Impact of Carrier Diffusion in Reflectivity Modification for Stable Dual Wavelength Emission in Buried Heterostructure (BH) Laser

Soumi Pal
Department of Electrical Engineering
Indian Institute of Technology Jodhpur
Jodhpur, India
Email: soumi.1@iitj.ac.in

Arpit Khandelwal
Department of Electrical Engineering
Indian Institute of Technology Jodhpur
Jodhpur, India
Email: arpitkhandelwal@iitj.ac.in

Nitin Bhatia
Department of Electrical Engineering
Indian Institute of Technology Jodhpur
Jodhpur, India
Email: nitin@iitj.ac.in

***Abstract*—We incorporate the effect of two-dimensional (2D) carrier diffusion in a BH laser source to establish the condition on modal reflectivity for stable dual polarized mode oscillation.**

I. Introduction

A dual wavelength laser source can be achieved by exploiting the birefringence property of buried heterostructure (BH) laser for a typical application of microwave generation [1]. In this method, the reflectivity of one target mode is required to be adjusted for its simultaneous oscillation with the maximum gain mode [1]. The burying and clad layers of the BH laser provide a higher optical field and carrier confinement in the active layer in a 2D manner. As a result, the modal fields exhibit greater intensities at the midpoint of the active layer with gradually decreasing towards the burying and clad layer [1]. Due to this, the carriers injected inside the active region experience a higher recombination rate at the higher intensity region in the center as compared to the boundaries [2]. This leads to carrier diffusion from the boundary regions towards the center of the active region [3]. The analytical model of the rate equation with one-dimensional (1D) carrier diffusion has already been established in [2]– [3]. In the 1D structure, the carrier distribution along the height of the active layer is assumed to be homogeneous. However, in the 2D confined structures, the carrier diffusion both in lateral and transverse directions needs to be considered. In this work, the rate equation incorporating the effect of 2D carrier diffusion is derived. An explicit expression of the average carrier density and the inhomogeneity parameter of the carrier density using a spaced-averaged carried density approach is computed in Section II. The reflectivity modification of the target mode for achieving stable dual polarized mode oscillation near the threshold vicinity is estimated in Section III. The work is concluded in Section IV.

II. Rate equation

The dominant field component for x and y polarized mode (E_x and E_y, respectively) for the BH laser can be expressed as

$$\psi_p(x,y,z) = \Psi_p(x,y)\sin\left(\frac{m_p \pi z}{L}\right) \tag{1}$$

Here, p could refer to x or y polarization, $\Psi_p(x,y)$ is the transverse mode distribution for the dominant electric field component in the x and y polarization estimated in [1], m_p is the longitudinal mode number, and L is the length of the cavity. Due to the carrier diffusion, the inhomogeneous carrier distribution can be expressed by the first order Fourier series as [3], [4]

$$N(x,y,t) = N_0(t) - N_1(t)\cos\left(\frac{\pi x}{a}\right)\cos\left(\frac{\pi y}{d}\right) \tag{2}$$

Here, $2a$ and $2d$ are the width and height of the active region, N_0 is the average carrier density and N_1 is the inhomogeneity parameter of the carrier density. We assume that the carrier in the z direction is uniformly distributed [2]. By incorporating 2D carrier diffusion, the rate equation model of the BH laser can be modified as

$$\begin{aligned}\frac{dE_p}{dt} = i(\omega-\omega_p)E_p + \frac{1}{2}[\{\Gamma_p v_{g_p} g_{0p}(N_0 - N_t - f_p N_1) \\ -\frac{1}{\tau_{p_x}}\}(1-i\alpha)]E_p\end{aligned} \tag{3}$$

with,

$$f_p = \frac{\int_v |\psi_p|^2 \cos(\frac{\pi x}{a})\cos(\frac{\pi y}{d})\,dv}{\int_v |\psi_p|^2\,dv} \tag{4}$$

$$\begin{aligned}\frac{dN(x,y,t)}{dt} = \frac{I_{th}}{eV} - \frac{N(x,y,t)}{\tau_e} - \sum_p^{x,y}\Gamma_p v_{g_p} g_{0p} V|\psi_p|^2 \\ \times\{N(x,y,t) - N_t\}|E_p|^2 + D\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right)N(x,y,t)\end{aligned} \tag{5}$$

Here, D is the diffusion coefficient and N_t is the carrier density at transparency. Other parameters in Eq (3) and (5) are described in [1]. To compute the explicit rate equation of N_0, we multiply $\cos(\frac{\pi m x}{a})\cos(\frac{\pi n y}{d})$ for $m,n=0$ and take volume integral both side of Eq. (5), we get

$$\begin{aligned}\frac{dN_0}{dt} = \frac{I_{th}}{eV} - \frac{N_0}{\tau_e} - \sum_p^{x,y}\Gamma_p v_{g_p} g_{0_p}\{q_{0_p}(N_0 - N_t) \\ -q_{1_p} N_1\}|E_p|^2\end{aligned} \tag{6}$$

with,

$$q_{0_p} = \int_v |\psi_p|^2 \, dv \tag{7}$$

and

$$q_{1_p} = \int_v |\psi_p|^2 \cos\left(\frac{\pi x}{a}\right) \cos\left(\frac{\pi y}{d}\right) \, dv \tag{8}$$

To compute explicit rate equation of N_1, we multiply $\cos(\frac{\pi m x}{a})\cos(\frac{\pi n y}{d})$ for $m, n = 1$ and take volume integral both side of Eq. (5), we get

$$\begin{aligned}\frac{dN_1}{dt} &= \sum_p^{x,y} 4\Gamma_p v_{g_p} g_{0p} \{q_{1_p}(N_0 - N_t) - q_{2_p} N_1\} |E_p|^2 \\ &\quad - \frac{N_1}{\tau_e} - \frac{L_D}{\tau_e}\left\{\left(\frac{\pi}{a}\right)^2 + \left(\frac{\pi}{d}\right)^2\right\} N_1\end{aligned} \tag{9}$$

with,

$$q_{2_p} = \int_v |\psi_p|^2 \cos^2\left(\frac{\pi x}{a}\right) \cos^2\left(\frac{\pi y}{d}\right) \, dv \tag{10}$$

and $L_D = \sqrt{D/\tau_e}$ is the diffusion length.

