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基于 Sagnac 环梳状滤波编码的全光模数转换

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摘　要:提出一种基于多个并行 Sagnac 环梳状滤波器实现波长编码的方法,可用于孤子自频移全光模数转换的光学编码.仿真结果表明:该方法在 1 601 nm～1 707 nm 孤子自频移波段成功实现了 5 bits 的光学编码,最大微分线性误差和积分线性误差分别为 0.088LSB 和 0.482LSB.与其他波长编码方式相比,该方法结构简单、工作波长范围宽,并且具有非常好的编码位数扩展性.

关键词:模数转换器;光子学;光学编码;孤子自频移;Sagnac 环
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Sagnac-loop-based Optical Coding for All-optical Analog-to-digital Conversion Employing Soliton Self-frequency Shift

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Abstract: A novel optical coding scheme employing parallel Sagnac-loops is proposed for all-optical analog-to-digital converters based on soliton self-frequency shift effect. The proposed coding scheme is numerically demonstrated in a 5-bit SSFS-based all-optical ADC with a wavelength range of 1 601 nm to 1 707 nm, where the results show that the maximum differential nonlinearity error and the integral nonlinearity error are 0.088 and 0.482 Least Significant Bit (LSB), respectively. Compared with other wavelength coding counterparts, the proposed optical coding scheme has a simple architecture and a broad operation wavelength range, and is easy to achieve a larger coding bit.

Key words: Analog-to-digital conversion; Photonics; Optical coding; Soliton self-frequency shift; Sagnac-loop-filter
OCIS Codes: 250.0250; 070.1170; 070.2615

0 Introduction

An Analog-to-Digital Converter (ADC), which converts analogue signals into digital ones, is an essential interface component in the applications such as communication, radar and instrument. Recently,

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electronic ADCs are widely used in practical applications[1-2]. However, due to the electron mobility limitation, the sampling rate and the analog bandwidth of electronic ADCs cannot meet the rapidly growing requirements of the advanced ultra-wideband applications such as 5 G wireless communication, synthetic aperture radar, backbone optical fiber communication and ultra-high-speed real-time measurement[3].

In the past few years, photonic ADCs sprung up to be the promising candidates to provide superior performance over its electronic counterparts[4-7]. In particular, all-optical ADCs have attracted intensive interest because of its superiorities such as ultra-high speed, broad bandwidth, and free of a serial-to-parallel conversion architecture to match the ultra-high speed of the sampled optical pulse train to the relatively slow response of the electronic ADCs compared with other photonic ADC schemes[8]. Identical to its electronic counterpart, an all-optical ADC is basically composed of sampling, quantization and coding. Optical sampling is generally achieved through the intensity modulation of an ultra-short pulse train via a broadband Mach-Zehnder electro-optic modulator. To date, optical sampling of radio frequency (RF) signals with frequencies up to 40 GHz can be achieved with a sampling rate of multi-tens of GS/s and a time aperture jitter less than 50 fs, where the performance is definitely superior over the state-of-the-art electronic ADCs[9]. Optical quantization can be realized by the ultrafast power-dependent nonlinear optical effects in an optical fiber or an optical waveguide such as Self-Phase Modulation (SPM), cross-phase modulation (XPM), supercontinuum generation, high-order soliton formation and Soliton Self-Frequency Shift (SSFS)[10]. Among these effects, SSFS is regarded as an effective one to realize high-speed power-to-wavelength mapping, and finally achieve high-resolution quantization in the wavelength domain[11]. SSFS-based quantization is firstly proposed by T. Konishi et al. in 2002, which utilizes intrapulse Raman scattering in a spool of high nonlinear fiber with anomalous dispersion to red shift the whole pulse spectrum according to its energy[12]. The resolution of the quantization scheme is determined by the ratio of the maximum central wavelength shift to the spectral width. In silica fibers, the central wavelength shift is saturated around 1 700 nm due to the large absorption loss beyond this wavelength. Hence, spectral compression is an efficient way to improve the quantization resolution, which is realized via compensating negative chirp in the optical pulse with the positive chirp induced by nonlinear optical effects such as SPM and electro-optic phase modulation[13]. For the SSFS-based all-optical ADCs, optical coding is achieved through identification of the wavelength information, which can be realized based on two methods, i.e., optical interconnection and interleaved optical filtering. A 100 GS/s all-optical ADC scheme with a 4-bit quantization was reported by Takashi Nishitani et al. in 2008, which employs optical interconnection to output binary code in a bit-parallel format[14]. However, the structural complexity of the optical interconnection method increases exponentially with quantization resolution, and it is extremely difficult to compensate the pulse delay introduced by the anomalous Group Velocity Dispersion (GVD) in the optical quantization process. To solve the above-mentioned problem, interleaved optical filtering is recognized as a promising method, which can be realized by using either fiber Bragg grating arrays or a waveshaper. Up to date, waveshaper is the most generally used filtering method for wavelength separation. In 2015, M. Hasegawa et al. experimentally realized a 10 GS/s 3-bit photonic ADC employing a waveshaper for coding, in which, the resolution is limited by the operation bandwidth of the waveshaper[15].

