Solid-State Electronics 122 (2016) 52–55

Contents lists available at ScienceDirect

Solid-State Electronics

journal homepage: www.elsevier.com/locate/sse

Single-mode tapered terahertz quantum cascade lasers with lateral gratings

C. Yao, T.H. Xu, W.J. Wan, H. Li, J.C. Cao *

Key Laboratory of Terahertz Solid-State Technology, Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, 865 Changning Road, Shanghai 200050, China

ARTICLE INFO

Article history:
Received 24 November 2015
Received in revised form 19 March 2016
Accepted 20 April 2016
Available online 4 May 2016

The review of this paper was arranged by Prof. E. Calleja

Keywords:
Terahertz
Quantum cascade lasers
Tapered lasers
Lateral gratings

ABSTRACT

We report on tapered terahertz quantum cascade lasers with lateral gratings. The proposed devices exhibit not only low horizontal divergence due to tapered structure but also single-mode operation by using lateral grating structure. The tapered region and lateral gratings can be fabricated with the ridged waveguide in one etching step without inducing complexity into the fabrication. Side-mode suppression ratio ~20 dB is obtained for proposed devices from threshold to rollover currents at all measure temperatures, with the peak output power of ~30 mW at 10 K in pulsed mode and lateral divergence angle reduced by half. The proposed devices are good candidates for high-power, single-mode operation and low-divergence laser with easy fabrication.

1. Introduction

The terahertz (THz) region of the electromagnetic spectrum, which remains underdeveloped in large part, has many potential applications, such as remote sensing, communication, astronomy, biology and medicine [1]. Terahertz quantum cascade lasers (THz QCLs) are compact solid-state sources of coherent radiation in the 1–5 THz region, leading them to be key components for THz science. Since the first demonstration of THz QCLs in 2002 [2], many great efforts have been made to improve their performances [3–5]. Among them, tapered waveguide structure was adopted to realize THz QCLs with low horizontal divergence of beam profile and high output power [6], overcoming the strong sub-wavelength confinement. However, the emission spectrum of tapered THz QCLs typically exhibits multiple modes characteristic of Fabry–Perot (FP) cavities. For numerous sensing and spectroscopy applications, THz QCLs with both low divergence and single mode operation are desirable.

In this paper, single-mode tapered THz QCLs are designed and fabricated, where low horizontal divergence characteristic is maintained by taper waveguides and mode selection is achieved by implementing lateral gratings. Compared to THz QCLs with a distributed-feedback (DFB) grating realized by slits in the top metal contact of the laser ridge [7–9], lateral gratings [10,11] can be fabricated with ridged waveguides in one etching step, without introducing complexity into the fabrication process, thus reducing the fabrication cost. Moreover, since high-order lateral modes experience stronger loss than the fundamental mode due to overlapping more with gratings, proposed devices can maintain fundamental lateral mode operation simultaneously. Fabricated devices emit at about 3.4 THz, with peak output power >30 mW at 10 K in pulse mode, side-mode suppression ratio (SMSR) >20 dB from threshold to rollover currents at all measure temperatures, and significantly reduced lateral divergence angle.

2. Device design and fabrication

The active region design of THz QCLs presented in this paper is based on a bound-to-continuum transition with a one-well injector reported in [12] (total thickness of active region ~11 μm), which was grown by molecular beam epitaxy on a SI GaAs substrate. The designed center frequency of laser is ~3.4 THz. The proposed structure of THz QCLs is depicted in Fig. 1(a), consisting of two sections, tapered and lateral grating regions. An enlarged view of the gratings unit is shown in Fig. 1(b).

* Corresponding author.
E-mail address: jccao@mail.sim.ac.cn (J.C. Cao).

http://dx.doi.org/10.1016/j.sse.2016.04.008
0038-1101/

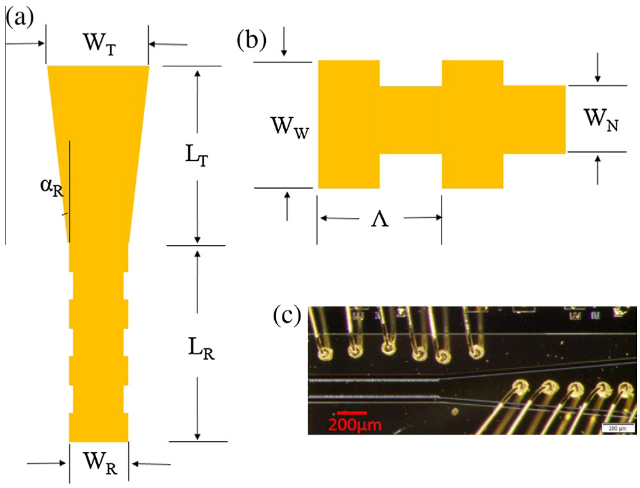

Fig. 1. (a) Schematic diagram of a tapered THz QCL with lateral gratings. L_T and W_T denote the length and width of the taper region of the device, respectively. L_R and W_R are the length and width of grating region, respectively. α_R is the half-taper angle. (b) Illustration of lateral gratings. Λ is the grating period. W_N is the width of narrow ridge of gratings and W_W is the width of wide ridge. (c) The top view of the fabricated tapered THz QCL with lateral gratings.

