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High power, high efficiency continuous-wave 808 nm laser diode arrays



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ABSTRACT

The continuous-wave 100 W-class 808 nm laser diode arrays with extremely high power conversion efficiency of 68% were reported at the heatsink temperature of 25 °C. To the best of our knowledge, this was the highest power conversion efficiency at continuous-wave 106 W 808 nm laser diode array with 50% fill factor so far. An asymmetric broad waveguide epitaxial structure with very low internal optical loss of 0.5 cm^{-1} was presented. In order to improve the efficiency, various fill factor devices were studied. The 50 W laser diode array with 30% fill factor and 1.0 mm cavity length demonstrated power conversion efficiency of 71% at heatsink temperature of 15 °C.

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1. Introduction

High-power and high-efficiency 808 nm laser diode arrays (LDAs) as ideal pumping source for solid-state lasers were widely used in industrial, scientific, medical, biological applications and so on. Diode-pumped solid-state (DPSS) system with high-efficiency LDAs had many advantages such as compact volume, lower weight and energy savings [1]. Recently, high-efficiency continuous-wave (CW) 808 nm LDAs were reported in many literatures [2]. To develop next generation 808 nm laser diode pumping sources with high power, high efficiency and long lifetime are crucial [3]. For GaAs-based laser diodes, the emission wavelengths from 915 nm to 980 nm were proved to easily achieve the highest power conversion efficiency (PCE). To date, the highest PCE about 76% was reported for 976 nm under CW operation at 100 W [4], whereas the highest PCE of 808 nm diode laser array was only 65% at room temperature so far [5]. The 808 nm LDAs usually have lower PCE (commercial products about 50–55%) mainly due to the large optical absorption loss of GaAs-based epitaxial materials.

In order to reduce p-type waveguide and cladding optical absorption loss, an extreme, double asymmetric (EDAS) large optical cavity structure was designed and experimented with reference devices [6]. The maximum PCE of single emitter with emission wavelength of 910 nm was about 62% with EDAS designs. High-efficiency 50 W CW TE/TM polarized 808 nm diode laser bar at Lasertel was reported [7], the PCE of 64% at heat-sink with the temperature of 25 °C was achieved. The JENOPTIK Diode Lab reported

the 808 nm diode laser bar of 1.5 mm cavity length with the fill factor of 20% and the wall plug efficiency of 65% [5]. AlGaAs-based lasers by MBE growth were demonstrated with low internal loss of 0.75 cm^{-1} and high efficiency of 65.5% for 808 nm single emitter at room temperature was achieved [8]. AlGaAs-based materials had better thermal conductivity and electrical conductivity and Aluminum composition could be varied easily to control the light absorption loss, thermal resistance, series resistance, operating voltage and so on. It was obviously that AlGaAs-based materials were better choice for both P-type and N-type waveguide, cladding layers with lower electrical resistance, lower thermal resistance and lower optical absorption loss. In this paper, an asymmetric broad waveguide epitaxial structure was developed so as to achieve the high power and high efficiency. Meanwhile, wall-plug efficiencies under different heatsink temperature were characterized.

2. Theoretical design and fabrication of high efficiency device

The electrical to optical conversion efficiency η_c , also called wall-plug efficiency was empirically expressed as:

$$\eta_c = \eta_i \frac{h\nu}{q} \frac{I - I_{th}}{I(V_d + IR_s)} \frac{\alpha_m}{\alpha_i + \alpha_m} \quad (1)$$

where η_i was the internal quantum efficiency, I_{th} was the threshold current, V_d was the diffusion voltage, R_s was the series resistance, α_m was the mirror loss, α_i was the internal loss, $h\nu$ was the photon energy, q was the electron charge. In order to achieve the maximum conversion efficiency η_c , the following requirements must be achieved [9]: (a) high internal quantum efficiency by reducing the

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Table 1
Optimized material and doping for epitaxial structure.

Description	Material	Thickness (μm)	Doping (cm^{-3})
P-clap	GaAs	0.2	C, 1×10^{19}
P-cladding	$\text{Al}_{0.55}\text{Ga}_{0.35}\text{As}$	0.8	C, 2×10^{18}
P-waveguide	$\text{Al}_{0.35}\text{Ga}_{0.65}\text{As}$	0.3	None
Active region	InAlGaAs/AlGaAs	0.007	None
N-waveguide	$\text{Al}_{0.35}\text{Ga}_{0.65}\text{As}$	0.5	None
N-cladding	$\text{Al}_{0.55}\text{Ga}_{0.35}\text{As}$	1	Si, 4×10^{17}
N-buffer	GaAs	2	Si, 2×10^{18}

carrier leakage and increasing the electron injection efficiency, (b) low the operating voltage as to minimize the voltage drop, (c) low series resistance of device, (d) low internal loss including free-carrier absorption loss, scattering loss with defects and rough interfaces, (e) low threshold current. In this work, optimized the epitaxial structure and improved fabrication process were both used to achieve the goals above.

