ALL-OPTICAL SAMPLING BASED ON NONLINEAR POLARIZATION ROTATION IN SEMICONDUCTOR OPTICAL AMPLIFIERS

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A novel all-optical sampling method based on nonlinear polarization rotation in a semiconductor optical amplifier is proposed. An analog optical signal and an optical clock pulses train are injected into semiconductor optical amplifier simultaneously, and the power of the analog light modulates the intensity of the output optical pulse through controlling the rotated angle of nonlinear polarization rotation of the optical pulse. Therefore, the sampling signals are delivered from the analog light to the optical clock pulses. The simulated results show that the all-optical sampling has good linear slope and large linear dynamic range, and the operating power of the pump light can be less than 1mW. The presented all-optical sampling method can potentially operate at the sampling rate up to hundreds GS/s and needs considerable low optical power, which is suitable for high-speed signal processing.

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Keywords: Optical signal processing, All-optical sampling, Semiconductor optical amplifier, Nonlinear polarization rotation

1. Introduction

All-optical signal processing technologies are considered as a possible long-term route in the evolution of current telecommunication network and high-speed signal processing system [1]. In all-optical signal processing, all-optical analog-to-digital (A/D) conversion is very important, which can have ultra-fast operating speed and eliminate the need of conversions between electronics and optics. The process of all-optical A/D conversion consists of all-optical sampling, quantizing, and coding, and the sampling rate determines the capacity of A/D conversion [2]. Many techniques, such as self-phase modulation (SPM), cross-phase modulation (XPM) [2, 3], four wave mixing (FWM) [4], and Raman soliton self-frequency shifting in fibers [5-7], have been used to implement all-optical sampling functions. As these schemes are based on the nonlinear effects in fibers, they require tens of kilometers long fibers with high nonlinearity and optical pulses with high power to induce the nonlinear effects, and it is difficult to control the relationships between the sampling optical pulses and the analog optical signals accurately in practice, and only 3 bits resolution of these A/D converters was reported [2, 5].

Recently, much attention has been paid to optical signal processing based on nonlinear polarization rotation (NPR) in semiconductor optical amplifier (SOA) [8-10]. In this paper, we investigate NPR in an SOA in the context of all-optical sampling. In the case of optical sampling, the role of the saturating control beam is taken over by the analog signal optical light, and the probe light is replaced by the high-speed optical clock pulses train. The feasibility of the scheme is numerically demonstrated with polarization-dependent gain saturation rate equations model. The optimized operating parameters are investigated as functions of the input polarization angle, the phase induced by the polarization controller, and the orientation of the polarization beam splitter.

2. Theoretical description

The NPR in SOA operates in a similar principle to the Mach-Zehnder modulator, but the role of the different arms is replaced by transverse electric (TE) mode and transverse magnetic (TM) mode of the incoming coherent light [10]. The general scheme of the all-optical sampling is shown in Fig.1. The sampler consists of a SOA, three polarization controllers, an optical band pass filter (BPF), and a polarization beam splitter (PBS). A continuous-wave (CW) optical signal at wavelength λ_p to be sampled is injected into the SOA as the pump light, and an optical clock pulse train at wavelength λ_b is injected as the probe light. The output of the SOA is fed into the PBS and the probe light (λ_b) is filtered through the BPF. The first polarization controller (PC1) is used to adjust the polarization of the probe light to be an appropriate angle relative to the orientation of the SOA layers, while the second polarization controller (PC2) adjusts the polarization of the amplified probe light to the orientation of the PBS. When the SOA's gain is saturated by the injected high-intensity pump light, the polarization state of the probe light will be rotated due to the birefringence of the SOA, and the polarization rotating angle of the probe light could be controlled by the intensity of the pump light. If the intensity of the pump light carries a signal, the signal could be modulated onto the pulsed probe light. Thus, all-optical sampling is obtained.

