Journal of the Optical Society of Korea, Vol. 10, No. 2, June 2006, pp. 86-90

External Feedback Effects on the Relative Intensity Noise Characteristics of InAlGaN Blue Laser Diodes

Hyung Uk Cho and Jong Chang Yi*
School of EEE, Hongik University, Sangsu 72-1, Mapo, Seoul 121-791, KOREA

(Received June 14, 2006 : revised June 16, 2006)

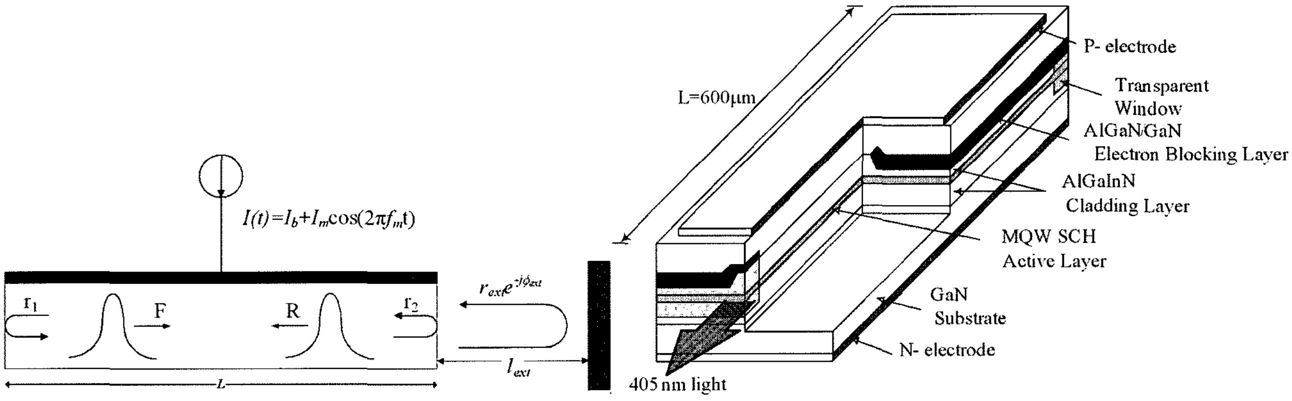
The external feedback effect on the relative intensity noise (RIN) characteristics of blue InAlGaN laser diode has been analyzed taking into account the spontaneous emission noise and the injection current for the high frequency modulation. A Langevin diffusion model was exploited to characterize its relative intensity noise. The simulation parameters were quantitatively evaluated from the optical gain properties of the InAlGaN multiple quantum well active regions by using the multiband Hamiltonian for the strained wurtzite crystals. The extracted parameters were then applied to the rate equations taking into account the external feedback and the high frequency modulation current. The RIN characteristics were investigated to optimize the low frequency laser diode noise characteristics.

OCIS codes : 210.0210, 140.5960, 270, 2500

I. INTRODUCTION

InAlGaN blue laser diodes are important building blocks for the next-generation optical data storage. Their data access time and the operation speed are limited in part by the noise of the laser diodes used in the optical pick-up. In this paper an intensity noise characteristic known as the relative intensity noise has been analyzed for laser diodes having the wurtzite crystal as the active region [1]. The effect of the external feedback into the laser cavity from the reflection by the disc surface as shown in Figure 1 (a) has been investigated using the rate equations [2].

The primary source of the intensity noise in the semiconductor laser diode is the spontaneous emission between the conduction and the valence bands in the active regions. Such quantum noises have been modeled after the quantum Langevin formalism [3]. The required material parameters have also been extracted by using the multiband Hamiltonian for strained wurtzite crystals [4,5]. To show the validity of this method, the simulation results were compared to the analytic solutions when



(a) (b)

FIG. 1. (a) Schematic diagram for laser diode cavity with external feedback. (b) Schematic diagram of the InAlGaN MQW laser diode structure.

