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Normalized transfer function for characterizing conversion efficiency and harmonic distortion of all-optical sampling

ZHANG ShangJian*, LIN ChangYu, LI Xuan, ZOU ZhiTai, LIU Yong & LIU YongZhi

State Key Laboratory of Electronic, Thin Film and Integrated Devices, School of Optoelectronic Information, University of Electronic Science & Technology of China, Chengdu 610054, China

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A novel method for characterizing the nonlinearity of all-optical sampling is proposed based on the normalized transfer function. Simulation results demonstrate the effectiveness of our method. Furthermore, an all-optical sampling experiment is performed to verify our method. Both simulation and experiment show consistency between our method and the measurements. The method only requires normalization and polynomial fitting of the transfer curve, and enables direct expression of the nonlinearity with the coefficients of the normalized transfer function.

optical signal processing, all-optical sampling, linearity, nonlinear distortion

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Nonlinearity of all-optical sampling is very critical to the resolution of all-optical analog-to-digital conversion [1–3], and distortion analysis is needed to achieve a good sampling performance. In most cases, conversion efficiency and harmonic distortion are introduced to characterize the nonlinearity and optimize the sampling performance [4,5]. The conversion efficiency represents the signal promotion, while the harmonic distortion reflects the signal distortion. In traditional spectrum measurement, a sinusoidal signal is input as the analog signal to be sampled, and the harmonics of the output signal are measured for comparison, from which the nonlinearity can be evaluated [6–8]. This method is very accurate; however, the measurement should be repeated for both input and output signals once the input signal is updated, which is not suitable for properly choosing the operating parameters in advance.

Prior to this work, we reported the concept of a nonlinear transfer function, with which the harmonics of the output signal at any input sine or cosine signal can be calculated through function composition [8]. The method avoids repeatable spectrum measurement; however, the Fourier expansion of the function composition leads to non-uniform expression and redundant computation. In this paper, we propose a normalized transfer function which can avoid both spectrum measurement and function composition. The consistency between our method and the function composition method is investigated in the simulation. Furthermore, the method is applied to characterize the all-optical sampling experiment, and is compared with spectrum measurement to check the accuracy.

1 Theoretical description

As is shown in Figure 1, the transfer function can be obtained by a polynomial fitting of the transfer curve and written as

$$y_i = h(x_i) = \sum_{k=0}^{m} a_k x_i^k, i = 1,\cdots,n, \tag{1}$$

where x_i and y_i (i=1,2,$\cdots$, n and $x_1<x_2<\cdots<x_n$) represent the intensity of the input analog signal and that of the output

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*Corresponding author (email: sjzhang@uestc.edu.cn)

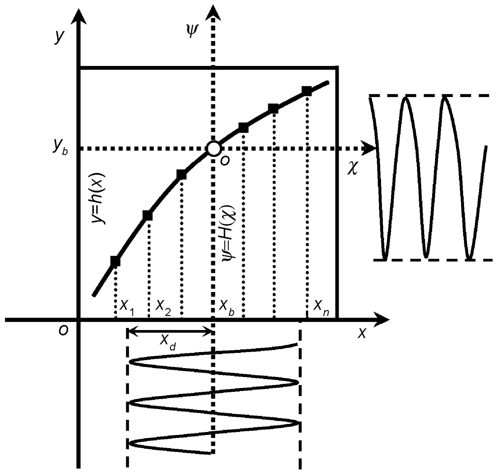

Figure 1 Schematic of the normalized transfer function.

probe signal. In the case of m=1, the sampling is linear, whereas in the case of m>1, nonlinearity will occur and give rise to distortion in all-optical sampling.

We assume the input analog signal to be sampled is a cosine signal as follows,

$$x(t) = x_b + x_d \cos \omega t, \tag{2}$$

where x_b is the bias power and x_d is the modulation amplitude. Substituting eq. (2) into eq. (1), the output signal can be obtained as

$$y(t) = h\left(x(t)\right) = \sum_{k=0}^{m} a_k \left(x_b + x_d \cos \omega t\right)^k . \tag{3}$$

