Spatial Mode Conversion by Non-degenerate Four Wave Mixing

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Abstract: We investigate coupling and power transfer between two transverse modes in a single quantum-well traveling wave semiconductor optical amplifier (SOAs) by non-degenerate four wave mixing. By this approach the mode purity achieve 99.99% at the end of active region of SOA and the mode conversion can be controlled by the adjusting pump and probe power.

1 INTRODUCTION

The mode conversion recently has found applications in optical communication, especially in spatial mode division multiplexing, wavelength filters, sensors, dispersion compensators, optical switching (Tim Hellwig, Sep 2013) and generation the orbital angular momentum (Yao, 2011). The mode conversion by using the devices like spatial light modulator, cylindrical lens (Yao, 2011), Bragg grating (Dietmar Johlen, Nov 2000, Tim Hellwig, Sep 2013), and multimode interference (Yutaka Chaen, Oct. 27 - 30, 2013) are well-known. In this paper, we demonstrate a new method for mode converting and spatial mode modulating based on the SOAs. The applicability of SOAs in optical switching and optical processing and their capability in integration are proved (Connelly, 2004). Here, we obtain the efficient conversion on the conjugate frequency between two excited modes in multi modes geometry of active region by non-degenerate four wave mixing.

2 THEORY

Due to the nonlinearity effect, coupling between two or more light beams can occur in a single waveguide (Yaron Silberberg, 1987). In our investigations we have used the GaAs as active region (or waveguide). First the modal analysis on the typical structure of TW-SOAs has been performed and the obtained results is used as a guided modes that can be excited in the active region(Yamada, Sep 1983, Yaron Silberberg, 1987). These guided modes and their effective refractive index for pump, probe and conjugate (or signal) frequency are shown in figure 1. The first and third order susceptibility that depend on the carrier density are derived by density matrix method and represented by(Yamada, 1989):

$$\chi^{(1)}(N) = k\left\{(\alpha_p - i)\cdot\left[N - N_g^{(1)} - b(\lambda_m - \lambda_0)^2\right]\right\} = \chi^{(1)\prime} + i\chi^{(1)\prime\prime}. \tag{1a}$$

$$\chi^{(3)}(N) = 4k\left(\frac{\tau_{in}}{\hbar}\right)^2 \cdot \langle M\rangle^2 \cdot (\alpha_p - i)\cdot\left(N - N_g^{(3)}\right) = \chi^{(3)\prime} + i\chi^{(3)\prime\prime}. \tag{1b}$$

Where k and b are constant coefficient, for GaAs are $1.61\times10^{-26}\ m^3$ and $3\times10^{19}\ m^{-3}\mathring{A}^{-2}$ respectively. α_p is a line width enhancement factor, $N_g^{(1)}$ and $N_g^{(3)}$ are first order and third order transparency carrier density, λ_p is a peak wavelength, λ_m is a wavelength of interaction beam, τ_{in} is an intra-band relaxation time, $\hbar$ is a plank constant, $\langle M\rangle^2$ is a dipole moment. Also the $\chi^{(3)}(N)$ like a simplified susceptibility due to the spectral hole burning that has been introduced in (A. Uskov, Aug 1994).

The optical field of guided modes in active region can be expressed as:

$$E_i = \exp(i\omega_i t)\sum_{j=1,2} A_{i,j}(z) F_{i,j}(x,y)\exp(i\beta_{i,j} z) \tag{2}$$

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$$=(E_1+E_2).\exp(i\omega_i t)$$

Where A is amplitude, β is the propagation constant and $F(x, y)$ is the normalized transverse distribution of optical field. Subscribe i indicates the pump, probe and conjugate optical field respectively, and subscribe j indicates the fundamental and second mode, respectively. Also the relation between frequencies is $\omega_2 = 2\omega_0 - \omega_1$.

