Quantum Electronics **48** (3) 197–200 (2018)

LASERS AND AMPLIFIERS

https://doi.org/10.1070/QEL16545

Effect of the waveguide layer thickness on output characteristics of semiconductor lasers with emission wavelength from 1500 to 1600 nm

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Abstract. **The effect of the waveguide layer thickness on output characteristics of AlGaInAs/InP quantum-well semiconductor lasers is analysed. The samples of semiconductor lasers with narrow and wide waveguides are experimentally fabricated. Their comparison is carried out and the advantages of particular constructions depending on the current pump are demonstrated.**

Keywords: *semiconductor laser, heterostructure, AlGaInAs/InP, output power.*

1. Introduction

The field of possible practical applications of semiconductor lasers with emission wavelengths from 1500 to 1600 nm is permanently expanding. Recently, alongside with low-power single-mode lasers for telecommunication applications, high-power semiconductor laser sources of this range have attracted particular interest. The present paper continues a series of papers by the authors, aimed at finding such heterostructure constructions that provide the fabrication of semiconductor lasers with predetermined characteristics. A traditional way to increase the output power of semiconductor lasers is to use heterostructures with broadened waveguides. This approach was successfully applied to the construction of laser sources with wavelengths in the range from 750 to 850 nm [1, 2], from 850 to 1050 nm [3, 4] and from 1300 to 1600 nm [5, 6]. Its main advantage consists in a reduction of intrinsic optical losses and, consequently, in an increase in the differential quantum efficiency of lasers, as well as in the lowering of the optical radiation density at the exit face of the laser cavity, which allows a higher power to be achieved without the output mirror damage. At the same time, a number of papers demonstrate potential advantages of using heterostructure lasers with narrow and ultra-narrow waveguides. These advantages include a decreased thermal and series electric resistance, reduced losses due to delocalisation of charge carriers transferred from the active region to the waveguide and, finally, the possibility of preserving the linearity of the light–current curve for higher pump currents and reducing its ‘thermal’ bend. The efficiency of this approach was demonstrated in the construction of semiconductor lasers emitting at the above wavelengths (Refs [7], [8], and [9], respectively).

A specific feature of lasers studied in the present papers that differentiates them from the sources of shorter-wavelength near-IR range is the increased intensity of the Auger recombination processes, which brings down the level of a maximal achievable output power and enhances the temperature sensitivity of the output characteristics. Here the search for the ways to increase the output power in such lasers was carried out with this feature taken into account.

Our goal was to determine the heterostructure construction most preferable for high-power semiconductor lasers with the emission wavelengths 1500–1600 nm.

2. Experiment

Laser AlGaInAs/InP separate-confinement quantum-well heterostructures were grown by MOVPE. The thickness of the waveguide layers amounted to 0.1 and 2.0 μm. The active region consisted of two strain compensated InGaAs quantum wells. The waveguide AlGaInAs layers with the active region were separated from the emitter InP layers by wide-band AlInAs barriers [6, 9]. The grown heterostructures were used to fabricate laser diodes (LDs) with a strip contact having a width of 100 μm and a cavity length of 1000–3000 μm. Antireflecting and reflecting coatings with reflection coefficients $R_1 \approx 0.05$ and $R_2 \approx 0.95$ were deposited on the cavity faces. The LDs were mounted on a copper heatsink; their output characteristics were studied both in the pulsed regime (a pulse duration of 100 ns and a repetition rate of 1 kHz) and in the cw regime at a heatsink temperature of 25 °C.

3. Results and discussion

Let us qualitatively compare the main parameters of AlGaInAs/InP quantum-well semiconductor lasers with narrow and wide waveguides as typical representatives of the above approaches to increasing the output power. We assume that the considered heterostructures are identical, except for the waveguide thickness.

