High-Power Ridge-Waveguide Tapered Diode Lasers at 980nm

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Abstract: High-power ridge-waveguide tapered InGaAs-AlGaAs lasers emitting at 980nm were fabricated. Lasers with a total length $L = 1850\mu m$ and different lengths of the ridge waveguide L_{rw} were processed to study the influence of the straight section on the spatial mode filtering. When L_{rw} is $450\mu m$, the devices have the optimized maximum output power and beam quality, and the output power P is 4.28W. The beam propagation ratio M^2 is 3.79 at 1W.

Key words: tapered; ridge-waveguide; 980nm; beam propagation factor
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1 Introduction

Erbium-doped fiber amplifiers (EDFAs) are important devices in dense wavelength-division multiplexing (DWDM) systems. 980nm pump laser diodes have been identified to be practical pump sources for EDFAs. There is a growing demand for 980nm pump lasers with high output power and nearly diffraction-limited beam quality in order to obtain high brightness. Ridge-waveguide diode lasers at 980nm with output powers below 500mW cannot meet this demand. Broad area (BA) devices at 980nm with an output power of several watts suffer from poor beam quality with $M^2 > 10$. Taking into consideration the demand for low-cost fabrication, ridge-waveguide tapered lasers are a promising concept for nearly diffraction-limited beam quality at high output powers.

Ridge-waveguide tapered lasers consist of a straight index-guided section formed by a ridge waveguide (RW) section and a gain-guided tapered section. Light with a single mode is emitted from the RW section and amplified in the tapered section. The power density of the facet can be reduced, and the effect of self-focusing can be weakened[1]. Figure 1 shows the profile of a ridge-waveguide tapered laser.

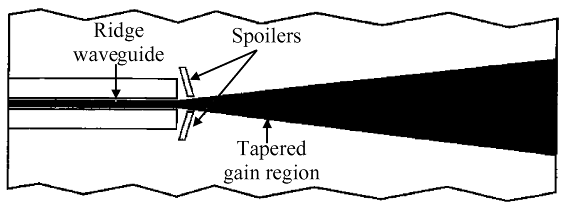

Fig.1　Schematic two dimensional view of a tapered laser

In 1993, ridge-waveguide tapered lasers at 980nm with nearly diffraction-limited beam quality at $P_{max} = 3.2W$ were first reported by Kintzer *et al*.[2]. Therefrom, tapered lasers with GaAs base and $M^2 < 4$ were reported[3~6]. Long wavelength taper lasers with nearly diffraction-limited beam quality at 1W were also reported in the past few years[7~9]. However, few works focusing on the optimization of the length of the RW section with the goal of high output power together with better beam quality have been reported besides those by Donnely *et al*. (1998)[10] and Sumpf *et al*.(2003)[4].

In this paper, we first report on 980nm tapered lasers with optimized structure. Devices optimized concerning maximum output power and excellent beam quality reach a beam propagation factor smaller than 3.79 at an output power of $P = 1W$.

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2 Device structure and fabrication

The devices were fabricated from a strained-layer graded-index separate confinement heterostructure (GRINSCH) InGaAs-AlGaAs laser structure grown by low-pressure metal organic chemical vapor deposition (MOCVD). The thickness and composition of the layers are given in Table 1.

Table 1 Thickness and composition of the epitaxial layers

GaAs	0.2μm	$p=1\times10^{20}cm^{-3}$
$Al_{0.35}Ga_{0.65}As$	1.6μm	$p=1\times10^{18}cm^{-3}$
$Al_xGa_{1-x}As$	90nm	x: 0→0.35
GaAs	20nm	Barrier
$In_{0.2}Ga_{0.8}As$	7.5nm	Well
GaAs	20nm	Barrier
$Al_xGa_{1-x}As$	90nm	x: 0.35→0
$Al_{0.35}Ga_{0.65}As$	1.6μm	$n=1\times10^{18}cm^{-3}$
GaAs	0.21μm	$n=1\times10^{18}cm^{-3}$

