

Analytical Characterization of Optical Pulse Propagation in Polarization-Sensitive Semiconductor Optical Amplifiers

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Abstract—In this paper, we perform analytical characterization of optical pulses propagating through a polarization-sensitive semiconductor optical amplifier (SOA). We derive analytical expressions for the carrier density, gain and phase evolution along the SOA and show how these expressions prove useful in optical signal processing applications. The propagation of counter-propagating pulses as well as pulse streams across SOAs have been analysed and expressions for energy gain have been derived in all these cases. We also show that our analytical results reduce to corresponding results of polarization insensitive SOAs already published. The analytical results are in excellent agreement with detailed numerical simulations done in MATLAB using the NIMROD portal. The analytical calculations lead to significant savings with regard to simulation time and processing capacity requirements. We further prove that the energy gain difference for counter-propagating pulse streams is directly proportional to the difference delay between in them and hence can be used as a measure of the delay difference. This theoretical result agrees well with experimental results.

Index Terms—Analytical results, polarization sensitivity, semiconductor optical amplifier (SOA).

I. INTRODUCTION

OPTICAL signal processing based on polarization rotation in strained bulk semiconductor optical amplifiers (SOAs) has recently attracted a lot of attention from researchers

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[1]–[10]. In such SOAs, the dependence of the polarization sensitivity on the wavelength and the gain can be varied by varying the tensile strain [11], [12]. It has been shown that error-free inverted and noninverted wavelength conversion at data-rates up to 10 Gb/s can be realized using this phenomenon [13]. A mode-locking scheme has been proposed in [3] in which an initially broad pulse is shortened using polarization rotation in SOAs. Self-induced polarization rotation in SOAs has been used to build an all-optical header processing system, an all-optical seed pulse generator for packet synchronization, and an all-optical arbiter that finds application in optical buffering [4]. Polarization switches based on this phenomenon are of great use in all-optical logic implementations. An all-optical XOR gate based on cross-polarization modulation is described in [5]. In [10], an all-optical flip-flop memory based on two coupled nonlinear polarization switches has been proposed. An all-optical label and payload separator based on nonlinear polarization rotation in a SOA has been demonstrated, in which the separation is obtained by using the constant power differential phase-shift keying (DPSK) modulated payload signal as a pumping light source [6]. This phenomenon can also be used to erase the intensity modulated label super-imposed on the high-speed angle modulated payload in optical label switching packet networks [7] as well as for suppression of waveform distortion caused when an SOA is used for amplification [8]. Fig. 1(a) shows the polarization sensitive SOA based power equalizer, which we have analyzed in detail in [9].

In [14], the polarization dependent gain in semiconductor lasers is numerically studied by solving the equation of motion for the density matrix in a semi-classical manner. However, this model has limited practical applications as a design-tool for optical switching configurations. The numerical model used in our paper is based on the decomposition of the polarized optical field in a polarization sensitive SOA into a transverse electric (TE) and transverse magnetic (TM) component [15]. In a SOA with a rectangular active layer structure, the confinement factor of the TE polarization is larger than that of TM polarization. However, this difference, and hence the polarization sensitivity, is varied by introducing a small tensile-strain into the active layer [16]. The tensile strain built into the bulk medium causes TM to be favoured over TE transitions. In [15], this asymmetry between the two transition types is modeled by introducing a population imbalance factor f . The TE and TM modes interact

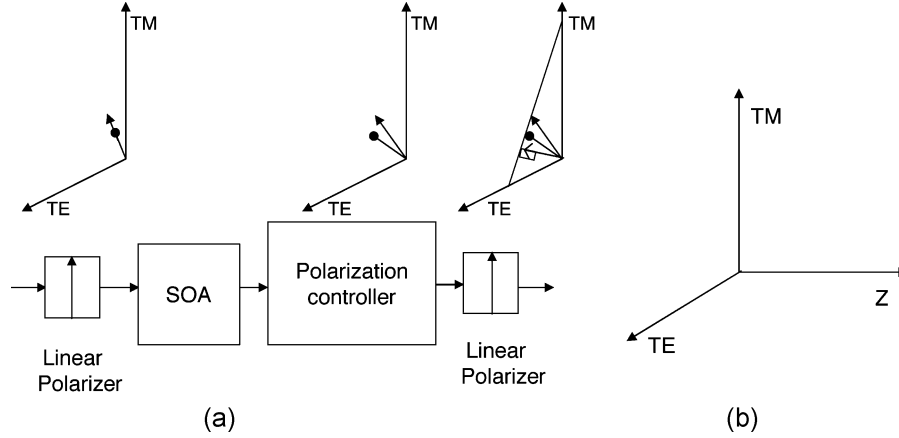


Fig. 1. a) SOA based power equalizer. High and low level input signals are represented by lines ending with •, ▲ respectively. Line ending with Λ represents the output signal. The elliptically polarized output signal from the SOA is linearized by using the polarization controller after the SOA b) Coordinate convention followed in the paper.

with each other indirectly via the gain saturation but otherwise propagate independently [15].

Numerical models that are in excellent agreement with obtained experimental results have been developed for polarization rotation in SOAs [4], [15]. The objective of this paper is to derive simple analytical expressions for polarization rotation that can give us a deep insight into the phenomenon without depending on time-consuming numerical simulations. The obtained expressions for carrier density, gain and phase evolution will find application in estimating the output power when a bulk-strained polarization sensitive SOA is used for optical signal processing applications such as power equalization [9], wavelength conversion [2] or amplification with reduction in waveform distortion [8] for optical pulses. In [17], Premaratne *et al.* have derived expressions for the longitudinal carrier-density evolution and the related optical-gain response in a polarization insensitive optical amplifier. In Section II, we use a similar approach as in [17] to analyze carrier-density, phase and gain evolution in a birefringent SOA for optical pulses while clearly mentioning the approximations involved. We also show how these equations reduce to the corresponding equations obtained in [17] for a polarization insensitive SOA. We further demonstrate how these expressions can be used to emulate polarization rotation and hence calculate the output power of a polarization sensitive SOA. These expressions are then extended to the case when two counter-propagating pulses or pulse streams propagate along the SOA and the energy gain calculated analytically in all these cases. This analysis is useful when the SOA is used for synchronization or distance measurement applications.

Numerical simulations in MATLAB using the model in [15] are performed in Section III. Here, we have shown that the analytical results closely match the values obtained through numerical integration. We further show that the energy gain difference for counter-propagating identical pulse streams is directly proportional to the delay difference between them and this result obtained using analytical expressions is verified by simulation results. In Section IV, we describe an experiment in which counter-propagating pulse streams were incident on a SOA. It is observed that the power difference for similar counter-prop-

agating pulse streams is directly proportional to the delay difference between them when the pulse streams do not overlap. This observation further confirms the validity of our analytical expressions. Finally, Section V summarizes the main results of this paper.

II. APPROXIMATE ANALYSIS

This paper uses the coordinate conventions in Fig. 1(b). Optical transitions between conduction band and valence band states in the SOA structure with x , y , and z polarizations can occur in principle. Since the optical field is propagating in the z -direction here, transitions with z -polarization do not occur. The remaining two transitions with x - and y -polarizations correspond to TE and TM polarization eigenmodes, respectively, and these two transitions define two relevant hole reservoirs with corresponding numbers $N_x(z, t)$ and $N_y(z, t)$, respectively [15]. Let us assume that $H_{T_w}(t)$ is the intensity profile of a optical pulse linearly polarized at an angle θ with a full-width at half maximum (FWHM) of T_w , carrier-recovery lifetime τ_e and energy E_g

$$E_g = A \int_{-\infty}^{\infty} H_{T_w}(t) dt \quad (1)$$

where A is the cross-sectional area of the active region. The intensity profile $H_{T_w, \text{TE}}(t)$, $H_{T_w, \text{TM}}(t)$ incident on TE and TM axes is given as

$$H_{T_w, \text{TE}}(t) = H_{T_w}(t) \cos^2 \theta \quad (2)$$

$$H_{T_w, \text{TM}}(t) = H_{T_w}(t) \sin^2 \theta. \quad (3)$$

The difference in group velocity v_g along TE and TM axes is of the order of 1% and hence it need not be accounted for in case of an amplifier that is not too long [19]. From [15], the dynamic response of the SOA along TE and TM axes is given by

$$\begin{aligned} \frac{\partial}{\partial z} I^{\text{TE}}(z, t) + \frac{1}{v_g} \frac{\partial}{\partial z} I^{\text{TE}}(z, t) \\ = g^{\text{TE}}(z, t) I^{\text{TE}}(z, t) - \alpha^{\text{TE}} I^{\text{TE}}(z, t) \end{aligned} \quad (4)$$

$$\frac{\partial}{\partial t} N_x(z, t) = \wp_x - \frac{N_x(z, t)}{\tau_e} - g^{\text{TE}}(z, t) \frac{\lambda I^{\text{TE}}(z, t)}{hc} \quad (5)$$

$$\frac{\partial}{\partial z} I^{\text{TM}}(z, t) + \frac{1}{v_g} \frac{\partial}{\partial z} I^{\text{TM}}(z, t) = g^{\text{TM}}(z, t) I^{\text{TM}}(z, t) - \alpha^{\text{TM}} I^{\text{TM}}(z, t) \quad (6)$$

$$\frac{\partial}{\partial t} N_y(z, t) = \wp_y - \frac{N_y(z, t)}{\tau_e} - g^{\text{TM}}(z, t) \frac{\lambda I^{\text{TM}}(z, t)}{hc} \quad (7)$$

where z is distance measured along the SOA, t is time, $I^{\text{TE}}(z, t)$, $I^{\text{TM}}(z, t)$ are the intensities for the TE and TM-polarized electric field components, α^{TE} and α^{TM} are the loss coefficients for the TE and TM electric field components, λ is the mean operating wavelength, h is Planck's constant, and c is the speed of light in vacuum. Here, $N_x(z, t)$ and $N_y(z, t)$ denote the number of holes involved in the x and y transitions and N_0 is the total number of electronic states involved. Assuming that total number of holes equal to the number of electrons, we can write

$$g^{\text{TE}}(z, t) = \Gamma^{\text{TE}} a^{\text{TE}} [2N_x(z, t) + N_y(z, t) - N_0] \quad (8)$$

$$g^{\text{TM}}(z, t) = \Gamma^{\text{TM}} a^{\text{TM}} [2N_y(z, t) + N_x(z, t) - N_0] \quad (9)$$

where Γ^{TE} and Γ^{TM} are the TE and TM confinement factors, and a^{TE} and a^{TM} are the TE and TM gain coefficients. Our analysis is limited to situations not involving ultrafast dynamics and so $N_x(z, t)$ and $N_y(z, t)$ can be assumed to be tightly coupled together [15]. Let equilibrium values of carrier density be $\bar{N}_x$, $\bar{N}_y$

$$\bar{N}_x = f \bar{N}_y. \quad (10)$$

Here f is the population imbalance factor, which is used to model the asymmetry between TE and TM transitions [15]. This implies

$$\wp_x = \frac{\bar{N}_x}{\tau_e} = \frac{\bar{N}f}{\tau_e(1+f)} \quad (11)$$

$$\wp_y = \frac{\bar{N}_y}{\tau_e} = \frac{\bar{N}}{\tau_e(1+f)} \quad (12)$$

$$\text{where } \bar{N} = \frac{I}{qV}. \quad (13)$$

Here I is the input current, q is the electronic charge and V is the device volume. For ease of analysis, the reference frame is changed to a moving coordinate system that is moving along with the forward propagating pulse. The delayed time coordinate τ is centered on the arrival time of the pulse at each plane ξ along the amplifier. Hence

$$\xi = z; \quad \tau = t - \frac{z}{v_g}. \quad (14)$$

Using these transformations, the following two differential operators are obtained for time and spatial derivatives:

$$\frac{\partial}{\partial z} = \frac{\partial}{\partial \xi} - \frac{1}{v_g} \frac{\partial}{\partial \tau}; \quad \frac{\partial}{\partial t} = \frac{\partial}{\partial \tau}. \quad (15)$$

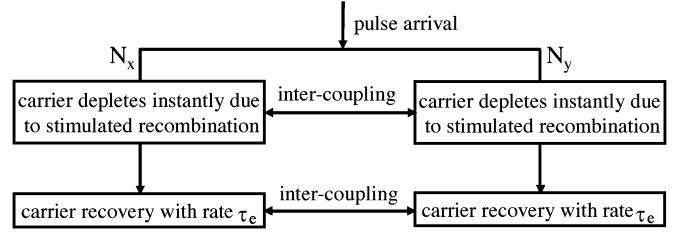


Fig. 2. Illustration of model carrier-density evolution in a polarization-sensitive SOA when $T_w \ll \tau_e$.

