A Theoretical Model of a Wavelength-Locked Fabry–Pérot Laser Diode to the Externally Injected Narrow-Band ASE

Kun-Youl Park, Sil-Gu Mun, Ki-Man Choi, and Chang-Hee Lee, *Member, IEEE*

***Abstract*—We propose a theoretical model of the wavelength-locked Fabry–Pérot laser diode (F-P LD) to the externally injected narrow-band amplified spontaneous emission. The model explains the dynamics of the wavelength-locked F-P LD. The simulation results with the proposed model show good agreement with the experimental results.**

***Index Terms*—Incoherent light injection, wavelength-division-multiplexed passive optical network (WDM-PON), wavelength-locked Fabry–Pérot laser diode (F-P LD).**

I. Introduction

THERE have been several attempts to implement a cost-effective source for the wavelength-division-multiplexed passive optical network (WDM-PON). Recently, a wavelength-locked Fabry–Pérot laser diode (F-P LD) with the external injection of the narrow-band amplified spontaneous emission (ASE) was proposed. It is very attractive because of its cost-effectiveness and colorless operation, in other words, the wavelength-independent operation [1]. Since the wavelength-locked F-P LD was proposed as a low-cost source for WDM-PON, many experimental results and the system demonstrations have been announced [2]–[4]. However, there is no theoretical model that describes underlying physics of the wavelength-locked F-P LD.

In this letter, we proposed a theoretical model of the wavelength-locked F-P LD based on the rate equations for the semiconductor laser diode. The model explains experimentally observed intensity noise suppression and its dependence on the many physical parameters. The simulation results with the proposed model show good agreement with the experimental results.

II. Theoretical Model

The dynamics of an F-P LD with the external injected light can be described with the following rate equations for the carrier density inside the active region N and the electric field of the active region E which is normalized, such that $|E(t)|^2$ corresponds to the photon density [5], [6].

$$\frac{dE_0}{dt} = \frac{1}{2}(1+j\alpha)(G_0-\gamma)E_0(t) + F_E^0(t) + k_c E_{N\mathrm{ASE}}(t)\exp(j2\pi\Delta f) \quad (1)$$

$$\frac{dE_i}{dt} = \frac{1}{2}(1+j\alpha)(G_i-\gamma)E_i(t) + F_E^i(t) \quad (2)$$

$$\frac{dN}{dt} = \frac{I}{qV} - \gamma_e N - \sum_i G_i|E_i|^2 \quad (3)$$

with

$$G_i = \frac{\Gamma v_g a(N-N_0)}{\left\{\left[1+\left(\frac{2i\Delta f_{\mathrm{mode}}}{\Delta f_g}\right)^2\right]\cdot\left[1+\varepsilon\sum|E_i|^2\right]\right\}} \quad (4)$$

$$\gamma = v_g(\alpha_{\mathrm{int}}+\alpha_m), \quad \alpha_m = \frac{1}{2L}\cdot\ln\left(\frac{1}{R_f R_b}\right) \quad (5)$$

$$\gamma_e = \left(A_{nr}+BN+CN^2\right), \quad \Delta f = f_{N\mathrm{ASE}} - f_0^{\mathrm{th}} \quad (6)$$

$$k_c = \frac{v_g(1-R_f)}{2L\sqrt{R_f}}\sqrt{\frac{\eta(\sqrt{R_f}+\sqrt{R_b})(1-\sqrt{R_f}\sqrt{R_b})}{\sqrt{R_b}(1-R_f)\ln\left(\frac{1}{\sqrt{R_f R_b}}\right)}} \quad (7)$$

where E_i is the complex amplitude of the ith mode, f_0^{th} the frequency of the zeroth mode at the threshold, $f_{N\mathrm{ASE}}$ the center frequency of the narrow-band ASE, G_i the gain of the ith mode, γ the loss of the cavity, k_c the coupling efficiency [6], Δf the frequency detuning between the narrow-band ASE and the laser mode at the free running state, α_m the mirror loss, and γ_e is the carrier recombination rate. The gain of the ith mode G_i is approximated by the Lorentzian function with the gain compression effect [5]. $F_E^i(t)$ is the spontaneous emission noise coupled into the ith mode. The other notations are summarized in Table I. The narrow-band ASE is injected into the zeroth mode.