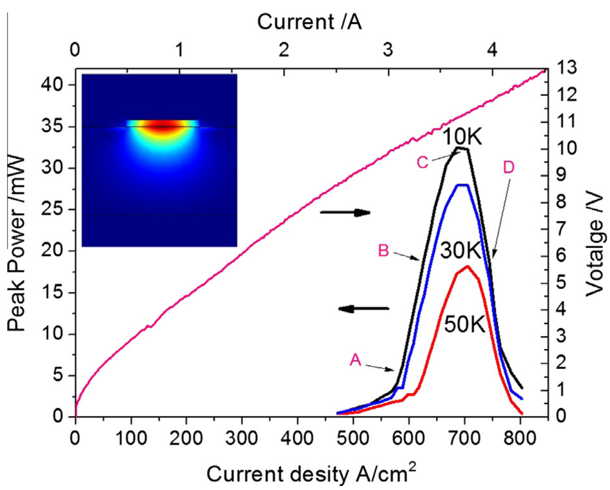

Fig. 2. (a) Typical current–voltage-peak output power characteristics of a 2.5 mm-long tapered QCLs with lateral gratings. Four typical working points are selected to measure emission spectra of the devices. A: 3 A (low injection current, near the threshold current), B: 3.2 A (moderate injection current), C: 3.6 A (near the rollover current, for output power roll-off), and D: 3.8 A (the injection current far beyond the rollover current). The inset plots the calculated fundamental mode field of 120 μm-wide waveguide.

A 2-D finite-element simulation was carried out to calculate the effective index of waveguides with different widths by a commercial tool [13]. The parameters for refractive indices of the semiconductor materials are referred to [14]. The grating duty cycle is 50%. In order to obtain single transverse mode operation, W_W and W_N are chosen to be approximately 120 μm and 100 μm, respectively, according to the simulation. The calculated fundamental mode field distribution of 120 μm-wide waveguide was plotted in the inset of Fig. 2. The effective refractive indices (n_{eff}) of these two types of waveguides are calculated to be 3.594 and 3.59, respectively. Therefore the average wavelength λ in the material is estimated to 24.56 μm. For first order gratings, the grating period Λ is chosen to be 12.28 μm ($\Lambda \sim \lambda/2$). Based on our previous measurement results which have not been published, straight lateral DFB lasers with 80 grating periods can work in single-mode, thus 80 grating periods are also used here (i.e., $L_R \sim 982$ μm). The half-taper angle 5° is designed to achieve both low lateral divergence and high output power according to the theoretical model developed in our previous work [15]. The tapered region is 1.6 mm long (L_T) to obtain low optical propagation loss.

Devices presented in this paper are based on semi-insulation surface-plasmon waveguide structure, which usually exhibits higher output power and better beam quality [12]. Ti–Au metal contact was defined on top of the active region by optical lithography and lift-off process. In order to define the tapered and lateral grating regions, firstly, the inductive coupled plasma etching technology was employed to etch off about 10 μm of the active region. Then the rest of the active region was etched by wet etching to polish the side wall of waveguides and eliminate defects induced by dry etching. The Ge/Au/Ni/Au was evaporated and annealed to form the bottom contact. After thinning down the substrate to about 150 μm, the Ti/Au layer was deposited to the back of the devices. The samples were cleaved to about 2.5 mm long and soldered onto the Cu heat sink and wire bonded for measurements. Fig. 1(c) shows the final device configuration, where lateral gratings located on the right part of the figure. Tapered THz QCLs without lateral gratings were also fabricated on the same wafer for comparison.

3. Results and discussions

For testing, samples were mounted to the cold finger of a closed-cycle helium cryostat with a polyethene window. A Winston cone was used to collect light from the facet of lasers. Pulsed light–current characteristics were measured by a thermopile power meter (OPHIR). Spectra were recorded with a Fourier transform infrared spectrometer (Bruker, v66) in rapid scan mode at the resolution of 0.25 cm^{-1}. Driven currents with pulse width of 5 μs at a repetition rate of 5 kHz (duty cycle 1%) were employed in all measurements.

Fig. 2 shows light–current characteristics of 2.5 mm-long tapered QCLs with lateral gratings in pulsed mode. The maximum peak power of ∼30 mW measured at 10 K is obtained, which takes the loss of the polyethene window into account. Lasing ceases around 65 K, which is not shown here. The threshold current density at 10 K is measured to be about 550 A/cm^2, lower than that of devices without lateral gratings (about 590 A/cm^2). The slope efficiency is around 65 mW/A, which is lower than that of devices without lateral gratings (∼83 mW/A) as a result of the scattering loss caused by rough waveguide sidewalls. Higher slope efficiency can be expected by optimization of etching conditions in future.

Fig. 3(b) presents the emission spectra of tapered QCLs without lateral gratings. The observed laser linewidth is limited by the resolution of the experimental apparatus. Multimode emission is observed at all measurement injection currents. Four typical emission spectra of tapered THz QCLs with lateral gratings are shown in Fig. 3(c). The photonic bandgap Δf of the gratings is about 0.55 THz. When the injection current increases from threshold to rollover current (∼3 A–∼3.6 A), single mode operation can be observed with SMSR ∼20 dB which is high enough for applications. Another longitudinal mode only appears as injection current increases far beyond rollover, resulting in SMSR decreasing below 10 dB. This can be explained by a gain that shifts to higher