Numerical analysis of extinction ratio improvement in gain lever laser diode

S. PIRAMASUBRAMANIAN*, M. GANESH MADHAN
Department of Electronics Engineering, Madras Institute of Technology Campus, Anna University, Chennai, India, 600 044

In this paper, extinction ratio improvement is predicted in 1.3 µm, bisection multiple quantum well laser diode employing gain lever effect. Two section laser diode is modeled by rate equations and numerically solved by fourth order Runge - Kutta method. The optical power variation with longer and shorter section currents are analyzed. Slope efficiency is evaluated for different shorter section currents at constant current injection in the longer section of the bisection laser diode. Higher slope efficiency of the gain lever case than unlever condition is utilized for extinction ratio improvement in the bisection laser diode. The effect of shorter section current on extinction ratio is analyzed. Extinction ratio is calculated for gain lever and unlever conditions for various shorter section currents. For a longer section biased of 35 mA, an extinction ratio improvement of 10.53 dB is obtained for an electrical pulse injection of 4 mA amplitude biased at $2I_{ath}$ at the shorter section.

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1. Introduction

Large extinction ratio is one of the important requirement for optical transmitters in high speed digital optical links and regenerators, to improve the link performance [1] - [5]. Extinction ratio improvement in laser diodes subsequently enhances the eye opening, leads to better BER characteristics in directly modulated optical link [5]. Two section laser diode can exhibit optical bistability, gain lever and self pulsation phenomenon [6] - [10]. Gain lever effect, is a mechanism investigated to improve the modulation efficiency in two or multiple section laser diodes [11]-[15]. Gain lever effect was analyzed by Vahala et al. [9] in two section quantum well laser. The detailed rate equation analysis of gain lever single quantum well GaAlAs laser diode was provided by Moore et al [10]. Gain lever effect in bulk and multiple quantum well laser was demonstrated by Seltzer et al [11]. For a laser diode, to exhibit gain lever effect, the active region has to be divided in to two unequal sections. RF current is given to the shorter section of laser diode and the larger section is dc biased at high gain level [11] - [15]. Gain lever phenomenon results due to the non linear transfer characteristic of laser diode. In this work, gain lever effect in bisection laser diode is utilized for extinction ratio enhancement, by providing electrical pulse instead of RF current.

2. Rate equation model for gain lever effect

Gain lever is a measure of slope efficiency improvement in the laser diode. The slope efficiency of two section laser diode is higher than the slope efficiency of unlevered laser diode [12]. The structure of two section laser diode is provided in Fig. 1. However detailed description of device structure can be obtained in ref [7]. The longer (a_1) and shorter (a_2) sections are electrically isolated and optically connected. Electrical pulse along with bias current (I_a) is applied to the shorter section, dc current (I_g) is applied to longer section. At lasing threshold, total optical gain overcomes the cavity loss. An increase in gain in one section of the laser diode allows equal decrease in gain in other section [9]. When current in shorter section I_a decreases, circulating optical power decreases, which results in increase of carrier density N_g in other section. The relation between optical gain and carrier density is sub linear [9]. Hence a small amount of increase in carrier density N_g results in AM efficiency enhancement in such multi section laser diodes [9] - [15]. Current pulses representing digital data is given to the shorter section (a_2) of laser diode and the larger section (a_1) is DC biased at high gain level (Fig. 1).

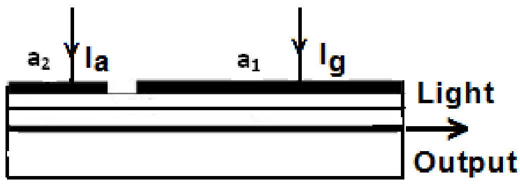

Fig. 1. Bi section gain lever laser diode

The gain lever laser diode is modelled by using rate equations as given below [8,9]

$$\frac{dN_g}{dt} = \frac{I_g}{a_1 qV} - BN_g^2 - v_g g_g (N_g - N_{og}) S(1 - \in S) - \frac{N_g}{\tau_{nr}} \quad (1)$$

$$\frac{dN_a}{dt} = \frac{I_a}{a_2 qV} - BN_a^2 - v_g g_a (N_a - N_{oa}) S (1 - \in S) - \frac{N_a}{\tau_{nr}} \quad (2)$$

$$\frac{dS}{dt} = -\frac{S}{\tau_p} + [a_1 v_g g_g (N_g - N_{og}) + a_2 v_g g_a (N_a - N_{oa})] \Gamma S (1 - \in S) + \Gamma \beta B (a_1 N_g^2 + a_2 N_a^2) \quad (3)$$

