DOI: 10.21917/ijct.2010.0011

# ABSORPTIVE OPTICAL BISTABILITY IN HYBRID LASER STRUCTURE

**Tan Chee Leong[1] and Pukhraj Vaya[2]**

[1]*School of Photonics Science, Gwangju Institute of Science and Technology (GIST), 261 Cheomdan- gwagiro (Oryong-dong), Buk-gu, Gwangju, 500-712, Republic of Korea*

E-mail: ccheelong@yahoo.com

[2]*Department of Electronics and Communication, Amrita School of Engineering, Kasavanahalli, Bangalore, India*

E-mail: pukhrajvaya@yahoo.com

***Abstract***

***A hybrid bistable semiconductor laser structure consisting of an edge-emitting laser as a gain region and a vertical cavity laser as an absorber region, which translates lateral emission to vertical emission is analyzed. The device is modeled using appropriately modified rate equations and simulated using PSPICE circuit simulator. The dc sweep exhibits bistability. The hysterisis width of the bistable characteristics is found to depend on the reverse dc sweep, source resistance, and temperature. It is also noticed that the threshold currents and the hysterisis width can be controlled by the physical dimensions of gain and absorber regions and the driver circuit parameters. Turn-on delay decreases as the input current is increased.***

***Keywords:***

***Optical bistability, Edge emitting laser, Vertical cavity laser, Threshold current, Hysteresis width***

## 1. INTRODUCTION

Bistable semiconductor laser (BSL) is one of the key devices used in optical communication, optical switching and optical memory because it provides inherent advantages such as high optical gain, low optical switching power and high switching speed. In the past one decade, many BLS switching devices such as bipolar cascade bistable, Integrated VCSEL with MESFET and VCSEL cascade-able switching devices are developed [1, 2]. These BSLs can switch either laterally or vertically. Here, we propose a hybrid bistable semiconductor laser (HBSL) structure consisting of an edge emitting laser as gain region and vertical cavity laser (VCSEL) as an absorber region which changes lateral emission to vertical emission for many possible applications. Circuit modeling technique, which can incorporate source impedance, package parasitics and device circuit interactions, is adopted to analyze the proposed device [3]. The circuit is simulated using the circuit simulator PSPICE.

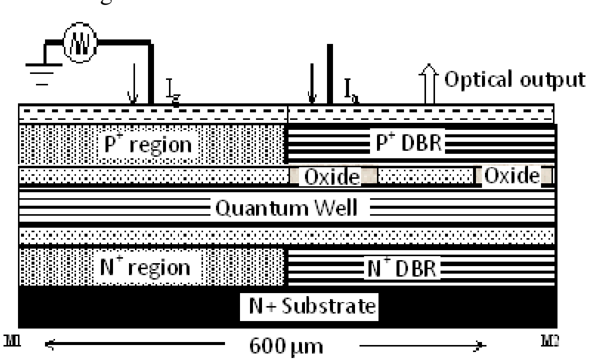


Fig.1. Proposed hybrid semiconductor laser structure for absorptive optical bi-stability

## 2. HYBRID BISTABL SEMICONDUCTOR LASER STRUCTURE

The proposed HBSL structure consists of an edge emitting quantum well laser (QWL) as a gain region and a vertical cavity surface emitting laser (VCSEL) as an absorber region as shown in Fig. 1. The QWL has three InGaAs-AlGaAs strained quantum wells sandwiched between two undoped AlGaAs SCH layers. The gain region is 300 $\mu$m long while the cavity length of QWL is 600 µm, the ridge width is 2.5µm, and the width of quantum well and the barrier is 6 nm each. VCSEL and QWL share the same quantum wells. The effective aperture of VCSEL for optical output is taken as 2.5µm x 2.5µm. The active region in VCSEL is sandwiched by AlAs-GaAs DBR mirrors with reflectivity of 0.98.

