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Enhancement in the gain recovery of a semiconductor optical amplifier by device temperature control

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Abstract. We present a numerical investigation on the temperature dependence of gain recovery, of a semiconductor optical amplifier (SOA). It is shown that the decrease in temperature significantly speed-up the gain recovery of the SOA. Under typical operating conditions, a 20 K reduction in temperature of the SOA results in a decrease of 150 ps in the gain recovery time. A comparative estimation of device temperature and assisted-light power requirements for enhancing the gain recovery has also been carried out. It is found that, a decrease of 8 K in the temperature of the SOA, is as effective in enhancing the gain recovery as injection of 25 dBm assisted-light power in the counter-propagating mode. Our study shows that under moderate current biasing conditions, temperature reduction is a better and convenient option to speed-up the gain recovery of an SOA, than the use of external assisted-light injection, which requires an additional laser source and wavelength division multiplexing (WDM) components for coupling and de-coupling, leading to insertion losses in the communication channel.

Keywords. Semiconductor optical amplifier; gain recovery; assisted-light; optical-pumping-near-transparency.

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1. Introduction

Semiconductor optical amplifier (SOA) is an important active optoelectronic device that amplifies an input light signal under suitable operating conditions. It is a versatile component in modern optical communication systems both as an optical amplifier and as an all-optical signal processing unit. SOA based devices are used to carry out most of the all-optical functions such as wavelength conversion, add-drop multiplexing and all-optical logic gates [1–3].

Dynamic characteristics of the SOA are governed by the gain recovery time (RT) [4]. The reported gain recovery time of the bulk SOA is about 300 ps, depending on the injected current density [5,6]. For high speed applications, the SOA must have fast gain recovery to avoid system penalties arising from bit pattern dependencies [7,8]. Gain recovery is also necessary in high speed optical routers, to achieve gain uniformity for high bit-rate input signals. Therefore, it is essential to reduce the gain recovery time of the SOA to meet the demands of high speed optical communication systems. Quantum dot based SOA is reported to have improved gain dynamics [9,10], but it is still beyond real system application, due to certain fabrication issues.

Three techniques have been reported to enhance the speed of the bulk SOA: (1) two-electrode SOA, (2) ultralong SOA and (3) assisted-light injections. Two-electrode designs have been reported for improved carrier dynamics [11], but these SOAs require two independent current sources. Fabrication of longer length SOA reduces the gain recovery time, but it also enhances the amplified spontaneous emission (ASE) noise [12]. Another method is to use a high power continuous wave (CW) ‘assisted-light’ in the amplifier’s active medium along with the signal [13–15]. The ‘assisted-light’ refers to a CW optical beam of appropriate wavelength injected into the SOA along with the signal, in a co- or counter-propagating configuration, to control the carrier concentration in the amplifying medium. There are several reports on assisted-light optical pumping near transparency (OPNT) wavelength in SOAs, which considerably enhances the gain recovery [14–18]. However, this scheme requires additional wavelength division multiplexing (WDM) components at the input and the output of SOA for coupling and de-coupling of the assisted-light, which are associated with the coupling losses. In this paper, a numerical investigation is presented, on the influence of temperature on enhancing the gain recovery of the SOA.

With the decrease in temperature of the device, improvement in the static characteristics, such as gain and saturation behaviour of the SOA, has been reported [5]. To the best of our knowledge, we are the first to report the enhancement in the gain recovery of the SOA with decrease in the device temperature.

In this paper we discuss in detail, the effects of temperature on the dynamics of gain recovery of an SOA. In §2, we briefly present the modelling equations used in the numerical simulation. These equations are based on the Connelly model [19] and its simplified form used by Wang *et al* [20]. In §3, the results of the simulation study are presented. Comparative study has also been carried out which shows that the effect of temperature is equivalent to the role of assisted-light in enhancing the gain recovery of the SOA, at moderate biasing current. In a commercial SOA, it is possible to control the temperature of the SOA through its power supply unit, or alternatively an on-chip thermoelectric (TE) cooling can be incorporated as shown in figure 1. As the assisted-light injection requires additional laser and wavelength division multiplexing (WDM) components for coupling and de-coupling, it would be convenient to use the temperature effect, to considerably enhance the speed of the SOA.

