Waveguide Optimization for a 9.0μm GaAs-Based Quantum Cascade Laser*

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Abstract: Improved waveguide designs for 9.0μm GaAs-based quantum cascade laser (QCL) structures are presented. Modal losses and confinement factors are calculated for TM modes with the transfer matrix method (TMM) and effective index method (EIM). The thicknesses of the cladding layer and waveguide layer, the ridge-width, and the cavity length are all taken into account. Appropriate thicknesses of epilayers are given with lower threshold gain and more economical material growth time.

Key words: quantum cascade laser; transfer matrix method; effective index method
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1 Introduction

The quantum cascade laser (QCL), invented at Bell Laboratory in 1994[1], is a promising light source in the mid-infrared range. Great achievements have been made[2~4] in the past few years. Continuous wave operation at room temperature of InP-based QCLs and pulsed room temperature operation of GaAs-based QCLs have been reported. Although GaAs/AlGaAs QCLs have the potential for flexible design due to good lattice matching over the entire alloy composition, one of the critical problems limiting the performance of GaAs-based QCLs is the thick cladding layers. Thus, optimizing the waveguide structure, which can reduce losses, improve the confinement factors, and thereby reduce the threshold, is a feasible way to enhance device performances.

There are several initial considerations in the design of waveguides for GaAs-based QCLs. To get a higher confinement factor, a greater index contrast between the active region and cladding layers is necessary to reduce the leak of modes. However, due to the considerable extinction coefficients (imaginary part of the refractive index) of the cladding layers, the waveguide losses must be decreased by separating the active region from the cladding layers by waveguide layers, which are normally comprised of low-doped GaAs. In the early design of GaAs-based QCLs, AlGaAs was used as the material of the cladding layers[5] because it has a higher index than the active region. However, in AlGaAs layers, variations of the ionized carrier concentrations produce strong instabilities in device thresholds and slope efficiencies. In addition, the growth of thick AlGaAs layers is difficult due to residual strain. The main problem is that AlGaAs layers have poorer electrical and thermal conductivity than the GaAs layers. Therefore, Al-free cladding layers have been adopted. Most recently, heavily-doped GaAs has been used as the material of cladding layers. The heavily-doped GaAs layers decrease the refractive index and shift the plasma frequency of the cladding layers close to that of the lasers[6]. Due to the plasma resonance, the real part of the refractive index dramatically decreases, but the extinction coefficient also increases. It seems that enhancing the optical confinement is incompatible with decreasing the waveguide losses. Besides the effect of epilayer thickness, the width of the ridge is an

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important parameter of lasers that also plays an important role in improving device performance.

In this paper, modal losses and confinement factors are calculated for different thicknesses of waveguide and cladding layers with the transfer matrix method (TMM). The appropriate thicknesses of epilayers are recommended that yield lower losses and a higher confinement factor, and simultaneously shorten the growth time. The effect of different ridge widths is then taken into consideration by the effective index method (EIM) with the recommended structure. In our calculation, material losses are represented by the imaginary part of the refractive index.

2 Theory and methodology

2.1 TMM and EIM

For analyzing the mode profile of a 1D multilayer slab waveguide, the well known TMM, which requires little computational power, is an efficient method. In the calculation, only TM modes are taken into account because of the intersubband lasing nature of the QCL. When the influence of the ridge width is introduced, the EIM[8] is applied at the same time, in the following manner. As shown in Fig. 1(a), the rib waveguide is first divided into three regions, each of which can be represented as a 1D slab optical waveguide. For each 1D waveguide, the effective index along the x axis is calculated by TMM. A slab waveguide is then modeled by placing the effective indices calculated in the former step along the y axis (See Fig. 1 (b)). Eventually the effective index is obtained by solving the model with TMM once again, but assuming TE polarized modes (y direction). In the calculation only the base mode is considered because it is predominant in all modes.

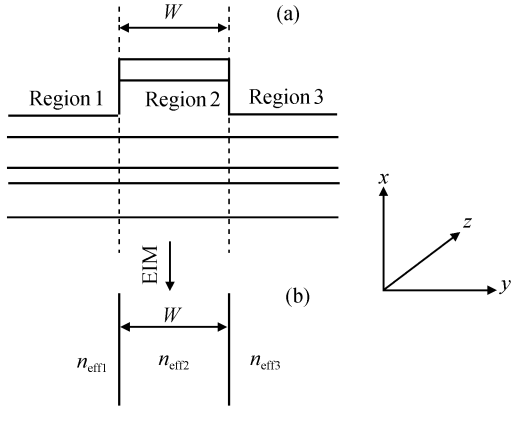

Fig. 1 Concept of the effective index method

2.2 Waveguide model

When the effect of epilayer thickness is considered, we use a simplified slab structure in our calculation, as shown in Fig. 2. The cladding layer, waveguide layer, and substrate are all made of GaAs, and the doping concentrations are 6×10^{18}, 4×10^{16}, and $2\times10^{18}\,\mathrm{cm}^{-3}$, respectively. The active region consists of 30 periods, the detailed structure of which is described in Ref. [9], and the injector layers are doped to $6\times10^{17}\,\mathrm{cm}^{-3}$. The complex permittivity is obtained by using the Drude model, which gives us