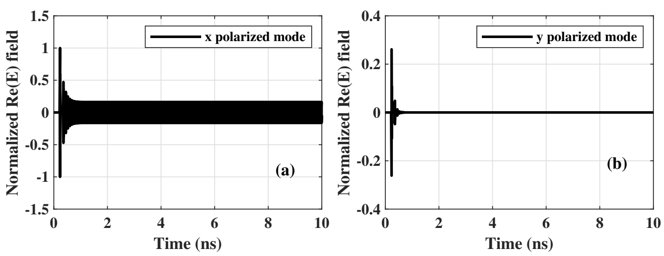

Fig. 1. Electric field dual mode oscillation incorporating carrier diffusion with $I_{th} = 50$ nA

For stable dual mode oscillation, the net gain of both modes must be equal [1]. Without accounting for the effect of carrier diffusion, the reflectivity of y polarized mode (R_y) is computed as 31.13% using net gain equalization for stable dual mode oscillation with $R_x = 30\%$ [1]. However, with carrier diffusion included in the rate equation, these parameters do not ensure dual mode stability. Fig. 1 shows the oscillation of only one mode with the above parameters, and incorporating diffusion phenomenon. Thus, after incorporating carrier diffusion in the rate equation model, further modification in the reflectivity of the target mode is desirable.

III. Reflectivity modification

We modify the reflectivity of the target mode to achieve stability of two modes simultaneously. The stable dual mode oscillation is achieved when the net gain for both modes is equal. Therefore,

$$R_y = \exp\left(lnR_x \cdot \frac{g_{0y}\Gamma_y(N_0 - N_t - f_y N_1)}{g_{0x}\Gamma_x(N_0 - N_t - f_x N_1)}\right) \tag{11}$$

is obtained. As N_0 and N_1 are time-dependent parameters, we take the average value of these to modify the reflectivity. Using Eq. (11), the modified reflectivity of the y polarized mode is calculated as 32.68%. This can generate simultaneous stable oscillations of electric field for both x and y polarized modes, as shown in Fig. 2(a). The normalized power spectrum of the electric field for x and y polarized modes depicts a frequency difference of 107 GHz as shown in Fig. 2(b). We study the changes in reflectivity of the target mode with the variation in threshold current (I_{th}). Since the modification of reflectivity depends on N_0 and N_1, the variation in I_{th} also leads to a variation in the modified reflectivity. However, the frequency difference remains constant with variations of I_{th}. Fig. 3 shows the reflectivity required for the y polarized mode, along with the variation of the average value of N_0 and N_1, to achieve stable dual mode oscillation with respect to the changes in I_{th}. It is observed that the changes in N_0 are minimal with I_{th}. However, N_1 changes considerably with I_{th} leading to a change in carrier density inside the active region due to the diffusion process.

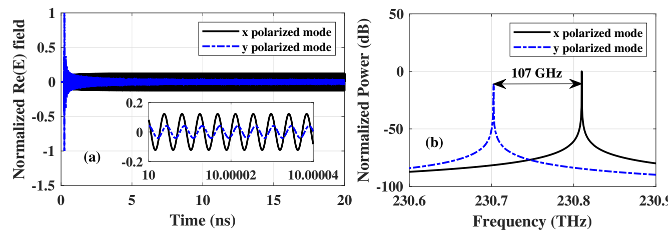

Fig. 2. (a) Electric field of stable dual mode oscillation incorporating carrier diffusion having $I_{th} = 50$ nA, (b) Normalized power spectrum of x and y polarized mode

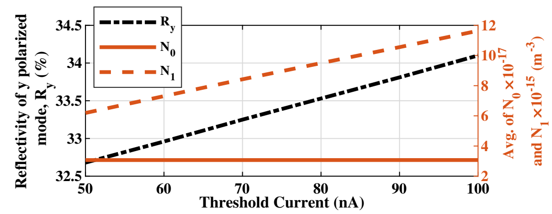

Fig. 3. Variation of estimated reflectivity of y polarized mode, average of N_0 and N_1 with respect to the threshold current for stable dual mode oscillation

IV. Conclusion

The rate equation model that takes with the impact of 2D carrier diffusion is obtained for stable dual polarized mode oscillation. The stability condition for dual mode oscillation is derived near the threshold vicinity. The stable oscillation can be established using reflectivity modification in the presence of carrier diffusion.

References

[1] S. Pal, A. Khandelwal, and N. Bhatia, "Theoretical Analysis of Buried Heterostructure Laser for Stable Dual Wavelength Generation," Applied Optics, Vol. 63, No. 14, pp. 3955-3964, May 2024

[2] K. Kishino, S. Aoki and Y. Suematsu, "Wavelength variation of 1.6 μm wavelength buried heterostructure GaInAsP/InP lasers due to direct modulation," IEEE Journal of Quantum Electronics, vol. 18, no. 3, pp. 343-351, March 1982

[3] K. Furuya, Y. Suematsu, and T. Hong, "Reduction of resonancelike peak in direct modulation due to carrier diffusion in injection laser," Applied Optics, vol. 17, no. 12, pp. 1949-1952, June 1978.

[4] G. P. Tolstov, Fourier series, Dover publication, Inc., New York, 1976.