To simplify the Fourier expansion of the function composition, we propose a normalized transfer function: the origin of the xoy coordinate is translated to (x_b, y_b), and both the x-axis and y-axis are normalized with the same ratio of $1/x_d$. In the new coordinate $\chi o \psi$, the input signal is $\chi(t)$= $\cos\omega t$, and the output probe signal can be simplified to

$$\psi(t) = H\left(\chi\left(t\right)\right) = \sum_{k=0}^{m} \alpha_k \cos^k \omega t, \tag{4}$$

where α_k (k=0,1,···,m) are the coefficients of the normalized transfer function. To observe the harmonics, we need to further translate the power of the trigonometric function into a multiple-angle function with the power-reduction formulas as follows [9,10],

$$\cos^{2n} \theta = \frac{1}{2^{2n-1}} \left[\sum_{k=0}^{n-1} C_{2n}^{k} \cos\left(2n-2k\right)\theta + \frac{1}{2} C_{2n}^{n} \right], \tag{5a}$$

$$\cos^{2n+1} \theta = \frac{1}{2^{2n}} \left[\sum_{k=0}^{n} C_{2n+1}^{k} \cos\left(2n-2k+1\right)\theta \right]. \tag{5b}$$

Thus, we have

$$\psi(t) = H\left(\cos \omega t\right) = \sum_{k=0}^{m} \rho_k \cos k\omega t, \tag{6}$$

$$\rho_k = \sum_{i=0}^{\left[(m-k)/2\right]} \frac{\alpha_{k+2i} C_{k+2i}^{i}}{2^{k+2i-1}}, \tag{7}$$

where [(m–k)/2] gives the greatest integer less than or equal to (m–k)/2. Therefore, the conversion efficiency and harmonic distortion can be obtained as

$$e_f = \rho_1, d_k = \left|\rho_k / \rho_1\right|, k = 2,3,\cdots,m. \tag{8}$$

The method basically includes three steps: (i) Translate (x_i, y_i) of xoy into (χ_i, ψ_i) of $\chi o \psi$ through $\chi_i=(x_i-x_b)/x_d$ and $\psi_i=(y_i-y_b)/x_d$; (ii) Construct the transfer function $\psi=\Sigma\alpha_k\chi^k$ from the normalized transfer curve $\psi_i=H(\chi_i)$; and (iii) Calculate the conversion efficiency e_f and harmonic distortion d_k with the coefficients α_k. From eqs. (7) and (8), the novelty of our method lies in the fact that the nonlinearity only depends on the polynomial coefficients and the Fourier expansion becomes avoidable.

2 Experiment and results

As shown in Figure 2, we first test our method with a simulated transfer curve that is cited from [8]. In the normalized coordinate, the polynomial transfer function is

$$\psi = H(\chi) = \sum_{k=0}^{4} \alpha_k \chi^k ,$$

where the polynomial coefficients are α_0=0.0118, α_1= 2.3647, α_2=–1.6519, α_3=0.5229, α_4=–0.0441. With the polynomial coefficients, we have

$$\rho_1 = \alpha_1 C_1^0 + \alpha_3 C_3^1 / 4 = 2.7569,$$

$$\rho_2 = \alpha_2 C_2^0 / 2 + \alpha_4 C_4^1 / 8 = -0.8480,$$

$$\rho_3 = \alpha_3 C_3^0 / 4 = 0.1307,$$

$$\rho_4 = \alpha_4 C_4^0 / 8 = 0.0055.$$

Substituting the coefficients ρ_k into eq. (8), the conversion efficiency and harmonic distortion can be obtained and are

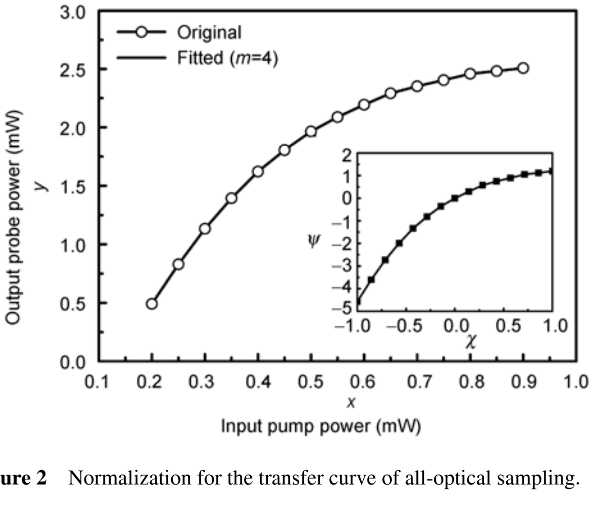

Figure 2 Normalization for the transfer curve of all-optical sampling.

Table 1 Simulated results from our method (I) and [8](II)

	e_f	d_2	d_3	d_4
I	2.7569	0.3076	0.0474	0.0024
II	2.7571	0.3082	0.0482	0.0026

listed in Table 1, where the results in [8] are also shown for comparison. The agreement of the results indicates the consistency of both methods. Moreover, our method omits Fourier expansion and leads to a more concise calculation.

