Polarization-independent wavelength conversion using a single semiconductor optical amplifier

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Polarization-independent wavelength conversion is demonstrated by using four-wave mixing (FWM) in a single semiconductor optical amplifier (SOA). In this scheme, all the incident fields are split into two orthogonal-polarized parts by polarizing beam splitters (PBS). Each of the two parts is then transmitted into one facet of the SOA and they are counter-propagating through the same amplifier. Wavelength conversion with the polarization sensitivity less than 1.3 dB is obtained over a range from 1510 to 1620 nm.

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Wavelength converter plays a very important role in all-optical communications, and four-wave mixing (FWM) in semiconductor optical amplifiers (SOAs) is a promising technique for the realization of all-optical wavelength conversion. It has the advantages such as rapid response speed and independence of bit-rate and modulation. In SOA gain medium, the new wave generated during the nonlinear optical process has an amplitude proportional to the product of the signal and pump amplitudes; its phase and frequency are the sum and difference of those of the incident fields, respectively. This means that the new wave contains phase and amplitude information of the input signal. But in conventional FWM system, which is pumped by a single beam, the wavelength conversion efficiency drops rapidly with the increase of conversion range[1,2]. In order to get a broad wavelength conversion spectrum, people began to investigate FWM in SOA pumped by two orthogonal-polarized beams[3−5]. Unfortunately, in the real communication network the uncontrollable nature of the polarization state of the input signal induces the uncertainty of the conversion efficiency. The investigations on solving such problems have been one of the recent focuses[6,7].

In this paper, we study a new scheme to achieve polarization-independent and broad-range wavelength conversion. In this scheme, the incident signal and the two pumps are split into two orthogonal-polarized parts counter-propagating through the SOA. By using FWM, we realize the wavelength conversion in C- and L-band. The maximum variation of conversion efficiency is no more than 1.3 dB for arbitrary polarization state of the signal.

Figure 1 shows the schematic of the investigation. The signal and the two pump waves are split into two orthogonal-polarized parts, respectively. The two parts are then individually transmitted into one facet of the SOA, where they are counter-propagating with each other. In each propagation direction, the polarization state of the signal wave is parallel to pump 1 and perpendicular to pump 2. Strictly speaking, mixing process exists both in co-propagating and counter-propagating waves. But in a broad frequency detuning range, the conversion efficiency of FWM in counter-propagating waves is so low that we can consider the mixing process with co-propagating waves only. Under this approximation, we can explain FWM in SOA by the same way as introduced in Ref. [5,8]. The new wave generated during the process of mixing is called conjugate wave, its amplitude can be expressed by

$$\begin{aligned} E_{\rm c} &= E_2(E_{\rm s}\cdot E_1)r(\Delta\omega_1=\omega_{\rm s}-\omega_1) \\ &\quad\times\exp\{{\rm i}[(\omega_{\rm s}-\omega_1+\omega_2)t+\phi_{\rm s}-\phi_1+\phi_2]\} \\ &\quad+E_{\rm s}(E_2\cdot E_1)r(\Delta\omega_2=\omega_2-\omega_1) \\ &\quad\times\exp\{{\rm i}[(\omega_2-\omega_1+\omega_{\rm s})t+\phi_2-\phi_1+\phi_{\rm s}]\}, \qquad (1)\end{aligned}$$

where $E_{\rm s}$, E_1, and E_2 represent the amplitudes of the input signal, pump 1, and pump 2 after transmitting through gain medium, respectively. The corresponding frequencies and phases are $\omega_{\rm s}$, ω_1, ω_2, and $\phi_{\rm s}$, ϕ_1, ϕ_2, respectively. $|r(\Delta\omega)|^2=R(\Delta\omega)$ is the relative conversion efficiency[2]. In orthogonal-polarized pumps scheme, Eq. (1) can be simplified into

$$\begin{aligned} E_{\rm c} &= E_2(E_{\rm s}\cdot E_1)r(\Delta\omega_1=\omega_{\rm s}-\omega_1) \\ &\quad\times\exp\{{\rm i}[(\omega_{\rm s}-\omega_1+\omega_2)t+\phi_{\rm s}-\phi_1+\phi_2]\}, \qquad (2)\end{aligned}$$

$r(\Delta\omega_1=\omega_{\rm s}-\omega_1)$ is a function of the detuning $\Delta\omega_1=\omega_{\rm s}-\omega_1$ between pump 1 and signal only, it is irrelevant

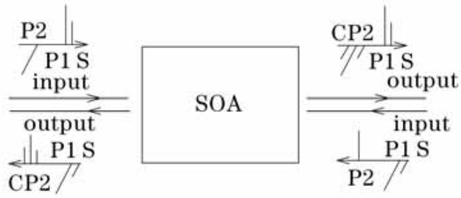

Fig. 1. Schematic of the two-pump polarization-diversity configuration. S: signal; P1: pump 1; P2: pump 2; C: converted signal.

