第 23 卷第 1 期 半 导 体 学 报 Vol. 23, No. 1
2002 年 1 月 CHINESE JOURNAL OF SEMICONDUCTORS Jan., 2002

Small Signal Equivalent Circuit Model and Modulation Properties of Vertical Cavity-Surface Emitting Lasers*

Mao Luhong[1], Chen Hongda[1], Tang Jun[1], Liang Kun[1], Wu Ronghan[1], Nian Hua[2], Guo Weilian[2] and Wu Xiawan[2]

(1 *State Key Laboratory on Integrated Optoelectronics, Institute of Semiconductors, The Chinese Academy of Sciences, Beijing* 100083, *China*)

(2 *Electronic & Information School, Tianjin University, Tianjin* 300072, *China*)

Abstract: Small signal equivalent circuit model and modulation properties of vertical cavity-surface emitting lasers (VCSEL's) are presented. The modulation properties both in analytic-equation calculation and in circuit model simulation are studied. The analytic-equation calculation of the modulation properties is calculated by using Mathcad program and the circuit model simulation is simulated by using Pspice program respectively. The results of calculation and the simulation are in good agreement with each other. Experiment is performed to testify the circuit model.

Key words: VCSEL; circuit model; modulation property

EEACC: 4320J; 2560B

CLC number: TN248.4 **Document code**: A **Article ID**: 0253-4177(2002)01-0082-05

1 Introduction

Vertical cavity-surface emitting lasers (VCSEL's) have been very useful for various applications for the last few years. The recent work was done in the understanding of the underlying physics, in the fabrication technology, and in the growth design to allow their commercial availability at low cost. The most significant attributes of VCSEL's include a low threshold current, single-longitudinal-mode operation, a circular beam profile, high-speed-modulation capabilities and wafer integrability[1,2]. VCSEL's are attractive as compact light sources for applications in optical communications and interconnects. An important consideration for such applications is the modulation properties of VCSEL's under high-speed. In order to study the relationship between the modulation properties and material parameters, we developed two ways to calculate the modulation properties. They are analytic calculation and circuit model calculation. The analytic solutions of the modulation properties are calculated by using Mathcad program and the circuit model is simulated by using Pspice program respectively. The results of both calculation and simulation are is good agreement with each other. Experiment was performed to testify the calculations.

2 Modeling modulation properties of VCSELs

The adopted rate equations proposed by Lu

* Project supported by National Natural Science Foundation of China (Nos. 69896260, 69789802, 69776036)

Mao Luhong professor, PhD. His research interests are in VCSEL's, photo detectors and semiconductor optoelectronic circuits.

Received 16 March 2001, revised manuscript received 28 September 2001

et al[3,4] to describe the carriers inside the spacer layer N_s, and the active layer N, and photon number S in a quantum well (QW) semiconductor laser are given by

$$\frac{dN_S}{dt} = \frac{I}{q} - \frac{N_S}{\tau_S} - \frac{N_n}{\tau_n} \quad (1)$$

$$\frac{dN}{dt} = \frac{N_S}{\tau_S} - \frac{N}{\tau_n} - \frac{G(N)S}{1+\epsilon S} \quad (2)$$

$$\frac{dS}{dt} = \frac{G(N)S}{1+\epsilon S} - \frac{S}{\tau_p} + \frac{\Gamma\beta N}{\tau_n} \quad (3)$$

The QW semiconductor laser´s rate equations are suitable to VCSEL´s for the reasons of below. The first, a VCSEL of semiconductor is with the QW structure, the second, the spacer region in VCSEL is the same structure as the separate confinement heterostructure (SCH) region in QW semiconductor laser. So we can redefine N_S and τ_S. Where N_S represents the carrier density in the spacer region, τ_S is the time of carrier transport across the spacer region[5]. Therefore, the equations can describe a VCSEL. The parameter I is the injection current, τ_n is the bimolecular recombination lifetime, τ_p is the photon lifetime, Γ is the optical confinement factor, β is the spontaneous emission factor and $G(N) = g_0(N - N_e)$ is the carrier number dependent gain function[3,4], N_e is the transparency carrier number, ϵ is compression factor.