As shown in Figure 3, in our experiment a mode-locked fiber ring laser (λ_b=1550.20 nm) emits 1.4 ps pulses at 40 GHz. The pulse train with an average power of –1.3 dBm is injected into the semiconductor optical amplifier (SOA) as the probe signal. An optical cosine signal at 2.5 GHz is coupled into the SOA as the pump signal. The SOA is operated at a bias current of 276 mA. The all-optical sampling scheme can be found in [11,12], here we only focus on the experimental results.

The measured and normalized transfer curves are shown in Figure 4(a) and (b). The polynomial coefficients of the normalized transfer function are α_0=–0.0024, α_1=3.1156, α_2=–0.4888, α_3=–0.4457, α_4=0.1961, with which the conversion efficiency and the harmonic distortion can be directly obtained and are listed in Table 2. To check the accuracy of our method, both the waveform and the spectrum of the output probe signal are also measured and shown in Figure 5. The nonlinearity from the spectrum measurement is also listed in Table 2 for comparison. The difference, which is less than 5%, is mainly because the truncation error of the limited order of the polynomial function. The difference could be further decreased by increasing the order of the polynomial function, but it does not affect the optimization of the operating parameters of all-optical sampling.

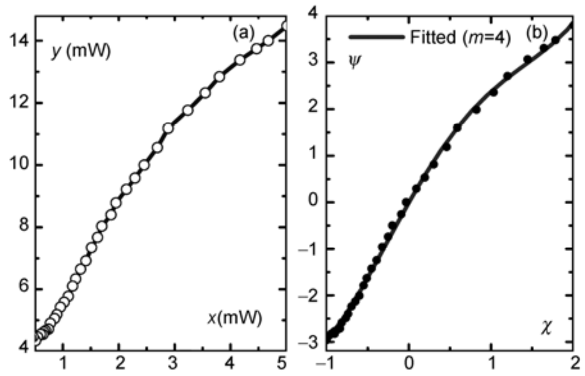

Figure 4 (a) Measured transfer curve and (b) its normalized transfer function.

Table 2 Experimental results with our method (I) and spectrum measurement (II)

	e_f	d_2	d_3	d_4
I	2.7813	0.0526	0.0386	0.0088
II	2.6425	0.0547	0.0372	0.0086

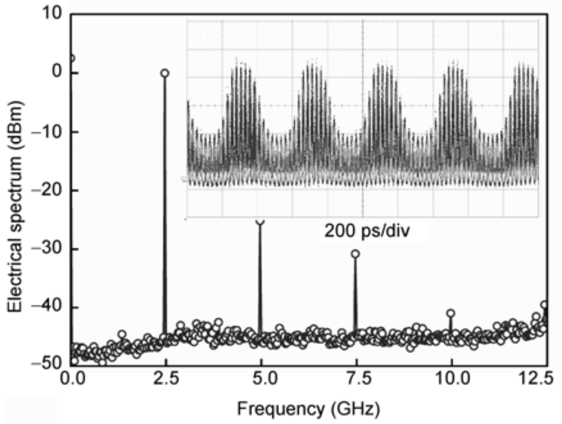

Figure 5 Measured spectrum of the output probe signal. Inset: Waveform of the output probe signal.

3 Conclusions

We have proposed a normalized transfer function to characterize the nonlinear distortion of all-optical sampling. Different from the traditional method and our previous work, our method enables a uniform expression of conversion efficiency and harmonic distortion in terms of the polynomial coefficients, which avoids both spectrum measurement and Fourier expansion. Both simulated and experimental results show consistency between our method and measurement. The method is simple and useful for distortion characterization and parameters optimization of all-optical sampling.

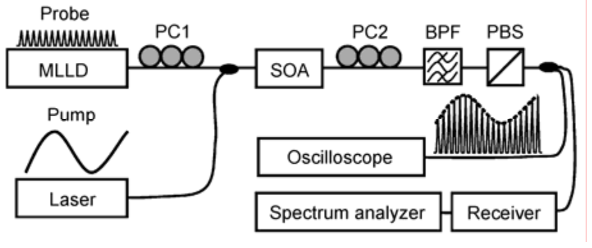

Figure 3 Schematic of all-optical sampling based on nonlinear polarization rotation. SOA, Semiconductor optical amplifier; MLLD, mode lock laser diode; PC, polarization controller; BPF, optical band pass filter; PBS, polarization beam splitter.

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