These transformations, when substituted in (4)–(7), result in significantly simpler forms of the equations as

$$\frac{\partial}{\partial \xi} I^{\text{TE}}(\xi, \tau) = g^{\text{TE}}(\xi, \tau) I^{\text{TE}}(\xi, \tau) - \alpha^{\text{TE}} I^{\text{TE}}(\xi, \tau) \quad (16)$$

$$\frac{\partial}{\partial \tau} N_x(\xi, \tau) = \wp_x - \frac{N_x(\xi, \tau)}{\tau_e} - g^{\text{TE}}(\xi, \tau) \frac{\lambda I^{\text{TE}}(\xi, \tau)}{hc} \quad (17)$$

$$\frac{\partial}{\partial \xi} I^{\text{TM}}(\xi, \tau) = g^{\text{TM}}(\xi, \tau) I^{\text{TM}}(\xi, \tau) - \alpha^{\text{TM}} I^{\text{TM}}(\xi, \tau) \quad (18)$$

$$\frac{\partial}{\partial \tau} N_y(\xi, \tau) = \wp_y - \frac{N_y(\xi, \tau)}{\tau_e} - g^{\text{TM}}(\xi, \tau) \frac{\lambda I^{\text{TM}}(\xi, \tau)}{hc}. \quad (19)$$

In this paper, we aim to find analytical solution to this set of equations. Let us initially limit our analysis to pulses that are significantly narrower than the carrier-recovery lifetime, i.e., $T_w \ll \tau_e$. Later in this section, we look at what happens when this assumption is relaxed. Here, we assume that stimulated emission induced carrier depletion by a short pulse can be considered instantaneous [17], [18], [20]. Thus, when the pulse arrives, the carrier density $N_x(z, t)$, $N_y(z, t)$ deplete instantly with no time for the gain to recover. While this happens, there is indirect interaction between the TE and TM modes via the carriers. After the pulse has passed through influencing stimulated emission, the depleted carrier density replenishes with a time constant τ_e . As before, there is inter-coupling between TE and TM modes due to the carriers. We illustrate the whole process in Fig. 2. Applying this to (17) and (19), we get

$$\frac{\partial}{\partial \tau} N_x(\xi, \tau) = -g^{\text{TE}}(\xi, \tau) \frac{\lambda I^{\text{TE}}(\xi, \tau)}{hc} \quad (20)$$

$$\frac{\partial}{\partial \tau} N_y(\xi, \tau) = -g^{\text{TM}}(\xi, \tau) \frac{\lambda I^{\text{TM}}(\xi, \tau)}{hc}. \quad (21)$$

Differentiating (9) with respect to τ

$$\frac{\partial}{\partial \tau} g^{\text{TM}}(\xi, \tau) = \Gamma^{\text{TM}} a^{\text{TM}} \left[\frac{\partial}{\partial \tau} N_x(\xi, \tau) + 2 \frac{\partial}{\partial \tau} N_y(\xi, \tau) \right]. \quad (22)$$

Substituting (20) and (21) in (22) gives

$$\frac{\partial}{\partial \tau} g^{\text{TM}}(\xi, \tau) = -\frac{\Gamma^{\text{TM}} a^{\text{TM}} \lambda}{hc} \times [g^{\text{TE}}(\xi, \tau) I^{\text{TE}}(\xi, \tau) + 2g^{\text{TM}}(\xi, \tau) I^{\text{TM}}(\xi, \tau)]. \quad (23)$$

Solving (16) and (18), we get the following expressions for the intensities corresponding to TE and TM modes along the SOA:

$$I^{\text{TE}}(\xi, \tau) = H_{T_w, \text{TE}}(\tau) G^{\text{TE}}(\xi, \tau) \quad (24)$$

$$I^{\text{TM}}(\xi, \tau) = H_{T_w, \text{TM}}(\tau) G^{\text{TM}}(\xi, \tau) \quad (25)$$

where $G^{\text{TE}}(\xi, \tau)$ and $G^{\text{TM}}(\xi, \tau)$ are given by

$$G^{\text{TE}}(\xi, \tau) = \exp \left(-\alpha^{\text{TE}} \xi + \int_0^\xi g^{\text{TE}}(\xi, \tau) d\xi \right) \quad (26)$$

$$G^{\text{TM}}(\xi, \tau) = \exp \left(-\alpha^{\text{TM}} \xi + \int_0^\xi g^{\text{TM}}(\xi, \tau) d\xi \right). \quad (27)$$

Physically, $G^{\text{TE}}(\xi, \tau)$ and $G^{\text{TM}}(\xi, \tau)$ represent the effective integrated gain corresponding to TE and TM modes at each point of the pulse profile. By making the coordinate transformation, we are thus able to represent the output signal from the SOA corresponding to TE and TM modes as exponentially amplified versions of the input signal components along TE and TM axis. However, it should be noted that the output pulse will be delayed in real time with respect to the input pulse by the time L/v_g it takes to transit through the amplifier. Taking the logarithm of (26) and (27) and differentiating with respect to τ , we get

$$\frac{1}{G^{\text{TM}}(\xi, \tau)} \frac{\partial}{\partial \tau} G^{\text{TM}}(\xi, \tau) = \frac{\partial}{\partial \tau} \int_0^\xi g^{\text{TM}}(\xi, \tau) d\xi. \quad (28)$$

Substituting (23) in (28) yields

$$\begin{aligned} \frac{1}{G^{\text{TM}}(\xi, \tau)} \frac{\partial}{\partial \tau} G^{\text{TM}}(\xi, \tau) &= -\frac{\Gamma^{\text{TM}} a^{\text{TM}} \lambda}{hc} \\ &\times \int_0^\xi [g^{\text{TE}}(\xi, \tau) I^{\text{TE}}(\xi, \tau) + 2g^{\text{TM}}(\xi, \tau) I^{\text{TM}}(\xi, \tau)] d\xi. \end{aligned} \quad (29)$$

After substituting (16), (18), (24), and (25) in (29) and integrating with respect to ξ , we get

$$\begin{aligned} \frac{\partial}{\partial \tau} \ln(G^{\text{TM}}(\xi, \tau)) &= -\frac{\Gamma^{\text{TM}} a^{\text{TM}} \lambda}{hc} \\ &\times \left(H_{T_w, \text{TE}}(\tau) (G^{\text{TE}}(\xi, \tau) - 1) + \int_0^\xi \alpha^{\text{TE}} I^{\text{TE}}(\xi, \tau) d\xi \right. \\ &\quad \left. + 2H_{T_w, \text{TM}}(\tau) (G^{\text{TM}}(\xi, \tau) - 1) + 2 \int_0^\xi \alpha^{\text{TM}} I^{\text{TM}}(\xi, \tau) d\xi \right) \end{aligned} \quad (30)$$

In order to evaluate the integral, we make the assumption, to be relaxed later, that differential gain is uniform along the SOA [17]. This implies there exists uniform gain coefficients $\bar{g}^{\text{TE}}$, $\bar{g}^{\text{TM}}$, such that $G^{\text{TE}}(\xi, \tau) \approx \exp(\bar{g}^{\text{TE}} \xi - \alpha^{\text{TE}} \xi)$ and $G^{\text{TM}}(\xi, \tau) \approx \exp(\bar{g}^{\text{TM}} \xi - \alpha^{\text{TM}} \xi)$. Using (2), (3), (24), and (25), we obtain the following approximate expressions for the

pulse intensities corresponding to TE and TM modes along the SOA:

$$\int_0^\xi I^{\text{TE}}(\xi, \tau) d\xi \approx \frac{H_{T_w}(\tau) \cos^2(\theta)}{\bar{g}^{\text{TE}} - \alpha^{\text{TE}}} (G^{\text{TE}}(\xi, \tau) - 1) \quad (31)$$

$$\int_0^\xi I^{\text{TM}}(\xi, \tau) d\xi \approx \frac{H_{T_w}(\tau) \sin^2(\theta)}{\bar{g}^{\text{TM}} - \alpha^{\text{TM}}} (G^{\text{TM}}(\xi, \tau) - 1). \quad (32)$$

Let Δg be the difference between the uniform TE and TM gain coefficients. We use $\Delta \alpha$ to represent the difference between the loss coefficients corresponding to TE and TM modes. Now, substituting (31) and (32) in (30), we get

$$\begin{aligned} \frac{\partial}{\partial \tau} \ln(G^{\text{TM}}(\xi, \tau)) &= -\frac{\Gamma^{\text{TM}} a^{\text{TM}} \lambda}{hc} H_{T_w}(\tau) \\ &\times \left(\frac{\bar{g}^{\text{TE}} \cos^2(\theta)}{\bar{g}^{\text{TE}} - \alpha^{\text{TE}}} (G^{\text{TM}}(\xi, \tau) \exp(\Delta \bar{g} \xi - \Delta \alpha \xi) - 1) \right. \\ &\quad \left. + \frac{2\bar{g}^{\text{TM}} \sin^2(\theta)}{\bar{g}^{\text{TM}} - \alpha^{\text{TM}}} (G^{\text{TM}}(\xi, \tau) - 1) \right) \end{aligned} \quad (33)$$

$$\Delta g = \bar{g}^{\text{TE}} - \bar{g}^{\text{TM}}$$

$$\Delta \alpha = \alpha^{\text{TE}} - \alpha^{\text{TM}} \quad (34)$$

Rearranging, this can be written as

$$\begin{aligned} \frac{\partial}{\partial \tau} \ln(G^{\text{TM}}(\xi, \tau)) &= f^{\text{TM}}(\xi) H_{T_w}(\tau) (G^{\text{TM}}(\xi, \tau) - \Re^{\text{TM}}(\xi)) \\ f^{\text{TM}}(\xi) &= -\frac{\Gamma^{\text{TM}} a^{\text{TM}} \lambda}{hc} \left(\frac{\bar{g}^{\text{TE}} \cos^2(\theta)}{\bar{g}^{\text{TE}} - \alpha^{\text{TE}}} \exp(\Delta \bar{g} \xi - \Delta \alpha \xi) \right. \end{aligned} \quad (35)$$

$$\left. + \frac{2\bar{g}^{\text{TM}} \sin^2(\theta)}{\bar{g}^{\text{TM}} - \alpha^{\text{TM}}} \right) \quad (36)$$

$$\begin{aligned} \Re^{\text{TM}}(\xi) &= \frac{2 + g_{\text{ratio}}}{2 + g_{\text{ratio}} \exp(\Delta \bar{g} \xi - \Delta \alpha \xi)} \end{aligned} \quad (37)$$

$$\begin{aligned} g_{\text{ratio}} &= \frac{\bar{g}^{\text{TE}} \bar{g}^{\text{TM}} - \alpha^{\text{TM}}}{\bar{g}^{\text{TM}} \bar{g}^{\text{TE}} - \alpha^{\text{TE}}} \cot^2(\theta). \end{aligned} \quad (38)$$

After manipulating algebraically, this becomes

$$\frac{\partial}{\partial \tau} \left(\ln \frac{G^{\text{TM}}(\xi, \tau)}{G^{\text{TM}}(\xi, \tau) - \Re^{\text{TM}}(\xi)} \right) = -f^{\text{TM}}(\xi) \Re^{\text{TM}}(\xi) H_{T_w}(\tau). \quad (39)$$

Now, we integrate this expression with respect to τ . Let us refer to the gain before the arrival of the pulse as $G_{\text{init}}^{\text{TM}}$ and just after it influences stimulated emission as $G_{\text{final}}^{\text{TM}}$. On rearranging the result of integration, we get

$$G_{\text{final}}^{\text{TM}}(\xi) = \frac{\Re^{\text{TM}}(\xi) G_{\text{init}}^{\text{TM}}(\xi)}{\Re^{\text{TM}}(\xi) g_{\text{init}}^{\text{TM}} + G_{\text{init}}^{\text{TM}}(\xi) (1 - g_{\text{init}}^{\text{TM}})} \quad (40)$$

$$\mathbf{g}_{\text{init}}^{\text{TM}} = \exp\left(\frac{\Gamma^{\text{TM}} a^{\text{TM}} \lambda E_g}{hcA} \times \left(\frac{\bar{g}^{\text{TE}} \cos^2(\theta)}{\alpha^{\text{TE}} - \bar{g}^{\text{TE}}} + \frac{2\bar{g}^{\text{TM}} \sin^2(\theta)}{\alpha^{\text{TM}} - \bar{g}^{\text{TM}}}\right)\right) \quad (41)$$

Similarly, for the TE component of the optical field, we get

$$\frac{\partial}{\partial \tau} \left(\ln \frac{G^{\text{TE}}(\xi, \tau)}{G^{\text{TE}}(\xi, \tau) - \Re^{\text{TE}}(\xi)} \right) = -f^{\text{TE}}(\xi) \Re^{\text{TE}}(\xi) H_{T_w}(\tau). \quad (42)$$

The different terms used in this expression have been described below

$$f^{\text{TE}}(\xi) = -\frac{\Gamma^{\text{TE}} a^{\text{TE}} \lambda}{hc} \times \left(\frac{2\bar{g}^{\text{TE}} \cos^2(\theta)}{\bar{g}^{\text{TE}} - \alpha^{\text{TE}}} + \frac{\bar{g}^{\text{TM}} \sin^2(\theta)}{\bar{g}^{\text{TM}} - \alpha^{\text{TM}}} \exp(\Delta\alpha\xi - \Delta\bar{g}\xi) \right) \quad (43)$$

$$\Re^{\text{TE}}(\xi) = \frac{2g_{\text{ratio}} + 1}{2g_{\text{ratio}} + \exp(\Delta\alpha\xi - \Delta\bar{g}\xi)}. \quad (44)$$