$$\varepsilon = \varepsilon_b + \mathrm{i}\frac{ne^2\tau}{\omega m^*(1-\mathrm{i}\omega\tau)} \tag{1}$$

where ω is the angular frequency of the radiation, ε_b the relative (free-space) dielectric constant, n the carrier concentration, e the elementary charge, m^* the effective electron mass, and τ the momentum relaxation time. For these simulations, ε_b is set at 12.4 and m^* is set at $0.067m_0$ for GaAs. The Drude relaxation times for GaAs used in this paper are 100fs for the highly doped (cladding) layers, 500fs for the lightly doped (waveguide) layers, and 300fs for the medium doped (injector) layers[10,11]. The parameters for the Au contact layer are taken as $\tau = 21$ps and $\varepsilon_b = 8$, $n = 5.9\times10^{22}\,\mathrm{cm}^{-3}$ and $m^* = m_0$[12]. The refractive index of SiO_2 used is given in Ref. [13].

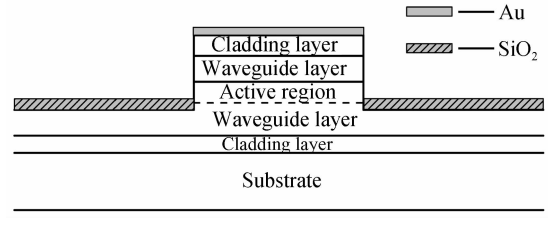

Fig. 2 Simplified model of QCL ridge waveguide structure

2.3 Threshold gain

For the comparison of different waveguide structures, we use the threshold gain g_{th} as a figure-of-merit, which is given by

$$g_{th} = \frac{\alpha_w + \alpha_m}{\Gamma} = \frac{2\mathrm{Im}(\beta) - \ln(R)/L}{\Gamma} \tag{2}$$

where $\alpha_w = 2\mathrm{Im}(\beta)$ is the absorptive loss contributed by the waveguide, and β, the propagation constant of the base mode in the QCL, is determined by $\beta = \frac{2\pi n_{\mathrm{eff}}}{\lambda}$, with n_{eff} being the effective refractive index of the mode; $\alpha_m = -\ln(R)/L$ is the mirror loss, L is the cavity length, R is the facet reflectivity which for a GaAs/air interface is normally ~ 0.32[10]; and Γ is the confinement factor. All the parameters except α_m on the right side of Eq. (2) are determined by the passive waveguide structure. Since lower threshold gain is more propitious to the reduced threshold current density and increased operating temperature, better device performances may be achieved with waveguide optimization to reduce the threshold gain.

3 Results

3.1 Thickness variation of waveguide layer

First, the thickness of the cladding layers L_c is fixed, and the various thicknesses of the waveguide layer L_w are investigated. In the calculation, infinite (1D) and finite ridge widths are considered. For the case in which the thickness of the cladding layers is 1μm and the cavity length is 1mm, the plot of the threshold gain versus the thickness of the waveguide layer is shown in Fig. 3. The lowest threshold gain occurs at a waveguide layer thickness of 2.5μm. For detailed discussion, the effects of α_w/Γ and α_m/Γ for 1D analysis, as an example, are shown in the inset of Fig. 3. The data for the 2D case differ insignificantly from the 1D case. The waveguide layer thickness dramatically influences the waveguide loss and confinement factor. A thicker waveguide layer will keep the active region away from the heavily-doped cladding layer and yield a much lower waveguide loss, although this is accompanied by a decrease in the confinement factor as the mode overlaps the thicker waveguide layer more. Thus the term α_w/Γ decreases as the waveguide layer thickness increases. However, since the facet loss α_m is nearly independent of the waveguide structure, the α_m/Γ term begins to blow up with increasing waveguide layer thickness as the confinement degrades. Therefore, at a certain thickness of waveguide layer, the minimal threshold gain can be found.

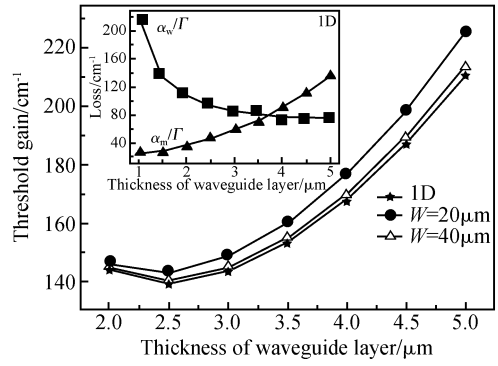

Fig. 3　Threshold gain versus the thickness of waveguide layer for a constant cladding layer of 1μm and cavity length of 1mm　The 1D condition and finite ridge widths of 20μm and 40μm are considered. The inset is the contribution from the waveguide and mirror losses to the threshold gain as the waveguide layer thickness increases in 1D.