The qualitative dependence of the threshold current density j on the waveguide thickness is presented in Fig. 1a. Its behaviour is mainly determined by the character of the dependence of the optical confinement factor in the active region on the same parameter [10]. It is seen that there is a range of waveguide thicknesses that provide the minimal values of the

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Received 20 October 2017; revision received 25 December 2017
Kvantovaya Elektronika **48** (3) 197–200 (2018)
Translated by V.L. Derbov

threshold current density, and the deviation of the thickness to either side leads to the growth of *j*. Therefore, the same threshold current density can be obtained using heterostructures with both narrow and wide waveguides.

For further analysis, we settle on this case and consider two heterostructure geometries providing the same threshold current density, but having a different thickness of waveguide layers (shown by a dashed line in Fig. 1a). Then the level of intrinsic optical losses in lasers with a wide waveguide will be lower [10], since the electromagnetic wave will less penetrate into the doped emitter layers and will be less scattered by free carriers (Fig. 1b). In this case, the widening of waveguide layers will lead to the growth of series electric resistance (Fig. 1c) and thermal resistance (Fig. 1d) of the laser heterostructure. This facilitates an increase in the heat release, worsens the heat removal from the active region and, consequently, increases the threshold current density and enhances the processes of Auger recombination and delocalisation of carriers in quantum wells [11]. At higher levels of the pump, part of carriers will leave the active region and fill the waveguide leading to the appearance of an additional source of intrinsic optical losses [12]. It is clear that a wide waveguide is capable of accumulating a greater number of such carriers with all other conditions being equal. Their number is naturally expected to grow with the width of the waveguide if the rate of arrival of carriers at the waveguide from the active region essentially exceeds the loss of carriers due to recombination processes and leakage into emitter layers [13].

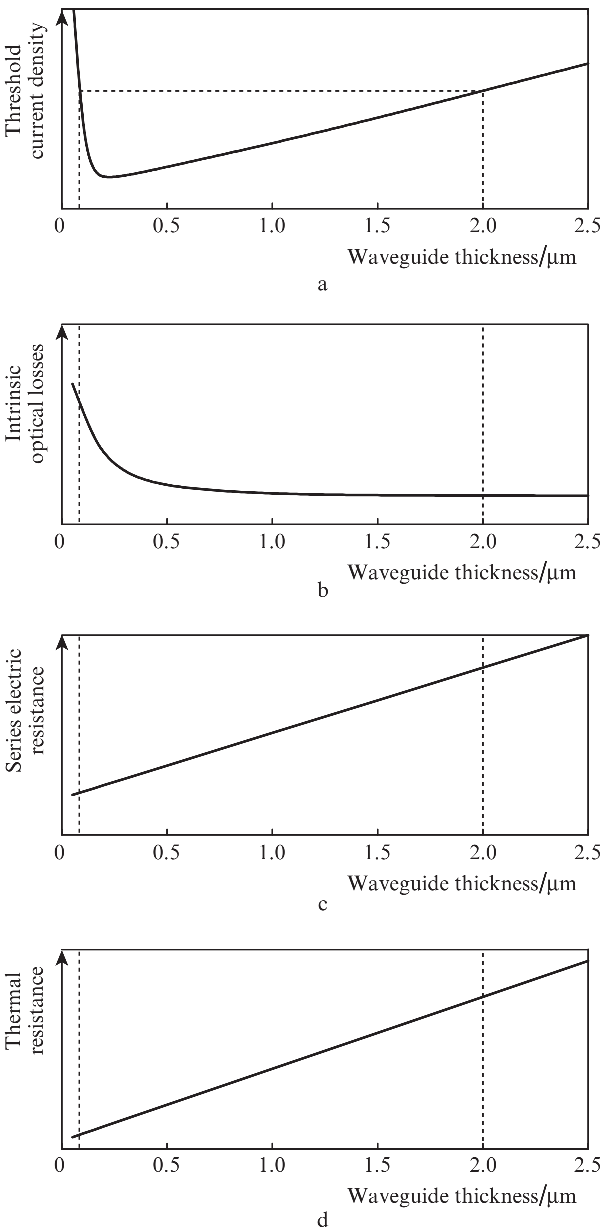

Figure 1. Dependences of the waveguide thickness on (a) the threshold current density, (b) intrinsic optical losses, (c) series electric resistance and (d) thermal resistance in the semiconductor laser.