Where 'N_g', 'N_a' are carrier densities in section length a_1 and a_2, respectively. The total photon density is 'S' and the total volume of active region is denoted as 'V'. Optical power output is calculated from photon density by the following equation

$$P = \frac{chV\eta S}{\Gamma \tau_p \lambda} \quad (4)$$

The extinction ratio is defined as the ratio of power required to transmit '1' bit (P_1) to the power required to transmit'0'bit(P_0) [1]. The extinction ratio (ER) is

$$ER(dB) = 10\log(\frac{P_1}{P_0}) \quad (5)$$

3. Simulation results

The rate equations (1) - (3) are numerically solved by using fourth order Runge-Kutta method to obtain its static characteristics in MATLAB®. All the parameters used in this simulation are similar to that of ref [7]. For static conditions, left hand side of equations (1),(2) and (3) are made equal to zero and the solutions are obtained for carrier densities and photon density, with respect to applied injection currents in the respective sections.

The optical power is calculated by the equation (4) with fixed shorter section current of 3 mA and un pumped conditions ($I_a = 0$). The longer section current is varied from 0 to 150 mA and optical power variation is shown in Fig. 2. The longer section threshold current of 54 mA is obtained when the shorter section is not injected with any current. This result matches well with the experimental result of Uenohara et al [7] and verifies our simulation results for the same device structure used in our analysis.

The calculation for power with shorter section current varied from 0 to 15mA at constant longer section bias of 15 mA, 25 mA, 35 mA and 45 mA is shown in Fig. 3. The longer section current should be higher than the shorter section current to exhibit gain lever effect. The longer section currents are assumed in the range of 15 mA to 45 mA, which satisfies this condition. However, any set of current values ($I_g > I_a$) may be chosen for this analysis. The optical power variation for shorter section current indicates slope efficiency increment for increase in longer section current. The optical power is found to increase with increase in longer section current. A decrease in threshold current is predicted for increase in longer section current.

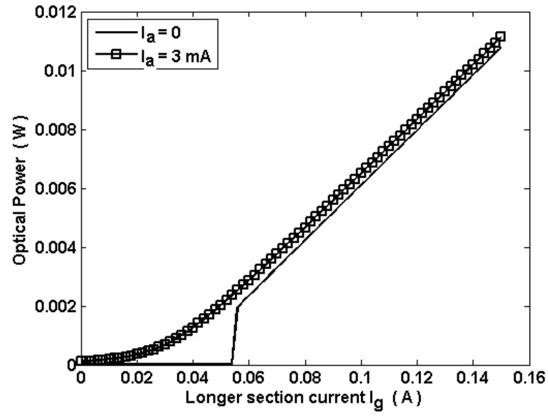

Fig. 2. Optical power variation with longer section current

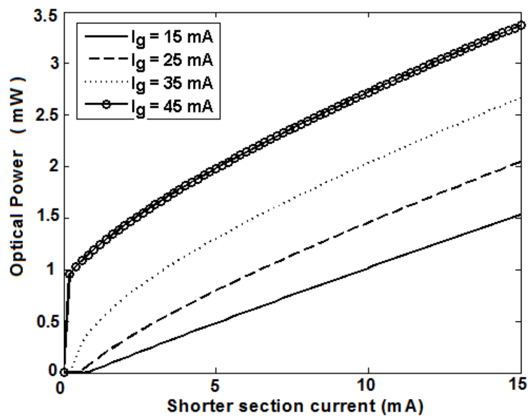

Fig. 3. Optical power variation with shorter section current

The optical power variation with shorter section current is plotted for 35 mA longer section current (I_g) to evaluate the slope efficiency (Fig. 4a). A threshold current of 0.4 mA is obtained in this case. The calculations are repeated for unlever laser diode where both of the sections are shorted together ($I_g = I_a$). The slope efficiency is evaluated and plotted as shown in Fig. 4b. The shorter section bias current is varied from $2I_{ath}$ to 10 I_{ath} for a 4 mA pulse. A maximum slope efficiency of 0.22 (mW / mA) is obtained for gain lever case at a bias of $2I_{ath}$. The slope efficiency is found to reduce for increase in bias current. The slope efficiency is 0.08 (mW / mA) for unlever case under same bias conditions. A similar trend is observed for other bias currents too. It is evident that the slope efficiency of bisection laser diode is higher than the normal laser (unlever) diode.

