Different influences of u-InGaN upper waveguide on the performance of GaN-based blue and green laser diodes*

Feng Liang(梁锋)[1,2], De-Gang Zhao(赵德刚)[1,3,†], De-Sheng Jiang(江德生)[1], Zong-Shun Liu(刘宗顺)[1], Jian-Jun Zhu(朱建军)[1], Ping Chen(陈平)[1], Jing Yang(杨静)[1], Wei Liu(刘炜)[1], Xiang Li(李翔)[1], Shuang-Tao Liu(刘双韬)[1], Yao Xing(邢瑶)[1], Li-Qun Zhang(张立群)[4], Mo Li(李沫)[5], and Jian Zhang(张健)[5]

[1] *State Key Laboratory on Integrated Optoelectronics, Institute of Semiconductors, Chinese Academy of Science, Beijing* 100083, *China*
[2] *College of Materials Science and Opto-Electronic Technology, University of Chinese Academy of Sciences, Beijing* 100049, *China*
[3] *School of Electronic, Electrical and Communication Engineering, University of Chinese Academy of Sciences, Beijing* 100049, *China*
[4] *Suzhou Institute of Nano-tech and Nano-bionics, Chinese Academy of Sciences, Suzhou* 215123, *China*
[5] *Microsystem & Terahertz Research Center, Chinese Academy of Engineering Physics, Chengdu* 610200, *China*

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Performances of blue and green laser diodes (LDs) with different u-InGaN upper waveguides (UWGs) are investigated theoretically by using LASTIP. It is found that the slope efficiency (SE) of blue LD decreases due to great optical loss when the indium content of u-InGaN UWG is more than 0.02, although its leakage current decreases obviously. Meanwhile the SE of the green LD increases when the indium content of u-InGaN UWG is varied from 0 to 0.05, which is attributed to the reduction of leakage current and the small increase of optical loss. Therefore, a new blue LD structure with $In_{0.05}Ga_{0.95}N$ lower waveguide (LWG) is designed to reduce the optical loss, and its slope efficiency is improved significantly.

Keywords: GaN-based laser diode, slope efficiency, waveguide

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1. Introduction

GaN-based laser diodes (LDs) have attracted much attention due to their wide applications in high-density optical storage and small portable projectors.[1–7] Compared with the traditional LD structure proposed by Nakamura,[7,8] the optical characteristics, especially the optical field distribution, could be improved by using a complex upper waveguide (UWG) with an unintentionally-doped InGaN (u-InGaN) interlayer.[9–11] To meet the demands of practical application, both optical and electrical characteristics should be studied carefully. In particular, the slope efficiency (SE) of GaN-based LD is necessary to be further investigated, which determines the electro-optic conversion efficiency and the possibility of its commercialization, although there is some research on the different influences of u-InGaN UWG on the slope efficiencies (SEs) for the blue and green LDs, including theoretical analyses and experimental research of the slope efficiency of GaN-based LDs.[12,13]

In this work, the u-$In_xGa_{1-x}N$ ($0 \leq x \leq 0.05$) layer is designed to be the UWG and the effects of u-InGaN UWG on the optical and electrical characteristics for blue and green LDs are investigated based on the theoretical calculations using the two-dimension simulator LASTIP. In particular, the different influences of u-InGaN UWG on the slope efficiency (SE) are studied systematically. The results are considered to be useful for the practical LD structure design and will be beneficial to improving the performances of GaN-based blue and green LDs.

2. LD structure and calculation

The device structure of GaN-based blue and green laser diodes is shown in Fig. 1, including the thickness and doping concentration of each layer. The cavity length and ridge width of these GaN-based blue and green lasers are 600 μm and 3 μm, respectively. The active region consists of two-period unintentionally-doped InGaN/GaN multiple quantum wells (MQWs). For the blue and green laser diodes, the indium contents of the InGaN quantum well (QW) are 0.22 and 0.37, respectively, whose corresponding lasing wave lengths are 446 nm and 540 nm, respectively. For the blue and green LDs, a 100 nm u-InGaN layer is designed as the UWG, which is located between the last GaN quantum barrier and the $Al_{0.2}Ga_{0.8}N$ electron blocking layer. The indium content of u-InGaN UWG is varied from 0 to 0.05 with a background concentration of 1×10^{17} cm^{-3}.