In this paper, a new optical coding scheme based on parallel Sagnac-loop comb-like filters with a wide wavelength range is proposed. A 5-bit SSFS-based all-optical ADC using the proposed coding scheme is numerically demonstrated. The maximum differential nonlinearity (DNL) and integral nonlinearity (INL) are calculated to be 0.088 and 0.482 Least Significant Bit (LSB), respectively.

1 Operation principle

Figure 1 presents the schematic diagram of a SSFS-based all-optical ADC system employing the proposed Sagnac-loop-based optical coding scheme. In the sampling stage, the input RF signal is modulated onto the ultra-short optical pulse train output from a Mode-Locked Laser (MLL) via an electro-optic Mach-Zehnder Modulator (MZM), where the peak power (or energy) of the output optical pulse represents the sampling value at the corresponding moment. In the quantization stage, the sampled ultra-short optical pulses with various peak power propagate in a high nonlinear fiber with an anomalous GVD (i.e., HNLF0 in Fig. 1), where SSFS occurs and the pulse spectrum is red-shifted according to its peak power. The subsequent three sections of Single-Mode Fibers (SMFs) and HNLFs are employed to compress the pulse spectrum in order to enhance the quantization resolution. In the coding stage, a section of Dispersion Compensation Fiber (DCF) is used to compensate the wavelength-dependent pulse delay occurring in the quantization stage. Then, the optical pulse train with correct time sequence is equally divided into N streams, each of which is sent to a Sagnac-loop-based comb filter with a Free Spectral Range (FSR) 2^{n-1} times of that of channel 1 to be coded (n is the sequence number of the channel).

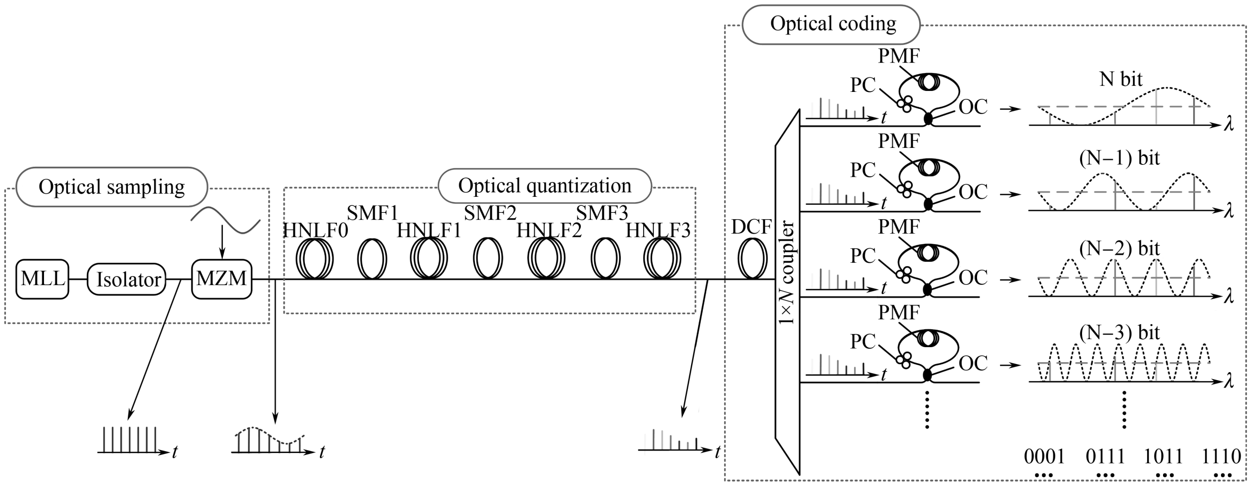


Fig.1 Schematic diagram of a SSFS-based all-optical ADC employing the proposed Sagnac-loop-based coding scheme