The high-efficiency epitaxial structure was optimized including the thickness, doping and composition for each of the layer structure, as shown in Table 1. In this structure, the buffer laser of $2 \mu\text{m}$ n-GaAs with doping concentration of $2 \times 10^{18} \text{ cm}^{-3}$ was grown on the n-doped GaAs substrate. The $1 \mu\text{m}$ n-cladding $\text{Al}_{0.55}\text{Ga}_{0.35}\text{As}$ with doping of $4 \times 10^{17} \text{ cm}^{-3}$ and $0.8 \mu\text{m}$ p-cladding $\text{Al}_{0.55}\text{Ga}_{0.35}\text{As}$ with doping of $2 \times 10^{18} \text{ cm}^{-3}$ were both optimized in order to reduce the optical absorption loss. The $0.3 \mu\text{m}$ undoped $\text{Al}_{0.35}\text{Ga}_{0.65}\text{As}$ and $0.5 \mu\text{m}$ undoped $\text{Al}_{0.35}\text{Ga}_{0.65}\text{As}$ were employed as P- and N-waveguide, respectively. The compressive strained InGaAlAs/AlGaAs active region was optimized on the strain and thickness. The 7 nm single quantum well was the best choice with the highest gain and efficiency in order to achieve high power and high efficiency. The barriers of $\text{Al}_{0.25}\text{Ga}_{0.75}\text{As}$ were well optimized to reduce the carrier leakage from active region and increase the electron injection efficiency. The so-called voltage defect was also minimized by designing several gradient interface layers and the doping distribution.

The design of the epitaxial layer structure should be optimized to minimize the internal loss, which results in a high differential quantum efficiency and a low threshold current. The optical loss of each region in the vertical structure was reduced by the electrons concentration, holes concentration, and optical confinement factor base on the expression of $\alpha_i = \Gamma(\sigma_n n + \sigma_p p)$. Total loss

includes two parts in a laser diode: the internal loss and the mirror loss. The internal loss includes the absorption of the free carriers and the photon scattering loss on free carriers, defects and rough interfaces, as shown in following empirical expressions [10,11,12],

$$\alpha_i = \Sigma \alpha_j + \alpha_{\text{scat}} \quad (2)$$

$$\alpha_j = \Gamma_j \alpha_j^l \quad (3)$$

$$\Sigma \Gamma_j = 1 \quad (4)$$

$$\alpha_j^l = \sigma_n n_j + \sigma_p p_j \quad (5)$$

where α_i is the internal loss of a laser diode, α_j is the internal optical loss for the j th layer, Γ_j is the optical confinement factor in the j th layer; α_j^l , the internal optical loss coefficient for the j th layer, σ_n and σ_p are the absorption coefficients of electron and hole on free carriers, respectively, n_j and p_j are the carrier concentrations in the j th layer of electron and hole, respectively.

The total internal loss of the optimized wafer structure was about 0.5 cm^{-1} from the simulation results, and the optical confinement factor of active layer is 1.24% . The optical absorption of the active layer is calculated to be 0.18 cm^{-1} . Due to the relationship of $\sigma_p > \sigma_n$ [13], a novel asymmetric broad waveguide structure was developed by optimizing the waveguide thickness, doping level and composition for P-waveguide and P-cladding layers so as to reduce the carrier absorption loss and operating voltage. The result is shown in Fig. 1. The loss of P-waveguide and P-cladding is around 0.15 cm^{-1} which is a little larger than the loss of N-waveguide around 0.12 cm^{-1} . Meanwhile, the optical field extends into P-cladding layer, resulting in the loss of 0.02 cm^{-1} in this layer.

The wafer was grown by metal organic chemical vapor deposition (MOCVD) on the N-GaAs substrate. The optimized growth conditions and substrates orientation were extensively studied to improve the crystal quality and to reduce the internal loss and defects. The wafer was processed using standard procedures. The strip was fabricated by wet-chemical etching through the P-doping GaAs cap layer and partial p-cladding layer. SiN_x was deposited as the insulating layer. After deposition of Ti/Pt/Au as the P-electrode, the wafer was thinned to about $120 \mu\text{m}$, and AuGeNi/Au was deposited as the N-electrode. After annealing,

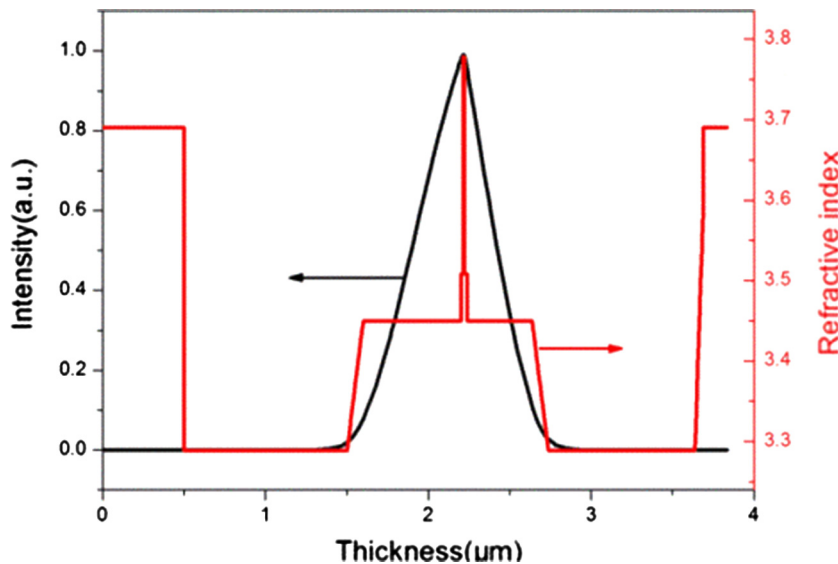


Fig. 1. Optical field and refractive index for asymmetric broad waveguide epitaxial structure.

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