The small-signal solution of the equations is done by first making following substitution:

$$I = I_0 + ie^{j\omega t}, N_S = N_{S0} + ne^{j\omega t}, N = N_0 + ne^{j\omega t},$$

$$S = S_0 + se^{j\omega t}, G = G_0 + g_0 se^{j\omega t}.$$

After the small-signal quantities are substituted into Eqs. (1) ~ (3), the steady-state quantities are set to zero. The small-signal equations are

$$j\omega n_S = i/q + a_{11}n_S \quad (4)$$

$$j\omega n = a_{21}n_S + a_{22}n + a_{23}s \quad (5)$$

$$j\omega s = a_{32}n + a_{33}s \quad (6)$$

The results are expressed in the transfer matrix $A(\omega)$

$$A(\omega)\begin{pmatrix} n_s \\ n \\ s \end{pmatrix} = \begin{pmatrix} a_{11} - j\omega & 0 & 0 \\ a_{21} & a_{12} - j\omega & a_{23} \\ 0 & a_{32} & a_{33} - j\omega \end{pmatrix}\begin{pmatrix} n_s \\ n \\ s \end{pmatrix} = -\begin{pmatrix} i/q \\ 0 \\ 0 \end{pmatrix} \quad (7)$$

where

$$a_{11} = -\frac{1}{\tau_S} - \frac{1}{\tau_n}, \quad a_{21} = -\frac{1}{\tau_S}, \quad a_{22} = \frac{1}{\tau_S} - \frac{g_0 S_0}{1+\epsilon S_0} \quad (8)$$

$$a_{23} = -\frac{G(N_0)}{(1+\epsilon S_0)^2}, \quad a_{32} = \frac{\Gamma g_0 S_0}{1+\epsilon S_0} + \frac{\Gamma\beta}{\tau_n}, \quad a_{33} = \frac{G(N_0)}{(1+\epsilon S_0)} - \frac{1}{\tau_p} \quad (9)$$

The modulation response normalized to the response at zero(dc) frequency, $M(\omega)$, is given by

$$M(\omega) = \frac{\det A(0)}{\det A(\omega)} = \frac{A}{(-j\omega)^3 + A_2(-j\omega)^2 + A_1(j\omega) + A_0} \quad (10)$$

where $\det A(\omega)$ is the determinant of the matrx $A(\omega)$, and

$$A_0 = a_{11}a_{22}a_{33} - a_{11}a_{23}a_{32}$$
$$A_1 = a_{11}a_{22} + a_{22}a_{23} + a_{33}a_{11} - a_{22}a_{32}$$
$$A_2 = a_{11} + a_{22} + a_{33} \quad (11)$$

3 Small signal equivalent circuit model of a VCSEL

Multiplying both sides of equation (4) with qV_a/V_s, V_a is the active layers volume and V_s is the spacer region volume, let

$$i_S = qn_S V_a/(V_s\tau_S) \quad (12)$$

where i_S is the small signal current for spacer region. Multiplying both sides of equation (5) with q. Multiplying both sides of equation (6) with $\eta V_T/(N_0 a_{32})$, let

$$V_1 = \eta V_T n/N, \quad i_L = q(-a_{22})s \quad (13)$$

where η is the injection constant, $V_T = kT/q$, where V_T is the thermal voltage, k is Boltzman's constant, T is the absolute temperature, q is the electron charge. V_1 represents the small signal voltage drop of VCSEL, and i_L represents the small signal photon number s. Then we get

$$\tau_S \times j\omega i_S = iV_a/V_s - i_S - i_S\tau_S/\tau_n \qquad (14)$$

$$C \times j\omega V_1 = i_S - V_1/R - i_L \qquad (15)$$

$$L \times j\omega i_L = V_1 - R_{SC}\, i_L \qquad (16)$$

where C is the usual diffusion capacitance resulting from the storage effect of the injected carriers, R is a modified differential diode resistance.