A Sagnac-loop filter, which is employed for a single-bit optical coding, consists of a Polarization Controller (PC), a section of Polarization Maintaining Fiber (PMF), and a 2×2 Optical Coupler (OC) whose coupling ratio is 50/50. Port 3 and port 4 of the OC are connected with the PC and the PMF. The wavelength-shifted optical pulse train injects into the Sagnac-loop filter through port 1, and outputs from port 2 of the OC, respectively. The transmission spectrum of the Sagnac-loop filter can be written as

$$t = 1 - (\cos^4\psi + \sin^4\psi + 2\cos^2\psi\sin^2\psi\cos\Delta\varphi) = t_0 \cdot \sin^2(\Delta\varphi/2) \tag{1}$$

where t_0 is a constant peak transmission coefficient. $\Delta\varphi = 2\pi BL/\lambda + \varphi$ is the phase difference between the linearly polarized light along the two principal axes of the PMF, where λ is the wavelength in vacuum, φ is the phase difference introduced by the PC, and B and L are the birefringence coefficient and the length of PMF, respectively. Therefore, the transmission peak of the Sagnac-loop-based comb filter can be tuned by varying the PC status, and the FSR $\Delta\lambda$ is calculated as

$$\Delta\lambda \approx \lambda^2/(BL) \tag{2}$$

where $\Delta\lambda$ is determined by the birefringence BL of the PMF in the loop, and can be varied through changing the length of the PMF. Additionally, it should be noted that the fiber length in each Sagnac-loop should be set to be equal through adding additional SMF in order to maintain the time sequence of the N streams.

2 Results and discussion

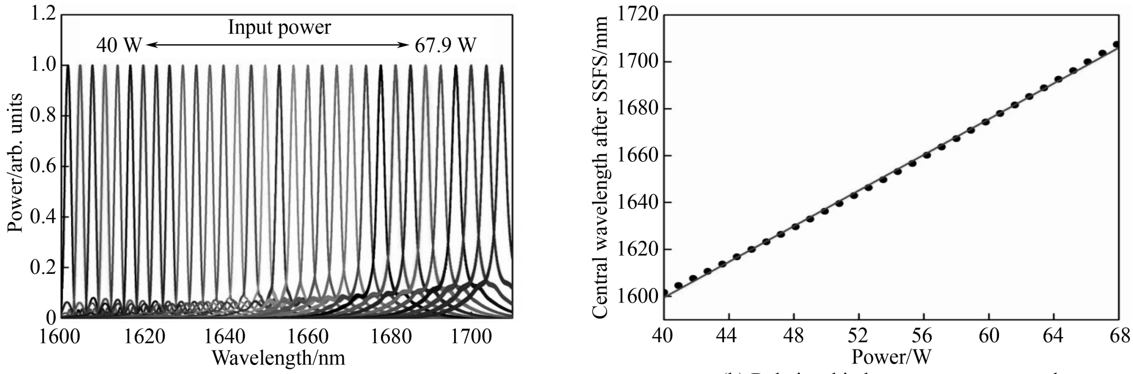
2.1 Simulation results

In this section, numerical simulation is implemented to verify the feasibility of the proposed Sagnac-loop-based optical coding scheme in a SSFS-based all-optical ADC. The propagation of the ultra-short optical pulses in the fibers are described by the Generalized Nonlinear Schrödinger Equation (GNLSE), which is numerically solved using the split-step Fourier method [16]. In the quantization stage, the sampled optical pulse is set to be a hyperbolic secant one with a Full-Width at Half-Maximum (FWHM) of 200 fs and a central wavelength of 1 550 nm. The parameters of the fibers employed for quantization are listed in Table 1.

Table 1 Fiber parameters

	$\alpha/(\mathrm{dB \cdot km^{-1}})$	$\beta_2/(\mathrm{ps^2/ \cdot km^{-1}})$	$\beta_3/(\mathrm{ps^3 \cdot km^{-1}})$	$\gamma/(\mathrm{W^{-1} \cdot km^{-1}})$	L/m
HNLF0	1.3	−3.826	0.026	10	1 000
SMF1	0.2	−21	0.49	2	2.8
HNLF1	0.9	−3	0.036	11.5	60
SMF2	0.2	−21	0.49	2	20
HNLF2	0.9	−3	0.036	11.5	100
SMF3	0.2	−21	0.49	2	10
HNLF3	0.9	−3	0.036	11.5	120

