High Power High Beam Quality 1060-nm Large Optical Cavity Asymmetric Waveguide Semiconductor Laser Diode

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Abstract High power high beam quality 1060-nm InGaAs/GaAs quantum well (QW) semiconductor laser diode with an asymmetric large optical cavity (LOC) is designed and fabricated. The laser diode consists of compressively strained double InGaAs/GaAs quantum wells and a GaAs/AlGaAs separate confinement structure. To improve the high power performance, the transversal optical cavity is optimized to have low fast axis far-field divergence angle, large optical spot size and low facet optical density, low internal optical absorption loss and high internal quantum efficiency. By employing a weak optical confinement $Al_{0.1}Ga_{0.9}As$ waveguide with thickness of 4 μm, a low transversal far-field divergence angle of 20° and large optical spot size near 1 μm are obtained. By detuning the QW position, the asymmetric waveguide with thinner p-side waveguide enables the laser diode high internal quantum efficiency even in high current injection level. Based on the optimization, 1.3 W continue wave optical power is achieved for broad area lasers with cavity length and strip width of 2 mm and 50 μm, respectively. For single spatial mode ridge waveguide laser diodes with same cavity length, 600 mW continue wave optical power is obtained at 10 ℃.

Key words lasers; optical design; high power; waveguide
OCIS codes 140.5960; 230.7370; 230.0230

大功率高光束质量 1060 nm 大光腔非对称波导半导体激光二极管

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摘要 设计并制备了大功率高光束质量的 1060 nm 波长的非对称波导半导体激光二极管. 本激光二极管包含压应变 InGaAs/GaAs 双量子阱和 GaAs/AlGaAs 分别限制结构。为提高激光二极管的大功率性能,设计激光器二极管的垂直结构具有小快轴远场发散角,大光斑面积及低腔面光能密度,低光腔内吸收损耗和高内量子效率等性能。通过引入 4 μm 厚弱光限制 $Al_{0.1}Ga_{0.9}As$ 波导,激光器二极管的远场发散角降到 20°,光斑宽度增到接近 1 μm。量子阱位置偏调后得到的薄上波导层非对称波导结构可以使激光二极管即使在大电流注入时也能保持高的内量子效率。根据以上设计,分别制备了 50 μm 宽条和窄条脊波导激光二极管。2 mm 腔长的宽条激光二极管得到 1.3 W连续光功率。单模脊波导激光器的直流光功率为 600 mW。

关键词 激光器; 光学设计; 大功率; 光波导
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1 Introduction

1060-nm high power semiconductor laser diodes have many important applications in the fields of communication, spectroscopy, frequency conversion and pumping solid and fiber lasers for their advantages, such as high efficiency,

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compact size, low cost and high reliability. These applications require semiconductor laser diodes who can provide relatively high power[1].

Many efforts are done in this field to increase the output power of semiconductor laser diodes[2-5]. Among these efforts, internal loss, internal quantum efficiency, optical mode size and far field angle are the key points to study. The optimizations are focused on designing a proper kind of vertical waveguide. One promising approach is expanding the thickness of optical waveguide beside the active layer to form a large optical cavity (LOC) waveguide[4-5]. With this LOC waveguide, more optical power is confined in the waveguide layer and less is spread in the doped cladding layers. Although in this approach, many optical modes are supported in the waveguide. The problem can be dealt with properly designing of the cladding layer and quantum well (QW) position. While for further reduce the internal loss, far field divergence angle, weak optical confinement waveguide should be used. In this case, the free carriers confine effect is weaken. The injected electrons escape from the QW region where they should locate to the p-side waveguide, which results in high leak current and low internal quantum efficiency[6-7]. This situation is more severe in narrow stripe waveguide laser diode and at high injection level.

