Improvement of Absorption and Emission Phenomena of 1.55μm Quantum Dot Laser using Indium Nitride

Md. Abdullah Al Humayun
Department of EEE, Eastern University, Bangladesh
humayun0403063@gmail.com

Mohd Abdur Rashid
Department of EEE, Noakhali Science and Technology University, Bangladesh | Division of Electronics and Informatics, Gunma University, Japan
marashid.eee@nstu.edu.bd
(corresponding author)

Anna Kuwana
Division of Electronics and Informatics, Gunma University, Japan
kuwana.anna@gunma-u.ac.jp

Haruo Kobayashi
Division of Electronics and Informatics, Gunma University, Japan
koba@gunma-u.ac.jp

Received: 23 November 2022 | Revised: 19 December 2022 | Accepted: 23 December 2022

ABSTRACT

This paper presents the improvement of emission and absorption phenomena of 1.55μm quantum dot laser by enhancing the stability of oscillation frequency and minimizing absorption loss. Among the key parameters related to these absorption and emission phenomena, the effective density of state, rate of change of carrier mobility, and optical feedback level were extensively investigated to reduce the fluctuation of the oscillation frequency of the emitted light as well as the absorption loss. These phenomena were investigated through mathematical analysis and numerical simulation using AlN, GaN, and InN quantum dots as the active material of the laser structure. The numerical results were compared, confirming that the InN quantum dot in the active layer significantly improved the absorption and emission phenomena of the quantum dot laser. At the same time, InN is capable of emitting light at a wavelength of 1.55μm due to its band gap of 0.7eV. Consequently, InN has a superior potentiality to other existing materials to fabricate the quantum dot laser operating at the 1.55μm wavelength, which is the window of an optical fiber communication system that offers the lowest attenuation. Therefore, the InN quantum dot laser is expected to be a promising candidate not only in the field of semiconductor technology but also in the field of optical communication in the imminent future.

Keywords-density of state; feedback level; frequency fluctuation; momentum relaxation time; laser

I. INTRODUCTION

Nowadays researchers focus on the absorption and emission phenomena of Quantum Dot (QD) as a top priority, which has led to its use as monolithic coherent light source such as lasers, electroabsorption modulators, and saturable absorber mirrors [1]. Lasers fabricated from such an active layer exhibit higher device performance compared to the traditional semiconductor lasers based on bulk or Quantum Well (QW), or Quantum Wire (QWR) active medium. Improvements in Quantum Dot Laser (QDL) performance have appeared in wide modulation bandwidth, relative noise intensity, minimum lasing threshold, output power temperature sensitivity, reduced linewidth enhancement factors, reduced crosstalk between amplified signals at low power level, and improved four-wave mixing at high power levels and longer device lifetime [2-5]. Currently, the absorption properties of QDL such as effective density of state, carrier density at the threshold, level of optical feedback, rate of change of mobility of carriers, and emission properties have become the focus of numerous theoretical and experimental investigations for further improvement [3, 6]. The stability of laser characteristics depends on the structural parameters and alterations of the density of the carriers and photons along the length of the cavity structure and its dependence on the current above-threshold conditions [7]. Among the absorption properties, effective density of state and mirror reflectivity are the most important parameters assisting optical feedback, which plays an important role in ensuring more uniformity in the mobility (reduction of the rate of change of mobility) of the carrier and finally in improving the stability of the semiconductor laser frequency. The active region of the laser can be designed in the form of three-dimensional bulk materials, two-dimensional QWLs, single-dimensional QWRs, or zero-dimensional QDs [8]. Recently, it has been discussed that enhancement of device characteristics is expected for lasers with lower dimensionality of the active region. This reduction in the dimensionality was achieved by introducing QWR and QD as the active layer material of the laser structure. In QD, the motion of the carriers is restricted in all three directions, which helps overcome the problems of QWL and other available categories of material [8, 9].