The electrical pulse input and corresponding optical outputs are shown in Fig. 5, for gain lever condition. The electrical pulse is biased at 0.8 mA ($2I_{ath}$) with 4 mA amplitude. The longer section is biased with 35 mA constant current. The output optical power is switched from 0.11 mW to 1.37 mW. The extinction ratio is calculated by using equation (5) and 11.11 dB is obtained under this condition.

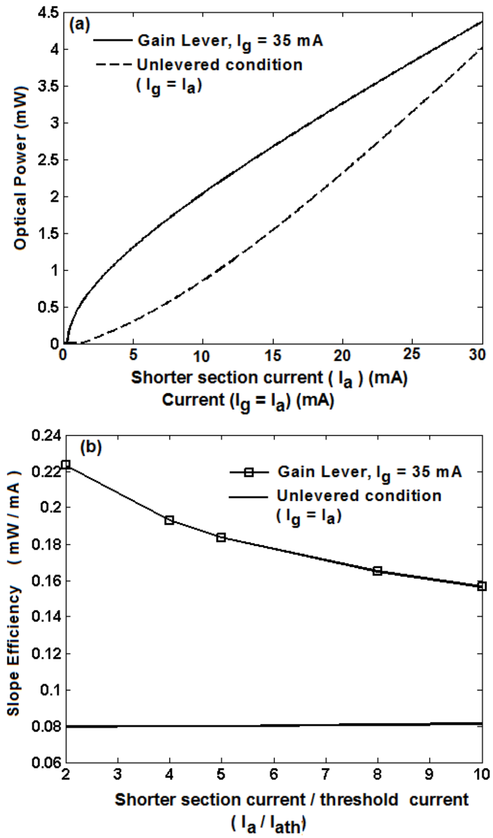

Fig. 4. (a) Static characteristics of gain lever (Ig = 35 mA) and unlever laser diode (Ia = Ig). (b) slope efficiency variation with current

The analysis is repeated for unlever case (Fig. 6). The extinction ratio improvement (dB) is calculated as the difference between the extinction ratio of laser diode under gain lever condition to the extinction ratio of the device under normal unlever mode. The characteristics of bisection laser diode under unlever condition is analyzed by shorting both of the electrodes [9] - [12]. In the simulation, equal currents are provided to the both the sections ($I_g = I_a$) to get the similar results. Hence, both the sections are biased at 17.9 mA with 2 mA magnitude ($I_g = I_a$) (Fig. 6). This is equal to the 4 mA pulse (I_a, 0.8 mA to 4.8 mA) provided to the shorter section and 35 mA (I_g) current injection at the longer section.

The optical power output is switched from 1.99 mW to 2.27 mW under unlever case and extinction ratio is 0.572 dB. A 10.53 dB improvement in extinction ratio is predicted under this case. The average transmitted power is high in this condition. Hence it is predicted that the gain lever laser diode can exhibit higher extinction ratio than the conventional laser diode with low average transmitted power.

The analysis is repeated for other value of shorter section currents and extinction ratio are evaluated for gain lever and unlever laser diode (Fig. 7). The extinction ratio is found to decreases for increase in bias current. This value is almost constant for unlever laser diode. It is observed that the extinction ratio is higher for gain lever than unlever condition.

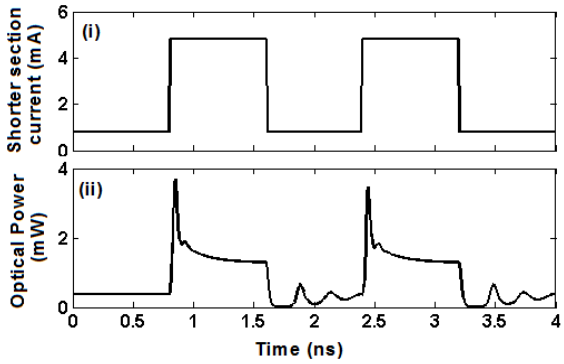

Fig. 5. (i) input electrical pulse for gain lever laser diode (ii)output optical power. The longer section current Ig = 35 mA