The optical and electrical characteristics of the GaN-based blue and green LDs are theoretically simulated by LASTIP (Crosslight Software Inc.). It is a powerful cal-

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†Corresponding author. E-mail: dgzhao@red.semi.ac.cn

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culation software for semiconductor laser diodes in two dimensions, in which the Poisson's equation and the current continuity equations are solved by using the finite element method.[14,15] During our calculation, both the p-type and n-type electrodes are set to be an ideal ohmic contact, and only 25% of the theoretical value[16] of the polarization field is applied. The absorption coefficients of the n-type and p-type layers are set to be 5 cm^{-1} and 50 cm^{-1}, respectively, except for the heavily Mg-doped $Al_{0.2}Ga_{0.8}N$ electron blocking layer (EBL) and the heavily Mg-doped GaN (p^{++}-GaN) contact layer whose absorption coefficients are taken as 100 cm^{-1}. In addition, the refractive indexes of the InGaN-based and AlGaN-based materials are obtained by using an approximate method as follows:

$$n(In_xGa_{1-x}N) = [n(InN) - n(GaN)]x + n(GaN), \quad (1)$$

$$n(Al_xGa_{1-x}N) = [n(AlN) - n(GaN)]x + n(GaN). \quad (2)$$

For the blue LDs with a lasing wave length of 446 nm, the refractive indexes of InN, GaN, and AlN used in Eqs. (1) and (2) are 3.7918, 2.485, and 2.235, respectively. For the green LDs with a lasing wave length of 540 nm, the refractive indexes of InN, GaN, and AlN in Eqs. (1) and (2) are 2.8796, 2.435, and 2.2475, respectively.

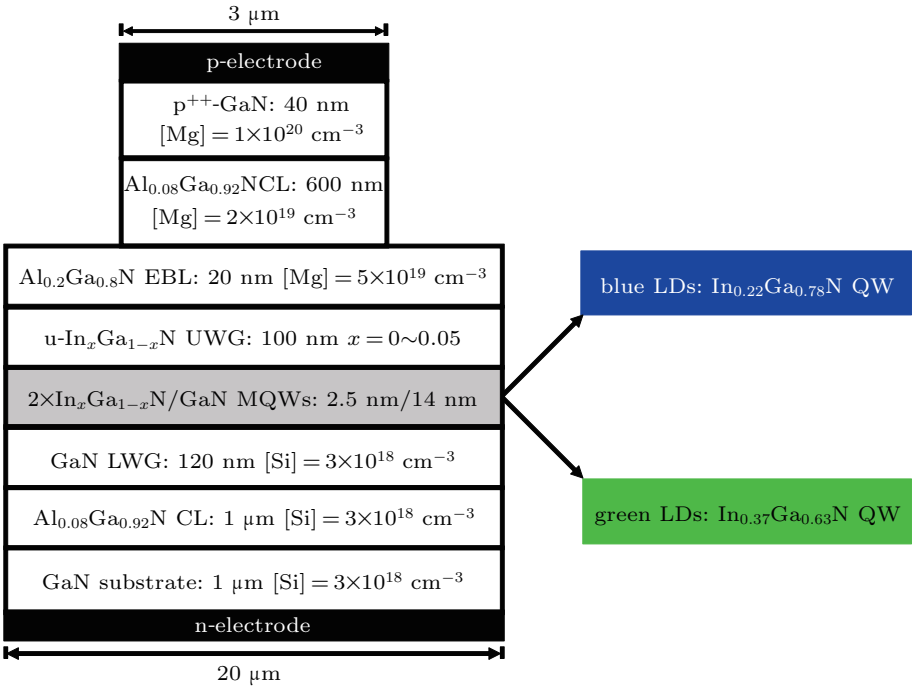


Fig. 1. (color online) Schematic structure of GaN-based blue and green LDs with u-InGaN UWG. [Si]: doping level of Si. [Mg]: doping level of Mg. CL: cladding layer. LWG: lower waveguide. UWG: upper waveguide. EBL: electron blocking layer.

