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Independent Control of Mode Selection and Power Extraction in Terahertz Quantum Cascade Lasers

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Abstract—**We demonstrate novel THz quantum cascade lasers with a gain endowed photonic crystal (PhC) and a grating coupler (GC) formed on each end of the ridge. The PhC acts as a reflection mirror with extremely narrow bandwidth, and the GC enables high radiation efficiency. Such configuration independently controls the mode control and power extraction, and results in stable single mode emission with very high output power.**

I. INTRODUCTION

SINGLE mode emission and high output power are of core importance for semiconductor lasers, and exhibit significant advantages in the applications including imagining, spectroscopy, ultra-high bit rate wireless communication, trace gas analysis, biological diagnosis, etc.

Distributed feedback and coupled-cavity are the main mechanisms implemented in the compact semiconductor lasers to realize single mode emission [1-14]. The former can further be catalogued into distributed feedback (DFB) lasers [1-6], distributed Bragg reflector (DBR) lasers [7-8], and vertical cavity surface emitting lasers (VCSEL) [9-10]. Although numerous efforts have been devoted to improve the stabilization of single mode emission and the output power, in most cases, these two performances constrain each other. Single mode operation requires that the desired mode has sufficiently lower threshold gain than the competitors. High output power demands a large gain media and high power efficiency. However, an enlarged gain media (*i.e.* laser cavity) will contain more laser modes and high power efficiency indicates a high radiation loss of the laser mode, both factors degrading the mode competition and even resulting in multimode operation.

Up to now, few mechanisms have been proposed to realize simultaneously stable single mode emission with an enlarged gain media and high power efficiency. For DFB lasers – although strategies such as chirped grating, graded photonic heterostructure, and hybrid Bragg grating have been developed to improve the power efficiency [1-6] – the laser ridge should be short enough to eliminate high order longitudinal modes. For DBR lasers, several different DBR gratings such as high-order grating and sampled grating have been demonstrated to narrow the band of high reflectivity [7-8]. But the length of the active region section is still restricted to make the free spectral range larger than the reflection bandwidth. For VCSELs, in the short cavity between the DBR mirrors, the thin active region should overlap the peak of the fundamental mode to enhance the discrimination against the adjacent longitudinal modes [9-10]. Also for the coupled-cavity lasers, the primary cavity should be short to enhance the mode discrimination and to avoid mode hopping [11-14]. The small usable active region severely limits the maximum output power in each laser element.

In this work, we demonstrate a novel mechanism to independently control the mode selection and power extraction of a semiconductor laser, i.e., to realize stable single mode emission with controllable radiation efficiency and maximized length of the active region. The concept is implemented on terahertz quantum cascade lasers (THz QCLs) with metallic waveguides. Stable single-mode emission at ~ 3.1 THz is realized with the peak output power as high as 273 mW at 77 K. The output power is comparable to the state-of-the-art ever reported. More notably, both the peak output power and the slope efficiency reported in this work are several times higher than the multimode FP cavity counterparts with single plasmon waveguide, which is previously the mature configuration to reach high output for THz QCLs.

II. RESULTS

Figure 1(a) illustrates the scheme of the device. The device is based on a metal-metal waveguide, where the active region is sandwiched between the bottom and the top metallic layers. On top of the ridge, a PhC (photonic crystal, containing a square lattice of air holes in the metallic layer) together with an absorbing boundary (consisted of the highly doped n^+ GaAs contact layer uncovered by the top metallic layer) is formed on one end. On the other end, a grating coupler (GC) consisting of periodic air slits in the top metallization is formed near the cleaved facet [15]. The PhC, the laser ridge, and the GC share the same active region. Fig. 1(b) shows schematically the gain distribution of the active region.

The PhC together with the absorbing boundary act as a DBR mirror that reflect the THz wave injected along the ridge. Depending on the structure design and bias level, this DBR mirror will operate in different regime and exhibit significantly different performance. When the PhC is passive or is slightly biased that the material gain is considerably less than the total loss (material loss and cavity loss), the reflection spectrum features a broad plateau where the peak reflectivity is close to unity, together with symmetrical side peaks. The broad plateau corresponds to the photonic band gap of the PhC, whose width is usually in the order of 0.1 THz. However, when the PhC is designed to have a high Q-factor and the active region is biased so that the gain almost compensates the total loss of the PhC, the reflection spectrum changes dramatically. As shown in Fig. 1(c), the gain endowed PhC features two very narrow reflection peaks which corresponds to the band edge modes. The two band edge modes have similar cavity loss, but the low-frequency mode shows higher mode confinement factor than the other, indicating lower threshold gain. Essentially, when the frequency of the incident THz wave is in resonance with the low-frequency band edge mode, the wave will oscillates many times inside the PhC and be amplified and finally reflected back into the ridge. For a gain endowed PhC, The full width of half maximum (FWHM) of the reflectivity peak is only ~7 GHz, over one order of magnitude narrower than the band width caused by a passive PhC. Note, for a FP cavity whose length is 3 mm, the free spectral range (FSR) is about 15 GHz. Consequently, the gain endowed PhC acts as a DBR mirror with extremely narrow reflection band width, and greatly releases the constraints on the ridge length. By aligning the gain peak with the low-frequency reflection peak, single mode emission is expected even for a long laser ridge.