$$C = qN_0/(\eta V_T), \quad R = [C \times (-a_{22})]^{-1} \qquad (17)$$

$$L = [C \times (-a_{23}a_{32})]^{-1}, R_{se} = L(-a_{33}) \qquad (18)$$

Because each parameter in equations (14) and (15) has current dimension and each parameter in equations (16) has voltage dimension, the equations (14) ~ (16) can be set up for a circuit model. The VCSEL small signal model is represented by the right hand of the dashed line of equivalent circuit in Fig. 1. In Fig. 1

$$i_1 = i(V_s - V_a)/V_s, \quad i_2 = \tau_S \times j\omega i_S,$$

$$i_3 = i_S\tau_S/\tau_n, \quad i' = iV_a/V_s \qquad (19)$$

i_L represents the optical intensity of VCSEL.

$$s = G_1 i_L, \quad G_1 = 1/q(-a_{22}) \qquad (20)$$

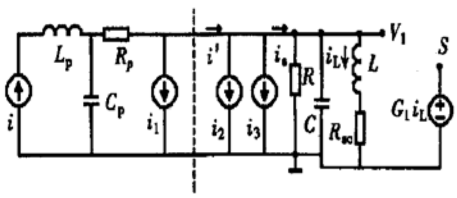

Fig. 1 Small signal circuit model of VCSEL

The circuit model also gives the parasitic parameter in Fig. 1. L_p is a series inductor representing the wirebond, a shunting capacitor C_p representing the contact capacitance, and a series resistor R_s representing the contact resistance and the Bragg mirror stacks.

4 Calculation results, simulation results and experiment results of modulation response

The parameters used in calculations are from References[4, 5], $\tau_s = 3$nS, $\tau_n = 3$nS, $\tau_p = 4$pS, $g_0 = 1 \times 10^5 S^{-1}$, $\Gamma = 0.158$, $\beta = 1 \times 10^{-3}$, $V_a = 6.2 \times 10^{-18}$ m^{-3}, $N_0 = 1.1 \times 10^7$, $\epsilon = 1 \times 10^{-7}$, $V_a/V_s = 0.8$. N_{S0}, N_0 and S_0 are calculated by solving the steady state equations of the Eqs. (1) ~ (3). The parasitic parameters are $R_s = 76\Omega$, $L_s = 2.28$nH, $C_s = 0.39$pF[6].

Figure 2 shows the results of calculating equation (10) by using Mathcad program. Figure 3 shows the results of Pspice program simulation by using the circuit model in Fig. 1. For the purpose of comparison. parasitic parameters are not used in

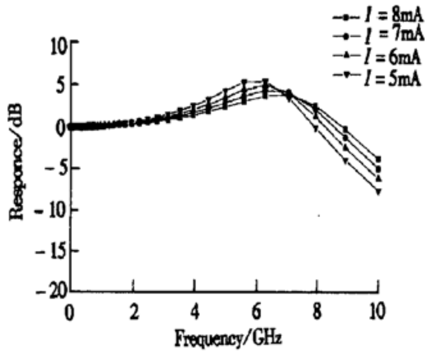

Fig. 2 Calculation results of frequency response in Mathcad program

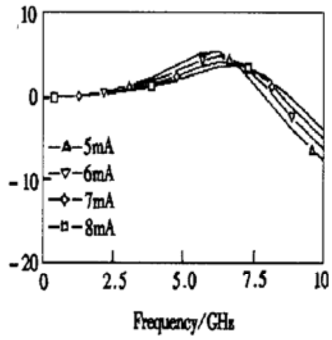

Fig. 3 Simulation results of frequency response in Pspice program

Fig. 3, That is, let $R_s = L_s = C_s = 0$ in Fig. 1. The two kinds of results are very close to each other because the calculations used for the results have the same parameters. The difference is that the two results of calculations were generated from different ways. Figure 4 shows the experimental results by using a network analyzer, mode HP 8720D, to test a VCSEL. The device product number of the VCSEL is 8085-1000 by EMCORE Corp. The threshold current of the device is 3mA and the operating current are 5, 6, 7, 8mA respectively. The bandwidth in Fig. 4 is lower than those in Figs. 2 and 3. The reason is that the practical measured VCSEL is in packaging, so the parasitic parameters must be considered. If one compares the measurement with circuit model, the model must be added with parasitic parameters. Figure 5 shows the simulation results with parasitic parameter in Fig. 1. Comparing the Fig. 4 with Fig. 5, one can see the experimental results are approximate with the simulation results. This testifies that the circuit model is correct. The calculations we listed above are useful for the design and application of VCSEL.

