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Simultaneous demonstration on 10 Gb/s wavelength conversion four-wave mixing and cross-gain modulation in semiconductor optical amplifier

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A study is presented on wavelength conversion in semiconductor optical amplifier (SOA) when the power of the input pump light is as much as that of the input signal light, in which the four -wave mixing (FWM) effect and the cross-gain modulation (XGM) effect occur obviously at the same time and the modulation format of the converted signal light is inverted to that of the input signal light. Experimental results are in agreement with theoretical analysis.

Keywords: semiconductor optical amplifier (SOA), cross-gain modulation (XGM), four-wave mixing (FWM), wavelength conversion.

1. Introduction

All-optical wavelength converters are expected to be crucial components in future all optical networks based on wavelength-division-multiplexed (WDM) technology since they have the potentials to enable wavelength reuse and dynamic routing, to alleviate wavelength congestion in optical cross-connects (OXC), and to make the network management flexible [1]. Several wavelength conversion techniques, exploiting the strong nonlinearities of semiconductor optical amplifiers (SOA), have been proposed in the literature, such as cross-gain modulation (XGM) [2], cross-phase modulation (XPM) [3], and four-wave mixing (FWM) [4], [5]. Among these techniques, the XGM scheme is simple to implement and has shown impressive performance for high bit rates, large wavelength conversion range, as well as high conversion efficiency. But it has two drawbacks: the extinction ratio can significantly be degraded in wavelength up-conversion process and the converted signal light has relatively large chirp. The XPM scheme allows smaller chirp and wavelength up- and down-conversion without extinction ratio degradation. However, its structure is very complicated, and SOAs should be monolithically integrated into the Mach–Zehnder interferometer for stable operation. FWM wavelength conversion is transparent to modulation format and transmission speed, and yet its polarization sensitivity and conversion span dependence pose an obstacle for applying in realistic communication systems.

A number of experimental and theoretical studies on XGM wavelength converters and FWM wavelength converters have been carried out up to the present. In most FWM wavelength conversion experiments in the SOA, a strong pump light and a weaker signal light are injected into the SOA, and the new signal, called the converted signal light, is extracted from the SOA. The modulation formats of the converted signal light and the signal light are inverted. In order to acquire high conversion efficiency, the power of the pump signal light is much greater than that of the signal light. If the power of the pump light is much smaller than that of signal light, the XGM process will be seen distinctly instead of the FWM process. This is called XGM wavelength conversion in the SOA. In this wavelength conversion, the converted signal light and the signal light have the same modulation format. However, few studies on the wavelength conversion under the condition that the power of the signal light is as much as that of the pump light have not been reported. In this paper, we present a study on wavelength conversion of 10 Gb/s in SOA under this condition.

The paper is organized as follows: in Sec. 2 theoretical analysis is introduced. Description of the experimental setup is presented in Sec. 3, and experimental results are discussed in Sec. 4. Finally, in Sec. 5, we draw a conclusions.

2. Theoretical analysis

The essential propagation equation in the SOA used as all-optical wavelength converter can be written as

$$\frac{1}{V_g}\frac{\partial A_j(z,t)}{\partial t}+\frac{\partial A_j(z,t)}{\partial z} = [\Gamma g_j(N)(1-i\alpha)-\gamma]A_j(z,t) + \frac{\Gamma}{2\varepsilon_0 c n_j}\left[i\omega_j P^{NL}(z,t)-\frac{\partial P^{NL}(z,t)}{\partial t}\right]. \tag{1}$$

In the above equation, V_g denotes the group velocity, Γ – the mode confinement factor, $g_j(N)$ – the gain factor at the angular frequency ω_j, α – the Henry's linewidth enhancement factor, γ – the scattering loss coefficient, $A_j(z, t)$ and $P^{NL}(z, t)$ are the slowly varying envelope of the electric field $E_j(z, t)$ and the nonlinear induced electric polarization at ω_j, respectively. $P^{NL}(z, t)$ is given by

$$P^{NL}(z,t) = \sum_j p_j^{NL}(z)\exp(-j\omega_j t) = \varepsilon_0\left\{\chi_j^{(1)}E_j(z)+\sum_{k,l,m}\chi_{jklm}^{(3)}(\omega_j=\omega_k-\omega_l+\omega_m)E_k(z)E_l^*(z)E_m(z)\right\}. \tag{2}$$

