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All-optical wavelength conversion scheme to reduce the crosstalk among the two multiplexed channels for polarization multiplexing system

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ABSTRACT

This paper presents the polarization rotation effect in SOA for polarization-multiplexed signals. Based on the theoretical analysis, a polarization diversity parallel dual-pump FWM scheme to reduce the crosstalk between the two multiplexed channels is proposed. The comparison on several factors including the frequency spacing between two pumps, different modulated data rate and the conversion efficiency, are investigated by simulation. Moreover, we have discussed the injection current of SOA in different modulated data rate. The optimum injection current of SOA is studied for the 40 Gbit/s data. The results indicate that the proposed scheme is better than the conventional scheme.

1. Introduction

All-optical wavelength conversion (AOWC) has been regarded as a key technique for optical networks. It can improve the efficiency in wavelength division multiplexing (WDM) networks and simplify network management [1,2]. Several approaches, including cross-gain modulation (XGM), cross-phase modulation (XPM), and cross-absorption modulation (XAM) are proposed for wavelength conversion [3–6]. Four-wave mixing (FWM) in semiconductor optical amplifiers (SOAs) is a promising scheme because of its inherent compact size, fast response time, low noise properties, and modulation-format and bit-rate transparency [7–9]. Moreover, the SOAs have gain advantages for the possibility to be integrated (see Table 1).

Nowadays, the polarization multiplexing (Pol-Mux) are widely recognized as an indispensable enable technique for 40 Gbps/100 Gbps transmission due to the doubled capacity by transmitting two signals via two orthogonal polarization states [10–12]. AOWC for polarization multiplexing signals based on four-wave mixing in nonlinear medium have been investigated [13–17]. However, there is an issue about the nonlinear interaction in the SOA that it is a detrimental factor for a transparent conversion of PolMuxed-signals by using FWM [17]. Furthermore the nonlinear crosstalk elimination scheme among the multiplexed channels in AOWC system for polarization multiplexing signals has not been reported yet. In this paper, we have theoretically discussed the cause of the crosstalk for polarization multiplexing signals in SOA. Then, we proposed a polarization diversity configuration with two SOAs for AOWC to reduce such crosstalk. In the proposed scheme, the input to each SOA is composed of two pump fields and the co-polarized component of the signal field, and two independent FWM performed in the two SOAs. Hence, the polarization crosstalk caused by the polarization rotation induced by polarization-dependent SOA's gain is reduced.

The rest of this paper is organized as follows. In Section 2, we theoretically analyze the polarization rotation effect on polarization-dependent SOA's gain, and then we propose a novel polarization diversity scheme with two independent SOAs for wavelength conversion. Two independent modes propagating in two SOAs in the proposed scheme and the principle of wavelength conversion based on a simple "lumped" model is derived. In Section 3, the simulation based on the proposed scheme is built and the simulation results show that the crosstalk among the two polarization multiplexed channel arising from the polarization rotation is reduced. Several factors which can affect the system are then discussed, including the frequency spacing between pumps, different modulated data rate and the injection current of SOA. We found that the best injection current of SOA is 0.65 mA at 40 Gbit/s per polarization modulated data rate.

2. Theory

Currently, most commercial semiconductor optical amplifiers have been improved, but they still remain polarization-dependent.

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Table 1
SOA parameters definitions.

Parameters	Symbols	Units
Phase modulation coefficient	α^{TE}, α^{TM}	
Optical confinement factor	Γ^{TE}, Γ^{TM}	
Gain coefficient	ξ^{TE}, ξ^{TM}	ps^{-1}
Group velocity	$\upsilon_g^{TE},\ \upsilon_g^{TM}$	$\mu m/ps$
Hole imbalance factor	f	
Electrical current	I	mA
Optical transition state number	N_0	
SOA length	L	μm

Polarization-dependent SOA's gain can induce polarization rotation effect [18].

