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Investigation of Transient Amplified Spontaneous Emission in Semiconductor Laser Amplifier

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***Abstract*- Spontaneous emission is one of the important noise sources in semiconductor laser amplifiers (SLAs). In this paper we analyze the dynamic behavior of this phenomenon in SLA based on numerical solution of the carrier and field rate equations. From the numerical results we obtain the evolution of the gain and amplified spontaneous emission dynamics which presented for the first time.**

***Keywords*- Semiconductor laser Amplifier, Transient Response, Amplified Spontaneous Emission**

I. INTRODUCTION

ONE of the major milestones in the evolution of optical transmission systems was the development of optical amplifiers in the late 1980's. SLAs nowadays are essential component in transmission systems and networks to compensate for system losses. This kind of amplifier can be used in many different configurations such as preamplifier, power amplifier or line amplifier and also can be used for many applications like optical switch, gate, and wavelength converter because of its great exhibition of non-linear properties. Therefore, for modeling and analyzing these applications static and dynamic behavior of SLA should be understood carefully. Mathematical models are required for design of SLAs and prediction of their operational characteristics. Many of such models have been presented in the literature [1]–[5]. However, these models make assumptions that restrict the range of operating conditions over which the SLA can be modeled. These assumptions are used either to obtain the analytic solutions for the amplifier characteristics, or to aid the numerical computation.

SLAs can be used to simultaneously amplify a number of signals at different wavelengths. To model such an application, a wideband model of SLA is required. In this paper, a comprehensive wideband model of a bulk InP–InGaAsP SLA is presented. The important feature of our model is consideration of the exact dependency of gain on material parameters. Through the use of suitable gain models it can be extended to SLAs with quantum-well active regions. In the model, the relationship between spontaneous and stimulated emission is clarified. This relationship does not require the use of a spontaneous emission factor used in many models. Spontaneous emission within the amplifier is modeled by traveling-wave power equations, which neglect the phase of the spontaneous signal. The model can be applied to determine the steady-state and dynamic properties of a SLA over a wide range of operating regimes. A numerical algorithm is described [1] which enables efficient implementation of the model.

This model is used to study the transient amplified spontaneous emission of SLA with a new gain spectrum. As the input pulse propagates in the waveguide, some spontaneous power is added to it that we will obtain its transient behavior in different positions of the amplifier cavity.

II. AMPLIFIER STRUCTURE AND BULK MATERIAL MODEL

The modeled SLA is a 1.55μm InP–$In_{1-x}Ga_xAs_yP_{1-y}$ homogeneous buried ridge stripe device with schematic cross-section shown in Fig. 1 [6]. y and x are the molar fractions of Arsenide and Gallium, respectively, in the undoped active region. Lattice matching is assumed for x=0.47y. The device structure consists of a central active region of the width W, thickness d, and length L_c. The active region narrows linearly as a lateral taper of the width W at the central region to zero width at each end. Each taper has the length L_t.

As a first approximation, the SLA is modeled as a device with the mean length L, given by:

$$L = L_c + L_t \tag{1}$$

Pertinent geometrical and material parameters for the device under consideration are given in [6]. The InGaAsP direct bandgap bulk-material active region has a material gain coefficient g_m, given by [7]:

$$g_m(\nu,n) = \frac{c^2}{4\sqrt{2}\pi^{3/2} n_1^2 \tau \nu^2}\left(\frac{2m_e m_{hh}}{\hbar(m_e + m_{hh})}\right)^{3/2} \times\sqrt{\nu - \frac{E_g(n)}{h}}\left(f_c(\nu) - f_v(\nu)\right). \tag{2}$$

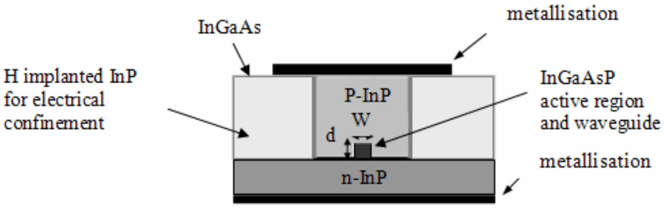


Fig. 1 Cross-section of SLA.

where

c	speed of light in vacuum;
v	optical frequency;
n_1	active region refractive index;
τ	radiative recombination lifetime;
$\hbar$	Planck's constant divided by 2π;
m_e	conduction band (CB) electron mass;
m_{hh}	valence band (VB) heavy hole mass;
n	CB carrier (electron) density.

