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Abstract. An innovative all-fiber low-pedestal spectral compression scheme based on a two-stage structure employing a high nonlinear fiber (HNLF) connected with a nonlinear optical loop mirror (NOLM) is proposed and demonstrated. Both numerical and experimental results showed that the spectral pedestal and side-lobe component after spectral compression in the HNLF can be efficiently suppressed by the NOLM, simultaneously improving the spectral compression ratio. The measured spectral compression ratio increases by a factor of 2 from 3.39 to 6.91 and the side-lobe level is reduced from –7.47 to –9.36 dB. The spectral pedestal ratio is 15.7% using the proposed scheme, which is nearly one-third of that using the conventional feedthrough HNLF alternative. © *The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI.* [DOI: 10.1117/1.OE.53.8.086111]

Keywords: two-stage spectral compression; pedestal suppression; self phase modulation; high nonlinear fiber; nonlinear optical loop mirror.

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1 Introduction

All-optical analog-to-digital conversion (ADC) in which the whole process is realized in the optical domain is the key technique to convert optical analog signals into optical digital ones. In an all-optical ADC based on a soliton self-frequency shift (SSFS) quantization scheme, the resolution, one of the vital factors, can be effectively enhanced by compressing the spectrum after SSFS.[1] Spectral compression, a common technology in passive picosecond pulse shaping,[2] can be achieved by passing an initially negative-chirped optical pulse through an optical fiber. [3,4] It can be also realized by passing a transform-limited optical pulse (or an optical pulse with a low chirp) through an anomalous dispersion fiber.[5,6]

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. In general, the compressed spectrum is accompanied by an undesired pedestal that may account for up to half of the energy of the output spectrum.[7–9] The pedestal is the product of the mismatch between the dispersion-induced (or initial) linear negative chirp and the SPM-induced nonlinear positive chirp where the SPM-induced nonlinear chirp distributed at the leading and trailing-edge of the optical pulse is responsible for the uncompressed spectrum part. The spectral side-lobe components in the pedestal would disable the resolution improvement of the all-optical ADC system based on spectral quantization. To the best of our knowledge, only a few works to date have focused on spectral pedestal elimination.[10,11] In Ref. 11, a comb-like dispersion profiled fiber composed of 19 concatenations of standard single-mode fibers (SMF) and dispersion shifting fibers is applied to keep adiabatic soliton propagation during its spectral compression, so that the spectral pedestal is largely suppressed. However, extreme care is required in maintaining the dispersion and nonlinearity balance and fusion splicing among 19 segment fibers, which greatly increases the complexity of the whole system.

In this paper, a novel two-stage architecture employing a segment of high-nonlinear fiber (HNLF) as the first stage and a nonlinear optical loop mirror (NOLM) composed of another segment of HNLF in the loop (HNLF-NOLM for short) as the second stage is introduced. The HNLF realizes the first-stage spectral compression, while the NOLM is employed for the second-stage spectral compression and pedestal suppression due to its chirp-related spectrum filtering effect. Both numerical and experimental results indicate that spectral compression with a larger compression ratio and a lower pedestal can be achieved in the proposed two-stage structure, compared to its feedthrough HNLF alternative.

2 Operation Principle

NOLMs, well known for their excellent time-domain nonlinear self-switching characteristics, are generally used in all-optical processing devices, especially in the pulse shaper to simultaneously achieve pulse compression and pedestal suppression.[12–18] In fact, spectral compression and pedestal suppression of an optical pulse can also be realized in a NOLM structure whose operation principle is introduced in this paper. Figure 1 shows the configuration of the proposed two-stage spectral compression scheme based on an

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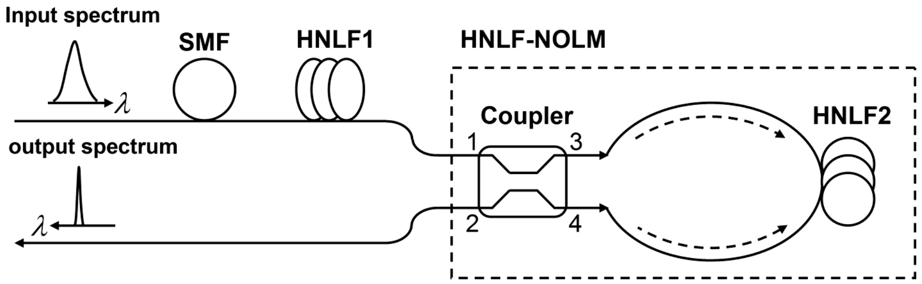


Fig. 1 Configuration of the two-stage scheme.

