RESEARCH ARTICLE

# Experimental investigation on slow light via four-wave mixing in semiconductor optical amplifier

**Yin ZHANG, Xinliang ZHANG (✉), Xi HUANG, Cheng CHENG**

Wuhan National Laboratory for Optoelectronics, College of Optoelectronic Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

**Abstract**   Optical buffer is a key component in all optical information processing systems. Slow light at room temperature via four-wave mixing (FWM) in semiconductor optical amplifier (SOA) is experimentally investigated. Time delay of 0.40 ns is achieved for a sinusoidal modulation signal at 0.1 GHz, corresponding to a delay bandwidth product (DBP) of 0.04. Factors that affect the experimental results are discussed. It is found out that the variable optical delay via FWM in SOA can be controlled either electrically by changing the SOA bias or optically by varying the pump power or pump-probe detuning.

**Keywords**   optical communication, slow light, four-wave mixing (FWM), semiconductor optical amplifier (SOA)

## 1   Introduction

Variable optical delay lines are essential for optical signal processing and communication systems such as optical networks and phased-array antenna. To control optical delay, two methods are generally exploited: one is modifying the group refractive index of optical medium, and the other is utilizing dispersive devices [1–11]. The first approach makes use of nonlinear optics such as electromagnetically introduced transparency (EIT), coherent population oscillation (CPO), and Raman and Brillouin amplification. The second approach utilizes Fabry-Perot resonators, high $Q$ cavities, and photonic crystals. Atomic vapors, solid state crystals, fibers, and semiconductors are considered for variable optical delay. Among these media, semiconductors are attractive due to their compactness, direct current control, large bandwidth, and easy integration with electrical and photonic circuits. In the past few

years, slow light using EIT, CPO, and four-wave mixing (FWM) in semiconductor optical amplifiers (SOAs) have been intensely studied [3–4,8–11]. Investigation of slow light and fast light in a high-gain SOA via CPO and FWM with a single microwave modulated beam has been reported [11], similar to the slow light effect reported in solid state crystals [2]. Our work differs from these earlier works, where a separate modulation is applied on a probe laser, which is different from the pump laser. In this paper, we investigate tunable delays for a sinusoidal modulated signal, propagating through the SOA in the presence of a strong pump beam, and some factors that affect the experimental results are discussed. Dependence of this delay on various parameters such as pump power, pump-probe detuning, and SOA bias has been investigated. A tunable delay of 0.40 ns is obtained for a sinusoidal modulated signal at 0.1 GHz, corresponding to a delay bandwidth product (DBP) of 0.04.

## 2   Physical principle

The theory of FWM in SOAs has been discussed extensively [12]. We consider a continuous wave (CW) pump beam with angular frequency $\omega_0$ (strong power, amplitude $E_0$) and a probe signal (weak power, amplitude $E_1$) at center frequency $\omega_1$ with parallel polarizations injected into an SOA, where the SOA have a large linewidth enhancement factor and operating in gain regime. Thus, the beating of the pump and the probe fields in SOA leads to modulation of various parameters of the waveguide medium at the beating frequency $\Omega = \omega_1 - \omega_0$ (i.e., detuning frequency). FWM results from the pump and probe fields mixing nonlinearly, and it results in carrier density pulsations (CDPs) at the detuning frequency, when $|\Omega \tau_s| \leqslant 1$ ($\tau_s$ is carrier lifetime), the interband effects, i.e., CDP, dominate over the intraband modulation, and the latter can be neglected. Due to wave

mixing effect, the group velocity of the probe beam can be either reduced or increased [8–10]. The refractive index experienced by the probe beam due to wave mixing effect can be expressed as

$$n_{\mathrm{wm}}(\omega_1) = \frac{\alpha c g_0}{2\omega_1} \cdot \frac{I_0}{(\Omega\tau_{\mathrm{s}})^2 + (1+I_0)^2}$$

$$= \frac{\alpha c g_0}{2\omega_1} \cdot F_0(\Omega\tau_{\mathrm{s}}, I_0), \qquad (1)$$

where $g_0$ is the linear modal gain in the SOA; $I_0 = \tau_{\mathrm{s}} v_{\mathrm{bg}} g_N S_0$ is the dimensionless saturation parameter; $S_0$ is the pump photon density; $g_N$ is the differential gain; $v_{\mathrm{bg}} = c/n_{\mathrm{bg}}$, $n_{\mathrm{bg}}$ is the background refractive index; and $\alpha$ is the linewidth enhancement factor. Moreover, the function