Fig.2 shows the output spectra after quantization under various input peak power, and the relationship between the output central wavelength and the input peak power, respectively. It can be seen from Fig. 2 that the central wavelength of the optical pulse increases almost linearly with the input peak power in the range of 40 W to 67.9 W, and at least 32 independent colored levels for identification are successfully provided, which is able to achieve at least 5-bit optical quantization and coding. It should also be pointed out that the spectral width on the longer wavelength side is slightly larger than that on the shorter wavelength side, which attributes to the insufficient chirp compensation in the spectrum compression process. Both the deviation from a linear peak-power-to-wavelength mapping relationship and the nonuniform spectral width may induce coding error in the following optical coding stage.

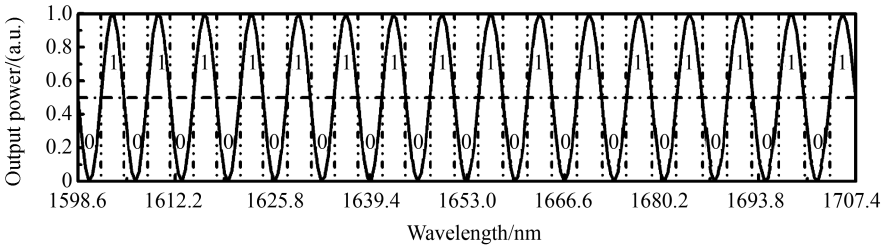


(a) Output spectra

(b) Relationship between output central wavelength and input peak power

Fig.2 Simulation results for optical quantization

In the coding stage, firstly, the wavelength-shifted pulse train is fed to a section of DCF with a total dispersion of −4.84 ps/nm, which can effectively compensate the wavelength-dependent pulse delay occurring in the quantization stage. After compensation, the maximum amount of pulse delay is 90 ps, which is sufficient to guarantee a sampling rate of 10 GS/s. Then, a 5-bit optical coding architecture employing five Sagnac-loop filters is designed to code the wavelength-shifted optical pulse. It is shown in Fig. 2 that the wavelength interval varies in the range of 2.9 nm to 3.8 nm, which makes it different to choose appropriate FSRs of the Sagnac-loop-based comb filters. In order to obtain minimum coding bit error rate, the PMF length is optimized. After optimization, the lengths of PMFs ($B=3.1\times10^{-6}$) in the five Sagnac-loops are set to be 1.295 m, 0.648 m, 0.324 m, 0.162 m and 0.081 m, corresponding to FSRs of 6.8 nm, 13.6 nm, 27.2 nm, 54.4 nm, and 108.8 nm, respectively. Fig. 3 presents the transmission spectra of the five Sagnac-loops, where 5-bit coding can be realized through setting appropriate judgement