HNLF connected with an HNLF-NOLM. The HNLF-NOLM is composed of a HNLF and an optical coupler with a power coupling ratio of $\alpha{:}1-\alpha$ ($\alpha \neq 0.5$). The SMF is used to prechirp the input pulse. The two-stage structure is employed to compensate the negative chirp induced by the SMF through the SPM effect, providing two-stage spectral compression. The spectral compression in the HNLF is well understood as a process of chirp compensation.[5,9] The origin of the spectral pedestal is the unmatched compensation of the SPM-induced nonlinear chirp, mainly distributed at the leading and trailing edge 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 the NOLM.[12] Therefore, the spectrum pedestal can be efficiently filtered out by the NOLM architecture in its transmission mode, which is called the chirp-related spectrum filtering effect in this paper. Besides spectral pedestal suppression, HNLF-NOLM provides a further spectral narrowing for the forestage shaped spectrum. Consequently, the two-stage spectral compressor can simultaneously achieve a higher spectral compression ratio and a low-pedestal spectrum.

Actually, the propagation of ultrashort pulses in the HNLF-NOLM is a complex process involving various nonlinear effects, most important of which are SPM, cross-phase modulation, four-wave mixing, Raman-induced frequency shift, and soliton formation. In this paper, the input pulse has sufficient low peak power and subpicosecond duration. After its propagation in the first SMF, the pulse width broadens to several picoseconds, and the peak power is also greatly reduced. Therefore, various nonlinear effects, with the exception of SPM, can be neglected in the proposed scheme.

3 Simulation

The proposed two-stage scheme's simulation setup is shown in Fig. 1. In the simulation, a 20 m-long SMF with a group velocity dispersion value of 16.1 ps/nm/km is connected with the first segment of HNLF (HNLF1) whose nonlinear coefficient, loss coefficient, dispersion coefficient (β_2), and length are 11.5 $\mathrm{W}^{-1}\,\mathrm{km}^{-1}$, 0.9 dB/km, $-2.5491\ \mathrm{ps}^2/\mathrm{km}$, and 1000 m, respectively. The output of HNLF1 is connected with Port1 of the HNLF-NOLM. The HNLF-NOLM is composed of a coupler with a coupling ratio of 60/40 and a second segment of HNLF (HNLF2) whose nonlinear coefficient, loss coefficient, dispersion coefficient (β_2), and length are 27 $\mathrm{W}^{-1}\,\mathrm{km}^{-1}$, 0.939 dB/km, $-2.7875\ \mathrm{ps}^2/\mathrm{km}$, and 1000 m, respectively. A chirp-free hyperbolic-secant pulse, with a central wavelength of 1560 nm, a duration of 300 fs (FWHM), and a peak power of 6.667 W, is used as the input.

The propagation of a single optical pulse in an SMF or/and HNLF is described by the generalized nonlinear Schrödinger (GNLS) equation.[19] The evolution of the two counter propagating pulses in the HNLF-NOLM is described by the coupled GNLS equations.[19] Both GNLS and coupled GNLS equations are solved using the split-step Fourier method[19] for simulating the spectral compression procedure in both the two-stage structure and the feedthrough HNLF schemes.

There are three parameters with which to evaluate the spectral compression performance, i.e., spectral compression ratio (SCR), defined as the ratio of the input to the output spectral width full width at half maximum (FWHM); spectral pedestal ratio (SPR), defined as the ratio of the pedestal energy to the whole spectrum; and side-lobe suppression ratio (SLSR), defined as the ratio of spectral peak level to side-lobe level.

Figures 2(a) and 2(b) present the calculated spectra of the input and output pulses for the two-stage scheme and the feedthrough HNLF scheme (also with an input 20m-long SMF as shown in Fig. 1), respectively. It can be seen that the SCR is increased from 4.63 to 6.27. The spectral pedestal is sharply suppressed by the HNLF-NOLM. The SPR of the two-stage scheme is only 10.45%, which is much smaller than that of the feedthrough HNLF scheme (48.39%). The spectral side-lobe level is reduced from −6.2 to −12.23 dB.

