Output light power of InGaN-based violet laser diodes improved by using a u-InGaN/GaN/AlGaN multiple upper waveguide*

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], Shuang-Tao Liu(刘双韬)[1], Yao Xing(邢瑶)[1], Li-Qun Zhang(张立群)[4], Wen-Jie Wang(王文杰)[5], Mo Li(李沫)[5], Yuan-Tao Zhang(张源涛)[1], and Guo-Tong Du(杜国同)[1]

[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*

(Received 3 August 2017; revised manuscript received 31 August 2017; published online 20 October 2017)

The upper waveguide (UWG) has direct influences on the optical and electrical characteristics of the violet laser diode (LD) by changing the optical field distribution or barrier of the electron blocking layer (EBL). In this study, a series of InGaN-based violet LDs with different UWGs are investigated systematically with LASTIP software. It is found that the output light power (OLP) under an injecting current of 120 mA or the threshold current (I_{th}) is deteriorated when the UWG is u-$In_{0.02}Ga_{0.98}N$/GaN or u-$In_{0.02}Ga_{0.98}N/Al_xGa_{1-x}N$ ($0 \leq x \leq 0.1$), which should be attributed to small optical confinement factor (OCF) or severe electron leakage. Therefore, a new violet LD structure with u-$In_{0.02}Ga_{0.98}N$/GaN/$Al_{0.05}Ga_{0.95}N$ multiple layer UWG is proposed to reduce the optical loss and increase the barrier of EBL. Finally, the output light power under an injecting current of 120 mA is improved to 176.4 mW.

Keywords: InGaN-based violet LDs, u-InGaN/GaN/AlGaN multiple upper waveguide

PACS: 42.55.Px, 42.82.Et **DOI:** 10.1088/1674-1056/26/12/124210

1. Introduction

The InGaN-based laser diodes (LDs) have been studied for many years and remarkable progress has been made so far due to their broad applications in optoelectronics as light sources, including mobile laser projection, laser TV, full color display, high-density data storage, biological agent detection systems and medical applications.[1–6] In particular, InGaN-based violet LDs promise to be the next generation of laser sources for high density optical disc systems, such as blue-ray disc (BD), high definition-DVD (HD-DVD), and other applications.[7–9] However, the electrical-to-optical power conversion efficiency of the commercialized InGaN-based LDs is still less than 40%.[10,11] In the past, much work on the structure design and material growth of the InGaN-based violet LDs has been done. Shuji *et al.*[12] improved the characteristics of the violet LDs by modulating the doped strained-layer superlattices grown on the epitaxially laterally overgrown GaN substrate. Zhao *et al.*[13] improved the electro-luminescence intensities of InGaN-based violet LDs by using growing quantum wells and barriers under the same temperature. Alahyarizadeh *et al.*[14] enhanced the output power by using a delta barrier close to the electron blocking layer (EBL). However, obtaining superior performance of InGaN-based violet LD remains a challenge. In this work, the influence of the upper waveguide (UWG) on the optical and electrical characters of InGaN-based violet LDs is investigated numerically by using the LASTIP software. Unlike the above-mentioned violet LD whose UWG is a single layer, a new violet LD structure with u-InGaN/GaN/AlGaN multiple UWG is proposed in this study and its output light power is improved significantly.

2. Laser structure and simulation parameters

Schematic diagram of violet LD structure for the calculation is shown in Fig. 1. All the layers of the violet LDs in this study are the same, except for the upper waveguide layer (UWG). The total thickness of UWG is 100 nm, which includes the thickness of one u-InGaN layer or one u-AlGaN layer or the combination of u-InGaN and u-AlGaN. To make our investigation clearer, layer information of UWG for some violet LDs are listed in Table 1. The cavity length and ridge width are 600 μm and 3 μm, respectively. Power reflectivity values on the front and rear facet are both set to be the

*Project supported by the National Key R & D Program of China (Grant Nos. 2016YFB0400803 and 2016YFB0401801), the National Natural Science Foundation of China (Grant Nos. 61674138, 61674139, 61604145, 61574135, 61574134, 61474142, 61474110, 61377020, and 61376089), the Science Challenge Project, China (Grant No. TZ2016003), and the Beijing Municipal Science and Technology Project, China (Grant No. Z161100002116037).