2. Modelling equations

We have used the wideband Connelly model [19] to analyse the effect of temperature on the dynamic characteristics of the SOA. This model is in good agreement with the experimental results. This model is based on position dependent rate equations for the carrier density. Propagation for injected input signals is considered only in the forward direction [20]. Propagation of the amplified spontaneous emission is considered in both forward and backward directions. When the signal is injected into the SOA, changes occur in the carrier and photon densities within the active region that can be described by using the rate equations. For simulation, the SOA is divided into n number of segments. The carrier density and signal power are assumed to be constant within each segment. However, the carrier density and the signal power change from segment to segment, depending on the input power, ASE and the carrier density of the previous segment. Therefore, the model also accounts for a non-uniform carrier distribution along the length of the SOA.

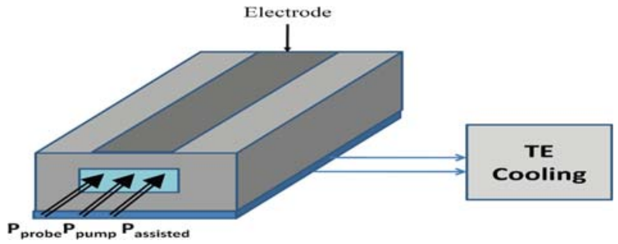

Figure 1. Schematic of the on-chip temperature control by TE cooling of the base of the SOA to enhance the gain recovery and hence speed-up the device dynamic performance.

The gain in the active medium of the amplifier is described by the two energy level model [19]. In this model, material gain coefficient g_{m}, which is dependent on the carrier density N, and the input signal wavelength λ, for the InGaAsP active region is given by

$$g_{\mathrm{m}}(\nu, N) = \frac{c^2}{4\sqrt{2}\pi^{3/2} n_1^2 \tau \nu^2} \left(\frac{4\pi m_{\mathrm{e}} m_{\mathrm{hh}}}{h(m_{\mathrm{e}}+m_{\mathrm{hh}})}\right)^{3/2} \times \sqrt{\left(\nu - \frac{E_{\mathrm{g}}(N)}{h}\right)}\,(f_c(\nu) - f_v(\nu)), \quad (1)$$

where c is the speed of light in vacuum, ν is the optical frequency, n_1 is the active region refractive index, τ is the radiative carrier recombination lifetime and h is the Planck's constant; m_{e} and m_{hh} are the conduction band (CB) electron and valence band (VB) heavy-hole effective masses respectively and N is the CB carrier (electron) density. Temperature dependence comes from the probability of occupation of energy levels, which increases with decrease in temperature. The Fermi–Dirac distributions in the CB and VB are given by

$$f_c(\nu) = \left\{\exp\left(\frac{E_a - E_{fc}}{kT}\right) + 1\right\}^{-1}, \quad (2)$$

$$f_v(\nu) = \left\{\exp\left(\frac{E_b - E_{fv}}{kT}\right) + 1\right\}^{-1}, \quad (3)$$

where

$$E_a = (h\nu - E_{\mathrm{g}}(N))\frac{m_{\mathrm{hh}}}{m_{\mathrm{e}} + m_{\mathrm{hh}}}, \quad (4)$$

$$E_b = -(h\nu - E_{\mathrm{g}}(N))\frac{m_{\mathrm{e}}}{m_{\mathrm{e}} + m_{\mathrm{hh}}}, \quad (5)$$

where T is the absolute temperature and k is the Boltzmann constant. E_{g} is the carrier-dependent bandgap of the material. E_{fc} is the quasi-Fermi level of the CB relative to the bottom of the band. $E_{f\nu}$ is the quasi-Fermi level of the VB relative to the top of the band. These terms are also temperature dependent and can be estimated using the approximation given by Nilsson [21], which was also used by Connelly [19]

$$E_{fc} = \{\ln\delta + \delta[64 + 0.05524\delta(64 + \sqrt{\delta})]^{-1/4}\}kT, \tag{6}$$

$$E_{f\nu} = -\{\ln\varepsilon + \varepsilon[64 + 0.05524\varepsilon(64 + \sqrt{\varepsilon})]^{-1/4}\}kT, \tag{7}$$

where

$$\delta = \frac{N}{N_c}; \quad \varepsilon = \frac{P}{P_\nu} \tag{8}$$

N_c and P_ν are also functions of temperature as

$$N_c = 2\left(\frac{2\pi m_{\mathrm{e}}kT}{h^2}\right)^{3/2}; \qquad P_\nu = 2\left(\frac{2\pi m_{\mathrm{dh}}kT}{h^2}\right)^{3/2} \tag{9}$$

where

$$m_{\mathrm{dh}} = \left(m_{\mathrm{hh}}^{3/2} + m_{\mathrm{lh}}^{3/2}\right)^{2/3}. \tag{10}$$