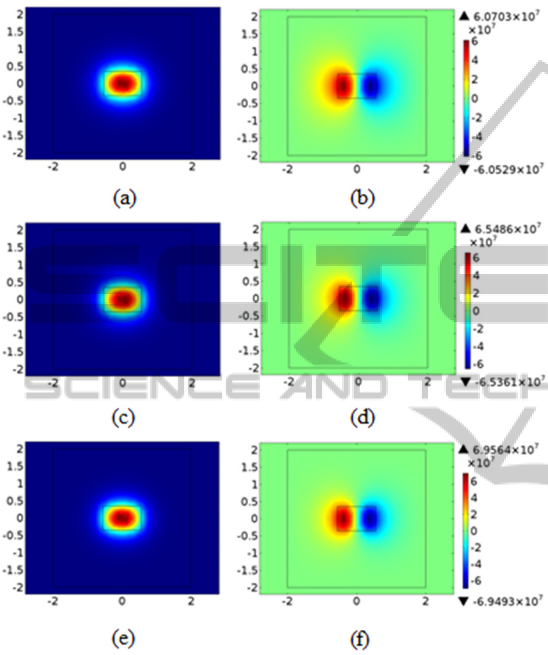


Figure 1: Electric Field (x component) of Modes in multimode geometry of Active region, Active region width=1.1 µm, Active region thickness=0.7 µm. (a)-(b) fundamental and second mode in signal (Conjugate) frequency, 353 THz, $n_{eff2,1}$ = 3.5702, $n_{eff2,2}$ = 3.5438. (c)-(d) fundamental and second mode in pump frequency, 371.5 THZ, $n_{eff0,1}$ = 3.572, $n_{eff0,2}$ = 3.5466. (e)-(f) fundamental and second mode in probe frequency, 390 THZ, $n_{eff1,1}$ = 3.5737, $n_{eff1,2}$ = 3.5493.

The nonlinear coupling due to the nonlinear polarization can be represented by(Jensen, Oct 1982, P.Agrawal, 2001):

$$-i\frac{\partial A_{i,j}(z)}{\partial z} = \frac{\omega_i}{P_0} e^{-i\beta_{i,j}z} \iint F_{i,j}^{*} P^{NL}\, dxdy \qquad (3)$$

P^{NL} is a perturbing nonlinear polarization that is the summation of all nonlinear polarization in the specific frequency and these perturbing nonlinear polarization terms are defined in (.Boyd, 2008) and P_0 is a normalized power. The carrier density equation for SOA in time independent state is:

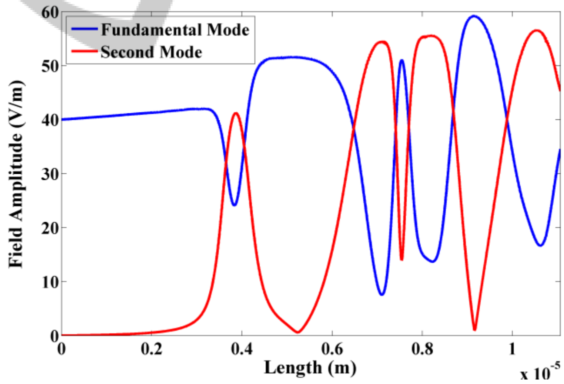
$$\overline{N(z)} = \frac{\frac{I}{qAL} + \sum_{i=0,1,2} \frac{\alpha_{n,i} N_{tr,i}}{\hbar\omega_i}\left(\Gamma_{i,1}|A_{i,1}|^2 + \Gamma_{i,2}|A_{i,2}|^2\right)}{\frac{1}{\tau_s} + \sum_{i=0,1,2} \frac{\alpha_{n,i}}{\hbar\omega_i}\left(\Gamma_{i,1}|A_{i,1}|^2 + \Gamma_{i,2}|A_{i,2}|^2\right)} \qquad (4)$$

Where V is the active region volume, α_n is a differential gain, τ_s is spontaneous lifetime, Γ is a confinement factor and N_{tr} is a transparency carrier density depends on wavelength, in other words $N_{tr} = N_g^{(1)} + b(\lambda_m - \lambda_0)^2$.

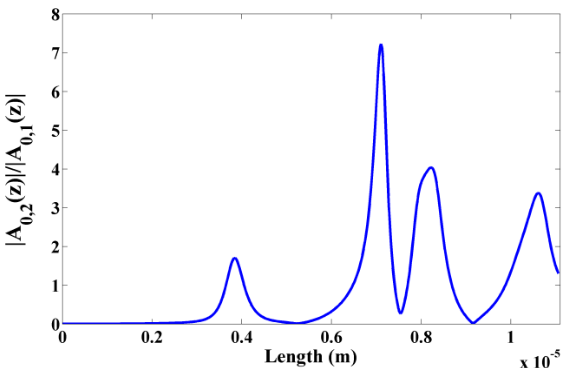
Finally, we have a differential equations set that include six coupled equations due to the SOA linear rate equation and four wave mixing coupling equations, these equations obtain the amplitude of fundamental and second mode in pump, probe and conjugate (or signal) frequency.