The proposed model is the extended version of an injection-locked semiconductor laser diode to coherent injection light [5]. The last term in (1) represents the external injection of the narrow-band ASE. The complex amplitude of the narrow-band ASE $E_{N\mathrm{ASE}}(t)$ can be expressed as

$$E_{N\mathrm{ASE}}(t) = F^{-1}\{F[E_{\mathrm{ASE}}(t)]H(f)\} \quad (8)$$

where $E_{\mathrm{ASE}}(t)$ is the complex amplitude of the ASE that has in phase and quadrature component to E_0, and $H(f)$ the transfer function of the linear filter which determines the spectral shape of the narrow-band ASE to be injected to the F-P LD.

Manuscript received February 28, 2005; revised April 11, 2005. This work was conducted under the National Research Laboratory Project funded by the Ministry of Science and Technology of Republic of Korea.

The authors are with the Department of Electrical Engineering and Computer Science, Korea Advanced Institute of Science and Technology, Daejeon 305-701, Korea (e-mail: chl@ee.kaist.ac.kr).

Digital Object Identifier 10.1109/LPT.2005.851886

TABLE I
PHYSICAL PARAMETERS OF THE WAVELENGTH F-P LD

λ	Wavelength at gain peak	1545 nm
L	Cavity length	600 um
w	Width of the active region	1.5 um
d	depth of the active region	0.2 um
Γ	Confinement factor	0.5
n_g	Group index	3.5
α	Line-width enhancement factor	3
β_{sp}	Spontaneous emission factor	4x10^{-3}
α_{int}	Internal loss	10 cm^{-1}
R_f	Reflectivity of the front facet	1 %
R_b	Reflectivity of the rear facet	30 %
a	Gain constant	2x10^{-16} cm^{-2}
N_0	Transparent carrier density	1.0x10^{18} cm^{-3}
A_{nr}	Nonradiative recombination coefficient	1.0x10^{8} cm^{-2}
B	Radiative recombination coefficient	2.0x10^{-10} cm^{-3}
C	Auger recombination coefficient	4.0x10^{-29} cm^{-3}
ε	Gain compression factor	3.6x10^{-17} cm^{-3}
η	Coupling efficiency between the pigtail fiber and the active region	0.4
Δf_g	3 dB gain Bandwidth.	5 THz
Δf_{mode}	Mode spacing of F-P LD	71.4 GHz

The optical power of the ith mode P_i is related to the complex amplitude of the ith mode E_i as [5]

$$P_i = \eta h\nu v_g \alpha_m \frac{V}{\Gamma}|E_i(t)|^2 \cdot \left[\frac{\sqrt{R_b}(1-R_f)}{(\sqrt{R_f}+\sqrt{R_b})(1-\sqrt{R_f}\sqrt{R_b})}\right] \quad (9)$$

where h is the Flank constant, ν the frequency, v_g the group velocity, and V the volume of the active region. The complex amplitude of the narrow-band ASE $E_{NASE}(t)$ is related to the injection power P_{ASE} which is measured outside the cavity

$$|E_{NASE}(t)|^2 = \frac{P_{ASE}\Gamma}{2h\nu v_g wd}. \quad (10)$$

III. RESULTS

The theoretical model of the wavelength-locked F-P LD was solved numerically by fourth-order Runge–Kutta method. The parameters used for simulation are summarized in Table I. The cavity length, the coupling efficiency, and the reflectivity were measured and the others were the typical parameters of the F-P LD [5]. We adjusted them within a factor of two to fit the calculated result with the experimental result. The calculated threshold current I_{th} at free running state was about 22.5 mA. The time interval Δt was chosen to $\Delta t = 1$ps. The complex amplitude $E_{ASE}(t)$ was generated by the random number generator. Then, the narrow-band ASE was calculated using (8). In simulation, an arrayed waveguide grating whose 3-dB bandwidth is 31.3 GHz was chosen as the linear filter. We assumed that the number of modes of the F-P LD is five. The bias current of the F-P LD was 1.2 I_{th}. The injection power of the narrow-band ASE was -13 dBm and the frequency detuning was zero. The simulation has been extended over 100 ns so that the frequency resolution is 10 MHz. We compared the simulation results with the experimental results.