The mechanism of internal quantum efficiency reduction is investigated. A high power high beam quality 1060-nm InGaAs/GaAs quantum well semiconductor laser diode with an asymmetric LOC is designed and fabricated. To improve the overall high power performance, the transversal optical cavity is optimized to have low fast axis far-field divergence angle, large optical spot size and low facet optical density, low internal optical absorption loss and especially for high internal quantum efficiency. By detuning the QW position, the asymmetric waveguide with thinner p-side waveguide enables the laser diode high internal quantum efficiency even in high current injection level. Based on the optimization, broad area and narrow stripe waveguide laser diodes are fabricated. 1.3 W continue wave optical power is achieved for broad area lasers with cavity length and strip width of 2 mm and 50 μm, respectively. For single spatial mode ridge waveguide laser diodes with same cavity length, 600 mW continue wave optical power is obtained at 10 ℃。

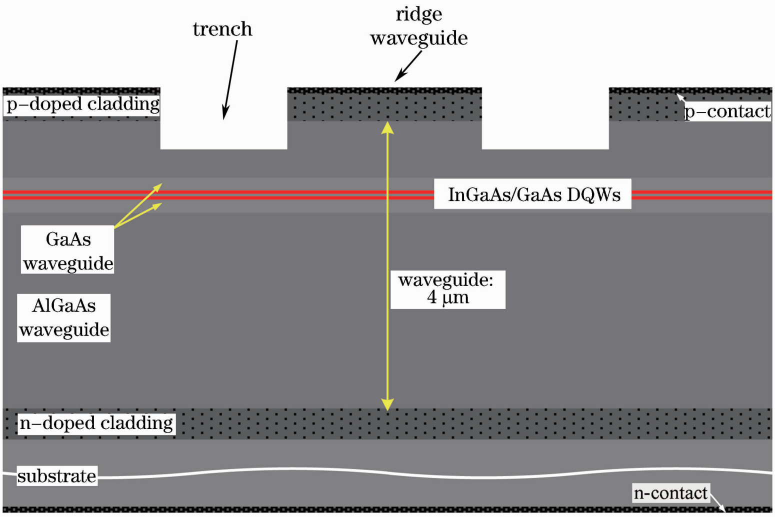

Fig. 1 Schematic cross-sectional view of laser diode with LOC

2 Structure design

The asymmetric super large optical cavity ridge waveguide laser diode structure is shown in Fig. 1. The transversal structure of the laser diode consistes of double InGaAs/GaAs QW with gain wavelength around 1.06 μm, AlGaAs waveguide layers, cladding layers and contact layers. $Al_{0.1}Ga_{0.9}As$ material is employed as the waveguide layer. Figure 2 shows the dependence of fundamental mode full width at half maximum (FWHM) farfield angle and effective optical spot size on the vertical waveguide thickness. To achieve a low farfield divergence angle of 20° and an effective spot size near 1 μm, the thickness of the vertical waveguide thickness of 4 μm is used. In such large waveguide up to 7 optical modes can be supported. By optimizing the n-AlGaAs cladding layer, higher order mode is suppressed by introducing leaky loss to the GaAs substrate and single mode operation is obtained.

Diode structure with weak optical confinement waveguide, the free carrier confinement changes in various operation conditions. In the case of low forward current injection when the laser diode operates near threshold

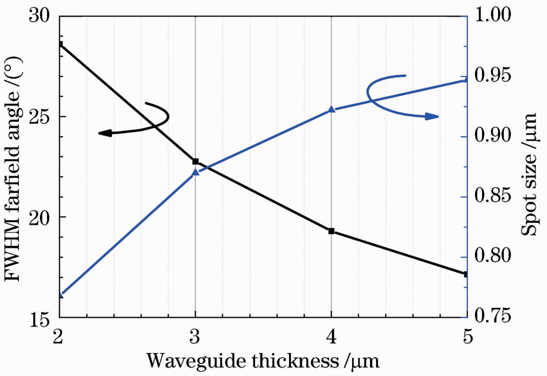

Fig. 2 Dependence of FWHM farfield angle and spot size on waveguide thickness

condition, the energy band of waveguide and QW layer is flat based flat band theory. The injected electron and hole at concentrated at the QW layer and recombined. The concentration of carriers in QW is clapped. While at high injection level the situation changes. For small hole mobility, the p-side waveguide energy band is curved and conductive band drops and electron escapes from QW layers to p-side waveguide and be accumulated. This effect reduces the free carrier recombination in the QW layer and increase the recombination in the p-side waveguide layer, which have no contribution on lasing. As a result, the internal efficiency and slope efficiency of the laser device drops off. The situation is more severe in large optical cavity laser diode with narrow ridge waveguide at high injection level.

This problem is dealt with reducing the p-side waveguide layer thickness and maintaining the total waveguide thickness of 4 μm. By this method the p-side waveguide energy band bending effect is suppressed and the electron escape from QW and accumulation at the p-side waveguide layer is reduced, thus it maintains high internal quantum efficiency at high injection level.