The width and etch depth of the RW section should be optimized by theoretical and experimental methods in order to realize a single spatial mode beam[11,12]. The effective refractive index method was used in estimating the single mode operation condition. The first mode cutoff width is of the form[13]:

$$W=\frac{\lambda_0}{2\sqrt{n_{\mathrm{eff2}}^2-n_{\mathrm{eff1}}^2}} \quad (1)$$

where n_{eff2} is the effective refractive index of the ridge waveguide, and n_{eff1} is the effective refractive index outside the ridge waveguide. The residual thickness of the upper cladding layer is 0.2~0.3μm when the first mode cutoff width is 2.6~3.3μm, according to the dependence of the residual thickness of the upper cladding layer on the first mode cutoff width.

The angle of the tapered section should be less than the ray angle of the lowest-order mode in the RW section in order to avoid mode conversion from the lowest-order mode to higher order modes. It has been proved that the angle of the tapered section should be less than 6°[14,15]. The ray angle of the lowest-order mode is of the form[16]:

$$\theta=\frac{\lambda}{nW}\times\left[2\tan^{-1}\left(\frac{b}{1-b}\right)^{1/2}\times\frac{1}{\pi}\right] \quad (2)$$

$$b=\frac{n_{\mathrm{eff}}^2-n^2}{n_{\mathrm{eff}\text{-}n}^2-n^2} \quad (3)$$

where n is the bulk index, n_{eff} is the effective index for finite W, and $n_{\mathrm{eff}\text{-}n}$ would be its effective index for $W=\infty$.

In this paper, we report the investigation of tapered lasers with $L_{\mathrm{rw}}=450, 700, 950$μm and an identical total cavity length $L=1850$μm. The width of the RW section is 3μm and the etch depth of all devices is 1.5μm. The tapered section has a total flared angle of 5°. For the above-mentioned geometries, the power-current characteristics and the beam propagation factor will be presented. These investigations lead to optimized structures.

Cavity-spoiling elements[1], consisting of grooves etched down through the active region, were also fabricated. The grooves are angled to deflect and scatter unwanted radiation away from the tapered region and into the substrate. If this cavity-spoiling were not utilized, the device would be likely to oscillate in undesired Fabry-Pérol cavity modes.

The process of fabrication is as follows. The RW section was first achieved by a wet etching method. Then the cavity-spoiling grooves of 2.0μm in depth were also achieved by the same method. The SiO_2 layer was deposited and the film in the RW section, and the tapered section was removed by a wet etching method. A Ti-Pt-Au multilayer was sputtered to form the metallization on the p-side contact. After thinning and n-metallization by evaporating the AuGeNi layer, the wafer was cleaved and coated by ECR plasma CVD. The front facet was antireflection coated ($R_{\mathrm{f}}\approx1\%$), and the rear facet was high-reflection coated ($R_{\mathrm{f}}\approx95\%$). The devices were mounted p-side (epi-side) down on copper heat sinks with indium solder. The n-side was contacted by wire bonding. Then the devices were tested.

3 Experimental results

Figure 2 shows power-current characteristics of the tapered lasers with RW sections of different lengths (The pulse width is 50μs, and the pulse frequency is 200Hz.).

The threshold currents of the three devices decreased in turn, with values of 0.12A ($L_{\mathrm{rw}}=450$μm), 0.11A ($L_{\mathrm{rw}}=700$μm), and 0.10A ($L_{\mathrm{rw}}=950$μm). The slope efficiencies of the three de-