## 3. RATE EQUATIONS

The optical fields in QWL and in VCSEL are assumed to be oscillating in TE and TM mode respectively. The effect of carrier interchange in SCH region of the QWL is incorporated in the rate equations of [4, 5]. The optical output of the HBSL is a function of the carrier concentration in absorber region, which depends on the operating conditions of both gain and absorber regions. Simple thermal equivalent circuit is added to the rate equations by making the assumption that the temperature effect in VCSEL is much larger than that in QWL. Hence the temperature effect such as leakage current in QWL region is neglected. The modified rate equations are obtained as:

$$\frac{dN_{gs}}{dt} = \frac{I_g}{qV_{gs}} - \frac{N_{gs}}{\tau_{gs}} - \frac{N_{gs}}{\tau_{gn}} \tag{1}$$

$$N_w \frac{dN_{gQ}}{dt} = \alpha_g \frac{N_{gs}}{\tau_{gn}} - N_w \frac{N_{gQ}}{\tau_{gn}} - N_w G_g(N_{gQ})(1-\varepsilon P)P \tag{2}$$

$$\frac{dN_{as}}{dt} = \frac{I_a}{qV_{as}} - \frac{N_{as}}{\tau_{as}} - I_{Las} + \alpha_1 \frac{N_{aQ}}{\tau_{atte}} \tag{3}$$

$$N_w \frac{dN_{aQ}}{dt} = \alpha_a \frac{N_{as}}{\tau_{as}} - I_{LaQ} - N_w \frac{N_{aQ}}{\tau_{an}} - \alpha_1 \frac{N_{aQ}}{\tau_{atte}} - N_w G_a(N_{aQ})(1-\varepsilon P)P \tag{4}$$

$$\frac{dP_a}{dt} = N_w G_g(N_{gQ})(1-\varepsilon P_g)P + N_w G_a(N_{aQ})(1-\varepsilon P)P + \Gamma\beta N_w\left(\frac{N_{gQ}}{\tau_{gn}} + \frac{N_{aQ}}{\tau_{an}}\right) - \frac{S}{\tau_p} \tag{5}$$

$$T = T_D + (IV - P_{hv})R_{th} - \tau_{th}\frac{dT}{dt} \tag{6}$$

where, I, N and P are the current applied, the carrier density and the photon density respectively. The subscripts g, a, s and Q are used for gain region, absorber region, SCH region and QW region respectively. The gain is modeled as a linear function of carrier density [3]. The photon lifetime is given by $\tau_p = (v_g(\alpha_m + \alpha_{\text{int}}))$, where $\alpha_m (= \frac{1}{L_L} \ln \frac{1}{R})$ is the mirror loss and $\alpha_{\text{int}}$ in the internal loss. Transport time constant across SCH region is taken as $L_S^2 / 2D_a$. The equivalent thermal circuit is modeled based on equation (6). Leakage current, differential gain of absorber region $g_a$, and transparency carrier density $N_{aQ}$ are sensitive to temperature [2, 6].