2.1. Analysis of the polarization rotation in SOA

Fig. 1 shows the waveguide structure of SOA. In polarization multiplexing system, the incoming arbitrarily polarized electric field is decomposed into a component parallel to the layers in the waveguide transverse electric (TE) mode and a perpendicular component (TM) mode. Based on the rate equation theory, the signal-gain g^{TE} and g^{TM} in SOA for (TE) and transverse magnetic (TM) polarization can be expressed as follows [18]:

$$\begin{aligned} g^{TE}(z,t) &= \xi^{TE}[n_c(z,t) + n_x(z,t) - N_0] \\ g^{TM}(z,t) &= \xi^{TM}[n_c(z,t) + n_y(z,t) - N_0] \end{aligned} \tag{1}$$

where ξ^{TE} and ξ^{TM} are the gain coefficient for the TE and TM mode respectively; $n_c(z,t)$ denotes the number of electrons in the conduction band; $n_x(z,t)$ and $n_y(z,t)$ denote the number of holes involved in the x and y transitions; N_0 is the total number of electronic states involved in the optical transition. Since we do not consider applications that involve ultrafast dynamics here, the relationship between $n_x(z,t)$ and $n_y(z,t)$ can be written as: $n_x(z,t) = fn_y(z,t)$, where f is the magnitude of the anisotropy. SOA parameters definitions are shown in Table 2. The different refractive-index changes for TE and TM

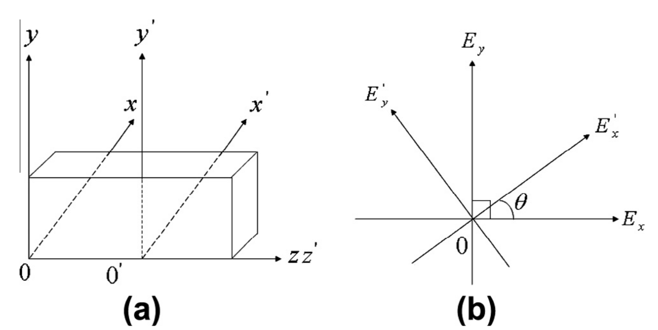

Fig. 1. Waveguide structure of SOA (a) and definition of two coordinate system (b).

Table 2
Parameters of the SOA.

Parameters	Values
Active layer length	0.0005 m
Active layer width	3.0 μm
Active layer thickness	0.08 μm
Optical confinement factor	0.3
Internal loss	2000 m^{-1}
Differential gain	2.78×10^{-20} m^2
Carrier density at transparency	1.4×10^{24} m^3
Recombination coefficient	1.43×10^{8} s^{-1}
Recombination coefficient	$1 \times 10^{-16} m^3$ s^{-1}
Recombination coefficient	$3 \times 10^{41} m^5$ s^{-1}
Initial carrier density	3×10^{24} m^3

leads to a different gain between these two modes. Different gain between the two modes leads to different phase on the TE and TM modes are given by [18,19]:

$$\begin{aligned} \varphi^{TE} &= \frac{1}{2}\left(\frac{\alpha^{TE}\Gamma^{TE}g^{TE}}{\upsilon_g^{TE}}\right)L \\ \varphi^{TM} &= \frac{1}{2}\left(\frac{\alpha^{TM}\Gamma^{TM}g^{TM}}{\upsilon_g^{TM}}\right)L \end{aligned} \tag{2}$$