Similar to what was done for the TM mode, we integrate this expression with respect to τ and then rearrange the result to get

$$G_{\text{final}}^{\text{TE}}(\xi) = \frac{\Re^{\text{TE}}(\xi) G_{\text{init}}^{\text{TE}}(\xi)}{\Re^{\text{TE}}(\xi) \mathbf{g}_{\text{init}}^{\text{TE}} + G_{\text{init}}^{\text{TE}}(\xi) (1 - \mathbf{g}_{\text{init}}^{\text{TE}})} \quad (45)$$

$$\mathbf{g}_{\text{init}}^{\text{TE}} = \exp\left(\frac{\Gamma^{\text{TE}} a^{\text{TE}} \lambda E_g}{hcA} \times \left(\frac{2\bar{g}^{\text{TE}} \cos^2(\theta)}{\alpha^{\text{TE}} - \bar{g}^{\text{TE}}} + \frac{\bar{g}^{\text{TM}} \sin^2(\theta)}{\alpha^{\text{TM}} - \bar{g}^{\text{TM}}}\right)\right) \quad (46)$$

Taking the logarithm of (26) and (27) and substituting (8) and (9), we can represent the carrier distribution along the SOA due to $G_{\text{final}}^{\text{TE}}$ and $G_{\text{final}}^{\text{TM}}$ as

$$\frac{\ln(G_{\text{final}}^{\text{TE}}(\xi)) + \alpha^{\text{TE}}\xi}{\Gamma^{\text{TE}} a^{\text{TE}}} + N_0\xi = \int_0^\xi (2N_{x,f}(\xi) + N_{y,f}(\xi)) d\xi \quad (47)$$

$$\frac{\ln(G_{\text{final}}^{\text{TM}}(\xi)) + \alpha^{\text{TM}}\xi}{\Gamma^{\text{TM}} a^{\text{TM}}} + N_0\xi = \int_0^\xi (2N_{y,f}(\xi) + N_{x,f}(\xi)) d\xi. \quad (48)$$

Here, $N_{x,f}(\xi)$ and $N_{y,f}(\xi)$ correspond to the carrier densities $N_x(\xi, \tau)$ and $N_y(\xi, \tau)$, respectively, just after the arrival of the pulse and its influence on stimulated emission. Solving the above given two equations, we get

$$\frac{2(\ln(G_{\text{final}}^{\text{TM}}(\xi)) + \alpha^{\text{TM}}\xi)}{3\Gamma^{\text{TM}} a^{\text{TM}}} - \frac{\ln(G_{\text{final}}^{\text{TE}}(\xi)) + \alpha^{\text{TE}}\xi}{3\Gamma^{\text{TE}} a^{\text{TE}}} + \frac{N_0\xi}{3} = \int_0^\xi N_{y,f}(\xi) d\xi \quad (49)$$

Let $N_{x\text{init}}(\xi)$ and $N_{y\text{init}}(\xi)$ represent the carrier densities $N_x(\xi, \tau)$ and $N_y(\xi, \tau)$, respectively, just before the arrival of the pulse. Differentiating (49) with regard to ξ and rearranging after substituting (40) and (45)

$$N_{y,f}(\xi) = N_{y\text{init}}(\xi) - \frac{2}{3}N_{\text{diff}}^{\text{TM}}(\xi) + \frac{1}{3}N_{\text{diff}}^{\text{TE}}(\xi) \quad (50)$$

$$N_{\text{diff}}^{\text{TM}}(\xi) = N_{\text{unpol}}^{\text{TM}}(\xi) + N_{\text{pol}}^{\text{TM}}(\xi) \quad (51)$$

$$N_{\text{diff}}^{\text{TE}}(\xi) = N_{\text{unpol}}^{\text{TE}}(\xi) + N_{\text{pol}}^{\text{TE}}(\xi). \quad (52)$$

Here, we get (53)–(56), shown at the bottom of the page. It can be shown that $N_{\text{unpol}}^{\text{TM}}(\xi)$ and $N_{\text{unpol}}^{\text{TE}}(\xi)$ reduce to the corresponding term in a polarization insensitive SOA. Also, in a polarization insensitive SOA, $N_{\text{pol}}^{\text{TM}}(\xi) = 0$ and $N_{\text{pol}}^{\text{TE}}(\xi) = 0$. Similarly, it can be proved that

$$N_{x,f}(\xi) = N_{x\text{init}}(\xi) - \frac{2}{3}N_{\text{diff}}^{\text{TE}}(\xi) + \frac{1}{3}N_{\text{diff}}^{\text{TM}}(\xi). \quad (57)$$

It should be noted that for pulses of high intensity, a^{TE} and a^{TM} should be corrected for saturation due to carrier heating [15]. However, to make our problem analytically tractable, we have omitted this in our formulation and so our analytical expressions are not valid for very high intensity pulses (see [17]).

$$N_{\text{unpol}}^{\text{TM}}(\xi) = \frac{\left(2N_{y\text{init}}(\xi) + N_{x\text{init}}(\xi) - N_0 - \frac{\alpha^{\text{TM}}}{\Gamma^{\text{TM}} a^{\text{TM}}}\right)}{\frac{\Re^{\text{TM}}(\xi) \mathbf{g}_{\text{init}}^{\text{TM}}}{G_{\text{init}}^{\text{TM}}(\xi)(1 - \mathbf{g}_{\text{init}}^{\text{TM}})} + 1} \quad (53)$$

$$N_{\text{pol}}^{\text{TM}}(\xi) = \frac{(\Delta\bar{g} - \Delta\alpha)}{\Gamma^{\text{TM}} a^{\text{TM}} \left(\frac{2}{g_{\text{ratio}} \exp((\Delta\bar{g} - \Delta\alpha)\xi)} + 1 \right) \left(\frac{\Re^{\text{TM}}(\xi) \mathbf{g}_{\text{init}}^{\text{TM}}}{G_{\text{init}}^{\text{TM}}(\xi)(1 - \mathbf{g}_{\text{init}}^{\text{TM}})} + 1 \right)} \quad (54)$$

$$N_{\text{unpol}}^{\text{TE}}(\xi) = \frac{\left(2N_{x\text{init}}(\xi) + N_{y\text{init}}(\xi) - N_0 - \frac{\alpha^{\text{TE}}}{\Gamma^{\text{TE}} a^{\text{TE}}}\right)}{\frac{\Re^{\text{TE}}(\xi) \mathbf{g}_{\text{init}}^{\text{TE}}}{G_{\text{init}}^{\text{TE}}(\xi)(1 - \mathbf{g}_{\text{init}}^{\text{TE}})} + 1} \quad (55)$$

$$N_{\text{pol}}^{\text{TE}}(\xi) = -\frac{(\Delta\bar{g} - \Delta\alpha)}{\Gamma^{\text{TE}} a^{\text{TE}} (2g_{\text{ratio}} \exp((\Delta\bar{g} - \Delta\alpha)\xi) + 1) \left(\frac{\Re^{\text{TE}}(\xi) \mathbf{g}_{\text{init}}^{\text{TE}}}{G_{\text{init}}^{\text{TE}}(\xi)(1 - \mathbf{g}_{\text{init}}^{\text{TE}})} + 1 \right)} \quad (56)$$

A. Time-Evolution of SOA Gain

We now return to the laboratory co-ordinate system for ease of analysis. Since $\xi = z$ in (14), (50), and (57) remains unchanged. From [17], the carriers in the SOA will replenish by injection, at a rate governed by the carrier recovery life-time, once carrier depletion has taken place. We can neglect the stimulated recombination terms in (5) and (7) for this gain recovery period [21]. Thus, we can write

$$\frac{\partial}{\partial t} N_x(z, t) = \wp_x - \frac{N_x(z, t)}{\tau_e} \quad (58)$$

$$\frac{\partial}{\partial t} N_y(z, t) = \wp_y - \frac{N_y(z, t)}{\tau_e}. \quad (59)$$

We solve these two equations with the initial conditions $N_x(z, 0) = N_{x,f}(z)$ and $N_y(z, 0) = N_{y,f}(z)$ to get

$$N_x(z, t) = \tau_e \wp_x \left(1 - \exp\left(-\frac{t}{\tau_e}\right) \right) + N_{x,f}(z) \exp\left(-\frac{t}{\tau_e}\right) \quad (60)$$

$$N_y(z, t) = \tau_e \wp_y \left(1 - \exp\left(-\frac{t}{\tau_e}\right) \right) + N_{y,f}(z) \exp\left(-\frac{t}{\tau_e}\right). \quad (61)$$

Now, we evaluate the modal gain of the SOA along TM axes. Using (60) and (61) in (27) and rearranging, we get

$$G^{\text{TM}}(z, t) = G_{\text{ref}}^{\text{TM}}(z) \left(\frac{G_{\text{final}}^{\text{TM}}(z)}{G_{\text{ref}}^{\text{TM}}(z)} \right)^{\exp(-\frac{t}{\tau_e})} \quad (62)$$

$$G_{\text{ref}}^{\text{TM}}(z) = \exp\left(-\alpha^{\text{TM}} z + \Gamma^{\text{TM}} a^{\text{TM}} \tau_e (2\wp_y + \wp_x) z - \Gamma^{\text{TM}} a^{\text{TM}} N_0 z\right). \quad (63)$$

Here, $G_{\text{final}}^{\text{TM}}$ is given by (40). Similarly, in terms of $G_{\text{final}}^{\text{TE}}$ [given by (45)], we can express modal gain of the SOA along the TE axes as

$$G^{\text{TE}}(z, t) = G_{\text{ref}}^{\text{TE}}(z) \left(\frac{G_{\text{final}}^{\text{TE}}(z)}{G_{\text{ref}}^{\text{TE}}(z)} \right)^{\exp(-\frac{t}{\tau_e})} \quad (64)$$

$$G_{\text{ref}}^{\text{TE}}(z) = \exp\left(-\alpha^{\text{TE}} z + \Gamma^{\text{TE}} a^{\text{TE}} \tau_e (2\wp_x + \wp_y) z - \Gamma^{\text{TE}} a^{\text{TE}} N_0 z\right). \quad (65)$$

The total gain of the SOA then assumes the form

$$G(z, t) = G^{\text{TE}}(z, t) \cos^2(\theta) + G^{\text{TM}}(z, t) \sin^2(\theta). \quad (66)$$

Thus, we have derived an expression for the modal gain along the SOA output for a linearly polarized input pulse. This expression will be used for calculation of output power from the amplifier in later sections.

B. Time-Evolution of Phase Difference Between TE and TM Axes

The nonlinear phase evolution of TE and TM mode can be expressed as [15]

$$\frac{\partial}{\partial z} \Phi^{\text{TE}}(z, t) = \frac{1}{2} \alpha_{\text{phase}}^{\text{TE}} g^{\text{TE}}(z, t) \quad (67)$$

$$\frac{\partial}{\partial z} \Phi^{\text{TM}}(z, t) = \frac{1}{2} \alpha_{\text{phase}}^{\text{TM}} g^{\text{TM}}(z, t). \quad (68)$$

Here, $\alpha_{\text{phase}}^{\text{TE}}$ and $\alpha_{\text{phase}}^{\text{TM}}$ are the phase modulation coefficients. Integrating (67) and (68) with respect to z and substituting (26) and (27), we can write

$$\Phi^{\text{TE}}(z, t) = \frac{1}{2} \alpha_{\text{phase}}^{\text{TE}} (\ln(G^{\text{TE}}(z, t)) + \alpha^{\text{TE}} z) \quad (69)$$

$$\Phi^{\text{TM}}(z, t) = \frac{1}{2} \alpha_{\text{phase}}^{\text{TM}} (\ln(G^{\text{TM}}(z, t)) + \alpha^{\text{TM}} z). \quad (70)$$

Hence, using (69) and (70), the phase difference between TE and TM modes $\Phi_{\text{diff}}(z, t)$ can be expressed as

$$\begin{aligned} \Phi_{\text{diff}}(z, t) &= \Phi^{\text{TE}}(z, t) - \Phi^{\text{TM}}(z, t) \\ &= \ln \left(\frac{(G^{\text{TE}}(z, t) \exp(\alpha^{\text{TE}} z))^{\frac{\alpha_{\text{phase}}^{\text{TE}}}{2}}}{(G^{\text{TM}}(z, t) \exp(\alpha^{\text{TM}} z))^{\frac{\alpha_{\text{phase}}^{\text{TM}}}{2}}} \right) \end{aligned} \quad (71)$$

This expression shows that as the pulse propagates through the SOA, the phase difference between TE and TM components changes as a function of the TE and TM gains. Since gain is a function of position along the SOA, the state of polarization of the pulse changes significantly as it propagates through the SOA and the output pulse is no longer linearly polarized.

