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Letter

Stable single-mode distributed feedback quantum cascade lasers at $\lambda \sim 4.25\ \mu m$ with low power consumption

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ABSTRACT

Short-wavelength (4.25 μm) distributed-feedback quantum cascade laser operating in continuous wave (cw) mode at room temperature with low power consumption was presented. Stable single-mode operation with a side-mode-suppression-ratio above 25 dB was maintained for the whole measured current and temperature range by enlarging gain difference and strong grating coupling. Because of the strong coupling, very low threshold current and power consumption were achieved. For a device of 9-μm-wide and 2-mm-long, the cw threshold current and power consumption at 293 K were as low as 126 mA and 1.45 W, respectively. All results above were from the device without using buried heterostructure geometry.

1. Introduction

Distributed-feedback (DFB) quantum cascade lasers (QCLs) have attracted much attention for their single longitudinal mode operation, compact module and continuous wave (cw) operation, which are essential for practical application [1–3]. In many applications such as portable gas sensing and space exploration, output light power of a few mW is enough, while low input electrical power is very desirable. In order to lower the power consumption of the device and cooling system, small size gain region and improved heat dissipation are generally adopted [4–6]. DFB QCLs with low power consumption have also been demonstrated over the wavelength range from 3.36 μm to 10.8 μm [5,7–9].

In practice, stable single-mode operation of DFB QCLs is very important, but is still a challenge. For DFB QCLs, grating can be fabricated on top of the upper InP cladding layer or beneath the upper cladding layer, which are called surface grating or buried grating. Surface grating DFB QCLs with complex coupling mechanism can avoid dual modes or mode hopping by enlarging loss difference of the two band edge modes [10–12], but the surface plasmon loss is detrimental to achieve single-mode low power consumption device. On the contrary, buried grating with low waveguide loss can provide strong coupling which can lower threshold current density, thus leading to low power consumption [13]. In fact, very low power consumption DFB QCLs were all using buried grating [5,7–9]. But the two band edge modes with same amount of loss cannot be distinguished and stable single-mode operation cannot be ensured [14,15]. Though mode-hop free tuning was observed sometimes in strong coupling DFB QCL, the yield ratio was not high, and the lasing of high frequency mode or low frequency mode was dependent on the facet random phase.

To get stable single-mode operation, second-order buried grating has been utilized to generate loss difference, but surface emitting loss also increases the threshold current. DFB laser with a quarter wave phase shift ($\lambda/4$ PS) can work in defect mode, thus competition between the two band edge modes can be avoided. But electron beam lithography must be used for the fabrication of $\lambda/4$ PS grating, which is time-consuming and expensive. In addition, gain coupled DFB laser is a good choice to achieve stable single-mode operation for conventional semiconductors laser [16]. Though it is unrealistic for DFB QCLs to eliminate gain of one band edge mode (like in near-infrared gain coupled semiconductors laser), the gain of the two modes can be different. Once the difference is large enough, stable single-mode operation will be maintained.

In this paper, we focused on the realization of stable single-mode DFB QCLs by enlarging gain difference of the two modes at

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the expense of some output power loss. The grating with the corresponding wavelength away from the center of the gain spectrum was designed and fabricated. In such way, the absolute value of $\Delta g/\Delta\lambda$ was large (where g was gain coefficient, and λ was wavelength). Combining with the strong coupling of the buried grating, with a large $\Delta\lambda$, Δg was maximized. Meanwhile strong coupling can also lower threshold current and input electrical power consumption [13]. DFB QCLs of 9-μm-wide and 2-mm-long were fabricated, and stable wavelength tuning was achieved at $\lambda \sim 4.25$ μm. In cw operation, stable single-mode with a side-mode-suppression-ratio (SMSR) above 25 dB was maintained from 283 K to 323 K. All measured devices lased at low frequency mode, regardless of the performance. Here the size of gain region was not as small as other reports [4–6], low power consumption was achieved only by strong coupling. At 293 K, the threshold power consumption was as low as 1.45 W. It is believed that combination of off center wavelength and strong coupling is very valuable for stable single-mode low power consumption DFB QCLs.

2. Device design and fabrication

The QCL wafer was grown on n-doped (Si, 3×10^{17} cm^{-3}) InP substrate. The active region is based on the two-phonon resonance design, which is similar to Ref. [17]. The 30 stages of strain-compensated InGaAs/InAlAs super lattice sandwiched between two 300 nm-thick lattice-matched InGaAs confinement layers were grown by solid-source molecular beam epitaxy (MBE). Before and after the MBE growth, 3 μm-thick low doping InP (Si, 2×10^{16} cm^{-3}) was deposited as waveguide layers by metal organic vapor phase epitaxy (MOVPE). On top of the upper InP waveguide layer, a 500 nm high doping InP (Si, 5×10^{18} cm^{-3}) was grown as contact layer.

Fig. 1 shows the measured electroluminescence (EL) spectrum (black solid line), which was measured from a DFB QCL device at sub-threshold condition. As shown, there are two dips on the right side of the measured curve caused by CO_2 absorption, which (from HITRAN database) was also plotted in the upper panel to support our assignment. The blue dashed line shows the approximate EL spectrum after correction for CO_2 absorption, which represents the real gain shape at the measured condition. The spectrum is centered at 4.37 μm and the FWHM is about 19.2 meV (namely 290 nm, from 4.23 μm to 4.52 μm).

