شبیه‌سازی جامع بهره لیزر تابش از سطح با کاواک عمودی با در نظر گرفتن اثر دمایی و وابستگی حامل

رامین اسدی[۱]، نسرین‌دخت باطنی پور[۲]

[۱]دانشجوی دانشگاه آزاد اسلامی، واحد دماوند، گروه الکترونیک، دماوند، ایران، ramin1393@chmail.ir

[۲]استادیار دانشگاه آزاد اسلامی، واحد دماوند، گروه الکترونیک، دماوند، ایران، batenipour_nd @srbiau.ac.ir

چکیده – در این مقاله، از یک مدل نوری-الکتریکی-حرارتی برای بررسی رفتار دینامیک لیزر تابش از سطح با کاواک عمودی چاه کوانتومی (QW-VCSELs) استفاده می‌شود. این مدل عددی با استفاده از روش حوزه زمان تفاضل محدود در سیستم مختصات استوانه ای حل شده است. ما با استفاده از دو مدل مختلف وابستگی بهره به چگالی حامل استفاده می‌کنیم: بهره خطی (LG) و بهره وابسته به حامل غیر خطی (CDNG). نتایج شبیه سازی نشان می‌دهد که مدل CDNG پروفایل بهره بهتری دارد. تاثیر ضریب پهن‌شدگی جریان تزریقی بر خروجی لیزر نیز بررسی شده است. علاوه بر این، رفتار بهره دینامیک لیزر مورد بررسی قرار بررسی گرفته است. نتایج شبیه‌سازی نشان می‌دهد که تزریق جریان بالا، تنزل کیفیت پرتو خروجی به دلیل ظهور پدیده SHB و مدهای عرضی مرتبه بالاتر را منجر خواهد شد.

کلید واژه- مدل بهره غیرخطی وابسته به چگالی حامل، دینامیک لیزر تابش از سطح با کاواک عمودی چاه کوانتومی با هدایت ضریب شکست، پدیده سوختگی طیفی،رفتار دینامیک لیزر.

A Comprehensive Gain Simulation of Vertical-Cavity Surface-Emitting Laser Considering Thermal Effect and Carrier-Dependent

Ramin Asadi[1], Nasrindokht Batenipour[2]

[1]The Department of Electrical Engineering Damavand Branch, Islamic Azad University Damavand, Iran,
ramin1393@chmail.ir

[2]The Department of Electrical Engineering Damavand Branch, Islamic Azad University Damavand, Iran,
batenipour_nd @srbiau.ac.ir

Abstract- In this paper, an opto-electro-thermal model is used to investigate dynamic gain behavior of quantum well vertical-cavity surface-emitting lasers (QW-VCSELs). This numerical model is solved by using finite difference time domain method in cylindrical coordinate system. We use two different models to present carrier-dependency of the gain: linear gain (LG) and carrier dependent nonlinear gain (CDNG). Our simulation results show that CDNG model has better gain profile. We study the effect of current spreading factor and injected current on the output gain of laser. Moreover, we investigate dynamic gain behavior of examined laser. We show that high current injection degrades output beam quality because of improvement of SHB effect and manifestation of higher order transverse modes.

Keywords: Carrier dependent nonlinear gain model; Index-guided Quantum well vertical-cavity surface-emitting laser; Spatial hole burning effect; Dynamic behavior of laser.

A Comprehensive Simulation of Vertical Cavity Surface Emitting Laser Gain Considering Temperature Effect and Carrier Dependent

Ramin Asadi
Department of Electrical Engineering
Damavand Branch, Islamic Azad University
Damavand, Iran
ramin1393@chmail.ir

Nasrindokht Batenipour
Department of Electrical Engineering
Damavand Branch, Islamic Azad University,
Damavand, Iran
batenipour_nd @srbiau.ac.ir

1 Introduction

Vertical-cavity surface-emitting lasers (VCSELs) with quantum well (QW) layers as the active region have received considerable attention due to their low threshold current, circular output beam with low divergence, inherent single longitudinal mode, [1]. QW structure in active layer is used to improve some undesirable characteristics of semiconductor lasers such as spatial-hole burning (SHB) of carrier concentration, excitation of side mode and broadening of line-width [2]. Some important applications of the QW-VCSELs are in high speed current modulation for optical data transmission, switching, and compact disk systems [3-4].

In index-guided VCSELs, an oxide-layer is located close to the peak of the electrical field. The central aperture of the oxide confines the current flow and therefore the spreading of the active region [5].

