Measurement of the carrier recovery time in SOA based on four-wave mixing on narrow-band ASE spectrum*

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Carrier recovery time is a key parameter that determines the performance of a semiconductor optical amplifier (SOA). A measurement method of carrier recovery time in SOA based on a nearly degenerate four-wave mixing of narrow-band amplified spontaneous emission (ASE) spectra is presented. The results show the carrier times are 50.2, 44.6, and 23.6 ps when the injected currents are 120, 180, and 240 mA, respectively, which are in agreement with the nominal values of the sample.

Keywords: amplified spontaneous emission, narrow band, nearly degenerate four-wave mixing, semiconductor optical amplifier

PACC: 4265M, 4280S, 4281C

1. Introduction

Recently, due to its various nonlinearities, semiconductor optical amplifier (SOA) has become an attractive candidate in the application of optical signal processing in all-optical networks, such as wavelength conversion,[1] all optical logic gates,[2] format conversion,[3] and so on. However, the operating speed is limited by the recovery time of the carrier density, which takes place on a time scale being typically of dozens to several hundreds of picoseconds, and this weakness may lead to patterning effects[4] on the output signal, which become detrimental at high bitrates. Therefore the carrier recovery time is a key issue which determines the performance of SOA. Many approaches have been made to measure the carrier recovery time, such as pump-probe technique, four-wave mixing (FWM) effect,[5] external optical/electric modulation,[6] cross gain modulation,[7] and patterning effect technique, and so on. However, some of those approaches above utilized many types of equipment in the measurement configuration; as a result, the accuracy and reliability of the measurement results may be affected by the performance caused by these devices.

In this study, we present a simple approach to measure the carrier recovery time of SOA, based on the application of the FWM of narrow band amplified spontaneous emission (ASE) spectra. In our approach, only two erbium-doped optical fibre amplifiers (EDFAs) and one polarization controller (PC) are employed. We utilize the FWM effect between a narrow band ASE from two EDFAs and a distributed feedback (DFB) laser, therefore the configuration of the experimental setup becomes much simpler. The SOA we used in the experiment is a quantum well SOA (QW-SOA) of CIP Technologies (sample type No. SOA-NL-OEC-1550).

2. Operation principle and experimental setup

In the case of the nondegenerated FWM in the SOAs, the pump and probe waves modulate in the medium and create a beat frequency at Ω ($\Omega = \omega_1 - \omega_0$, ω_0 and ω_1 are the angular frequencies of the pump and probe waves, respectively), and the beat frequency creates a dynamic gain and index grating whose effectiveness is governed by the carrier recovery time τ_s.

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We assume that only TE modes are stimulated in semiconductor medium with the same propagation direction. Figure 1 shows the schematic diagram of FWM in the SOA.

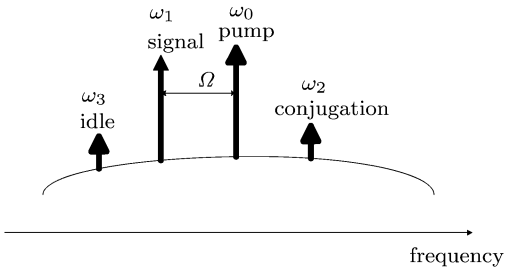


Fig. 1. Schematic diagram of four-wave mixing.

The total intracavity optical field is given by

$$\begin{aligned} E(z,t) = {} & E_1 \exp[\mathrm{i}\, k_1 z - \mathrm{i}(\omega_0 - \Omega)t] \\ & + E_0 \exp(\mathrm{i}\, k_0 z - \mathrm{i}\, \omega_0 t) \\ & + E_2 \exp[\mathrm{i}\, k_2 z - \mathrm{i}(\omega_0 + \Omega)t], \end{aligned} \tag{1}$$

where E_0, E_1, and E_2 are the amplitudes of the optical field for the pump, probe, and conjugation waves, respectively, and k_0, k_1, and k_2 are the wave vectors for the waves. Generally, the power of pump wave is larger than those of the probe and conjugation waves. The conversion efficiency is defined as $\eta = |E_2(L)|^2/|E_1(L)|^2$, which is detuning frequency-dependent. Generally, the conversion efficiency decreases when the detuning between pump and probe increases, thus the relationship between the detuning frequency, whose conversion efficiency decreases 3 dB from the maximum value $\Delta f_{3\,\mathrm{dB}}$, and the carrier recovery time τ_s is given by[8]