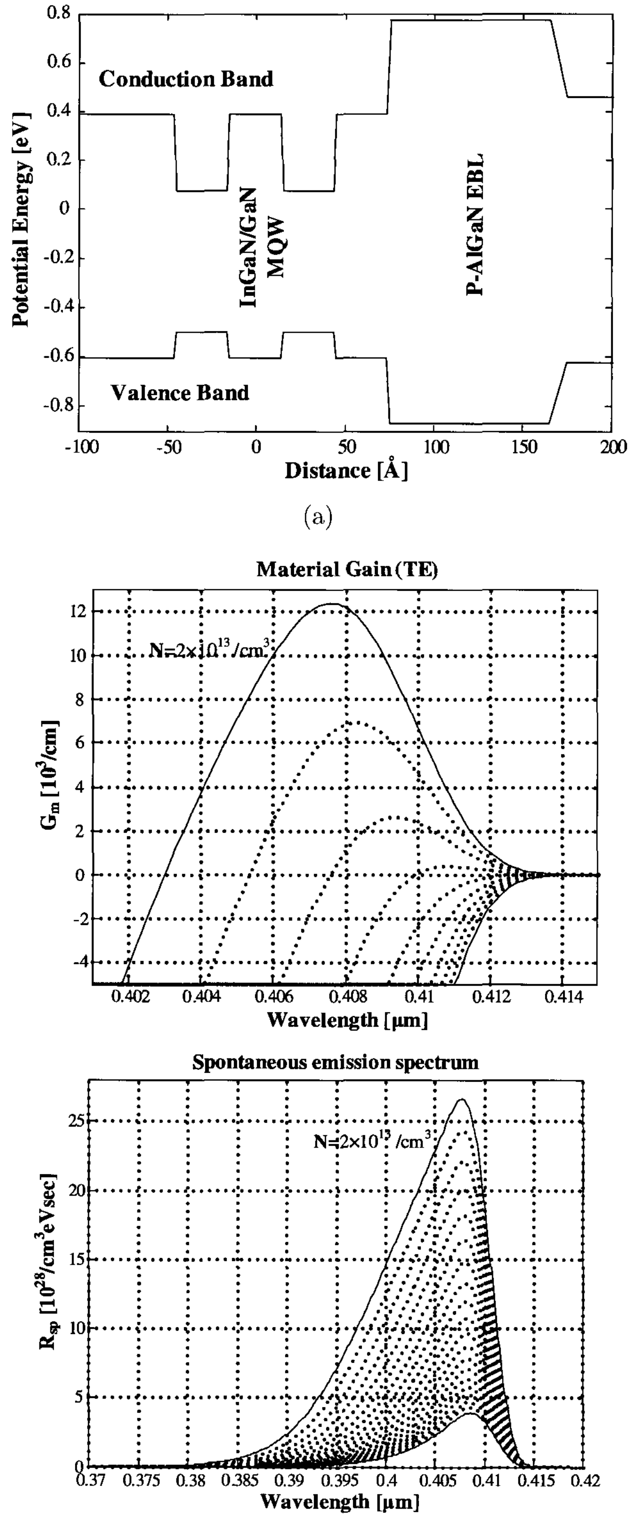
the external feedback effect is ignored, there is good agreement. The simulation results of the RIN taking the external feedback effect into account for various feedback strength shows that mere 0.1% external feedback would deteriorate the RIN by more than 20 dB. One way to reduce the external feedback effect is to modulate the injection current to the laser cavity up to a certain high frequency. The optimum current injection frequency for the RIN characteristics has been investigated to reduce the external feedback effect that is inevitable in DVD-ROM or RW pick-up systems.