The existing materials used to design QDL are ternary $Ga_{47}In_{53}As$ [10] and quaternary InGaAsN [11], InGaAsN [9], GaN, and AlN [10]. As these materials are difficult to grow and not compatible with 1.55μm emission, researchers are looking for alternative materials. Recent findings showed that InN has a band gap of around 0.7eV, which is compatible with 1.55μm emission [12]. The emission energy depends on many parameters, both on the physical properties of QD, such as shape, dimensions, strain, and chemical compositions. Additionally, the emission energy depends on the composition and the residual strain of the confinement layers as well as the ground-quantized energy levels of carriers. These parameters depend not only on the design of the structure but also on growth conditions [11]. For long-wavelength operations at 1.55μm, InN QDL is predicted to be suitable for long-distance communication with high-performance and low-power consumption light sources for optical fiber systems [12]. The growth technique is very vital as the operating wavelength of the laser varies with the active layer thickness. The wavelength variations and tenability of the device are estimated to be about 0.15nm [5].

This study investigates the effective density of state, carrier density at threshold, feedback level of the gain medium, uniformity of carrier mobility, the stability of laser frequency, and the minimization of absorption loss. These major absorption and emission properties were investigated using GaN, AlN, and InN QD in the active layer of the laser structure. The numerical results were compared to analyze the improvement of these phenomena of QDL using InN. The result comparison revealed that the effective density of state, carrier density at threshold, and the feedback level of QDL are higher by using InN QD than GaN's and AlN's in the active layer of the laser structure. Furthermore, the rate of change of the mobility of the carrier and fluctuation of the laser frequency along with the absorption loss were also minimized significantly by employing InN QD in the active layer of the laser structure.

II. MATERIALS AND METHODS

A. Device Structure

A laser structure composed of an InN-based quantum dot in the active layer was considered to investigate the improvement of the cavity length dependence on the laser characteristics operating at the 1.55μm wavelength. The details of the laser structure with InN-based quantum dot are shown in Table I [4].

TABLE I. LAYER STRUCTURE OF INN-BASED QDL

p GaN contact layer (77 nm)
P $Al_{0.13}Ga_{0.87}N$ upper cladding layer (1000 nm)
p $In_{0.82}Ga_{0.18}N$ guiding layer (117 nm)
InN undoped QDs active layer (2.7 nm)
n $In_{0.82}Ga_{0.18}N$ guiding layer (117 nm)
n $Al_{0.13}Ga_{0.87}N$ Lower cladding layer (1000 nm)
n- GaN contact layer (77 nm)
C sapphire(0001) substrate

The structure of the InN-based QDL consists of an InN-plane sapphire wafer (oriented along 0001 direction) as the substrate along with a 77nm thick n+GaN contact layer, a 1000nm thick n $Al_{0.13}Ga_{0.87}N$ lower cladding layer, a 117nm thick n $In_{0.82}Ga_{0.18}N$ guiding layer, a 2.7nm thick InN active region with single layer undoped quantum dots, a 117nm thick p $In_{0.82}Ga_{0.18}N$ guiding layer, a 1000nm thick p $Al_{0.13}Ga_{0.87}N$ upper cladding layer, and a 77nm thick p+GaN contact layer. Thus, the mean size of the quantum dot was 2.7nm and the optical confinement layer thickness was 236.7nm. The FIB etching technique was used to form Fabry-Perot cavity mirrors by etching facets, providing high-quality etched facets. A Fabry-Perot resonator is composed of two highly reflective mirrors that allow small portions of light to pass through while reflecting most of the light back through the active region, where it can be further replicated through stimulated emission. A pair of parallel planes (or facets) was etched. Under the appropriate biasing conditions, the laser light would be emitted from these planes. The two remaining sides were roughened to eliminate lasing in any direction other than the main.

B. Numerical Analysis

This section presents the numerical analysis of some of the major characteristics of the QDL. These QDL characteristics were analyzed using InN, GaN, and AlN QD as the active layer material of the laser structure. The characteristics of the laser analyzed in this study were the effective density of state of the carriers, momentum relaxation, absorption loss, optical feedback level, and oscillation frequency fluctuation.

1) Effective Density of State

The QD semiconductor materials have discrete energy levels. Due to these discrete energy levels, symmetric emission of light is obtained, which is predicted to be one of the subjects of great current interest to enhance the sensitivity of QDL to those optical feedback levels. QDL has gained greater importance after significant progress in nanostructure growth through the self-assembling technique [13]. The effective density of state per unit volume in the QD heterostructure is given by [14]:

$$\rho = 2\left(\frac{m_e \pi K_B T}{h^2}\right)^{\frac{3}{2}} \tag{1}$$

where m_e is the electron's effective mass, K_B is Boltzmann's constant, h is Planck's constant, and T is the temperature.

