Quantum Electronics **50** (5) 489–492 (2020) ©2020 Kvantovaya Elektronika and IOP Publishing Limited

LASERS. CONTROL OF LASER RADIATION PARAMETERS

https://doi.org/10.1070/QEL17249

The influence of waveguide doping on the output characteristics of AlGaAs/GaAs lasers

K.Yu. Telegin, M.A. Ladugin, A.Yu. Andreev, I.V. Yarotskaya,
N.A. Volkov, A.A. Padalitsa, A.V. Lobintsov, A.N. Aparnikov,
S.M. Sapozhnikov, A.A. Marmalyuk

Abstract. **The influence of doping of waveguide layers on the output characteristics of lasers based on AlGaAs/GaAs double separate-confinement heterostructures is analysed. The heterostructures with narrow and broadened waveguides are studied. Samples of laser diode bars with undoped and doped waveguide layers are experimentally fabricated and compared. It is shown that the latter type of structures with a broadened waveguide allows one to increase the output power of the laser diode bars by 10 %–15 %, all other conditions being equal.**

Keywords: *semiconductor laser, laser diode bar, waveguide, doping, output power.*

1. Introduction

At present, an important field of application of semiconductor laser diodes (LDs) is diode pumping of solid-state and fibre lasers, which makes it possible to considerably increase the efficiency of pumped lasers and decrease their mass-dimensional characteristics and energy consumption. These LDs should emit at wavelengths within the absorption band of the active medium and have a high output power and efficiency. In particular, LD bars and arrays based on AlGaAs/GaAs heterostructures and emitting in the region of 808 nm are widely used for pumping of $\mathrm{YAG:Nd^{3+}}$ lasers.

Double separate-confinement heterostructures with one or two quantum wells are traditionally used in LDs. Higher output powers were achieved from laser diodes with a broadened waveguide allowing a decrease in the internal optical losses and, hence, an increase in the differential quantum efficiency. To decrease scattering from free carries, the waveguide layers of these laser diodes, as a rule, are not specially doped [1–3]. The maximum optical power in this case is limited mainly by scattering from free carries accumulated in the waveguide region adjacent to the p-emitter (the role of the other mechanisms of the output power saturation is noticeably less important) [4, 5]. At the same time, the low concentration of carriers in waveguide layers can lead to an increase in the diode series resistance and, as a result, to an increase in the heat release, which decreases the laser efficiency and limits the maximum achievable output power. This effect is especially pronounced in the p-type layers [6, 7]. Moreover, the authors of [8] noted an increase in the cutoff voltage of the current–voltage characteristic (CVC) with increasing waveguide thickness, which also negatively affects the efficiency and temperature characteristics of LDs. The negative effect of a broadened undoped waveguide is especially pronounced in multielement devices with intense heat release (LD bars and arrays), which makes it necessary to revise downwards the optimal thicknesses of waveguide layers for some or other applications, especially for waveguide layers adjacent to the p-emitter [7, 9–14].

In this situation, one of the ways to use the advantages of broadened waveguides in multielement lasers is to produce laser heterostructures with doped waveguides. In this case, one should use profiled doping at a relatively low level (10^{16}–10^{17} cm^{-3}), which makes it possible to decrease the cutoff voltage of the CVC and decrease the diode series resistance with only a slight increase in internal optical losses [15, 16]. It was additionally noted in [4] that an increase in the p waveguide doping level causes a decrease in the current leakage and suppression of the light–current characteristic (LCC) saturation. This approach was tested when creating LDs emitting at wavelengths from 800 to 1550 nm [7, 16–20]. In each case, the proposed doping profiles of waveguide layers varied depending on the chosen material system and the design of the laser heterostructure as a whole.

The present work is devoted to the study of the influence of doping of waveguides with different thicknesses on the output characteristics of AlGaAs/GaAs LD bars emitting in the region of 808 nm.

