An asymmetric broad waveguide structure for a 0.98-μm high-conversion-efficiency diode laser

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Abstract: A novel asymmetric broad waveguide diode laser structure was designed for high power conversion efficiency (PCE). The internal quantum efficiency, the series resistance, and the thermal resistance were theoretically optimized. The series resistance and the thermal resistance were greatly decreased by optimizing the thickness of the P-waveguide and the P-cladding layers. The internal quantum efficiency was increased by introducing a novel strain-compensated $GaAs_{0.9}P_{0.1}$/InGaAs quantum well. Experimentally, a single 1-cm bar with 20% fill factor and 900 μm cavity length was mounted P-side down on a microchannel-cooled heatsink, and a peak PCE of 60% is obtained at 26.3-W continuous wave output power. The results prove that this novel asymmetric waveguide structure design is an efficient approach to improve the PCE.

Key words: asymmetric broad waveguide; high power conversion efficiency; strain-compensated quantum well
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1. Introduction

High power diode lasers emitting at 0.98 μm have been extensively used in many applications, such as pumping high power solid-state lasers and rare-earth-doped fiber amplifiers[1−3]. Present commercial diode lasers have power conversion efficiencies (PCE) of about 50% and need a self-contained cooling facility to deal with a large quantity of generated heat, which leads to a high cooling system cost and a low equipment mobility. Therefore, to achieve a high PCE level is intensively focused on both in research and in commercial fields.

Theoretical analysis shows that high internal quantum efficiency, low internal loss, low series resistance, and low thermal resistance lead to high PCE[4]. Symmetric broad waveguides[5−7] and asymmetric waveguide structures[8−10] are common means to reduce the internal loss, which could improve the PCE of diode lasers. Doing so, some good results have been achieved. But series resistance and thermal resistance optimizations, used in asymmetric broad waveguide structures to improve the PCE, were rarely focused on. In this paper, a novel asymmetric broad waveguide structure was designed by optimizing the thickness and the component of the P-waveguide and the P-cladding layers in order to reduce the series resistance and the thermal resistance. In addition, GaAs was substituted with $GaAs_{0.9}P_{0.1}$ to act as a quantum barrier in order to improve the internal quantum efficiency. Ideal experimental results were obtained by these means.

2. Theoretical design

Erbert *et al.*[4] gave a simplified expression for the power conversion efficiency η_c.

$$\eta_{c} = \frac{P_{op}}{U_{op}I_{op}} = \eta_{i}\frac{I_{op}-I_{th}}{I_{op}}\frac{\hbar\omega}{q(V_{d}+I_{op}R_{s})}\frac{\alpha_{m}}{\alpha_{m}+\alpha_{i}}, \quad (1)$$

where P_{op} is the optical power, I_{op} is the operating current, U_{op} is the operating voltage, R_s is the series resistance, I_{th} is the threshold current, V_d is the diffusion voltage, η_i is the internal quantum efficiency, α_m is the mirror loss, and α_i is the internal loss.

Equation (1) shows that the internal loss and the series resistance directly affect the PCE. Internal loss mainly occurs in the highly doped cladding layer as the internal loss coefficient is proportional to the carrier concentration[11]. Therefore, a broad waveguide structure is used to decrease the internal loss by reducing the optical mode overlap in the cladding layer. However, the thick P-waveguide layer will result in a high series resistance as it is a major portion of the series resistance in a broad waveguide structure[4]. A high thermal resistance can also be caused by the thick P-waveguide layer. At the same time, the thick P-waveguide layer absorbs more emitted light; this is even more serious at high operating currents, which causes overheating and leads to a low PCE and a poor reliability[12]. Based on the facts that the majority of the series resistance and optical loss lies on the P-side of a laser diode and excess heat is mainly dissipated through the P-side[8], an asymmetric broad waveguide laser structure was designed. Figure 1 shows the schematic conduction band diagram of the laser structure. Compared with conventional symmetric broad waveguide structures, the P-waveguide and P-cladding layers were thinned down, which has the following advantages: (1) a low series resistance by the thin P-waveguide layer; (2) a low thermal resistance that resolves the heat dissipation problem; (3) a low internal loss by reducing the optical

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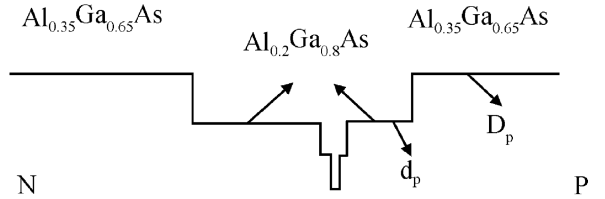

Fig. 1. Schematic conduction band diagram of the novel asymmetric waveguide structure, where d_P and D_P are the thicknesses of the P-waveguide layer and the P-cladding layer, respectively.