II. MODELING OF THE RELATIVE INTENSITY NOISE

The blue laser diode under investigation has typical InAlGaN MQW active structures as shown in Figure 1 (b). The quantum well regions are 3 nm $In_{0.12}Ga_{0.88}N$ and the barrier regions are $In_{0.02}Ga_{0.98}N$. The SCH regions are $Al_{0.2}Ga_{0.8}N$ and the cladding regions are N- and P-doped $Al_{0.13}Ga_{0.87}N$ sandwiched by GaN ohmic contact layers [6,7]. Figure 2 (a) shows the energy band diagram of the multiple quantum well (MQW) and the electron blocking layer (EBL). The gain and spontaneous emission spectra of the InAlGaN 2 QW LD are obtained by numerical analysis of the Hamiltonian equations for multiband strained wurtzite MQW structures [4,5]. Figure 2 (b) shows the calculated gain and spontaneous emission spectra from the InAlGaN 2 quantum well structures when the injection carrier density varies from 10^{12} to $2\times10^{13}/cm^2$ by the step of $2\times10^{12}/cm^2$ (G_m) and $1\times10^{12}/cm^2$ (R_{sp}).

III. MODELING OF THE QUANTUM NOISE DUE TO THE EXTERNAL FEEDBACK

The quantum noise due to the exdternal feedback from the optical disc surface into the laser cavity is modeled as shown in Figure 1 (a). F and R shown in the figure denote the forward and reverse traveling optical fields, r_{ext}, ϕ_{ext}, l_{ext} the reflection coefficient, phase retardation, and the length of the external cavity, respectively. The primary source of the intensity noise in the semiconductor laser diode is the spontaneous emission between the conduction and the valence bands in the active regions. Such quantum noises have been modeled after the quantum Langevin formalism [3] and the required material parameters have been extracted by using the multiband Hamiltonian as described earlier. The relative intensity noise [RIN] of the laser diode is defined as the ratio of the laser intensity noise $\delta P(t)$ to the average laser power $P_0(t)$, or



(a)

(b)

FIG. 2. (a) Band diagram of MQW & EBL region. (b) Calculated gain and spontaneous emission spectra of InAlGaN MQW structures from the multiband Hamiltonian equations for the strained wurtzite crystals. (Various carrier injections in steps of $2\times10^{12}/cm^2$ (G_m) and $1\times10^{12}/cm^2$ (R_{sp}))

$$RIN=\frac{S_P(\omega)}{P^2}=\frac{\int_{-\infty}^{\infty}d\tau\langle\delta P(t+\tau)\delta P(t)\rangle e^{-i\omega\tau}}{P^2} \tag{1}$$

The characteristics of the laser intensity noise can be obtained by analyzing the rate equations

$$\begin{aligned}\frac{d}{dt}N(t)&=\frac{I(t)}{q}-\frac{N(t)}{\tau_e}-G(t)P(t)+F_N(t)\\ \frac{d}{dt}P(t)&=(G(t)-\gamma)P(t)+R_{sp}+2\chi P_{fb}+F_P(t)\\ \frac{d}{dt}\phi(t)&=\frac{1}{2}\alpha(G(t)-\gamma)-\frac{n_m}{n_g}(\omega-\Omega)+\chi\phi_{fb}+F_\phi(t)\end{aligned} \tag{2}$$

with

$$\begin{aligned}P_{fb}&=\sqrt{P(t)P(t-\tau)}\cos[\omega\tau+\phi(t)-\phi(t-\tau)]\\ \phi_{fb}&=\sqrt{\frac{P(t-\tau)}{P(t)}}\sin[\omega\tau+\phi(t)-\phi(t-\tau)]\end{aligned} \tag{3}$$

where N denotes the carrier density, P, the photon density, ϕ, the instantaneous phase, F_i, the Langevin noise factors [8], χ, the external feedback coefficient, and τ, the round trip time for the external cavity, respectively [9]. The other parameters follow conventional notations. The Langevin noise functions show characteristic behaviors as following:

$$\begin{aligned}&\langle F_i(t)\rangle=0 && \text{for } i=P,N,\phi\\ &\langle F_i(t)F_j(t')\rangle=2D_{ij}\delta(t-t') && \text{for } j=P,N,\phi\end{aligned} \tag{4}$$