2. Experiment and discussion of its results

The AlGaAs/GaAs quantum-well separate-confinement heterostructures were grown by MOCVD. The active region contained one quantum well surrounded by $\mathrm{Al_{0.4}Ga_{0.6}As}$ waveguide layers, which provided a high quantum efficiency of the LD bars [9]. The AlGaAs waveguide thickness varied from 0.3 to 1.5 μm. We studied samples with specially undoped [$(1-5)\times10^{15}$ cm^{-3}] and doped [$(5-10)\times10^{16}$ cm^{-3}] waveguide layers. In the latter case, the waveguide layers

---

K.Yu. Telegin, M.A. Ladugin, A.Yu. Andreev, I.V. Yarotskaya, N.A. Volkov, A.A. Padalitsa, A.V. Lobintsov, A.N. Aparnikov, S.M. Sapozhnikov JSC M.F. Stel'makh Polyus Research Institute, ul. Vvedenskogo 3, korpus 1, 117342 Moscow, Russia;
e-mail: k.telegin@siplus.ru;
A.A. Marmalyuk JSC M.F. Stel'makh Polyus Research Institute', ul Vvedenskogo 3, korpus 1, 117342 Moscow, Russia; National Research Nuclear University MEPhI, Kashiskoe sh. 31, 115409 Moscow, Russia

Received 24 January 2020
Kvantovaya Elektronika **50** (5) 489–492 (2020)
Translated by M.N. Basieva

adjacent to the n- and p-emitters were doped with donor and acceptor impurities, respectively. We used profiled doping, i.e., the impurity concentration in the waveguide increased in the direction from its boundary with the active layer to the boundary with the emitter layer. From the grown heterostructures, we fabricated LD bars 0.5 mm long with a filling factor of 0.7. The cavity faces were coated with antireflection and high-reflection coatings with reflection coefficients $R_1 \approx 0.05$ and $R_2 \approx 0.95$, respectively. The LD bars were mounted on a copper heat sink, and their output characteristics were studied in a quasi-cw regime (200 μs, 20 Hz) at a heat sink temperature of 25 °C.

In many practical cases, the waveguide layers of LDs are specially undoped to achieve a low level of optical losses. It was demonstrated that the maximum achievable output power of lasers, including those emitting at a wavelength of 808 nm, increases with increasing the waveguide thickness [21–23]. At the same time, it was noted in [9, 13, 24] that the geometry of laser heterostructures with a narrow waveguide or waveguide layers with a decreased thickness adjacent to the p-emitter is preferable for creating LD bars. In these cases, heat removal from the active region is more efficient, which is especially important for multielement LD bars and arrays.

Figure 1 shows the light–current characteristics (LCCs) of LDs with undoped waveguides 0.3, 0.7, and 1.5 μm in thickness operating in a quasi-cw regime. One can see that an increase in the waveguide thickness is accompanied with an increase in the threshold current and a decrease in the differential quantum efficiency of the LDs. The most pronounced decrease in the LCC slope is observed for the sample with a 1.5-μm waveguide, while the samples with waveguide thicknesses of 0.3 and 0.7 μm have similar LCC slopes.

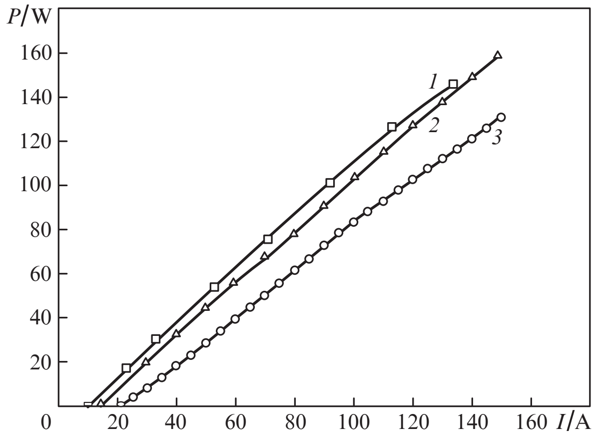

Figure 1. LCCs (200 μs, 20 Hz) of LD bars with undoped waveguides with thicknesses of (*1*) 0.3, (*2*) 0.7, and (*3*) 1.5 μm.

It is convenient to present the dependence of the LD output optical power on pump current I in the form [25]

$$P = \eta_i \frac{\alpha_{\text{ext}}}{\alpha_{\text{ext}} + \alpha_i} \frac{h\nu}{q} (I - I_{\text{th}}), \tag{1}$$