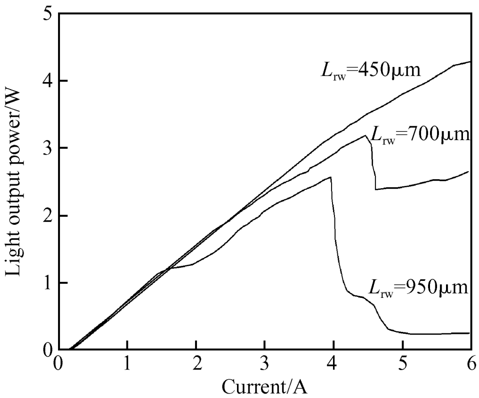

Fig. 2　Power-current characteristics of the 980nm tapered laser with different lengths of the RW section

vices increased in turn at $I < 1.5$A. However, for the device with ridge length $L_{rw} = 950\mu$m, there were kinks at output powers $P > 1$W, and COD (catastrophic optical mirror damage) occurred at output powers $P \geqslant 2.57$W in the power-current dependence. For the device with ridge length $L_{rw} = 700\mu$m, there were kinks at output powers $P > 2$W, and COD occurred at output powers $P \geqslant 3.19$W in the power-current dependence. For the device with ridge length $L_{rw} = 450\mu$m, there were no obvious kinks and COD didn't occur in the power-current dependence, and the saturation output power was 4.28W at $I = 6$A.

To evaluate the beam quality of the tapered lasers, the beam propagation factor $M^2_{1/e}$ was determined by the equation

$$M^2_{1/e} = \frac{\pi \omega_{1/e} d_{1/e}}{\lambda} \quad (4)$$

where $d_{1/e}$ is the radius of beam waist, and $\omega_{1/e}$ is half the angle in the far field. The knife-edge method of ISO standard 11146[17,18] was used to measure the beam radius and divergence in the far field. A lens with 15mm focal length firstly focused the nearly diffraction-limited beam of the taper lasers. When a knife-edge whose movement is controlled precisely in three dimensions moves along the x direction perpendicular to the beam, the beam will be partly covered. The beam waist of any position along the propagation direction will be calculated by measuring the positions of the knife at which the power was reduced to 13.5% and 86.5%. Then a hyperbola about the beam radius along the propagation direction was simulated and the least beam waist was gained. The full divergence in the far-field was calculated from the two asymptotes of the hyperbola. The testing equipment included a lens with 15mm focal length, a precise three-dimensional adjuster, a knife, a detector, and a He-Ne collimator. Figure 3 shows the dependence of the measured values for the half angle in the far field, the radius of the beam waist, and the beam propagation factor on the length of the RW.

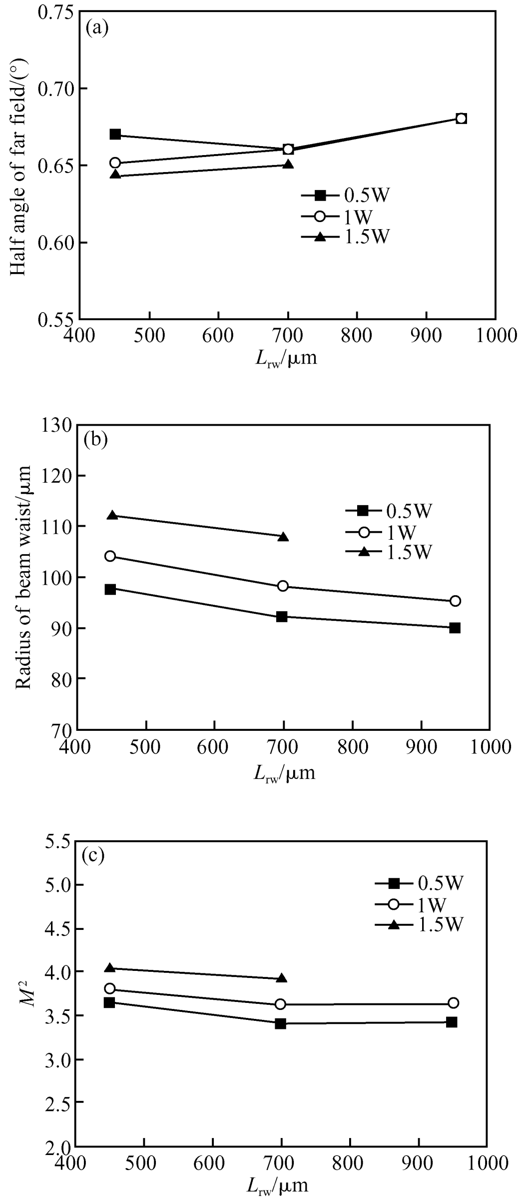

Fig. 3　Dependence of the measured values for the half angle in the far field (a), the radius of the beam waist (b), and the beam propagation factor (c) on the length of the RW