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

 http://iopscience.iop.org/cpb http://cpb.iphy.ac.cn

same value of 19%. The active region consists of two 2.5-nm $In_{0.15}Ga_{0.85}N$ quantum well (QW) layers separated by three 14-nm GaN quantum barriers (QBs), which results in an emission wavelength of 411 nm. It also consists of a 1-µm n-type GaN layer, a 1-µm n-type $Al_{0.08}Ga_{0.92}N$ cladding layer (n-CL), a 120-nm thick n-type lower GaN waveguide layer (LWG), a multiple quantum well (MQW) active area, a 20-nm p-type $Al_{0.2}Ga_{0.8}N$ electron blocking layer (EBL), a 600-nm p-type $Al_{0.08}Ga_{0.92}N$ cladding layer (p-CL), and a 40-nm p-type GaN contact layer. The background electron concentration is set to be 1×10^{17} cm^{-3} in each of the unintentionally-doped QW, QW, and UWG. In the n-type doped layer, the doping concentration is set to be 3×10^{18} cm^{-3}.

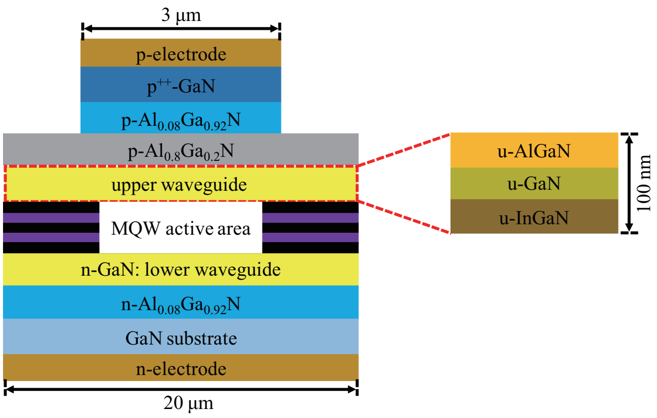

Fig. 1. (color online) Schematic structure of InGaN-based violet LD with different UWGs.

Table 1. Layer information of UWG and performances for different violet LDs. Output light powers under an injecting current of 120 mA.

Name	Upper waveguide/nm			OLP/mW
	u-$In_{0.02}Ga_{0.98}N$	u-GaN	u-$Al_{0.05}Ga_{0.95}N$	
LD1	100	0	0	162.5
LD2	90	10	0	147.4
LD3	0	100	0	164.2
LD4	90	0	10	166.6
LD5	35	0	65	170.7
LD6	35	60	5	176.4

The optical and electrical characteristics of these violet LDs are obtained by using LASTIP software (Crosslight Software Inc.), which can solve band structures, radiative and non-radioactive carrier recombination, the drift and diffusion equation of carriers, and photon rate equations.[15,16] 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[17] of the polarization field is taken. Meanwhile, the absorption coefficients of EBL and p^{++}-GaN contact layer are both taken as 100 cm^{-1}, and for the n-type and p-type layers they are set to be 5 cm^{-1} and 50 cm^{-1}, respectively. In addition, in this study, the refractive indexes of $In_xGa_{1-x}N$-based and $Al_xGa_{1-x}N$-based materials are obtained approximately by using the following expressions:

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

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

where the refractive indexes of InN, GaN and AlN are obtained from expressions (1) and (2) to be 2.6363, 2.565, and 1.94, respectively.