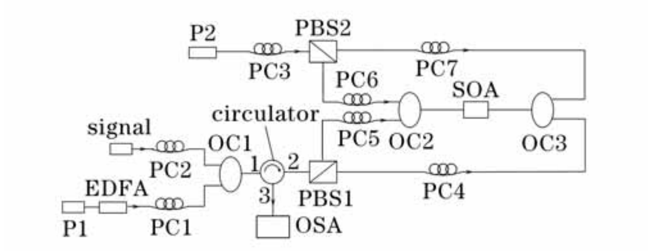

Fig. 2. Experimental setup.

to the detuning between pump 2 and pump 1. That is to say, the amplitude of the conjugate wave with a frequency $\omega_c = \omega_s - \omega_1 + \omega_2$ is independent of the wavelength conversion when the wavelength of pump 2 is changed in orthogonal-polarized pumps scheme. Expression (2) represents that the beat of pump 1 and signal scatters pump 2, and the converted signal has the same polarization as pump 2. According to Ref. [5], the optical power of the converted signal is

$$P_c = P_s \cdot P_1 \cdot P_2 \cdot G_{TE} \cdot G_{TE} \cdot G_{TM} \cdot R(\Delta\omega), \quad (3)$$

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 TE and TM modes in the SOA, respectively.

The experimental setup is shown in Fig. 2. After being amplified by erbium-doped fiber amplifiers (EDFAs), pump 1 (P1) is coupled with the signal by the 3-dB optical coupler 1 (OC1), then transmitted to the port 1 of the optical circulator. The signal and pump 1, from the port 2 of the circulator, are split into two orthogonal-polarized beams by the polarization beam splitter 1 (PBS1). The two beams then enter the two facets of SOA separately. A fiber polarization controller (PC1) is used to control the polarization state of pump 1 at the input port of PBS1, so that pump 1 can be split into two orthogonal-polarized beams with the same power. The fiber PC2 is used to simulate the arbitrary polarization state of the signal. Similarly, the tunable pump 2 is also split into two orthogonal-polarized beams with the same power by PBS2. After transmitting through OC2 and OC3, the signal, pump 1 from PBS1, and pump 2 from PBS2 are injected into the opposite facets of SOA. The polarization states of signal and pump 1 are aligned with the TM (TE) mode in the SOA by adjusting PC4 (PC5). Fiber PC6 and PC7 make the polarization states of pump 2 parallel to the TM and TE mode of SOA, respectively. In this way, along each of the propagation directions, polarization states of the two pumps are orthogonal. The two SOA outputs go back through the same path of the input and then are injected back in the PBS1 before they are coupled into one beam. The output from the port 3 of the optical circulator is detected by an optical spectrum analyzer (OSA). The use of PBS1 can prevent the interference between the converted signals with orthogonal polarization. The another advantage to use PBS1 is to improve the signal-to-noise ratio (SNR) of the output by attenuating input signal, pump 1, and amplified spontaneous emission (ASE) which have the different polarization with the converted signal. If the difference between the two arms of PBS1 is less than 0.5 cm (25-ps time delay), this wavelength converter works well for 10-Gb/s signal.

In this experiment, for a random input signal polarization, the ratio of the two output powers from PBS1 is assumed to be $k:(1-k)$. In Eq. (3), the conjugate wave power from PBS1 is sum of the converted signal power coming from the opposite facets of the SOA and should be written as

$$\begin{aligned} P_c &= k \cdot P_{si} \cdot P_1 \cdot P_2 \cdot G_{TE} \cdot G_{TE} \cdot G_{TM} \cdot R(\Delta\omega) \\ &+ (1-k) \cdot P_{si} \cdot P_1 \cdot P_2 \cdot G_{TE} \cdot G_{TM} \cdot G_{TM} \cdot R(\Delta\omega) \\ &= P_{si} \cdot P_1 \cdot P_2 \cdot G_{TE} \cdot G_{TM} \cdot R(\Delta\omega) \\ &\cdot [k \cdot G_{TE} + (1-k) \cdot G_{TM}], \end{aligned} \quad (4)$$

where P_{si} is the input signal power to PBS1 (assuming PBS1 is lossless), and we do not take account of the losses in the optical couplers OC2 and OC3. P_1 and P_2 are the input powers to SOA. Equation (4) can be expressed in dB form by

$$\begin{aligned} P_c &= P_{si} + P_1 + P_2 + G_{TE} + G_{TM} + G_{TM} \\ &+ R(\Delta\lambda) + 10\log \cdot \left(1 + k\frac{G_{TE} - G_{TM}}{G_{TM}}\right). \end{aligned} \quad (5)$$

The last term of Eq. (5) is the change of the converted signal power resulting from the input signal polarizations that are parallel to the TE mode and TM mode of SOA, respectively. The term can be written as

$$\Delta P_c = 10\log \cdot \left(1 + k\frac{G_{TE} - G_{TM}}{G_{TM}}\right). \quad (6)$$

Equation (5) indicates that the converted signal power is relevant to the gain difference of TE and TM modes in SOA. The conjugate wave power is independent of the polarization state of the input signal when $G_{TE} = G_{TM}$. Figure 3 shows the conjugate wave power varies with the input signal polarization. It indicates that the change of the converted signal resulting from variation of the signal polarization is very small (less than 0.8 dBm) under our experiment conditions.