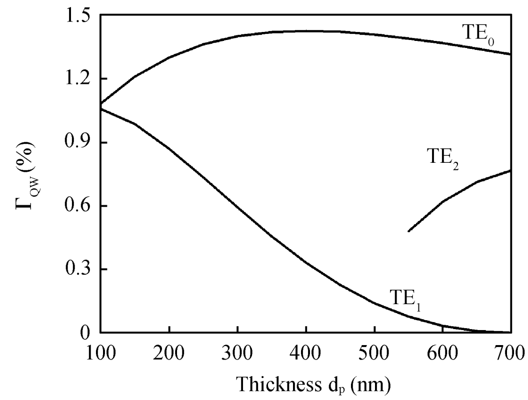

Fig. 2. Calculated optical confinement factor versus P-waveguide thickness d_P.

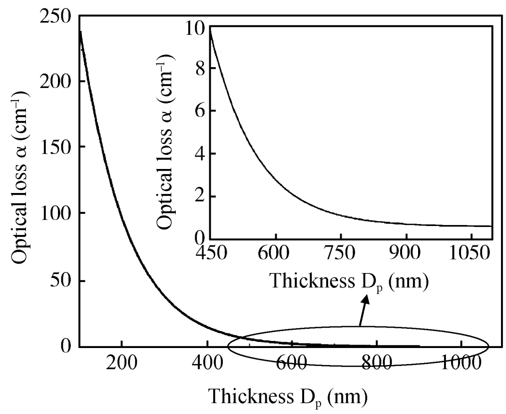

Fig. 3. Calculated optical loss versus P-cladding thickness D_P with d_P = 500 nm.

mode overlap on the P-side; (4) a low fundamental optical mode confinement Γ_{QW} in the QW and a high equivalent spot size d/Γ_{QW} (d is the thickness of the quantum well) improve the output power.

The P-waveguide thickness is an important factor for a PCE improvement. On one hand, a thin P-waveguide thickness makes the confinement factor in the highly doped P-cladding layers increase rapidly and causes a rapidly internal loss increase. However, on the other hand, a thick P-waveguide thickness causes a high series resistance as the carrier mobility in the P-side is much lower than that in the N-side. And the waveguide is usually not doped. As a result, the proper thickness of the P-waveguide can be obtained by optimization. As can be seen in Fig. 2, with an N-waveguide thickness of d_n = 700 nm, when the P-waveguide layer is thinner than 500 nm, the first order mode confinement factor Γ_{TE1} increases with decreasing P-waveguide thickness d_P. This leads to a mode competition between TE_0 and TE_1. When the P-waveguide layer is thicker than 500 nm, the second order mode can be activated and a mode competition occurs between TE_0 and TE_2. Both of the mode competitions cause a 'P–I' kink and reduce the external differential quantum efficiency. From the above analysis, a P-waveguide thickness of 500 nm is optimal.

The P-cladding layer thickness is another important factor for the PCE improvement, which is often neglected. In fact, the unnecessary thick cladding layer not only costs more wafer growth time and material consumption, but also leads to higher series resistance and thermal resistance, which finally results in the heat dissipation problem and a strong impact on both the PCE and the output power. On the other hand, a very thin cladding layer may cause a great internal loss[13, 14]. In order to find out the minimum required thickness of a P-cladding layer, the optical loss as a function of the P-cladding layer thickness D_p is calculated by the transfer matrix method[14, 15]. Figure 3 shows the calculated internal loss versus the P-cladding thickness D_p when d_p = 500 nm. As shown, when D_p < 800 nm, the internal loss α_i decreases rapidly as D_p increases. When D_p > 800 nm, α_i remains almost constant. So, the P-cladding layer thickness was set to 800 nm. In addition, in order to further reduce the electrical and thermal resistances, a low Al component ($Al_{0.35}Ga_{0.65}As$), different from the conventional high Al component[8, 16, 17], was adopted in the cladding layer.