Here $\chi_j^{(1)}$ and $\chi_{jklm}^{(3)}(\omega_j = \omega_k - \omega_l + \omega_m)$ are the first-order susceptibility and the third-order susceptibility, respectively. Since semiconductors are materials with inversion symmetry, the (2n)th-order nonlinear susceptibilities are zero. Furthermore, all (2n + 1)th-order nonlinear susceptibilities with $n > 1$ have been neglected for the derivation of Eq. (2).

The first term in Eq. (2) accounts for the saturation induced by carrier depletion. In SOAs, the saturation effect is the strongest nonlinearity. Due to this effect the carrier density can be modulated by an intensity modulated input signal. This also yields a modulation of the gain. The modulation of the gain by an intensity modulated input signal is exploited by all-optical wavelength converters based on XGM. The latter term in Eq. (2) contains several kinds of the third-order nonlinearity. Among these nonlinearities, the FWM effect corresponding to the case $k \neq l \neq m$ is most important.

So, when the pump light and the signal light are injected into the SOA, the XGM effect induced by the saturation effect, the strongest nonlinearity in SOA, must occur. Whereas, the FWM effect belonging to third-order nonlinearity just occurs under certain conditions. The FWM conversion efficiency, one of the most important parameters in determining transmission performance of the FWM signal through SOA, can indicate the strength of the FWM effect. It is defined as the ratio between the output power of the conversion light and the input power of the signal light

$$\eta = \frac{\left|E_c(z)\right|^2\Big|_{z=l}}{\left|E_s(0)\right|^2} = \frac{\left|E_c(l)\right|^2}{\left|E_s(0)\right|^2} = G|\kappa|^2, \tag{3}$$

$$\begin{aligned}\kappa &= -\frac{1}{2}\,\frac{\left|E_p(0)\right|^2}{\left|E_s(0)\right|^2 + \left|E_p(0)\right|^2}\,\ln\left(\frac{G_0}{G}\right)A \\ &= -\frac{1}{2}\,\frac{1}{1 + \dfrac{\left|E_s(0)\right|^2}{\left|E_p(0)\right|^2}}\,\ln\left(\frac{G_0}{G}\right)A,\end{aligned} \tag{4}$$

where:

$$A = \frac{1 - i\alpha}{1 - i\Omega\tau_s} + \frac{\varepsilon_{sh}P_s}{1 - i\Omega\tau_2} + \frac{g_0}{g}\left[1 + \frac{G+1}{2(G-1)}\ln\frac{G_0}{G}\right]\frac{(1 - i\beta)\varepsilon_{ch}P_s}{(1 - i\Omega\tau_1)(1 - i\Omega\tau_2)},$$

and $|E_s(0)|^2$, $|E_p(0)|^2$ are the input signal light power and the input pump light power, respectively. From Eqs. (3) and (4), it can be seen that the FWM conversion efficiency is the function of the ratio $|E_s(0)|^2/|E_p(0)|^2$. When the pump power is much greater than the signal power, $|E_s(0)|^2/|E_p(0)|^2 \approx 0$ and $\eta \to \eta_{\max}$, the high FWM conversion efficiency can be obtained. However, in this case the extinction ratio of

XGM wavelength conversion is very low. So, the FWM effect predominates over the XGM effect. This is the FWM wavelength converter. When the pump power is much smaller than the signal power, $|E_s(0)|^2/|E_p(0)|^2 \to \infty$ and $\eta \to 0$, the FWM conversion efficiency tends to zero, the FWM effect cannot occur. Yet, in this case the extinction ratio of XGM wavelength conversion is very high. So, only the XGM effect occurs. This is the XGM wavelength converter. If the pump power is as much as the signal power, $|E_s(0)|^2/|E_p(0)|^2 \approx 1$ and $\eta \approx \eta_{\max}/2$, the FWM conversion efficiency is not very high. At the same time, the extinction ratio of XGM wavelength conversion is not very high, too. Under this condition, the FWM effect and the XGM effect should both occur obviously.

