On the Line Form and Natural Linewidth; Simulation and Interpretation of Experiments

M.G. Noppe
Novosibirsk State Technical University, 20 K. Marx Ave., 630092, Novosibirsk, Russia, noppe@ieee.org

Abstract - A new formula for line form inside and outside laser is derived. The linewidth is calculated on the basis of the derived formula for the line form. Our simulation of the linewidth for three Fabry-Perot lasers allows explaining all known to us experimental measurements of semiconductor laser natural linewidth.

I. Introduction

The problem of natural linewidth in semiconductor lasers is of fundamental importance both theoretically and practically (narrow linewidth lasers are in great demand in coherent optical communication systems [1]). The measurements of natural linewidth for high power lasers: GalnAs/GalnAsP (SCH), (QW), (DFB LDs) lasers [1], gain-guided V-groove laser and oxide stripe laser [2], DFB Lasers [3-5], VCSEL laser [6], **microcavity laser** [7] and Fabry-Perot lasers [8-9] have shown various functional deviations from Schawlow-Townes formula for natural linewidth $\Delta\nu$ for one mode (the main of which is minimum of function $\Delta\nu$ =F(1/P), P is output power). The primary goal is to develop a theoretical model which allows explaining all known experimental measurements of semiconductor laser natural linewidth and simulation of three semiconductor lasers. Another goal is to calculate line forms versus frequency for some values of power.

II. A New Formula for the Line Form

Our approach to the problem is based on the following basic concepts: a laser model distributed in space; an experimentally measured dependence of the refractive index of the laser active zone on the electric field intensity E. From experiments [10] it follows that

$$n = n_0 + n_1(\omega)|E| + n_2(\omega)E^2. \quad (1)$$

The formula (1) will be used for deriving the line form and natural linewidth of the mode, basing on the representations of t creating a laser line form as a result of superposition of spontaneous radiation on laser radiation studied by a special method of the spectral theory of stochastic processes [11] which is developed in the present paper. In our paper, the formula for the line form for radiation inside the laser is derived as

$$L(\omega) = (1/2\pi)\int_{-\infty}^{\infty} \exp(-i(\omega-\omega_0)\tau - -A_p|\tau| - B_A\tau^2 - C_A|\tau|^3)d\tau, \quad (2)$$

where $A_P = A_S^2/4E^2\Delta t,\ B_A = (\varphi A_s)^2/8,\ C_A = (\varphi A_s)^2/12\Delta t$, (3)

where A_S is a spontaneous fluctuation amplitude; Δt is the average time between two acts of emission of spontaneous fluctuations, m is the number of mode; for Fabry-Perot lasers

$$\varphi = -\frac{c\,\pi m(n_1 + 2n_2|E|)}{L_z(n_0 + n_1|E| + n_2E^2)^2}, \quad (4)$$

where L_z is the length of laser, c the light velocity. A formula for laser form, differing from (2) in that $B_A = 0$, was proposed in [11]. But the calculations made in the paper have shown that B_A defining the peak fluctuations influences the natural linewidth. Hence it is impossible to neglect B_A. If φ=0, a general expression for the line form (2) takes the form of Lorentz line, where natural linewidth is $\Delta\omega = A_S^2/2\Delta t E^2$; it is a modification of Schawlow-Townes formula [12]. The calculations made for one model of transmission coefficient have shown an insignificant change in the natural linewidth and the line center outside the laser. Therefore the line form looks like (2). Formulas for parameters (3) are derived.