III. SLA MODEL

The SLA model developed in [1] is based on the numerical solution of the carrier density equation. In the model, N_s signals are injected with optical frequencies ν_k (k=1 to N_s). This equation is time and space dependent:

$$
\begin{aligned}
\frac{dn(z)}{dt} &= \frac{I}{edLW} - R(n(z)) \\
&- \frac{\Gamma}{dW}\left\{\sum_{k=1}^{N_s} g_m(\nu_k, n(z))\left(N_{Sk}^{+}(z) + N_{Sk}^{-}(z)\right)\right\} \\
&- \frac{2\Gamma}{dW}\left\{\sum_{j=0}^{N_m-1} g_m(\nu_j, n(z))K_j\left(N_j^{+}(z) + N_j^{-}(z)\right)\right\}
\end{aligned}
\qquad (3)
$$

where I is the amplifier bias current and Γ is the confinement factor. In (3) it is assumed that all of the bias current passes through the active region only and not the surrounding InP regions. The bias current is assumed to have a uniform distribution across the active region width. The first term on the right hand side of (3) represents the addition of carriers to the active region from the bias current. These injected carriers are then depleted by various mechanisms occurring within the amplifier. $R(n)$ is the recombination rate term.

The third and fourth terms represent the radiative recombination of carriers due to the amplified signal and amplified spontaneous emission, respectively. The factor of two in the forth term accounts for the fact that the spontaneously emitted photons can exist in one of two mutually orthogonal polarizations (TE or TM). In the model, the SLA is assumed to be polarization independent. Polarization dependence can be included by the use of different TE and TM optical confinement factors. N_m is a positive integer. The value of N_m depends on the gain bandwidth of the SLA and the accuracy required for the numerical solution of the model equations. K_j is the normalization factor which is derived in [6]. N_{Sk}^+ and N_{Sk}^- are the photon rates of the wave in the positive and negative directions, respectively. N_j^+ and N_j^- are the spontaneous emission photon rates for a particular polarization traveling in the positive and negative directions, respectively.

We also need to solve the traveling wave equations to get the photon rates corresponding to the signal light and ASE:

$$
\frac{dE_{Sk}^{\pm}(z)}{dz} = \pm\frac{1}{2}\left[\Gamma g_m(\nu_k, n(z)) - \alpha(n)\right]E_{Sk}^{\pm}(z) \qquad (4)
$$

$$
\begin{aligned}
\frac{dN_j^{\pm}(z)}{dz} &= \pm\left[\Gamma g_m(\nu_j, n(z) - \alpha(n)\right]N_j^{\pm}(z) \\
&+ R_{Sp}(\nu_j, n(z))
\end{aligned}
\qquad (5)
$$

where $E_{Sk}^{\pm}$ is the spatially varying component of the field propagating in the positive and negative directions of z. The modulus squared of the amplitude of a traveling-wave is equal to the photon rate of the wave in that direction. The function R_{Sp} represents the spontaneously emitted noise coupled into N_j^+ or N_j^-.

IV. SIMULATION AND RESULTS

The steady state characteristics can be obtained using the numerical algorithm which is presented before in [1]. Results show that at low input powers, the carrier density has a symmetrical spatial distribution, peaking at the center of the SLA and tailing off toward the input and output facets. At high input powers, the carrier density spatial distribution becomes more asymmetrical, with the peak moving toward the input facet. This is caused by the input signal dominating over amplified spontaneous emission.

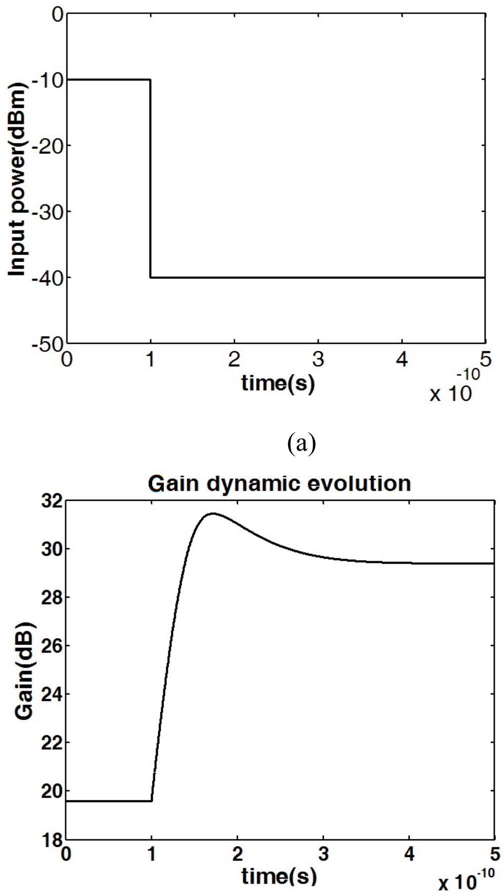
In order to predict the response of SLAs to the modulated signal, we must consider the transient state. We still use the equations presented in section III. To obtain the transient solution between two steady states, we first solve for the initial state, then let the carrier density $n(z,t)$ evolve according to the carrier density (3) with small increments of time [6]. The applied signal power and the gain response are shown in Figs 2(a) and 2(b), respectively. It's seen that the gain overshoot occurs. This phenomenon is caused by the carrier life time.