3. Results and discussion

3.1. u-$In_{0.02}Ga_{0.98}N$/GaN UWG

The UWG is designed to consist of two layers firstly, i.e. u-$In_{0.02}Ga_{0.98}N$ and u-GaN. The total thickness of u-$In_{0.02}Ga_{0.98}N$/u-GaN UWG is 100 nm, and the thickness of u-GaN increases from 0 nm to 100 nm. As shown in the inset in Fig. 2, it can be seen that the threshold current and the output light power under an injecting current of 120 mA first decrease and then increase when the thickness of u-GaN increases from 0 nm to 100 nm, and the values of threshold current and output light power decrease to the smallest values when the thickness of u-GaN is 10 nm. It can be seen that the slope efficiency first decreases and then increases with thickness of u-GaN layer increasing. In fact, the slope efficiency is inversely proportional to the optical loss and it is proportional to the injection efficiency according to the analysis by Hager *et al.*[18] Meanwhile, the injection efficiency should be in proportion to the barrier of the electron blocking layer, which means that the slope efficiency is also proportional to the barrier of the electron blocking layer.

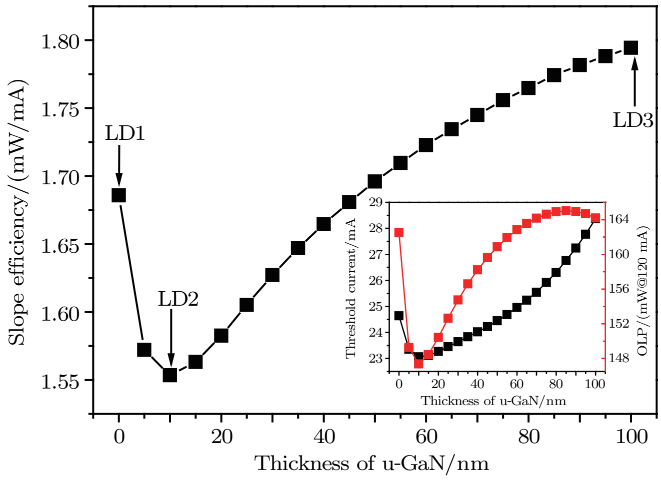

Fig. 2. (color online) Slope efficiency of InGaN-based violet LDs with different u-$In_{0.02}Ga_{0.98}N$/GaN UWGs. The inset shows the threshold current (black) and output light power (OLP) under an injecting current of 120 mA (red).

Therefore, optical distribution and barrier of electron blocking layer are calculated and shown in Figs. 3(a) and 3(b), respectively. The barrier of electron blocking layer is defined as the energy difference between the Fermi level (E_F) of the last quantum well and the conduction band (E_C) of electron blocking layer. In Fig. 3(a), it can be seen that the optical field is pushed away from the p-type area, and the optical confinement factor and optical loss decrease obviously as the thickness of u-GaN layer increases from 0 nm to 100 nm. On the other side, the barrier of the electron blocking layer decreases sharply from 226.7 meV to 165.9 meV when the thickness of u-GaN layer increases from 0 nm to 15 nm, and then it increases to 191.8 meV when the thickness of u-GaN layer increases to 100 nm. It can be seen that reduction of the barrier results in a deterioration of slope efficiency when the thickness of u-GaN increases from 0 nm to 10 nm, although the optical loss decreases from 14.32 cm^{-1} to 13.79 cm^{-1}.