$$F_0(\Omega\tau_{\mathrm{s}}, I_0) = I_0 / \left[ (\Omega\tau_{\mathrm{s}})^2 + (1+I_0)^2 \right],$$

and the corresponding slow-down factor can be expressed as

$$S = n_{\mathrm{bg}} + \frac{\alpha c g_0 \tau_{\mathrm{s}}}{2} \cdot \frac{\mathrm{d}F_0(\Omega\tau_{\mathrm{s}}, I_0)}{\mathrm{d}\Omega}$$

$$= n_{\mathrm{bg}} + \alpha c g_0 \tau_{\mathrm{s}} \cdot \frac{(-\Omega\tau_{\mathrm{s}}) \cdot I_0}{\left[ (\Omega\tau_{\mathrm{s}})^2 + (1+I_0)^2 \right]^2}. \qquad (2)$$

In fact, FWM causes the signal to experience a change in gain ($g_{\mathrm{wm}}$) and a change in refractive index ($n_{\mathrm{wm}}$), both strongly dependent on the detuning $\Omega$ [9]. The beating between the pump and probe beam in SOA results in CDP at detuning frequency that leads to the creation of instant gain and the refractive index gratings at the detuning frequency, the gratings, in turn, lead to two effects: the generation of conjugate signal as well as the modification of the dispersion relationship for the probe depending on the pump power [10]. The modification of the probe dispersion implies the change of the group refractive index of the probe. Correspondingly, a modulated probe beam traveling through the SOA experiences delay, which is dependent on the pump power, pump-probe detuning, and SOA bias.

# 3  Experimental scheme

The experimental setup is shown in Fig. 1. A multiple quantum well (MQW) SOA is used in this experiment from Kamelian Ltd. The parameters of the SOA are as follows: the fiber-to-fiber unsaturated gain is 30 dB, the saturation output power is 20 dBm, and the operating band is 1530–1570 nm. When SOA is operated at the maximum current of 300 mA, its small signal regime gain is greater than 20 dB.

The outputs of two distributed feedback (DFB) lasers are used as the pump and the probe, respectively. The wavelengths of both DFB lasers are centered at 1550 nm and tuned by temperature to achieve the desired detuning. The pump is the fixed at wavelength 1549.82 nm. The probe is modulated at radio frequency (RF) frequency $f_m$ by a LiNbO$_3$ external modulator before being combined with the pump by a fiber directional coupler. The radio frequency output sinusoidal modulated signal at 0.1 GHz. A polarization controller is used to maintain the polarization of probe beam parallel to the pump beam. At the output, in addition to the pump and probe, the conjugate signal is also present. Hence, the detected RF signal at the output will also have contributions from modulation side bands of conjugate.
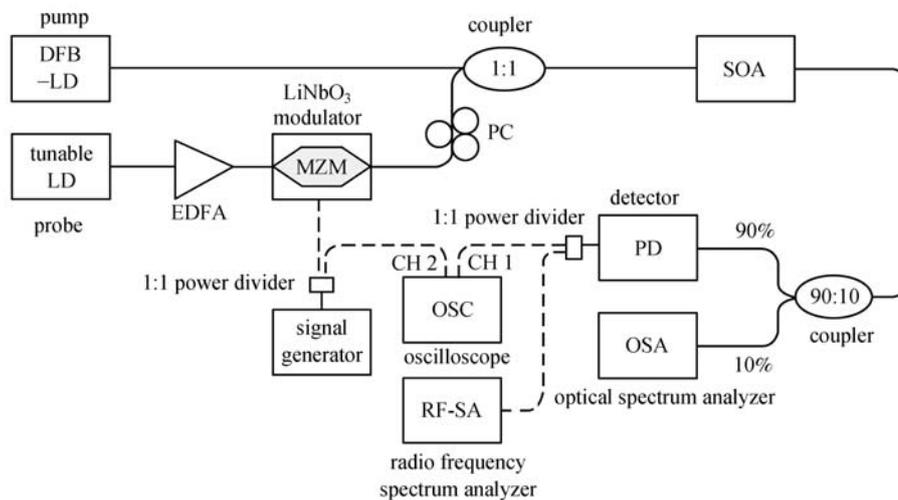


**Fig. 1**  Experimental setup to investigate tunable delay in SOA: PD (SHF 47100A O/E convertor, bandwidth: 40 GHz, center operating wavelength at 1550 nm); OSA: oscilloscope (Tektronix TDS 3052B, bandwidth: 500 MHz); RF-SA: radio frequency spectrum analyzer (Anritsu MS2667C, 9 kHz–30 GHz); OSA: optical spectrum analyzer (Anritsu MS9710C, 600–1750 nm); and radio frequency signal generator (Agilent E8247C, 250 kHz–20 GHz)