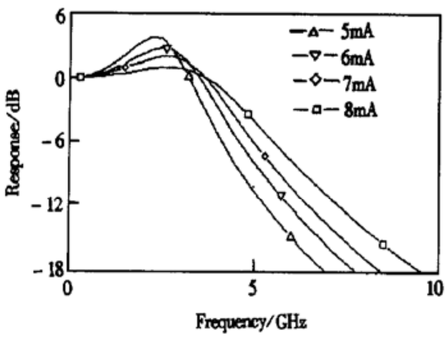

Fig. 4 Simulation results of frequency response in Pspice program with parastic parameters

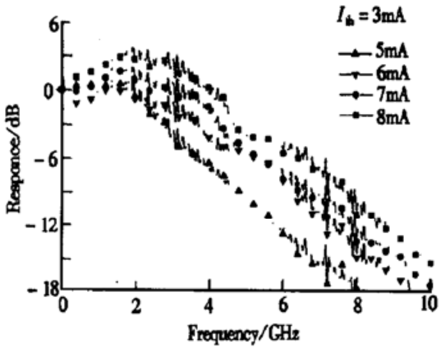

Fig. 5 Experimental results of frequency response of a VCSEL

5 Conclusion

We use the rate equations of QW semiconductor laser to describe those of VCSEL and redefine the N_s and τ_s in spacer ragine. We developed two ways to calculate the frequency response of a VCSEL. They are the analytic-equation calculation and the circuit model simulation. The results of calculation and the results of simulation are in good agreement with each other. Experiment was performed to testify the circuit model. The two ways are useful for the design and application of VCSEL.

Acknowledgements The authors wish to acknowledge Zhu Ninghua and Liu Yu for their assistance in experiment. The work is supported by the open projects of Chinese State Key Laboratory on Integrated Optoelectronics and R&D Center for Optoelectronics.

References

[1] Chang-Hasnain C J, et al. Dynamic polarization and transvers mode characteristics of VCSEL's. IEEE J Quatum Electron, 1991, 27: 1402

[2] Torrn M S, Ranea-Sandoval H F. Modulation response of multiple transverse modes in vertical-cavity surface-emitting lasers. IEEE J Quatum Electron, 2000, 36(1): 112

[3] Lu M F, Deng T S, Juang C, et al. Equivalent circuit model of quantum-well laser. IEEE J Quantum Electronics, 1995, QE-31(8): 1418

[4] Mcdonald D, O'Dowd R F. Comparision of two-and three-level rate equations in the modeling of quantum-well lasers. IEEE J Quantum Electronics, 1995, QE-31(11): 1927

[5] Yu S F. Dynamic behavior of vertical-cavity surface-emitting lasers. IEEE J Quantom Electronics, 1996, 32(7): 1168

[6] Bruensteiner M, Papen G C. Extraction of VCSEL rate-equation parameters for low-bias system simulation. IEEE J Selected Topics in QE, 1999, 5(3): 487

垂直腔面发射激光器的小信号电路模型和调制特性*

毛陆虹[1] 陈弘达[1] 梁 琨[1] 唐 君[1] 吴荣汉[1] 粘 华[2] 郭维廉[2] 吴霞宛[2]

(1 中国科学院半导体研究所 国家集成光电子重点实验室, 北京 100083)
(2 天津大学电子与信息工程学院, 天津 300072)

摘要: 给出了垂直腔面发射激光器的小信号电路模型和调制特性, 调制特性用解析计算和电路模型模拟两种方法得到, 解析计算和电路模型模拟的结果一致, 实验证实了电路模型的正确性.

关键词: VCSEL; 电路模型; 调制特性
EEACC: 4320J; 2560B
中图分类号: TN248.4 **文献标识码**: A **文章编号**: 0253-4177(2002)01-0082-05

* 国家自然科学基金资助项目(批准号: 69896260, 69789802, 69776036)

毛陆虹 教授, 博士, 目前从事VCSEL、光探测器和光电集成电路的研究.

2001-03-16 收到, 2001-09-28 定稿