3. Experimental setup

In our experiments, we use a strained multi-quantum well (MQW) structure SOA with a 12 dB-small-signal gain, which was made by our laboratory, as the mixing device. The experimental setup for all-optical wavelength conversion is shown in Fig. 1. A 10 Gb/s signal light was generated by an Error Test set, which has an output wavelength of 1539.12 nm. The input pump light is provided by a tunable laser with

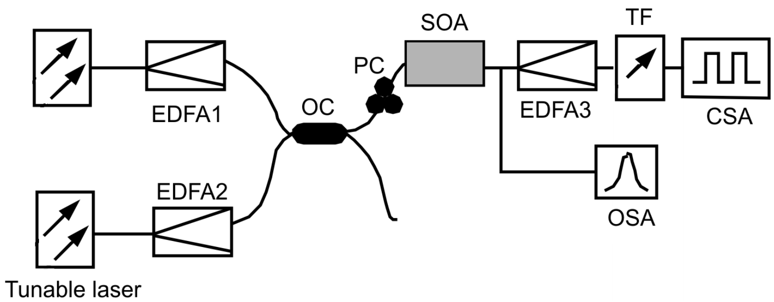

Fig. 1. Experimental setup for all-optical wavelength conversion based on SOA: TF – tunable filter, OC – optical coupler, PC – polarization controller, CSA – communication signal analyzer, OSA – optical spectrum analyzer.

a wavelength tunable range of 100 nm and a power tunable range of 10 dBm. After being amplified by EDFA1 and EDFA2, respectively (EDFA – erbium-doped fiber amplifier), the signal light and the pump light couple into SOA, in which the FWM process (or the XGM process) occurs. The output optical spectra from SOA can be seen from the optical spectrum analyzer (OSA). After they are amplified by EDFA3, the signal lights will be filtrated by the 1 nm tunable bandpass filter (TF). By tuning up the tunable filter, we can see the waveform of a certain light from the communication signal analyzer (CSA). The polarization controller is used to control the polarization of input light.

4. Results and discussions

In the experiments the input signal light wavelength is 1539.12 nm with the power of –2.95 dBm, and the pump light wavelength is fixed at 1536.83 nm with the power of –1.10 dBm. The signal light power is slightly smaller than the pump light power. Figure 2 shows the optical spectra at the output of the SOA. From Fig. 2, two new small optical spectra can be seen, except for the optical spectra of the signal light and the pump light. The wavelengths of the leftmost spectrum and the rightmost spectrum are 1534.68 nm and 1541.30 nm, respectively. Calculations indicate that the spacing between the leftmost new optical spectrum and the signal light, the signal light and the pump light, the pump light and the rightmost new optical spectrum are 2.15, 2.29 and 2.18 nm, respectively. Since the distinguishability of the optical spectrum analyzer is 0.2 nm, taking into account the measuring error effect, it can be concluded that the spacings are approximlately equal. This proves that the two new optical spectra are the converted signal light and the satellite wave, which are generated by the FWM effect in the SOA. That is to say, the FWM effect is occurred in the SOA.

Figure 3 shows the waveforms of the signals at the output of the tunable filter. The modulate format of the input signal light is "11101110". Figure 3**a** shows the waveform of the signal light. Figures 3**b** and **c** show the waveforms of the pump light and the converted signal light, respectively. From Fig. 3, it can be seen that the modulate formats of the pump light and the converted signal light are inverted. In our experiments, it can also be seen that the modulation format of the satellite light and the signal light are inverted, too. This indicates that the FWM and the XGM process obviously occur at the same time in SOA. The XGM effect causes that the modulation