3. Results and discussion

3.1. Optical and electrical characteristics of blue and green LDs

The optical characteristics of blue and green LDs with different u-InGaN UWG are investigated. As shown in Fig. 2(a), for the blue LDs, the center position of the optical field increases from 2.135 μm to 2.189 μm as the indium content of InGaN UWG increases from 0 to 0.05, and it moves from the active region to u-InGaN UWG when the indium content of u-InGaN UWG is more than 0.03. On the other hand, for the green LDs, the center position of the optical field increases from 2.103 μm to 2.151 μm with the increase of the indium content in u-InGaN UWG, and it moves from n-GaN LWG to the active region when the indium content of u-InGaN UWG is more than 0.01. Moreover, the full width at half maximum (FWHM) of the blue and green LDs is also calculated to more clearly illustrate the optic field distribution, as shown in Fig. 2(b). Here, the FWHM is defined as the full width at half maximum of the optical field distribution along the vertical direction, which is the direction from the n-type contact layer to the p-type contact layer as shown in Fig. 1. It reveals that the FWHM of blue LDs decreases from 370 nm to 268 nm, and the FWHM of green LDs decreases from 560 nm to 477 nm. In Fig. 2(c), the optical confident factors of blue and green LDs increase obviously, and the optical confident factor of blue LDs is larger than that of green LDs when the indium content of u-InGaN UWG increases from 0 to 0.05. In addition, the total optical loss is also calculated as shown in Fig. 2(d). It can be seen that the total optical loss of blue and green LDs increases when the indium content of u-InGaN UWG increases from 0 to 0.05. Additionally, the total optical loss of blue LDs is larger than that of green LDs when the indium content is equal to or more than 0.01. It demonstrates that for the blue and green LDs, the increase of the indium con-

tent in u-InGaN UWG is beneficial to pushing the optical field towards the p-type area and squeezing the optical field distribution, because the refraction indexes of InGaN-based materials increase with increasing indium content and the difference in refraction index between the UWG and cladding layer is enlarged. That is why the optical confident factors of blue and green LDs increase obviously. On the other side, the optical losses of blue and green LDs also increase, because the center of the optical field is close to the p-type area, which would result in an increase of the optical loss caused by the absorptions of the electron blocking layer and the cladding layer.

It is also noted that the optical loss of blue LDs is greater than that of green LDs. It can be seen that the FWHM of blue LDs is larger than 200 nm, and smaller than that of green LDs. It means that comparing to green LDs, the proportion of optical field in the p-type area and the optical loss of blue LDs would increase more severely when the center of the optical field is pushed towards to the p-type area. According to our calculation, for the green LDs, the proportion of optical field in the electron blocking layer increases from 18.6% to 23.8%. However, for the blue LDs, the proportion of optical field in the electron blocking layer increases from 22.0% to 38.1%. That is why the optical loss of blue LDs is larger than that of green LDs.

The threshold current and output light power of blue and green LDs are shown in Figs. 3(a) and 3(b), respectively. It can be seen that the threshold current of blue LDs decreases from 26.4 mA to 24.4 mA, while the threshold current of green LDs increases from 27.1 mA to 29.9 mA, when the indium content of u-InGaN UWG increases from 0 to 0.05. In addition, under an injecting current of 120 mA, the output light powers of blue and green LDs first increase and subsequently decrease with increasing indium content of u-InGaN UWG, and the peak points of the output light power for blue and green LDs appear at 0.03 and 0.01, respectively. It indicates that the increase of the indium content of u-InGaN UWG can reduce the threshold current of blue LDs, nevertheless, it is a disadvantage for the threshold current of green LDs.

It is noted that for the blue and green LDs, the tendencies of threshold current and indium content of UWG are different. It is known that the threshold current is proportional to the optical confinement factor and inversely proportional to the optical loss. In Figs. 2(c) and 2(d), it can be seen that the optical confinement factors and optical losses of blue and green LDs increase with increasing indium content of u-InGaN UWG. It means that for the blue LDs, the reduction of the threshold current is caused by the increasing optical confinement factor, although its optical loss increases. On the other side, for the green LDs, the increase of the optical loss results in the increase of the threshold current, although its optical confinement factor increases.

