Widely tunable all-optical wavelength converter based on four-wave mixing using two orthogonally polarized pumps

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The principle of broad-band orthogonal-pump (BOP) four-wave mixing in semiconductor optical amplifiers is analyzed in theory. The conversion efficiency reduces rapidly as the detuning of wavelength between the signal and pump increase which can be solved by introducing a BOP method. The constant conversion efficiency and signal-to-noise ratio are obtained over a large wavelength detuning range. The wavelength conversion efficiency with variation smaller than 3.88 dB over 52-nm range has been experimentally demonstrated by using BOP, with the 10-GHz output of distributed feedback/electro-absorption modulator as signal. Conventional single-pump scheme is also performed for comparison and the experimental results fit well with the theory.

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Wavelength division multiplexing (WDM) has been proposed to fully exploit the huge fiber transmission bandwidth and to allow easy routing and switching in optical networks. In this frame, wavelength conversion is a promising technique to avoid wavelength blocking and enable interconnection between independently managed networks[1]. To achieve all-optical wavelength conversion, various strategies have been investigated, such as cross-gain modulation (XGM)[2], cross-phase modulation (XPM)[3], and four-wave mixing (FWM) in semiconductor optical amplifiers (SOAs), of which only FWM is transparent to both modulation format and signal bit rate[4]. However, the all-optical wavelength converter using conventional FWM in SOA has a serious problem. Its conversion efficiency reduces rapidly as the detuning of wavelength between the signal and pump increase. This can be solved by introducing a broad-band orthogonal-pump (BOP) method[5]. However, in Ref. [5], the signal to be converted is continuous wave (CW), not pulse. In this paper, we analyzed that using two orthogonally polarized pumps enable to obtain constant conversion efficiency (η) and signal-to-noise ratio (SNR) over a large detuning range of pump and signal. The wavelength conversion efficiency with a variation smaller than 3.88 dB over a 52-nm detuning range has been successfully obtained with the 10-GHz output of distributed feedback/electro-absorption modulator (DFB/EAM) as signal.

Figure 1 shows the spectrum at the output of the SOA for FWM using two orthogonally polarized pumps.

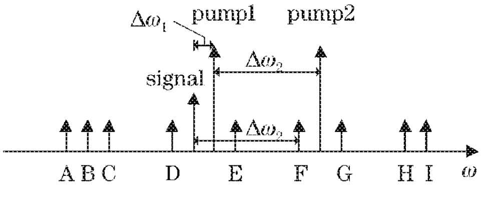

Fig. 1. Spectrum generated by FWM in a SOA with two orthogonally polarized pumps.

The output component of interest is F or G, which is a replica of the input signal and is shifted in frequency by $\Delta\omega_2$ or $\Delta\omega_2 + 2\Delta\omega_1$, respectively. According to Zhou's lumped model[6], the optical field $E_{\rm F}$ is

$$\begin{aligned} E_{\rm F} = {} & \left(\overrightarrow{A_s} \cdot \overrightarrow{A_1}\right) r\left(\omega_s - \omega_1\right) \overrightarrow{A_2} \\ & \times \exp\left\{i\left[\left(\omega_s - \omega_1 + \omega_2\right)t + \phi_s - \phi_1 + \phi_2\right]\right\} \\ & + \left(\overrightarrow{A_2} \cdot \overrightarrow{A_1}\right) r\left(\omega_2 - \omega_1\right) \overrightarrow{A_s} \\ & \times \exp\left\{i\left[\left(\omega_2 - \omega_1 + \omega_s\right)t + \phi_2 - \phi_1 + \phi_s\right]\right\}, \quad (1) \end{aligned}$$