There are small differences in the half angle in the far-field. The radius of the beam waist and the beam propagation factor $M^2_{1/e}$ increase with the increasing of output power. The beam propagation factor $M^2_{1/e}$ is similar for the three devices at same output power. For example, the beam propagation factor $M^2_{1/e}$ is 3.79 for $L_{rw} = 450\mu m$, 3.62 for $L_{rw} = 700\mu m$, and 3.64 for $L_{rw} = 950\mu m$ at $P = 1W$. The beam propagation factor $M^2_{1/e}$ are 5.65 at 2W and 5.89 at 2.5W for $L_{rw} = 450\mu m$ (the values haven't been shown in Fig.3). The beam propagation factor $M^2_{1/e}$ increases markedly at $P \geqslant 2W$.

From these results, we conclude that the optimum length of the RW is $L_{rw} = 450\mu m$. Here the highest output powers together with good beam propagation factor could be measured. Figure 4 shows the spectrum of the device at $P = 1W$ under CW operation. The central wavelength is 975nm.

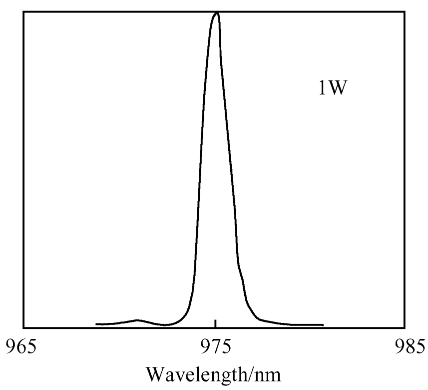

Fig.4 Spectrum of the 980nm tapered laser

4 Discussion

The threshold gain of quantum-well lasers is of the form:

$$G_{th} = \Gamma g_0 \ln \frac{J_{th}}{J_{tr}} \tag{5}$$

where Γ is the confinement factor of the active region, g_0 is the gain coefficient of the material, J_{th} is the threshold current density, and J_{tr} is the transparent current density.

The total losses of the tapered lasers are[9,15]

$$\alpha_{ges} = \alpha_i + \alpha_m + \alpha_{geom} = \alpha_i + \frac{1}{2L}\ln\left(\frac{1}{R_1 R_2}\right) + \frac{1}{2L}\ln\left(\frac{4\lambda L_{taper}}{W^2 n_{eff}}\right) \tag{6}$$

where α_i are the internal propagation losses, α_m are the mirror losses, and α_{geom} are the additional geometrical losses. α_{geom} describes the percentage of reflected wave that couples back into the single-mode section. L and L_{taper} are the total device length and taper length, respectively. W depicts the ridge width, and n_{eff} is the effective index of refraction. The lasers with short RW section and relevant long tapered section have high taper losses and total losses. Thus a slightly high current density and larger proportion led to a slightly high threshold current. As a result, the threshold current decreased from 0.12 to 0.10A with the length of the RW section increasing from 450 to $950\mu m$.

