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Improved reduced models for single-pass and reflective semiconductor optical amplifiers

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ABSTRACT

We present highly accurate and easy to implement, improved lumped semiconductor optical amplifier (SOA) models for both single-pass and reflective semiconductor optical amplifiers (RSOA). The key feature of the model is the inclusion of the internal losses and we show that a few SOA subdivisions are required to achieve a computational accuracy of <0.12 dB. For the case of RSOAs, we generalize a recently published model to account for the internal losses that are vital to replicate the observed RSOA behavior. The results of the improved reduced RSOA model show large overlap when compared to a full bidirectional travelling wave model for over a 40 dB dynamic range of input powers and a 20 dB dynamic range of reflectivity values. The models would be useful for the rapid system simulation of signals in communication systems, i.e. passive optical networks that employ RSOAs, signal processing using SOAs.

1. Introduction

Modeling semiconductor optical amplifiers (SOA) has been a topic for over two decades [1–4]. Recently models of reflective SOAs (RSOA) have emerged [3,4], mainly driven by RSOA exploitation within passive optical networks (PON) [5,6]. Reduced (or lumped) SOA models [1–3] allow for solving the gain and refractive index dynamics without having to solve computationally intensive propagation equations [4]. In all the reduced SOA models presented, the inclusion of internal scattering losses in the lumped SOA models have proven to be elusive due to the fact that no analytical solution arises when the internal scattering losses are non-zero [1,7].

In this paper we propose an improved reduced model for both SOAs and RSOAs that approximates the inclusion of the internal scattering losses. The assumption is based on considering the SOA's gain coefficient to be constant over a certain length of SOA. This assumption is certainly valid for (i) short SOA sections; (ii) when the optical power is much less than the SOA saturation power and (iii) under strong saturation conditions when the gain is depleted to the extent such that there are no large longitudinal variations in the gain coefficient. For single pass SOAs, the maximum discrepancy of 1 dB was found when calculating output power by considering a *single calculation step over the entire SOA* as opposed to splitting the SOA up into 40 subsections.

The improved reduced model for SOAs is extended to RSOAs and builds upon the simpler of the two recently published reduced RSOA models [3], allowing for the inclusion of the internal scattering losses. The results from the improved reduced model are compared with the full travelling wave model (TWM) [4], showing excellent agreement with discrepancies <1 dB over a 40 dB dynamic range of input powers combined with a 20 dB dynamic range of reflectivity values. In addition, we also show how the losses are incorporated in accounting for the intraband contributions to the nonlinear gain. The inclusion of these effects enables the simulation of all-optical signal processing using four-wave mixing (FWM).

The method obviates the need for an (R)SOA model with many distance steps, allowing for rapid and accurate system performance calculations when analyzing the propagation (and or processing) of $>10^5$ signal symbols through (R)SOAs.

2. Improved reduced SOA model

We begin the analysis by transcribing the SOA propagation and gain dynamics equations [1]

$$\frac{d|E(z,t)|^2}{dz} = (g(z,t) - \alpha_{loss})|E(z,t)|^2 \quad (1)$$

$$\frac{d\phi(z,t)}{dz} = -\frac{1}{2}\alpha_H g(z,t) \quad (2)$$

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$$\frac{dg(z,t)}{dt}=\frac{g_0-g(z,t)}{\tau_S}-\frac{g(z,t)|E(z,t)|^2}{\tau_S P_{sat}} \tag{3}$$

Eqs. (1) and (2) describe the amplification and phase shift accumulation of the optical field, $E(z,t)$, along the SOA with z and t being the spatial and temporal variables; the optical power is given by $|E(z,t)|^2$. α_{loss} describes the internal scattering losses. g is the gain coefficient whose dynamics are described by Eq. (3); the second term on the right hand side of which describes gain depletion due to stimulated emission while the first term describes gain recovery back to the unsaturated value g_0. The gain recovery time, τ_S, is the carrier lifetime. P_{sat} is the saturation power. The gain-phase coupling is determined by α_H. The reduced models rely on integrating the gain over a length, L, of the SOA. Equating h as the spatially-integrated SOA gain coefficient over L:

$$h(t)=\int_0^L g(z,t)dz\equiv g_{av}(t)L. \tag{4}$$

We define $g_{av}(t)$ as the spatially-averaged gain coefficient. The assumption is valid as long as the spatial profile of the gain coefficient is constant. In principle, unidirectional signal amplification along the SOA causes the gain coefficient to monotonically decrease along the length of the SOA, thus requiring for the SOA to be broken up into many sections in order to capture the correct gain profile. Assuming a constant gain coefficient allows us to write an approximate analytical expression for the integral of the second term on the right hand side of Eq. (3). The input optical field to the SOA is given as $E_{in}(t)=E(0,t)$; using (4), Eqs. (1) and (3) can be re-written as

$$|E(z,t)|^2\approx|E_{in}(t)|^2\exp\{(g_{av}(t)-\alpha_{loss})z\} \tag{5}$$

$$\frac{dh(t)}{dt}\approx\frac{h_0-h(t)}{\tau_S}-\frac{g_{av}(t)|E_{in}(t)|^2\int_0^L\exp\{(g_{av}(t)-\alpha_{loss})z\}dz}{\tau_S P_{sat}} \tag{6}$$

The integral in (6) can be performed by inserting the result for $|E(z,t)|^2$ from (5) and substituting h for g_{av} using (4) to give

$$\frac{dh(t)}{dt}\approx\frac{h_0-h(t)}{\tau_S}-\frac{h(t)}{h(t)-\alpha_{loss}L}\frac{[\exp\{h(t)-\alpha_{loss}L\}-1]|E_{in}(t)|^2}{\tau_S P_{sat}} \tag{7}$$

An expression for the total phase change is written as

$$\phi_{tot}(t)=-\tfrac{1}{2}\alpha_H h(t) \tag{8}$$

The output optical field is simply expressed as

$$E_{out}(t)=E_{in}(t)\exp\{\tfrac{1}{2}(-\alpha_{loss}L+(1-j\alpha_H)h(t))\} \tag{9}$$

It should be noted that Eqs. (7) and (9) reduce to the analytic formalism when $\alpha_{loss}=0$ [1], because the true analytical solution for $h(t)$ holds irrespective of the spatial gain profile $g(z,t)$.