where $\overrightarrow{A_m} = A_{mx} \cdot \overrightarrow{x} + A_{my} \cdot \overrightarrow{y}$ ($m = 1, 2$, and s), A_x and A_y are the amplitude of the optical field in the x and y polarization state, respectively (where $\overrightarrow{x}$ and $\overrightarrow{y}$ are orthogonal unit vectors), ϕ is the phase of the optical field, and $\left|r\left(\Delta\omega\right)\right|^2 = R\left(\Delta\omega\right)$, $R\left(\Delta\omega\right)$ is the relative conversion efficiency function which decreases with increasing frequency detuning $\Delta\omega$. Since the two orthogonally polarized pumps do not beat, the frequency-shift dependent term has zero magnitude. That is to say, Eq. (1) can be simplified to

$$\begin{aligned} E_{\rm F} = {} & \left(A_s \cdot A_1\right) r\left(\Delta\omega_1\right) \overrightarrow{A_2} \\ & \times \exp\left\{i\left[\left(\omega_s - \omega_1 + \omega_2\right)t + \phi_s - \phi_1 + \phi_2\right]\right\}. \quad (2) \end{aligned}$$

And the resultant field has the same polarization state as pump2 with power

$$P_{\rm F} = \overrightarrow{E_{\rm F}} \cdot \overrightarrow{E_{\rm F}}^* = \left(A_1 A_2 A_s\right)^2 \left|r\left(\Delta\omega_1\right)\right|^2. \quad (3)$$

By using the definitions: $A_1 = \sqrt{P_1 G_x}$, $A_2 = \sqrt{P_2 G_y}$, and $A_s = \sqrt{P_s G_x}$ (where G_x, G_y are gains of the SOA for x- and y-polarized signals, respectively), one can conclude that

$$\eta\left(\Delta\omega_2\right)=\frac{P_{\mathrm{F}}}{P_s}=P_1P_2G_x^2G_yR\left(\Delta\omega_1\right), \qquad (4)$$

$$\mathrm{SNR}\left(\Delta\omega_2\right)=\frac{P_{\mathrm{F}}}{P_{\mathrm{ASE}}}=\frac{P_1P_2P_sG_x^2G_yR\left(\Delta\omega_1\right)}{P_{\mathrm{ASE}}}, \qquad (5)$$

where P_{ASE} is optical power of the SOA's amplified spontaneous emission (ASE) in 0.1-nm bandwidth. In Eqs. (4) and (5), η and SNR are independent of the frequency $\Delta\omega_2$, as long as $\Delta\omega_1$ is fixed and the gain of the SOA is independent of optical frequency. Performing the same analysis for field G leads to the same conclusion. That is to say, if the above conditions are satisfied, η and SNR can be obtained over a large wavelength detuning range.

Our experimental setup is shown in Fig. 2. A CW fiber laser constructed by an IRE-POLUS's EAD60 EDFA1 (erbium-doped fiber amplifier) and Santec tunable filter (TF1) are used as pump1. The output of TUNICS-Plus continuously tunable laser diode (LD) is used as pump2 (tunable from 1500 to 1640 nm). The 10-GHz pulse train of DFB/EAM centered at 1554.2 nm acts as the input signal. The typical fiber-to-fiber gain of the SOA is 17.7 dB, with 6.5-dBm saturation output power. The polarization dependent gain is 0.3 dB and the noise figure is 10.5 dB. The output result is sent into Ando AQ-6315A optical spectrum analyzer (OSA), and also filtered out and amplified by EDFA2 before being sent into Agilent 86100B wide-bandwidth oscilloscope.

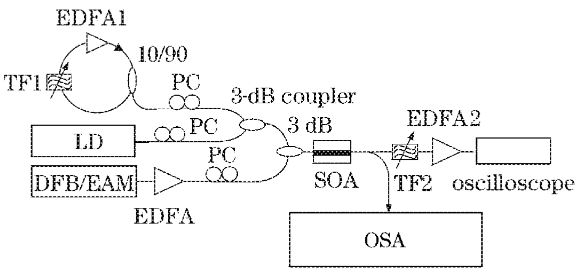

Fig. 2. Experimental setup of all-optical wavelength conversion using broad-band orthogonally polarized pumps.