The tapered section can be regarded as a tapered amplifier, and its initial power is provided by the output power of the RW section. Ridge waveguide lasers with different cavity lengths were fabricated. The measured values of output power of ridge waveguide lasers were 240mW for $L = 450\mu m$, 300mW for $L = 700\mu m$, and 360mW for $L = 950\mu m$. One can obtain the output power of a tapered amplifier from the following equation by numerical methods,

$$\frac{\partial P}{\partial L_{taper}} = \left(\frac{\gamma_u}{1 + \dfrac{P}{\varphi L_{taper} I_{sat}}} - \alpha_i\right) p \tag{7}$$

Here γ_u is the unsaturated gain of the tapered amplifier, $\gamma_u = \gamma_0 \ln(J/J_{tr})$, φ is the taper angle, and I_{sat} is the saturation power intensity, $I_{sat} = h\nu J_{tr}/q\gamma_0$. Figure 5 shows the calculated P-I characteristic of tapered amplifiers with different taper lengths. Here the slope efficiency and output power increase with the increasing of the length of the RW section. For $L_{rw} = 950\mu m$, an output power $P = 6W$ can be obtained at $I = 6A$. The effect of self-focusing in the tapered section is not considered in this model.

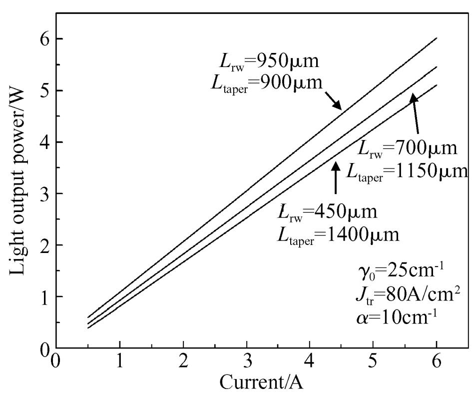

Fig.5 Calculated output power versus amplifier current for different length of the RW

Although the ridge section provides a spatially single-mode beam, degradation can frequently be observed in the tapered section. It is caused by inhomogeneities in temperature and carrier distribution, leading to self-focusing and filamentation. For those with long input ridge sections and short taper sections, a large fraction of the output power suddenly becomes concentrated in a small region at the center of the output aperture of the taper instead of being fairly uniformly distributed over the entire output aperture. In Fig. 2, the self-focusing took place at $P \geqslant 1W$ for $L_{rw} = 950\mu m$ and at $P \geqslant 2W$ for $L_{rw} = 700\mu m$. No obvious self-focusing took place for $L_{rw} = 450\mu m$.

The beam quality will become poor if the length of the RW is too short to filter the spatial mode sufficiently and suppress intensity of back-reflected light adequately. Thus the beam propagation factor $M^2_{1/e}$ for $L_{rw} = 450\mu m$ has a tendency of accretion. For an even longer ridge at constant total length, one can speculate that the RW is too strongly excited, and a broadening of the mode occurs. On the other hand, at the same output power from the smaller aperture of the facet more light is back-reflected into the taper. The ridge is not able to filter all the backscattered light. Thus the beam propagation factor $M^2_{1/e}$ for $L_{rw} = 950\mu m$ also has a tendency of accretion.

5　Conclusion

In summary, tapered diode lasers with a total length $L = 1850\mu m$ were optimized for high output power and good beam quality. The optimum length of the RW was found to be $L_{rw} = 450\mu m$. Here the highest measured output power was $P = 4.28W$, together with a good beam propagation factor $M^2 = 3.79$ at 1W.

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高功率 980nm 锥形增益区脊形波导量子阱激光器的优化

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摘要： 利用 MOCVD 生长 980nm InGaAs-AlGaAs 渐变折射率分别限制异质结单量子阱激光器外延片，采用锥形增益区脊形波导结构制备器件．保持总腔长 1850μm 不变，改变脊形区的长度分别为 450，700 和 950μm，对比三种情况的 *P-I* 特性和光束质量．发现 $L_{RW}=450\mu m$ 时，器件特性参数和远场光束质量最优，斜率效率达 0.83W/A，饱和功率为 4.28W．输出功率为 1W 时，远场发散角为 7.5°×30.6°，M^2 因子为 3.79．

关键词： 锥形增益；脊形波导；980nm；光束质量因子

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