Tunnel regenerated coupled multi-active-region large optical cavity laser with high quality beam*

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A novel coupled multi-active-region large optical cavity structure cascaded by tunnel junction is proposed to solve the problems of catastrophic optical damage (COD) of facet and large vertical divergence caused by the thin emitting area in the conventional laser diode. For the laser with three active regions, a slope efficiency as high as 1.49 W/A, a vertical divergence angle of 17.4°, and a threshold current density of 271 A/cm^2 are achieved. By optimizing the structure parameters, the beam quality is greatly improved, and the level of COD power increases more than two times compared with that of the conventional laser.

Keywords: large cavity, vertical divergence angle, catastrophic optical damage, beam quality

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1. Introduction

The conventional edge laser with fundamental transversal mode typically has a large transverse beam divergence ranging from 40° to 60°. Reducing beam divergence angle not only improves the light collection efficiency of the lense, but also relaxes the requirement for aberration correction. The vertical divergence angle is the fast Fourier transform (FFT) result of the near field pattern. So the near field distribution size has a direct effect on the size of the vertical angle. The beam divergence can be reduced by reducing the source size when it is below a certain value.[1,2] And it can also be reduced by increasing the light spot size using waveguides with smaller refractive index steps or thinner active layers.[3,4] However, these methods are limited either by the increase of unacceptable threshold current density or by the onset of higher-order modes and more serious catastrophe of optical damage (COD).

In this paper, a cascaded multi-active region novel structure device is designed and fabricated. The experimental results show that the new structure can effectively reduce both the light power density and the vertical beam divergence. Furthermore, this structure also shows the other advantages, including a low threshold current density and a high slope efficiency. Based on a careful design, the active regions and the tunnel junction can be wholly coupled into a large optical cavity, therefore, a single transverse mode operation can be realized.

2. Physical principle and structure design

The structure of the novel semiconductor laser is based on the cascaded several usual active regions by tunnel junctions (TJs).[5,6] The novel semiconductor laser has several active regions, while the conventional laser has only one active region. The basic physical principle is described as follows. After an electron–hole pair is radiatively recombined in the first active region, the electron in the valance band of p-side will tunnel into the conduction band of n-side and participate in the radiative recombination of the next active region by a reverse tunnel junction. Thus the quantum efficiency of the device can be increased by the tunnel junction to a value even larger than one. The optical confinement factor also increases in proportion to the increasing number of the active regions, because the emitting area becomes bigger. So we can obtain the higher light output power under the lower injection current and the low threshold current.

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Figure 1 shows the position-dependent refractive index and the near field optical distribution of the new structure in the epi-layer growth direction of the novel structure. In this structure, there are three $In_{0.2}Ga_{0.8}As$ active regions cascaded by two $Al_{0.1}Ga_{0.9}As$ tunnel junctions. The main function of the tunnel junction is to regenerate carriers from the valence band to the conduction band. On the other hand, it influences the near field pattern as a passive waveguide. The outside $Al_{0.3}Ga_{0.7}As$ cladding layer is designed for widening the optical field distribution. The inner side $Al_{0.45}Ga_{0.55}As$ cladding layer is designed for reducing the optical field intensity at the tunnel junction to reduce the absorption loss. The thickness of the inner side cladding layer is important due to its effect on the laser characterization. To assure that all layers are coupled into a large optical cavity, the thickness of the inner side cladding layer must be chosen to be between 10 nm and 150 nm. If it is increased beyond this limit, the vertical divergence angle $\theta_\perp$ will decrease. But the confinement factor will decrease, which means a higher threshold current density J. To trade off both $\theta_\perp$ and J, the thickness of the inner cladding layer is chosen to be 60 nm. At this value, the calculated $\theta_\perp$ and J are 18° and 243 A/cm^2, respectively, the confinement factor is 2.04%, and the full width at half maximum (FWHM) of the near field optical spot size is 1176 nm. It is a very large optical cavity (LOC) compared with that of the conventional InGaAs/GaAs/AlGaAs laser diode, which has a typical value of 500–600 nm. A more notable difference from the LOC structure with one active region (AR) is the almost flat optical distribution in the coupled cavity with three ARs, so the optical power density will be reduced.

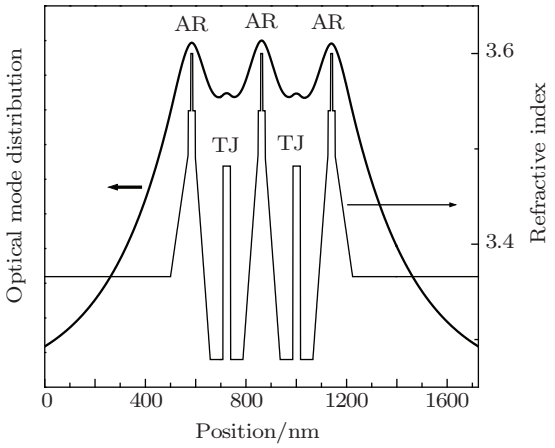


Fig. 1. Refractive index and simulated near field pattern distribution.