2) Momentum Relaxation and Absorption Loss

The mobility of the cladding layer is an important parameter, which affects the minority carrier leakage current. The mobility of the carrier is related to the momentum relaxation time by [5]:

$$\mu(T) = \mu_0 \left(\frac{\tau_0}{\tau(T)}\right) \tag{2}$$

The free carrier absorption loss is given by [14]:

$$\alpha_{fc} = \alpha_{fc_0} \left(\frac{\tau(T)}{\tau_0}\right) \tag{3}$$

where α_{fc_0} is the free carrier absorption loss at room temperature, τ is the momentum relaxation time, and T is the temperature. The temperature dependence of momentum relaxation time is given by [13]:

$$\tau(T) = \frac{\tau_0}{1+\beta\left(\frac{T-T_0}{T_1-T_0}\right)} \tag{4}$$

where τ_0 is the momentum relaxation time at room temperature, T_0 is the lower limit of the operating temperature, and T_1 is the upper limit of the operating temperature range. To investigate the effect of temperature variation on the mobility of the carrier and the carrier absorption loss, using (4) in (2) and (3) gives:

$$\mu(T) = \mu_0\left[1 + \beta\left(\frac{T-T_0}{T_1-T_0}\right)\right] \tag{5}$$

$$\alpha_{fc} = \frac{\alpha_{fc_0}}{1+\beta\left(\frac{T-T_0}{T_1-T_0}\right)} \tag{6}$$

3) Carrier Density at Threshold

This section investigates the phenomenon of carrier density at threshold. The gain coefficient and the photon lifetime have a significant role in the carrier densities at threshold [15]. The relationship between the photon lifetime and the carrier density threshold is given by:

$$\rho_{th} = \rho_0 + \frac{1}{\tau_p G} \tag{7}$$

where ρ_0 is the carrier density at transparency, τ_p is the photon lifetime, and G is the modal gain coefficient.

4) Optical Feedback Level

The optical feedback level of a laser depends on several parameters, has further effects on the operating characteristics of a diode laser, and is given by:

$$\gamma = \frac{\sqrt{R_{eff}}}{\tau_{active}} \tag{8}$$

where τ_{active} is the round-trip time in the active region, given by:

$$\tau_{active} = \frac{2L}{v_g} \tag{9}$$

where L is the length of the cavity and v_g is the group velocity of the light wave in the gain medium of the laser.

5) Fluctuation of Laser Frequency

The fluctuation of laser frequency depends strongly on the refractive index and is given by [16]:

$$\delta\omega = -\frac{E_g}{hn_g}\Delta n_{eff} \tag{10}$$

where E_g is the band gap energy of the active layer material, h is Planck's constant, Δn_{eff} is the total effective refractive index variation due to plasma and the effect of QD, and n_g is the refractive index of the active layer material. In this equation, the minus sign indicates the decrement in the laser frequency. Now, taking the modulus on both sides of (5) gives:

$$|\delta\omega| = \frac{E_g}{hn_g}\Delta n_{eff} \tag{11}$$

III. RESULTS AND ANALYSIS

This section presents the results obtained using the numerical analysis mentioned above. The improvement of QDL's characteristics using InN was achieved in terms of higher effective density of state of the carriers, enhanced optical feedback level, reduced frequency fluctuation, and reduced rate of change momentum relaxation and mobility as well as minimization of absorption loss.

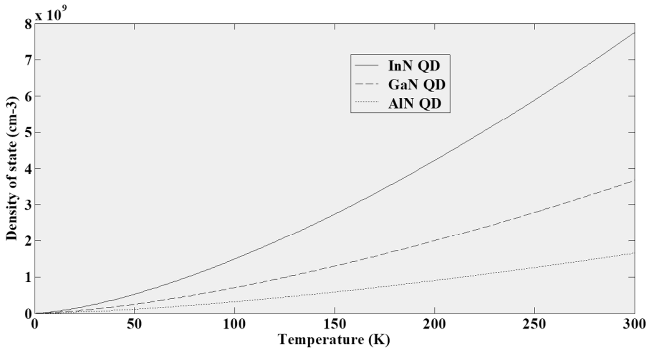


Fig. 1. Effect of temperature on the effective density of state of QDL using InN, GaN, and AlN QD as active layer material of the laser.