The carrier density rate equation in the ith segment is given by [20]

$$\begin{aligned}\frac{\mathrm{d}N_i(z)}{\mathrm{d}t} &= \frac{I}{edWL} - R(N_i(z)) \\ &\quad - \frac{\Gamma}{\mathrm{d}W}\sum_{k=1}^{3}\frac{g[N_i(z),\nu_k]}{h\nu_k}P_k(z,t) \\ &\quad - \frac{2\Gamma}{\mathrm{d}W}\left\{\sum_{j=0}^{N_m-1}\frac{g[N_i(z),\nu_j]}{h\nu_j}\right. \\ &\quad \left.\times K_j[P_{\mathrm{ASE}}^{+}(N_i(z)) + P_{\mathrm{ASE}}^{-}(N_i(z))]\right\},\end{aligned} \tag{11}$$

where I is the amplifier bias current, which has been assumed to pass through the active region only. k =1, 2, 3 stand for the probe, the pump and the assisted-light respectively. N_{m} is the number of ASE components in the gain spectrum, used for simulation. The first term represents the addition of carriers to the active region of the SOA from the injection current source. These injected carriers are then depleted by various recombination mechanisms, occurring within the active medium of the amplifier. The recombination rate $R(N)$ is the sum of the radiative and non-radiative carrier recombination rates, and can further be represented as polynomials in N [19]. The third and fourth terms in eq. (11) represent stimulated recombination of carriers due to amplified signals and the amplified spontaneous emission in the gain spectrum respectively. Different symbols have their usual meanings as described by Connelly [19] and Wang *et al* [20].

Propagations of different fields in the SOA are given by

$$\frac{\mathrm{d}P_{\mathrm{Pump}}}{\mathrm{d}z} = (\Gamma g_{\mathrm{Pump}} - \alpha)P_{\mathrm{Pump}}, \tag{12}$$

$$\frac{\mathrm{d}P_{\mathrm{Probe}}}{\mathrm{d}z} = (\Gamma g_{\mathrm{Probe}} - \alpha)P_{\mathrm{Probe}}, \tag{13}$$

$$\frac{\mathrm{d}P_{\mathrm{Assisted}}}{\mathrm{d}z} = (\Gamma g_{\mathrm{Assisted}} - \alpha)P_{\mathrm{Assisted}}, \tag{14}$$

where Γ is the confinement factor and α is the material loss coefficient.

Equations (1)–(14) are adopted to investigate the temperature dependence of gain recovery time, for an SOA having a cross section of 2 × 0.15 μm and a confinement factor of 0.3 [20]; parameter used in simulations are given in table 1. For the simulation, the SOA is divided into hundred equal segments of length $l = L/100$ each, where L is the length of the SOA.

3. Results and discussion

Figure 2 shows the evolution of the normalized output probe power, for −40 dBm input at a wavelength of

Table 1. Parameters used in simulations.

Symbol	Parameter	Value
L	Length of the SOA	1000 μm
w	Width of the active region	2 μm
d	Depth of the active region	0.15 μm
I	Biased current	200 mA
K_j	Filter factor	1
Γ	Confinement factor	0.3
N_{m}	No. of ASE components	450
n	No. of segments along the length	100
T	Temperature of the active region	Variable
n_{eq}	Equivalent refractive index of the active region	3.22 [18]
m_{e}	Effective mass of the electron	4.10×10^{-32} kg [18]
m_{lh}	Effective mass of the light hole	5.06×10^{-32} kg [18]
m_{hh}	Effective mass of the heavy hole	4.19×10^{-31} kg [18]

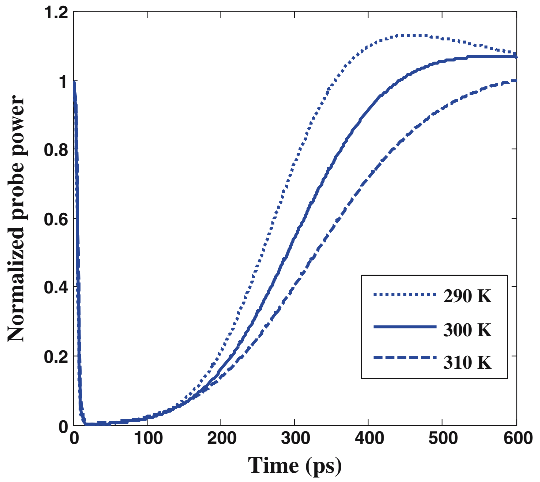

Figure 2. Normalized probe power evolution at 290, 300 and 310 K temperature for a 1000 μm long SOA, biased at 200 mA.

