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Comparison of pulse propagation and gain saturation characteristics among different input pulse shapes in semiconductor optical amplifiers

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ABSTRACT

This paper presents the pulse propagation and gain saturation characteristics for different input optical pulse shapes with different energy levels in semiconductor optical amplifiers (SOAs). A finite-difference beam propagation method (FD-BPM) is used to solve the modified nonlinear Schrödinger equation (MNLSE) for the simulation of nonlinear optical pulse propagation and gain saturation characteristics in the SOAs. In this MNLSE, the gain spectrum dynamics, gain saturation are taken into account those are depend on the carrier depletion, carrier heating, spectral hole-burning, group velocity dispersion, self-phase modulation and two photon absorption. From this simulation, we obtained the output waveforms and spectra for different input pulse shapes considering different input energy levels. It has shown that the output pulse shape has changed due to the variation of input parameters, such as input pulse shape, input pulse width, and input pulse energy levels. It also shown clearly that the peak position of the output waveforms are shifted toward the leading edge which is due to the gain saturation of the SOA. We also compared the gain saturation characteristics in the SOA for different input pulse shapes.

1. Introduction

In recent years, high-speed communication systems and all-optical signal processing techniques play an important role to avoid electro-optic conversions which may create data-flow bottlenecks. Semiconductor optical amplifiers (SOAs) are widely used in many functional applications, such as wavelength conversion, optical switching, optical signal processing pulse reshaping, and power limiting. SOAs are the key component for short optical pulse amplification and optical switching at a very high speed communications because of their small size, a low switching energy, non-linear characteristics and ability to integrate with other optical devices [1–4].

The purpose of modelling an SOA is to relate the internal variables of the amplifier with external variables, such as the output signal power and output saturation power [3]. When a short input optical pulse is injected into the active region of the SOA, stimulation emission takes place resulting in optical signal amplification. Therefore, the carrier density reduces and causes a drop of the SOA gain [2]. The amplification rate and gain saturation varies according to the input pulse shapes. The modified nonlinear Schrödinger equation (MNLSE) is used in most pulse propagation models that include the SOA non-linearities [5]. Pulse propagation through an SOA is strongly dependent on the input pulse shape [6].

The main objective of this paper is to investigate the nonlinear optical pulse propagation and gain saturation characteristics depending on different types of input pulse shapes and energy levels in SOAs for high speed communication systems. This analysis is based on the MNLSE considering the non-linearities in SOA, such as self-phase modulation (SPM), two-photon absorption (TPA), group velocity dispersion (GVD), carrier depletion (CD), carrier heating (CH), spectral-hole burning (SHB), gain spectrum dynamics, and gain saturation in the SOA [5,7]. To solve the MNLSE, the finite-difference beam propagation method (FD-BPM) is used because of its short convergence time and excellent accuracy of the simulated results [8–16]. For simulation of pulse propagation with small propagation steps, FD-BPM is considered as the best method compared to others [8–14]. In this paper, we have numerically investigated and compared the output waveforms or

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propagated pulses characteristics and the gain saturation characteristics for different types of input pulse shapes in SOAs. The input pulse shapes were considered as, (i) Secant hyperbolic pulse, (ii) Gaussian pulse, and (iii) Lorentzian-shaped pulse.

2. Modified nonlinear Schrödinger equation (MNLSE) for SOA modelling

The theoretical model of short optical pulses propagation in SOAs will be briefly described in this section. Starting from Maxwell's equations, we reach to the propagation equation of short optical pulses in SOAs which are governed by the wave equation in the frequency domain [15,17–22]:

$$\nabla^2\bar{E}(x, y, z, \omega) + \frac{\varepsilon_r}{c^2}\omega^2\bar{E}(x, y, z, \omega) = 0 \tag{1}$$

where, $\bar{E}(x, y, z, \omega)$ is the electromagnetic field of the pulse in the frequency domain, c is the velocity of light in vacuum and ε_r is the non-linear dielectric constant which is dependent on the electric field in a complex form. By using the slowly varying envelope approximation and integrating the transverse dimensions, the pulse propagation equation in SOAs is [15,23]:

$$\frac{\partial V(\omega, z)}{\partial z} = -i\{\frac{\omega}{c}[1 = \chi_m(\omega) + \Gamma\tilde{\chi}(\omega, N)]^{1/2} - \beta_0\}V(\omega, z) \tag{2}$$

where, $V(\omega, z)$is the Fourier-transform of $V(t, z)$ representing pulse envelope, $\chi_m(\omega)$ is the background (mode and material) susceptibility, $\tilde{\chi}_m(\omega)$ is the complex susceptibility which represents the contribution of the active medium, N is the effective population density, β_0 is the propagation constant. The quantity Γ represents the overlap/confinement factor of the transverse field distribution of the signal with the active region as defined in [15].

Using mathematical manipulations [19,23], which includes the real part of the instantaneous non-linear Kerr effect as a single non-linear index n_2 and by adding the TPA term, the MNLSE for the phenomenological model of semiconductor laser and amplifiers is obtained [24].

