Ultrabroad-band wavelength converter with high flattening conversion efficiency in a semiconductor optical amplifier

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The efficiency of ultrabroad-band wavelength conversion using orthogonal-pump four-wave mixing in a semiconductor optical amplifier is measured for the wavelength shifts from 1500 to 1640 nm. The variation of conversion efficiency is < 0.9 dB over the wavelength range from 1530 to 1560 nm (C-band), and < 4.5 dB over the wavelength range from 1560 to 1610 nm (L-band). The maximum conversion efficiency is about -8.7 dB.

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Wavelength converters are key devices in all optical communication networks. Four-wave mixing (FWM) in semiconductor optical amplifiers (SOAs) is a promising technique for all-optical wavelength conversion due to its significant advantages, including transparency to bit-rate and modulation format. However, the conversion efficiency of FWM in SOAs drops rapidly with increasing conversion range[1]. To obtain widely tuning range, the experiment using two orthogonal-pump FWM in a semiconductor have been reported[2,3]. In orthogonal-pump scheme, there are many problems that need to be solved, such as large shift from C-band to L-band and flattening of conversion efficiency, because different output powers can cause gain saturation of optical amplifiers in a wavelength division multiplexing (WDM) network. One of the research focuses in wavelength conversion is the conversion efficiency, which depends on so-called relative conversion efficiency function by lumped model[4].

In this letter, we report the measurement of the relative conversion efficiency and a widely tunable wavelength conversion with high efficiency flattening over an 87-nm range (up-conversion) and a 53-nm range (down-conversion) by utilizing very simple devices.

Figure 1 shows the experimental setup. The input signal and two pumps were coupled into the SOA via optical couplers. The input signal was fixed at a wavelength of 1553.0 nm. Considering International Telecommunication Union (ITU) recommended channel spaces of 50 GHz, pump 1 was set at a wavelength of 1552.6 nm. The output from another tunable laser was used as the second pump beam (wavelength: $1500 - 1640$ nm). Polarization controllers were used to align pump 1 and the input signal to the TE mode of the SOA, and pump 2 to the TM mode. The SOA (Alcatel 1901) was biased at 180 mA, with < 1.1 dB gain difference between the TE and TM modes. The powers of the input signal, pump 1 and pump 2, measured at the SOA input, were -10.0, -2.8 and -2.7 dBm, respectively. We did not use EDFAs to amplify pump lasers.

In principle, the beat of pump and signal waves in the SOA active layer creates dynamic gain and index gratings, and the subsequent scattering of the input fields from these gratings generates upper and lower sidebands[5]. The main mechanisms of the FWM here are carrier density modulation caused by both inter-band and intra-band transitions. The former is dominant when wavelength detuning is smaller than 5 nm, and the latter becomes significant when the detuning is larger than

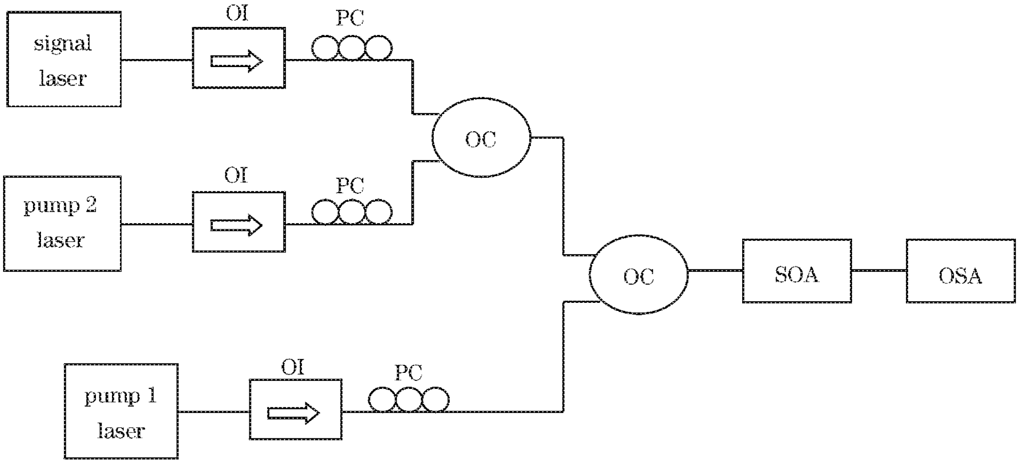

Fig. 1. Experimental setup. OI: optical isolator; PC: polarization controller; OC: optical coupler; SOA: semiconductor optical amplifier; OSA: optical spectrum analyzer.