Figure 1 shows the effect of temperature on the effective density of state of the carriers of QDL using InN, GaN, and AlN QD as the active layer material of the laser structure. The effective density of state increased with a temperature increase for any material. InN QDL experienced an increase of 2×10^9cm^{-3} in the density of state, from 5.9×10^9 to 7.9×10^9cm^{-3} over the temperature range of 250-300K. GaN QDL experienced an increase of 7×10^8cm^{-3}, from 2.9×10^9 to 3.6×10^9cm^{-3}, and AlN experienced an increase of 7×10^8cm^{-3}, from 1.2×10^9 to 1.5×10^9 within the same temperature range. Remarkably, InN QDL experienced the highest upward trend in the density of state, showing that a prominent enhancement of the effective density of state was achieved using InN, and therefore, it more promising to provide higher effective density of state than other existing materials.

Figure 2 shows the temperature dependence of the momentum relaxation time using InN, GaN, and AlN QD as the active material of the laser. InN QDL experienced a decrease of 0.0125nsec in the momentum relaxation time, from 0.755 to 0.5625nsec due to a change in temperature from 250 to 300K. GaN QDL experienced a decrease of 0.025nsec, from 0.5 to 0.475nsec, and AlN experienced a decrease of momentum relaxation time of 0.025nsec, from 0.4 to 0.375nsec within the same temperatures. Therefore, InN showed the highest momentum relaxation time at any temperature among the three materials. Thus, using InN QD as active layer material offers a longer time for momentum relaxation, which helps achieving uniformity of carrier mobility.

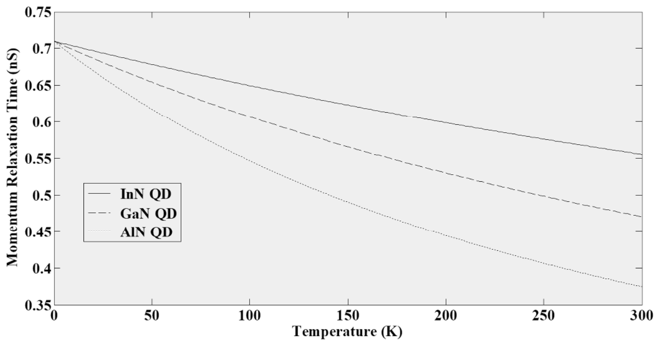


Fig. 2. Temperature dependence of momentum relaxation time using InN, GaN, and AlN QD as active layer material of the laser structure.

Figure 3 demonstrates the temperature dependence of the mobility of the carrier using InN, GaN, and AlN QD as the active layer material of the laser structure. AlN QDL experienced an increase of $59cm^2V^{-1}s^{-1}$ in mobility, from 1066 to $1125cm^2V^{-1}s^{-1}$ over the temperature range of 250-300K. GaN QDL experienced an increase of $33.34cm^2V^{-1}s^{-1}$ in mobility, from 866.66 to $900cm^2V^{-1}s^{-1}$ and InN experienced an increase of $25cm^2V^{-1}s^{-1}$ in mobility, from 750 to $775cm^2V^{-1}s^{-1}$ within the same temperature range. InN showed the lowest rate of change of mobility concerning temperature among the three materials used in the simulation, providing strong evidence that it is the most promising to provide the lowest rate of change in mobility with an increase in temperature.

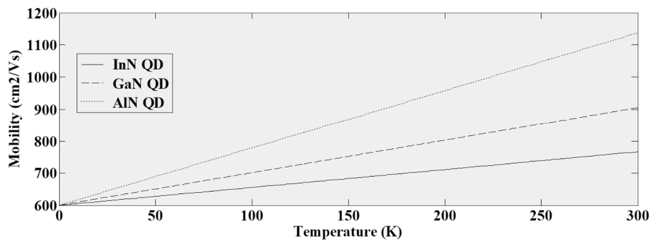


Fig. 3. Temperature dependence of the mobility of carrier using InN, GaN, and AlN QD as active layer material of the laser structure.