Here, we use a numerical opto-electro-thermal model to investigate dynamic gain behavior of QW-VCSEL [6]. We use finite difference time domain (FDTD) method for dynamic analysis.

2 Index-Guided QW-VCSEL Structure

Fig.1 illustrates a schematic structure of the analysed laser. It is a GaAs-based vertical-cavity surface-emitting laser with a QW active layer and a top oxide-layer for optical guiding. The active region is a triple 10 nm-$Al_{0.3}Ga_{0.7}As$ QW sandwiched by 7 nm-GaAs barriers. This 3-QW layer has been considered for our simulation supposed to emit a light in 850 nm wavelength. As shown in the figure, the active layer is sandwiched between two spacer layers and two distributed Bragg reflectors (DBRs). The top p-type DBR is 19.5 periods and the bottom n-type DBR is 27.5 periods. The p-type and n-type dopants are Be with doping concentration 3×10^{18} to 5×10^{19} cm^{-3} and Si with doping concentration 3×10^{18} cm^{-3}, respectively [6].

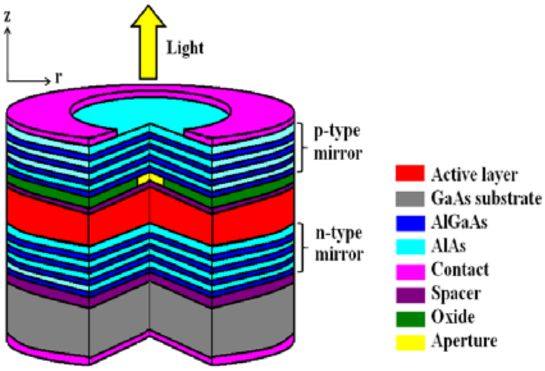

Figure 1: GaAs-based index-guided GaAs/AlGaAs QW-VCSEL schematic structure.

3. Modelling

In index-guided VCSELs, the dynamic gain is affected by electrical, optical and thermal mechanisms. For electrical consideration, by assuming uniform carrier density along the z direction in the active region, the diffusion equation can be expressed as [7]:

$$\frac{\partial N(r,t)}{\partial t} = D_n \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial N(r,t)}{\partial r}\right) - \frac{N(r,t)}{\tau_s} - \frac{g(N(r,t))P_a\left|\overline{E}_t(r,t)\right|^2}{hv} + \frac{I(r,t)}{qd} \quad (1)$$

Where $N(r,t)$ is carrier density which is the function of radius r and time t, D_n is the electron diffusion coefficient, τ_s is the carrier lifetime, $g(N(r,t))$ is the gain of the QW structure, P_a is the average density of optical power in the cavity, E_t is the intensity distribution of the field, h is Planck's constant, v is the laser operation frequency, $I(r,t)$ is the current density distribution entering the active layer, q is the electron charge, and d is the thickness of the active layer.

The TE mode gain spectra of the quantum well structure can be written as [7],

$$g(E) = \frac{e^2\hbar}{m_0^2 n_r \varepsilon_0 c E_i} \times \sum_J \sum_n \int_{E_g+E_{Cn}+E_{Vn}^J}^{\infty} \rho^J(E) M_J^2(E)(f_{Cn} - f_{Vn}^J) L(E) dE \tag{2}$$

Where E is energy value, $e=1.6\times10^{-19}$ J, $\hbar$ is the reduced Plank constant, m_0 is the electron free mass, n_r the refractive index, ε_0 is the permittivity of free space, c is the light velocity, E_i is the photon energy, E_g is the bulk band gap energy, E_{Cn} is the electron energy level, E_{Vn} is the hole energy level, index J refers to either heavy hole or light hole, index n refers to number of energy states in conduction and valance bands, $\rho_J(E)$ is the reduced density of state, $M(E)$ is the dipole matrix element, $f_{Cn}(E)$ and $f_{Vn}(E)$ are the Fermi functions of the conduction band and valence band, respectively, and $L(E)$ is the Lorentzian function.

The refractive index is in the influence of heat (thermal lensing effect) and carrier concentration (self-focusing effect). So refractive index is expressed by [7],

$$\Delta n_r(r) = \frac{\partial n_r}{\partial N}\Delta N(r) + \frac{\partial n_r}{\partial T}\Delta T(r) \tag{3}$$

$$\frac{\partial n_r}{\partial N} = -\frac{q^2}{2 n_0 \varepsilon_0 \omega^2 m_n} \tag{4}$$

Here, T is temperature value, n_0 is active layer refractive index, ω is angular frequency, m_n is electron effective mass, and $\partial n_r / \partial T \cong 4\times10^{-4} K^{-1}$.