10 nm. In the copolarized-pump FWM scheme, because conversion efficiency decreases with large wavelength detuning due to the intra-band effect, the orthogonal-pump scheme is used to obtain a uniform conversion efficiency.

In the lumped model[4], the SOA is modeled as an averaged saturable gain followed by a third-order nonlinearity. The three input beams undergo FWM in the gain medium of the SOA and produce wave-mixed signals at different wavelengths. The generated optical wave can be written as[3,4]

$$\begin{aligned} E_c &= (E_s \cdot E_1)E_2\gamma(\omega_s - \omega_1)\exp[j(\omega_c t + \Delta\phi)] \\ &\quad + (E_2 \cdot E_1)E_s\gamma(\omega_2 - \omega_1)\exp[j(\omega_c t + \Delta\phi)], \end{aligned} \quad (1)$$

where $\omega_c = \omega_2 \pm |\omega_s - \omega_1|$; ω_1, ω_2, ω_s, ω_c, E_1, E_2, E_s, and E_c are the frequencies and the field amplitudes of pump 1, pump 2, the input signal, and the converted signal, respectively; $\Delta\phi = \phi_s - \phi_1 + \phi_2$ is the phase difference between the interacting waves; $|\gamma(\Delta\omega)|^2 = R(\Delta\omega)$, where $R(\Delta\omega)$ is the relative conversion efficiency function and decreases rapidly with increasing $|\Delta\omega|$[1]. The first term in Eq. (1) represents that the beat of pump 1 and signal waves scatters pump 2, and the converted signal has the same polarization as pump 2. The second term represents that the beat of pump 1 and pump 2 waves scatters the signal, and the converted signal has the same polarization as the signal. In the orthogonal-pump scheme, two pumps are orthogonally polarized. Hence, the second term in Eq. (1) containing the dot product of the two fields vanishes. Equation (1) is now reduced to

$$E_c = (E_s \cdot E_1)E_2\gamma(\omega_s - \omega_1)\exp[j(\omega_c t + \Delta\phi)]. \quad (2)$$

During the tuning process, although ω_2 is changing, $\omega_s - \omega_1$ remains unchanged, so that $\gamma(\omega_s - \omega_1)$ remains unchanged. Hence a near constant output power of the converted signal can be obtained with a large wavelength detuning. The optical power of the converted signal is

$$P_c = E_c \cdot E_c^*. \quad (3)$$

According to the lumped model, the optical fields of the pump and input signal waves are given by

$$E_1 = \sqrt{P_1 G_{TE}}, \quad (4)$$

$$E_2 = \sqrt{P_2 G_{TM}}, \quad (5)$$

$$E_s = \sqrt{P_s G_{TE}}, \quad (6)$$

where P_1, P_2, and P_s are the powers of pump 1, pump 2, and the input signal, respectively. G_{TE} and G_{TM} are the saturated gains of the SOA for the TE and TM modes. Using Eqs. (2)−(6), the conversion efficiency, defined as the ratio between the converted signal output power and input signal power, is given by

$$\eta = \frac{P_c}{P_s} = P_1 \cdot P_2 \cdot G_{TE} \cdot G_{TE} \cdot G_{TM} \cdot R(\Delta\omega). \quad (7)$$

Equation (7) can be expressed in dB by

$$\eta = P_1 + P_2 + G_{TE} + G_{TE} + G_{TM} + R(\Delta\lambda), \quad (8)$$

where $R(\Delta\lambda)$ (which is a function of detuning $\Delta\lambda$ between pump 1 and signal only and does not depend on the tuning between P_1 and P_2) is the relative conversion efficiency function and independent of gain and input power over a definite range of both drive current and input power[6]. We checked $R(\Delta\lambda)$ by using a pump and a signal fields that polarized in the TE direction in our experiment.

Figure 2 plots the experiment measurements on efficiency η of wavelength conversion and relative conversion efficiency $R(\Delta\lambda)$ in the single-pump scheme, made by the method similar to Ref. [6].