# 4 Results and discussion

Figure 2 shows tunable delay of a sinusoidally modulated signal. Time domain traces of a detected modulated signal of different values of the detuning are shown. The probe beam is externally modulated to produce a sinusoidal signal at the desired frequency. The modulation frequency of the sinusoidal signal is 0.1 GHz in this experiment. The amplitude of modulation is maintained well below the saturation power of SOA to avoid gain fluctuations due to modulated signal.
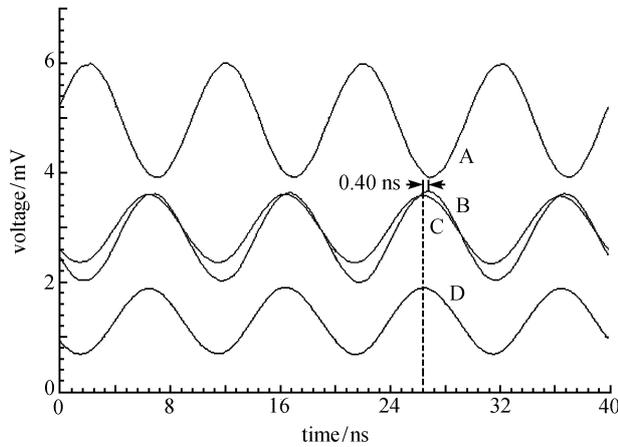


**Fig. 2** Oscilloscope time traces of modulated probe signal (0.1 GHz) for different detuning values (A signal: a sinusoidal modulated signal at 0.1 GHz from signal generator, as a reference signal; B, C, D signal: all sinusoidal modulated signal at 0.1 GHz, detected modulated signal for detuning of $-6.66$ GHz, $-23.82$ GHz and $-28.98$ GHz, respectively)

When the detuning frequency between the pump and the probe is set at $-6.66$ GHz (B signal) and $-23.82$ GHz (C signal), respectively, a tunable relative delay of 0.40 ns was achieved, corresponding to a DBP of 0.04. When the detuning is large ($>10$ GHz), the delay is almost zero, for example, the detuning is set at $-23.82$ GHz (C signal) and $-28.98$ GHz (D signal). As the detuning decreases, the time delay is increased. The delay measured relatively to the trace, obtained for large pump-probe detuning ($-28.98$ GHz), is nonzero only if the detuning is not very large in comparison with the inverse carrier lifetime (~100 ps). This behavior is related to the origin of the delay that is FWM via carrier density pulsations, which will take place only at the small detuning ($|\Omega\tau_s|\leqslant 1$). As the detuning decreases, the time delay is increased. We also observed that the delay is dependent on the precise polarization matching of the pump and the probe beams. The inability to maintain the precise polarization in a single mode fiber results in fluctuations of the observed signal at the output. Hence, the results reported here are time averaged values of the delay.

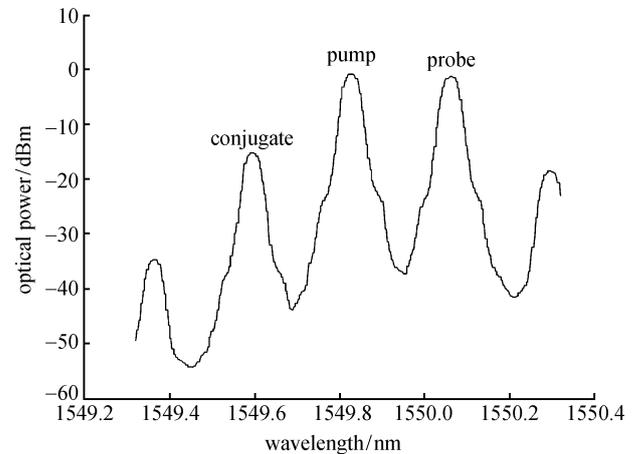Figure 3 shows the optical spectrum as the pump-probe

detuning is varied. The conjugate, the pump and the probe are indicated in this figure, respectively. It can be seen that the conjugate power at the output can be lower than the probe power for small negative frequency detuning values
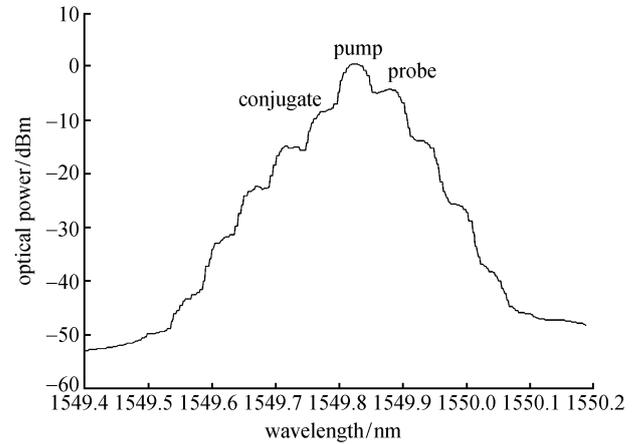