The key to obtain a large gain difference is to choose a wavelength where Δg between the two modes is large enough and the performance of QCL will not deteriorate. Here we define a quantity $|\Delta g/g|$ as relative gain difference, which indicates the degree of suppression of the higher gain mode to the lower gain mode. Based on the gain shape, the relative gain difference ($|\Delta g/g|$) was obtained by the formula: $\Delta g/g = (\Delta g/\Delta\lambda)\cdot\Delta\lambda/g$, where $\Delta g/\Delta\lambda$ is the derivative of the gain spectrum, $\Delta\lambda$ is the mode gap between the two bands, and g is the gain. Here a $\Delta\lambda$ of 3 cm^{-1} was taken for calculation. Firstly, $\Delta g/g$ was calculated from the corrected gain spectrum (blue dash line) in Fig. 1 and plotted as the black solid line in Fig. 2. As shown, the measurement noise became too disturbing. In order to eliminate influence from the measurement noise, the corrected EL curve was fitted with Gaussian function and then differentiated. The red dashed line in Fig. 2 shows the result. It is observed that the maximum $|\Delta g/g|$ occurs at about 2180 cm^{-1} or 2400 cm^{-1}, which is beneficial for gain coupling. But to ensure the performance of QCL, the selected wavelength cannot be too far away from peak. Based on previous research [18], for a detuning of the DFB wavelength as large as 3% from the gain peak, the device performance of DFB QCLs can be ensured. In addition, the gain spectrum normally gets narrower when increases the bias. We have taken all above and the application for CO_2 sensing into consideration by selecting a wavelength around 2350 cm^{-1}. In this way, even for the changed gain spectrum as the bias increases, the selected wavelength can still get a large gain difference. In our design, the low frequency mode with high gain was supposed to lase.

To fabricate the buried grating, the upper InP was removed down to the upper InGaAs layer. The first-order Bragg grating with a period of 664 nm was patterned on the upper InGaAs layer by holographic lithography and wet chemical etching. The grating depth and duty cycle were around 160 nm and 30%, respectively. Here we simulated the DFB QCL structure with different grating depths using finite element method (COMSOL software). Fig. 3 shows the two band edge modes frequency (blue) and grating coupling coefficient κ (red) as functions of grating depth, where the duty cycle is 30%. Based on the simulation, a coupling coefficient of 34.6 cm^{-1} was achieved and the mode gap was 3.4 cm^{-1}. The

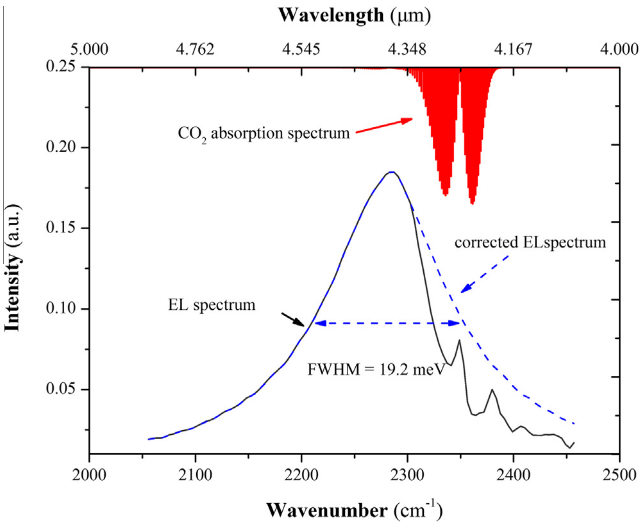

Fig. 1. The EL spectrum of the QCL wafer, the black solid line is the measured curve and the blue dashed line is the corrected curve by eliminating CO_2 absorption (the red line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

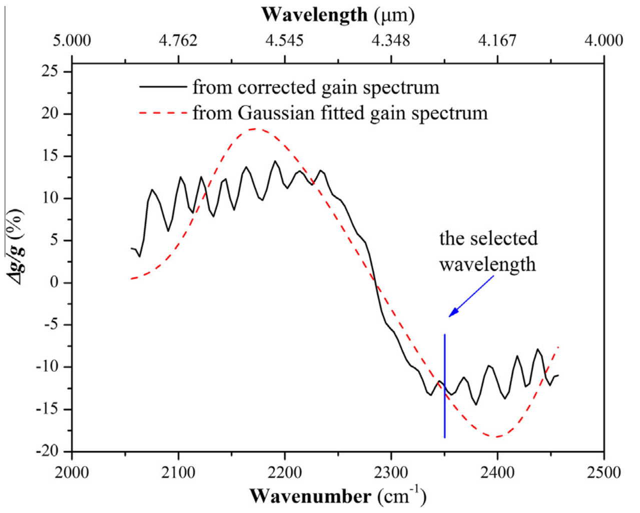

Fig. 2. The calculated curve of $\Delta g/g$ versus wavelength from the corrected gain spectrum (the black solid line) and from the Gaussian fitted gain spectrum (the red dashed line). The selected wavelength was given as blue line in the figure. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)