Phase-controlled slow and fast light in current-modulated semiconductor optical amplifiers

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Abstract: We present a theoretical study of the slow and fast light propagation in semiconductor optical amplifiers based on coherent population oscillations. By modulating the injection current we control the delay or advancement of light signals.

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1. Introduction

Recent dramatic experimental demonstration of slow and fast light has stimulated considerable interest in the dynamic control of the group velocity of light. Coherent population oscillations (CPOs) have been shown to be a robust physical mechanism which allows for the variation of group velocity. CPO produces a narrow hole in the absorption or gain profile as a consequence of the periodic modulation of the ground state population at the beat frequency between a strong control field and a weak probe field sharing a common atomic transition. Slow and fast light at room temperature originated by CPO has been experimentally observed in solid state crystals [1], erbium doped fibers (EDFs) [2, 3], among others. Slow and fast light in semiconductor optical amplifiers (SOAs) has also been studied extensively in recent years [4], because those such systems have the advantage of providing compactness, easy integration with optical systems, and large bandwidth due to fast carrier dynamics. In the conventional CPO studies in SOAs, the optical beam is modulated in the RF range and delay or advancement of the detected signal is measured depending on the value of the DC bias current (below or above the transparency current). Here, we will analyze the possibility of realization of slow and fast light in a SOA by considering the simultaneous modulation of the optical beam and the bias current in such a medium.

2. Theoretical model of forced population oscillations

A laser field $\mathcal{E}(t)$ with angular frequency ω couples the transition between the semiconductor valence band and the conduction band . The slowly-varying amplitude of the optical field is comprised of a strong control beam E_0 and two sidebands E_1 and E_{-1} separated by the modulation angular frequency δ which lies within the RF range, i.e., $E(t) = E_0(t) + E_1(t)e^{-i\delta t} + E_{-1}(t)e^{i\delta t}$. When this modulated beam goes through the SOA, the three components of the electric field interact with the carriers in the semiconductor through stimulated emission and will impose a modulation on the carrier density due to the frequency beating between the optical waves. The carrier density N attained for a selected bias current I, is obtained by solving the following rate equation:

$$\frac{d\,N}{d\,t} = \frac{I}{qV} - \frac{N}{\tau} - \frac{1}{2} n_{bg} c \epsilon_0 \frac{\alpha\,(N - N_t)}{\hbar\omega} |E(t)|^2\,, \tag{1}$$

where q is the electron charge, V is the active volume, α is the gain cross-section, N_t is the carrier density at which the active region becomes transparent, τ is the carrier lifetime, and n_{bg} is the background refractive index of the material. Here, we will analyze the possibility of improving slow and fast light performance in SOAs by considering the simultaneous modulation of the optical beam and the bias current in such a medium. Both magnitudes are modulated at the same frequency δ and it is assumed that the modulated current could be out of phase with respect to the modulation of the optical weak probe field by a magnitude Ψ, which can be externally changed, $I(t) = I_0 + I_{+1}e^{-i(\delta t - \Psi)} + I_{-1}e^{i(\delta t - \Psi)}$. The feasibility to produce modulations in the bias current in the RF range has been previously addressed from a theoretical point of view [5]. We assume that the carrier density can be described by a DC term and small AC terms modulated at the same beating frequency, i.e., $N(t) = N_0 + N_1 e^{-i\delta t} + N_{-1}e^{i\delta t}$. We arrive at the following equation for the carrier density oscillation:

$$N(t) = N_0 + N_t \left[\frac{R_1 e^{i\Psi} - (N_0/N_t - 1) q_1}{1 + q_0 - i\delta\tau} \, e^{-i\delta t} + c.c. \right] \, , \tag{2}$$

where we have defined the normalized currents $R_{0,\pm 1} = I_{0,\pm 1}\tau/(qVN_t)$, the normalized optical powers $q_0 = (1/2) n_{bg} c\epsilon_0 |E_0|^2/P_{sat}$, $q_1 = (1/2) n_{bg} c\epsilon_0 (E_0^* E_1 + E_0 E_{-1}^*)/P_{sat}$, the saturation power $P_{sat} = \hbar\omega/(\alpha\tau)$, and the static carrier density $N_0 = N_t(R_0 + q_0)/(1 + q_0)$. A close inspection of equation (2) reveals that population oscillation works as a temporal grating whose amplitude depends both on the coupling between the DC and the side-bands of the probe field, and on the modulation term of the injection current R_1. The response of the system to the weak probe field can be obtained by solving the scalar wave equation where the induced polarization is given by [6] $\mathcal{P}(z,t) = -i(c\epsilon_0/\omega)\alpha\,(N(t) - N_t)\,\mathcal{E}(z,t)$. Then, we arrive at the following set of equations for the amplitudes of the optical fields in the SVEA approximation:

$$\begin{aligned}
\frac{\partial E_0}{\partial z} &= \frac{\alpha N_t}{2\omega_c}\left[(R_0-1)E_0 + \frac{\left(\omega_c R_1 e^{i\Psi} - (R_0-1)\,q_1\right)}{\omega_c - i\delta\tau}E_{-1} + \frac{\left(\omega_c R_1 e^{-i\Psi} - (R_0-1)\,q_1^*\right)}{\omega_c + i\delta\tau}E_1\right] \, , \qquad (3)\\
\frac{\partial E_1}{\partial z} &= \frac{\alpha N_t}{2\omega_c}\left[(R_0-1)E_1 - \frac{(R_0-1)\,q_1}{\omega_c - i\delta\tau}E_0 + \frac{\omega_c R_1 e^{i\Psi}}{\omega_c - i\delta\tau}E_0\right] \, ,\\
\frac{\partial E_{-1}}{\partial z} &= \frac{\alpha N_t}{2\omega_c}\left[(R_0-1)E_{-1} - \frac{(R_0-1)\,q_1^*}{\omega_c + i\delta\tau}E_0 + \frac{\omega_c R_1 e^{-i\Psi}}{\omega_c + i\delta\tau}E_0\right] \, ,
\end{aligned}$$