Based on the simulation, the four factors (input pulse peak power, length of HNLF1, length of HNLF2, and coupler ratio) which influence the SCR, SPR, and SLSR in the two-stage scheme are also analyzed. Figures 3(a) and 3(b) show the output spectrum and the output pulse chirp, respectively, and Fig. 3(c) illustrates the SCR, SPR, and SLSR during the pulse propagation in the two-stage scheme with different input pulse peak powers. The calculated results indicate that there is an optimal input peak power to simultaneously achieve the maximum SCR, minimum SPR, and a high SLSR (e.g., between 6 and 7 W in this paper). When the input pulse peak power is larger than 8 W, the chirp induced at the leading and trail edges of the pulse is nonlinear and the compressed spectrum rapidly degrades.

Figures 4(a) and 4(b) exhibit the output spectrum and the output pulse chirp, respectively, and Fig. 4(c) shows the SCR, SPR, and SLSR of the two-stage scheme with a different length of HNLF1. It is implied that the SPR and SCR are approximately proportional, but the SLSR is in inverse ratio to the length of HNLF1, which means that a shorter HNLF1 yields a better SPR and SLSR but a degraded SCR. There is,

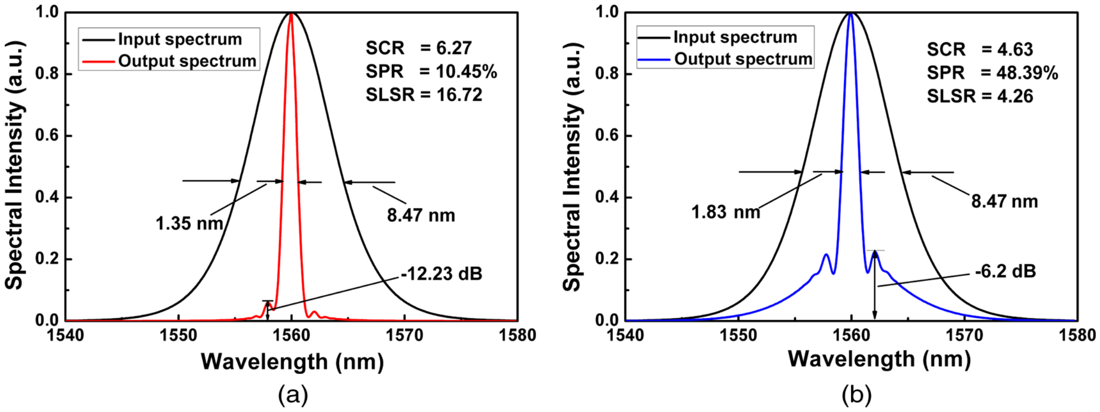


Fig. 2 Calculated input and output spectra for (a) the two-stage scheme and (b) the feedthrough HNLF scheme.

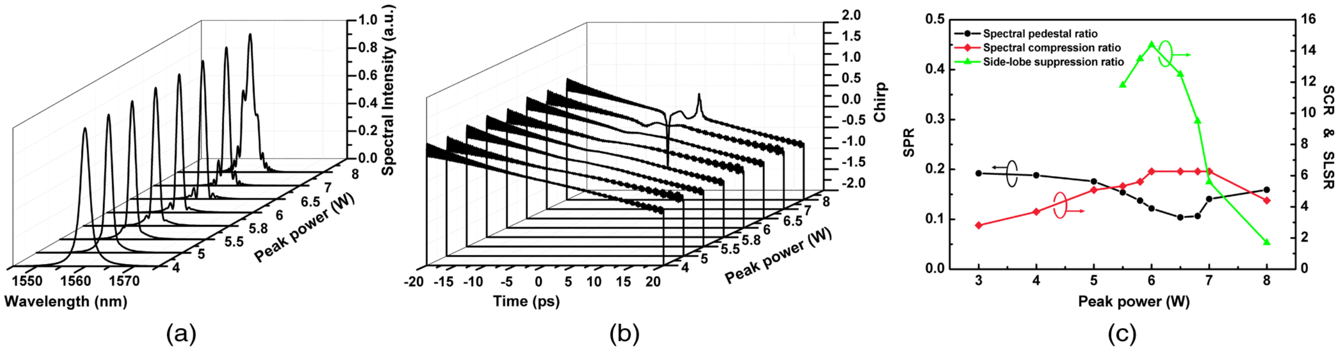


Fig. 3 (a) Output spectrum, (b) output pulse chirp and (c) SCR, SPR and SLSR with different input peak power.

