Wideband Steady-State Model of a Strained MQW-SOA

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Abstract- A wideband steady-state model of a MQW-SOA is described. Least-squares fitting of the model to experimental polarization resolved amplified spontaneous spectra were used to obtain difficult to measure model parameters such as the intraband broadening energy, Auger recombination coefficient and the bandgap shrinkage coefficient. Simulations and comparisons with experiment are given which demonstrate the accuracy and versatility of the model.

I. INTRODUCTION

[*]Optical networks require the availability of small, inexpensive and integratable optical amplifiers. InP-based semiconductor optical amplifiers (SOAs) with InGaAsP/InGaAsP multi-quantum-well (MQW) active regions are good candidates for 10 Gb/s coarse WDM communications. These devices should provide a wide optical bandwidth and be polarization insensitive. InGaAsP quaternary MQWs have already been investigated for SOA applications. Polarization insensitive operation can be obtained by stacking tensile and compressive QWs in the active layer. In [1] it was shown that polarization independent active material gain coefficients can be achieved along with a wide optical bandwidth, by using one-width MQWs. The measured amplified emission spectrum (ASE) however had relatively high polarization sensitivity. To this effect it is necessary to develop a wideband model of the SOA that can be used to aid optimization of the device performance especially with regard to polarization insensitivity. In this paper we describe such a model, which uses full bandstructure calculations to obtain the gain coefficients and spontaneous recombination rate, traveling-wave equations for the amplified signal and ASE and a carrier density rate equation. Unknown model parameters were obtained by using least-squares fitting of the model to the measured ASE spectra.

II. GEOMETRY, BANDSTRUCTURE AND MATERIAL GAIN

The SOA active region consists of three 14 nm thick $In_{0.53}Ga_{0.47}As_{0.96}P_{0.04}$ QWs with $In_{0.8}Ga_{0.2}As_{0.45}P_{0.55}$ barriers. The SOA length and active stripe width are 2 mm and 1.75 μm respectively. The QW bandstructure was calculated by solving the Lüttinger–Kohn Hamiltonian, including tetragonal strain, confinement effects and taking into account the interfacial discontinuity condition [2-5]. The energy E dependent spontaneous gain and material gain coefficients per well are given by

$$g_{sp}^{TE/TM}(E) = \frac{\hbar e^2}{m_0^2 \varepsilon_0 n_r c L_w E} \sum_m \sum_n \int_0^\infty \frac{k_\perp}{\pi} |M_{mn}^{TE/TM}(k_\perp)|^2 \times f_c(E_m(k_\perp))(1 - f_v(E_n(k_\perp)) L(E_{mn}(k_\perp)) dk_\perp \quad (1)$$

$$g_m^{TE/TM}(E) = \left[1 - \exp\left(\frac{E - \Delta E_F}{kT}\right)\right] g_{sp}^{TE/TM} \quad (2)$$

$|M_{nm}^{TE/TM}(k_\perp)|^2$ are the momentum dependent matrix elements, E_m and E_n the m-th conduction and n-th valence band energy levels, E_{mn} the transition energies, L_w the well width and n_r the refractive index. $L(E_{mn}(k_\perp))$ is a Lorentzian broadening function. f_c and f_v are the conduction and valence band Fermi-Dirac functions. ΔE_F is the quasi-Fermi level difference. The quasi-Fermi levels are obtained by numerically solving charge neutrality equations. Typical plots of g_m and g_{sp} are shown in Fig. 1.

For a given carrier density spatial distribution in the SOA the signal photon rate I_s at a distance z from the SOA input is given by

$$I_s(z) = \frac{P_{in}}{E_s} \exp\left(\int_0^z g_s \, dz\right) \quad (3)$$

g_s is the net gain coefficient (includes optical confinement factors and scattering losses) at the signal energy E_s and polarization and P_{in} the input optical power. The forward and backward travelling ASE photon rates $N_{TE/TM,k}^{\pm}$ in the k-th spectral slice of energy width dE centered at energy E_k are