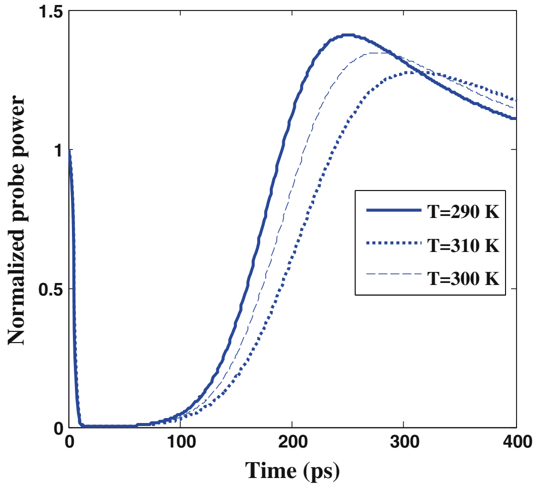

Figure 3. Normalized probe power evolution at 290, 300 and 310 K temperature for a 1000 μm long SOA, biased at 250 mA.

1550 nm, at different temperatures, when the gain of the SOA is depleted by a 10 ps Gaussian pump pulse of 10 dBm peak power at 1560 nm wavelength. Intraband effects have been neglected in the simulation study, as these effects are not noticeable if the pulse energy is less than 1 pJ [22].

Figure 2 shows that gain recovery is faster in the SOA with decrease in temperature. Gain recovery time decreases significantly from 305 ps to 155 ps, with 20 K reduction in device temperature, which is an improvement of 150 ps. This is mainly due to three factors. Electrons are distributed over a narrow range at lower temperature and hence the number of electrons available for participating in optical transition, thus providing gain, at a given energy becomes more. Nonradioactive recombinations, which decrease with decrease in the device temperature, cause an increase in the gain for a given current. Third contributing factor is the leakage current of the double hetrostructure, which increases with the temperature. Thus, for high speed applications, the SOA must be operated at a lower temperature.

Figure 3 shows that, with increase in the biasing current, the effect of temperature on the reduction of gain recovery time of the SOA is weaker. For a biasing current of 250 mA, 20 K decrease in the temperature of SOA leads to improvement of recovery time by 87 ps only. This is due to the decrease in gain variation with temperature on increasing the biasing current [5]. Increased carrier density due to the higher bias current diminishes temperature-dependent effect, in enhancing the gain recovery. Therefore, at lower biasing conditions (<200 mA) or for an SOA-based device, which is limited by the biasing current (100–200 mA), the gain recovery can speed-up significantly by lowering the device temperature.

The use of assisted-light increases the speed of the SOA, as reported in [16–18]. Interestingly, we find that decrease in temperature has a better effect in accelerating the gain recovery of SOA, as compared to the case of assisted-light (AL) injection. As shown in figure 4, 20 dBm assisted-light power (in the counter-propagating mode) does not increase the gain recovery time of the SOA as much as 20 K decrease in temperature. Moreover, the use of external assisted-light is not as simple as decreasing the temperature of SOA, because

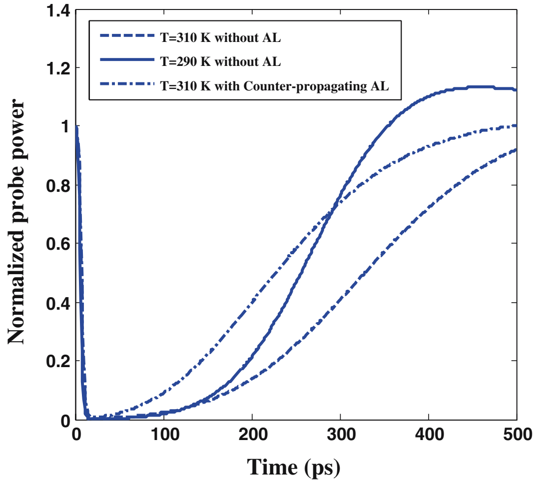

Figure 4. Normalized probe power without and with 20 dBm assisted-light (AL) at 310 K in counter-propagating mode; and without assisted-light at 290 K.