3 SIMULATION RESULTS

In this section, we demonstrate the coupling between fundamental and second mode in pump, probe and



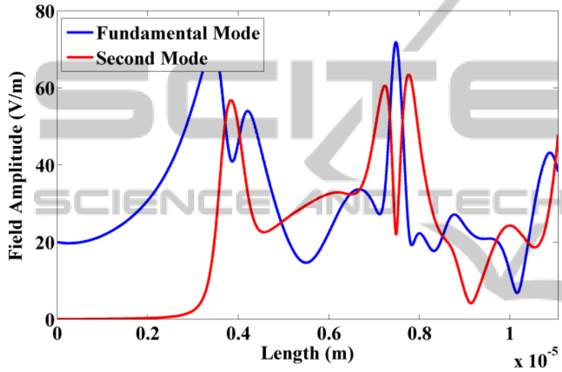
(2a)



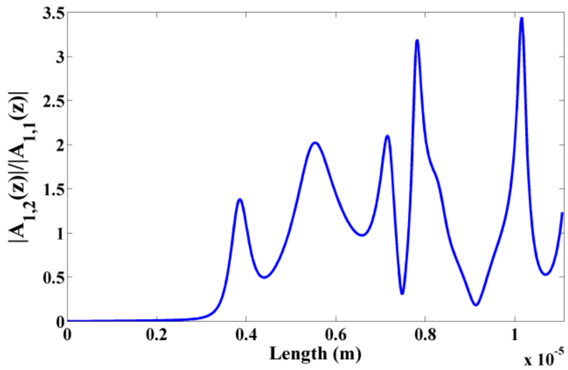
(2b)

Figure 2: (2a) The coupling of amplitude of fundamental and second modes in pump frequency. (2b) The ratio of second mode amplitude to fundamental mode amplitude of pump.

conjugate wave, due to the highly non-degenerate four wave mixing, and dynamic gain, refractive index grating (Agrawal, Jan 1988). Figure 2 shows a coupling process between two transvers mode for pump. As the figure (2a) shows, the second mode in this frequency has been excited and coupling has occurred on the length. The figure (2b) shows the ratio of second mode amplitude to fundamental mode amplitude on the length of active region, as this figure shown, the efficiency of mode conversion in pump frequency is insignificant.



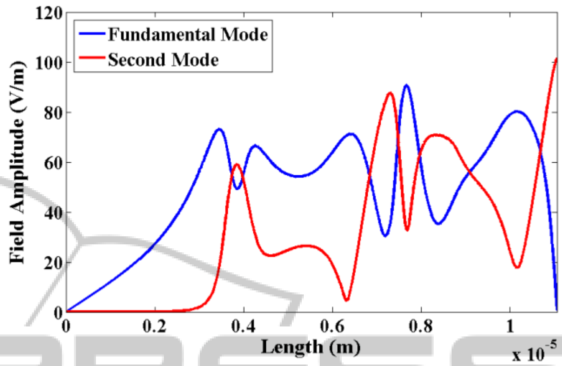
(3a)



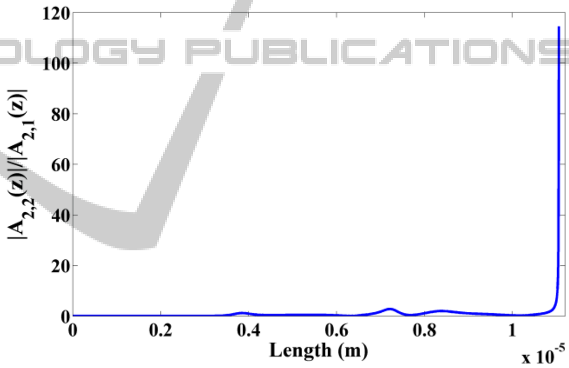
(3b)

Figure 3: (3a) The coupling of amplitude of fundamental and second modes in probe frequency. (3b) The ratio of second mode amplitude to fundamental mode amplitude of probe.

Finally, figure 4 shows a coupling between fundamental and second mode for signal (conjugate) wave due to the non-degenerate four waves mixing and a dynamic gain and refractive index grating. As figure (4a) shows the coupling and mode conversion has been occurred between fundamental and second mode in conjugate frequency (ω_2). Figure (4b) shows the ratio of second mode amplitude to fundamental mode amplitude in this frequency. As this figure shows, this ratio at the end of active region is about 115, and mode purity achieves 99.99 percent.



(4a)



(4b)

Figure 4: (4a) The coupling of amplitude of fundamental and second modes in signal (conjugate) frequency. (4b) The ratio of second mode amplitude to fundamental mode amplitude of signal.

4 CONCLUSIONS

In this paper we demonstrate the efficient mode conversion in TW-SOAs by highly non-degenerate four wave mixing. This flexible mode conversion can be occurred for both probe and conjugate wave by adjusting pump and probe amplitude.

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