III. Calculations of Line Form and Natural Linewidth

The intention in this section is to simulate the natural linewidth $\Delta\nu$ versus inverse power (1/P) for three lasers (see Fig.1, 3): possessing very small $\Delta\nu$ (SCH laser, see Fig.3. in [1]) and possessing very large $\Delta\nu$ (V-groove and oxide stripe lasers, see Fig.2. in [2]). Another goal is to calculate line forms versus frequency $\nu=(\omega-\omega_0)/2\pi$ for some values $1/P_k$ (see Fig.2). We present some calculations for Fabry-Perot (p-GaAs) - laser with

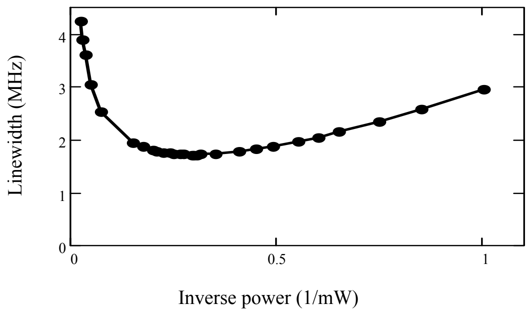

Fig.1. Calculated natural linewidth $\Delta\nu$ versus inverse power (1/P) simulates experimental natural linewidth (SCH laser, see Fig.3 in [1])

the following model parameters: C is the acceptor with concentration N_a=$2 10^{18}cm^{-3}$; T=293K; $(L_x:L_y:L_z)$= (0.2µm:20µm:350µm); R_1=0,99; R_2=0,01. Selecting other parameters, we can present the results of the experimental natural linewidth simulation (see Fig.3 in [1] and Fig.2 in [2]) in Fig.1, 3 respectively. The line forms $L(\nu)$ versus frequency ν for some values $(1/P_k)$ from Fig.1 are transformed into one amplitude. These are presented in Fig.2.

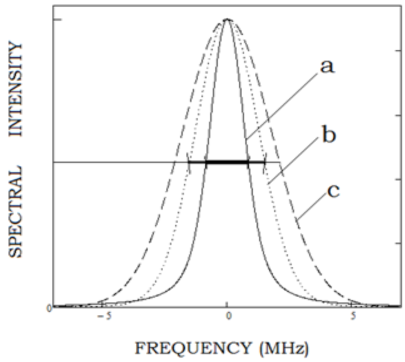

Fig.2. Calculated laser line forms versus frequency ν=(ω-ω₀)/2π for some values $1/P_k$ (from Fig.1): a) $(1/P_a)$=0,3(mW^{-1}); $\Delta\nu_a$ = 1,72 (MHz);

b) $(1/P_b)$=0,05(mW^{-1}); $\Delta\nu_b$ = 3,05 (MHz);

c) $(1/P_c)$= 0,025(mW^{-1}); $\Delta\nu_c$ = 4,24 (MHz).

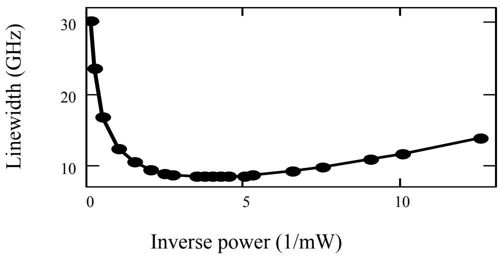

Fig.3. Calculated natural linewidth $\Delta\nu$ versus inverse power (1/P) simulates experimental natural linewidth (see Fig.2 in [2]).

Comparison of the calculated natural linewidth (Fig.1,3) with the experimental natural linewidth (see Fig.3 in [1] and Fig.2 in [2]) shows their good fit.

IV. EXPLANATION of EXPERIMENTS

1. Thus, simulation of experimental measurements of natural linewidth for the Fabry-Perot semiconductor laser has been conducted and presented in Fig.1, 2. In view of generality of physical background for deriving (2) for different types of lasers it is possible to ascertain qualitative generality of the obtained simulation results of Fabry-Perot lasers for other types of lasers. It allows us to explain the behavior of all known experimental measurements of semiconductor laser natural linewidth which have a minimum [1-8] within the framework of our theoretical model.

2. We can explain the minimum, basing on the formulas (2) – (4) derived: the influence of phase perturbations of spontaneous radiation decreases with the growth of power (see (3) for A_P); the influence of amplitude perturbations of spontaneous radiation increases with the growth of power (see (3) for B_A); their influence is identical for some $(1/P)_{min}$.