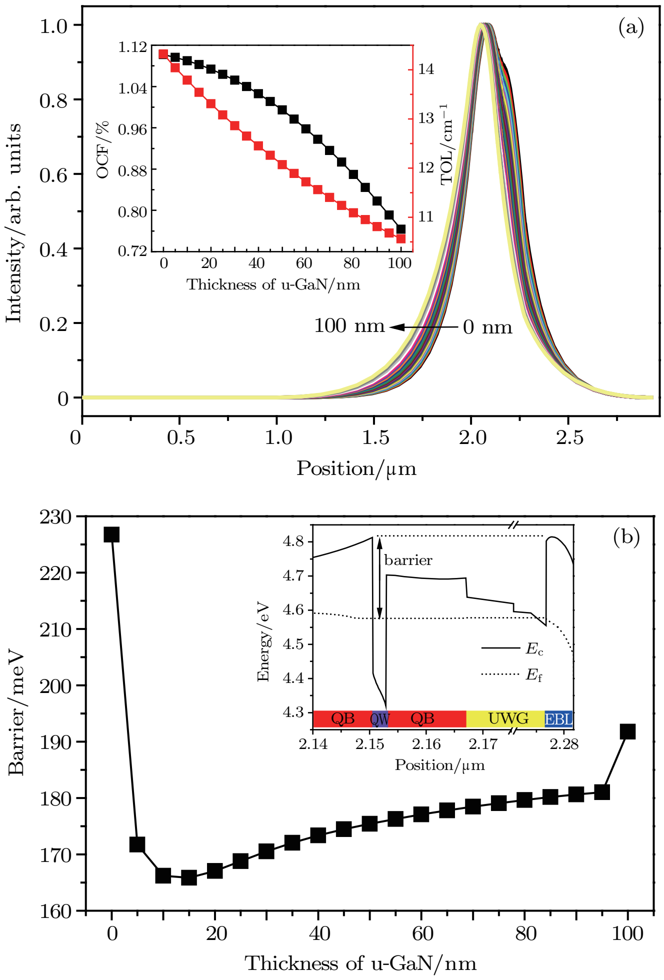

Fig. 3. (color online) Optical field distribution (a) and the barrier of the electron blocking layer (b) of InGaN-based violet LDs with different u-$In_{0.02}Ga_{0.98}N$/GaN UWGs. The inset in panel (a) shows the optical confinement factor (OCF) and the total optical loss (TOL), which are marked as black and red color, respectively. The inset in panel (b) indicates the conduction band diagram of LD1 and the definition of barriers.

It is known that the piezoelectric polarization-induced electric field (E_{pe}) in the u-GaN layer increases as the thickness of u-GaN QB increases from 0 nm to 100 nm, whose direction is the same as those of the built-in electric field (E_{in}) and the spontaneous polarization-induced electric field (E_{sp}) but its direction is opposite to the external electric field (E_{ex}). Therefore, as the thickness of u-GaN layer increases, the tilt level of E_c for UWG decreases and then the barrier of the electron blocking layer is improved. On the other hand, it is also noted that the barrier of the electron blocking layer decreases as the thickness is lower than or equal to 15 nm. It is found that the voltage under an injecting current of 120 mA increases as the thickness increases, thus the tilt level of E_c in the upper waveguide increases and then the barrier of the electron blocking layer decreases. That is why the barrier of the electron blocking layer decreases when the thickness of u-GaN layer increases from 0 nm to 15 nm.

3.2. u-$In_{0.02}Ga_{0.98}N/Al_xGa_{1-x}N$ ($0 \le x \le 0.1$) UWG

To further increase the barrier of the electron blocking layer, u-$Al_xGa_{1-x}N$ with high aluminum content ($0 \le x \le 0.1$) is designed to improve the performances of InGaN-based violet LDs. Meanwhile, as shown in the inset in Fig. 2, the threshold current is lowest when the thickness of u-GaN is 10 nm, although its output light power is smallest. Therefore, the thickness values of u-$In_{0.02}Ga_{0.98}N$ and u-$Al_xGa_{1-x}N$ ($0 \le x \le 0.1$) are set to be 90 nm and 10 nm, respectively. As shown in Fig. 4, the output light power increases sharply from 147.4 mW to 168.7 mW as the aluminum content of u-AlGaN layer increases from 0 to 0.1. The inset in Fig. 4 demonstrates that the barrier of electron blocking layer increases obviously from 166.2 meV to 365.1 meV as the aluminum content of u-AlGaN layer increases from 0 to 0.1. It is noted that the optical loss is larger than that of LD2 when the aluminum content of u-AlGaN layer is larger than or equal to 1%. It indicates that improvement of the output light power is attributed to the increase of the barrier of the electron blocking layer when the aluminum content of u-AlGaN layer increases and the deterioration of threshold current is caused by the increase of optical loss.