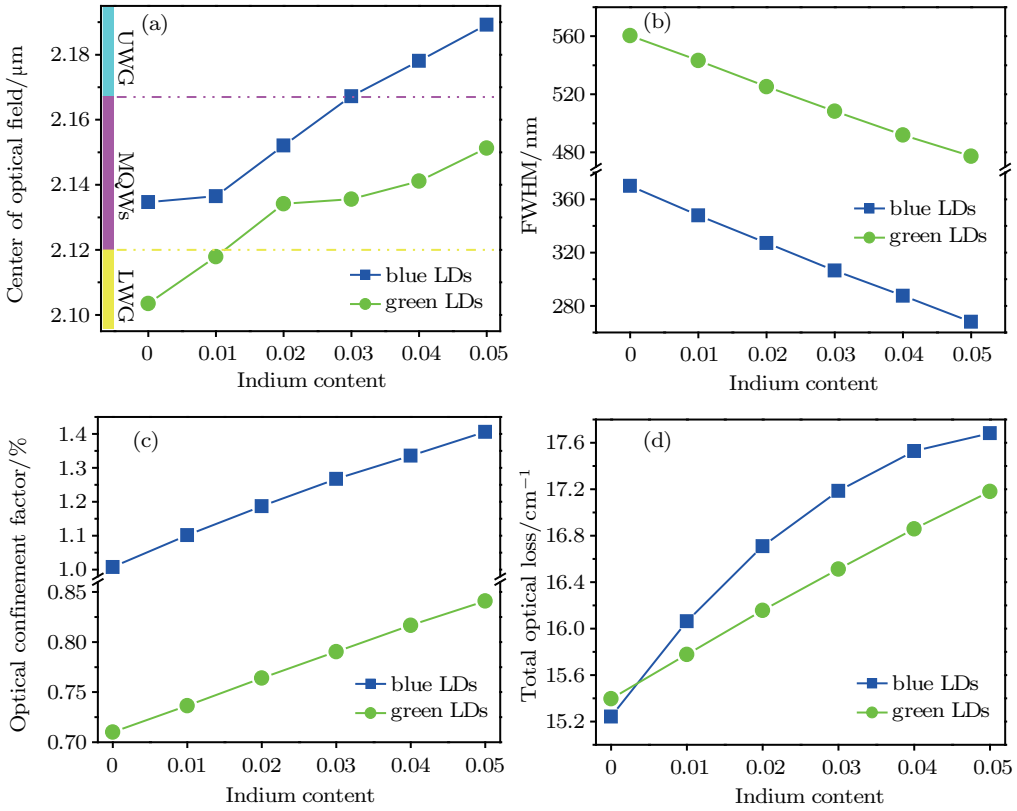


Fig. 2. (color online) Optical characteristics of blue and green LDs: (a) center of optical field, (b) FWHM of the optical field, (c) optical confinement factor, and (d) total optical loss. The interface between n-GaN CL and the active region, and the interface between the active region and u-InGaN UWG are marked by yellow and magenta dashed-dotted lines, respectively.

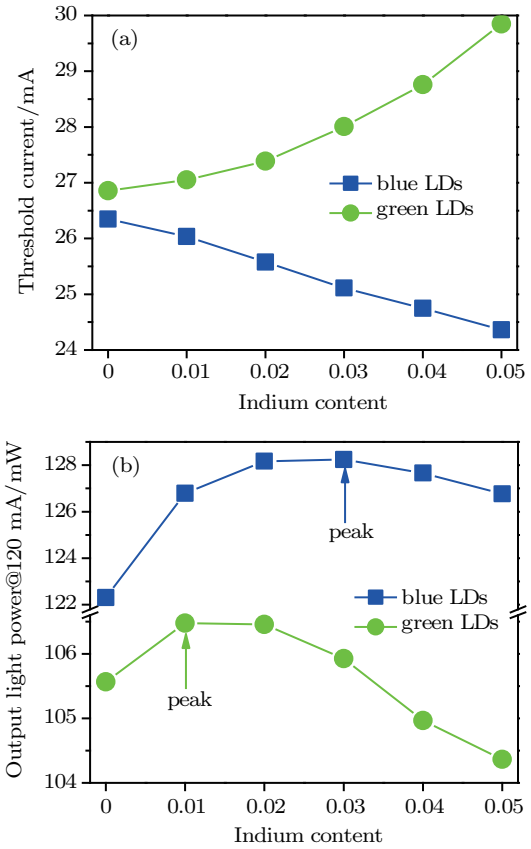


Fig. 3. (color online) Variations of (a) threshold current and (b) output light power with the indium content of u-InGaN UWG under an injecting current of 120 mA for blue and green LDs.