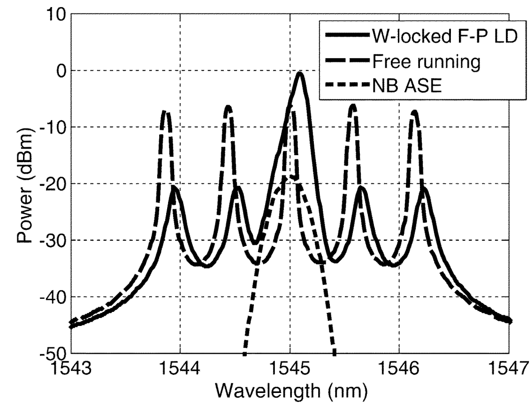

Fig. 1. Simulated optical spectra of the wavelength-locked F-P.

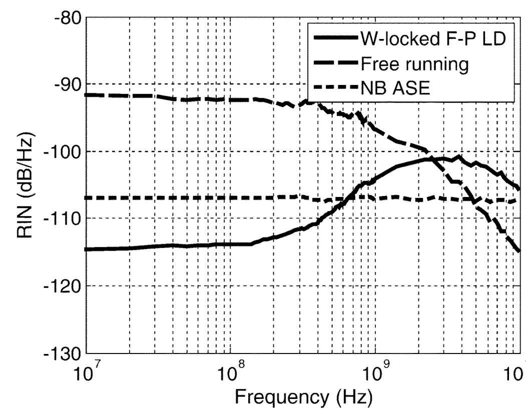

Fig. 2. Calculated RIN spectra of the wavelength-locked F-P LD.

We show the calculated optical spectra of the wavelength-locked F-P LD in Fig. 1. The narrow-band ASE forces the F-P LD to oscillate at a quasi-single mode. The sidemode suppression ratio is about 20 dB. As shown in the Fig. 1, the mode frequency of the F-P LD is shifted to negative frequency side, although we set the detuning at free running state Δf to zero. As a result, there exits the frequency difference between the narrow-band ASE and the actual laser mode after the injection. It can be explained as depletion of the carrier density with external injection. The decrease of the carrier density increases the refractive index of the active region. Then the mode frequency decreases (wavelength increases). This effect is observed in the experiment. We define the frequency difference between the narrow-band ASE and the actual laser mode as the effective detuning.

Fig. 2 shows the calculated relative intensity noise (RIN) spectra of the wavelength-locked F-P LD. The dashed line is the RIN spectrum of the zeroth mode at the free running state which shows the high noise density in the low frequency region because of the mode partition noise. The dotted line is the RIN spectrum of the injected ASE. The solid line represents the RIN spectrum of the zeroth mode for the wavelength-locked

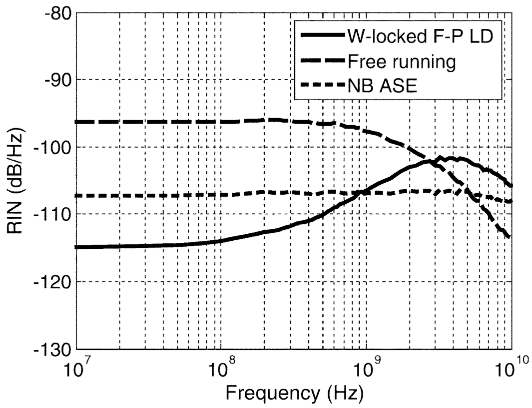

Fig. 3. Measured RIN spectra of the wavelength-locked F-P.