(a) 1st bit

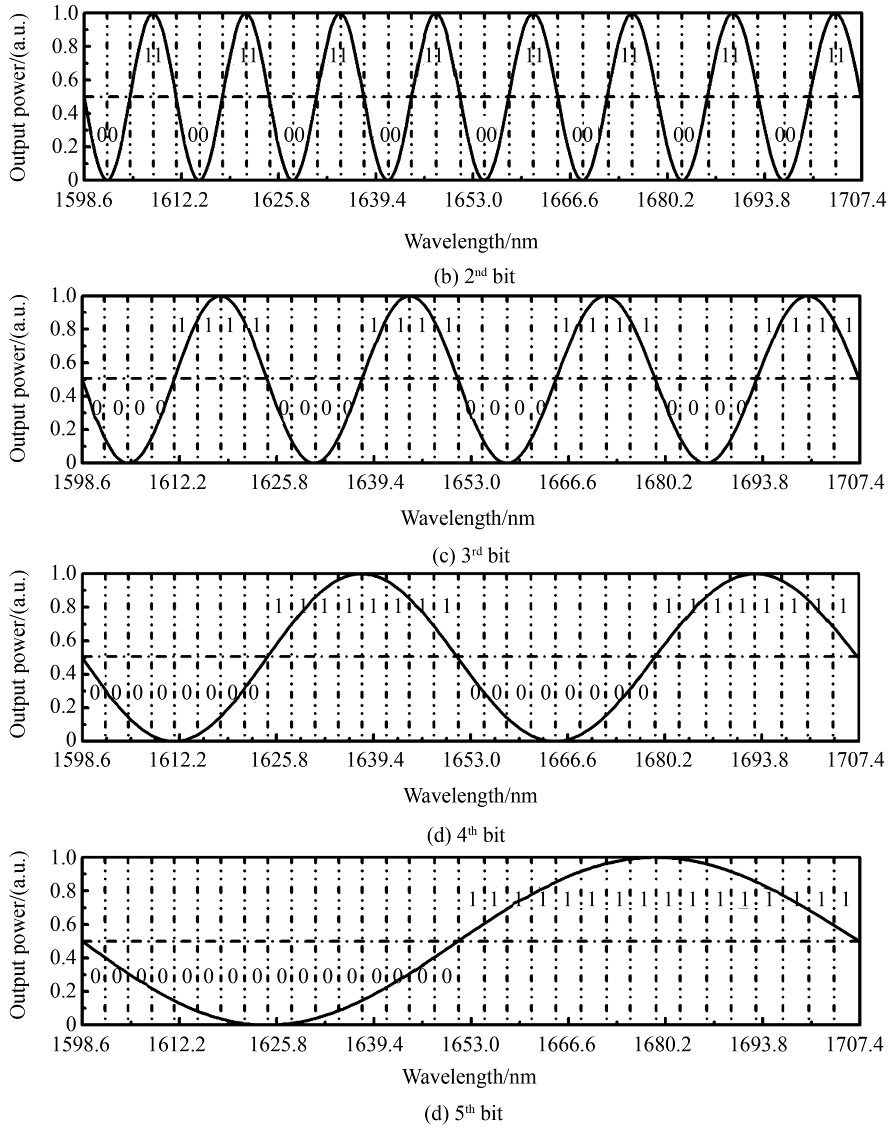
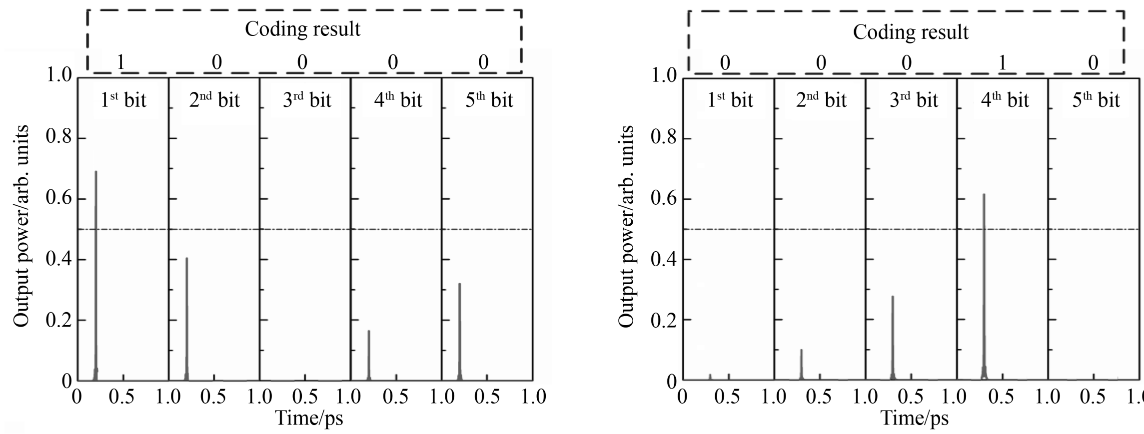


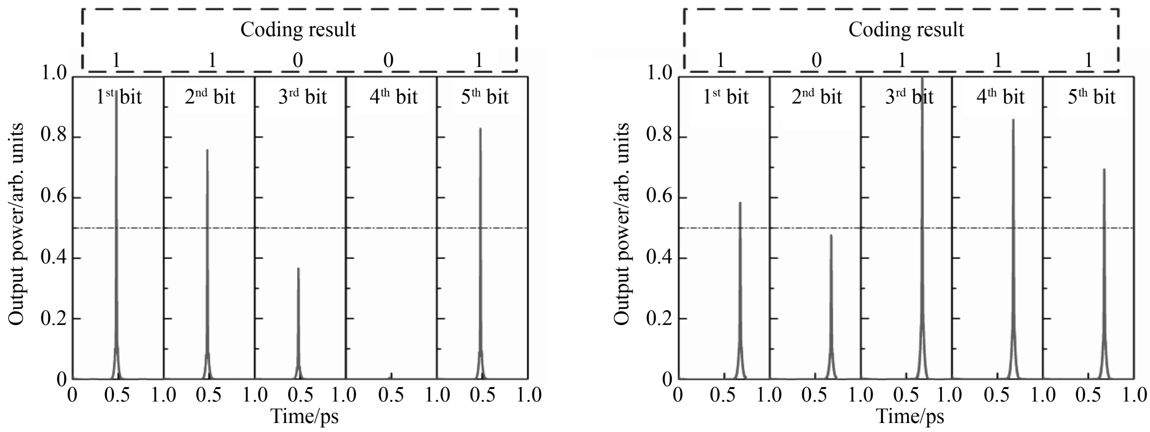
Fig.3 Transmission spectra of the five Sagnac loops