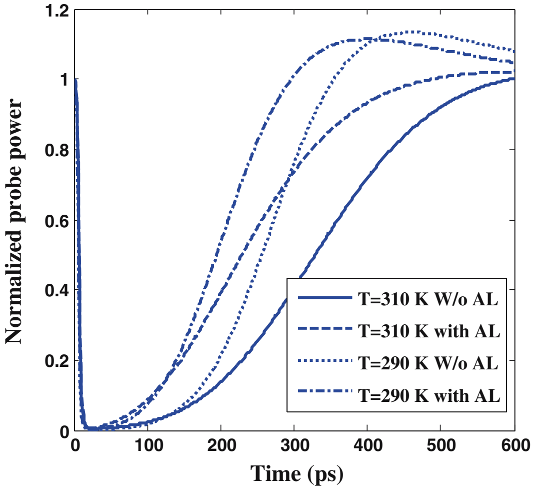

Figure 5. Normalized probe power without (W/o) assisted-light (AL) and with assisted-light at 310 and 290 K.

it requires an extra source of laser and WDM components for coupling of assisted-light, which introduces additional losses.

Effect of assisted-light, in decreasing the recovery time, also weakens with decrease in temperature, as shown in figure 5. At 310 K, 20 dBm counter-propagating light improves the gain recovery of SOA by 40 ps while at 290 K it improves only by 10 ps. Thus, at lower operating temperature, assisted-light injection is not as useful as at higher temperature.

It is reported that the recovery time decreases with the increase in assisted-light power [23]. Figure 6 shows the variation of recovery time of SOA with the power of the assisted-light at 310 K. It shows that with the injection of assisted-light of 25 dBm power, the recovery time decreases from 301 ps to 235 ps; an improvement of 71 ps. The same reduction of RT can be achieved by decreasing the temperature by 8 K. So a decrease of 8 K is as effective in decreasing the RT as injection of 25 dBm assisted-light power in the counter-propagating mode (though 25 dBm power is practically towards very high side, it is just considered for comparison). Figure 6 also shows that a 20 K decrease in temperature decreases the RT by 150 ps. Thus, temperature is more effective in decreasing the RT compared to the assisted-light injection.

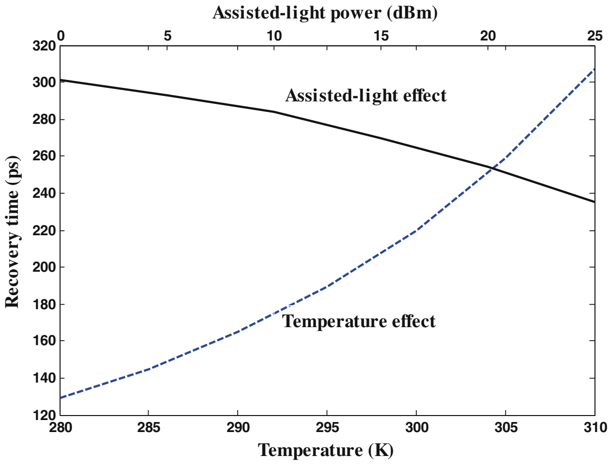

Figure 6. Gain recovery time with the power of assisted-light in counter-propagating mode at 310 K and with the temperature of the device without assisted-light, for a 1000 μm long SOA, biased at 200 mA.

4. Conclusions

The effect of temperature on the dynamic characteristics of the semiconductor optical amplifier has been analysed. Our study shows that the decrease in temperature affects the performance of SOA significantly in terms of gain recovery, a 20 K reduction in temperature of SOA results in a decrease of 150 ps in the gain recovery time. This effect is more prominent if the SOA is biased at lower currents. A comparative estimation of the decrease in gain recovery time with decrease in temperature and increase in power of assisted-light injection has been carried out. It was found that at lower operating temperature, assisted-light injection is not as useful as at higher temperature. Decrease in temperature of the SOA is equivalent to the role of assisted-light in enhancing the gain recovery. We conclude that, it is simpler and advantageous to regulate the temperature of the device than the external injection of 'assisted-light' for enhancing the gain recovery of SOA.

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