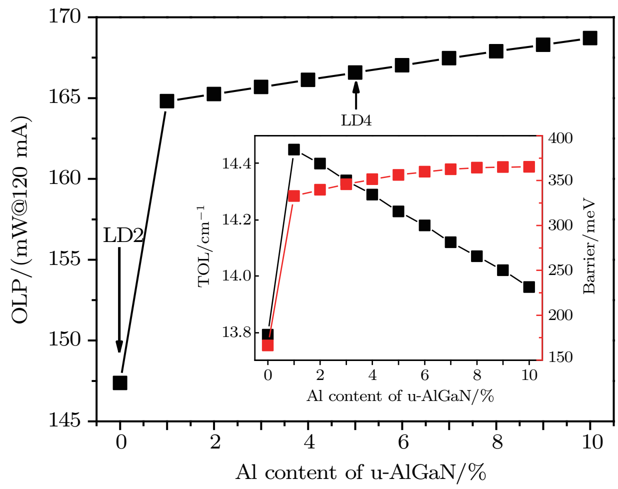

Fig. 4. (color online) Output light powers under an injecting current of 120mA for InGaN-based violet LDs with different u-$In_{0.02}Ga_{0.98}N/Al_xGa_{1-x}N$ ($0 \le x \le 0.1$) UWGs. The inset shows the total optical loss (black) and the barrier of the electron blocking layer (red).

As shown in Fig. 5(a), the optical field distribution is anomalous near to the p-type area, which should be caused by the studied change of a refractive index between the u-$In_{0.02}Ga_{0.98}N$ and u-$Al_xGa_{1-x}N$ ($0 \le x \le 0.1$) due to thin u-$Al_xGa_{1-x}N$ ($0 \le x \le 0.1$) layers. This anomalous field distribution is a disadvantage for serving as light sources. Meanwhile, the threshold current is still high, although the output light power is improved with increasing aluminum content of u-AlGaN layer. Therefore, thickness of u-$Al_xGa_{1-x}N$ could be one way to improve the performance of violet LD, especially the optical field distribution. To keep the output light power high and the threshold current proper, the aluminum is set to be 5%, i.e., u-$Al_{0.05}Ga_{0.95}N$, when violet LDs with different thickness values of u-$Al_xGa_{1-x}N$ layer are calculated. As shown in Fig. 5(b), the anomalous field distribution weakens when the thickness of u-$Al_{0.05}Ga_{0.95}N$ increases from 10 nm to 100 nm.