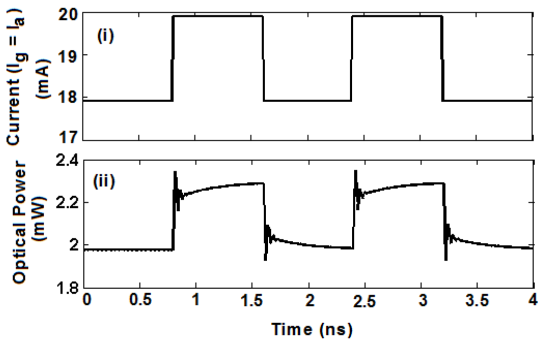

Fig. 6. (i) input electrical pulse for unlever laser diode (ii)output optical power

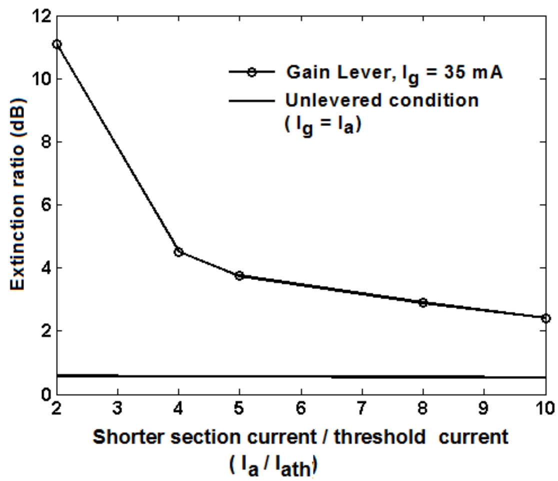

Fig. 7. Extinction ratio variation with shorter section current

The improvement in extinction ratio is plotted in Fig. 8a under various shorter section currents. The extinction ratio improvement is calculated with respect to unlevered laser diode, where both the electrodes are shorted together ($I_g = I_a$).

The extinction ratio is found to reduce for increase in shorter section bias current. The extinction ratio improvement for different longer section currents are evaluated and plotted (Fig. 8b). The longer section current is varied from 5 mA to 35 mA for this analysis. The shorter section current is fixed as twice of shorter section threshold current (2 I_{ath}). The extinction ratio is found to increase for increase in longer section bias current. The analysis is repeated for the shorter section currents of 4 I_{ath} and 5 I_{ath} respectively. A maximum extinction ratio of 10.53 dB is obtained when the longer section is biased at 35 mA. It is predicted that gain lever effect can be utilized to improve the extinction ratio in bisection laser diodes.

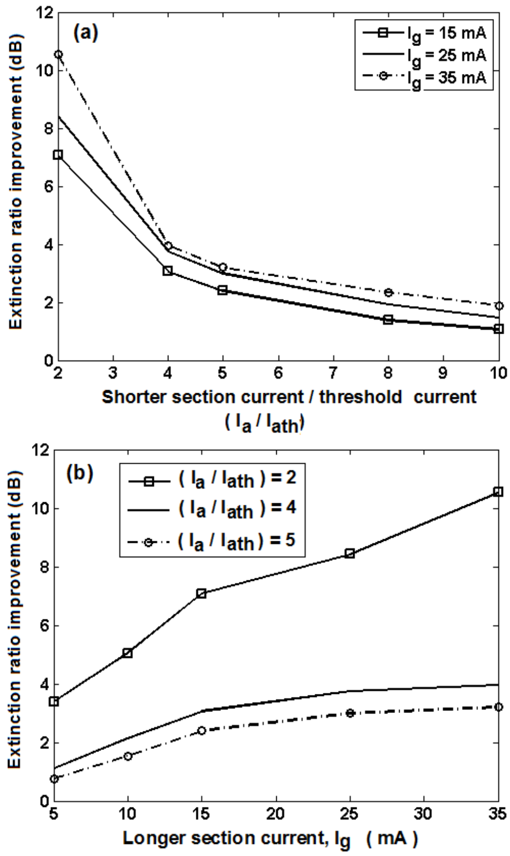

Fig. 8. Extinction ratio improvement with a) shorter section current and b) longer section current

4. Conclusions

In this work, extinction ratio improvement is predicted in 1.3 µm, bisection multiple quantum well laser diode employing gain lever effect. The rate equations are numerically solved in this simulation.

The effect of shorter section current on extinction ratio is analyzed. An extinction ratio improvement of 10.53 dB is obtained for an electrical pulse injection of 4 mA amplitude biased at 2I_{ath} to the shorter section, for a longer section bias of 35 mA. It is predicted that gain lever laser diode is found useful for high speed optical communication, optical switching and optical signal processing applications.

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*Corresponding author: spsnanthan@gmail.com