3.2 Thickness variation of cladding layer

With the same cavity length as above and waveguide layer thickness of 2.5μm, the results of threshold gain versus thickness of cladding layer are shown in Fig. 4. Whatever the ridge width, the threshold gain decreases as the cladding layer thickness increases. However, after the thickness L_c exceeds 1.4μm, the rate of decrease slows gradually. More details can be obtained in 1D analysis as an example as shown in the inset of Fig. 4. Due to the large contrast between the indexes of the waveguide and cladding layers, the mode will be limited effectively in the active re-

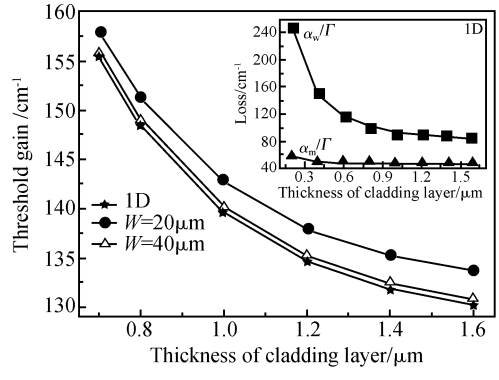

Fig. 4　Threshold gain versus the thickness of cladding layer for a constant waveguide layer of 2.5μm and cavity length of 1mm　The 1D condition and the finite ridge widths of 20μm and 40μm are considered. The inset is the contribution from the waveguide and mirror losses to the threshold gain as the cladding layer thickness increases in 1D.

gion. A thicker cladding layer will result in a higher confinement factor, while at the same time the waveguide loss will decrease as the mode overlaps the lossy heavily-doped cladding layer less. However, the mode limit is not directly proportional to the thickness of the cladding layer, and less and less modal intensity is pushed into the active region as the cladding layer thickness increases sequentially, thus slowing the increase of the confinement factor. Therefore, although the terms α_w/Γ and α_m/Γ both decrease with increasing cladding layer thickness, they change little for very thick cladding layers. Because of the difficulties of long-period material growth, uninterruptedly increasing the thickness of the cladding layer merely to get a slightly lower threshold gain is not feasible. From the above analysis, we highly recommend a cladding layer thickness of 1.4μm.

3.3 Variation of cavity length

Finally, the effect of cavity length is considered. As indicated by Eq. (2), the variation of cavity length only affects the mirror loss α_m. From the above discussion, the mirror loss is nearly constant as the thickness of the cladding layer changes, but it plays an important role in the contribution to the threshold gain while altering the waveguide layer thickness. Thus only the variation of the waveguide layer thickness is considered in the calculation. For the case in which the ridge width is 20μm and the thickness of the cladding layer is fixed at 1.4μm as recommended above, the result is shown in Fig. 5. The trend of threshold gain is almost the same when the cavity length increases from 1 to 3mm. However, the lowest threshold gain is displayed at a waveguide layer thickness of 3μm when the cavity length is 2 or 3mm, which is different from the case in which the cavity length is 1mm. Since the cavity length is mainly selected to be 1～3mm in device fabrication, the value of the waveguide layer thickness should be reconfirmed to be some value between 2.5～3μm.

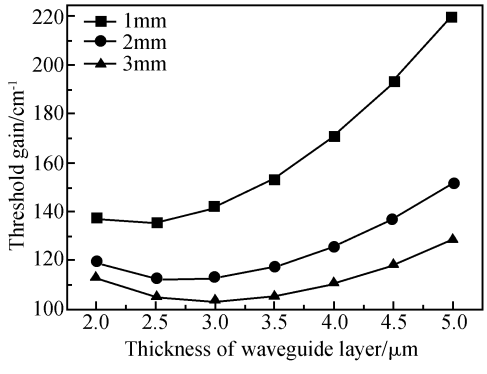

Fig. 5 Threshold gain versus cavity length for a constant cladding layer thickness of 1.4μm and ridge width of 20μm

4 Conclusion

Using the TMM and EIM, we have calculated the losses and confinement factors of the base mode for a 9.0μm GaAs-based QCL structure. In addition to the waveguide thicknesses, the ridge width and cavity length are all involved in our calculation. The results indicate that a structure with waveguide layer thickness of 2.5～3μm and cladding layer thickness of 1.4μm is optimal for lowering the threshold gain, and simultaneously economizes the period of material growth.

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9.0μm GaAs 基量子级联激光器的波导优化*

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摘要：通过转移矩阵法和有效折射率法计算了 9.0μm GaAs 基量子级联激光器波导的模式损耗和限制因子，从而对其波导结构进行优化. 计算中考虑了各外延层的厚度、脊宽和腔长的影响. 给出了在较低阈值下节约材料生长时间的各外延层厚度.

关键词：量子级联激光器；转移矩阵法；有效折射率法

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