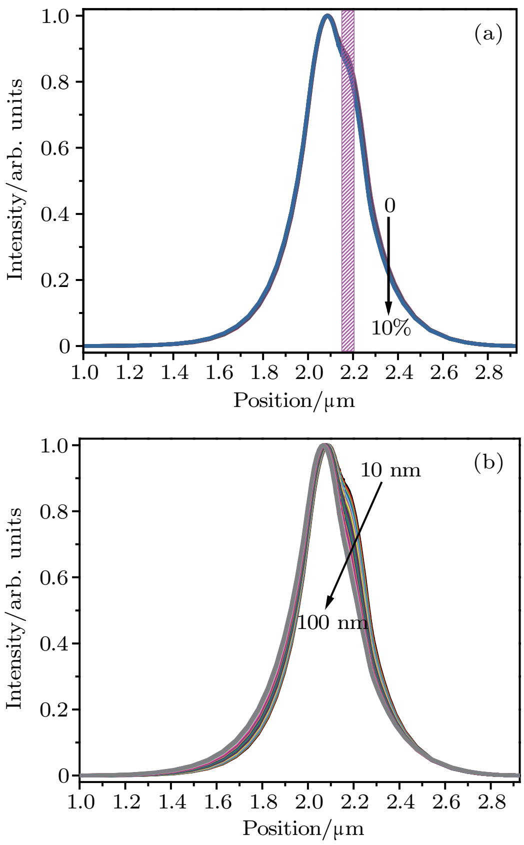

Fig. 5. (color online) Optical field distributions of InGaN-based violet LDs (a) with different aluminum content values of u-$Al_xGa_{1-x}N$ ($0 \le x \le 0.1$) and (b) with different thickness values of u-$Al_{0.05}Ga_{0.95}N$. In Fig. 5(a), the shaded rectangle marks the anomalous area of the optical field.

Moreover, the electrical characteristics of the violet LDs with different thickness values of u-$Al_{0.05}Ga_{0.95}N$ layer are also studied. In Fig. 6(a), it can be seen that the threshold current increases, and the output light power under an injecting current of 120 mA first increases and then decreases, when the thickness of u-$Al_{0.05}Ga_{0.95}N$ layer increases from 10 nm to 100 nm. Figure 6(b) shows that total optical loss and barrier of electron blocking layer decrease with the thickness of u-$Al_{0.05}Ga_{0.95}N$ layer increasing. It indicates that the increase of the threshold current and the decrease of output light power may be caused by the obvious decreasing of the barrier, which decreases from 356.1 meV to 245.1 meV as the thickness of u-$Al_{0.05}Ga_{0.95}N$ layer increases from 10 nm to 100 nm. As mentioned before, the piezoelectric polarization-induced electric field (E_{pe}) in the u-$Al_{0.05}Ga_{0.95}N$ layer increases and the tilt level of E_c for UWG decreases, and then the barrier of electron blocking layer is improved as thickness of u-$Al_{0.05}Ga_{0.95}N$ layer increases. Meanwhile, the voltage under an injecting current of 120 mA increases as the thickness increases, thus the tilt level of E_c for UWG increases and then the barrier of the electron blocking layer decreases. Finally, the result is that the barrier of the electron blocking layer decreases as the thickness of u-$Al_{0.05}Ga_{0.95}N$ layer increases.

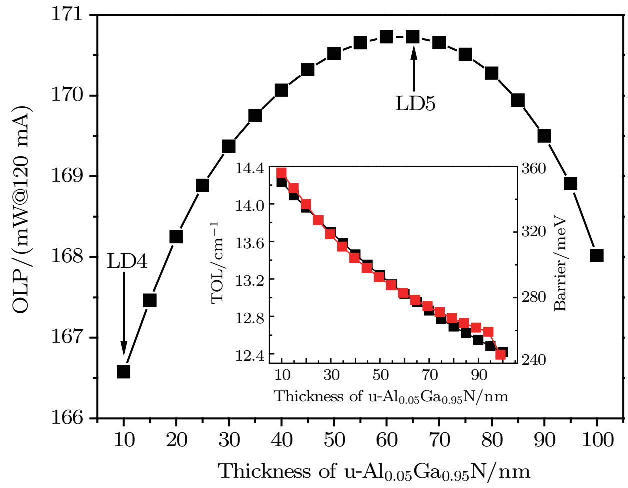

Fig. 6. (color online) Output light powers under an injecting current of 120mA for InGaN-based violet LDs with different thickness values of u-$Al_{0.05}Ga_{0.95}N$ layer. The inset shows the total optical loss (black) and the barrier of the electron blocking layer (red).