Figure 4 shows the temperature dependence of the absorption loss using InN, GaN, and AlN QD as the laser's active material. InN had the lowest absorption loss at any temperature, as it experienced a decrease of $0.135cm^{-1}$ in absorption loss, from 0.925 to $0.79cm^{-1}$ during a temperature change from 250 to 300K. GaN QDL experienced a decrease of $0.095cm^{-1}$, from 0.9 to $0.805cm^{-1}$, and AlN experienced a decrease in absorption loss of 0.0075 cm^{-1}, from 0.81 to $0.8025cm^{-1}$ within the same range. Therefore, InN QDL had the lowest absorption loss and the slope of the solid curve is minimal, indicating that the absorption loss had the least temperature dependence.

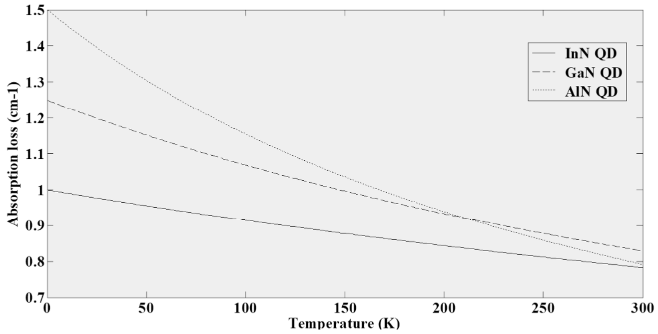


Fig. 4. Temperature dependence of absorption loss using InN, GaN, and AlN QD as active layer material of the laser structure.

Figure 5 represents the carrier density at threshold of QDL as a function of photon lifetime, which decreases exponentially with the increase of photon lifetime. InN QDL experienced a decrease of $1.525\times10^8cm^{-3}$ in carrier density at threshold, from 5.215×10^9 to 5.0625×10^9 cm^{-3} due to the change in photon lifetime from 0.5 to 1s. GaN QDL experienced a decrease of 10^8cm^{-3}, from 5.175×10^9 to $5.075\times10^9cm^{-3}$, and AlN experienced a decrease of $3.75\times10^7cm^{-3}$, from 5.125×10^9 to $5.0875\times10^9cm^{-3}$ within the same temperature range. Among the three materials used, InN showed the highest density of carrier at any cavity length and is the most promising in providing a higher effective density of state as well as the highest carrier density at threshold, which enhances the amplification of light.

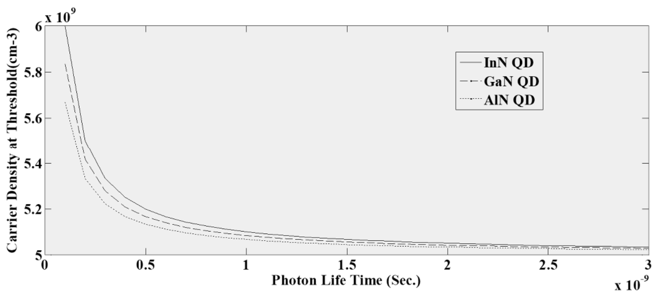


Fig. 5. Dependence of carrier density at the threshold on photon lifetime using InN, GaN, and AlN QD as active layer material of the laser structure.

Figure 6 describes the cavity length dependence of the optical feedback level of QDL, which reduces as the cavity length increases for GaN, AlN, and InN as the active layer material. InN QDL experienced a decrease of 0.2 (20%) in the feedback level, from 0.3727 to 0.1727 due to the change in cavity length from 40 to 100μm. GaN QDL experienced a decrease of 0.164 (16.4%) from 0.309 to 0.145, and AlN experienced a decrease of 0.16 (16%) from 0.28 to 0.12 within the same cavity range. As InN QD in the active layer of the laser provided the highest feedback level for any cavity length, it is the most promising in providing an enhanced level of feedback along with the highest carrier concentration and effective density of state.