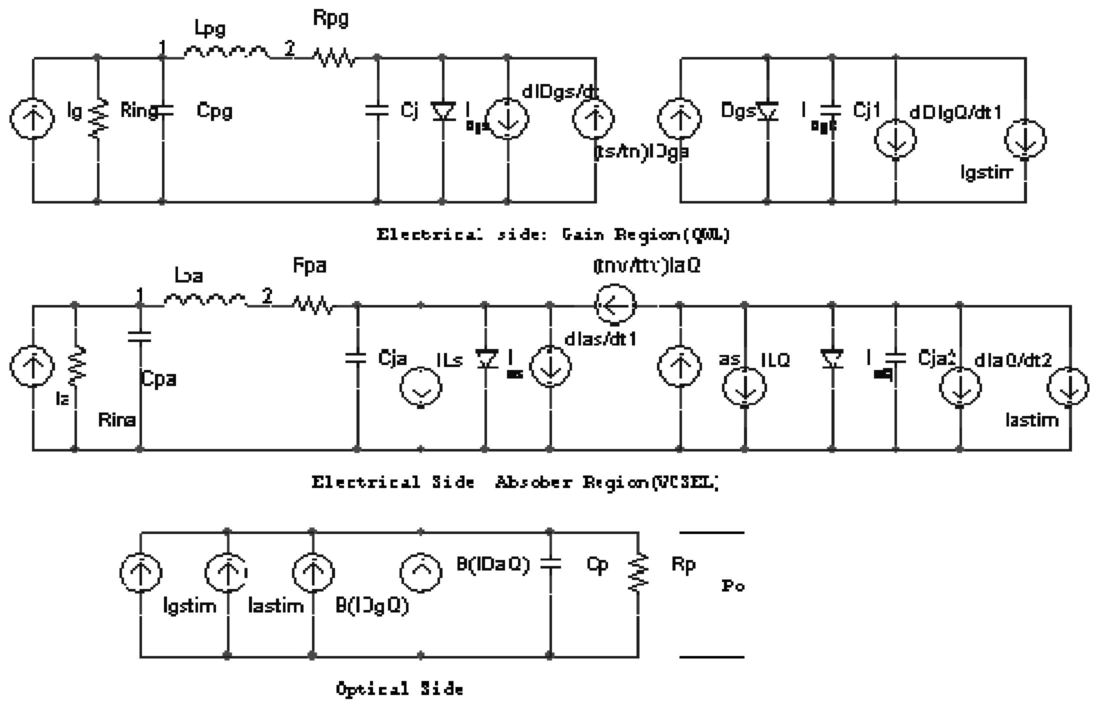


Fig.2. Equivalent electrical circuit of hybrid bistable semiconductor laser

$$I_L = I_D * C_{leak}(\exp(T / T_{ol}) - 1) \quad (7)$$

$$g_a(T) = g_a \exp[-T / T_{oa}] \quad (8)$$

$$N_{aQ}(T) = N_{aQ} \exp[T / T_{oa}] \quad (9)$$

Multiplying equations (1), (2), (3) and (4-5) by $qV_{gs}$, $qV_{gQ}$, $qV_{as}$ and $qV_{aQ}$ respectively, we can obtain the following expressions:

$$I_g = \tau_{gs} \frac{dI_{Dgs}}{dt} + I_{Dgs} - I_{Dgs} \frac{\tau_{gs}}{\tau_{gn}} \quad (10)$$

$$\alpha_g I_{Dgs} = \tau_{gs} \frac{I_{DgQ}}{dt} + I_{DgQ} + I_{gstim} \quad (11)$$

$$I_a = \tau_{as} \frac{dI_{Das}}{dt} + I_{Das} + I_{Ls} + I_{DaQ} \frac{\tau_{an}}{\tau_{atte}} \quad (12)$$

$$\alpha_a I_{Das} = \tau_{as} \frac{I_{DaQ}}{dt} + I_{DaQ} + I_{LQ} + I_{DaQ} \frac{\tau_{an}}{\tau_{atte}} + I_{astim} \quad (13)$$

$$C_p \frac{dP_o}{dt} = I_{gstim} + I_{astim} + \Gamma\beta(I_{DgQ} + I_{DaQ}) - \frac{P_o}{R_p} \quad (14)$$

where

$$I_{Dgs} = \frac{qV_{gs}N_{gs}}{\tau_{gs}}, \quad I_{Das} = \frac{qV_{as}N_{as}}{\tau_{as}},$$

$$I_{DgQ} = \frac{N_w qV_{gQ}N_{gQ}}{\tau_{gn}}, \quad I_{DaQ} = \frac{N_w qV_{aQ}N_{aQ}}{\tau_{an}}$$

$$I_{gstim} = N_w qV_{gQ} g_g (N_{gQ} - N_{og})(1 - \varepsilon PS_c)PS_c$$

$$I_{astim} = N_w qV_{aQ} g_a(T)(N_{aQ} - N_{oa}(T))(1 - \varepsilon PS_c)PS_c$$

The optical storage and losses are modeled as $C_p = qV_{gQ}S_c$ and $R_p = \frac{\tau_p}{C_p}$ respectively. The large signal electrical equivalent circuit is obtained by combining equations (10)-(14) following the scheme proposed by Ganesh et al [2] as shown in Fig 2. The source resistance and package parasitics are also included in the equivalent circuit. The optical output is assumed to be equivalent to the output voltage, $P_0$, across $R_p$. The parameter descriptions and values used in the presented study are given in Table.1.