(a)
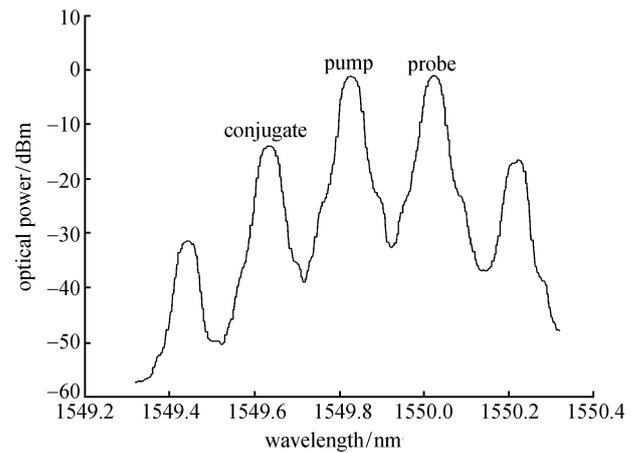


(b)



(c)

**Fig. 3** Optical spectrum for various pump-probe detuning. (a) Optical spectrum as detuning is $-6.66$ GHz; (b) optical spectrum as detuning is $-23.82$ GHz; (c) optical spectrum as detuning is $-28.98$ GHz

that is in agreement with the theory of FWM in SOA [9]. Note that the predictions for slow and superluminal light in SOA were done in assumption that the conjugate signal is negligible in comparison with the probe [8]. Figure 3 also shows that the probe and the conjugate signals can be comparable to each other, and the conjugate signal can affect the probe signal propagation at the SOA output.

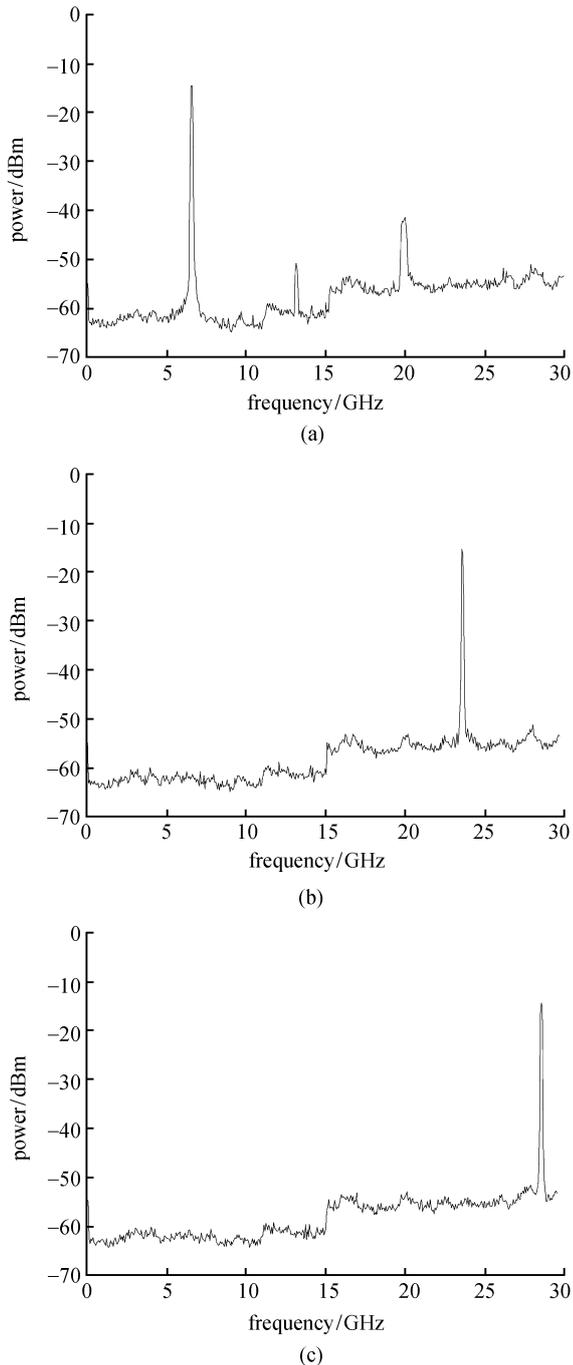Figure 4 shows the beating frequency spectrum as the pump-probe detuning is varied. It can be seen that the beating frequency were −6.66 GHz (B signal), −23.82 GHz (C signal), and −28.98 GHz (D signal), respectively, corresponding to the side mode suppression ratio of the beating of 48 dBm, 40 dBm, and 39 dBm. As the detuning decreases, the beating intensity is increased.