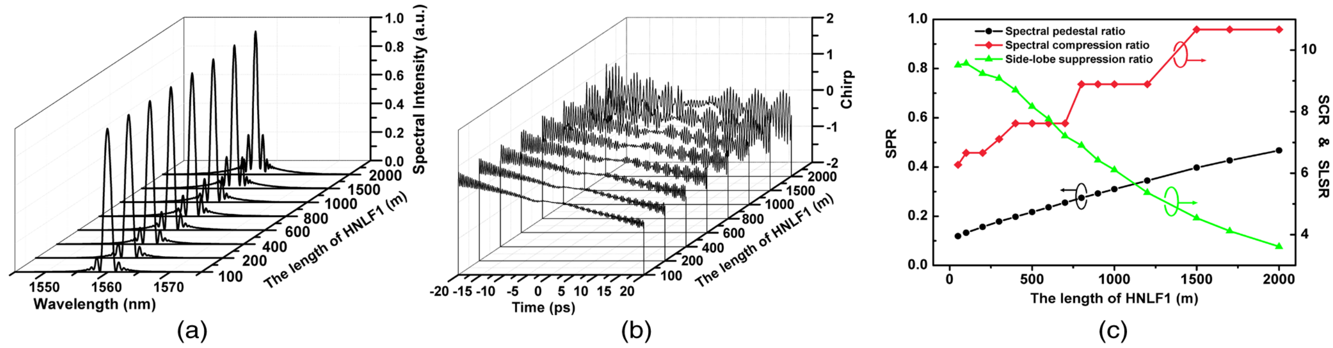


Fig. 4 (a) Output spectrum, (b) output pulse chirp and (c) SCR, SPR and SLSR with different length of HNLF1.

consequently, a trade-off among these three parameters to obtain an optimized compressed spectrum.

Figures 5(a) and 5(b) give the output spectrum and the output pulse chirp, respectively, and Fig. 5(c) displays the SCR, SPR, and SLSR of the two-stage scheme with a different length of HNLF2 in NOLM when the length of HNLF1 is 1000 m. The results reveal that there is an optimal HNLF2 length with which to achieve a minimum SLSR and high enough SCR and SPR.

Figures 6(a) and 6(b) illustrate the output spectrum and the output pulse chirp, respectively, and Fig. 6(c) shows the SCR, SPR, and SLSR of the two-stage scheme with a different coupler ratio. The results suggest that a smaller coupler ratio (>0.5) leads to a maximum SLSR, a high enough SCR (≥7), and a low enough SPR (≤0.1), which means that there should be a compromised consideration among these three parameters (e.g., 0.52 in this paper).

4 Experimental Setup and Results

The experimental setup of the two-stage scheme is shown in Fig. 7. The input hyperbolic-secant pulse is generated by a passively mode-locked Er-doped fiber laser source with a central wavelength of 1565.6 nm, a spectral width of 5.8 nm (FWHM), a peak power of 6.2 W, and a repetition rate of 50 MHz, respectively. The first variable optical attenuator (VOA1) is used to reduce the input power of the SMF, eliminating the nonlinear effect during the pulse propagation in the SMF. After its propagation in the SMF, the pulse peak power is amplified to 6.7 W by an erbium-doped fiber amplifier (Amonics AEDFA 1L-23-8-FA, Hong Kong). Then the