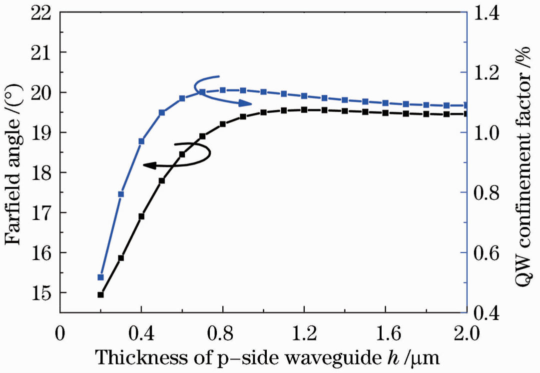

Fig. 3 Dependence of farfield angle and QW confinement factor on QW position

When changing QW position, the QW optical confinement is affected. Figure 3 shows the effect of QW position on the farfield angle and QW confinement factor. By reducing the thickness of p-side waveguide from 2 μm to 0.8 μm, the farfield angle and fundamental mode QW confinement factor experience slight change. While further reducing thickness of p-side waveguide, the QW confinement factor drops dramatically, which affects the lasing threshold current. As a tradeoff between carrier confinement and QW optical confinement, the optimized p-side waveguide thickness is 0.8 μm.

3 Laser diodes fabrication and characterization

The material growth and device fabrication procedure is developed from our previous report[8-9]. The epitaxial layers of the laser diode are grown by low pressure metal organic chemical vapor deposition (LP-MOCVD) in one step. The epitaxial process starts from the growth of n-GaAs buffer to n-$Al_{0.26}Ga_{0.74}As$ cladding layer, $Al_{0.1}Ga_{0.9}As$ waveguide layer, GaAs spacer, $In_{0.21}Ga_{0.79}As$/GaAs DQWs, symmetric GaAs spacer and $Al_{0.1}Ga_{0.9}As$ waveguide layer, the p-$Al_{0.26}Ga_{0.74}As$ cladding layer and then p^+-GaAs contact layer. The n- and p-cladding layer is Si and C doped, respectively.

The lateral optical confinement is provided by a dry etched strip which is realized by inductively coupled plasma

(ICP) reactor. The etching is stop in the $Al_{0.1}Ga_{0.9}As$ waveguide layer with a residual waveguide thickness of 0.4 μm. The resulted effective refractive index difference is between 0.003 and 0.004. The width of ridge waveguide and trench is 6.5 μm and 8.5 μm, respectively. For broad area laser diode the ridge width is 50 μm.

TiAu is performed after SiO_2 insulation layer is opened on the top of the ridge waveguide. Finally, the wafer is lapped to 100 μm and backside ohmic contact is made by AuGeNi/Au metallization after backside polishing. Broad area and ridge waveguide laser diode bars are cleaved。 For continue wave (CW) measurements, the lasers are coated at front and rare facets, with reflectivities of 5% and 95%, respectively. Laser diodes are soldered p-side up on Cu submounts and attached to a copper heatsink.

Figure 4 shows the measured inverse differential quantum well efficiency ($1/\eta_d$) as a function of cavity length. Linear fitting of the measured data indicates the internal loss of the waveguide is low as 0.8 cm^{-1} with an internal quantum well efficiency of 76%. The measured results match well with the design ones taking experimental deviation into consideration.

CW power-current (*P-I*) performance of the broad area laser with cavity length of 2000 μm is investigated at 10 ℃, as shown in Fig. 5. From the *P-I* curve, the threshold current is 200 mA and front facet slope efficiency above threshold current is 0.79 W/A and the total output power of 1.3 W is obtained which is limited by test equipment.