To verify Eqs. (7) and (9), and to highlight the improvement of the current approach, we subdivide the SOA into separate sections and note the number of required subsections before the output power reaches a consistent value. The scenario is depicted in Fig. 1 with K being the number of considered subsections. This is performed for continuous wave (CW) signals whose input power ranges from −40 to 10 dBm, with K varying from 1 to 40. The results are shown in Fig. 2 using the SOA parameters given in Table 1; the net unsaturated SOA gain is ~28 dB. We define the discrepancy between the output power calculation by considering K subdivisions and 40 subdivisions as

$$D(K)=10\log_{10}\left(\frac{P_{out}^{(K)}}{P_{out}^{(40)}}\right) \tag{10}$$

As predicted for low input powers, there is no discrepancy between the output power calculation because the SOA gain profile is constant as the power in the SOA is much less than P_{sat}. Though when the input power increases, the gain profile no longer remains flat thus requiring more subdivisions to get an accurate value for the output power. As it is clear from Fig. 2, a maximum discrepancy of just 1 dB is found over the entire input power range up to 10 dBm by considering a single subdivision, this is an acceptable error in most circumstances. For the cases when greater accuracy is required, the discrepancy could be reduced below 0.12 dB by only considering 3 subdivisions, as is evident from Fig. 2.

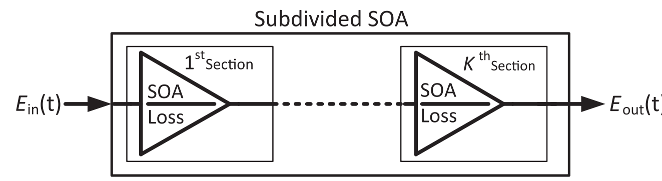

Fig. 1. Simulation setup employed to show the splitting of the SOA into K subsection SOAs. The optical field output for the $(k-1)$th section becomes the input to the kth section.

3. Four-wave mixing

The previous reduced models [2] also accounted for the intraband contributions to the nonlinear SOA gain [7]. FWM is the only 3rd order nonlinear process that is transparent to the modulation format and has been used to process a variety of signals with amplitude and/or phase encoding [2,8,9]. We will now show how the intraband effects can be included in the improved model. Starting with the rate equation describing the dynamics of carrier heating (CH) [2,7]:

$$\frac{d\Delta g_{ch}(t)}{dt}=-\frac{\Delta g_{ch}(t)}{\tau_{ch}}-\frac{g(t)|E(z,t)|^2}{P_{sat\_ch}\tau_{ch}} \tag{11}$$

where Δg_{ch} is the gain change due to CH, τ_{ch} is the associated time constant with carrier-phonon collisions and is ~500 fs. g is the optical gain defined in Eq. (1) and P_{sat_ch} is the saturation powers associated with CH. Using the technique outlined in (4)–(7) and invoking the adiabatic limit, that changes in $|E_{in}(t)|^2$ occur over timescales longer than τ_{ch} i.e. $d\Delta g_{ch}/dt=0$, the spatially integrated version (11) yields the contribution to the gain of

$$\Delta h_{ch}(t)\approx-\frac{h(t)}{h(t)-\alpha_{loss}L}\frac{[\exp\{h(t)-\alpha_{loss}L\}-1]|E_{in}(t)|^2}{P_{sat\_ch}} \tag{12}$$

A similar expression could be written for spectral hole burning (SHB) [2,7]. Solving (11) in the adiabatic limit restricts signal-pump detunings to be less than $1/2\pi\tau_{CH}$ (about 300 GHz in this case). Invoking the adiabatic limit allows us to include the intraband effects without having to excessively oversample the input field to calculate $\Delta h_{ch}(t)$. The output optical field is given by

$$E_{out}(t)\approx E_{in}(t)\exp\{\tfrac{1}{2}(-\alpha_{loss}L+(1-j\alpha_H)h(t)+(1-j\alpha_{ch})\Delta h_{ch}(t)+\Delta h_{shb}(t))\} \tag{13}$$

With α_{ch} describing the refractive index dynamics associated with CH. The contribution arising from SHB is given by Δh_{shb}. We now replicate the carefully obtained experimental results of FWM products [8] using the SOA parameters given in Table 2. The situation is outlined in Fig. 3 with two equal power pumps P_1 and $P_2=100$ μW at the SOA input. The two pumps interact in the SOA creating two SOA idlers, I_3 and I_4 via FWM. The SOA input field is given as

$$E_{in}(t)=\sqrt{P_1}+\sqrt{P_2}\exp(j2\pi f_d t) \tag{14}$$

The detuning, f_d, is varied from 8 to 300 GHz. The power of the pumps and idlers are extracted from the calculated output spectrum. The results are shown in Fig. 4 and agree quite well with the experimental and travelling-wave simulation results [8]. The output power for both pumps show quite strong cross-gain