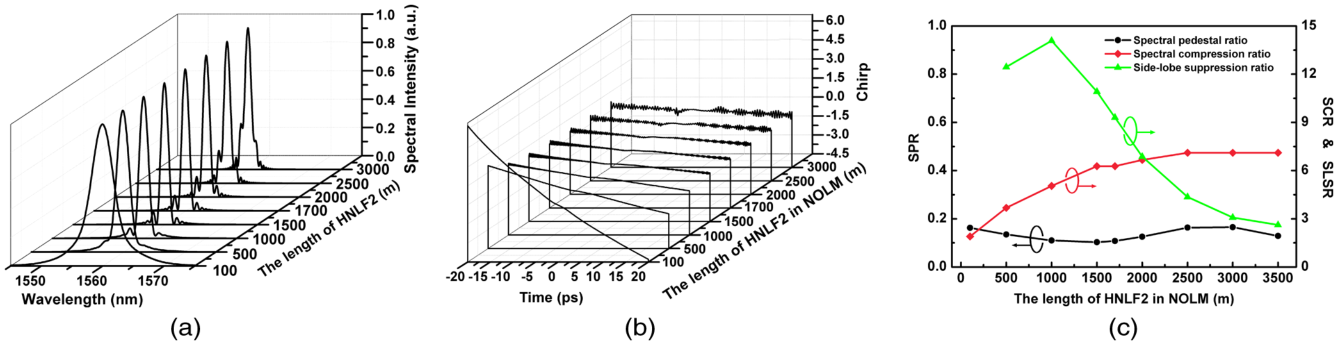


Fig. 5 (a) Output spectrum, (b) output pulse chirp and (c) SCR, SPR and SLSR with different length of HNLF2 in NOLM.

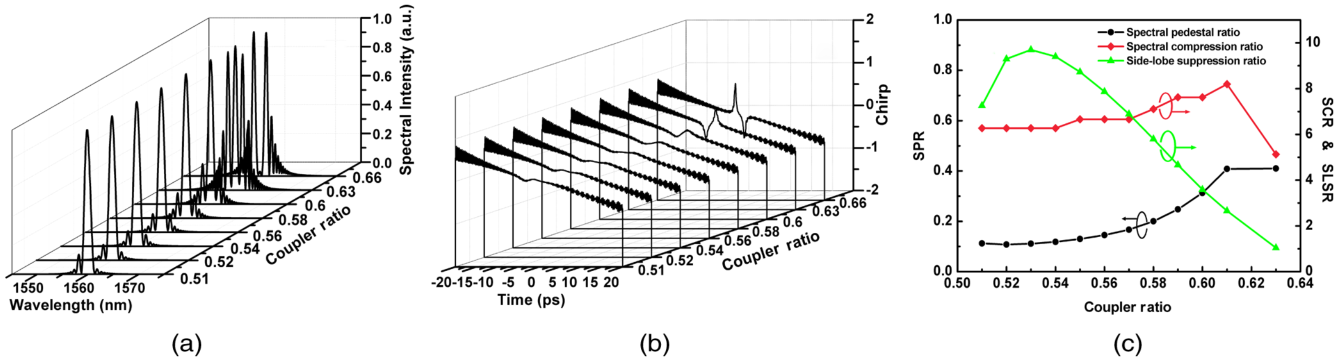


Fig. 6 (a) Output spectrum, (b) output pulse chirp and (c) SCR, SPR and SLSR with different coupler ratio of NOLM.

pulse is injected into the first HNLF (HNLF1). After a 1.94 dB attenuation by VOA2, the pulse with a peak power of 3.23 W is coupled into the HNLF2-NOLM for second-stage spectral compression and pedestal suppression. The parameters of SMF, HNLF1 and HNLF2 can be found in the simulation section above. The output spectrum from the transmission port (i.e., Port 2) of the HNLF-NOLM is measured using an optical spectrum analyzer [optical spectral analyzer (OSA), Yokogawa AQ6370, Japan].

The measured spectra of the input and output pulses using both schemes are presented in Figs. 8(a) and 8(b), respectively. The experimental results show that the SCR increases by a factor of two and the SPR decreases by nearly three times. Moreover, the pedestal side lobe level is reduced from −7.47 dB to −9.36 dB. It can be concluded that the experimental results agree with the numerical ones, demonstrating that excellent spectral compression and pedestal elimination can be achieved in the two-stage scheme