Figure 2 shows the theoretically calculated result of far-field optical pattern with an FWHM of 18°.

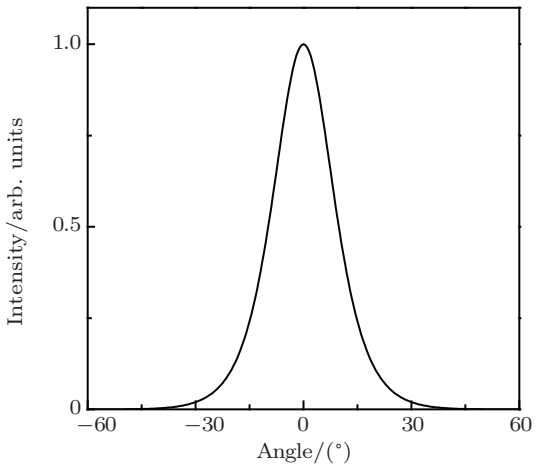


Fig. 2. Calculated vertical far field pattern.

3. Device fabrication

The InGaAs/GaAs/AlGaAs LD epitaxial layer structure was grown by low-pressure metalorganic chemical vapor deposition (MOCVD) on an n-GaAs substrate misoriented 2° toward the ⟨111⟩A. TMGa, TMAl, and TMIn were used as group V element precursors. Dopants for n-type and p-type materials were obtained from silane (SiH_4) and carbon tetrachloride (CCl_4), respectively. After the material growth, a stripe of 50 μm width was first formed by photolithography and chemical wet etching. Then SiO_2 was deposited as the insulated layer, which defined the metal contact stripe. After the deposition of Ti/Au as p-electrode, the wafer was thinned to 100 μm, and then n-electrode was deposited by using AuGeNi/Au. The wafer was cleaved into bars each with a cavity length of 930 μm. High reflecting (HR) and anti-reflecting (AR) films were deposited on each facet of the bar. The reflectivitis were 95% and 5%, respectively. After chipping, the chips were mounted on copper heatsinks with the p-side down.

The measured photoluminescence (PL) spectrum of the active layer is shown in Fig. 3. The peak wavelength of the quantum well (QW) layer is 980.1 nm, and the FWHM is 36 nm.

The scanning electron microscope (SEM) image of the device is shown in Fig. 4. It shows that the thickness of the epitaxial layer is consistent with the designed value, and the quality is very good, as we

can see a smooth interface in this image.

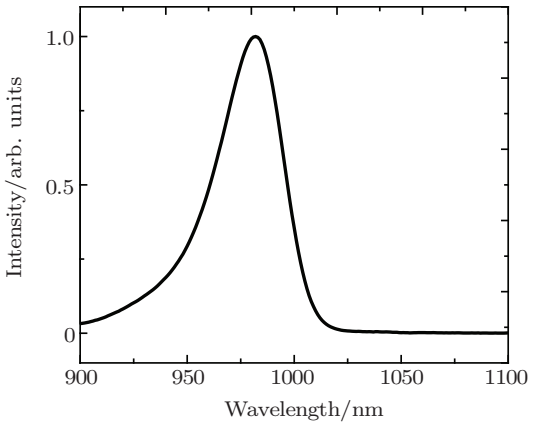


Fig. 3. Measured material PL.

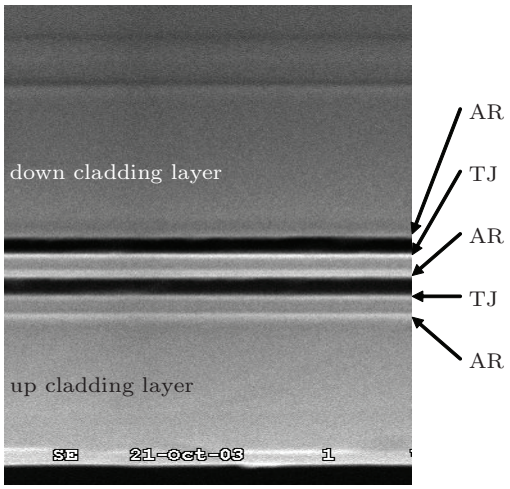


Fig. 4. The SEM image of material.

Figure 5 gives the light output power–current (P–I) and the voltage–current (V–I) characteristics measured under 0.2% duty cycle pulse injection condition at room temperature. The threshold current density is 271 A/cm^2. The maximum output power exceeds 400 mW at the current of 400 mA, which gives a slope efficiency higher than one that cannot be obtained in the conventional laser. The obtained slope efficiency is 1.49 W/A. This result indicates that the material property is very good so that the photon loss and the nonradiation recombination are very small in the waveguide, especially the higher doped tunnel junction does not produce a higher loss due to the designed lower optical intensity and thinner thickness. At the expense of the characteristics of high power and small divergence angle, we obtain a threshold current density slightly higher than that of the conventional single-quantum-well laser, whose typical value is in a range of 180–220 A/cm^2.