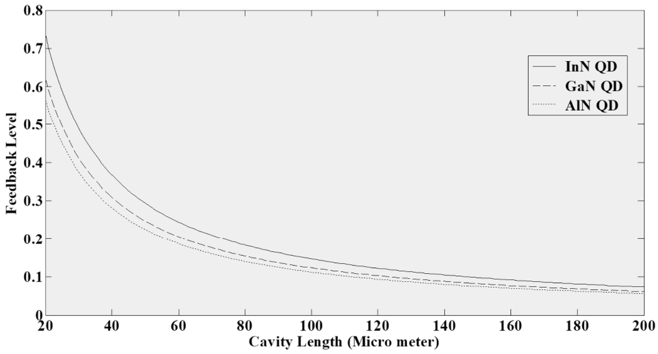


Fig. 6. Dependence of feedback level of laser on cavity length using InN, GaN, and AlN QD as active layer material of the laser structure.

Figure 7 illustrates the effect of the refractive index on the fluctuation of laser oscillation frequency using InN, GaN, and AlN QD as the active layer material of the laser. InN, GaN, and AlN QDL experienced a frequency fluctuation of 1.8×10^7Hz, 6×10^7Hz, and 8.9×10^7 Hz, for a 1.5 refractive index. The refractive index value was considered for the most widely used silica fibers around the globe. The fluctuation of the oscillation frequency of QDL is higher for AlN and GaN compared to InN. Additionally, the slope of the curve for InN QD was flatter than the other materials, indicating that the stability of the frequency of the laser output was improved significantly.

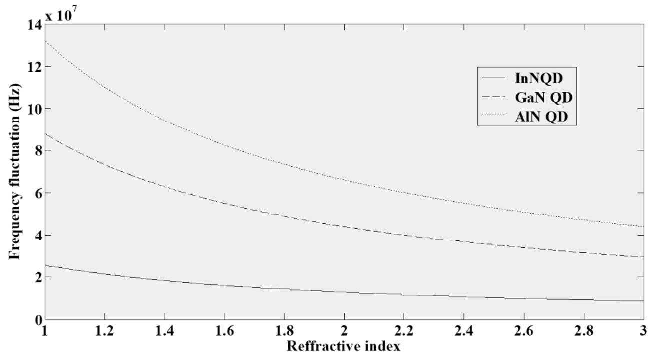


Fig. 7. Effect of refractive index on the fluctuation of laser frequency using InN, GaN, and AlN QD as active layer material of the laser structure.

IV. DISCUSSION

Among the three communication windows of optical fiber communication systems (0.89um, 1.3μm, and 1.55μm), 1.55μm offers the lowest attenuation, greater repeater spacing, and higher bit rate. These phenomena made it possible to use coherent optical sources compatible with the standard silicon fibers used in optical fiber communication [17]. Semiconductor sources and detectors with Group III-V compounds in active layers have been studied extensively and used almost exclusively for the present light-wave communication systems in these three wavelength regions [19-21]. Among the Group III nitride trios, InN has a unique band gap of 0.7eV, which is compatible with 1.55μm. In addition, InN QDL achieved the highest effective density of state of the carriers and reduced frequency fluctuation, rate of change momentum relaxation, and mobility as well as minimized absorption loss.

V. CONCLUSION

This study investigated extensively the major absorption and emission phenomena of QDL, focusing mainly on the absorption loss and stability of laser frequency and their key parameters. The effective density of state, carrier density at threshold, feedback level, and rate of change of mobility are the most important phenomena to enhance the stability of the oscillation frequency of QDL and minimize absorption loss. Considering the results of the numerical analysis, it can be concluded that InN provides higher effective density of state, enhanced feedback level, and higher uniformity in the mobility of the carrier. The improvement of these key parameters significantly minimized the fluctuation of laser frequency and absorption loss. Therefore, InN is a promising material for enhancing the absorption and emission properties of QDL, like higher stability of laser oscillation frequency and reduction of absorption loss.

ACKNOWLEDGMENT

The authors acknowledge the partial financial support provided by the Department of Electrical and Electronic Engineering of Eastern University, Dhaka, Bangladesh.

REFERENCES

[1] M. Smit et al., "An introduction to InP-based generic integration technology," *Semiconductor Science and Technology*, vol. 29, no. 8, Mar. 2014, Art. no. 083001, https://doi.org/10.1088/0268-1242/29/8/083001.