We decompose the incoming arbitrarily polarized electrical field into a TE-mode and a TM mode. In fact, apart from their indirect interaction through the carrier dynamics in the device, these two polarizations propagate independently from each other [10].The gains and phase difference for TE/TM modes can be expressed as

$$G^i = \exp\left[\left(\Gamma^i g^i - \alpha^i_{\mathrm{int}}\right)L\right], \quad (i = TE \ or \ TM) \ , \tag{1}$$

and

$$\Delta\varphi = \varphi^{TE} - \varphi^{TM} = \left(\alpha^{TE}\Gamma^{TE}g^{TE} - \alpha^{TM}\Gamma^{TM}g^{TM}\right)L/2 \, , \tag{2}$$

respectively, where the superscript i corresponds to TE mode and TM mode, Γ is the confinement factor, g is the unit gain assumed to be a constant along the light propagation in the SOA, α is the phase-modulation parameter, and α_{int} is the unit modal loss.

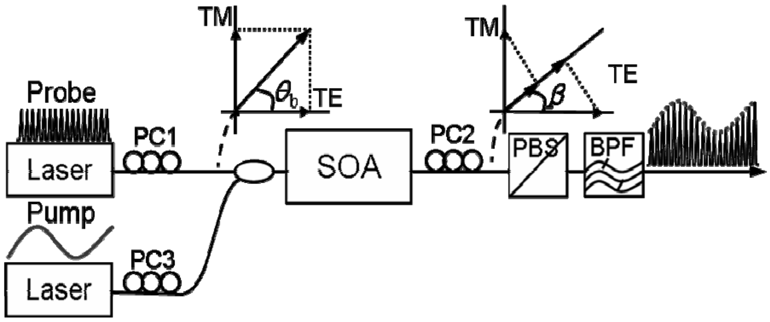

Fig. 1 Schematic setup of all-optical sampling based on nonlinear polarization rotation. PC: Polarization Controller, SOA: Semiconductor Optical Amplifier, PBS: Polarization Beam Splitter, BPF: Optical Bandpass Filter.

The two optical modes have indirect interaction via the carriers. It is assumed that both the TE polarization and the TM polarization couple the electrons in the conduction band with two distinct reservoirs of holes [9]. The number of electrons in the conduction band is denoted by $n_c(z, t)$, and the number of holes involved in the x transition and the y transition is denoted by $n_{te}(z, t)$ and $n_{tm}(z, t)$, respectively. The two populations n_{te} and n_{tm} will be clamped tightly together, i.e., $n_{te}(z, t)=f\, n_{tm}(z, t)$ and $n_c(z, t)=n_{te}(z, t)+n_{tm}(z, t)$, where f is the hole population imbalance factor representing the anisotropy magnitude of the SOA [9]. In the case of tensile strain, TM gain will be larger than TE, i.e., $f<1$. The small-signal gain g can be written by[9,10]

$$g^i = \xi^i \left(n_c + n_i - n_0\right), \quad (i = TE \ or \ TM)\ , \tag{3}$$

where ξ^{TE} and ξ^{TM} are the gain coefficients for the TE mode and the TM mode, respectively.

As shown in Fig.1, the two modes' components of probe light that are parallel to the PBS orientation are combined together. Since these components are coherent, they interfere with each other. The optical intensity of the probe light through the PBS is given by

$$S_{bout} = S_{bout}^{TE} + S_{bout}^{TM} + 2\sqrt{S_{bout}^{TE} S_{bout}^{TM}} \cos\left(\Delta\varphi + \phi_{pc}\right)\ , \tag{4a}$$

$$S_{bout}^{TE} = S_b \cos^2\theta_b \cos^2\beta \cdot G^{TE}\ , \tag{4b}$$

and

$$S_{bout}^{TM} = S_b \sin^2\theta_b \sin^2\beta \cdot G^{TM}\ . \tag{4c}$$

In formula (4), S_b and S_{bout} represent the input probe light and output probe light, respectively, θ_b and θ_p are the input polarized angles of probe light and pump light related to the orientation of the SOA layers, respectively. Φ_{pc} is a phase bias induced by the PC2, and β is the angle between the orientation of the PBS and the SOA layers.