3. Our model may serve as a basis for simulation of experimental measurements of semiconductor laser natural linewidth. The first examples of simulation $\Delta\nu$ =F(1/P) (small $\Delta\nu$ [1] and large $\Delta\nu$ [2]) are presented in this paper. Comparison of the calculated natural linewidth with the experimental natural linewidth shows their close agreement.

4. Recommendations for the decrease of $\Delta\nu$ on the basis of the developed theory and simulation conducted have been worked out. The potential for elaborating further recommendations has not been exhausted.

5. We suggest that experimenters measure $L(\nu)$ and compare it with the calculated $L(\nu)$ by way of (2).

REFERENCES

[1] S. Takano, T.Sasaki, H.Yamada, M.Kitamura, I.Mito, "Sub-MHz spectral linewidth in 1.5µm separate-confinement heterostructure (SCH), quantum-well, DFB LDs", *Elect. Let.,* vol.25, pp.356-358, 1989.

[2] W. Elsasser, E.O. Gobel, J. Kuhl. "Coherence properties of gain- and index-guided semiconductor lasers", *IEEE Journal of Quantum Electronics,* vol.19, pp.981-985, 1983.

[3] F.-J. Vermersch, V. Ligeret, S. Bansropun, M. Lecomte, O. Parillaud, M. Calligaro, M. Krakowski, G. Giuliani "High-Power Narrow Linewidth Distributed Feedback Lasers With an Aluminium-Free Active Region Emitting at 852 nm", *IEEE Phot. Tech. Lett*., vol. **20**, pp.1145-1147, 2008.

[4] S. Spieβberger, M. Schiemangk, A. Wicht, H. Wenzel,O. Brox, G.Erbert, "Narrow Linewidth DFB Lasers Emitting Near a Wavelength of 1064 nm*", J. of Light. Tech*., vol. **28,** pp.2611-2616, 2010.

[5] Y.Inaba, M.Kito, T.Takizava, H.Nakayama et al., "Reduced Spectral Linewidth in High Output Power DFB Lasers", *Semiconductor Laser Conference*, pp.85-86, 2000. 07803-6259-4/00/$10.00©2000 IEEE

[6] T. Fordell, A.M. Lindberg, "Experiments on the linewidth-enhancement factor of vertical-cavity surface-emitting laser", *IEEE J. of Quantum Electronics,* vol.43, pp.6-15, 2007.

[7] M.Baghery, M.H. Shin, S.J Choi., J.D.O'Brien, P.D.Dapkus, "Microcavity Laser Linewidth Close to Threshold", IEEE J. of Quantum Electronics **45,** 945-949, 2009.

[8] P.G. Eliseev, "Switching lasers", In *Proc. of P.N. Lebedev Phys. Inst*." **v**216. 3-55, 1992 (in Russian).

[9] D. Welford, A. Mooradian, "Output power and temperature dependence of the linewidth of single frequency cw (GaAl)As diode lasers", *Phys. Lett*., v40, pp.865-867, 1982.

[10] A. Partovi, E.Garmire, "Band-edge photorefractivity in semiconductors: Theory and experiment*", J. Appl.Phys,* v.69, pp.6885-6897, 1991.

[11] A.P. Kovalevski, M.G. Noppe "On New Formulas for Line Form and Natural Linewidth in Semiconductor Lasers." In *Proc. of IX Intern. Conf. on Actual Problems of Electronic Instrument Engineering Proceedings (APEIE – 2008), NSTU, Novosibirsk*, 2008, v.5, pp.32-37. 978-1-4244-2825-0/08/$25.00©2008 IEEE

[12] L.A. Rivlin, A.T. Semenov, S.D. Jakubovich, *The dynamics and spectrums of radiation of semiconductor lasers*, Radio and Communication, Moskow., 1983, 208p. (in Russian).