In view of nonlinear processes, e.g., two-photon absorption, which can directly or indirectly affect the power characteristics of the laser [14], an ultra-narrow waveguide also has some advantages. The effect of two-photon absorption on the laser characteristics manifests itself mainly in the fact that the charge carriers, produced in the waveguide due to this absorption, increase the intrinsic optical losses caused by free carriers. In the case of a wide or strongly asymmetric waveguide, this effect manifests itself particularly strongly [13], since the generated carriers cannot be quickly localised in the active region because of the normal current flow. In an ultra-narrow waveguide, on the contrary, the optical intensity is maximally concentrated near the active region, so that the carriers generated by two-photon absorption are quickly localised in it, which leads to a significantly smaller growth of intrinsic optical losses.

Let us discuss the expected light–current curve for the considered case (Fig. 2). Both samples with wide and narrow waveguides will be characterised by similar values of the threshold current due to the choice of the appropriate waveguide width (Fig. 1a). At the initial stage in the laser with a wide waveguide the light–current curve (LCC) has a greater slope because of smaller intrinsic optical losses (Fig. 1b). Indeed, keeping in mind the similarity of the active region geometry of both heterostructures and the identical parameters of the cavities, we can assume the similarity of the quantum yield of the stimulated radiation and optical losses at the output. Then, with other conditions being equal, the LCC slope will be determined by the intrinsic optical losses that are smaller for the construction with a wide waveguide, which follows from the known expression for the dependence of the output power P of a semiconductor laser on the pump current I [15]:

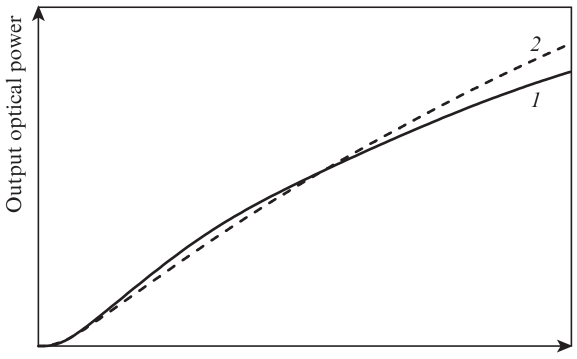

Figure 2. Qualitative view of light–current curves of a semiconductor laser with (*1*) wide and (*2*) narrow waveguides having the same threshold current.

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

where η_{int} is the internal quantum yield; α_{ext} is the output optical loss; α_{int} is the intrinsic optical loss; q is the electron charge; $h\nu$ is the photon energy; and I_{th} is the threshold current.

Thus, the lasers with a wide waveguide will demonstrate a higher output power at the same operating current. Veselov et al. [12] showed that in the considered geometry of AlGaInAs/InP heterostructures with a barrier between the waveguide and emitter layers, the growth of the pump current or temperature increases the rate of electron supply from the active region to the waveguide and, therefore, the concentration of electrons in the waveguide grows, too. This growth manifests itself in increased intrinsic optical losses and in the reduction of the LCC slope, according to Eqn (1). Moreover, this process is facilitated by an increased series resistance (Fig. 1c) and worse heat removal from the active region, inherent in heterostructures with a wide waveguide and leading to a rise of the active region temperature. Therefore, using the qualitative considerations, this effect of LCC slope reduction is expected to manifest itself stronger in the lasers with a wide waveguide. If the above assumptions are valid, then the light–current curves of the two compared lasers should have a crossing point. With a further increase in the operating current, the lasers with a narrow waveguide will demonstrate a higher output power (Fig. 2).

To check this hypothesis experimentally, we fabricated strip lasers based on the epitaxial AlGaInAs/InP heterostructures with narrow (0.1 μm) and wide (2 μm) waveguides. For the analysis, we chose the samples with similar parameters of the cavity. The measurements were carried out at room temperature of the heatsink.