We built two coordinate systems x, y, z and x', y', z' in SOA as shown in Fig. 1(a), where x, y, z is assumed as reference system, x', y', z' is SOA's inherent coordinate system, and z' axis is in the same direction with z axis. When lightwave transmits along $z(z')$ axis into SOA, the input electric field and the output electric field of the x', y', z' coordinate system can be written as $E'_{0x},\ E'_{0y}$ and $E'_{1x},\ E'_{1y}$, respectively. The relation between the input and output electric fields can be expressed as:

$$\begin{aligned} \vec{E}'_{1x} &= E'_{0x}\exp\left[\frac{1}{2}\left(\frac{\alpha^{TE}\Gamma^{TE}g^{TE}}{\upsilon_g^{TE}}\right)L\right] = E'_{0x}\exp[\varphi^{TE}] \\ \vec{E}'_{1y} &= E'_{0y}\exp\left[\frac{1}{2}\left(\frac{\alpha^{TM}\Gamma^{TM}g^{TM}}{\upsilon_g^{TM}}\right)L\right] = E'_{0y}\exp[\varphi^{TM}] \end{aligned} \tag{3}$$

where α^{TE}, α^{TM} are the phase modulation coefficient, and $\upsilon_g^{TE}, \upsilon_g^{TM}$ are the corresponding group velocity taken at the central frequency of the wave, Γ^{TE}, Γ^{TM} are the confinement factor. Coordinate system x, y, z is assumed, at polarization angle θ with respect to x', y', z' coordinate system, which is shown in Fig. 1(b). Then, the components of electric fields in the two coordinate systems can be expressed as:

$$\begin{aligned} \vec{E}'_x &= E_x\cos\theta + E_y\sin\theta \\ \vec{E}'_y &= -E_x\sin\theta + E_y\cos\theta \end{aligned} \tag{4}$$

Based on Eqs. (3) and (4), the relationship between components of input electric fields $\vec{E}_{0x},\ \vec{E}_{0y}$ and output electric fields $\vec{E}_{1x},\ \vec{E}_{1y}$ is obtained. It can be expressed as:

$$\begin{aligned} \vec{E}_{1x} &= (\varphi^{TE}\cos^2\theta + \varphi^{TM}\sin^2\theta)\vec{E}_{0x} + (\varphi^{TE} - \varphi^{TM})\cos\theta\sin\theta\,\vec{E}_{0y} \\ \vec{E}_{1y} &= (\varphi^{TE} - \varphi^{TM})\cos\theta\sin\theta\,\vec{E}_{0x} + (\varphi^{TE}\sin^2\theta + \varphi^{TM}\cos^2\theta)\vec{E}_{0y} \end{aligned} \tag{5}$$

The effect of SOA on the input electric fields can be expressed by SOA's transfer matrix. SOA's transfer matrix is defined as:

$$J = \begin{bmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{bmatrix}$$

According to Eq. (5), the elements of the matrix can be written as:

$$\begin{aligned} J_{11} &= (\varphi^{TE}\cos^2\theta + \varphi^{TM}\sin^2\theta) \\ J_{12} = J_{21} &= (\varphi^{TE} - \varphi^{TM})\cos\theta\sin\theta \\ J_{22} &= (\varphi^{TE}\sin^2\theta + \varphi^{TM}\cos^2\theta) \end{aligned} \tag{6}$$

As a result, Eq. (5) can be expressed by the matrix as:

$$\begin{bmatrix} \vec{E}_{1x} \\ \vec{E}_{1y} \end{bmatrix} = \begin{bmatrix} \varphi^{TETE}\cos^2\theta + \varphi^{TM}\sin^2\theta(\varphi^{TE} - \varphi^{TM})\cos\theta\sin\theta \\ (\varphi^{TE} - \varphi^{TM})\cos\theta\sin\theta\varphi^{TE} + \varphi^{TM}\cos^2\theta \end{bmatrix}\begin{bmatrix} \vec{E}_{0x} \\ \vec{E}_{0y} \end{bmatrix} \tag{7}$$

The polarization multiplexing signals before sending into SOA can be expressed by the matrix T as:

$$\vec{T} = \begin{bmatrix} T_x(t)e^{j[\omega_0 t + \varphi(t)]} \\ T_y(t)e^{j[\omega_0(t+\tau_0) + \varphi(t+\tau_0)]} \end{bmatrix} \tag{8}$$