The input signal power was −14.7 dBm, at a wavelength of 1552.8 nm, and the pump power was −7.0 dBm. The experiment demonstrated that $R(\Delta\lambda)$ is higher than that reported in Ref. [6] and is −33.0 dBm corresponding to detuning of 0.4 nm. The result was proved in Ref. [7], in which the used SOA (Alcatel 1901) was the same as our model. According to the input powers, bias current (180 mA) and measured conversion efficiency η, $R(\Delta\lambda)$ could be estimated.

Figure 3 shows the measured conversion efficiency η versus wavelength shifts.

The conversion efficiency, which is defined as the output signal power divided by the input signal power, reaches up to −8.7 dB. The changing of conversion efficiency is < 0.9 dB over the wavelength range from 1530 to 1560 nm (C-band), and < 4.5 dB over the

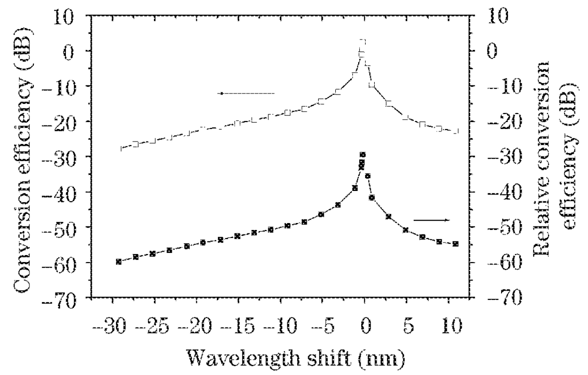

Fig. 2. Measured conversion efficiency η (open square) and relative conversion efficiency $R(\Delta\lambda)$ (solid square) versus wavelength shift. SOA is biased at 175 mA.

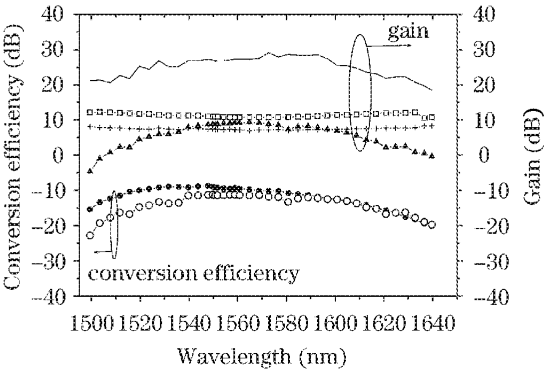

Fig. 3. Conversion efficiency and gain versus scanning wavelength. Dots and circles represent experimental and theoretical conversion efficiencies, respectively; triangles, crosses, and squares represent gain of pump 2, pump 1, and signal, respectively; and the solid line means total sum of gains.

wavelength range from 1560 to 1610 nm (L-band). The degradation of the conversion efficiency is less than −12.4 dB over a range of 140 nm (1500 − 1640 nm). The wavelength range of the used tunable laser limited measured the maximum wavelength shift in this work.

In Fig. 3, the gain (triangles) of pump 2 was given. The gains of the signal (fixed at 1553.0 nm) and pump 1 (fixed at 1552.6 nm) are also shown in the figure. They were also measured by scanning pump 2 across its entire lasing range (1500 − 1640 nm). The sum of gains of signal, pump 1 and pump 2 were plotted. In our experiment, $R(\Delta\lambda = 0.4 \text{ nm}) = -33.0$ dBm. Combining this value with the input powers and gains above mentioned, we calculated theoretical conversion efficiency η by Eq. (8), shown as circles in Fig. 3. As can be seen, the calculated results are in good agreement with experimental results. Equation (8) provides an excellent fit from 1590 to 1640 nm.

The quantity called relative conversion efficiency function is measured with wavelength shift. Due to high relative conversion efficiency function and orthogonal-pump FWM scheme, the conversion efficiency reaches up to −8.7 dB, and its variation is < 0.9 dB over C-band and < 4.5 dB over L-band. The degradation of the conversion efficiency is less than −12.4 dB over a 140-nm (1500 − 1640 nm) range. In WDM optical networks, a practical wavelength converter should be applied in both C-band and L-band. The experiment demonstrates that the technique for large wavelength shift using simply double-pump FWM in SOAs is capable of all optical networks.

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