From Eq. (4), it can be seen that the change of the pump light power alters both gain difference and phase difference between the TE mode and the TM mode of the probe light. Thus, it alters the output intensity of the probe light. The envelope of the input probe pulse train will vary with the input power of the pump light. In this way, signals carried by the pump light are delivered to the optical clock pulse train, and all-optical sampling can be achieved.

3. Simulated results

Several important characteristics of our proposed sampling can be analyzed with the equations (1)-(4). In the simulation, the wavelength of the probe light is 1550nm, the peak power of the probe sampling pulses is 0.126mW (-9dBm), the wavelength of the pump light is 1590nm. The parameters of the SOA are cited from reference [8].

The rotated polarization angle induced by NPR versus the input polarized angle of probe light is firstly obtained and shown in Fig. 2. It can be seen from that the maximum birefringent effect can be obtained when the input polarized angle of probe light is approximately 62°, which indicates the optimum orientation of PC1.

Next, the PC2 are set in such a way that the probe can not pass through the PBS when only the probe light is present. If a saturating pump beam is coupled into the SOA, the additional birefringence in the SOA leads to a phase difference between TM and TM modes of the probe light, causing the polarization of the probe light to be rotated. As a consequence, some probe light can pass through the PBS. Hence, an increase in the intensity of the pump light leads to an increase in the intensity of the probe light that outputs through the PBS. Thus the optical sampling is obtained. As is shown in Fig. 3, when Φ_{pc}=21° and β=43°, the intensity of the probe light that outputs through the PBS reaches minimum.

The optimum transfer curve can be achieved at the condition of I=160 mA, θ_b=62°, Φ_{pc}=21°, and β=43°, which is shown in Fig. 4. The transfer curve at the input polarization angle 45° is also given in the figure for comparison. From Fig. 5, we can see that the slope and linear range of the transfer curve at θ_b=62° is superior to that at θ_b=45°, which is not like what many have denoted that maximum birefringent effect could be achieved at the input angle of approximate 45°, and find the optimized input angle is necessary to improve the sampling accuracy.

When the intensity of the time-varying pump light ranges between 0.1mW and 0.6mW, the linearity of the transfer curve is better and the sampling result will be more accurate. The repeating frequency and FWHW of the probe pulse is 10GHz and 0.08ns, respectively. When the time-varying optical signal and timing optical clock pulses are inject into SOA, representing pump light and probe light, respectively, the power of the pump light controls the intensity of the output optical pulse through controlling the rotated angle of NPR of the optical pulse. As the clock optical probe light pulses pass through SOA, the sampling signals are delivered from the pump light to the optical clock pulses. The sampling results of our all-optical sampling model are shown in Fig. 5. As is shown in Fig. 5, the maximum power needed in sampling process is 0.5 mW, which is much lower than other sampling methods mentioned in [2-6].

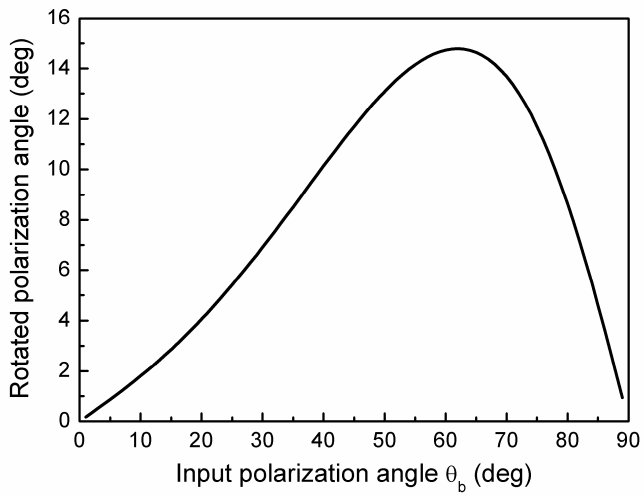

Fig. 2. Computed rotated polarization angle as a function of the input polarization angle of a probe light.