3.2. Influence of u-$In_xGa_{1-x}N$ ($0 \leq x \leq 0.05$) on slope efficiency

It is noted that the output light power of blue LDs decreases when the indium content of u-InGaN UWG is over 0.03, although the corresponding threshold current decreases. Meanwhile, the output light power of green LDs is improved as the indium content of u-InGaN UWG increases from 0 to 0.01, although the corresponding threshold current rises obviously. These two phenomena suggest that the slope efficiency has been changed when the indium content of u-InGaN UWG varies from 0 to 0.05. As shown in Fig. 4, the slope efficiencies of blue and green LDs are a function of indium content of u-InGaN UWG. Here, the slope efficiency is calculated by fitting the power–current curve when the injecting current is more than the threshold value. It can be seen that for the blue LDs, the slope efficiency first increases and then decreases, and the maximum slope efficiency appears at 0.02. On the other hand, the slope efficiency of green LDs always rises as the indium content of u-InGaN UWG increases from 0 to 0.05. These trends of the slope efficiency and the indium content of u-InGaN UWG, i.e., electro-optic conversion efficiency, are consistent with the results of the threshold current and output light power shown in Fig. 3. Furthermore, it also suggests that the increase of the indium content of u-InGaN UWG has different influences on the slope efficiencies of blue and green LDs. For the blue LDs, the electro-optic conversion efficiency is first improved and then weakened as the indium content of u-InGaN UWG increases. On the other hand, for the green LDs, the electro-optic conversion efficiency is always improved with increasing indium content of u-InGaN UWG. Thus, it implies that the mechanisms of the slope efficiency influenced by u-InGaN UWG might be different. It is known that the slope efficiency (SE) is defined by the following expression:[10]

$$\mathrm{SE} = \frac{\Delta P}{\Delta I} = \frac{hc}{q\lambda}\frac{\alpha_\mathrm{m}}{\alpha_\mathrm{m}+\alpha_\mathrm{i}}\eta_\mathrm{inj}, \tag{3}$$

where h, c, q, k, α_i, α_m, and η_inj are the Planck constant, the speed of light, the elementary charge, the lasing wave length, the internal absorption loss, the mirror loss, and the injection efficiency, respectively. α_m is expected to be constant during our calculation; and η_inj is defined as the proportion of injecting current that generates carriers in the active region. Therefore, the total optical loss could reflect the change of α_i for blue and green LDs with different indium contents of u-InGaN UWG, which is proportional to α_i. Meanwhile, η_inj should be inversely proportional to the percentage of electron leakage, which is defined as the ratio of the electron current overflowed into the p-type region to the total electron current injected into the QWs of the LDs. Therefore, the percentage of electron leakage could be used to analyze the effects of the internal absorption loss and injection efficiency on the slope efficiency, respectively, which are given in Fig. 5.

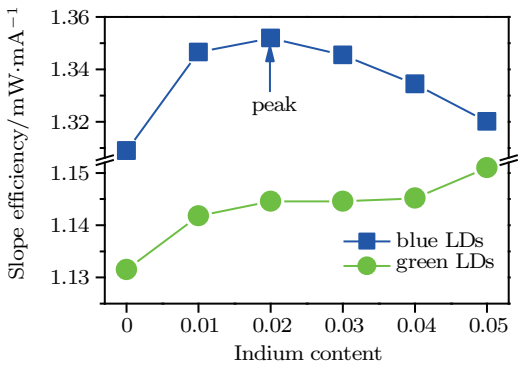


Fig. 4. (color online) Variations of slope efficiencies of blue and green LDs with indium content of u-InGaN UWG.

In Fig. 5, it can be seen that the total optical losses of blue and green LDs increase and the corresponding percentages of electron leakage current decrease, as the indium content of u-InGaN UWG increases from 0 to 0.05. Additionally, the total optical loss and percentage of electron leakage current of blue LDs are larger than those of green LDs when the indium content is more than or equal to 0.01. According to Eq. (3), increasing the total optical loss would lead to a decline of the slope efficiency, and reducing the leakage current would result

in an improvement of the slope efficiency. Therefore, it indicates that for the blue LDs, the slope efficiency is first determined by the percentage of electron leakage current when the indium content of u-InGaN UWG is less than or equal to 0.02, but it is determined by the optical loss when the indium content of u-InGaN UWG is more than 0.02. That is why the slope efficiency of blue LDs first increases and then decreases with the increase of indium content as shown in Fig. 4. However, for the green LDs, the major factor that affects the slope efficiency should be always the percentage of electron leakage current when the indium content of u-InGaN UWG varies from 0 to 0.05. Because the slope efficiency of green LDs would not be a monotonically increasing function of indium content of u-InGaN UWG, if the optical loss becomes a dominant factor. It is also noted that the leakage of electron current of blue LDs is larger than that of green LDs. Due to a larger indium content of InGaN quantum well, the polarization field of green LDs is larger than that of blue LDs, and it would result in a larger incline of the energy band level and more severe leakage of electron current. However, a larger indium content of InGaN quantum well means a deeper potential well and enhances the confinement of electrons in the quantum well. Therefore, the leakage of electron current of blue LDs is larger than that of green LDs.