On the other hand, although high quality anti-reflection (AR) coatings have been widely used in near- and mid-infrared ranges to control the radiation efficiency of the semiconductor lasers, extending the AR coatings to far-infrared or terahertz frequency range is still very challenging due to the extremely enlarged operation wavelength. To address this issue, we monolithically integrate a GC near the other end of the laser ridge (see Fig. 1(a)), which radiates the THz wave into the free space when it oscillates between the PhC and the cleaved facet. By judiciously designing the GC structure, we can manipulate the effective radiation loss in a wide range, varying from 1.5 to 6 cm^{-1} when the ridge length between the PhC and the GC is as long as 3mm, as shown in Fig. 1(d).

A series of devices have been processed and the results are presented in Fig. 2. Typically, the PhC and the GC contain respectively 46 and 30 periods, and the total cavity length is 4.7 mm. Fig. 2(a) shows the emission spectra of devices with different PhC periodicity. Single mode emissions are achieved for all the devices, and the emission wavelength increases approximately linearly from 102.1 µm to 104.7 µm when the PhC periodicity changes from 13.7µm to 14.3µm. It illustrates the emission wavelength is determined by the band edge mode of the PhC. Fig. 2(b) plots the light-current-voltage (*L-I-V*) curves of a typical device. Because a relatively high radiation loss (~6 cm^{-1}) is exploited in the design, the peak output power reaches to 366 mW at 20K, and remains 224 mW at 77K, measured in pulsed mode. Thanks to the metal-metal waveguide which gives rise to a near unity confinement effector, the maximum operation temperature reaches to 147K. Single-lobed far field beam pattern was obtained, and the divergence angle at FWHM is about 8°×33°.

III. Summary

In conclusion, we have demonstrated a new THz resonator in which the gain endowed PhC acts as a reflection mirror with extremely narrow bandwidth, and the GC significantly enhances the radiation efficiency. The combination of the PhC and GC enables independent control of mode selection and power extraction, resulting in stable single mode emission, enlarged dimensions of gain material and controllably high radiation efficiency. High power (226 mW) of single mode operation has been achieved at liquid nitrogen temperature in pulsed mode, which makes the lasers promising for real world applications.

The concept developed in this work can be straightforwardly extended to the mid- and near-infrared spectral ranges. Essentially, extremely narrow reflection band can be generalized once the total loss of any DBR structure is compensated by the material gain regardless the operation frequency, and the AR coatings with controllable facet reflectivity have been well developed in the mid- and near-infrared spectral ranges.

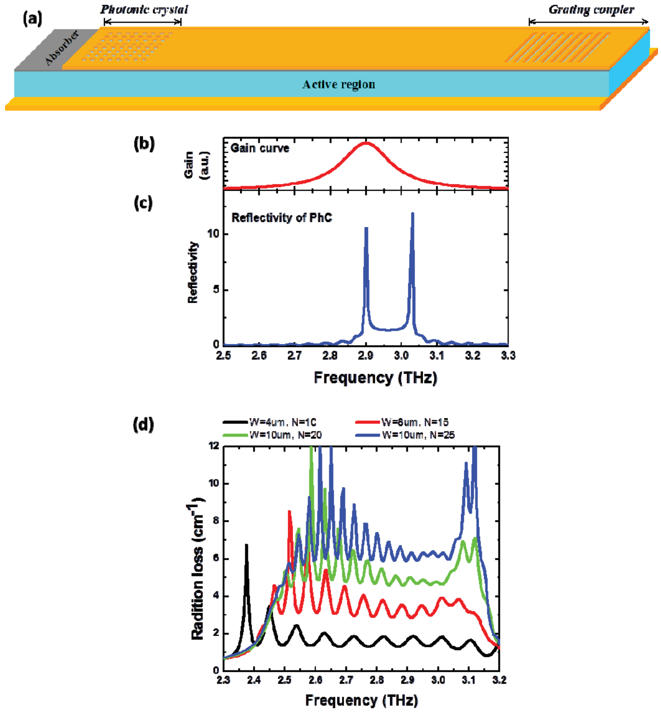

Fig. 1 (a) Schematic illustration of the device with a PhC and a GC near each end of the ridge. (b) Schematic gain curve of the active region. (c) Calculated reflectivity of a gain endowed PhC. (d) Calculated radiation loss of the GC with different W (slit width) and N (number of slits).

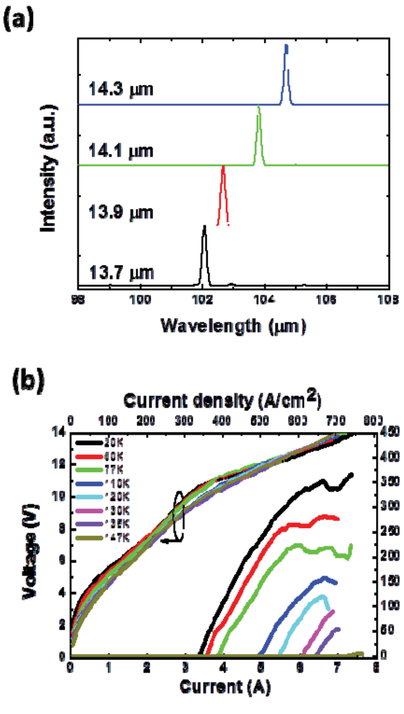

Fig. 2 (a) Emission spectra of devices where the PhC periodicity varies from 13.7µm to 14.3µm. *L-I-V* curves of a typical device measured in pulsed mode at different heat sink temperature.

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