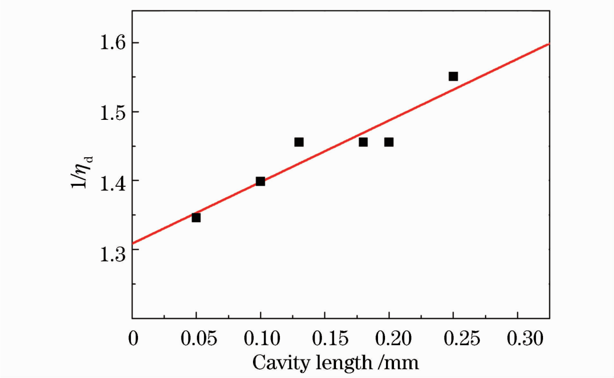

Fig. 4 Inverse external differential quantum efficiency $1/\eta_d$ as a function of cavity length

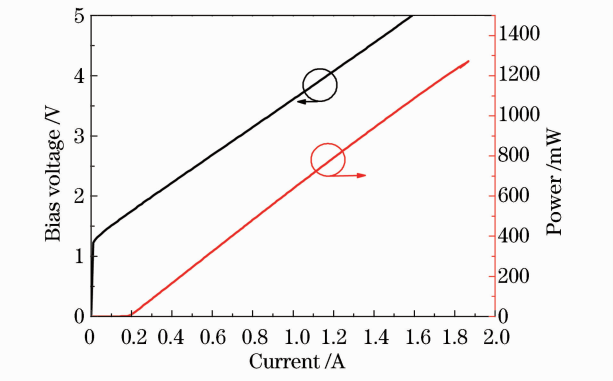

Fig. 5 CW *P-I* characteristics of broad area laser at 10 ℃

Figure 6 shows the *P-I* property of ridge waveguide lasers with cavity length of 2000 μm at 10 ℃. The threshold current is less than 60 mA and slope efficiency above threshold condition of higher than 0.62 W/A is obtained. The single mode operation current is up to 1200 mA and the single mode output power is up to 600 mW. The single lobe farfield profile in the vertical direction indicated that there is no higher order transversal mode excited. The full width half magnitude angles are 20° and 8° in the vertical and lateral direction, respectively.

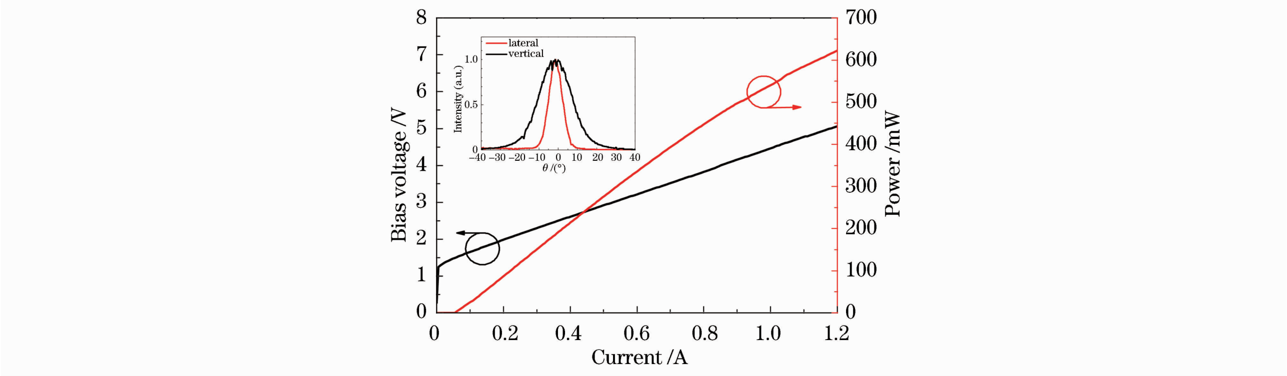

Fig. 6 CW *P-I* characteristics of broad area laser at 10 ℃, insert shows the farfield angle at 1.2 A injection

4 Conclusion

High power high beam quality 1060-nm InGaAs/GaAs quantum well semiconductor laser diode with an asymmetric large optical cavity is designed and fabricated. To improve the high power performance, the transversal optical cavity is optimized. By employing a weak optical confinement $Al_{0.1}Ga_{0.9}As$ waveguide with thickness of 4 μm, laser diode

with a low transversal far-field divergence angle of 20°, low internal loss of 0.8 cm^{-1} is obtained. By detuning the QW position, the asymmetric waveguide laser diodes with 0.8 μm p-side waveguide have high internal efficiency of 0.76. 1.3 W continues wave optical power is achieved for broad area lasers with cavity length and strip width of 2 mm and 50 μm, respectively. For single spatial mode ridge waveguide laser diodes with the same cavity length, 600 mW continue wave optical power is obtained at 10 ℃. Further optimizations of the high power laser diode will be focused on the concentration of upper waveguide layer and cladding layer.

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