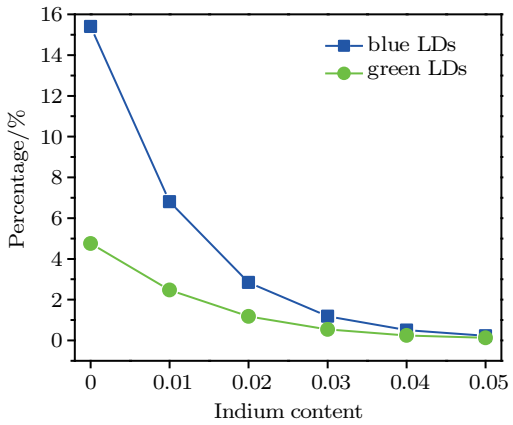


Fig. 5. (color online) Variations of percentages of electron leakage current for the blue and green LDs with indium content of u-InGaN UWG.

It can be surmised that the different influences on the slope efficiency between the blue and green LDs are caused by the different refractive index contrasts between the active region and the waveguide layer for the blue and green LDs. Specifically, the refractive index contrast between InGaN and AlGaN materials would be narrowed when the lasing wave length increases from blue to green. It means that the optical confinement would be weakened when the indium content of u-InGaN UWG is the same, thus less optical field would be distributed in UWG and optical loss is small compared with scenarios of the blue LDs, which can be observed in Figs. 2 and 5.

Based on the discussion above, to reduce the optical loss of blue LDs, using an InGaN LWG layer should be a good method, which improves the slope efficiency by pushing the optical field towards the n-type area. Therefore, compared with the blue LD with u-$In_{0.02}Ga_{0.98}N$ UWG (named LD2) whose slope efficiency is the biggest, another blue LD structure, named LD2-5, is also simulated. The UWG layer of LD2-5 is u-$In_{0.02}Ga_{0.98}N$ (the same as for the LD2), but the LWG layer is taken as $In_{0.05}Ga_{0.95}N$, whose indium content is much higher than that of GaN LWG in LD2. The optical field distributions of LD2 and LD2-5 are shown in Fig. 6(a). It can be seen that the optical field has been concentrated and pushed towards the n-type area as the indium content of LWG increases to 0.05 (LD2-5). Therefore, the optical loss decreases to 6.8 cm^{-1}. The *P–I* curves of LD2 and LD2-5 are shown in Fig. 6(b). As we expect, comparing with LD2, the slope efficiency of LD2-5 significantly increases to 1.56 mW/mA and the output power at 120 mA also increases to 148.9 mW, the threshold current of LD2-5 is also much lower than that of LD2.