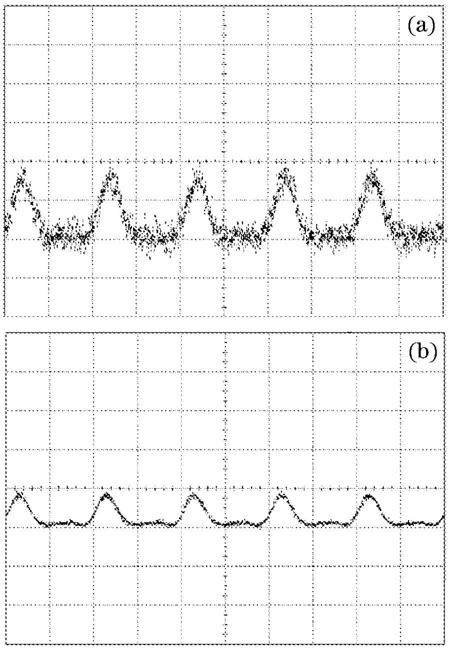

Fig. 3. Output signal of EAM (a) and conversion result of SOA-FWM wavelength converter (b).

Pump1 is fixed at 1552.4 nm and pump2 is tuned to produce the desired range of wavelength detuning. Polarization controllers (PCs) are used to align pump2 to be orthogonally polarized to pump1 and signal. In our experiment, the highest converted component is G shown in Fig. 1. With the SOA biased at 250 mA, the output conversion result is shown in Fig. 3(b). Compared with original DFB/EAM signal shown in Fig. 3(a), the large DC components in converted output are due to the ASE of EDFA2. The spectral results with wavelength of pump2 at 1547.099 and 1535.739 nm are shown in Fig. 4, respectively.

By tuning the wavelength of pump2, the conversion efficiency is measured with driven current of 230, 240, and 250 mA, respectively, as shown in Fig. 5(a). It is shown that the wavelength conversion efficiency with a variation smaller than 3.88 dB over more than 52-nm detuning range has been obtained with 250-mA driven current. (The detuning range for wavelength up-conversion is limited by the asymmetric characteristic of FWM in SOA and gain dropping at longer wavelength of SOA.) That is to say, with BOP we can get constant conversion efficiency over a large wavelength detuning range as described in theory. However, the conversion efficiency is relatively low in our experiment. The reasons are in a few aspects. Firstly, the conversion efficiency of FWM-SOA is inherently lower than those of XGM-SOA and XPM-SOA. Secondly, with the increasing of driven current of SOA, higher conversion efficiency and wider detuning range can be obtained, as shown in Fig. 5(a). However, due to the limitation of the SOA's driven

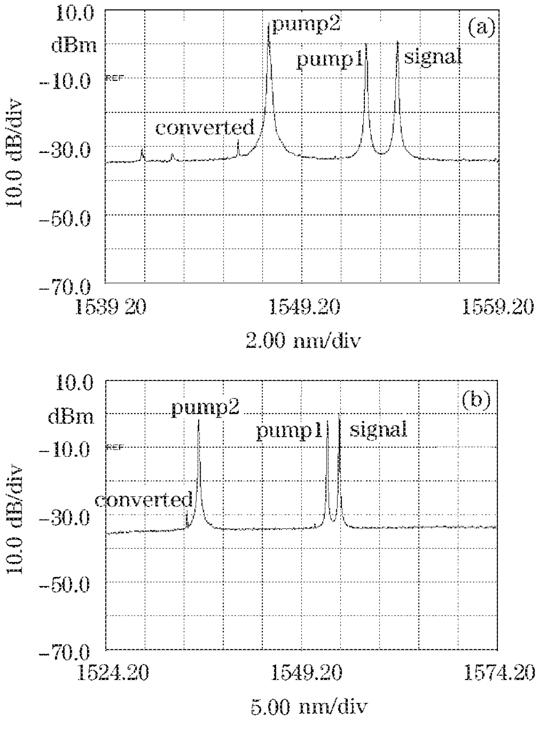

Fig. 4. SOA-FWM wavelength conversion results by using two orthogonally polarized pumps.

