Improvement of semiconductor optical amplifier dynamic behaviour by assist light injection

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Abstract: We present SOAs dynamic properties for high speed transmissions where pattern effects and waveform distortion appear if the amplifier does not provide the same gain for all data bits. The SOA recovery time can be shortened using a high-power continuous wave optical beam. In this article, an SOA dynamic model implemented in ADS is given. Simulation and experimental results, in temporal and in frequency domains, in presence of an assist light at transparency wavelength are achieved and discussed. An assist light power of 19 dBm injected at 1480 nm into the SOA in the counter-propagative scheme, improves the gain saturation, speeds up the gain recovery by a factor of two and shifts the high-pass SOA response to high frequencies.

1. Introduction

Semiconductor optical amplifier (SOA) is essentially a semiconductor laser where, in the basic structure, the addition of anti-reflection coated facets at SOA extremities permits a single passage traveling wave amplification (Fig. 1). The optical output signal is always accompanied by an amplified spontaneous emission (ASE). Today, SOAs can provide up to 30 dB of signal gain with relatively low power consumption, saturation output powers up to 13 dBm and a typical noise factor of about 7 dB over a bandwidth of about 50 nm (Table 1).

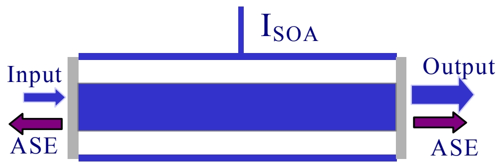

Fig. 1: SOA schematic diagram.

Table 1: SOAs performances.

SOA Features	**Value**
Maximum internal gain (dB)	30-35
Insertion loss (dB)	3-6
Polarization sensitive	<2dB
Pump source	Electrical
-3dB gain bandwidth (nm)	30-70
Saturation output (dBm)	5-13
Noise factor (dB)	7-12
Non-linear effects	Yes
Recovery times (ps)	100-1000
Integration	Yes
Functional device possibility	Yes

In spite of their inferior performances as in-line amplifiers compared to the erbium doped fiber amplifier (EDFAs), SOAs are believed to regain importance even as in-line amplifiers in spectral range where there are no evident candidates. Moreover, SOAs profit from several features such as compactness, integrability, low power consumption, a broad gain spectrum and possibly their lower cost.
In addition, SOAs have proven to be particularly promising nonlinear devices to perform key functions like optical switching, wavelength conversion and optical signal processing. Cross gain modulation (XGM) and cross phase modulation (XPM) are the two SOAs non-linearities which are commonly used.
For such SOAs, temporal responses for optical pulse are very important in long haul and high-speed transmission. Due to SOA gain saturation, the shape of an optical short pulse is distorted after its passage through the SOA since the carrier density, which decreases during the travelling of the pulse due to its amplification, does not recover shorter than recovery time limited to hundreds of picoseconds. Thereby, in high speed data transmission, pattern effects and significant distortion will appear if the amplifier does not provide approximately the same gain for all data bits. The recovery time can be shortened by increasing the SOA driving current and by using a longer SOA. An alternative approach is the injection of a high optical power continuous wave (CW) as assist light, sometimes noted as “holding beam”, into the SOA cavity [1-2]. In this article we will present SOAs dynamic properties which can be described by an effective SOA dynamic model implemented in ADS (commercially available software from Agilent Technologies). A propagation equation can be used to characterize the evolution of the electrical field and rate equations can be used to model carrier dynamics. Simulations and experimental results in presence of the assist light at transparency wavelength will be given and discussed.

2. SOA Model

The model of the SOA is shown in Fig. 2.

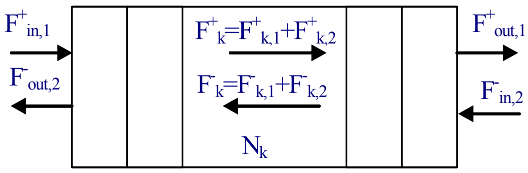

Fig 2. Schematic diagram of the SOA, longitudinally divided into sections.

In the propagation direction z the SOA is divided into sections which allows taking into account the longitudinal distribution of the carrier density N (z). In this model, intraband effect is not considered. A polynomial model which can fit the material gain for a large spectral region and a wide range of bias currents is considered [3].The propagation of the complex field envelopes in the kth section $F^{\pm}_k$ from z_k^- to z_k^+ spaced of length Δz are described in the time domain by:

$$F_k^{\pm}\left(t,z_k^{\pm}\right)=\sqrt{G_s}\,\exp\left(-j\Phi_k\right)\left(1-j\frac{1}{2}\frac{\partial g_n(\omega,N)}{\partial\omega}\Delta z\frac{\partial}{\partial t}\right)F_k^{\pm}\left(t-\tau_k,z_k^{\pm}\right)\quad(1)$$