where η_i is the internal quantum yield, α_{ext} is the external optical loss, α_i is the internal optical loss, q is the electron charge, $h\nu$ is the photon energy, and I_{th} is the threshold current, while waveguide broadening should lead, in addition to an increase in I_{th}, to a decrease in α_i [26] and η_i [27]. A decrease in α_i will cause an increase in the differential quantum efficiency and, vice versa, a decrease in η_i will decrease this efficiency. As a result, the LCC slope will be determined by the opposite contributions from the aforementioned parameters and, hence, will strongly depend on the laser heterostructure configuration. Under our experimental conditions, the increase in the waveguide thickness from 0.3 to 0.7 μm caused no noticeable decrease in the LCC slope at the initial stage. At the same time, the waveguide broadening decreases the optical power density on the output mirror, which makes it possible to postpone the catastrophic optical degradation of mirrors and achieve a higher output power. The sample with a narrow waveguide (0.3 μm) has a higher α_i but lower series and thermal resistances, which allows retention of its LCC slope up to rather high pump powers. However, at currents exceeding 100 A, the optical losses in this LD bar begin to grow and the output power begins to saturate. The waveguide broadening to 1.5 μm results in an even more pronounced decrease in the optical confinement factor in the active region, which increases I_{th} and, in combination with an increase in the series electrical and thermal resistances of the emitter, leads to a more considerable decrease in the LCC slope.

As a rule, single high-power LDs operate at pump currents exceeding the threshold current by tens (20–30) of times. Under these conditions, the difference between the threshold currents of lasers with narrow and broadened waveguides becomes insignificant. The situation considerably differs in the case of LD bars, for which the typical excess of the working current over the threshold current is considerably lower, usually 5–10 times. Because of this, LD bars with a broadened waveguide, which have even lower optical losses but a higher temperature load due to increased series electrical and thermal resistances, may fail to provide a desired high output power at such low working currents. At the same time, doping of broadened waveguides can allow one to decrease the series resistance and, hence, heat release, which should have a positive effect on the output laser characteristics [6, 7–16, 20, 28]. Due the low mobility of holes, doping of the waveguide layer adjacent to the p-emitter is especially important. Doping of waveguide layers with an adequate choice of its level and profile allows one to restrict an increase in the optical losses and achieve higher output power and efficiency. Moreover, doping of waveguides reduces current leakage in them [29], which increases the differential quantum efficiency.

The LCCs for LD bars with broadened undoped and doped waveguides are compared in Fig. 2. We used LD bars with waveguides 0.7 μm in thickness. This makes it possible, on the one hand, to decrease the internal optical losses in comparison with the losses in a narrow (0.3 μm) waveguide and, on the other hand, only slightly increase the series and thermal resistances. The average doping level of waveguide layers was $\sim 8 \times 10^{16}$ cm^{-3}. The LCCs of the LD bar with a doped broadened waveguide are noticeably better first of all due to a higher efficiency at high pump currents. Lasers with a broadened waveguide are characterised by accumulation of carriers in the p region of the waveguide, which increases the internal optical loses [30]. Doping reduces this effect.

Figure 3 shows the LCCs of LD bars with broadened doped and narrow undoped waveguides. As was expected, the LD with a broadened waveguide has a higher threshold current (this agrees with Fig. 1), but doping of the waveguide

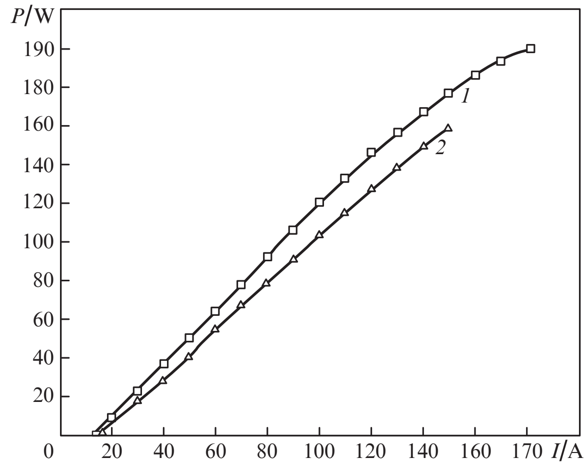

Figure 2. LCCs (200 μs, 20 Hz) of LD bars with broadened (0.7 μm) (*1*) doped and (*2*) undoped waveguides.

enabled us to increase the differential quantum efficiency of the bar, while this efficiency for LDs with undoped waveguides demonstrated no increase with increasing waveguide thickness. The doped LDs exhibit a weaker band bending in the waveguide region and, hence, a smaller accumulation of carriers and lower optical losses.