C. SOA Output Power With Linear Polarizer at Output

The effect of polarization rotation inside the SOA is evident when a linear polarizer is placed at the SOA output. A combination of input and output polarizers with an SOA can be used for power equalization, nonlinear polarization switching or wavelength conversion. Here we show how the formulae for gain and phase evolution, as derived above, can be used to calculate the output power and hence proves useful in all these applications. Assuming that the input optical field is linearly polarized at an angle θ , the field components $E^{\text{TE}}(L, t)$ and $E^{\text{TM}}(L, t)$ along the TE and TM axis at the output of an SOA of length L are as follows:

$$\begin{aligned} E^{\text{TE}}(L, t) &= \sqrt{G^{\text{TE}}(L, t) H_{T_w, \text{TE}}(L, t)} \\ &\quad \times \exp(-j\Phi^{\text{TE}}(L, t)) \end{aligned} \quad (72)$$

$$\begin{aligned} E^{\text{TM}}(L, t) &= \sqrt{G^{\text{TM}}(L, t) H_{T_w, \text{TM}}(L, t)} \\ &\quad \times \exp(-j\Phi^{\text{TM}}(L, t)). \end{aligned} \quad (73)$$

The output electric field $E_{L, \text{out}}$ corresponding to output polarizer placement angle of ψ is

$$E_{L, \text{out}} = E^{\text{TE}}(L, t) \cos(\psi) + E^{\text{TM}}(L, t) \sin(\psi). \quad (74)$$

Hence, the output intensity $H_{T_w, \text{out}}(t)$ is given as

$$H_{T_w, \text{out}}(t) = E_{L, \text{out}} \cdot E_{L, \text{out}}^* \quad (75)$$

From (72), (73), (74), and (75)

$$\begin{aligned} H_{T_w, \text{out}}(t) = & H_{T_w}(t) \cos^2(\theta) \cos^2(\psi) \\ & \times \left(G^{\text{TE}}(L, t) + 2\sqrt{G^{\text{TE}}(L, t)G^{\text{TM}}(L, t)} \right. \\ & \times \tan(\theta) \tan(\psi) \cos(\Phi_{\text{diff}}(L, t)) \\ & \left. + G^{\text{TM}}(L, t) \tan^2(\theta) \tan^2(\psi) \right). \quad (76) \end{aligned}$$

For a polarization insensitive SOA, this equation reduces to

$$H_{T_w, \text{out}}(t) = H_{T_w}(t) G(L, t) (\cos^2(\theta - \psi)). \quad (77)$$

Since $\theta - \psi = \pi/2$ when input and output polarizers are orthogonal, the output power will be zero for a polarization insensitive SOA. However, this is not the case for a polarization sensitive SOA and one can see from (76) that the output power will depend on the phase difference and SOA gain along TE and TM axes which in turn depends on the magnitude of input power and input pump current. If there is a polarization controller just before the output polarizer, then the total phase difference in (76) will also include phase difference induced by the polarization controller. By adjusting input power and input pump current, significant power can be obtained at the output even when the polarizers are orthogonal. Our derived formulae for gain and phase evolution can be used to determine the value of this output power.

D. Response to Counter-Propagating Pulses

In this section, we show how our analytical expressions can be extended to calculate the carrier density and gain evolution when we have two initially linearly polarized input pulses propagating along the SOA in opposite directions. Let us assume that the SOA is initially at its steady-state with no light incident on it. As shown in Fig. 3, the first pulse enters from the left and the second pulse enters the SOA τ seconds later from the right. The variables corresponding to the first and second pulse are identified by subscripts 1 and 2, respectively. The initial carrier-density and gain profiles of the SOA (shown in Fig. 3) for the TE and TM modes are as follows:

$$N_{x, \text{init}, 1}(z) = \tau_e \wp_x, \quad N_{y, \text{init}, 1}(z) = \tau_e \wp_y \quad (78)$$

$$G_{\text{init}, 1}^{\text{TE}}(z) = \exp(-\alpha^{\text{TE}} z + \Gamma^{\text{TE}} a^{\text{TE}} \times (\tau_e (2\wp_x + \wp_y) - N_0) z) \quad (79)$$

$$G_{\text{init}, 1}^{\text{TM}}(z) = \exp(-\alpha^{\text{TM}} z + \Gamma^{\text{TM}} a^{\text{TM}} \times (\tau_e (\wp_x + 2\wp_y) - N_0) z). \quad (80)$$

Until the second pulse enters the SOA, all calculations proceed in the same way as for a single pulse propagating through the

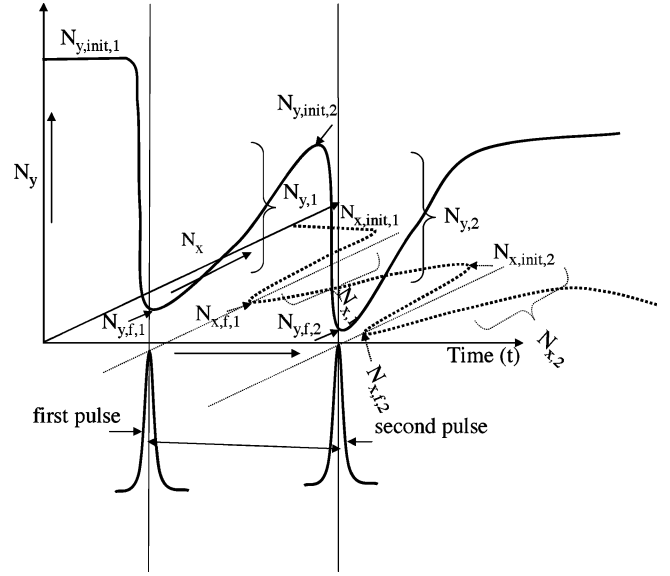


Fig. 3. Illustration of model carrier density evolution at an arbitrary point along a polarization-sensitive SOA when two counter-propagating pulses are incident on it with a delay τ between them.

SOA. We represent the carrier density corresponding to the transitions with x and y polarizations after the first pulse has entered the SOA as $N_{x,1}(z, t)$ and $N_{y,1}(z, t)$, respectively, and these are calculated using the equations for $N_x(z, t)$ and $N_y(z, t)$ in (60) and (61), respectively, as shown

$$N_{x,1}(z, t) = \tau_e \wp_x \left(1 - \exp\left(-\frac{t}{\tau_e}\right) \right) + N_{x,f,1}(z) \exp\left(-\frac{t}{\tau_e}\right) \quad (81)$$

$$N_{y,1}(z, t) = \tau_e \wp_y \left(1 - \exp\left(-\frac{t}{\tau_e}\right) \right) + N_{y,f,1}(z) \exp\left(-\frac{t}{\tau_e}\right). \quad (82)$$

$N_{x,f,1}(z)$ and $N_{y,f,1}(z)$ are directly given by the equations for $N_{x,f}(\xi)$ and $N_{y,f}(\xi)$ in (57) and (50), respectively, where we substitute z for ξ . Similarly, The TE and TM gains are given by $G_1^{\text{TE}}(z, t)$ and $G_1^{\text{TM}}(z, t)$ and these are calculated using (64) and (62), respectively. In this case, $\bar{g}_1^{\text{TE}}$ and $\bar{g}_1^{\text{TM}}$ are given by

$$\bar{g}_1^{\text{TE}} \approx \frac{\Gamma^{\text{TE}} a^{\text{TE}}}{L} \int_0^L (2N_{x, \text{init}, 1}(z) + N_{y, \text{init}, 1}(z) dz) - N_0 \quad (83)$$

$$\bar{g}_1^{\text{TM}} \approx \frac{\Gamma^{\text{TM}} a^{\text{TM}}}{L} \times \int_0^L (2N_{y, \text{init}, 1}(z) + N_{x, \text{init}, 1}(z) dz) - N_0. \quad (84)$$

Also, $\mathbf{g}_{\text{init}, 1}^{\text{TE}}$ and $\mathbf{g}_{\text{init}, 1}^{\text{TM}}$ are given by

$$\begin{aligned} \mathbf{g}_{\text{init}, 1}^{\text{TE}} = & \exp\left(\frac{\Gamma^{\text{TE}} a^{\text{TE}} \lambda E_{g,1}}{hcA} \left(\frac{2\bar{g}_1^{\text{TE}} \cos^2(\theta)}{\alpha^{\text{TE}} - \bar{g}_1^{\text{TE}}} + \frac{\bar{g}_1^{\text{TM}} \sin^2(\theta)}{\alpha^{\text{TM}} - \bar{g}_1^{\text{TM}}} \right)\right) \quad (85) \end{aligned}$$

$$\mathbf{g}_{\text{init},1}^{\text{TM}} = \exp\left(\frac{\Gamma^{\text{TM}} a^{\text{TM}} \lambda E_{g,1}}{hcA} \left(\frac{\bar{g}_1^{\text{TE}} \cos^2(\theta)}{\alpha^{\text{TE}} - \bar{g}_1^{\text{TE}}} + \frac{2\bar{g}_1^{\text{TM}} \sin^2(\theta)}{\alpha^{\text{TM}} - \bar{g}_1^{\text{TM}}}\right)\right). \quad (86)$$

The second pulse enters the SOA after time τ . For the second pulse, the initial carrier-density and gain profiles are given by

$$\begin{aligned} N_{x,\text{init},2}(z) &= N_{x,1}(z, \tau) \\ N_{y,\text{init},2}(z) &= N_{y,1}(z, \tau) \end{aligned} \quad (87)$$

$$\begin{aligned} G_{\text{init},2}^{\text{TE}}(z) &= G_1^{\text{TE}}(z, \tau) \\ G_{\text{init},2}^{\text{TM}}(z) &= G_1^{\text{TM}}(z, \tau). \end{aligned} \quad (88)$$

The carrier density along the SOA just after the pulse passes through and influences stimulated emission, is given by

$$N_{x,f,2}(z) = N_{x,\text{init},2}(z) - \frac{2}{3}N_{\text{diff},2}^{\text{TE}}(z) + \frac{1}{3}N_{\text{diff},2}^{\text{TM}}(z) \quad (89)$$

$$N_{y,f,2}(z) = N_{y,\text{init},2}(z) - \frac{2}{3}N_{\text{diff},2}^{\text{TM}}(z) + \frac{1}{3}N_{\text{diff},2}^{\text{TE}}(z) \quad (90)$$

$$N_{\text{diff},2}^{\text{TM}}(z) = N_{\text{unpol},2}^{\text{TM}}(\xi) + N_{\text{pol},2}^{\text{TM}}(\xi) \quad (91)$$

$$N_{\text{diff},2}^{\text{TE}}(z) = N_{\text{unpol},2}^{\text{TE}}(\xi) + N_{\text{pol},2}^{\text{TE}}(\xi). \quad (92)$$

Here

$$\begin{aligned} N_{\text{unpol},2}^{\text{TM}}(\xi) &= \frac{\left(2N_{y,\text{init},2}(z) + N_{x,\text{init},2}(z) - N_0 - \frac{\alpha^{\text{TM}}}{\Gamma^{\text{TM}} a^{\text{TM}}}\right)}{\frac{\Re^{\text{TM}}(L-z)\mathbf{g}_{\text{init},2}^{\text{TM}}}{G_{\text{init},2}^{\text{TM}}(L-z)(1-\mathbf{g}_{\text{init},2}^{\text{TM}})} + 1} \end{aligned} \quad (93)$$

$$\begin{aligned} N_{\text{pol},2}^{\text{TM}}(\xi) &= \frac{(\Delta\bar{g} - \Delta\alpha)}{\Gamma^{\text{TM}} a^{\text{TM}} \left(\frac{2}{g_{\text{ratio}} \exp((\Delta\bar{g} - \Delta\alpha)(L-z))} + 1\right)} \\ &\times \frac{1}{\left(\frac{\Re^{\text{TM}}(L-z)\mathbf{g}_{\text{init},2}^{\text{TM}}}{G_{\text{init},2}^{\text{TM}}(L-z)(1-\mathbf{g}_{\text{init},2}^{\text{TM}})} + 1\right)} \end{aligned} \quad (94)$$

$$\begin{aligned} N_{\text{unpol},2}^{\text{TE}}(\xi) &= \frac{\left(2N_{x,\text{init},2}(z) + N_{y,\text{init},2}(z) - N_0 - \frac{\alpha^{\text{TE}}}{\Gamma^{\text{TE}} a^{\text{TE}}}\right)}{\frac{\Re^{\text{TE}}(L-z)\mathbf{g}_{\text{init},2}^{\text{TE}}}{G_{\text{init},2}^{\text{TE}}(L-z)(1-\mathbf{g}_{\text{init},2}^{\text{TE}})} + 1} \end{aligned} \quad (95)$$

$$\begin{aligned} N_{\text{pol},2}^{\text{TE}}(\xi) &= -\frac{(\Delta\bar{g} - \Delta\alpha)}{\Gamma^{\text{TE}} a^{\text{TE}} (2g_{\text{ratio}} \exp((\Delta\bar{g} - \Delta\alpha)(L-z)) + 1)} \\ &\times \frac{1}{\left(\frac{\Re^{\text{TE}}(L-z)\mathbf{g}_{\text{init},2}^{\text{TE}}}{G_{\text{init},2}^{\text{TE}}(L-z)(1-\mathbf{g}_{\text{init},2}^{\text{TE}})} + 1\right)}. \end{aligned} \quad (96)$$

Once the pulse passes through, the carrier density replenishes at the carrier-recovery rate and we get

$$\begin{aligned} N_{x,2}(z, t) &= \tau_e \wp_x \left(1 - \exp\left(-\frac{t - \tau}{\tau_e}\right)\right) \\ &+ N_{x,f}(z) \exp\left(-\frac{t - \tau}{\tau_e}\right) \end{aligned} \quad (97)$$

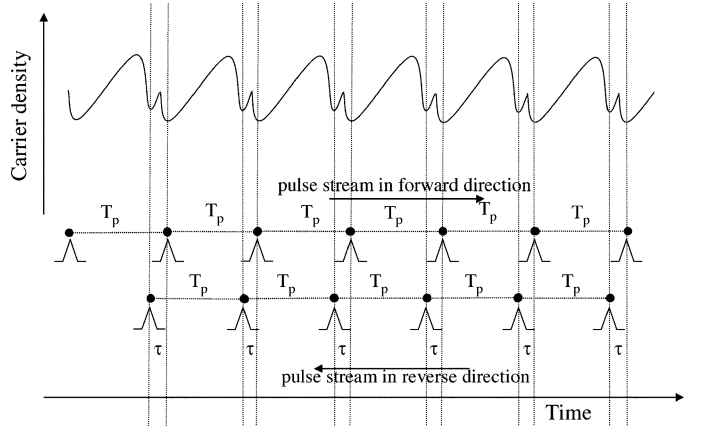


Fig. 4. Illustration of model carrier density evolution at an arbitrary point along a SOA when two identical counter-propagating pulse streams are incident on it with a delay τ between them.

