Wavelength conversion based on nonlinear polarization rotation in gain transparent SOA*

DOU Rong-she(豆荣社)[1]**, YU Chong-xiu**(余重秀)[1], **WANG Kui-ru**(王葵如)[1], **WANG Yong-jun**(王拥军)[2], **SANG Xin-zhu**(桑新柱)[1], **ZHANG Qi**(张琦)[2], and **YAN Bin-bin**(颜玢玢)[1]

1. *State Key Laboratory of Information Photonics and Optical Communications, Beijing University of Posts and Telecommunications, Beijing 100876, China*

2. *School of Electronic Engineering, Beijing University of Posts and Telecommunications, Beijing 100876, China*

We describe an all-optical wavelength conversion scheme for 1310 nm to 1550 nm based on nonlinear polarization rotation in a gain-transparent semiconductor optical amplifier (GT-SOA) which brings in the assistant light to improve the property of the converted light. From the SOA carrier density equations, the 1310 nm-to-1550 nm wavelength conversion scheme is analyzed by the Jones matrix. The phase shift between TE and TM modes and the converted light are simulated at bit rate of 30 Gbit/s. We also analyze the influence of the input signal power, the injected current and the assistant light power on the extinction ratio of the converted light.

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A key technology in all-optical network (AON) is all-optical wavelength conversion, which is considered as an important block[1]. Both 1310 nm and 1550 nm windows can be utilized in the optical communication network, so the wavelength conversion between 1310 nm and 1550 nm is necessary. There are many methods to realize all-optical wavelength conversion[2,3], for example, the expensive $LiNbO_3$ and the highly nonlinear microstructure fiber[4-6]. But the wavelength converter based on the nonlinear polarization rotation in semiconductor optical amplifier (SOA) has been paid more attention because of the advantages of simple structure, easy integration, high conversion efficiency and so on. The nonlinear polarization rotation can lead to the polarization state of probe light modulated by the power of the input signal, so as to realize wavelength conversion[7,8]. For example, the 1310 nm to 1550 nm wavelength conversion scheme based on the nonlinear polarization rotation in SOA was brought by J. P. R. Lacey, J. P. Turkiewicz et al[9,10]. However, the current research is restricted to give the bit error rate in the experiments, and the extinction ratio is severely degraded at a higher rate which is restricted by the carrier recovery time.

In order to improve the carrier recovery time and the wavelength conversion rate, we design a wavelength conversion scheme based on the nonlinear polarization rotation in a gain-transparent-SOA (GT-SOA) which adds the assistant light. The transmission characteristics and wavelength conversion characteristics are simulated, and then the effects of the injected current, the input signal power and the assistant light power on the extinction ratio are analyzed. The results have worthy significance for the research of the 1310 nm to 1550 nm wavelength conversion based on the nonlinear polarization rotation in GT-SOA.

The all-optical wavelength conversion scheme is shown in Fig.1. An intensity-modulated no-return-to-zero (NRZ) continuous signal is launched by LD1 with the direct current (DC) assistant light from LD2 at 1300 nm, and the DC probe light at 1500 nm from LD3 passes through the OC and finally enters the GT-SOA. Adjust PC1 and PC2 to make the polarization of the signal and assistant light parallel to the orientation of the SOA waveguide layer, and the polarization of the probe light is adjusted by PC3 to be 45° relative to the orientation of the SOA waveguide layer. The PC4 is adjusted to make sure that the polarization of the probe light is 45° relative to the orientation of the PBS's axis. Because the signal light injected into the SOA produces additional birefringence, the intensity of the probe light can be modulated by the power of the input signal, thereby the 1310 nm to 1550 nm wavelength conversion is realized.
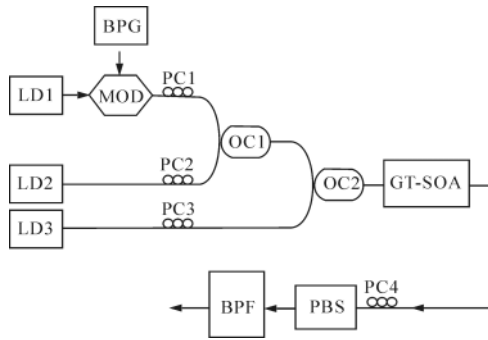
Fig.1 Schematic diagram of all-optical wavelength conversion

Because the probe light is at 1550 nm, and the photon energy is below the band-gap energy in GT-SOA, it can not produce simulated emission and gain, but only changes the refractive index. After passing through the SOA, the attenuations of the TE and TM modes are equivalent[11]. In addition, it has nothing to do with the optical power, but only relates to the injected current.