[2] F. L. Wang, X. W. Ma, Y. Z. Huang, Y.-D. Yang, J. Y. Han, and J. L. Xiao, "Relative intensity noise in high-speed hybrid square-rectangular lasers," *Photonics Research*, vol. 6, no. 3, pp. 193–197, Mar. 2018, https://doi.org/10.1364/PRJ.6.000193.

[3] M. T. Chughtai, "A Realization of Stabilizing the Output Light Power from a Laser Diode: A Practical Approach," *Engineering, Technology & Applied Science Research*, vol. 11, no. 4, pp. 7370–7374, Aug. 2021, https://doi.org/10.48084/etasr.4276.

[4] B. Liu, Y. Jiang, and H. Ji, "Sensing by Dynamics of Lasers with External Optical Feedback: A Review," *Photonics*, vol. 9, no. 7, Jul. 2022, Art. no. 450, https://doi.org/10.3390/photonics9070450.

[5] M. Seifouri and A. Faraji, "Simulation of the Optimized Structure of a Laterally Coupled Distributed Feedback (LC-DFB) Semiconductor Laser Above Threshold," *Engineering, Technology & Applied Science Research*, vol. 3, no. 5, pp. 522–525, Oct. 2013, https://doi.org/10.48084/etasr.376.

[6] M. A. Humayun, M. A. Rashid, F. Malek, and Y. Namihira, "Minimization of the performance degradation of laser parameters with operating time of quantum dot laser using indium nitride," *Physics Essays*, vol. 28, no. 1, pp. 134–137, Mar. 2015, https://doi.org/10.4006/0836-1398-28.1.134.

[7] M. Seifouri, F. Shahshahani, and A. Faraji, "Numerical Analysis of SHB Effects in Laterally-Coupled Distributed Feedback (LC-DFB) Lasers," *Engineering, Technology & Applied Science Research*, vol. 2, no. 5, pp. 273–277, Oct. 2012, https://doi.org/10.48084/etasr.196.

[8] F. P. García de Arquer, D. V. Talapin, V. I. Klimov, Y. Arakawa, M. Bayer, and E. H. Sargent, "Semiconductor quantum dots: Technological

progress and future challenges," *Science*, vol. 373, no. 6555, Aug. 2021, Art. no. eaaz8541, https://doi.org/10.1126/science.aaz8541.

[9] R. Carron, "Dilute-Nitride Low-Dimensional Nanostructures Formed on Non-Planar Substrates," Ph.D. dissertation, EPFL, Lausanne, Switzerland, 2013.

[10] R. Pawlus, L. L. Columbo, P. Bardella, S. Breuer, and M. Gioannini, "Intensity noise behavior of an InAs/InGaAs quantum dot laser emitting on ground states and excited states," *Optics Letters*, vol. 43, no. 4, pp. 867–870, Feb. 2018, https://doi.org/10.1364/OL.43.000867.

[11] S. Franchi, G. Trevisi, L. Seravalli, and P. Frigeri, "Quantum dot nanostructures and molecular beam epitaxy," *Progress in Crystal Growth and Characterization of Materials*, vol. 47, no. 2, pp. 166–195, Jan. 2003, https://doi.org/10.1016/j.pcrysgrow.2005.01.002.

[12] M. A. Humayun, M. A. Rashid, F. A. Malek, and A. N. Hussain, "Effect of lattice constant on band-gap energy and optimization and stabilization of high-temperature InxGa1−xN quantum-dot lasers," *Journal of Russian Laser Research*, vol. 33, no. 4, pp. 387–394, Jul. 2012, https://doi.org/10.1007/s10946-012-9294-7.

[13] D. O'Brien, S. P. Hegarty, G. Huyet, and A. V. Uskov, "Sensitivity of quantum-dot semiconductor lasers to optical feedback," *Optics Letters*, vol. 29, no. 10, pp. 1072–1074, May 2004, https://doi.org/10.1364/OL.29.001072.

[14] S. Kasap, *Principles of Electronic Materials and Devices*, 3rd ed. New York, NY, USA: McGraw-Hill, Inc., 2005.

[15] T. Ito *et al.*, "Femtosecond pulse generation beyond photon lifetime limit in gain-switched semiconductor lasers," *Communications Physics*, vol. 1, no. 1, pp. 1–8, Aug. 2018, https://doi.org/10.1038/s42005-018-0045-0.