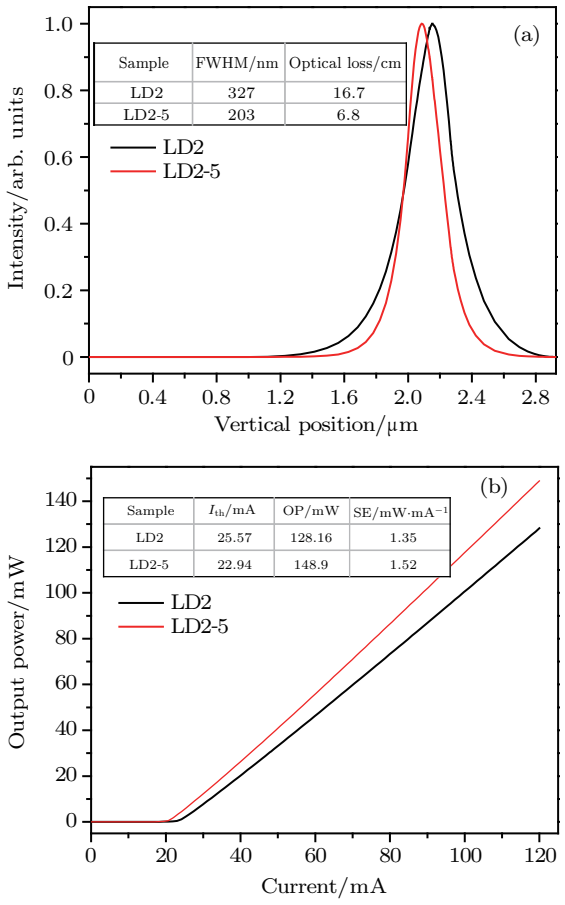


Fig. 6. (color online) Variations of (a) optical field distribution with vertical position and (b) output power with current curve for LD2 and LD2-5. I_{th} and OP are the threshold current and output power under an injecting current of 120 mA, respectively.

4. Conclusion

Different effects of u-$In_xGa_{1-x}N$ ($0 \leq x \leq 0.05$) upper waveguide on optical and electrical characteristics of blue and green LDs are studied by using LASTIP. It is found that due to the different optical confinements in the blue and green LDs, the dominant factors that affect the slope efficiency are different when the indium content of u-InGaN UWG varies from 0 to 0.05. For the blue LDs, the slope efficiency is mainly affected by the percentage of electron leakage current first and subsequently by the optical loss. Nevertheless, for the green LDs, the dominant factor is always the percentage of electron leakage current.

References

[1] Lutgen S, Avramescu A, Lermer T, Schillgalies M, Queren D, Müller J, Dini D, Breidenassel A and Strauss U 2010 *Phys. Status Solidi A* **207** 1318

[2] Sizov D, Bhat R and Zah C E 2012 *J. Lightwave Technol.* **30** 679

[3] Ren B, Hou Y and Liang Y N 2016 *J. Semicond.* **37** 124001

[4] Jiang L J, Liu J P, Tian A Q, Cheng Y, Li Z C, Zhang L Q, Zhang S M, Li D Y, Ikeda M and Yang H 2016 *J. Semicond.* **37** 111001

[5] Zhao D G, Yang J, Liu Z S, Chen P, Zhu J J, Jiang D S, Shi Y S, Wang H, Duan L H, Zhang L Q and Yang H 2017 *J. Semicond.* **38** 051001

[6] Zhao D G, Jiang D S, Le L C, Yang J, Chen P, Liu Z S, Zhu J J and Zhang L Q 2015 *Chin. Phys. Lett.* **34** 017101

[7] Shuji N, Masayuki S, Shin-ichi N, Naruhito I, Takao Y, Toshio M, Hiroyuki K and Yasunobu S 1996 *Jpn. J. Appl. Phys.* **35** L74

[8] Nakamura S, Senoh M, Nagahama S, Iwasa N, Yamada T, Matsushita T, Sugimoto Y and Kiyoku H 1997 *Appl. Phys. Lett.* **70** 1417

[9] Chen P, Feng M X, Jiang D S, Zhao D G, Liu Z S, Li L, Wu L L, Le L C, Zhu J J, Wang H, Zhang S M and Yang H 2012 *Appl. Phys.* **112** 113105

[10] Le L C, Zhao D G, Jiang D S, Chen P, Liu Z S, Yang J, He X G, Li X J, Liu J P, Zhu J J, Zhang S M and Yang H 2014 *Opt. Express* **22** 11392

[11] Chen P, Zhao D G, Jiang D S, Zhu J J, Liu Z S, Yang J, Li X, Le L C, He X G, Liu W, Li X J, Liang F, Zhang B S, Yang H, Zhang Y T and Du G T 2016 *AIP Advances* **6** 035124

[12] Hager T, Brüderl G, Lermer T, Tautz S, Gomez-Iglesias A, Müller J, Avramescu A, Eichler C, Gerhard S and Strauss U 2012 *Appl. Phys. Lett.* **101** 171109

[13] Piprek J 2016 *Opt. Quant. Electron.* **48** 471

[14] Li X, Zhao D G, Jiang D S, Chen P, Liu Z S, Zhu J J, Shi M, Zhao D M, Liu W, Zhang S M and Yang H 2015 *J. Semicond.* **36** 074009

[15] Pang Y, Li X and Zhao B Q 2016 *J. Semicond.* **37** 084007

[16] Fiorentini V and Bernardini F 2002 *Appl. Phys. Lett.* **80** 1204