where $\pm$ signs denote propagation in +z and –z directions. G_s, Φ_k are respectively the single pass gain and the phase change in the kth section, g_n is the net gain and τ_k is the sampling interval with $\Delta z = v_g\,\tau_k$ where v_g is the group velocity in the active region. The photon density in the kth section is given by:

$$S_k=\frac{1}{v_g E\,\Delta z_k}\int_{z_k^-}^{z_k^+}\left(\left|F_k^+(t,z_k^-)+F_k^-(t,z_k^+)\right|^2\right)dz\quad(2)$$

where E is the photon energy. Furthermore, the amplified spontaneous emission (ASE) intensity in the kth section is given by:

$$I^{\pm}_{ase,k}(z)=\frac{\beta_{eff}R_{sp,k}E}{2g_{n,k}}\left(C_k^{\pm}\exp\left(\pm g_{n,k}\left(z-z_k^{\mp}\right)\right)-1\right)\quad(3)$$

where β_{eff} is the effective spontaneous coupling factor and R_{sp} is the spontaneous emission rate.
The rate equation model is solved in each section to describe the carrier concentrations dynamics according to:

$$\frac{dN_k}{dt} = \frac{I_k}{q_e \Delta z_k wd} - R_{rec,k} - R_{ase,k} - \sum_i R_{st,i,k} \quad (4)$$

where I_k is the current into the active region of the kth section. q_e is the electron charge, $R_{rec,k}$ is the total spontaneous recombination rate, $R_{ase,k}$, $\Sigma R_{st,i,k}$ are the stimulated recombination rates due to ASE and injected signals respectively with $R_{ase,k} = v_g g_m S_{ase}$, and $R_{st,i,k} = v_g g_{m,i} S_{i,k}$ where S_{ase} and $S_{i,k}$ are in that order the photon densities due to ASE and injected signal at wavelength λ_i at which the modal gain is $g_{m,i}$. This dynamic SOA model is then adapted as an equivalent circuit model by using ADS from Agilent Technologies.

3. Dynamic properties

Two possible assist light injection configurations into the SOA cavity are shown in Fig. 3. The injection of the assist light power at the transparency improves the SOA performances without affecting its gain [1-2], such that reduces the carrier lifetime inside the SOA active region. In the following we investigate only the counter-propagation scheme as it presents better results [2].

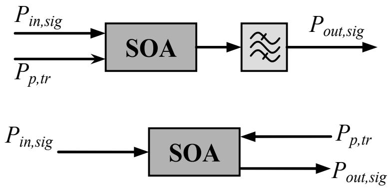

Fig. 3. Assist light injection set-up in co and counter propagative configurations.

The SOA speed capability can be assessed by optical small-signal modulation of the gain. Generally, the effective carrier lifetime in the active waveguide is used as a parameter to determine the modulation bandwidth in small-signal analysis. By considering a one section SOA, the carrier density and the output optical signal modulation response, respectively n_k and $p_{out,sig}$, both caused by a small-signal modulation of the optical input power $p_{in,sig}$ are given by:

$$n_k = -\frac{\tau_k R_{sig}}{P_{in,sig0}\left(1 + j\omega\tau_k\right)} p_{in,sig} \quad (5)$$

where
$$\tau_k^{-1} = \frac{\partial}{\partial N_k}\left(R_{rcc,k} + R_{ase,k} + \sum_i R_{st,i,k}\right) \quad (6)$$

$$p_{out,sig} = P_{in,sig} G_{sig} \left(1 - \varphi_k\right) \frac{1 + j\omega\left(\tau_k / (1 - \varphi_k)\right)}{1 + j\omega\tau_k} \quad (7)$$

where
$$\varphi_k = \frac{\tau_k \, \partial G_{sig} / \partial N_k \, R_{sig}}{G_{sig}}$$

G_{sig} and R_{sig} are respectively the signal gain and the signal stimulated recombination rate. Actually, n_k exhibits a low pass characteristic with a 3-dB bandwidth ($1/2\pi\tau_k$) while the amplified optical signal exhibits a high–pass filter characteristic due to SOA gain saturation.

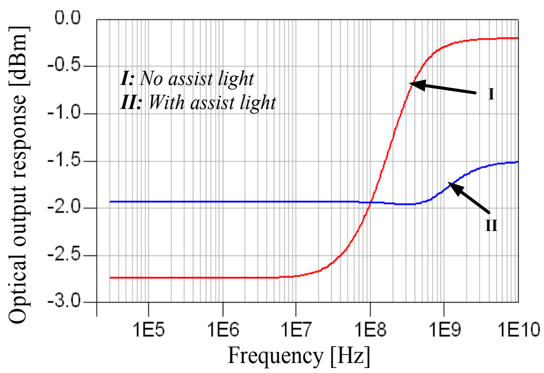

Fig. 4. Simulation results of optical output signal frequency responses in absence and in presence of an assist-light.