The carrier density and photon density in SOA can be described as[12]

$$\frac{\partial N(z,t)}{\partial t} = \frac{I}{qv} - \frac{N(z,t)}{\tau_c} - \frac{\Gamma g[N(z,t)]}{\hbar w A_{cross}} P , \quad (1)$$

where N denotes carrier density, I is the driving current, q is the electronic charge, v is the cavity volume, τ_c is the spontaneous carrier lifetime, and $\tau_c^{-1} = A + BN + CN^2$, where A, B and C are nonradioactive, bimolecular and auger recombination constants, respectively. $\hbar w$ is the photon energy, Γ is the confinement factor, and A_{cross} is active layer area. In order to fit the SOA's asymmetric gain curve, the gain coefficient is approximated to[13]

$$g(N) = g_N (N - N_0) - r_1 (\lambda - \lambda_N)^2 - r_2 (\lambda - \lambda_N)^3 , \quad (2)$$

where λ_N is the gain peak wavelength for carrier density N, which is given by

$$\lambda_N = \lambda_0 - \kappa_0 (N - N_0) , \quad (3)$$

where λ_0 is the peak gain wavelength, and κ_0 can denote the drift of peak gain wavelength according to the carrier density. g_N is the material gain constant, N_0 is the transparent carrier density, and r_1 and r_2 are gain constants.

The signal travels along the length of the SOA, and its power obeys the travelling-wave equation written as[14]

$$\frac{\partial P(z,t)}{\partial z} = P(z,t) \cdot [\Gamma g(N,\lambda) - \alpha_{int}] , \quad (4)$$

where α_{int} is the loss factor.

When the signal light is injected into the SOA, the effective refractive indices of TE and TM modes are given by[15]

$$n_{TE}(z) = n_{TE0} + \Gamma_{TE} \cdot N(z) \cdot (\frac{d n_{TE}}{d N}) , \quad (5)$$

$$n_{TM}(z) = n_{TM0} + \Gamma_{TM} \cdot N(z) \cdot (\frac{d n_{TM}}{d N}) , \quad (6)$$

where n_{TE0} and n_{TM0} are the natural refractive indices of TE and TM modes, respectively, Γ_{TE} and Γ_{TM} denote the optical confinement factors, and $d n_{TE}/dN$ and $d n_{TM}/dN$ are the differential refractive indices. The total phase shift of probe light can be obtained by the following integration over the cavity length of the amplifier[15]:

$$\Delta\varphi = \frac{2\pi}{\lambda} \int_0^L [n_{TE}(z) - n_{TM}(z)] d z . \quad (7)$$

We divide the light field of the probe light which is injected into the SOA into TE and TM modes, and the Jones matrices of the SOA and PBS can be described as:

$$J_1 = \begin{bmatrix} \alpha^{TE} e^{j\phi_{TE-TM}} & 0 \\ 0 & \alpha^{TM} \end{bmatrix} ,$$

$$J_2 = \begin{bmatrix} \cos^2 \theta & \frac{1}{2}\sin 2\theta \\ \frac{1}{2}\sin 2\theta & \sin^2 \theta \end{bmatrix} , \quad (8)$$

where θ is the angle between the orientation of the TE mode and the principal axis of the PBS. After passing through the SOA and the PBS, the complex amplitude of the probe light can be represented as

$$\begin{bmatrix} E_{TE}^{out} \\ E_{TM}^{out} \end{bmatrix} = J_2 \cdot J_1 \begin{bmatrix} E_{TE}^{in} \\ E_{TM}^{in} \end{bmatrix} , \quad (9)$$

where E_{TE}^{in}, E_{TM}^{in} and E_{TE}^{out}, E_{TM}^{out} are the light vectors of the incoming probe light and the transmitted probe light when leaving the PBS. Optical output power can be described as