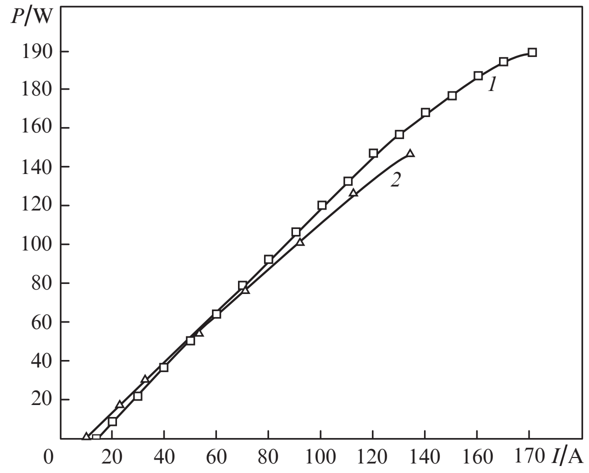

Figure 3. LCCs (200 μs, 20 Hz) of LD bars with (*1*) broadened (0.7 μm) doped and (*2*) narrow (0.3 μm) undoped waveguides.

As a result, we can conclude that, similar to other approaches to increasing the power of LD bars, the use of doped waveguides with an increased thickness makes it possible to find a balance between the local advantages of narrow and broadened waveguides for creating highly efficient lasers. In particular, heterostructures with doped waveguides allowed one to create LD bars with efficiencies exceeding 70 % [31] and LD arrays with efficiencies exceeding 60 % [32].

Thus, our investigations of the influence of waveguide doping on the output characteristics of LD bars based on AlGaAs/GaAs heterostructures showed that the use of moderately doped waveguide layers [$(5-10)\times10^{16}$ cm^{-3}] allows one to implement the broadened waveguide advantages and to increase the output power of LD bars by 10 %–15 % with the other conditions being the same.

Acknowledgements. This work was partially supported by the Competitiveness Enhancement Programme of the National Research Nuclear University MEPhI (Grant No. 02.a03.21.0005).

References

1. Mawst L.J., Bhattacharya A., Lopez J., Botez D., Garbuzov D.Z., DeMarco L., Connolly J.C., Jansen M., Fang F., Nabiev R.F. *Appl. Phys. Lett.*, **69**, 1532 (1996).
2. Pikhtin N.A., Slipchenko S.O., Sokolova Z.N., Stankevich A.L., Vinokurov D.A., Tarasov I.S., Alferov Zh.I. *Electron. Lett.*, **40**, 1413 (2004).
3. Pietrzak A., Crump P., Wenzel H., Erbert G., Bugge F., Tränkle G. *IEEE J. Sel. Top. Quantum Electron.*, **17**, 1715 (2011).
4. Wenzel H., Crump P., Pietrzak A., Wang X., Erbert G., Tränkle G. *New J. Phys.*, **12**, 085007 (2010).
5. Piprek J., Li Z.-M. *IEEE Photonics Technol. Lett.*, **30**, 963 (2018).
6. Avrutin E.A., Ryvkin B.S. *J. Appl. Phys.*, **113**, 113108 (2013).
7. Crump P., Erbert G., Wenzel H., Frevert C., Schultz C.M., Hasler K.-H., Staske R., Sumpf B., Maaßdorf A., Bugge F., Knigge S., Tränkle G. *IEEE J. Sel. Top. Quantum Electron.*, **19**, 1501211 (2013).
8. Botez D., Mawst L.J., Bhattacharya A., Lopez J., Li J., Kuech T.F., Iakovlev V.P., Suruceanu G.I., Caliman A., Syrbu A.V. *Electron. Lett.*, **32**, 2012 (1996).
9. Marmalyuk A.A., Ladugin M.A., Andreev A.Yu., Telegin K.Yu., Yarotskaya I.V., Meshkov A.S., Konyaev V.P., Sapozhnikov S.M., Lebedeva E.I., Simakov V.A. *Quantum Electron.*, **43**, 895 (2013) [*Kvantovaya Elektron.*, **43**, 895 (2013)].
10. Ryvkin B.S., Avrutin E.A., Kostamovaara J.T. *J. Appl. Phys.*, **114**, 013104 (2013).
11. Ladugin M.A., Koval' Yu.P., Marmalyuk A.A., Petrovskii V.A., Bagaev T.A., Andreev A.Yu., Padalitsa A.A., Simakov V.A. *Quantum Electron.*, **43**, 407 (2013) [*Kvantovaya Elektron.*, **43**, 407 (2013)].
12. Crump P., Frevert C., Ginolas A., Knigge S., Maaßdorf A., Lotz J., Fassbender W., Neukum J., Körner J., Töpfer T., Pranovich A., Divoky M., Lucianetti A., Mocek T., Ertel K., De Vido M., Erbert G., Tränkle G. *IEEE Photonics Technol. Lett.*, **27**, 1663 (2015).
13. Kaul T., Erbert G., Maaßdorf A., Knigge S., Crump P. *Semicond. Sci. Technol.*, **33**, 035005 (2018).
14. Zhukov A.E., Gordeev N.Yu., Shernyakov Yu.M., Payusov A.S., Serin A.A., Kulagina M.M., Mintairov S.A., Kalyuzhnyi N.A., Maksimov M.V. *Semiconductors*, **52**, 1462 (2018) [*Fiz. Tekh. Poluprovodn.*, **52**, 1351 (2018)].
15. Bezotosnyi V.V., Kumykov Kh.Kh., Markova N.V. *Quantum Electron.*, **27**, 481 (1997) [*Kvantovaya Elektron.*, **24**, 495 (1997)].
16. Kanskar M., Goodnough T., Stiers E., Botez D., Mawst L.J. *Proc. ICALEO 2005* (Miami, USA, 2005) p. 401.
17. Zhao J., Li L., Wang W., Lu Y. *IEEE Photonics Technol. Lett.*, **15**, 1507 (2003).
18. Kanskar M., Earles T., Goodnough T.J., Stiers E., Botez D., Mawst L.J. *Electron. Lett.*, **41**, 245 (2005).
19. Kageyama N., Torii K., Morita T., Takauji M., Nagakura T., Maeda J., Miyajima H., Yoshida H. *IEEE J. Quantum Electron.*, **48**, 991 (2012).
20. Garrod T., Olson D., Klaus M., Zenner C., Galstad C., Mawst L., Botez D. *Appl. Phys. Lett.*, **105**, 071101 (2014).
21. Wade J.K., Mawst L.J., Botez D., Nabiev R.F., Jansen M., Morris J.A. *Appl. Phys. Lett.*, **72**, 4 (1998).
22. Knauer A., Erbert G., Staske R., Sumpf B., Wenzel H., Weyers M. *Semicond. Sci. Technol.*, **20**, 621 (2005).
23. Andreev A.Yu., Leshko A.Yu., Lyutetskii A.V., Marmalyuk A.A., Nalet T.A., Padalitsa A.A., Pikhtin N.A., Sabitov D.R., Simakov V.A., Slipchenko S.O., Khomylev M.A., Tarasov I.S. *Semiconductors*, **40**, 611 (2006) [*Fiz. Tekh. Poluprovodn.*, **40**, 628 (2006)].
24. Malag A., Dabrowska E., Teodorczyk M., Sobczak G., Kozłowska A., Kalbarczyk J. *IEEE J. Quantum Electron.*, **48**, 465 (2012).