To obtain a high internal quantum efficiency, a strain-compensated $GaAs_{0.9}P_{0.1}$ barrier was substituted for a conventional GaAs barrier[5]. Meanwhile, a 10-nm $In_{0.17}Ga_{0.83}As$ layer was used as the quantum well to ensure a lasing wavelength of 0.98 μm. This increased the conduction band offset from 0.1 to 0.15 eV and provided good carrier confinement. In addition, the tensile strain barrier layer compensated the compression strain of the quantum well, which was favorable for decreasing the material defect concentration and the non-radiation recombination. Finally, their growth conditions were similar; so, it was easy to obtain a high quality laser material.

As mentioned above, epitaxial layers with asymmetric broad waveguide could be finally set as follows: 1000 nm highly doped N-$Al_{0.35}Ga_{0.65}As$ (N = 2 × 10^{18} cm^{-3}), 800 nm P-$Al_{0.35}Ga_{0.65}As$ (P = 2 × 10^{18} cm^{-3}) cladding layers, undoped 700 nm $Al_{0.2}Ga_{0.8}As$ N-waveguide, and 500 nm $Al_{0.2}Ga_{0.8}As$ P-waveguide layers. The 10 nm $In_{0.17}Ga_{0.83}As$ quantum well was sandwiched between 10 nm $GaAs_{0.9}P_{0.1}$ barriers. The schematic refractive index diagram and the fundamental mode distribution are shown in Fig. 4.

3. Device fabrication

The laser wafer was grown by low-pressure metalorganic chemical vapor deposition (LP-MOCVD) on a GaAs substrate. The source materials were trimethylgallium (TMGa), trimethylindium (TMIn), trimethylaluminum (TMAl), tributyl-phosphate (TBP), and 100% arsine. Diehylzinc (DEZn) was used as the P-type dopant and silane as the N-type dopant. The wafer was processed in standard procedures. A broad con-

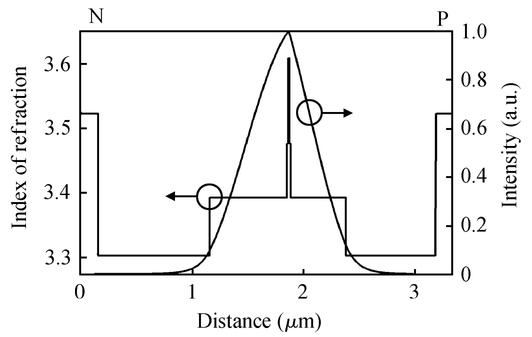

Fig. 4. Schematic diagram of the refraction index and the optical intensity profile of the asymmetric waveguide structure laser.

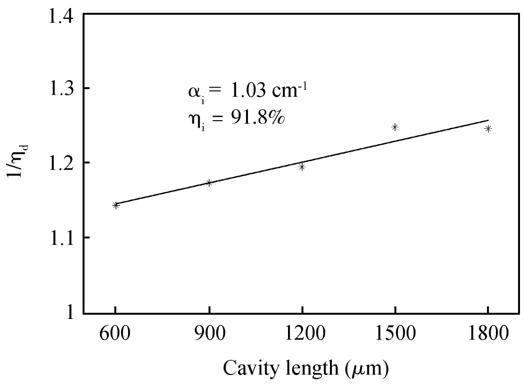

Fig. 5. Calculated reverse differential quantum efficiency versus the cavity length, $\alpha_{\rm i}$ is the internal loss and $\eta_{\rm i}$ is the internal quantum efficiency.

tact stripe was formed by wet-chemical etching through the P^+-GaAs cap layer outside the stripe, in order to prevent current spreading. SiO_2 was deposited as the insulating layer. After deposition of Ti/Pt/Au as the P-electrode, the wafer was thinned, and AuGeNi/Au was deposited as the N-electrode. Then, the wafer was cleaved into laser bars of different cavity length. Some laser bars were used to fabricate single emitters and the electro-optical parameters, such as the differential external efficiency $\eta_{\rm d}$, were tested; the other lasers were coated (5%/95%) and mounted P-side down on copper microchannel-cooled heatsinks.

4. Laser performance

The internal loss $\alpha_{\rm i}$ and the internal quantum efficiency $\eta_{\rm i}$ are very important parameters for high PCE lasers. They were calculated by the standard method of measuring low duty-cycle pulsed-current (50 μs 200 Hz) differential external efficiency $\eta_{\rm d}$ for a series of cavity lengths. The dependence of the differential external efficiency on the cavity length L is shown in Fig. 5. In the figure, the internal loss 1.03 cm^{-1} agrees approximately with the theoretical calculated result of 0.89 cm^{-1}. The low internal loss and the high internal quantum efficiency 91.8% provide a high external differential quantum efficiency.