$$P^{out} \propto (|E_{TE}^{out}|^2 + |E_{TM}^{out}|^2) . \quad (10)$$

Because the 1550 nm single light is in the transparent wavelength of the SOA, the attenuation $\alpha^{TE} = \alpha^{TM} = \alpha$. We can get $P^{out} \propto [\alpha(1 - \cos\phi_{TE-TM})]$ when $\theta = -\pi/4$, and then the optical output power is equal to zero if $\phi_{TE-TM} = 0$, and the optical output power reaches the maximum if $\phi_{TE-TM} = \pi$ similarly. ϕ_{TE-TM} is related to the optical signal power, so the 1310 nm to 1550 nm wavelength conversion can be achieved.

Using the theoretical model mentioned above, the simulation analysis of the phase shift, the results of wavelength conversion and the extinction ratio of converted light are all investigated.

Fig.2 shows the variation of the phase shift between the

TE and TM modes of the probe light. As can be seen, adding assistant light can effectively reduce the time of the phase shift recovery from π to 0.
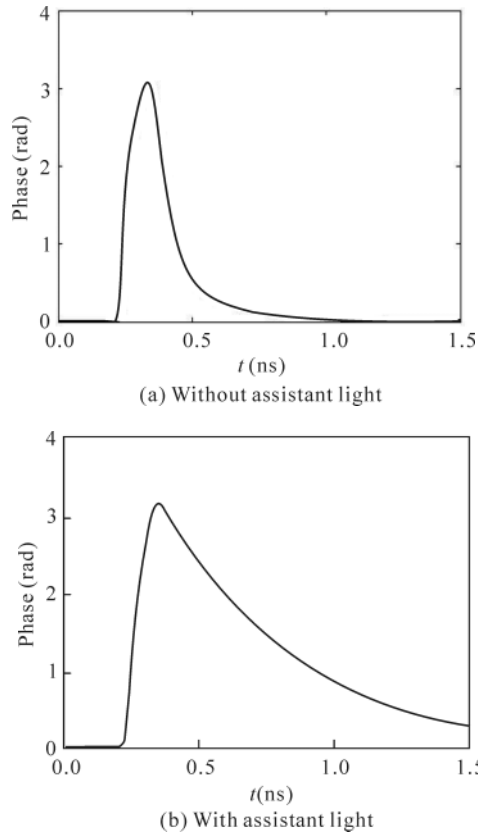

(a) Without assistant light

(b) With assistant light

Fig.2 Phase shift changes with time

(a) Input signal

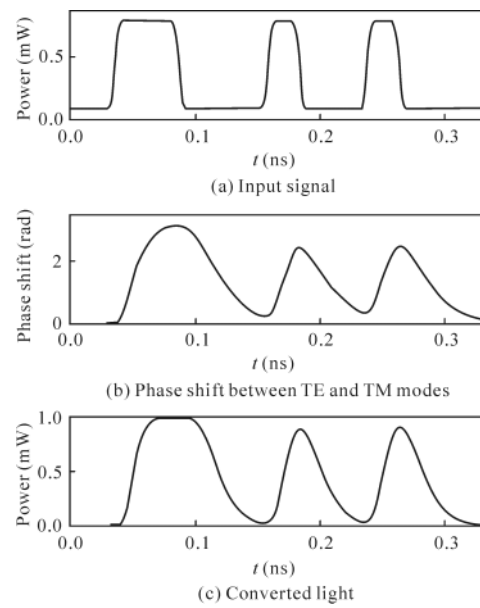(b) Phase shift between TE and TM modes

(c) Converted light

Fig.3 Simulation results of signal conversion at 30 Gbit/s
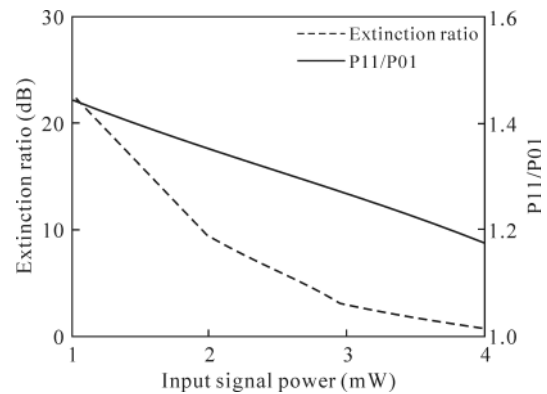
Fig.4 Influence of the input signal power on the extinction ratio and the waveform