For this modelling, Eq. (3) [9–14] is used for the simulation of pulse propagation with different input pulse shapes in SOAs. The MNLSE uses the complex envelope $V(\tau, z)$ function of an optical pulse which is given in Eq. (3).

$$\begin{aligned}&[\frac{\partial}{\partial z} - \frac{i}{2}\beta_2\frac{\partial^2}{\partial\tau^2} + \frac{\gamma}{2} + (\frac{\gamma_{2p}}{2} + ib_2)\ |V(\tau, z)|^2]\\ &\quad V(\tau, z) = \{\frac{1}{2}g_N(\tau)\ [\frac{1}{f(\tau)} + i\alpha_N] + \frac{1}{2}\Delta g_T(\tau)(1 + i\alpha_T)\\ &-i\frac{1}{2}\frac{\partial g(\tau, \omega)}{\partial\omega}|_{\omega_0}\frac{\partial}{\partial\tau} - \frac{1}{4}\frac{\partial^2 g(\tau, \omega)}{\partial\omega^2}|_{\omega_0}\frac{\partial^2}{\partial\tau^2}\}V(\tau, z)\end{aligned} \tag{3}$$

where,

$$g_N(\tau) = g_0\exp(-\frac{1}{W_s}\int_{-\infty}^{\tau} e^{-s/\tau_s}|V(s)|^2 ds) \tag{4}$$

$$f(\tau) = 1 + \frac{1}{\tau_{shb}P_{shb}}\int_{-\infty}^{+\infty} u(s)e^{-s/\tau_{shb}}|V(\tau - s)|^2 ds \tag{5}$$

$$\begin{aligned}\Delta g_T(\tau) = &- h_1\int_{-\infty}^{+\infty} u(s)e^{-s/\tau_{ch}}(1 - e^{-s/\tau_{shb}})|V(\tau - s)|^2 ds\\ &- h_2\int_{-\infty}^{+\infty} u(s)e^{-s/\tau_{ch}}(1 - e^{-s/\tau_{shb}})|V(\tau - s)|^4 ds\end{aligned} \tag{6}$$

$$\left.\frac{\partial g(\tau, \omega)}{\partial\omega}\right|_{\omega_0} = A_1 + B_1[g_0 - g(\tau, \omega_0)] \tag{7}$$

$$\left.\frac{\partial^2 g(\tau, \omega)}{\partial\omega^2}\right|_{\omega_0} = A_2 + B_2[g_0 - g(\tau, \omega_0)] \tag{8}$$

$$g(\tau, \omega_0) = g_N(\tau, \omega_0)/f(\tau) + \Delta g_T(\tau, \omega_0) \tag{9}$$

We introduce the frame of the local time $\tau(= t - z/v_g)$ which propagates with the group velocity v_g at the centre frequency of an optical pulse. The slowly varying envelope approximation is used in (3), where the temporal variation change of the complex envelope function is very slow compared with the cycle of an optical field. In (3), $V(\tau, z)$ is the time domain complex envelope function of an optical pulse and $|V(\tau, z)|^2$ corresponds to the optical intensity or power, and β_2 is the GVD. γ is the linear loss, γ_{2p} is the TPA coefficient, $b_2(= \omega_0 n_2/cA)$is the instantaneous SPM term due to the instantaneous nonlinear refractive index n_2 (Kerr's effect), $\omega_0(= 2\pi f_0)$ is the centre angular frequency of the pulse, c is the velocity of light in vacuum, $A(= wd/\Gamma)$ is the effective area (d and w are the thickness and width of the active region, respectively, and Γ is the confinement factor). $g_N(\tau)$ is the saturated gain due to CD, g_0 is the linear gain, W_s is the saturation energy, τ_s is the carrier lifetime, $f(\tau)$ is the SHB function, P_{shb} is the SHB saturation power, τ_{shb} is the SHB relaxation time, and α_N and α_T are the line width enhancement factor associated with the gain changes due to the CD and CH. $\Delta g_T(\tau)$ is the resulting gain change due to the CH and TPA. $u(s)$ is the unit step function, τ_{ch} the CH relaxation time, h_1 is the contribution of stimulated emission and free-carrier absorption to the CH gain reduction, and h_2 is the contribution of TPA. Finally,A_1 and A_2 are the slope and the curvature of the linear gain at ω_0 respectively, while B_1 and B_2 are constants describing changes in these quantities with saturation. In this simulation, the gain spectrum of an SOA is approximated by the following second-order Taylor expansion in$\Delta\omega$:

$$g(\tau, \omega) = g(\tau, \omega_0) + \Delta\omega\left.\frac{\partial g(\tau, \omega)}{\partial\omega}\right|_{\omega_0} + \frac{(\Delta\omega)^2}{2}\left.\frac{\partial^2 g(\tau, \omega)}{\partial\omega^2}\right|_{\omega_0} \tag{10}$$

The coefficients $\partial g(\tau, \omega)/\partial\omega|_{\omega_0}$ and $\partial^2 g(\tau, \omega)/\partial\omega^2|_{\omega_0}$ are related to A_1, A_2, B_1 and B_2 as given by (7) and (8). We assumed the same values of A_1, A_2, B_1 and B_2 as for an AlGaAs/GaAs bulk SOA [9–14].

Generally, the fast Fourier transformation BPM (FFT-BPM) is used for analysis of the optical pulse propagation in optical fibres by successive iterations of the Fourier transformation and the inverse Fourier transformation. In the FFT-BPM, the linear propagation term (GVD term) and phase compensation terms (other than GVD, first- and second-order gain spectrum terms) will be separated in the nonlinear Schrödinger equation for the individual consideration of the time and frequency domain for the optical pulse propagation. However, in our model, (3) includes the dynamic gain change terms, i.e., the first- and second-order gain spectrum terms which are the last two terms of the right side in (3). Therefore, it is not possible to separate (3) into the linear propagation term and phase compensation term, and it is difficult to calculate (3) using the FFT-BPM. For this reason, we have used the FD-BPM [9–14] to solve this MNLSE.

3. Simulation results and discussion

In this section, simulation results of single pulse propagation