For optical consideration, the normalized intensity distribution of the field $\varphi_t(r)$ is calculated by

$$\left|\overline{E}_t(r,t)\right|^2 = \frac{\left|\varphi_t(r,t)\right|^2}{\frac{1}{2s}\int_{-\infty}^{+\infty}\left|\varphi_t(r,t)\right|^2 dr} \tag{5}$$

Here, $\varphi_t(r,t)$ is total transverse mode, s is the diameter of oxide aperture.

The simple distribution of current density can be defined by [5, 7],

$$I(r,t) = \begin{cases} I_0(t) & r \le s \\ I_0(t)\exp(-(r-s)/r_0) & r \ge s \end{cases} \tag{6}$$

Where, I_0 is current density initial value, r_0 is the extent of the current spreading. This parameter plays an important role at temperature behavior of VCSEL and suppress of the transverse mode operation from single to multimode.

For modelling the thermal consideration, heat equation can be written as [7],

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\sigma_{act}\frac{\partial T(r,t)}{\partial r}\right) + Q = 0 \tag{7}$$

Where σ_{act} is the specific thermal conductivity, T is the temperature, and Q is the distribution of internal heat source density. The thermal behavior boundary conditions are

$$\partial T/\partial r\big|_{r=0} = 0, \partial T/\partial r\big|_{r=r_s} = 0 \tag{8}$$

In the linear gain (LG) model, gain is the linear function of carrier concentration and defined as $g=a\ (N-N_{tr})$. Where a= 2.5 × 10−16 cm^2 is gain coefficient and $N_{tr}=2.5\times10^{18}$ cm^{-3} is transparency carrier concentration.

For carrier dependent nonlinear gain (CDNG) model, the gain is described as $g=aN^3-bN^2+cN-d$. Where $a=1.4\times10^{-53}$, $b=2.8\times10^{-34}$, $c=2.4\times10^{-15}$ and $d=3.4\times10^3$ [6].

4. Results and Discussions

In our simulation, the oxide aperture diameter sets to 5μm, the active layer radius varies in the range of 0 to 20 μm, and the injected current is $I=2.5\times I_{th}$.

In this paper, we have used the gain model of [6] to analysis the temporal and spatial dependency of gain to the structural properties. Albeit, in mentioned paper, threshold current, spatial carrier concentration distribution, temperature, and intensity distributions are investigated and the dynamic and static gain are not considered.

Fig. 2 depicts the QW-VCSEL structure gain versus radius of active layer for two current spreading factors, r_0=4 and 0.02 μm, using LG and CDNG models. As shown in the figure, in each model, by increasing spreading factor r_0, the gain tail is broadening out of oxide aperture (r>2.5 μm). This is due to the fact that large r_0 means that a significant amount of injected current leakages to wider area outside the aperture which in turn leads to broadening of gain tail. We can conclude that CDNG model gain is more concentrated in the center of active region, r=0 μm, and the pick of gain is higher than LG one. As the final result of Fig. 2, it shows that r_0=0.02 μm and CDNG model results the best gain profile with proper confinement and higher maximum value.

Fig. 3 shows the laser gain versus radius of active layer for different times, using CDNG model and r_0=0.02 μm. It reveals that for t=0 ns, gain profile is confined to the center of active region and the

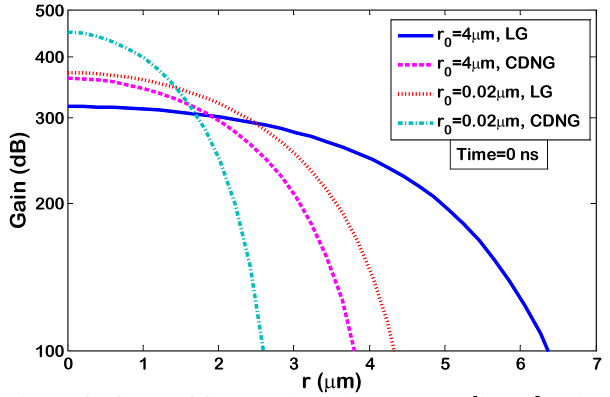

Figure 2: QW-VCSEL static gain versus radius of active layer for two different current spreading factor using LG and CDNG models.

maximum gain is at r=0 μm. By passing time, the spatial carrier hole burning is occurred specially in the center of active region; therefore, the pick of the gain extends from the center to the outer area. This phenomenon degrades spot beam and spatial coherency of output beam profile.