$$\begin{aligned} N_{y,2}(z, t) &= \tau_e \wp_y \left(1 - \exp\left(-\frac{t - \tau}{\tau_e}\right)\right) \\ &+ N_{y,f}(z) \exp\left(-\frac{t - \tau}{\tau_e}\right). \end{aligned} \quad (98)$$

Once the carrier density corresponding to x and y polarizations are known, the gain corresponding to TE and TM modes as well as the total gain can be easily estimated, as

$$G_2^{\text{TE}}(z, t) = G_{\text{ref}}^{\text{TE}}(z) \left(\frac{G_{\text{final},2}^{\text{TE}}(z)}{G_{\text{ref}}^{\text{TE}}(z)}\right)^{\exp\left(-\frac{t - \tau}{\tau_e}\right)} \quad (99)$$

$$G_2^{\text{TM}}(z, t) = G_{\text{ref}}^{\text{TM}}(z) \left(\frac{G_{\text{final},2}^{\text{TM}}(z)}{G_{\text{ref}}^{\text{TM}}(z)}\right)^{\exp\left(-\frac{t - \tau}{\tau_e}\right)} \quad (100)$$

$$G_2(z, t) = G_2^{\text{TE}}(z, t) \cos^2(\theta) + G_2^{\text{TM}}(z, t) \sin^2(\theta). \quad (101)$$

$G_{\text{final},2}^{\text{TE}}(z)$ and $G_{\text{final},2}^{\text{TM}}(z)$ can be calculated using (45) and (40), respectively. Using (63) and (65), respectively, $G_{\text{ref}}^{\text{TE}}(z)$ and $G_{\text{ref}}^{\text{TM}}(z)$ can be calculated. $\bar{g}_2^{\text{TE}}$, $\bar{g}_2^{\text{TM}}$, $\mathbf{g}_{\text{init},2}^{\text{TE}}$, and $\mathbf{g}_{\text{init},2}^{\text{TM}}$ can be calculated for the second pulse in a similar manner as shown above for the first pulse, using (83), (84), (85), and (86), respectively.

We have experimentally demonstrated a simple time-of-flight SOA based rangefinder [22]. This time-of-flight rangefinder has been analytically characterized by Premaratne *et al.* in [17] for polarization-insensitive SOAs. Cross-gain modulation between counter-propagating pulse streams in an SOA was used for optical clock recovery in [23]. The cost of both these schemes can be reduced by using a SOA with residual polarization sensitivity that is cheaper to manufacture. Also, both schemes ideally have identical pulse trains propagating in opposite directions through the SOA, as shown in Fig. 4. Hence, it will be useful to analyze this scenario. Following the same approach as in [17], we show that our analytical expressions can be applied in this case. Due to the periodic nature of the pulse trains, the gain and carrier density are periodic. Let $G_{\text{Lt}}^{\text{TE}}$ and $G_{\text{Lt}}^{\text{TM}}$ be the TE and TM SOA gains just before the incidence of a pulse on the SOA left facet and let $G_{\text{fin},\text{Lt}}^{\text{TE}}$ and $G_{\text{fin},\text{Lt}}^{\text{TM}}$ be the TE and TM SOA gains after the pulse influenced stimulated emission. Suppose $G_{\text{Rt}}^{\text{TE}}$ and $G_{\text{Rt}}^{\text{TM}}$ are the gain of the SOA, momentarily before a pulse enters from

the SOA right facet and let $G_{\text{fin,Rt}}^{\text{TE}}$ and $G_{\text{fin,Rt}}^{\text{TM}}$ be the TE and TM SOA gains after this pulse influences stimulated emission. The pulse from the right is incident τ seconds after the pulse enters from the left. Since the counter-propagating pulse trains are periodic, we will obtain the same values of gain after a time interval equal to T_P , the period of the pulse trains. Here $\Re^{\text{TM}}$, $\Re^{\text{TE}}$, $\mathbf{g}_{\text{init}}^{\text{TE}}$, $\mathbf{g}_{\text{init}}^{\text{TM}}$, and g_{ratio} have different values corresponding to G_{Lt} and G_{Rt} . Using (40), (45), (62), and (64), for pulses incident on the right-hand side of the SOA, we can write

$$G_{\text{Rt}} = G_{\text{Rt}}^{\text{TE}} \cos^2(\theta) + G_{\text{Rt}}^{\text{TM}} \sin^2(\theta) \quad (102)$$

$$G_{\text{Rt}}^{\text{TE}} = G_{\text{ref}}^{\text{TE}} \left(\frac{G_{\text{fin,Lt}}^{\text{TE}}}{G_{\text{ref}}^{\text{TE}}} \right)^{\exp(-\frac{\tau}{\tau_e})} \quad (103)$$

$$G_{\text{Rt}}^{\text{TM}} = G_{\text{ref}}^{\text{TM}} \left(\frac{G_{\text{fin,Lt}}^{\text{TM}}}{G_{\text{ref}}^{\text{TM}}} \right)^{\exp(-\frac{\tau}{\tau_e})} \quad (104)$$

$$G_{\text{fin,Lt}}^{\text{TE}} = \left(\frac{\Re^{\text{TE}}(G_{\text{Lt}}) G_{\text{Lt}}^{\text{TE}}}{(\Re^{\text{TE}}(G_{\text{Lt}}) \mathbf{g}_{\text{init}}^{\text{TE}}(G_{\text{Lt}}) + G_{\text{Lt}}^{\text{TE}} (1 - \mathbf{g}_{\text{init}}^{\text{TE}}(G_{\text{Lt}})))} \right) \quad (105)$$

$$G_{\text{fin,Lt}}^{\text{TM}} = \left(\frac{\Re^{\text{TM}}(G_{\text{Lt}}) G_{\text{Lt}}^{\text{TM}}}{(\Re^{\text{TM}}(G_{\text{Lt}}) \mathbf{g}_{\text{init}}^{\text{TM}}(G_{\text{Lt}}) + G_{\text{Lt}}^{\text{TM}} (1 - \mathbf{g}_{\text{init}}^{\text{TM}}(G_{\text{Lt}})))} \right). \quad (106)$$

Similarly, gain momentarily before a pulse enters the SOA from the left-hand side can be expressed as

$$G_{\text{Lt}} = G_{\text{Lt}}^{\text{TE}} \cos^2(\theta) + G_{\text{Lt}}^{\text{TM}} \sin^2(\theta) \quad (107)$$

$$G_{\text{Lt}}^{\text{TE}} = G_{\text{ref}}^{\text{TE}} \left(\frac{G_{\text{fin,Rt}}^{\text{TE}}}{G_{\text{ref}}^{\text{TE}}} \right)^{\exp(-\frac{T_P - \tau}{\tau_e})} \quad (108)$$

$$G_{\text{Lt}}^{\text{TM}} = G_{\text{ref}}^{\text{TM}} \left(\frac{G_{\text{fin,Rt}}^{\text{TM}}}{G_{\text{ref}}^{\text{TM}}} \right)^{\exp(-\frac{T_P - \tau}{\tau_e})} \quad (109)$$

$$G_{\text{fin,Rt}}^{\text{TE}} = \left(\frac{\Re^{\text{TE}}(G_{\text{Rt}}) G_{\text{Rt}}^{\text{TE}}}{(\Re^{\text{TE}}(G_{\text{Rt}}) \mathbf{g}_{\text{init}}^{\text{TE}}(G_{\text{Rt}}) + G_{\text{Rt}}^{\text{TE}} (1 - \mathbf{g}_{\text{init}}^{\text{TE}}(G_{\text{Rt}})))} \right) \quad (110)$$

$$G_{\text{fin,Rt}}^{\text{TM}} = \left(\frac{\Re^{\text{TM}}(G_{\text{Rt}}) G_{\text{Rt}}^{\text{TM}}}{(\Re^{\text{TM}}(G_{\text{Rt}}) \mathbf{g}_{\text{init}}^{\text{TM}}(G_{\text{Rt}}) + G_{\text{Rt}}^{\text{TM}} (1 - \mathbf{g}_{\text{init}}^{\text{TM}}(G_{\text{Rt}})))} \right). \quad (111)$$

Let $G_a \in (G_{\text{Lt}}, G_{\text{Rt}})$. Here $G_{\text{ref}}^{\text{TE}}$, $G_{\text{ref}}^{\text{TM}}$, $\mathbf{g}_{\text{init}}^{\text{TE}}(G_a)$, and $\mathbf{g}_{\text{init}}^{\text{TM}}(G_a)$ are given by

$$G_{\text{ref}}^{\text{TE}} = \exp(-\alpha^{\text{TE}} L + \Gamma^{\text{TE}} a^{\text{TE}} \tau_e (2\wp_x + \wp_y) L - \Gamma^{\text{TE}} a^{\text{TE}} N_0 L) \quad (112)$$

$$G_{\text{ref}}^{\text{TM}} = \exp(-\alpha^{\text{TM}} L + \Gamma^{\text{TM}} a^{\text{TM}} \tau_e (\wp_x + 2\wp_y) L - \Gamma^{\text{TM}} a^{\text{TM}} N_0 L) \quad (113)$$

$$\mathbf{g}_{\text{init}}^{\text{TM}}(G_a) = \exp\left(-\frac{\Gamma^{\text{TM}} a^{\text{TM}} \lambda E_g}{hcA} \left(\left(1 + \frac{\alpha^{\text{TE}} L}{\ln(G_a^{\text{TE}})}\right) \cos^2(\theta) + \left(1 + \frac{\alpha^{\text{TM}} L}{\ln(G_a^{\text{TM}})}\right) 2 \sin^2(\theta) \right)\right) \quad (114)$$

$$\mathbf{g}_{\text{init}}^{\text{TE}}(G_a) = \exp\left(-\frac{\Gamma^{\text{TE}} a^{\text{TE}} \lambda E_g}{hcA} \left(\left(1 + \frac{\alpha^{\text{TE}} L}{\ln(G_a^{\text{TE}})}\right) 2 \cos^2(\theta) + \left(1 + \frac{\alpha^{\text{TM}} L}{\ln(G_a^{\text{TM}})}\right) \sin^2(\theta) \right)\right). \quad (115)$$

$\Re^{\text{TM}}(G_a)$ and $\Re^{\text{TE}}(G_a)$ can be expressed as

$$\Re^{\text{TM}}(G_a) = \frac{2 + g_{\text{ratio}}(G_a)}{2 + g_{\text{ratio}}(G_a) \frac{G_a^{\text{TE}}}{G_a^{\text{TM}}} \exp((\alpha^{\text{TE}} - \alpha^{\text{TM}}) L)} \quad (116)$$

$$\Re^{\text{TE}}(G_a) = \frac{2g_{\text{ratio}}(G_a) + 1}{2g_{\text{ratio}}(G_a) + \frac{G_a^{\text{TM}}}{G_a^{\text{TE}}} \exp((\alpha^{\text{TM}} - \alpha^{\text{TE}}) L)} \quad (117)$$

$$g_{\text{ratio}}(G_a) = \frac{\ln(G_a^{\text{TE}}) + \alpha^{\text{TE}} L \ln(G_a^{\text{TM}})}{\ln(G_a^{\text{TM}}) + \alpha^{\text{TM}} L \ln(G_a^{\text{TE}})} \cot^2(\theta). \quad (118)$$

Simultaneously solving transcendental (102)–(111) gives the values of G_{Rt} and G_{Lt} . Once these values are known, the time-evolution of gain can be estimated through (62) and (64).