As shown in Fig. 2 when the input power is -10 dBm, SLA is in the saturation state, so there is no population inversion and there are many empty states in the conduction band. After switching the input power to -40 dBm, the carrier density and so the photon generation rate increase in time. This causes rise time for the gain shape. This continues until the population inversion occurs. After this time, the gain value reaches its final (steady state) value.

In the next step, the amplified spontaneous emission is considered. To see the behavior of SLA in saturation and non-saturation conditions, the input signal is changed to a step like pulse which is shown in Fig.3. When this signal is incident into the SLA, the nonlinear effects of the amplifier appear, and affect the signal which propagates in the waveguide.

In the semiconductor laser amplifier the spontaneous emission is an undesired phenomenon which is added to signal and degrade the transparency of SLA to the input signal because of its random nature. Therefore, it acts as a noise source and should be estimated carefully. When the signal propagates through the waveguide, the spontaneous emission is added to it and increases its power in the steady state condition [1].

Since in the SLA model the forward and backward propagations in the waveguide are considered for each section, the spontaneous emission also had two components. The backward and forward spontaneous emission photon densities are shown in Figs. 5 and 6, respectively. In the saturation state when the power of the incident signal is -10 dBm, the population inversion doesn't occur, so when the input pulse power changes to -40dBm, it takes some time for population inversion to be established. But, when the signal power is -40dBm and the amplifier isn't in the saturation state, there are many carriers in the conduction band and so we have the population inversion. Therefore, by increasing the input pulse power to -10dBm, these carriers deplete from the conduction band and therefore it takes more transient time than in the saturation state, which is shown clearly in Figs. 5 and 6. This is because of the carrier life time.



(a)

(b)

Fig 2. (a) Input power to SLA (b) the gain dynamics

In the first section of the amplifier cavity, as shown in Fig. 5-a, the backward spontaneous emission photon rate is greater because of the amplification in previous sections through it's propagation through the waveguide. So, when it reaches to the left facet it has the maximum amplitude. But for the forward spontaneous emission, the photon rate is greater in the final section as shown in Fig. 6-c.

V. CONCLUSION

We used a versatile numerical model to obtain the dynamic behavior of SLA to investigate the amplified spontaneous photon rate in conversion and amplification processes. From the simulation results we can see the variation of the amplified spontaneous signal power and the carrier density in time along the cavity length. It is shown that in the first section the backward spontaneous signal is more powerful and in the final section the forward spontaneous signal is the major part of the total spontaneous signal.