where we have defined the dimensionless frequency $\omega_c = 1 + q_0$ which roughly measures the linewidth of the transparency hole created in the absortion/gain spectrum due to CPO. It is well known that the first two terms appearing in the equation of evolution of the sidebands lead to coherent dips in pump-probe spectroscopy [6]. Here, we should notice that the last term that contributes to the development of the sidebands arises from a net exchange from the DC component of the optical field which in turn arises as a consequence of the modulation of the current (R_1). In the case that $\Psi = 0$, the contribution of this term will produce an in-phase contribution to the index and gain gratings that will result in an enhancement/fall of the CPO depending on the value of the bias current to be below or above the transparency level. In the case that $\Psi = \pi$, it will produce a change that will turn delay into advancement. In the general case that $\Psi \neq 0, \pi$, the last term will result in a mixing of the gain grating and the index grating which is responsible for the enhancement of the phase delay/advancement.

3. Effect of current modulation on the phase delay/advancement

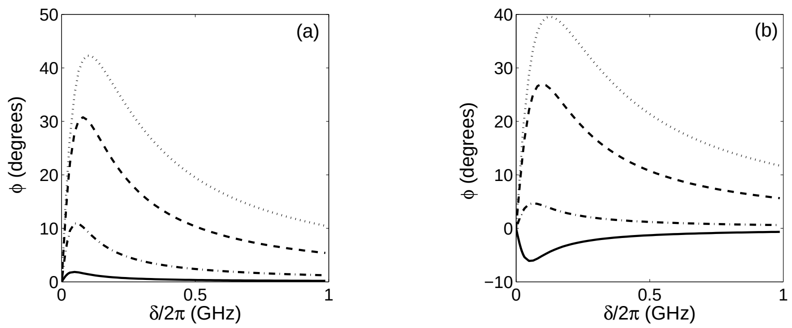

Fig. 1. Phase delay versus the modulation frequency for different values of the modulation depth: $R_1 = 0$ (solid line), $R_1 = 0.01R_0$ (dashed-dotted line), $R_1 = 0.05R_0$ (dashed line), and $R_1 = 0.1R_0$ (dotted line). DC injection current (a) $R_0 = 0.95$ (b) $R_0 = 1.15$. Other parameters are: $q_0 = 0.5$, $q_1 = 0.1 \times q_0$, and $\Psi = 0$.

In this section we will perform numerical simulations concerning the influence of the current modulation on the slow and fast light in a SOA. To illustrate this effect we use the following parameters: $\tau = 5$ ns, $N_t = 1 \times 10^{18}$ cm^{-3}, $\alpha = 2 \times 10^{-16}$ cm^2, $n_{bg} = 3.2$, and the length $L = 0.3$ mm. We present in figure 1(a) the results obtained for the case in which the injection current is below the transparency current ($R_0 < 1$). In this case the overall effect of the modulation current is to produce a huge increase of the maximum phase delay for moderate values of the modulation.

The most remarkable effect is obtained when operating above the threshold injection current ($R_0 > 1$) as it is shown in figure 1(b). There, we appreciate that for a moderate value of the modulation current (dashed-dotted curve) delay is achieved. Thus, the level of modulation of the current allows the control of the level of advancement and to switch from fast to slow light.

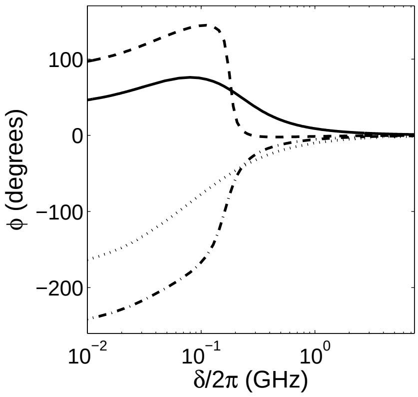

Fig. 2. Phase delay versus the modulation frequency for different values of the relative phase Ψ: $\Psi = 45^0$ (solid line), $\Psi = 100^0$ (dashed line), $\Psi = 120^0$ (dashed-dotted line), $\Psi = 180^0$ (dotted line). Operating point $R_0 = 0.95$, subject to a modulation $R_1 = 0.1R_0$. Other parameters as in figure 1.

In order to show how the relative phase shift of the modulation current to the modulated optical field (Ψ) influences the phase shift ϕ, we plot in figure 2 the phase delay versus the beat frequency for several values of Ψ. We have selected an operating point below the transparency current ($R_0 < 1$). Note that under these circumstances, by solely modifying the AC current (R_1) and by keeping $\Psi = 0$, we remain in the absorptive regime which always produces delay on the optical signal [see figure 1(a)]. However, when the modulation current is fixed while the relative phase is properly changed, a switch from absorption to gain is produced which results in turning delay into advancement of the optical signal. In other words, the phase Ψ may be used as an external parameter to control the magnitude of phase delay/advancement achieved for all the range of frequencies while keeping constant the rest of parameters.

In this work we have presented numerical simulations concerning to the enhancement of the delay/advancement based in CPO in SOA when the bias current is modulated at the same beating frequency. The depth of the modulation, and the reference phase are shown to have a dramatic influence on the magnitude of the phase delay.
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