E. Pulse Energy Gain Calculations

The efficiency with which a signal pulse extracts the available energy from a SOA is a very important parameter and has several applications. It is extensively used in the performance analysis of the optical pulse delay discriminator proposed in [17], which is based on a polarization-insensitive SOA. Let U_{in} and U_{out} denote the total energy in the input and output pulses. The total output pulse energy as well as input pulse energy is obtained using (24), (25), (39), and (42) as

$$U_{\text{in}} = \frac{\sin^2(\theta)}{\Re^{\text{TM}}(L) f^{\text{TM}}(L)} \times \ln \left(\frac{G_{\text{init}}^{\text{TM}}(L) (G_{\text{final}}^{\text{TM}}(L) - \Re^{\text{TM}}(L))}{G_{\text{final}}^{\text{TM}}(L) (G_{\text{init}}^{\text{TM}}(L) - \Re^{\text{TM}}(L))} \right) + \frac{\cos^2(\theta)}{\Re^{\text{TE}}(L) f^{\text{TE}}(L)} \times \ln \left(\frac{G_{\text{init}}^{\text{TE}}(L) (G_{\text{final}}^{\text{TE}}(L) - \Re^{\text{TE}}(L))}{G_{\text{final}}^{\text{TE}}(L) (G_{\text{init}}^{\text{TE}}(L) - \Re^{\text{TE}}(L))} \right) \quad (119)$$

$$U_{\text{out}} = \frac{\sin^2(\theta)}{f^{\text{TM}}(L)} \ln \left(\frac{G_{\text{final}}^{\text{TM}}(L) - \Re^{\text{TM}}(L)}{G_{\text{init}}^{\text{TM}}(L) - \Re^{\text{TM}}(L)} \right) + \frac{\cos^2(\theta)}{f^{\text{TE}}(L)} \ln \left(\frac{G_{\text{final}}^{\text{TE}}(L) - \Re^{\text{TE}}(L)}{G_{\text{init}}^{\text{TE}}(L) - \Re^{\text{TE}}(L)} \right). \quad (120)$$

Using (119) and (120), the total energy extracted from the amplifier is represented as U_{extr} and is given by [20]

$$\begin{aligned}
 U_{\text{extr}} &= U_{\text{out}} - U_{\text{in}} \\
 &= \frac{\sin^2(\theta)}{\Re^{\text{TM}}(L)f^{\text{TM}}(L)} \\
 &\quad \times \ln \left(\frac{G_{\text{final}}^{\text{TM}}(L)}{G_{\text{init}}^{\text{TM}}(L)} \left(\frac{G_{\text{final}}^{\text{TM}}(L) - \Re^{\text{TM}}(L)}{G_{\text{init}}^{\text{TM}}(L) - \Re^{\text{TM}}(L)} \right)^{\Re^{\text{TM}}(L)-1} \right) \\
 &\quad + \frac{\cos^2(\theta)}{\Re^{\text{TE}}(L)f^{\text{TE}}(L)} \\
 &\quad \times \ln \left(\frac{G_{\text{final}}^{\text{TE}}(L)}{G_{\text{init}}^{\text{TE}}(L)} \left(\frac{G_{\text{final}}^{\text{TE}}(L) - \Re^{\text{TE}}(L)}{G_{\text{init}}^{\text{TE}}(L) - \Re^{\text{TE}}(L)} \right)^{\Re^{\text{TE}}(L)-1} \right). \quad (121)
 \end{aligned}$$

The pulse energy gain is defined as the ratio of the pulse energy output to pulse energy input [20] and is given by

$$G_E = \frac{U_{\text{out}}}{U_{\text{in}}}. \quad (122)$$

Here, U_{in} and U_{out} are given by (119) and (120), respectively. As seen from the equation above, the maximum energy from the amplifier is obtained when the residual final gain is minimized. Similar to the case for a polarization insensitive SOA [18], we can see from (122) that the energy gain for a polarization sensitive SOA is independent of the pulse shape.

Now, let us examine how these equations can be applied to counter-propagating periodic pulse trains. The variables corresponding to left and right incident pulses are identified by subscripts Lt and Rt, respectively. The total input energy and output energy for left incident pulse streams is obtained as shown below using (119) and (120).

$$\begin{aligned}
 U_{\text{in,Lt}} &= \frac{\sin^2(\theta)}{\Re^{\text{TM}}(G_{\text{Lt}})f^{\text{TM}}(L)} \\
 &\quad \times \ln \left(\frac{G_{\text{Lt}}^{\text{TM}} \left(G_{\text{fin,Lt}}^{\text{TM}} - \Re^{\text{TM}}(G_{\text{Lt}}) \right)}{G_{\text{fin,Lt}}^{\text{TM}} \left(G_{\text{Lt}}^{\text{TM}} - \Re^{\text{TM}}(G_{\text{Lt}}) \right)} \right) \\
 &\quad + \frac{\cos^2(\theta)}{\Re^{\text{TE}}(G_{\text{Lt}})f^{\text{TE}}(L)} \\
 &\quad \times \ln \left(\frac{G_{\text{Lt}}^{\text{TE}} \left(G_{\text{fin,Lt}}^{\text{TE}} - \Re^{\text{TE}}(G_{\text{Lt}}) \right)}{G_{\text{fin,Lt}}^{\text{TE}} \left(G_{\text{Lt}}^{\text{TE}} - \Re^{\text{TE}}(G_{\text{Lt}}) \right)} \right) \quad (123)
 \end{aligned}$$

$$\begin{aligned}
 U_{\text{out,Lt}} &= \frac{\sin^2(\theta)}{f^{\text{TM}}(L)} \ln \left(\frac{G_{\text{fin,Lt}}^{\text{TM}} - \Re^{\text{TM}}(G_{\text{Lt}})}{G_{\text{Lt}}^{\text{TM}} - \Re^{\text{TM}}(G_{\text{Lt}})} \right) \\
 &\quad + \frac{\cos^2(\theta)}{f^{\text{TE}}(L)} \ln \left(\frac{G_{\text{fin,Lt}}^{\text{TE}} - \Re^{\text{TE}}(G_{\text{Lt}})}{G_{\text{Lt}}^{\text{TE}} - \Re^{\text{TE}}(G_{\text{Lt}})} \right). \quad (124)
 \end{aligned}$$

These equations are obtained by substituting $G_{\text{init,Lt}}^{\text{TM}}(L) = G_{\text{Lt}}^{\text{TM}}$ and $G_{\text{init,Lt}}^{\text{TE}}(L) = G_{\text{Lt}}^{\text{TE}}$. Here $G_{\text{Lt}}^{\text{TE}}$ and $G_{\text{Lt}}^{\text{TM}}$ are given by (108) and (109), respectively. $G_{\text{final,Lt}}^{\text{TE}}(L) = G_{\text{fin,Lt}}^{\text{TE}}$, $G_{\text{final,Lt}}^{\text{TM}}(L) = G_{\text{fin,Lt}}^{\text{TM}}$ are given by (105) and (106), respectively. The energy gain for left incident pulses $G_{E,\text{Lt}}$ can be calculated using (123) and (124) in (122).

The energy gain for right incident pulses $G_{E,\text{Rt}}$ can be calculated similarly. These expressions can then be used for analyzing the linearity of the optical pulse delay discriminator, similar to [17]. It can also be shown that all our results reduce to those obtained for a polarization insensitive SOA, given in [17].

F. Relaxing the Assumption $T_w \ll \tau_e$

Now let us see what happens when we relax the assumption $T_w \ll \tau_e$. When this is done, (20) and (21) are no longer valid. Then (23) becomes

$$\begin{aligned}
 &\frac{\partial}{\partial \tau} g^{\text{TM}}(\xi, \tau) \\
 &= \Gamma^{\text{TM}} a^{\text{TM}} \left[2\wp_y + \wp_x - \frac{N_0}{\tau_e} - \frac{g^{\text{TM}}(\xi, \tau)}{\Gamma^{\text{TM}} a^{\text{TM}} \tau_e} \right. \\
 &\quad \left. - \frac{\lambda}{hc} (g^{\text{TE}}(\xi, \tau) I^{\text{TE}}(\xi, \tau) + 2g^{\text{TM}}(\xi, \tau) I^{\text{TM}}(\xi, \tau)) \right]. \quad (125)
 \end{aligned}$$

Integrating this equation as before, we get

$$\begin{aligned}
 &\frac{\partial}{\partial \tau} \int_0^\xi g^{\text{TM}}(\xi, \tau) \\
 &= \Gamma^{\text{TM}} a^{\text{TM}} \left[\left(2\wp_y + \wp_x - \frac{N_0}{\tau_e} \right) \xi \right] - \frac{\ln(G^{\text{TM}}(\xi, \tau))}{\tau_e} \\
 &\quad - \frac{\alpha^{\text{TM}} \xi}{\tau_e} + f^{\text{TM}}(\xi) H_{T_w}(\tau) (G^{\text{TM}}(\xi, \tau) - \Re^{\text{TM}}(\xi)). \quad (126)
 \end{aligned}$$

Similar to the case for a polarization insensitive SOA [18], it is not easy to obtain a general solution analytically here. However, when $\tau_e \ll T_w$, we can neglect the time derivative on the right-hand side of (126) [18] and this gives the following implicit relation for TM gain along the SOA

$$\begin{aligned}
 &G^{\text{TM}}(\xi, \tau) \\
 &= G_{\text{ref}}^{\text{TM}}(\xi) \exp(\tau_e f^{\text{TM}}(\xi) H_{T_w}(\tau) (G^{\text{TM}}(\xi, \tau) - \Re^{\text{TM}}(\xi))) \quad (127)
 \end{aligned}$$

$G_{\text{ref}}^{\text{TM}}(\xi)$, $f^{\text{TM}}(\xi)$, and $\Re^{\text{TM}}(\xi)$ are given by (63), (36), and (37), respectively. Similarly, gain for the TE mode along the SOA can be expressed as

$$\begin{aligned}
 &G^{\text{TE}}(\xi, \tau) \\
 &= G_{\text{ref}}^{\text{TE}}(\xi) \exp(\tau_e f^{\text{TE}}(\xi) H_{T_w}(\tau) (G^{\text{TE}}(\xi, \tau) - \Re^{\text{TE}}(\xi))) \quad (128)
 \end{aligned}$$

where $G_{\text{ref}}^{\text{TE}}(\xi)$, $f^{\text{TE}}(\xi)$, and $\Re^{\text{TE}}(\xi)$ are given by (65), (43), and (44), respectively.

III. SIMULATION RESULTS AND ANALYTICAL MODEL LIMITATIONS

In this section, we compare the results obtained using our analytical approximation to that obtained using numerical simulations and show that the results match closely for a wide range of practically useful values. The numerical simulations were done by directly integrating the set of equations (1)–(13) in MATLAB

TABLE I
SOA PARAMETERS

Parameter	Value	Units
Active volume: $V=L \times W \times D$	$300 \times 1.5 \times 0.2$	μm^3
Confinement factors: Γ^{TE}, Γ^{TM}	0.3, 0.18	
Phase mod. coefficients: $\alpha_{\text{phase}}^{TE}, \alpha_{\text{phase}}^{TM}$	4, 4	
Gain coefficient: a^{TE}, a^{TM}	2.5, 2.14	10^{-16} cm^2
Transparency carrier density: N_o	10^{18}	cm^{-3}
Internal absorption: α^{TE}, α^{TM}	50, 50	cm^{-1}
Carrier lifetime: τ_s	350	ps
Group velocity: v_g	10^8	ms^{-1}
Input current: I	100	mA
Population imbalance factor: f	0.5	

numerically using the NIMROD portal.¹ The parameter values we used are the same as in [9] and are shown in Table I. While performing the simulation, the input polarizer placement angle is set to 45° with respect to the TE axis. In the figures in this section, dashed lines correspond to the numerical simulation whereas the solid lines depict the analytical solution. Fig. 5(a) shows gain in decibels against SOA length for different values of pump current. The last three plots are at the instant $t = 23$ ps when the Gaussian pulse center has just passed through the SOA. As expected, gain increases with pump current. The analytical calculations for gain are based on (62), (64), and (66) and the obtained results are in excellent agreement with numerical simulations.

Shown in Fig. 5(b) are the numerically simulated and analytically calculated [based on (71)] values of phase difference between TE and TM modes against SOA length, corresponding to pump current values 70, 90, and 110 mA. As before, the plots correspond to the instant $t = 23$ ps when the Gaussian pulse centre has just passed through the SOA and there is excellent agreement between the analytical calculations and numerical simulations. The phase difference between TE and TM polarization eigenmodes is a function of the SOA gain along the TE and TM axes and is hence dependent on the SOA length. We can infer from the plot that since the TE gain of the SOA is higher than the TM gain, the phase shift of the TE component is larger than that for the TM component. Fig. 5(c) shows the SOA output pulse when the input polarizer placement angle corresponds to 45° , for different values of input pump current. The analytical calculation of output power is based on the expression for gain evolution in (66).

Now, we numerically simulate the effect of having a linear polarizer at the SOA output and compare the obtained results with analytical calculations, for polarization insensitive and sensitive SOAs. We use the same parameters as in Table I to simulate a polarization insensitive bulk unstrained SOA. However we set $\Gamma = \Gamma^{TE} = \Gamma^{TM} = 0.3$, $a = a^{TE} = a^{TM} = 2.5 \times 10^{-16} \text{ cm}^2$, $f = 1$ to make the SOA polarization insensitive. The output polarizer placement angle is varied and the output polarizer is orthogonal to the input polarizer when the placement angle is 135° . As can be seen from (77), the output power should be zero when the polarizers are orthogonal. This is confirmed by Fig. 6(a) where we have plotted the

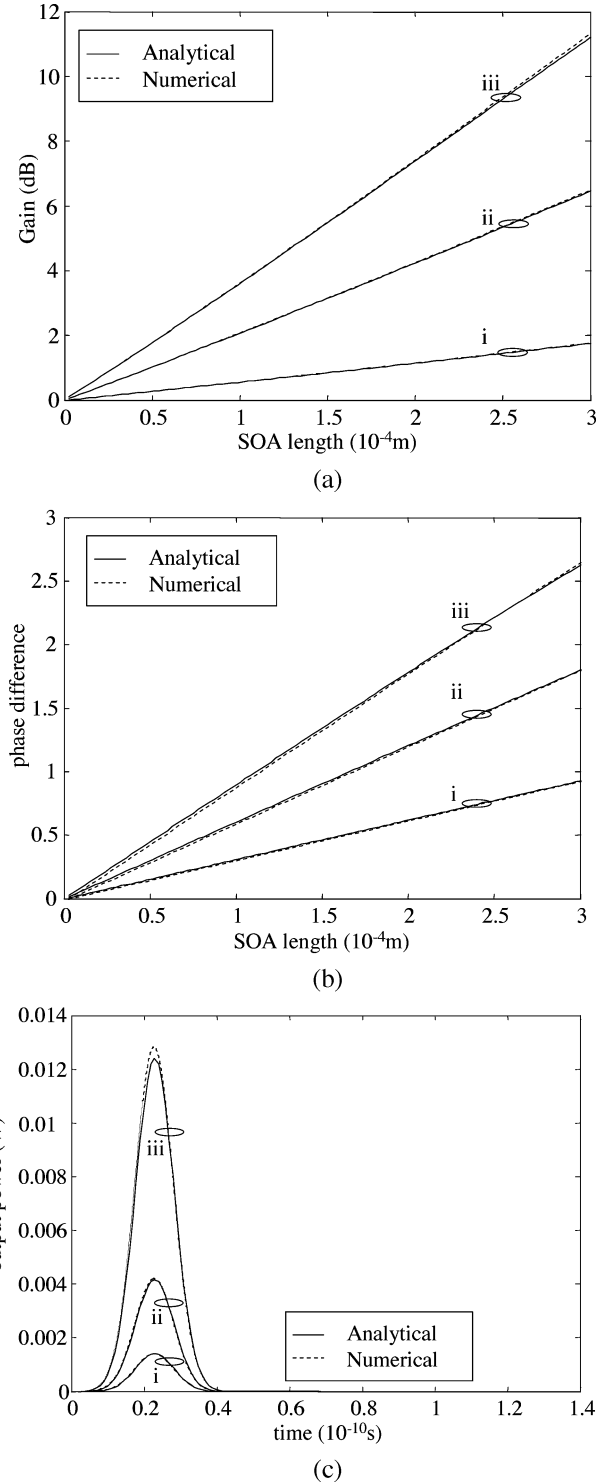


Fig. 5. (a) Plot of gain against SOA length (b) Plot of phase difference against SOA length (c) Plot of output power against time. The curves (i), (ii), (iii) correspond to pump current values 70 mA, 90 mA and 110 mA, respectively. Plots (a) and (b) are at the instant when the Gaussian pulse center has just passed through the SOA.

output pulse corresponding to different output polarizer placement angle values. In Fig. 6(b), we have plotted the output pulse corresponding to different values of output polarizer placement angle, based on (76), for a bulk strained SOA with parameters as in Table I. We can see that we get significant output power when

¹NIMROD can be accessed at <http://www.monash.edu.au>.