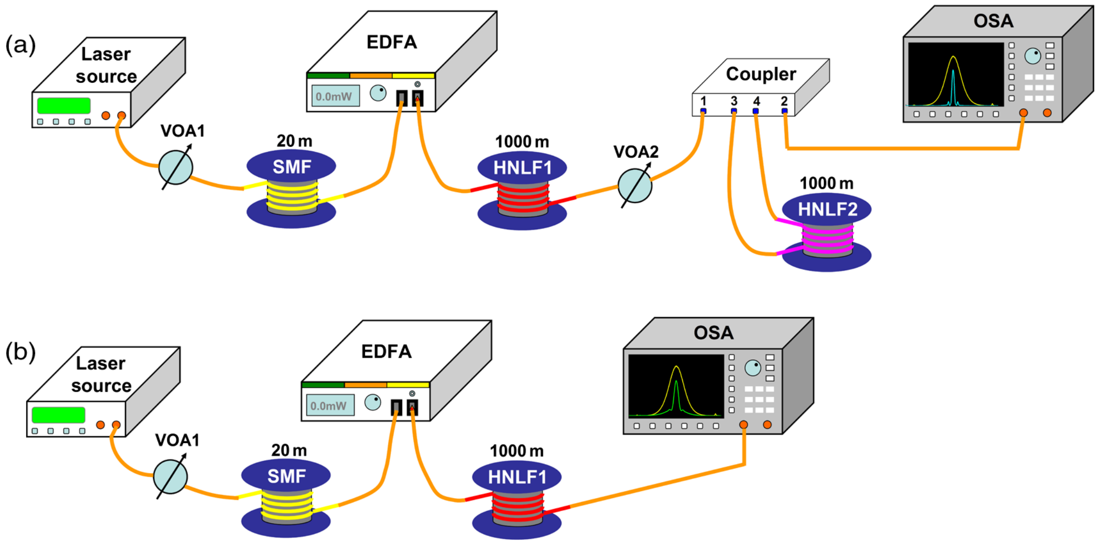
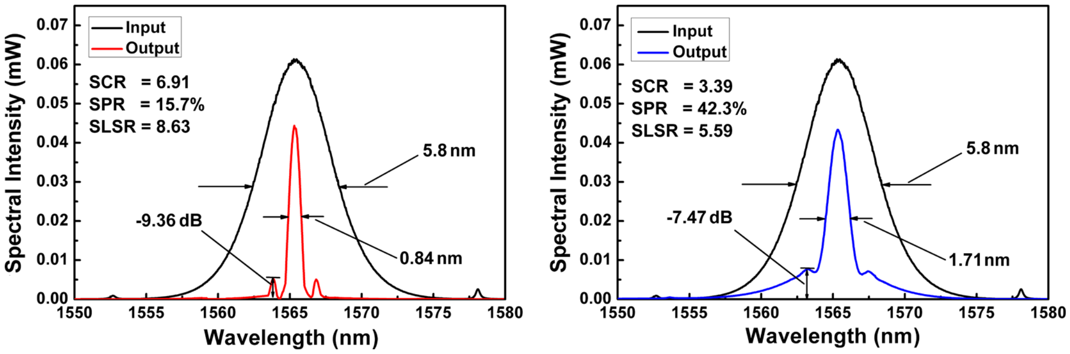


Fig. 7 (a) Experimental setup for spectral compression and pedestal reduction in a two-stage structure, (b) comparative spectral compression experimental setup using a feedthrough HNLF scheme. VOA: variable optical attenuator, SMF: single-mode fiber, EDFA: erbium-doped fiber amplifier, NOLM: nonlinear optical loop mirror, HNLF: high nonlinear fiber, OSA: optical spectral analyzer.



(a)

(b)

Fig. 8 Measured spectra of the input and output pulses for (a) the two-stage scheme and (b) the feed-through HNLF scheme.

compared to its feedthrough HNLF alternative. It should be pointed out that the spectral peaks around 1553 nm and 1578 nm are the Kerr sideband of the home-made passively mode-locked Er-doped fiber laser source, which cannot be counted as the spectral pedestal. As the primary characteristic of time-resolved spectral filtering in HNLF-NOLM, it can be predicted that the residual pedestal in Fig. 8(a) can be further eliminated using a multi-stage NOLM structure.

5 Conclusion

In conclusion, we have presented a novel spectral compression scheme based on a two-stage architecture which employs an HNLF as the first stage and an NOLM composed of an HNLF in the loop as the second stage. The chirp-related spectrum pedestal filtering effect of the NOLM is used to suppress the spectral pedestal after compression. Both numerical and experimental results show that a higher spectral compression ratio is obtained, and simultaneously, the spectral pedestal and side-lobe level are effectively suppressed by using the two-stage scheme, as compared to its feedthrough HNLF alternative. The proposed low-pedestal spectral compression and pedestal suppression scheme is especially favorable for improving the quantization resolution in the all-optical ADC system which utilizes a power-to-wavelength conversion quantization process.

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