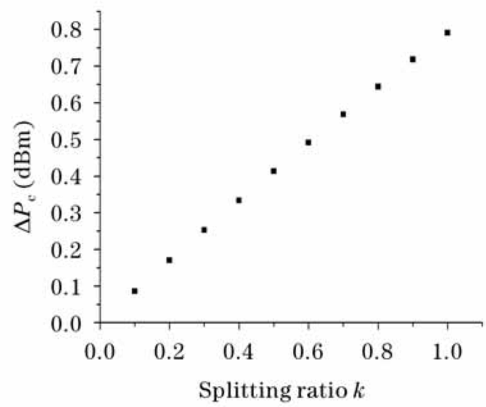

Fig. 3. The calculated power variation of the converted signal versus the splitting ratio resulting from the polarization change of the input signal under the condition of $G_{TE} = 9$ dBm, $G_{TE} - G_{TM} = 0.8$ dBm.

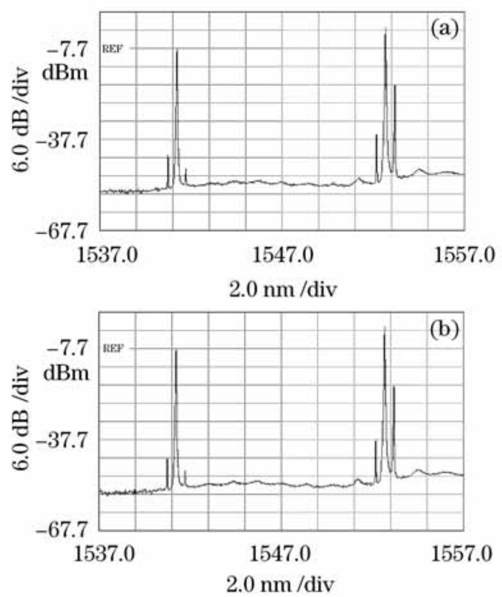

Fig. 4. Output spectra for input signal polarization producing maximum (a) and minimum powers (b) of the converted signal.

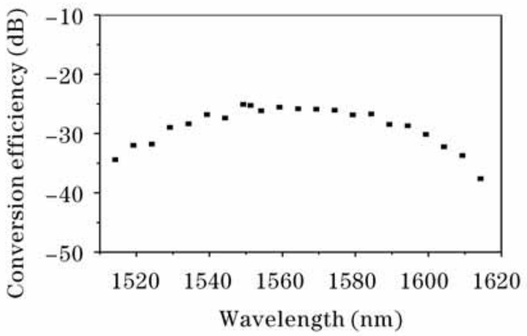

Fig. 5. Output conversion efficiency versus scanning wavelength.

In Fig. 4, pump 2 is fixed at the wavelength of 1541.0 nm, and pump 1 at 1553.6 nm. The small-signal gain of SOA is 25 dB. The saturated output power is 9 dB. When the biased current is 170 mA, the maximum discrepancy between gain of TE mode and TM mode is 0.8 dB. Considering the ITU (International Telecommunication Union) recommended channel space of 50 GHz, the input signal is fixed at 1554.0 nm. The powers of the input signal, pump 1, and pump 2 measured at the input port of SOA are −15.9, 4.8 and −2.3 dBm, respectively. Figures 4(a) and (b) show the maximum and minimum converted signal powers at the output of the circulator when the incident signal has an arbitrary polarization state. The maximal change of the converted signal power is less than 1.3 dBm, while not 0.8 dBm as shown in Fig. 3, because PBS1 and the optical couplers are not ideal ones.

Figure 5 indicates the relationship between the conversion efficiency and the wavelength of pump 2. The conversion efficiency is determined as the ratio between the power of the converted signal at the output port of the circulator and the signal power at the input port of SOA. When the wavelength of pump 2 changes between 1510 and 1610 nm, the conversion efficiency is between −25.0 and −35.0 dB.

We have demonstrated that conversion efficiency is independent of both polarization state of the input signal and the interval of wavelength conversion by using FWM in a single SOA pumped by two orthogonal-polarized beams. For arbitrary polarization state of the input signal, the polarization sensitivity is no more than 1.3 dB over a range from 1510 to 1610 nm.

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