We choose the super Gauss pulse as the input signal, and its corresponding bit sequence is '0110010100', the peak power is 5 dBm, its extinction ratio is 10 dB, and the assistant light power is 0.05 mW. We adjust the injected current in order that the phase shift of the modulated probe light varies from 0 to π, moreover we can get better results of the transformation waveform and extinction ratio when the maximum is π and the minimum is 0. The power of the converted light is normalized.

Fig.3 shows the simulation results of all-optical wavelength conversion at bit rate of 30 Gbit/s. We can find that the rising edge of the phase shift curve changes quickly. The reason is that the rising edge corresponds to the failing of the carrier density, and the failing edge corresponds to the rising of the carrier density, but the rising of the carrier density is faster than the failing.

The results in Fig.4 show that the input signal power can significantly affect the extinction ratio and the converted light. We define P_{11} as the peak power of the conversion light corresponding to the successive '1', while P_{01} is defined as the peak power of the un-successive '1'.

From Fig.4, we can get that the smaller the input signal power is, the larger the extinction ratio is, but the ratio of P_{11} to P_{01} is also increased. It is because the carrier density is consumed even more when the power is larger, which makes the phase shift of '0' recovering to 0 difficult, and then it leads to the decrease of the extinction ratio. So we should choose the appropriate input signal power in order to get better results of the wavelength conversion.

Fig.5 shows the influence of injected current on extinction ratio. From Fig.5 we can get that with the increase of the injected current, the extinction ratio is increased. However, if the injected current is so great that the phase shift is larger than π, the conversion light will be distorted. So the injected current also needs to be selected appropriately.
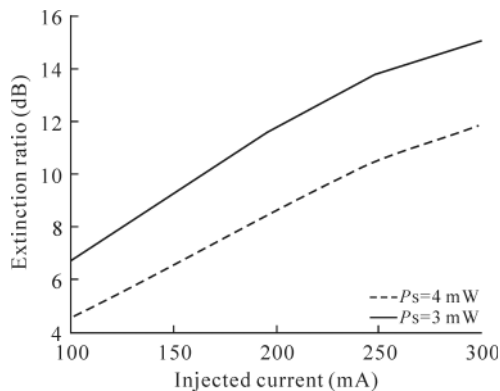
Fig.5 Influence of injected current on extinction ratio

Fig.6 shows the influence of assistant light on extinction ratio. The addition of assistant light can reduce the carrier recovery time, and then the extinction ratio can be increased. So the assistant light can improve the extinction ratio greatly.
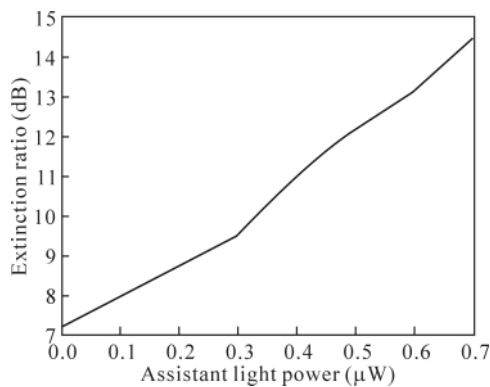

Fig.6 Influence of assistant light on extinction ratio

We propose an all-optical wavelength conversion system based on the nonlinear polarization rotation in GT-SOA which adds the assistant light. Using the theoretical model of SOA, we investigate the performance of the 1310 nm to 1550 nm wavelength conversion, and simulate the phase shift between TE and TM modes and the converted light at bit rate of 30 Gbit/s. The effects of the input signal power, the injected current and the assistant light power on the extinction ratio of the converted light are analyzed. The results indicate that the converted light and the extinction ratio can be improved when we choose the appropriate signal power and injected current. Since the assistant light is injected into SOA, the

phase shift, the converted signal and the extinction ratio are all improved effectively.

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