$$2D_{pp}=2n_{sp}\frac{\bar{P}}{\tau_P} \tag{5}$$

$$2D_{NN}=(2n_{sp}-1)\frac{\bar{P}}{\tau_P}+\frac{\bar{N}}{\tau_e} \tag{6}$$

$$2D_{PN}=-(2n_{sp}-1)\frac{\bar{P}}{\tau_P} \tag{7}$$

$$2D_{\phi\phi}=n_{sp}\frac{1}{2\bar{P}\tau_P} \tag{8}$$

where the photon lifetime and the population inversion factor are defined as:

$$\begin{aligned}\frac{1}{\tau_p}&=\nu_g(\alpha_c+\alpha_m)=\nu_g\left(\alpha_c+\frac{1}{L}\ln\frac{1}{R}\right)\\ n_{sp}(\omega)&=\frac{1}{1-\exp[(\hbar\omega-E_{qfp})/k_BT]}\end{aligned} \tag{9}$$

The optical gain in equation (2) can be expressed in terms of differential gain as:

$$G=\frac{\frac{dG}{dN}(N-N_{tr})}{1+\varepsilon P}\equiv\frac{G_N(N-N_{tr})}{1+\varepsilon P} \tag{10}$$

where the internal cavity loss α_c is 12 cm^{-1}, and the cavity length L is 600 μm. G_N is the differential gain, and N_{tr}, the transparency carrier concentration. The gain suppression coefficient ε is 8×10^{-9}. Figure 3 shows typical device parameters for the 405 nm InAlGaN MQW laser diodes such as the transition energy E_T, the Fermi energy separation versus the injection carrier concentration E_{qfp}, the population inversion parameter n_{sp}, the transparency carrier concentration N_{tr}, the maximum material gain G_{max}, and the differential gain G_N.