3.3. u-$In_{0.02}Ga_{0.98}N$/GaN/$Al_{0.05}Ga_{0.95}N$ multiple UWG

It is noted that the barrier of the electron blocking layer decreases from 356.1 meV to 278.6 meV, although the output light power of LD5 is maximal and the thickness of u-$Al_{0.05}Ga_{0.95}N$ is 65 nm. In order to further improve the output light power by increasing the barrier of the electron blocking layer, a u-GaN layer is inserted between the u-$In_{0.02}Ga_{0.98}N$ and $Al_{0.05}Ga_{0.95}N$ layers, i.e., u-$In_{0.02}Ga_{0.98}N$/GaN/$Al_{0.05}Ga_{0.95}N$ multiple UWG. For violet LDs with different u-$In_{0.02}Ga_{0.98}N$/GaN/$Al_{0.05}Ga_{0.95}N$ multiple UWGs, the thickness of u-$In_{0.02}Ga_{0.98}N$ remains unchanged, i.e., 35 nm, and the total thickness of u-GaN and u-$Al_{0.05}Ga_{0.95}N$ is 65 nm. As shown in Fig. 7, the output light power increases from 170.7 mW to 176.4 mW when the thickness of u-GaN increases from 0 nm to 60 nm. The inset in Fig. 7 shows that the optical loss decreases from 12.95 cm^{-1} to 11.85 cm^{-1} and the barrier of the electron blocking layer increases from 278.6 meV to 323.3 meV with increasing the thickness of u-GaN. It demonstrates that the output light power is improved due to the reduction of optical loss and increase of the barrier of electron blocking layer as the thickness of u-GaN increases, when the thickness of u-GaN in the u-$In_{0.02}Ga_{0.98}N/GaN/Al_{0.05}Ga_{0.95}N$ multiple UWG increases.

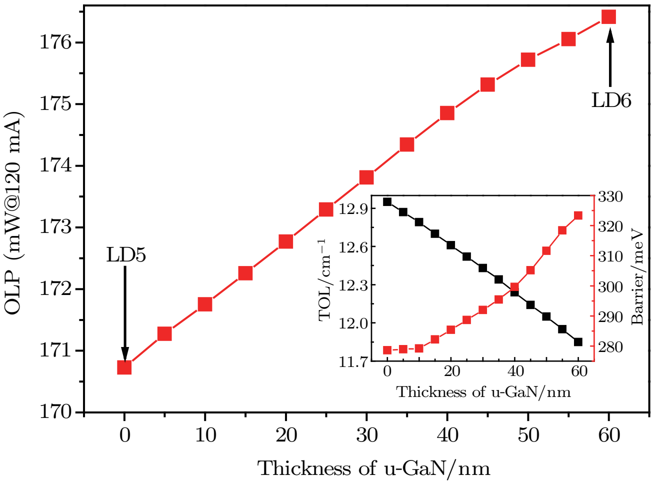

Fig. 7. (color online) Threshold current and output light power under an injecting current of 120 mA, with inset showing the total optical loss (TOL) and barrier of electron blocking layer for the InGaN-based violet LDs with different thickness values of u-GaN layer in the u-$In_{0.02}Ga_{0.98}N/GaN/Al_{0.05}Ga_{0.95}N$ multiple UWG.

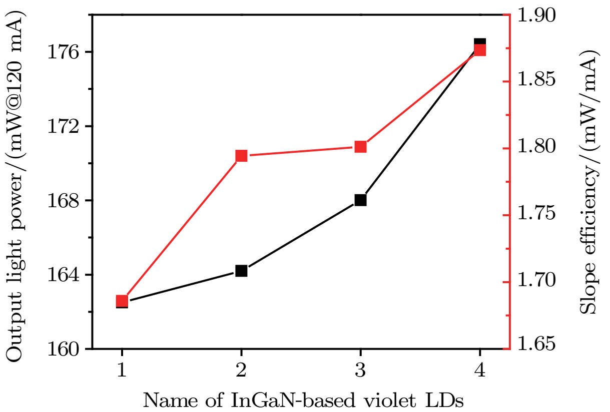

Fig. 8. (color online) Output light power (black) and slope efficiency (red) for LD1, LD3, LD4, and LD5.