## 4. SIMULATION RESULTS

The circuit model shown in Fig 2 is used to study the dc sweep and transient behavior of the HBSL. Fig 3 shows the bistable behavior of the hybrid structure. The hysterisis width of 11mA is obtained when $I_a$ = 10mA is applied to the absorber regions and $I_g$ is varied from 0-80mA.

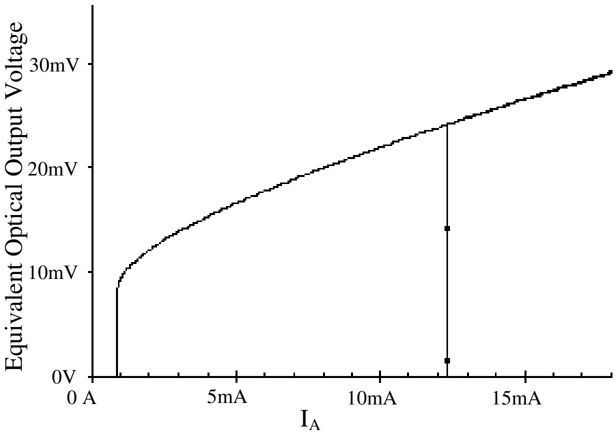


Fig.3. Bistability behavior of the HBSL

Table.1. Parameters used for the simulation study

| | Description | Value |
|---|---|---|
| $\tau_{gs}$ | Carrier transport time across SCH region in gain region | 45ps |
| $\tau_{as}$ | Carrier transport time across SCH region in gain region | 45ps |
| $\tau_{gn}$ | Bimolecular recombination lifetime in gain region | 1ns |
| $\tau_{an}$ | Bimolecular recombination lifetime in absorber region | 1ns |
| $\tau_{atte}$ | Thermionic emission lifetime in absorber QW | 5.6ps |
| $N_w$ | Number of Well | 3 |
| $\tau_p$ | Photon Carrier lifetime | 5.6e-12s |
| $V_{gs}$ | Volume of SCH in gain region | 22.5e-9cm$^3$ |
| $V_{as}$ | Volume of SCH in absorber | 0.225e-12cm$^3$ |
| $V_{gQ}$ | Volume of QW in gain region | 1.875e-12cm$^3$ |
| $V_{aQ}$ | Volume of QW in absorber region | 1.875e-13cm$^3$ |
| $S_c$ | Normalized Constant for Simulation to run | 1.3e18 |
| $\varepsilon$ | Gain compression factor | 1e-17 |
| $\beta$ | Spontaneous emission factor | 0.00001 |
| $T_{oa}$ | Characteristic temperature of active region | 200K |
| $R_{th}$ | Thermal resistance | 360CW$^{-1}$ |
| $T_D$ | Operating temperature | |
| $C_{leak}$ | Leakage current dimensionless constant | 1e-7 |
| $T_{ol}$ | Characteristic temperature of leakage current | 27K |
| $T_{th}$ | Thermal life time | 1e-6s |
| $\alpha_g$ | Ratio of gain region length to cavity length | 0.005 |
| $\alpha_a$ | Ratio of absorber region length to cavity length | 0.03 |

Fig. 4 shows that the hysteresis width and threshold currents are the function of the volumes of both gain and absorber regions. When volume of the gain region is increased, both forward and reverse threshold currents increase maintaining the hysteresis width. Whereas, when the volume of the absorber region is changed, the reverse threshold current increases without affecting the forward threshold current thus, reducing the hysteresis width. This shows that the hysteresis width and threshold current depend on the physical dimensions of HSBL device. Threshold current also depends on the source resistance. It reduces when the source resistance of the gain region is increased maintaining the hysteresis width at almost the same level. However, the hysteresis width increases with the source resistance in absorber region (see Fig. 5). Fig 6 shows that $I_{th}$ for the forward sweep remains unchanged in the temperature range of 273 -353 K; whereas, it increases for the reverse sweep. This reduces the hysteresis width at higher temperature.