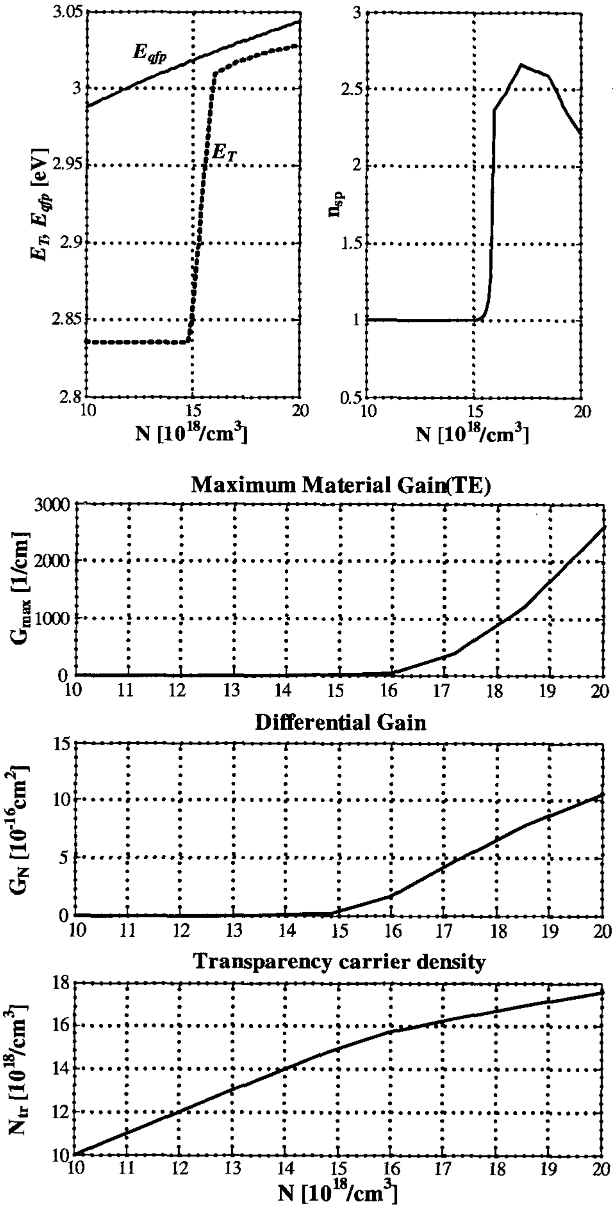
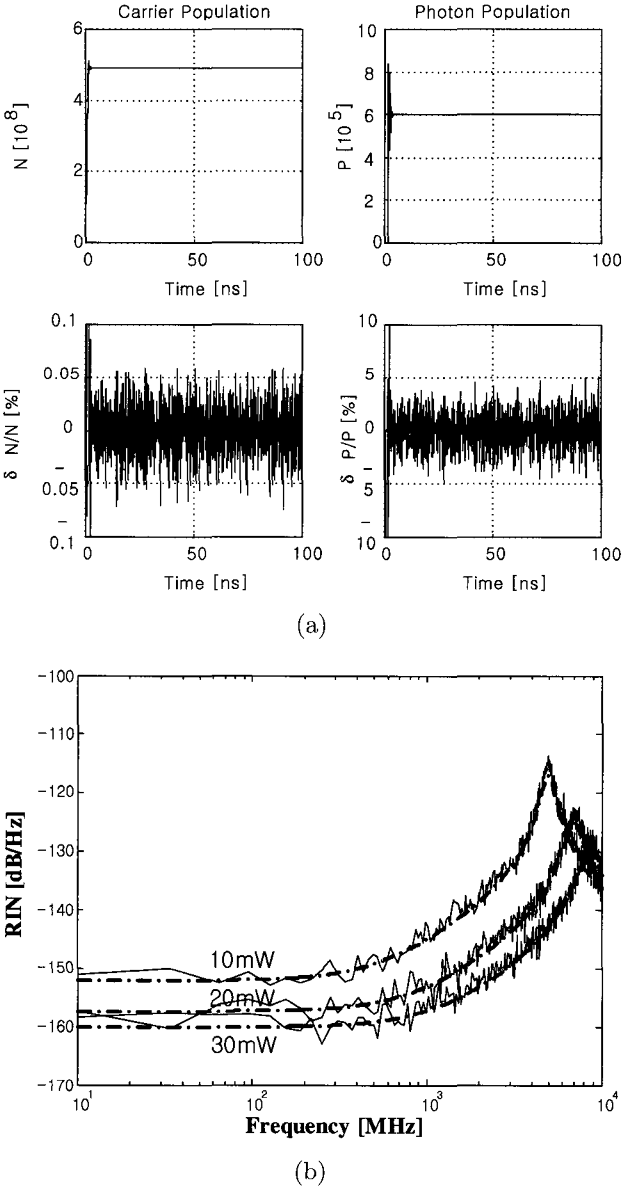


FIG. 3. Device parameters for the InAlGaN MQW laser diodes: the transition energy E_T, the Fermi energy separation E_{qfp}, versus the injection carrier concentration N; the population inversion parameter n_{sp}, the maximum material gain, G_{max}, the differential gain G_N, and the transparency carrier density N_{tr}.

IV. SIMULATION RESULTS

In the time domain analysis, the Langevin noise functions were implemented by random number generators with amplitude proportional to the square root of the diffusion coefficients. The simulation results of the carrier [N] and photon density [P] fluctuation after turn-on are shown in Figure 4 (a). The upper plots show the large signal evolutions, and the lower plots show the enlarged noisy fluctuations. Figure 4 (b) shows the Fourier transformed spectra of the noise terms for various optical output power levels of the laser diode. The numerically obtained RIN spectra show a good agreement with the analytic solutions as shown in dashed lines.