Figure 6 shows the PCE, the output power, and the operating voltage of the operating current with a cavity length of 900 μm at a heatsink temperature of 283 K. The peak PCE is

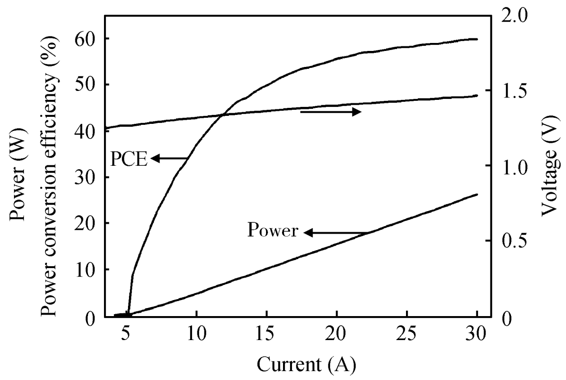

Fig. 6. Power conversion efficiency, output power, and forward voltage versus current for a 900 μm cavity length at 283 K.

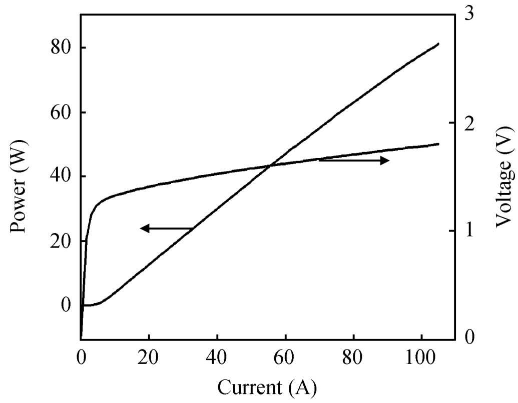

Fig. 7. Output power and forward voltage versus current for a 900 μm cavity length at 283 K.

60.0% at 30.0 A, with a corresponding optical power of 26.3 W under a continuous wave (CW) conduction and an external differential quantum efficiency of 1.07 W/A. The operating voltage is only 1.47 V as a result of the lower series resistance of 5.3 mΩ.

The CW output power of a diode laser was limited by either thermal rollover or catastrophic optical mirror damage (COMD). Figure 7 shows the output power and the operating voltage of the operating current with a cavity length of 900 nm at a 20% fill factor. As shown in Fig. 7, when the output power is as high as 81.1 W at an operating current of 105.0 A and the corresponding operating voltage is 1.80 V, no thermal roll or COMD is found. A high PCE and a low thermal resistance (around 0.3 K/W) help the laser diode to avoid thermal roll. Meanwhile, adopting an asymmetric broad waveguide reduces the optical density at the cavity facet and, therefore, avoids COMD.

Considering all the possible factors affecting the PCE, the following comparison between diode lasers with P-waveguide thicknesses of 700 nm and 500 nm reveals the main influencing aspects. Diode lasers with a 700-nm asymmetric broad P-waveguide thickness have a lower internal loss of 0.8 cm^{-1}, compared with 1.03 cm^{-1} of those lasers with a 500-nm P-waveguide thickness. Although the internal loss decreases, the series resistance increases from 5.3 to 7.2 mΩ, and the threshold current also increases. All these reasons cause the PCE of diode lasers with a 700-nm thick P-waveguide layer to decrease from 60% to 58%. In addition, the high thermal resistance of the diode lasers with a 700-nm thick P-waveguide layer also causes the maximum output power to decrease.

5. Summary

In summary, a 980-nm asymmetric broad waveguide structure diode laser is theoretically designed and analyzed . The optimization of key structural parameters, such as the series resistance, the internal quantum efficiency, and the thermal resistances, helps to improve the peak PCE to 60.0% at an output power of 26.3 W. Such a high PCE and such a low thermal resistance help the laser diode to achieve an output power as high as 81.1 W. The calculated and experimental results indicate that the asymmetric waveguide structure is an efficient way of improving the laser PCE and the output power. Further improvement of the PCE can be achieved by optimizing the cavity length and the doping concentration distribution in the broad waveguide layer.

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