The output light power under an injecting current of 120 mA and the slope efficiencies for LD1, LD3, LD4, and LD5 are shown in Fig. 8, whose layer information of UWG is listed in Table 1. In general, comparing with LD1 whose UWG is single u-$In_{0.02}Ga_{0.98}N$, the output light power and the slope efficiency are improved significantly by 8.6% and 10.7%, respectively. It demonstrates that the u-$In_{0.02}Ga_{0.98}N/GaN/Al_{0.05}Ga_{0.95}N$ multiple UWG is proved to be a good way to improve the performances of the InGaN-based violet LDs in this study.

4. Conclusions

A series of InGaN-based violet laser diodes (LDs) with different UWGs are investigated by using the two-dimensional simulator LASTIP. It is found that compared with the UWG using u-$In_{0.02}Ga_{0.98}N$ or u-$In_{0.02}Ga_{0.98}N/GaN$ or u-$In_{0.02}Ga_{0.98}N/Al_xGa_{1-x}N$ as the UWG, a new UWG using u-$In_{0.02}Ga_{0.98}N/GaN/Al_{0.05}Ga_{0.95}N$ multiple layers is a good way to improve the output light powers of the InGaN-based violet LDs in this study.

References

[1] Sizov D, Bhat R and Zah C E 2012 *J. Lightwave Technol.* **30** 679
[2] Jiang L R, 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
[3] Lutgen S, Dini D, Pietzonka I, Tautz S, Breidenassel A, Lell A, Avramescu A, Eichler C, Lermer T, Müller J, Bruederl G, Gomez-Iglesias A, Strauss U, Scheibenzuber W G, Schwarz U T, Pasenow B and Koch S 2011 *Proc. SPIE* **7953** 79530G
[4] Ren B, Hou Y and Liang Y N 2016 *J. Semicond.* **37** 124001
[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] Strauss U, Somers A, Heine U, Wurm T, Peter M, Eichler C, Gerhard S, Bruederl G, Tautz S, Stojetz B, Loeffler A 2017 *Koenig H Proc. SPIE* **10123** 101230A
[7] Alahyarizadeh G, AmirhoseinyM and Hassan Z 2016 *Opt. Laser Technol.* **76** 106
[8] Perlin P, Holc K, Sarzyński M, Scheibenzuber W, Marona L, Czernecki R, Leszczyński M, Bockowski M, Grzegory I, Porowski S, Cywiński G, Firek P, Szmidt J, Schwarz U and Suski T 2009 *Appl. Phys. Lett.* **95** 261108
[9] Stańczyk S, Czyszanowski T, Kafar A, Czernecki R, Targowski G, Leszczyński M, Suski T, Kucharski R and Perlin P 2013 *Appl. Phys. Lett.* **102** 151102
[10] Nakamura S, Fasol G 1997 *The blue laser diode* (Berlin: Springer)
[11] Piprek J 2016 *Opt. Quantum Electron.* **48** 471
[12] Shuji N, Masayuki S, Shin-ichi N, Naruhito I, Takao Y, Toshio M, Hiroyuki K, Yasunobu S, Tokuya K, Hitoshi U, Masahiko S, Kazuyuki C 1998 *Jpn. J. Appl. Phys.* **37** L627
[13] Zhao D G, Jiang D S, Le L C, Jing Y, Chen P, Liu Z Z, Zhu J J and Zhang L Q 2017 *Chin. Phys. Lett.* **34** 017101
[14] Alahyarizadeh G, Hassan Z, Thahab S M, Ghazai A J and Mahmodi H 2012 *NANOP* **6** 063514
[15] 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
[16] Pang Y, Li X and Zhao B Q 2016 *J. Semicond.* **37** 084007
[17] Fiorentini V, Bernardini F and Ambacher O 2002 *Appl. Phys. Lett.* **80** 1204
[18] 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