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obtained from finite-difference solutions to the traveling-wave equations

$$\frac{dN^{\pm}_{TE/TM,k}}{dz} = \pm g_k^{TE/TM} N^{\pm}_{TE/TM,k} \pm \Gamma_{TE/TM} g_{sp,k}^{TE/TM} dE \quad (4)$$

The carrier density n rate equation is given by

$$\frac{dn}{dt} = \frac{I}{e n_w L_w W L} - R(n) - \frac{\Gamma_{s,p}}{n_w L_w W} g_s I_s - \frac{1}{n_w L_w W} \sum_{i=TE,TM} \sum_k \Gamma_i(z) g_{m,k}^{i} \left[N^{+}_{i,k} + N^{-}_{i,k}\right] \quad (5)$$

The first term on the RHS of (5) is the electrical pumping due to the injected current I, The recombination rate term $R(n)$, takes into account carrier capture and release into the QWs, and spontaneous radiative and Auger recombination. The remaining terms account for carrier depletion due to the amplified signal and ASE.

III. NUMERICAL ANALYSIS

The SOA model equations cannot be solved analytically, so a numerical solution is required. The algorithm used is essentially the same as that described in [6, 7]. The SOA is split into 128 spatial sections and the ASE into 768 spectral slices covering a range of 1250 to 1650 nm. Initially the carrier density in the amplifier is set to some reasonable value (2 x 10^{24} m^{-3}). The material gain coefficients are calculated using (1) and (2) and the signal intensity and ASE photon rates are then estimated at the section interfaces using (3) and (4). The carrier density is then estimated at the center of each section using (5) with the time derivative set to zero, which is then used to update the material gain coefficients. These updated coefficients are used to update the signal and ASE. This process is continued until the values of the signal and ASE photon rates converge to within a tolerance of 0.1%. Unknown model parameters such as the linebroadening function energy width and Auger recombination were obtained by least-squares fitting of the TE/TM output ASE spectra to model predictions for various bias currents as shown in Fig. 2. The matching between the TE experimental and simulated ASE spectra is good but less so for the TM spectra. This is because the TM ASE power is significantly less than for TE, the complexity of the spectra shape for various bias currents (compared to that for bulk material) and also uncertainty in the calculated TE/TM optical confinement factors. Currently different lineshape functions are under investigation to see if the matching between experiment and simulation can be improved. Further simulations will be presented at the conference.

IV. CONCLUSION

A wideband model of a strained MQW-SOA has been described. The model predictions show good agreement with experimental ASE spectra. The model can be used to investigate the effects of different material and geometrical parameters on SOA performance under operating conditions ranging from low and high bias currents.

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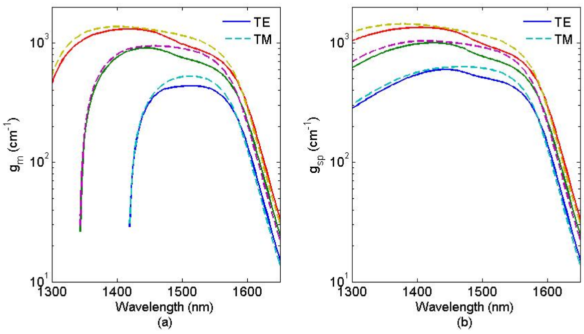

Fig. 1. (a) Material and (b) spontaneous gain coefficients for carrier densities of 2, 3 and 4 x 10^{24} m^{-3}.

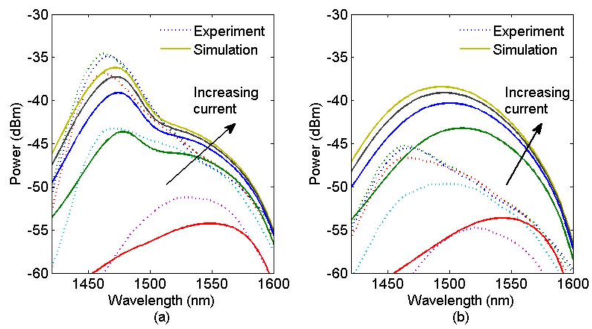

Fig. 2 Experimental and predicted (a) TE and (b) TM output ASE spectra for bias currents of 100, 200, 300, 400 and 500 mA. The resolution bandwidth is 0.1 nm.