 1.4$ at 1550 nm. The higher peak power of the pulse launched into the HNLF-NOLM, the narrower spectral width is obtained. With little center-wavelength shift, the maximal spectral compression ratio can reach 10.93, at $P_{\text{peak}} = 80\,\text{W}$.

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