In addition, higher pump power results in more efficient FWM and hence larger delay. However, if the pump power is much higher than the saturation power of SOA ($> 20$ dBm), then the gain of the SOA decreases resulting in smaller delays. Furthermore, slow light is observed at small positive detuning due to the contribution from the conjugate. In general, the delay increases as the pump power increases.

Finally, when the bias of SOA is varied, the qualitative investigation is made what effect on the delay. As the SOA bias is increased, the gain of the SOA increases in gain regime. These results in stronger beating between the pump and the probe and thus giving rise to larger delays. However, the gain of the SOA does not increase significantly at higher SOA bias and reaches a maximum value at 300 mA. At this bias, increasing the SOA current does not increase the gain significantly as the SOA operates in saturation regime.

## 5   Conclusions

In this paper, we present the experimental investigation on slow light via FWM processes in SOA at room temperature. A time delay of 0.40 ns is achieved for a sinusoidal modulation at 0.1 GHz, corresponding to a DBP of 0.04. The delay of the signal can be controlled electrically by changing the SOA bias and optically by varying the pump power or the pump-probe detuning. In this method, the DBP can be achieved for GHz order of magnitude. It is impossible to carry out high-speed broadband optical signal delay owing to the carrier lifetime limit in SOA.

**Fig. 4**   Beating frequency spectrum for different pump-probe detuning. (a) Beating frequency spectrum as detuning is −6.66 GHz; (b) beating frequency spectrum as detuning is −23.82 GHz; (c) beating frequency spectrum as detuning is −28.98 GHz

## References

1. Hau L V, Harris S E, Dutton Z, Behroozi C H. Light speed reduction to 17 meters per second in an ultracold atomic gas. Nature, 1999, 397(6720): 594–598

2. Bigelow M S, Lepeshkin N N, Boyd R W. Superluminal and slow light propagation in a room temperature solid. Science, 2003, 301 (5630): 200–202

3. Chang S W, Chuang S L, Ku P C, Chang-Hasnian C J, Palinginis P,

Wang H L. Slow light using excitonic population oscillation. Physical Review B, 2004, 70(23): 235333

4. Ku P C, Sedgwick F, Chang-Hasnain C J, Palinginis P, Li T, Wang H L, Chang S W, Chuang S L. Slow light in semiconductor quantum wells. Optics Letters, 2004, 29(19): 2291–2293

5. Minin S, Fisher M R, Chuang S L. Current-controlled group delay using a semiconductor Fabry-Perot amplifier. Applied Physics Letters, 2004, 84(17): 3238–3240

6. Vlasov Y A, O'Boyle M, Hamann H F, McNab S J. Active control of slow light on a chip with photonic crystal waveguides. Nature, 2005, 438(7064): 65–69

7. Okawachi Y, Bigelow M S, Sharping J E, Zhu Z M, Schweinsberg A, Gauthier D J, Boyd R W, Gaeta A L. Tunable all-optical delays via Brillouin slow light in an optical fiber. Physical Review Letters, 2005, 94(15): 153902

8. Uskov A V, Chang-Hasnain C J. Slow and superluminal light in semiconductor optical amplifiers. Electronics Letters, 2005, 41(16): 55–56

9. Uskov A V, Sedgwick F, Chang-Hasnain C J. Delay limit of slow light in semiconductor optical amplifiers. IEEE Photonics Technology Letters, 2006, 18(6): 731–733

10. Pesala B, Chen Z Y, Uskov A V, Chang-Hasnain C J. Experimental demonstration of slow and superluminal light in semiconductor optical amplifiers. Optics Express, 2006, 14(26): 12968–12975

11. Su H, Kondratko P, Chuang S L. Variable optical delay using population oscillation and four-wave mixing in semiconductor optical amplifiers. Optics Express, 2006, 14(11): 4800–4807

12. Agrawal G P. Population pulsations and nondegenerate four-wave mixing in semiconductor lasers and amplifiers. Journal of the Optical Society America B, 1988, 5(1): 147–159