$$\Delta f_{3\,\mathrm{dB}} = \frac{1}{\tau_\mathrm{s}}. \tag{2}$$

The evolution of the principle of our proposal is illustrated in Fig. 2. In the previous work, the optical spectrum of the wavelength conversion based on FWM is often sketched as in Fig. 2(a). The curve O at the centre of this figure is the pump light. The curves on the right-hand side of the pump light are the probe light of different wavelengths, and the conjugated tones based on FWM are on the left-hand side. With the variation of the wavelength of the probe light from the larger value (A) towards smaller one (C), the corresponding conjugated wave will increase from the smaller value (A') towards larger one (C'). The conversion efficiency can be concluded from the ratio of the power of conjugated waves to the power of the probe lights, A' to A, B' to B, and C' to C. To realize this configuration, a tunable laser for the probe light is necessary, and this makes the experimental procedure more complex, and the measurement results are highly dependent on the measuring error.

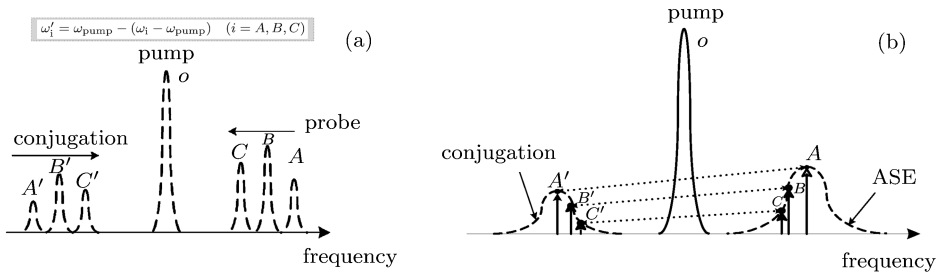


Fig. 2. The diagram of the operation in our measurement: (a) the spectra of the FWM between pump laser and the probe laser, (b) the spectra of the FWM between a pump light and narrow band ASE.

Inspired from this, a simple scheme based on FWM between narrow band ASE spectra and a pump light is proposed. The operation principle is given in Fig. 2(b). In Fig. 2(b), the line O is the pump light. The ASE spectra are on the right-hand side of the pump light and its conjugation spectra are on the left-hand side. We can consider the ASE spectra to be the combination of many continuous laser single frequency components (A, B, C, etc.). Additionally, each frequency component and the pump will generate a conjugated wave (A', B', C', etc.) based on FWM effect. Thus the envelope of these conjugation waves becomes the corresponding spectrum of the ASE spectra. Furthermore, because of the wide band of the ASE spectra, we can obtain the conversion efficiency of the different wavelengths by measuring only once, and each pair of single frequency component and its conjugation one are distributed symmetrically on

the two sides of the pump light, so what we need to do is comparing the spectra of the conjugation with their ASE spectra and data processing. Besides, ASE spectra are comparatively easier to obtain. Thus this scheme is much simpler than those in previous work.

The experimental setup is shown in Fig. 3. It consists of two erbium-doped fibre amplifiers (EDFAs), an optical coupler (OC), a DFB laser, a tunable bandpass filter (BPF) whose 3-dB bandwidth is 0.3 nm. A polarization controller (PC) is employed to adjust the polarization state of the two waves imput to the SOA. Here two EDFAs are needed because the power of only one EDFA is not large enough to generate obvious FWM effect. The DFB laser is utilized to provide an invariable laser wavelength. The wavelength of the pump wave is fixed at 1551.75 nm, while the power of the pump wave is fixed at 0.852 dB·m. The full width at half maximum (FWHM) of the BPF is 0.3 nm. The OC branching ratio is 50:50. The output of the SOA is recorded by an optical spectrum analyser (OSA) from Anritsu MS9710C. The minimum resolution of the OSA is 0.05 nm.

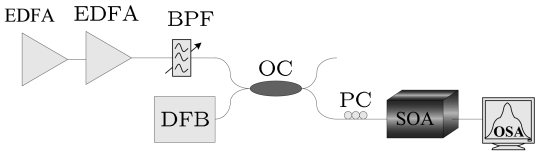


Fig. 3. The experimental setup of the measurement. EDFA: erbium-doped fibre amplifier. BPF: tunable bandpass filter of 0.3-nm bandwidth. PC: polarization controller. DFB: distributed feedback laser diode. OC: 50:50 optical coupler.