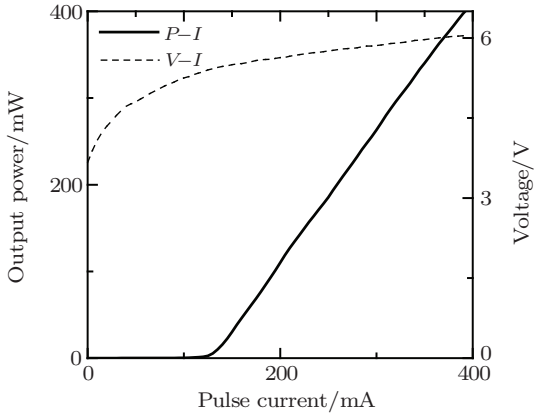


Fig. 5. Measured P–I and V–I curves of coupled tunnel cascaded semiconductor laser.

Figure 6 shows the results of far field divergence angle. The FWHM of the divergence angle in the direction perpendicular to the junction plane is 17.4° at 400 mW, which is consistent with the theoretical result and less than that of the conventional device, whose typical FWHM is larger than 30°. The far field patterns keep the fundamental transverse mode at different current injections, which is a result of the coupled cavity.

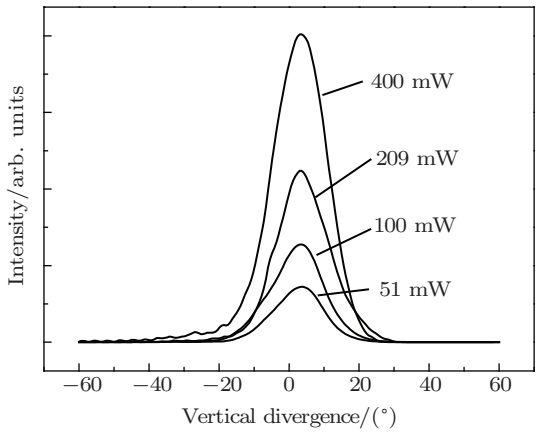


Fig. 6. Measured divergence angles at different output powers.

In light of the non-paraxial vectorial moment theory and the waveguide mode theory, we calculate the vertical beam quality factor M^2 and the angle θ_y. The M^2 is definited in Eq. (1) of Ref. [7], in which $W_y(0)$ is the vertical beam waist, and θ_y is the vertical divergence angle. We find that the thickness of the inner cladding layer in the device is the most important factor affecting the vertical beam quality factor and the angle. The vertical M^2 can reach 1.24 when the

thickness of the inner cladding layer is 60 nm. Compared with the conventional semiconductor laser, vertical M^2 reduces from 1.4 to 1.2. The lower value of M^2 implies a better beam quality.

In order to compare the COD levels of different kinds of devices, we use a low temperature equipment to measure the output powers of the novel device and the conventional device fabricated using the same process. The low temperature equipment can be cooled to 100 K by using liquid nitrogen. Both devices are of 30 μm-width stripe. All cavity surfaces are not treated. The results are shown in Fig. 7. From this figure, we can see that the novel device is damaged at 1395 mW, while the conventional device is damaged at 495 mW at 233 K. The COD level of the novel device is obviously higher than that of the conventional device. So we can see from the above results that the novel device obtains a low vertical divergence angle, overcomes the COD, and keeps a low threshold current density.

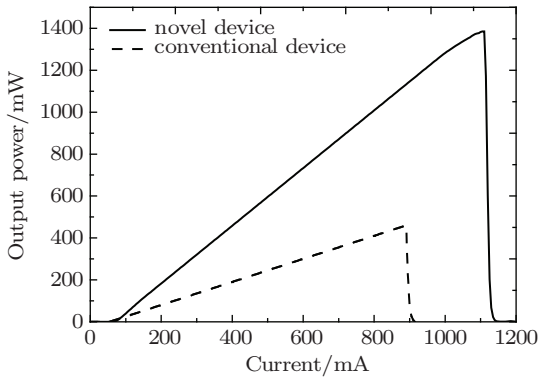


Fig. 7. Measurement results of novel and conventional devices at 233 K.

4. Conclusion

In this paper, we demonstrate a single transverse mode 980 nm InGaAs/GaAs/AlGaAs strained quantum well waveguide laser with a novel structure. It exhibits a low vertical divergence angle of 17.4° and a high slope efficiency of 1.49 W/A at the cavity length of 930 μm. The threshold current density is 271 A/cm^2. The device shows a higher output power at COD and improves the beam quality, the beam quality factor is reduced to 1.24.

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