The comparison of LCCs of the studied samples in the cw regime is presented in Fig. 3a. The shape of the curves qualitatively coincides with the results of the theoretical analysis shown in Fig. 2. Both samples had a threshold current of about 500 mA. The LCC slope at the initial part amounted to 0.5 W A^{-1} for the laser with a wide waveguide and 0.44 W A^{-1} for the laser with a narrow one. For a pump current of 6.8 A, the curves crossed. At this point the LCC slope for the laser with a wide waveguide visibly decreased and amounted to 0.40 W A^{-1}, while in the laser with a narrow waveguide the slope changed insignificantly (0.43 W A^{-1}). Naturally, under these conditions the laser with a narrow waveguide demonstrated a maximal output power of 3.8 W at a pump current of 13 A, and the laser with a wide waveguide achieved a level of 3 W only at a pump current of 11 A. The maximal power value was determined as the LCC saturation power. It is seen that if the required output power does not exceed 2–2.5 W, then it is preferable to use lasers with wide waveguides, and for the applications that require higher output powers it is reasonable to use lasers with narrow waveguides.

A similar situation was observed in the pulsed operation regime (100 ns, 1 kHz). Figure 3b shows the LCC of the studied samples in this regime. The laser with a narrow waveguide allows one to obtain a maximal output power of 16 W, and the laser with a wide waveguide – of only 10 W. Their LCCs have a crossing point at a pump current near 25 A. Since in the pulsed regime the overheating of the active region is not significant, the main mechanism of LCC saturation is, supposedly, the growth of intrinsic losses due to the expulsion of carriers into the waveguide [12]. As mentioned above, the wide waveguide is able to accumulate a greater number of expelled carriers and, therefore, to introduce higher intrinsic optical losses.

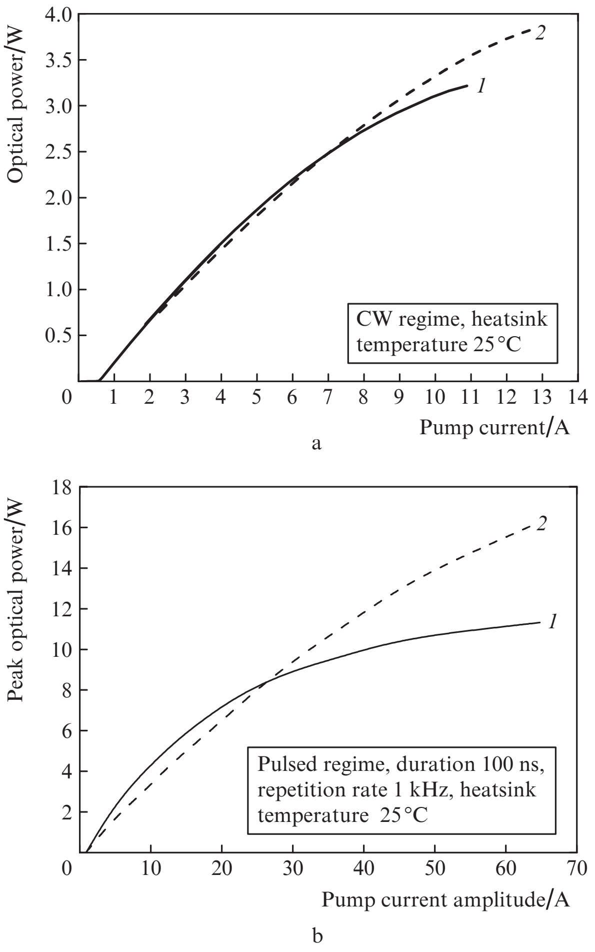

Figure 3. Experimentally measured light–current curves of semiconductor lasers based on the AlGaInAs/InP heterostructures with (*1*) wide and (*2*) narrow waveguides in (a) the cw and (b) pulsed (100 ns, 1 kHz) regimes.