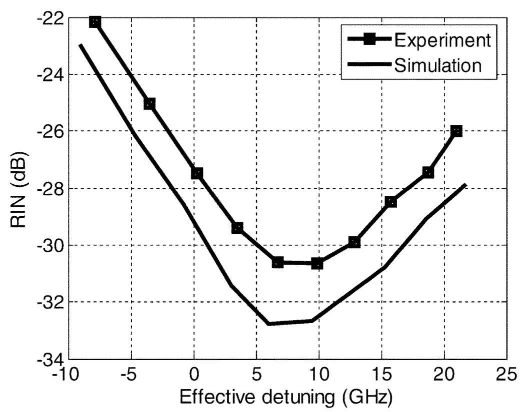

Fig. 4. RIN of the wavelength-locked F-P LD versus the effective detuning (Rx BW: 125 MHz).

F-P LD. The calculated results can be compared with the measure results shown in Fig. 3 at the same bias current and the injection power. Two figures show very similar features. The wavelength-locked output show about 8-dB suppression of the RIN at low frequency compared with the narrow-band ASE. It may be noted that the RIN of the wavelength-locked output is considerably lower than that of the free running laser, since the mode partition noise was suppressed by the ASE injection. The RIN spectrum of the wavelength-locked F-P LD exhibits a resonance peak about 3 GHz corresponding to the relaxation oscillation frequency.

We calculated the RIN as a function of the effective detuning as shown in Fig. 4. The receiver bandwidth was 125 MHz. The RIN curve is asymmetric and the optimal effective detuning is located at the positive side. This feature can be explained by the carrier density dependent refractive index and observed in the experiment [2], [3]. The carrier density decreases when the optical power increases due to the fluctuations. Then, the mode frequency shifts to lower frequency side (longer wavelength side). If the injection wavelength located at shorter wavelength side (positive effective detuning), the injection effect decreases, since the effective detuning increases. It brings about decrease of the optical power. In other words, a negative feedback occurs. Through this mechanism, the intensity noise of the output light is suppressed efficiently. If the injection wavelength is located

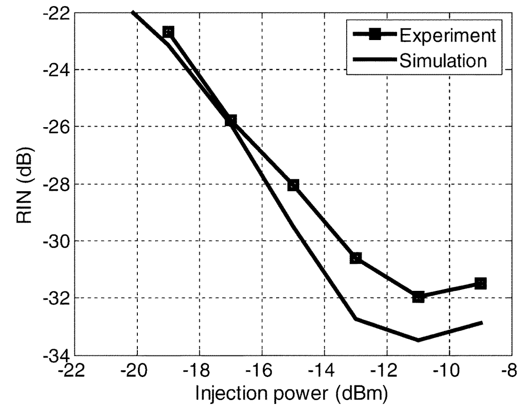

Fig. 5. RIN of the wavelength-locked F-P LD versus the injection power (Rx BW: 125 MHz).

at the longer wavelength side (negative effective detuning), the positive feedback mechanism decreases the intensity noise suppression. Therefore, the optimum detuning is located at positive detuning side and the RIN curves become asymmetric. The optimum detuning depends on the injection power.

Fig. 5 is the calculated RIN as a function of the injection power. As the injection power increases, the RIN is improved. However, the RIN increases eventually, when we increase the injection power further. This feature can be explained the decrease of the injection effect due to shrinkage of the overlap between the injected ASE and the zeroth mode. The theoretical results explain observed experimental results.

IV. Conclusion

We proposed the theoretical model of the wavelength-locked F-P LD to the externally injected narrow-band ASE. The rate equations of the semiconductor laser diode with a coherent injected signal were extended for the incoherent signal injection. The theoretical results explain many observed experimental results. The model can be used for in-depth understanding of the wavelength-locked FP LDs including the coherent properties of the light output and transmission characteristics.

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