[16] M. Gioannini and I. Montrosset, "Numerical Analysis of the Frequency Chirp in Quantum-Dot Semiconductor Lasers," *IEEE Journal of Quantum Electronics*, vol. 43, no. 10, pp. 941–949, Jul. 2007, https://doi.org/10.1109/JQE.2007.904306.

[17] J. M. Senior and M. Y. Jamro, *Optical Fiber Communications: Principles and Practice*. Harlow, UK: Pearson Education, 2009.

[18] M. M. Hossain, M. A.-A. Humayun, M. T. Hasan, A. G. Bhuiyan, A. Hashimoto, and A. Yamamoto, "Proposal of High Performance 1.55μm Quantum Dot Heterostructure Laser Using InN," *IEICE Transactions on Electronics*, vol. E95.C, no. 2, pp. 255–261, 2012, https://doi.org/10.1587/transele.E95.C.255.

[19] M. A. Humayun, M. A. Rashid, F. A. Malek, A. Hussain, and I. Daut, "Design of Quantum Dot Based LASER with Ultra-Low Threshold Current Density," *Applied Mechanics and Materials*, vol. 229–231, pp. 1639–1642, 2012, https://doi.org/10.4028/www.scientific.net/AMM.229-231.1639.

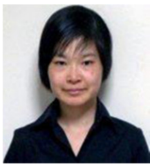
[20] M.-K. Lee, C.-H. Chu, Y.-H. Wang, and S. M. Sze, "1.55-μm and infrared-band photoresponsivity of a Schottky barrier porous silicon photodetector," *Optics Letters*, vol. 26, no. 3, pp. 160–162, Feb. 2001, https://doi.org/10.1364/OL.26.000160.

[21] M. A. Humayun, M. N. Hasan, M. A. Rashid, A. Kuwana, and H. Kobayashi, "Effect of optical fiber core diameter on Brillouin scattering loss," *Semiconductor Physics, Quantum Electronics and Optoelectronics*, vol. 24, no. 4, pp. 450–456, Nov. 2021, https://doi.org/10.15407/spqeo24.04.450.

AUTHOR PROFILES

Md. Abdullah Al Humayun was born in 1987 and received his Ph.D. in Electrical Systems Engineering from Malaysia Perlis University in 2015. His research work focused on semiconductor device design. He is currently working as an Associate Professor in the Department of Electrical & Electronic Engineering at the Eastern University, Dhaka, Bangladesh. Previously, he was a postdoctoral fellow at the International Islamic University of Malaysia and worked in different private universities in Bangladesh. He has authored over 30 publications. The area of his scientific interests includes physics and technology of semiconductor materials, hetero and hybrid structures, and optoelectronic devices (lasers, LEDs, solar cells, photodetectors, etc.), and their applications in optical fiber communication.

Mohd Abdur Rashid (member, IEEE) received his Ph.D. degree in Electrical and Information Engineering from the University of the Ryukyus, Japan. He is a Professor in the Department of Electrical and Electronic Engineering (EEE) at NSTU. He is currently working as a visiting scholar at Gunma University, Japan. He has also work experience in Malaysia, Japan, and Canada in academic fields. He has authored more than 96 technical articles in journals and conferences. His research interests include multidisciplinary fields, including mathematical modeling, electronic devices, and biomedical engineering.



Anna Kuwana (associate member, IEEE) received her B.S. and M.S. degrees in information science and her Ph.D. from Ochanomizu University, in 2006, 2007, and 2011, respectively. She worked at Ochanomizu University as a member of the technical staff. She is currently an Assistant Professor in the Division of Electronics and Informatics at Gunma University. Her research interests include computational fluid dynamics and signal analysis.

Haruo Kobayashi (senior member, IEEE) received his B.S. and M.S. degrees in information physics from the University of Tokyo in 1980 and 1982, respectively, his M.S. in electrical engineering from UCLA in 1989, and his Ph.D. in electrical engineering from Waseda University in 1995. He joined Yokogawa Electric Corporation, Tokyo, Japan, in 1982, and was involved in research and development related to measuring instruments. In 1997, he joined Gunma University, where he is currently a Professor in the Division of Electronics and Informatics. His research interests include mixed-signal integrated circuit design and testing, and signal processing algorithms.