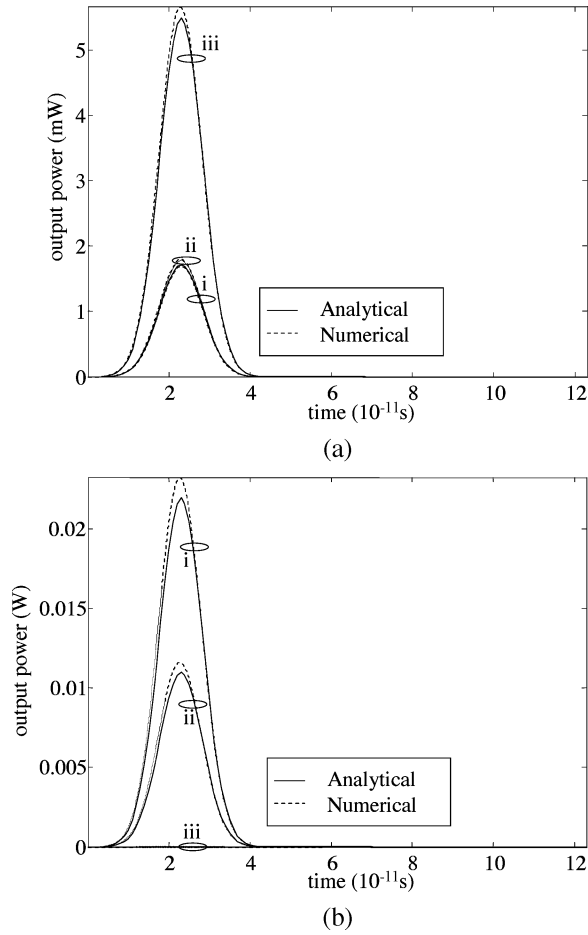


Fig. 6. (a) Plot of output power against time for polarization insensitive SOA (b) Plot of output power against time for polarization sensitive SOA. The curves (i), (ii), (iii) correspond to output polarizer placement angles of 45° , 90° and 135° , respectively. Input polarizer placement angle $\theta = 45^\circ$.

the output linear polarizer is placed orthogonal to the input polarizer at 135° to the TE axis. This happens due to polarization rotation and the output power is now dependent on the intensity of the input pulse and the SOA pump current, in addition to output polarizer placement angle. We can also see that the numerically simulated and analytically calculated values are in excellent agreement.

We have also plotted model carrier density $N_x(z, t)$, $N_y(z, t)$ against distance along the SOA at different instants of time for two counter-propagating pulses in MATLAB numerically and compared the results with those obtained through analytical calculations. The first pulse is incident from the left side of the SOA and the second pulse is incident from the right side. The distance axes has been marked to indicate the SOA facet it corresponds to. In Fig. 7(a) and (b), the delay between the counter-propagating pulses have been set at 5 ps. As time tends to infinity, the carrier density along the SOA converges to the equilibrium value determined by the pump current. Since $f = 0.5$, the carrier density $N_x(z, t)$ is approximately half that of $N_y(z, t)$. The analytically calculated values, based on (97) and (98) agree well with the numerically simulated values. In Fig. 8(a), we plot energy gain of the SOA against different values of input energy for an input pulse. As expected, the energy gain increases with

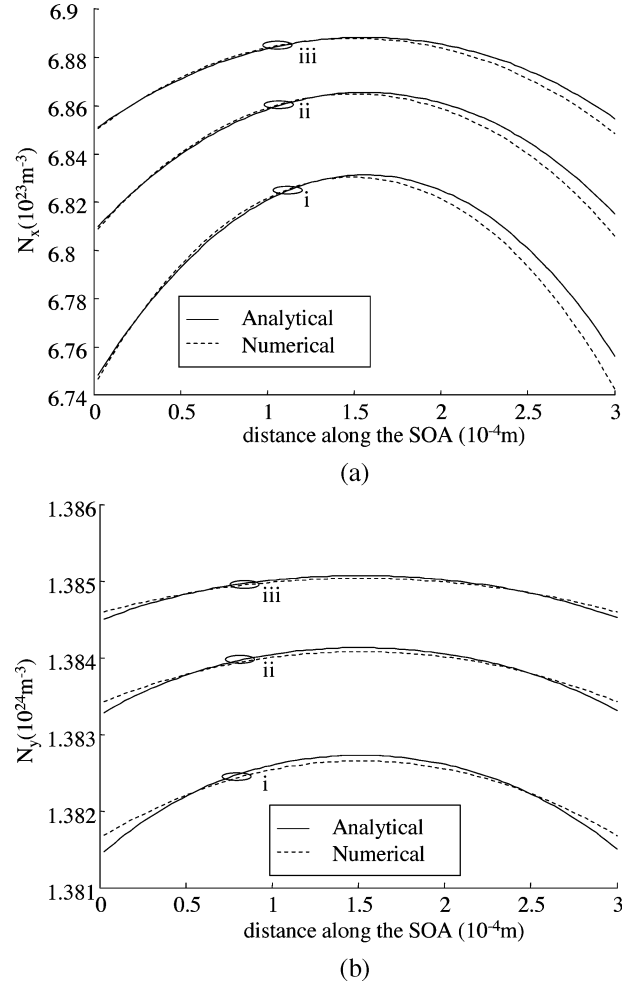


Fig. 7. (a) $N_x(z, t)$ against distance along the SOA (b) $N_y(z, t)$ against distance along the SOA when the delay between two counter-propagating pulses of energy 12.5 pJ is 5 ps. The pulses in (a) and (b) have a FWHM of 5 ps. The curves (i), (ii), (iii) correspond to 100 ps, 220 ps, 340 ps, respectively, after the first pulse has completely passed through the SOA.

pump current. We can also see that the energy gain decreases as the input energy increases. This is due to gain saturation. As before, the analytical results obtained using (122), closely match the numerically simulated values.

We have plotted the difference in energy gain for counter-propagating pulse streams against the delay difference in Fig. 8(b) when the pulses do not overlap. The delay difference has been scaled by addition of a constant in order to facilitate comparison with experimental results. We can see the difference in energy gain for counter-propagating pulse streams is directly proportional to the delay difference between them. This plot is based on (123), (124), and (122) and the result matches with those obtained through numerical simulations. It was observed that while the analytical calculation performed by MATLAB on a single computing node took under 4 minutes of central processing unit (CPU) time to execute, the numerical simulation, performed by using the NIMROD portal in a distributed computing environment using 19 nodes, took 528 CPU hours for execution. Thus the analytical expression can lead to significant savings with regard to the processing time. Similar high savings in processing time can be obtained for all other

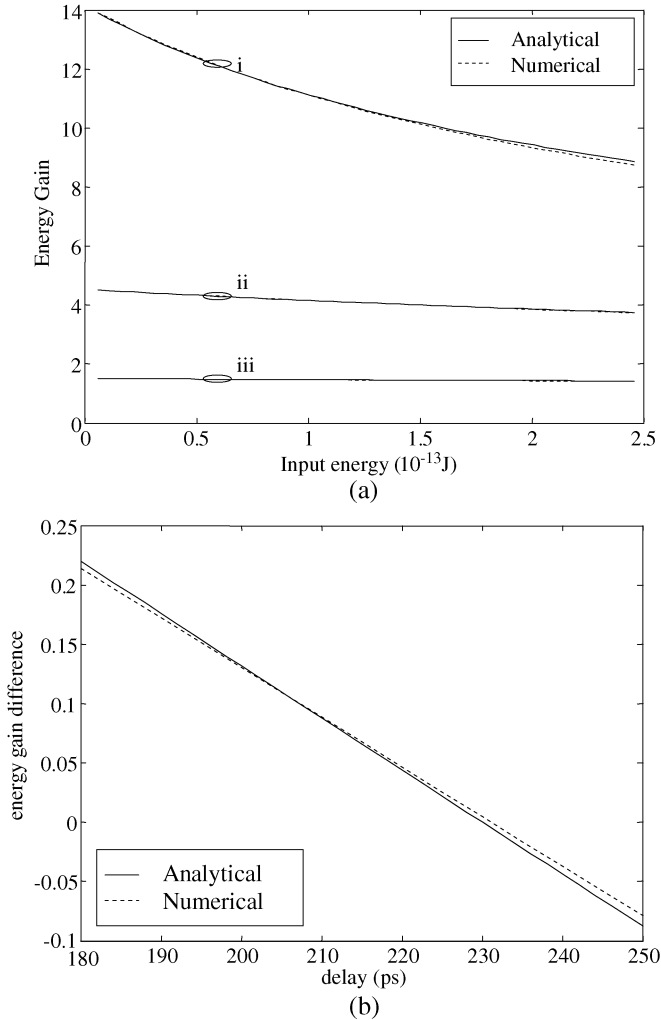


Fig. 8. (a) Plot of energy gain against input energy for an input pulse with FWHM 5 ps. The curves (i), (ii), (iii) corresponds to the cases when the pump current is 110 mA, 90 mA and 70 mA, respectively (b) Plot of difference in energy gain for counter-propagating pulses against delay difference scaled to facilitate comparison with experimental results. Input pulses have FWHM of 5 ps and pulse repetition rate is 10 GHz.

analytical calculations done in this section. Please note that the CPU time mentioned as required for analytical calculation is an upper bound and may also include the time required for data transfer to the NIMROD grid and back, and for loading the simulation on the NIMROD grid.

Our analytical model has some limitations that should be kept in mind while it is used for signal processing applications. It does not consider ASE noise. In [17], it has been shown that if ASE is small, our theory is a very good representation of behaviour of the SOA-based distance ranger in case of polarization insensitive SOAs. In [24], Premaratne *et al.* have recently developed an analytical expression for a polarization insensitive SOA that includes ASE noise and have shown that ASE reduces the sensitivity of the SOA-based optical pulse delay discriminator. Since ASE is isotropic, the same approach could be used for modelling ASE in a polarization-sensitive SOA and hence would yield similar results. The analytical calculations are valid only when the pulse width is much less than the carrier-recovery lifetime. The approach we have used is similar to that used in

[18] and [20] in developing analytical expressions for polarization-insensitive SOAs. For the SOA modelled in this session, our approximation holds well for pulses of width below 50 ps.

The analytically calculated results will be accurate approximations for the numerical results if SOA maximum gain is below 35 dB. If maximum gain of the SOA is well above 35 dB, then using the same gain coefficients $\bar{g}^{\text{TE}}$ and $\bar{g}^{\text{TM}}$ across the SOA length will be inaccurate. For example, if the SOA length was increased to 1 mm, it will have a small signal gain of around 80 dB and our analytical expressions will not be applicable here. To improve accuracy of the analytical calculations, it would then be better to perform the calculations by dividing the SOA length into subintervals, whose number will depend on the maximum value of SOA gain, with separate values of $\bar{g}^{\text{TE}}$ and $\bar{g}^{\text{TM}}$ for each subinterval and then repeat the analytical calculations in each section. However, in this case, the input light into the sections after first will not be linear and the algebraic structure of the final answer will be very complex.

It should be stated that to make the problem analytically tractable, we have omitted factors like nonlinear gain compression due to carrier heating and spectral-hole burning [25], Bimolecular recombination [26], Auger process [27]. Hence, our model is not valid for input pulses of high energy [17] in the order of pico joules. Our model also does not consider ultrafast phenomenon such as two-photon absorption [19], Kerr effect [28] and hence should not be applied for subpicosecond pulses. It also does not consider gain dispersion [3]. Also, to apply the model for a pulse stream that represents a pseudo-random bit sequence (PRBS), the analytical calculations will have to be repeatedly applied to individual pulses, just like we have shown for two counter-propagating pulses in Section II-D. However, the results obtained for identical counter-propagating pulse streams are based on gain periodicity and cannot be used here.