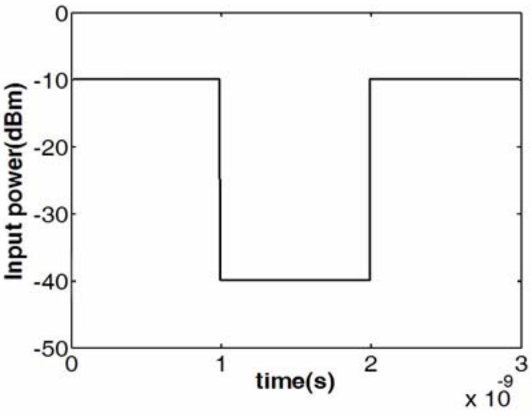


Fig. 3 Input signal power

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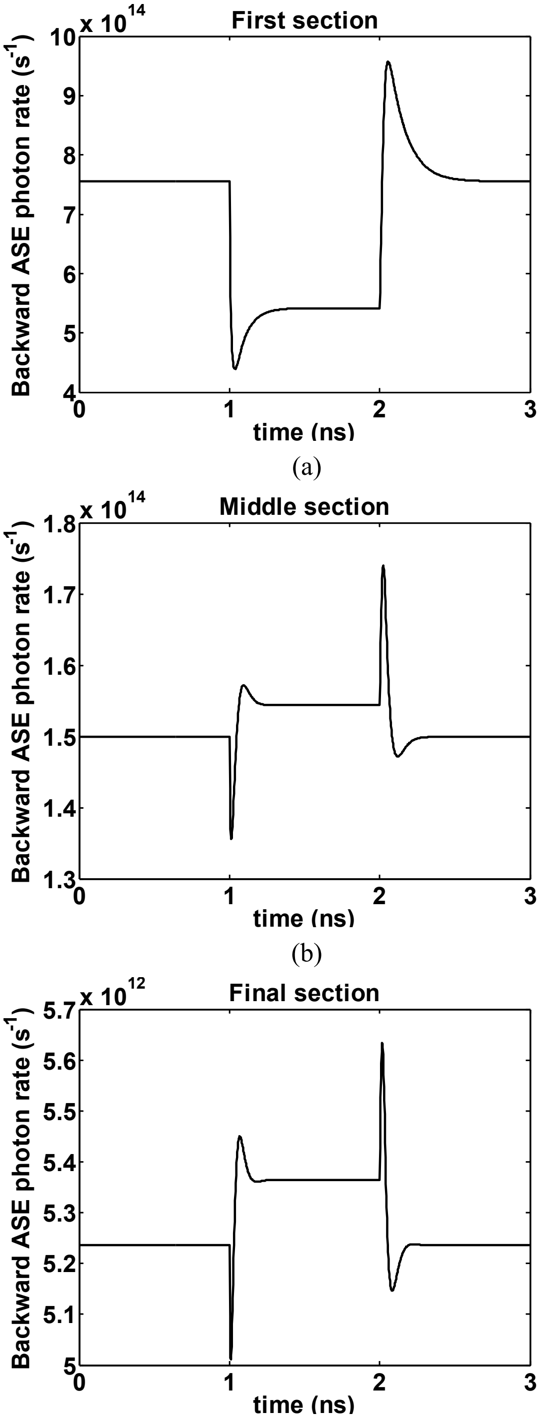
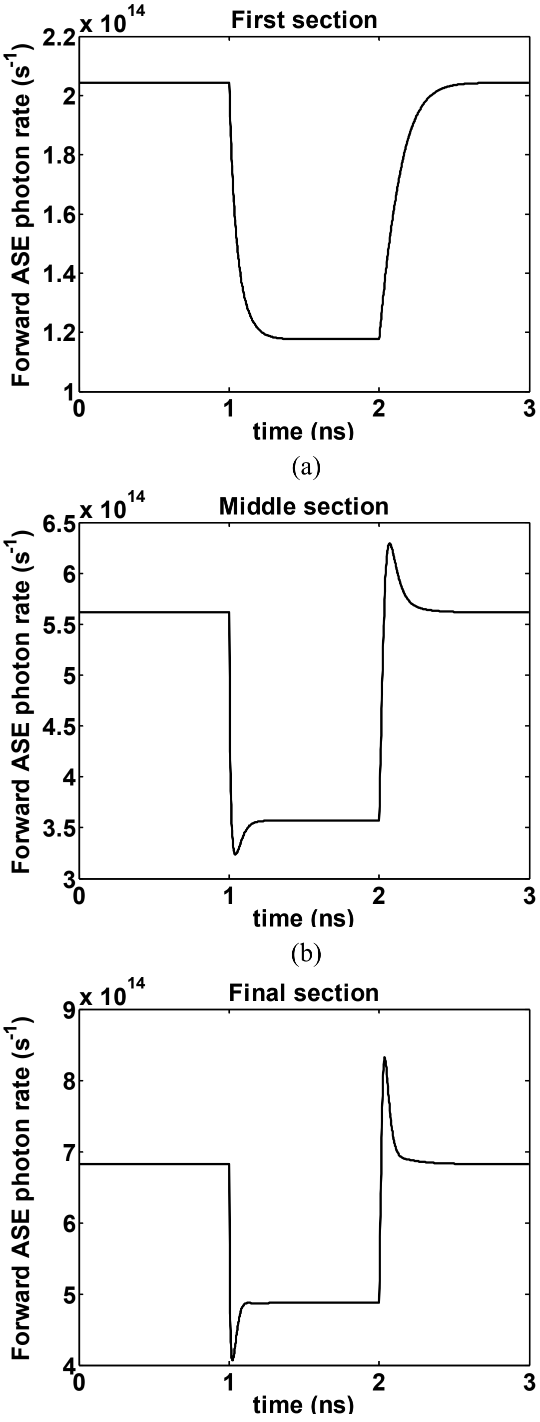


(a)

(b)

(c)

Fig. 5 Backward amplified spontaneous emission photon rate in (a) first section, (b) middle and (c) final section of amplifier.



(a)

(b)

(c)

Fig. 6 Forward amplified spontaneous emission photon rate in (a) first section, (b) middle and (c) final section of amplifier.