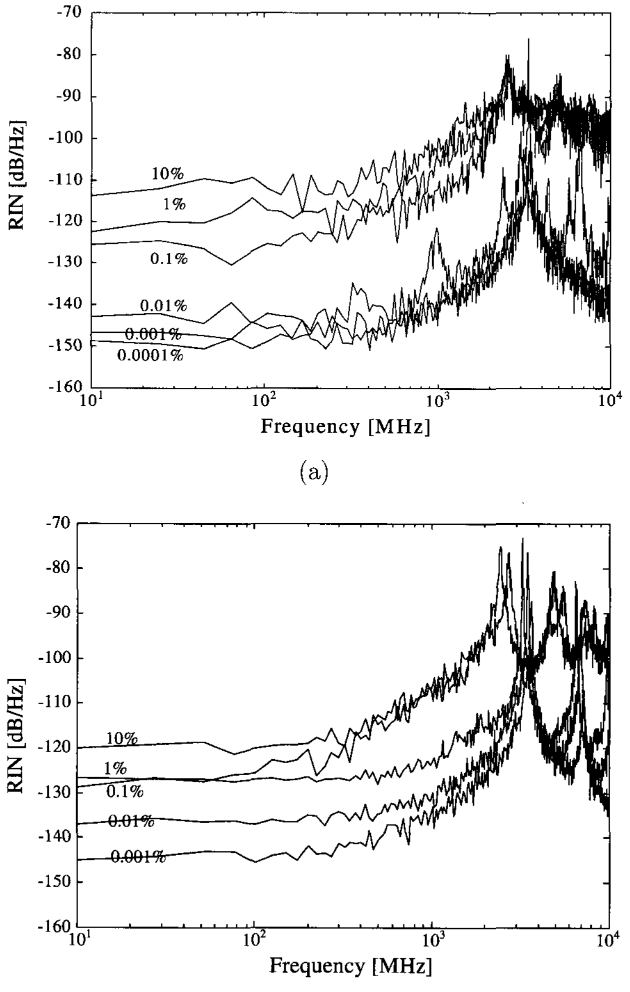
(a)

(b)

FIG. 4. (a) Carrier and photon density fluctuation after turn-on. (b) The Relative intensity noise (RIN) spectra.

Figure 5 shows the numerical simulation results of the RIN spectra when the external feedback is non-negligible. Those spectra were also compared for different material systems for the laser diodes. Figure 5 (a) shows those for 635 nm InAlGaP LD, and (b) for 405 nm InAlGaN LD [11]. They both show similar RIN characteristics. One can see that any external feedback larger than 0.1% would deteriorate the RIN by more than 20 dB.

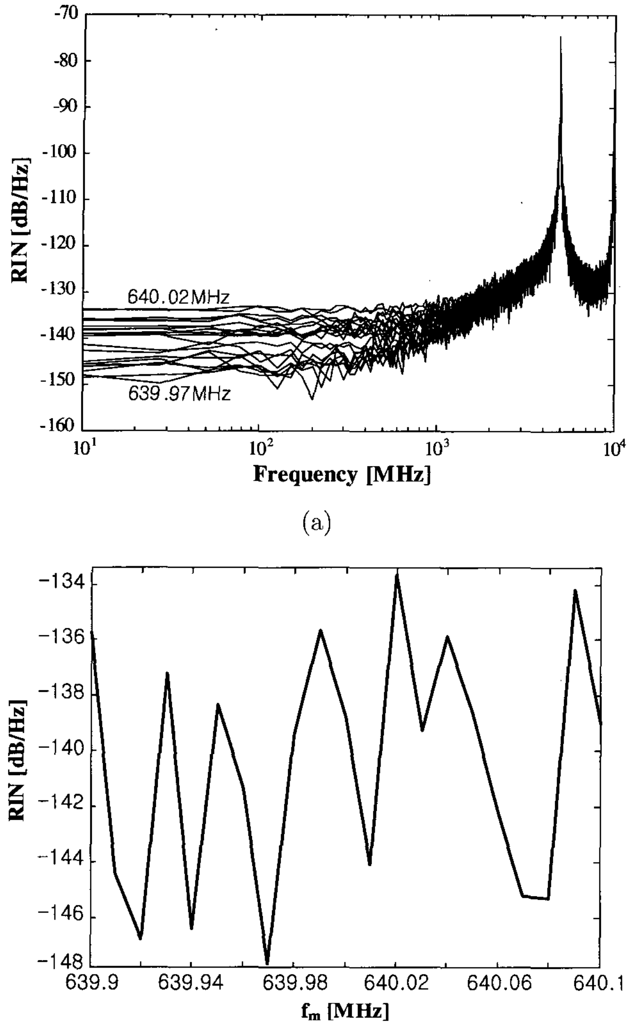
One way to reduce the external feedback effect is to modulate the injection current to the laser cavity up to a certain high frequency [10]. Figure 6 shows the dependence of the RIN characteristics on the current injection frequency for 0.1% external feedback. It shows that by optimizing the injection current levels and its frequency, for example, around 640 MHz with a modulation current level at 30 mA in this case, one can reduce the external feedback effect, which is inevitable