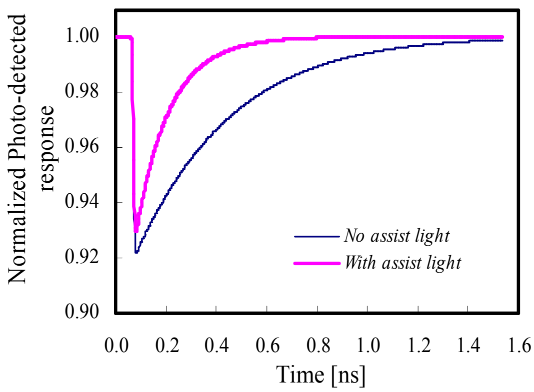

Fig. 5. Normalized calculated gain recovery photo-detected response.

By using the dynamic model in frequency domain, the SOA small-signal responses of the optical output signal have been achieved with and without of an assist-light at transparency wavelength (1480 nm) (fig. 4). We observe that the high-pass SOA response is significantly shifted to high frequency due to the reduction of the carrier lifetime in presence of the assist light. In addition, the high pass filtering difference is reduced due to the increase of the SOA 3-dB saturation output power.
In the time domain, numerical calculations in a pump-probe (1540 nm – 1535 nm) configuration permit to highlight the gain recovery time evolution in absence and in presence of the assist light. The injection of an assist light power speeds up the SOA recovery (fig. 5) which indicates a reduction of the carrier lifetime.

4. Experimental results

Experimental results are carried out on a 500 µm long SOA having a 15 dB fiber-to-fiber gain at a bias current of 150 mA for an optical signal incident at 1535 nm. An assist light power of 19 dBm is injected at wavelength 1480 nm in the counter-propagative direction. In small signal analysis, a 30 KHz – 3 GHz network spectrum analyzer is used to modulate the optical input signal which has an average input power of -11 dBm.
Besides, pump-probe measurements are performed to characterize the SOA gain recovery time. Here the pump is a 5 ps pulse of about 275 fJ with repetition rate of 454 MHz at 1540 nm. The probe signal is generated by a tunable laser set at 1535 nm with a CW power of -12 dBm such that it leaves the SOA gain unsaturated. A filter of 0.2 nm bandwidth is used at the SOA output to select the probe signal which is detected by a fast photodiode of 32 GHz bandwidth and then displayed on a 20 GHz bandwidth oscilloscope. Fig. 6 and 7 show the frequency response and the SOA gain recovery time evolution. In frequency domain, the high-pass SOA response is significantly shifted to high frequencies. In pump-probe measurements, the assist light reduces the gain recovery time to 400 ps, while it is around 750 ps without any assist light. Finally, both experimental results in time and in frequency domains are in good agreement with calculations.

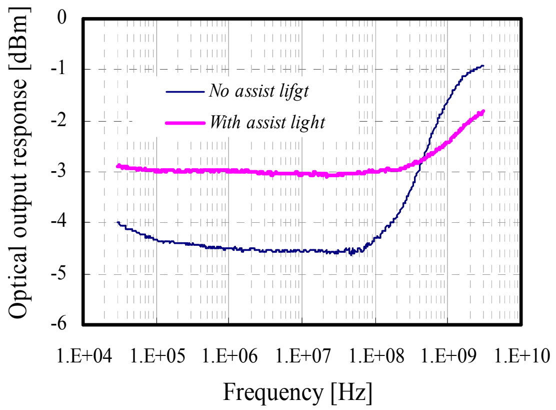

Fig. 6. Optical output signal frequency responses in absence and in presence of an assist-light.

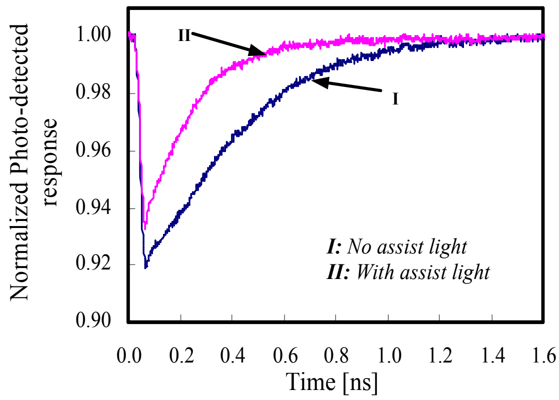

Fig. 7. Normalized measured gain recovery photo-detected response.

4. Conclusion

An SOA dynamic equivalent circuit model is given. Simulations and experimental results demonstrated that the assist light power speeds up the gain recovery time and shifts the high-pass SOA response to high frequency.

References

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