25. Coldren L.A., Corzine S.W. *Diode Lasers and Photonic Integrated Circuits. Second Edition* (Hoboken: John Wiley & Sons, Inc., 2012).
26. Pikhtin N.A., Slipchenko S.O., Sokolova Z.N., Tarasov I.S. *Semiconductors*, **38**, 360 (2004) [*Fiz. Tekh. Poluprovodn.*, **38**, 374 (2004)].
27. Ryvkin B.S., Avrutin E.A. *J. Appl. Phys.*, **97**, 113106 (2005).
28. Fecioru A., Boohan N., Justice J., Gocalinska A., Pelucchi E., Gubbins M., Mooney M., Corbett B. *Semicond. Sci. Technol.*, **31**, 045002 (2016).
29. Bulashevich K.A., Mymrin V.F., Karpov S.Yu., Demidov D.M., Ter-Martirosyan A.L. *Semicond. Sci. Technol.*, **22**, 502 (2007).
30. Avrutin E.A., Ryvkin B.S., Payusov A.S., Serin A.A., Gordeev N.Y. *Semicond. Sci. Technol.*, **30**, 115007 (2015).
31. Ladugin M.A., Marmalyuk A.A., Padalitsa A.A., Bagaev T.A., Andreev A.Yu., Telegin K.Yu., Lobintsov A.V., Davydova E.I., Sapozhnikov S.M., Danilov A.I., Podkopaev A.V., Ivanova E.B., Simakov V.A. *Quantum Electron.*, **47**, 291 (2017) [*Kvantovaya Elektron.*, **47**, 291 (2017)].
32. Ladugin M.A., Marmalyuk A.A., Padalitsa A.A., Telegin K.Yu., Lobintsov A.V., Sapozhnikov S.M., Danilov A.I., Podkopaev A.V., Simakov V.A. *Quantum Electron.*, **47**, 693 (2017) [*Kvantovaya Elektron.*, **47**, 693 (2017)].