IV. EXPERIMENTAL RESULTS

We had performed an experiment, shown in Fig. 9(a), in which counter-propagating pulse streams were made incident on an SOA [22]. The results obtained from this experiment are used to verify our analytical calculations. Here, the pulse stream reflected from the target formed the counter-propagating pulse stream. The pulses were of width 2 ps and they were generated using a mode-locked laser at 9.96 GHz at 1540.4 nm with input power of -14.4 dBm. We used an Alcatel A1901 SOA with a polarization sensitivity of around 1 dB. The reflected pulse stream was set to different values of input power. The difference in power between counter-propagating pulse streams was measured and plotted in Fig. 9(b) against different values of delay set on the free-space delay line. As the value of this delay changes, the delay difference between the counter-propagating pulse streams changes correspondingly. We can see from the figure that when the reflected pulse stream incident on the SOA is approximately the same power as the input pulse stream, the difference in power between the counter-propagating pulse streams is directly proportional to the delay difference between them, when the pulses do not overlap. This fact confirms our analytical calculation results and also shows that energy gain difference between counter-propagating pulse streams can be used as a measure of the delay difference. As delay difference is

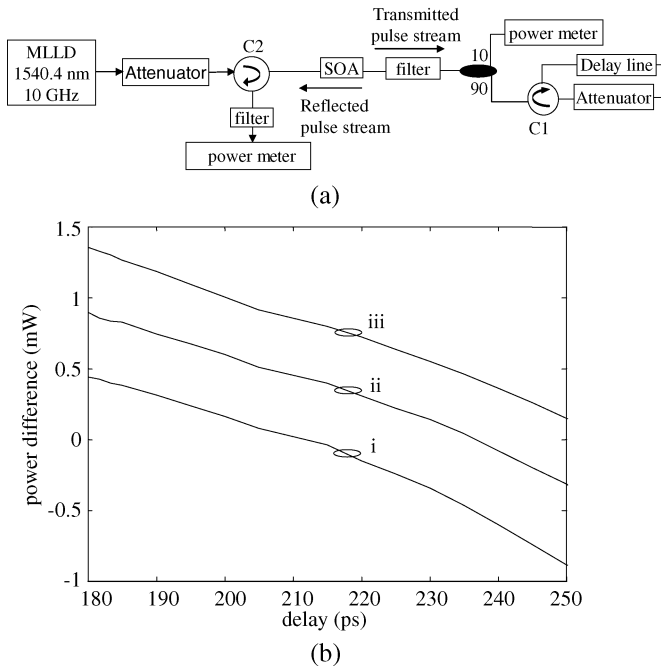


Fig. 9. (a) Experimental setup (b) Plot of difference in power for counter-propagating pulse streams against delay. Input pulses have input power -14.4 dBm and FWHM 2 ps. The pulse repetition rate is 9.96 GHz. The curves (i), (ii), (iii) correspond to the cases when the power of the reflected pulse stream was set as -13.0 dBm, -14.8 dBm and -16.6 dBm, respectively.

proportional to the difference in distance travelled by the pulse streams, polarization sensitive SOAs can be used for distance measurement. It should be noted that when the pulse streams overlap to various extents, there is very strong gain suppression and the relationship between power difference and delay is not linear. These values cannot be used for distance measurement [22] and are not shown in the figure.

V. SUMMARY

In this paper, we have derived analytical expressions for the carrier density, gain and phase evolution during optical pulse propagation for a polarization sensitive SOA. The expressions have been derived under the assumption that the pulse width is much shorter than the carrier-recovery lifetime. The expressions for TE and TM gain show that they decay with time exponentially. For a given SOA length, the phase difference between TE and TM modes is a logarithmic function of TE and TM gains and hence, the output signal polarization varies with SOA length. The pulse energy gain is found to be independent of the pulse shape. It has also been demonstrated that our analytical expressions will prove useful in estimating the output power when the SOA is being used for optical signal processing applications like power equalization, amplification with waveform distortion reduction or wavelength conversion. The output power obtained when the SOA is combined with a output linear polarizer is found to be a function of phase difference between TE and TM modes.

We have analysed the SOA response to counter-propagating pulses as well as pulse trains and have estimated the energy gain in each of these circumstances. We have also calculated the values for the SOA parameters involved using a numerical

model ([15]) and have shown that these values closely match the results obtained by using the analytical expressions. Simulations using our analytical expressions are much faster than the corresponding numerical calculations. Further, we have proved analytically that the difference in energy gain for counter-propagating pulse streams is directly proportional to the delay difference between them when the pulses do not overlap and hence acts as a measure of the delay difference. This fact, confirmed by numerical simulations done using the NIMROD portal in MATLAB and also observed experimentally, proves that polarization-sensitive SOAs can be used for distance measurement.

REFERENCES

- [1] B. F. Kennedy, S. Philippe, P. Landais, A. L. Bradley, and H. Soto, "Experimental investigation of polarisation rotation in semiconductor optical amplifiers," *Proc. IEE Optoelectron.*, vol. 151, pp. 114–118, Apr. 2004.
- [2] M. F. C. Stephens, M. Asghari, R. V. Penty, and I. H. White, "Demonstration of ultrafast all-optical wavelength conversion utilizing birefringence in semiconductor optical amplifiers," *IEEE Photon. Technol. Lett.*, vol. 9, no. 4, pp. 449–451, Apr. 1997.
- [3] Z. Li, X. Yang, E. Tangdiongga, H. Ju, G. D. Khoe, H. J. S. Dorren, and D. Lenstra, "Simulation of mode-locking by nonlinear polarization rotation in a semiconductor optical amplifier," *IEEE J. Quantum Electron.*, vol. 41, no. 6, pp. 808–816, Jun. 2005.
- [4] N. Calabretta, Y. Liu, F. M. Huijskens, M. T. Hill, H. de Waardt, G. D. Khoe, and H. J. S. Dorren, "Optical signal processing based on self-induced polarization rotation in a semiconductor optical amplifier," *J. Lightw. Technol.*, vol. 22, no. 2, pp. 372–381, Feb. 2004.
- [5] H. Soto, D. Erasme, and G. Guekos, "5-Gb/s XOR optical gate based on cross-polarization modulation in semiconductor optical amplifiers," *IEEE Photon. Technol. Lett.*, vol. 13, no. 4, pp. 335–337, Apr. 2001.
- [6] J. J. V. Olmos, I. T. Monroy, J. P. Turkiewicz, Y. Liu, and A. M. J. Koonen, "Self-controlled all-optical label and payload separator for variable length bursts in a time-serial IM/DPSK scheme," *IEEE Photon. Technol. Lett.*, vol. 17, no. 8, pp. 1692–1694, Aug. 2005.
- [7] N. Deng, Y. Yang, C. Chan, W. Hung, and L. Chen, "Intensity-modulated labeling and all-optical label swapping on angle-modulated optical packets," *IEEE Photon. Technol. Lett.*, vol. 16, no. 4, pp. 1218–1220, Apr. 2004.
- [8] W. Cai, Y. Dong, M. Zou, Q. Zhang, M. Chen, and S. Xie, "Reduction of waveform distortion in a semiconductor optical amplifier using internal birefringence and slope filtering," in *Proc. ECOC'01*, 2001, pp. 404–405, Paper We. P. 13.
- [9] B. S. Gopalakrishnapillai, M. Premaratne, A. Nirmalathas, and C. Lim, "Power equalization using polarization rotation in semiconductor optical amplifiers," *IEEE Photon. Technol. Lett.*, vol. 17, no. 8, pp. 1695–1697, Aug. 2005.
- [10] Y. Liu, M. T. Hill, H. de Waardt, G. D. Khoe, D. Lenstra, and H. J. S. Dorren, "All-optical flip-flop memory based on two coupled polarization switches," *Electron. Lett.*, vol. 38, pp. 904–906, Aug. 2002.
- [11] T. Kakitsuka, Y. Shibata, M. Itoh, Y. Kadota, Y. Tohmori, and Y. Yoshikuni, "Influence of buried structure on polarization sensitivity in strained bulk semiconductor optical amplifiers," *IEEE J. Quantum Electron.*, vol. 38, no. 1, pp. 85–92, Jan. 2002.
- [12] M. Itoh, Y. Shibata, T. Kakitsuka, Y. Kadota, and Y. Tohmori, "Polarization-insensitive SOA with a strained bulk active layer for network device application," *IEEE Photon. Technol. Lett.*, vol. 14, no. 6, pp. 765–767, Jun. 2002.
- [13] Y. Liu, M. T. Hill, E. Tangdiongga, H. de Waardt, N. Calabretta, G. D. Khoe, and H. J. S. Dorren, "Wavelength conversion using nonlinear polarization rotation in a single semiconductor optical amplifier," *IEEE Photon. Technol. Lett.*, vol. 15, no. 1, pp. 90–92, Jan. 2003.
- [14] Y. Takahashi, A. Neogi, and H. Kawaguchi, "Polarization-dependent nonlinear gain in semiconductor lasers," *IEEE J. Quantum Electron.*, vol. 34, no. 9, pp. 1660–1672, Sep. 1998.
- [15] H. J. S. Dorren, D. Lenstra, Y. Liu, M. T. Hill, and G. D. Khoe, "Nonlinear polarization rotation in semiconductor optical amplifiers: Theory and application to all-optical flip-flop memories," *IEEE J. Quantum Electron.*, vol. 39, no. 1, pp. 141–148, Jan. 2003.

- [16] M. Itoh, Y. Shibata, T. Kakitsuka, Y. Kadota, and Y. Tohmori, "Polarization-insensitive SOA with a strained bulk active layer for network device application," *IEEE Photon. Technol. Lett.*, vol. 14, no. 6, pp. 765–767, Jun. 2002.
- [17] M. Premaratne and A. J. Lowery, "Analytical characterization of SOA-based optical pulse delay discriminator," *J. Lightw. Technol.*, vol. 23, no. 9, pp. 2778–2787, Sep. 2005.
- [18] G. P. Agrawal and N. A. Olsson, "Self-phase modulation and spectral broadening of optical pulses in semiconductor laser amplifiers," *IEEE J. Quantum Electron.*, vol. 25, no. 11, pp. 2297–2306, Nov. 1989.
- [19] X. Yang, D. Lenstra, G. D. Khoe, and H. J. S. Dorren, "Nonlinear polarization rotation induced by ultrashort optical pulses in a semiconductor optical amplifier," *Opt. Commun.*, vol. 223, pp. 169–179, Jul. 2003.
- [20] A. E. Siegman, *Lasers*. Mill Valley, CA: University Science Books, 1986.
- [21] M. Eiselt, W. Pieper, and H. G. Weber, "SLALOM: sEmiconductor laser amplifier in a loop mirror," *J. Lightw. Technol.*, vol. 13, no. 10, pp. 2099–2112, Oct. 1995.
- [22] B. S. Gopalakrishnapillai, K. L. Lee, A. J. Lowery, M. Premaratne, S. Shinada, N. Wada, T. Miyazaki, A. Nirmalathas, and C. Lim, "Experimental demonstration of a simple time-of-flight rangefinder based on semiconductor optical amplifier," presented at the Proc. OFC'06, 2006, Paper OTuL5.
- [23] E. S. Awad, C. J. K. Richardson, P. S. Cho, N. Moulton, and J. Goldhar, "Optical clock recovery using SOA for relative timing extraction between counterpropagating short picosecond pulses," *IEEE Photon. Technol. Lett.*, vol. 14, no. 3, pp. 396–398, Mar. 2002.
- [24] M. Premaratne and A. J. Lowery, "Semiclassical analysis of the impact of noise in SOA-based optical pulse delay discriminator optical pulse delay discriminator," *IEEE J. Select. Topics Quantum Electron.*, vol. 12, no. 4, pp. 708–716, Jul.-Aug. 2006.
- [25] A. Mecozzi and J. Mork, "Saturation effects in nondegenerate four-wave mixing between short optical pulses in semiconductor laser amplifiers," *IEEE J. Select. Topics Quantum Electron.*, vol. 3, no. 10, pp. 1190–1207, Oct. 1997.
- [26] E. Scholl, D. Bimberg, H. Schumacher, and P. Landsberg, "Kinetics of picosecond pulse generation in semiconductor lasers with bimolecular recombination at high current injection," *IEEE J. Quantum Electron.*, vol. 20, no. 4, pp. 394–399, Apr. 1984.
- [27] J.-N. Fehr, M.-A. Dupertuis, T. P. Hessler, L. Kappei, D. Marti, F. Salleras, M. S. Nomura, B. Deveaud, J.-Y. Emery, and B. Dagens, "Hot phonons and Auger related carrier heating in semiconductor optical amplifiers," *IEEE J. Quantum Electron.*, vol. 38, no. 6, pp. 674–681, Jun. 2002.
- [28] S. Scotti, L. Graziani, A. D'Ottavi, F. Martelli, A. Mecozzi, P. Spano, R. Dall'Ara, F. Girardin, and G. Guekos, "Effects of ultrafast processes on frequency converters based on four-wave mixing in semiconductor optical amplifiers," *IEEE J. Select. Topics Quantum Electron.*, vol. 3, no. 10, pp. 1156–1161, Oct. 1997.

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