Figure 4 demonstrates the results of experimental determination of the internal quantum yield and intrinsic optical losses in the samples under study. To this end, we studied the output characteristics of both types of lasers with a varying length of the cavity. It is seen that at the lasing threshold the heterostructures with a wide waveguide provide an expectedly smaller level of intrinsic optical losses (2.2 cm^{-1}) as compared to 3.5 cm^{-1} for the heterostructures with a narrow waveguide. Note that such a low level of intrinsic optical losses in the latter case was achieved due to gradient doping of the heterostructure emitter layers. In this case, the values of the internal quantum yield were close for all samples and exceeded 90%, reflecting the identity of the active region construction in the studied heterostructures.

The studied lasers demonstrated a high temperature sensitivity of the output characteristics. Thus, the characteristic temperature T_0 describing the temperature dependence of the threshold pump current varied in the range 45–50 K for the lasers with a wide waveguide and was somewhat lower then T_0 in the lasers with a narrow waveguide (60–65 K) [8]. This behaviour was also observed in the temperature dependence of the differential quantum efficiency. The characteristic temperature T_1 for the laser with a wide waveguide was from

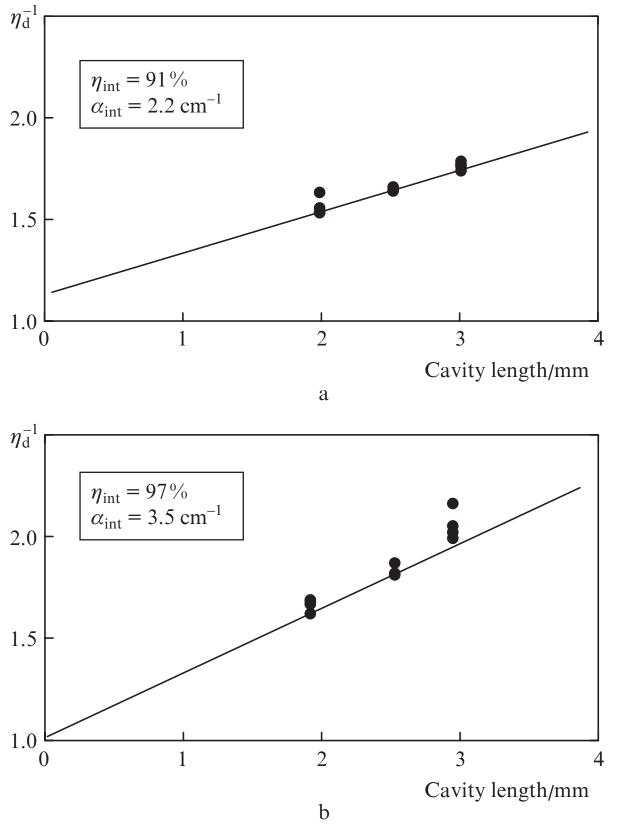

Figure 4. Inverse differential quantum efficiency η_d vs. cavity length of semiconductor lasers based on an AlGaInAs/InP heterostructure with (a) wide and (b) narrow waveguides.

120 to 140 K, and for the laser with a narrow waveguide it was from 180 to 200 K. These results provide an additional confirmation of a higher temperature sensitivity of the lasers with a wide waveguide and, consequently, faster saturation of their output power.

The final conclusion of this study is that under the conditions of the experiment, laser based on an AlGaInAs/InP heterostructure with a wide waveguide demonstrated more efficient operation at a relatively low excess of the pump current over the lasing threshold, while lasers with a narrow waveguide are preferable for achieving the maximum levels of the radiation power.

4. Conclusions

Thus, we compared theoretically and experimentally the light-current behaviour of the semiconductor lasers based on an AlGaInAs/InP heterostructure with narrow and wide waveguides, emitting at wavelengths from 1500 to 1600 nm. It is shown that lasers with a wide waveguide are characterised by a higher light–current slope at relatively small currents above the threshold, while lasers with a narrow waveguide support the light–current slope until higher pump currents and are preferable for achieving the limiting power characteristics.

Acknowledgements. The work was partially supported by the programme aimed at improving the competitiveness of the National Nuclear Research University ‘MEPhI’ (Agreement No. 02.a03.21.0005).

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