thresholds. Fig. 4 exhibits the output pulses and the coding results for the wavelength-shifted optical pulses with central wavelengths of 1 604.597 nm, 1 626.396 nm, 1 663.659 nm and 1 699.968 nm, respectively. It can be concluded that the coding results in Fig. 4 agree with the theoretical results.



(a) Central wavelength of 1604.597 nm

(b) Central wavelength of 1626.396 nm



(c) Central wavelength of 1663.659 nm

(d) Central wavelength of 1699.968 nm

Fig.4 Output pulses and coding results for different central wavelengths

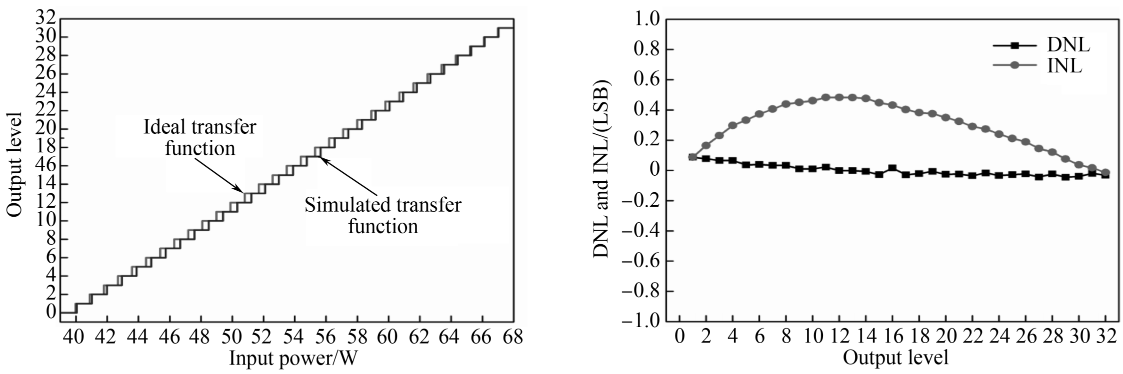
2.2 Discussion

DNL and INL are employed to evaluate the performance of the proposed Sagnac-loop-based coding scheme in the SSFS-based all-optical ADC, which can be calculated as

$$\mathrm{DNL}=\frac{M_i-\mathrm{LSB}}{\mathrm{LSB}} \tag{3}$$

$$\mathrm{INL}(k)=\sum_{0}^{k}\mathrm{DNL}(i) \tag{4}$$

where LSB is the least significant bit (i.e., the ideal step size), and M_i is the actual step size. Fig.5 presents the relationship between input power and output level, and the calculated DNL and INL, respectively. The maximum DNL and INL are 0.088 LSB and 0.482 LSB, respectively, which are comparable to those of commercial electronic ADCs. Thus, the feasibility of the proposed coding approach in a SSFS-based all-optical ADC is numerically demonstrated. In addition, it should be pointed out that the proposed coding scheme can be flexibly extended to a higher quantization resolution through simply adding more Sagnac-loops since its operating wavelength range is broad.



(a) Relationship between input power and output level

(b) DNL and INL

Fig.5 Simulation results for optical coding

3 Conclusion

Insummary, a new optical coding scheme based on parallel Sagnac-loop comb-like filters is proposed for SSFS-based all-optical ADCs. The proposed coding scheme is numerically demonstrated in a 5-bit SSFS-based all-optical ADC with a wavelength range of 1 601 nm to 1 707 nm. Simulation results show that the maximum DNL and INL are 0.088 LSB and 0.482 LSB, respectively, which is comparable to commercial electronic ADCs. A higher quantization resolution can be flexibly achieved through further compressing the spectral width of the wavelength-shifted optical pulses and simply adding more Sagnac-loops in the coding stage since the operating wavelength range of the Sagnac-loop is ultra-broad.

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