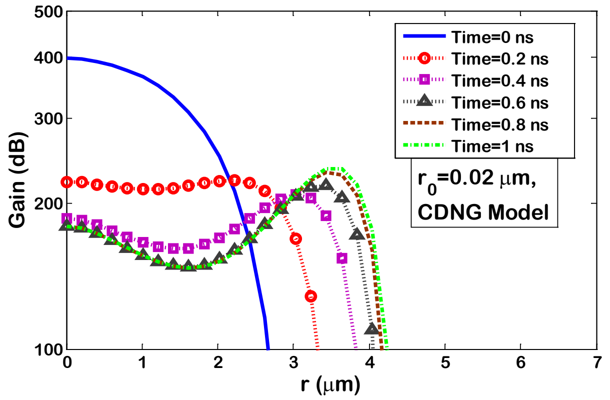

Figure 3: Quasi-3D gain profile versus radius of active region for different times calculated by CDNG model and r_0=0.02 μm.

Fig. 4 shows the laser gain versus radius of active layer for different values of injected current, using CDNG model and r_0=0.02 μm. As the figure describes, the higher the injected current density the higher gain and hence output power. By increasing injected current density, higher order transverse modes with further maximum are appeared. As the result of our discussions, high current injection which is necessary to increase output power, introduces higher order transverse modes with more SHB effect and destroy output beam quality.

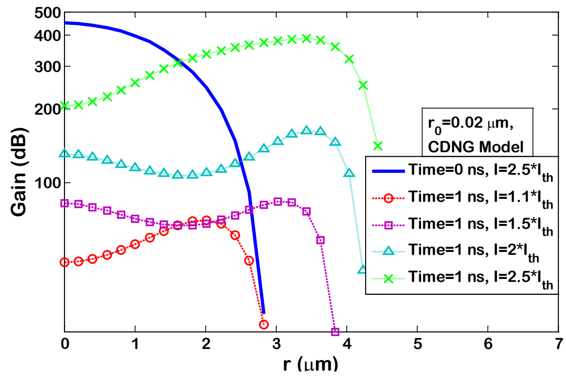

Figure 4: VCSEL gain versus radius of active layer for different values of current, using CDNG model and r_0=0.02 μm.

5. Conclusion

We compare gain profile of LG model and CDNG model for two case of high and low current spreading factor. It shows that CDNG model with low spreading factor results more confined profile with higher maximum value, so we choose this model for the rest of our simulation.

We also illustrate dynamic gain behavior of our laser. It shows that by increasing the operation time or injected current, SHB effect is occurred and higher order transverse modes are appeared. As the result, the pick of the gain profile extends and the quality of output beam decreases.

References

[1] H. Soda, K. Iga, C. Kitahara, and Y. Suematsu, "GaInAsP/InP surface emitting injection lasers," Jpn. J. Appl. Phys., vol. 18, no. 12, pp. 2329–2330, 1979.

[2] W. M. Man, S. F. Yu, "Comprehensive modeling of diffused quantum-well vertical-cavity surface-emitting lasers," IEEE J. Sel. Topics Quantum Electron., vol. 4, pp. 715–722, 1998.

[3] J. Gao, "An analytical method to determine small-signal model parameters for vertical-cavity surface emitting lasers," J. Lightwave Technol., vol. 28, pp. 1332–1337, 2010.

[4] S. F. Yu, "Analysis and design of vertical cavity surface emitting lasers for self-sustained pulsation operation," IEEE J. Quantum Electron., vol. 34, pp. 497–505, 1998.

[5] S. F. Yu, "Analysis and design of vertical cavity surface emitting lasers," John Wiley &Sons, Hoboken, New Jersey, 2003.

[6] M. Aghaeipour, V. Ahmadi, E. Darabi, "The effects of carrier dependent nonlinear gain on quantum well VCSEL characteristics," Opt. Quant. Electron., vol. 45, pp. 115–126, 2013.

[7] E. Sooudi, "Modelling and analysis of operation and characteristics of a quantum well VCSEL," M.Sc. Thesis, Tarbiat Modares University, Tehran, Iran, 2006.