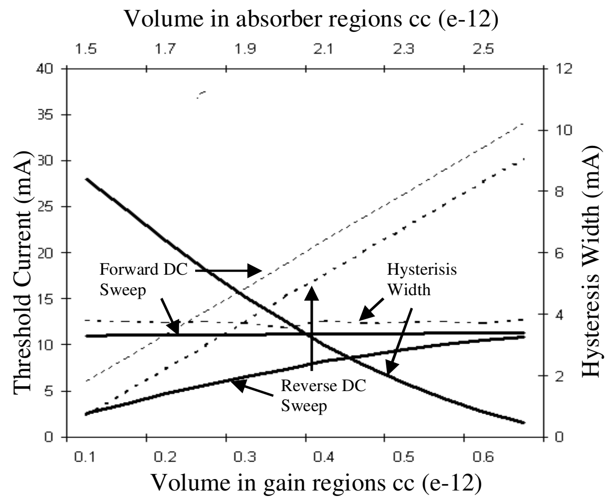


Fig. 4. Dependence of hysteresis width and threshold current on the volume of the gain region (doted line) and the volume of the absorber region (solid line)

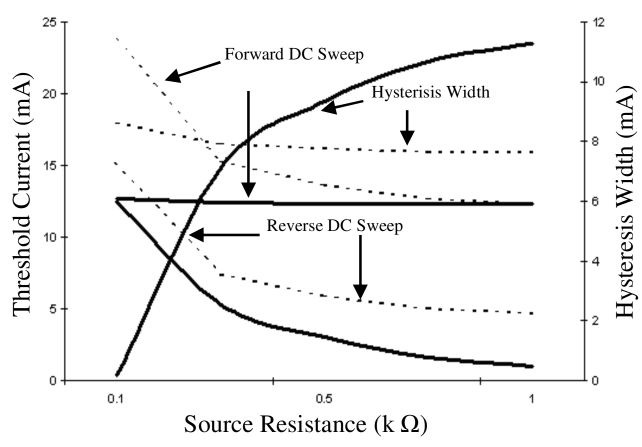


Fig. 5. Dependence of hysteresis width and threshold current on the source resistance of the gain region (doted line) and that of absorber region (solid line)

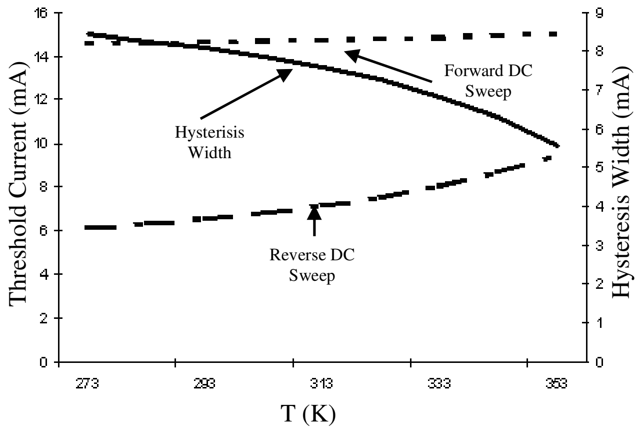


Fig.6. Variation of hysterisis width and threshold current with temperature

The transient response of the HBSL circuit model is simulated by biasing the gain region at 10 mA within the bistable region and applying positive pulse of 10mA height and 3ns width to the gain region. The device goes to the on-state and gives optical output. When a negative pulse of -10mA is applied, the optical output switches off as shown in Fig 7. We also noticed that the device shows a high turn-on delay due to the losses in the mirror (2 times longer than normal QWL). Turn-on delay can be reduced by applying a pulse of higher magnitude to the gain region (Fig 8). The optical output is found to increase with the input current.