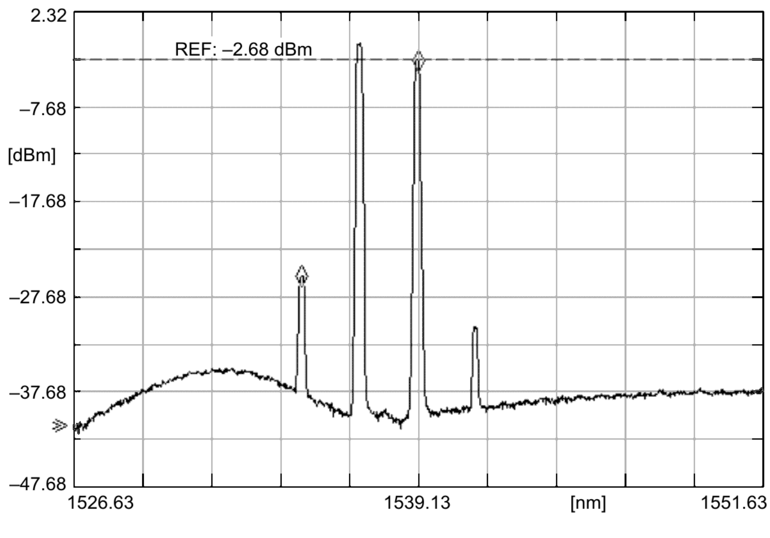

Fig. 2. Output optical spectra of wavelength conversion based on SOA. The wavelengths of the signal light, the pump light and the converted light are 1539.12, 1536.83 and 1534.68 nm, respectively.

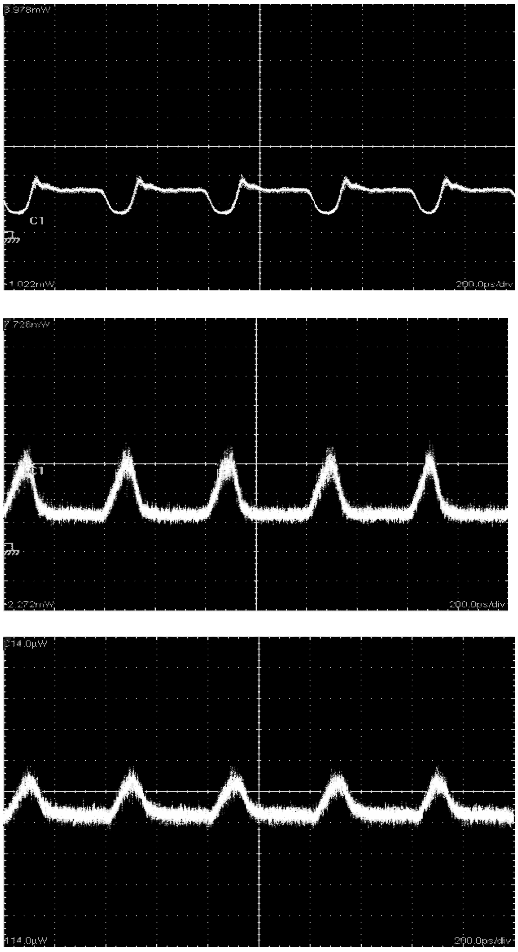

Fig. 3. Output waveform of the signal light (**a**), output waveform of the pump light (**b**) and output waveform of the converted signal light (**c**).

format of the pump light is inverse to that of the signal light. At the same time, the FWM effect causes that the modulation format of the satellite wave is the same as that of the pump light, that is, the modulation format of the satellite wave is inverted to that of the signal light. As the modulation formats of the converted signal light and the signal light are inverted it is considered that, on the one hand, due to the FWM effect, the modulation format of the converted signal light is the same as that of the signal light, but the converted signal light is very weak, it is modulated very feebly; on the other hand, since the XGM effect occurs between the signal, the pump light and the spontaneous radiation wave with the same frequency as the converted signal light, the modulation format of the converted signal light is inverted to that of the signal light. The result of superimposition is that the modulation format of the converted signal light and the signal light are inverted.

5. Conclusions

In this paper, a study has been presented of wavelength conversion in SOA when the power of the pump light is as much as that of input signal light. Under this condition, the FWM effect and the XGM effect obviously appear at the same time, and the modulation formats of the pump light and the converted signal light are inverted to that of the signal light.

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