3. Results and discussions

First, we disconnect the upper arm of the OC in Fig. 3 to allow only DFB light going through the SOA and record the trace of the DFB laser spectrum. Secondly we connect the upper arm and record the trace of spectrum of the DFB laser, the generated spectra and the narrow band ASE. Then we change the detuning between the peak of the ASE spectrum and the DFB laser by the BPF. Figure 4 shows the measured optical spectrum under the condition of injected current being 240 mA and the detuning wavelength between the pump light and peak of the ASE being 0.50 nm. The solid lines represent the DFB laser spectrum and the dotted line is the sum of the ASE, the generated FMW wave, and the spectrum of the DFB laser, so the FWM and the ASE spectra can be obtained from the solid line minus the dotted line. Hence the conversion efficiency of the FWM is the ratio of the power of the conjugation spectrum to the ASE spectrum. From the amplitude of the FWM, the conversion efficiency can be calculated and finally leads to the conclusion of the carrier recovery time using Eq. (2).

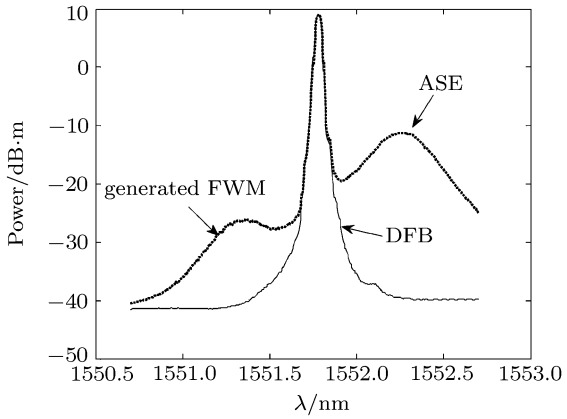


Fig. 4. Experimental spectrum of the waves. The injected current of the SOA is fixed at 240 mA, the detuning of the pump and the probe is 0.5 nm. The solid line is the wave of the DFB. The dotted line is the generated FWM spectrum.

We have measured the $1/e$ carrier recovery time when the injected current is 120, 180, or 240 mA. Figure 5 shows the normalized conversion efficiency of the FWM effect under these three different conditions. The detuning wavelength of the point of the curve that falls off 3 dB from the peak value indicates the $1/e$ carrier recovery time of SOA. We calculated the carrier recovery time, and the results are listed in Table 1. The data show that the carrier recovery time decreases remarkably with the increase of the injected current, which is in good agreement with the nominal value of the SOA sample under the injected currents of 120, 180, and 240 mA, respectively. The conclusions agree with the nominal value of the sample.

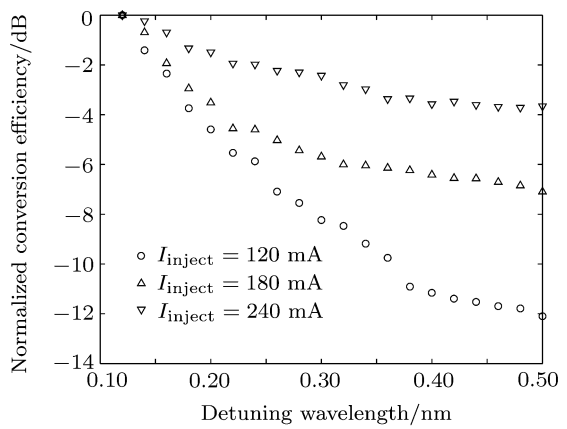


Fig. 5. The normalized conversion efficiency when the injected current is 120, 180, and 240 mA respectively.

Table 1. The carrier recovery time of the SOA of different injected currents.

injected current of SOA/mA	cutoff detuning wavelength/nm	carrier recovery time of the SOA/ps
120	0.16	50.2
180	0.18	44.6
240	0.34	23.6

4. Conclusion

We have proposed and demonstrated a novel and simple scheme based on the FWM of the ASE and DFB laser to measure the carrier recovery time of SOA. In this scheme, the results show that the carrier recovery times are 50.2, 44.6, and 23.6 ps when the injected currents are 120, 180, and 240 mA, respectively. The conclusions are in good agreement with the nominal values of the sample.

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