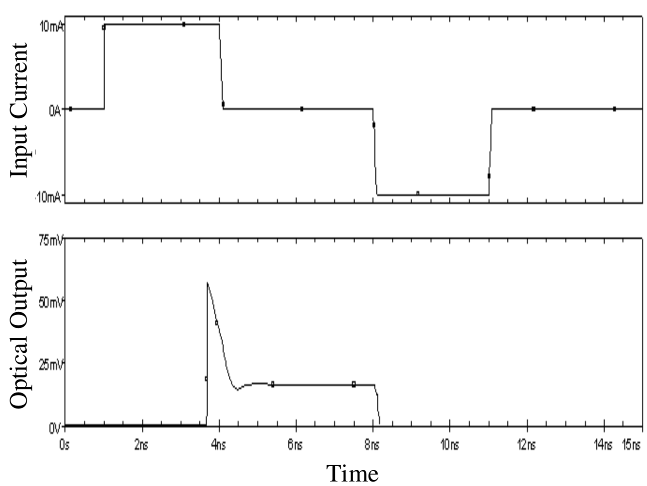


Fig.7. Transient Response of HBSL and the threshold current of hysterisis of the device

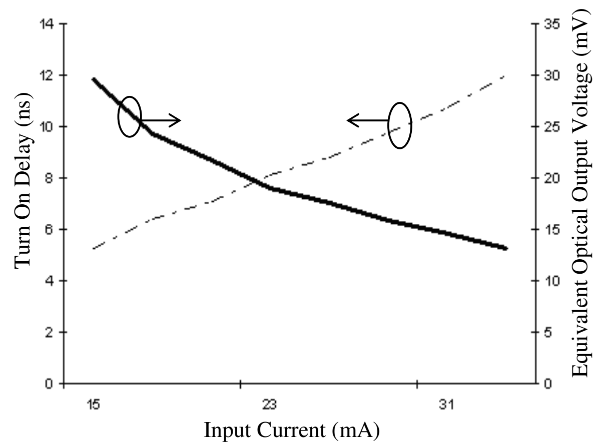


Fig.8. Effect of Input Current to the Transient Behaviour of the HBSL

## 5. CONCLUSION

In this paper, we have analyzed the hybrid semiconductor laser structure for optical bistability. The rate equations are transformed into equivalent electrical circuit. The circuit is stimulated using PSPICE to study the dc and transient behavior of the device. The dc sweep exhibits bistability. The hysterisis width and threshold current are found can be controlled by source resistance as well as by the device dimensions. The device exhibits long turn on delay, which can be improved by increasing the input current.

## REFERENCES

[1] Kawaguchi, H "Bistable laser diodes and their applications: state of the art " IEEE Journal of Selected Topics in Quantum Electronics, Vol. 3, Issue 5, Pg:1254 – 1270, October. 1997.

[2] M. Ganesh Madhan, P. R. Vaya, and N. Gunasekaran "Circuit Modeling of Multimode Bistable Laser Diodes" IEEE Photonics Technology Letters, Vol 11, No 1, January 1999.

[3] Rodney S. Tucker. "Circuit model of double-heterojunction laser below threshold". IEE PROC. 128:pp. 100-104, 1981.

[4] Yu S.F," Analysis and Design of VCSEL", John Wiley and son Inc,US, 2003.

[5] M.F.Lu, J.S.Deng, C. Juang, M.J. Jou and B.J. Lee, "Equivalent Circuit Model of Quantum Well Lasers", IEEE Journal of Quantum Electronic, Vol 31, No.8, pp1418-1422, August 1995.

[6] C.L. Tan and P.R.Vaya, "The Effect of Temperature on the Operation of Quantum Well Laser: A simulation study based on three level rate equations", Journal of Fiber and Integrated Optics, Vol. 25.6, pp. 441-450, 2006.