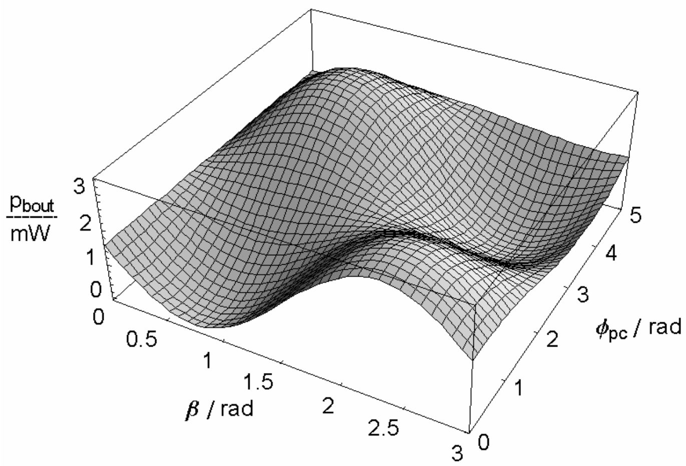

Fig. 3. The intensity of probe light that outputs through the PBS as functions of the phase induced by the PC2 and the orientation of the PBS.

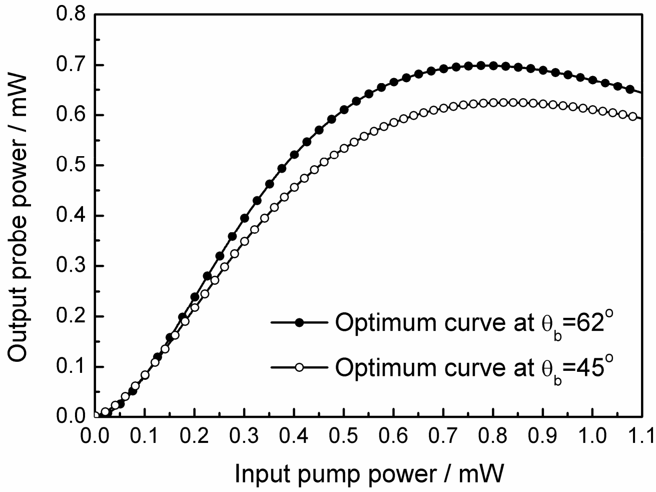

Fig. 4 The non-invert transfer curves of SOA at different input probe lights.

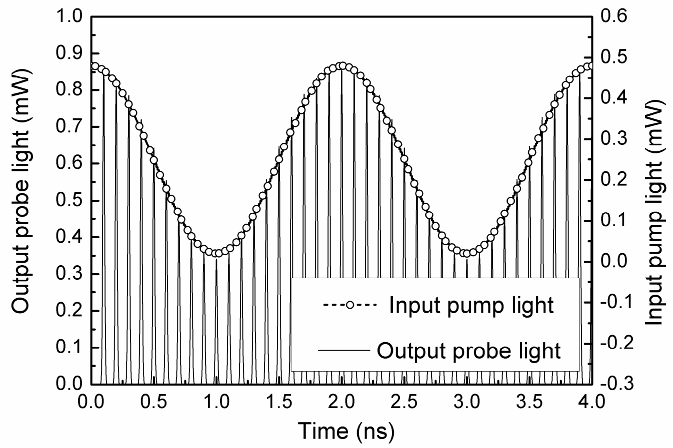

Fig. 5 The sampling result with all-optical sampling model

4. Conclusions

We have proposed a novel all-optical sampling method based on nonlinear polarization rotation in a semiconductor optical amplifier. The feasibility of the proposed scheme has been proved by the numerical investigation. The simulation results show that the maximum optical operating power required in our scheme is less than 1mW. The sampling process of the proposed scheme is to switch signals from pump light to the optical sampling pulses through the NPR in the SOA, which is similar to the process of wavelength conversion. As it has been demonstrated experimentally that the SOA-based wavelength conversion can reach a data rate at 320 Gbit/s [11], our method should be applicable for ultra high-speed sampling. Furthermore, the sampling devices are compatible with the optical network and suited for integration.

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