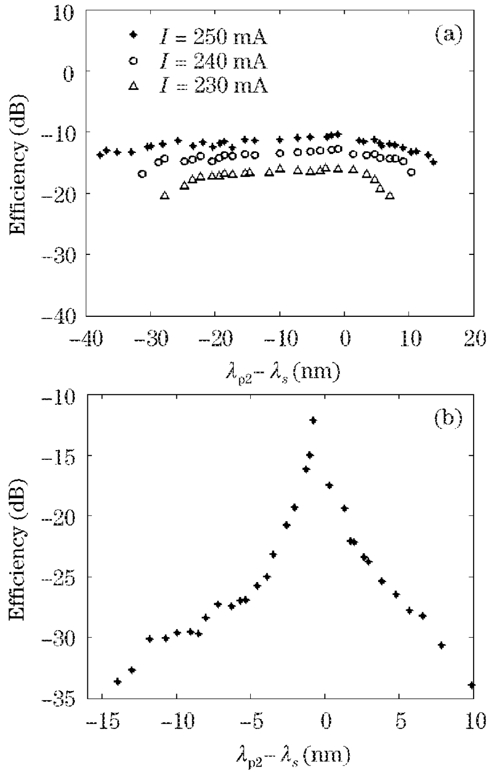

Fig. 5. Wavelength conversion efficiency as a function of wavelength detuning for BOP scheme (a) and conventional single-pump scheme (b).

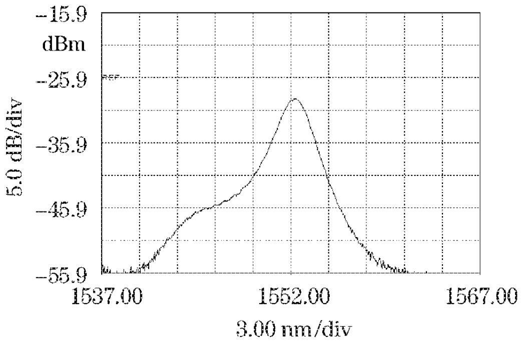

Fig. 6. Transmission spectrum of TF1 around 1552 nm.

current, we only get the data with driven current lower than 250 mA. Also, the peak small signal gain of this SOA is only 17.7 dB, which constraints the highest conversion efficiency we can obtain.

We also performed conventional signal-pump experiment for comparisons. In the single-pump scheme, pump1 was disconnected. Its conversion efficiency is shown in Fig. 5(b). For the scheme of conventional single-pump, the conversion efficiency reaches a peak of about −12 dB near the pump wavelength. However, as the converted wavelength is tuned away from the peak, the conversion efficiency drops rapidly, which leads to a 3-dB tuning range of smaller than 2 nm. Compared with conventional single-pump scheme, the BOP scheme shows more uniform conversion efficiency over the whole tuning range. This is consistent with the theory. In principle, the tuning range can be further increased using a SOA with a larger spectral gain-bandwidth.

Although the output SNR shows uniform over the whole tuning range, its value is only 6−8 dB. This is mainly due to large ASE of pump1. Because this fiber laser is constructed by us without any stabilization, it is easily affected by the mechanical vibrations and temperature variation. On the other hand, its filter with poor outband rejection (1.95±1 nm at 3 dB, insertion loss >3 dB) limits the linewidth and stability of laser output. Its transmission spectrum around 1552 nm is shown in Fig. 6. Also, we have not used band-pass filter for the experiment and the noise figure of SOA is so large. If these limitations are removed, better results will be obtained. Now further experiments are under way.

In conclusion, a widely tunable all-optical wavelength conversion scheme operated with two orthogonally polarized pumps has been successfully demonstrated. Compared with the conventional single-pump scheme, a nearly constant conversion efficiency (<3.88 dB) over 52-nm conversion range has been obtained by using BOP scheme.

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