(a)

(b)

FIG. 5. (a) The RIN spectra of 635 nm InAlGaP LD for various external feedbacks. (b) The RIN spectra of 405 nm InAlGaN LD for various external feedbacks.



(b)

FIG. 6. (a) The RIN spectra with various modulation frequency of the injection current. (b) The low-frequency RIN spectra with various modulation frequency of the injection current.

in the optical pick-up systems, by more than 15 dB/Hz.

V. CONCLUSIONS

In this work, the relative intensity noise characteristics in 405 nm laser diodes grown on wurtzite InAlGaN multiple quantum well structures were investigated using the rate equations with the quantum Langevin noise model. The device parameters were extracted from the optical gain properties of the MQW active region using the multiband Hamiltonian for the strained wurtzite crystal. The simulation result indicates that the RIN can be reduced by more than 15 dB by optimizing the device external feedback strength or injection current modulation.

ACKNOWLEDGMENTS

This work was supported by 2005 Hongik University Research Fund.

*Corresponding author : wave@hongik.ac.kr

REFERENCES

[1] G. R. Ray, A. T. Ryan, and G. P. Agrawal, "Control of optical-feedback-induced laser intensity noise in optical data recording," *Optical Engineering*, vol. 32, 739-45, 1993.

[2] J. C. Yi and J. Y. Kim, "Investigation of External Feedback Effects on Relative Intensity Noise Characteristics of 405 nm InAlGaN Laser Diodes", *Optical Data Storage*, 91-93, 2006.

[3] W. W. Chow, S. W. Koch, and M. Sargent III, *Semiconductor Laser Physics*, Springer-Verlag, Berlin, 1994.

[4] J. C. Yi and N. Dagli, "Finite-element analysis of valence band structure and optical properties of quantum-wire arrays on vicinal substrates," *IEEE J. Quantum Electronics*, vol. 31, pp. 208-18, 1995.

[5] J. Piprek, *Semiconductor Optoelectronic Devices*, Academic Press, San Diego, pp. 32-48, 2003.

[6] S. Nagahama, T. Yamamoto, M. Sano, and T. Mukai, "Blue-Violet Nitride Laser," *Phys. Stat. Sol. (A)*, vol. 194, no. 2, 423-427, 2002.

[7] J. Piprek and S. Nakamura, "Physics of high-power InGaN/GaN lasers," *IEE Proc.-Optoelectron.*, 149, no. 4, pp. 145-151, 2002.

[8] P. Gallion, F. Jeremier, and J. L. Vey, "Classical optical corpuscular theory of semiconductor laser intensity squeezed-light generation," *Optical and Quantum Electronics*, vol. 29, 65-70, 1997.

[9] G. P. Agrawal and N. K. Dutta, *Long-wavelength Semiconductor Lasers*, Van Nostrand Reinhold, NY, 1987.

[10] E. C. Gage and S. Beckens, "Effects of high frequency injection and optical feedback on semiconductor laser performance," *Proc. SPIE*, vol. 1316, *Optical Data Storage*, 199-204, 1990.

[11] S. J. Lee, "Differences in Design Considerations between InGaN and Conventional High-Brightness Light-Emitting Diodes," *Journal of the Optical Society of Korea*, vol. 2, no. 1, pp. 13-21, 1998.