High power terahertz quantum cascade laser

Jianyan Chen (陈剑燕), Junqi Liu (刘俊岐)*, Tao Wang (王 涛), Fengqi Liu (刘峰奇), and Zhanguo Wang (王占国)**

Key Laboratory of Semiconductor Materials Science, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China

**Corresponding author: jqliu@semi.ac.cn;* ***corresponding author: fqliu@semi.ac.cn*

Received January 21, 2013; accepted March 25, 2013; posted online July 17, 2013

We present high power terahertz quantum laser at about 3 THz based on bound-to-continuum active region design. At 10 K, corrected by the collection efficiency, the maximum peak power of 137 mW is obtained in pulsed mode. What's more, we firstly introduce monolithically integrated THz quantum cascade laser (QCL) array and the maximum peak power increased to 218 mW after correction. In total, the array shows better performance than single device, implying cheerful prospect.

OCIS codes: 040.1240, 140.5965.

doi: 10.3788/COL201311.S20401.

In recent years, the terahertz (THz) frequency range (0.1 $\sim$ 10 THz) has been concerned because of its great potential applications in medicine, biological analysis, chemical monitoring, security, and astronomy, etc. With the development of THz technique, the "THz gap", formed due to the lack of suitable sources to generate steady radiation, has been gradually filled up. However, high-power THz radiation sources are still much desired in many applications. Among the various methods of generating coherent THz radiation, quantum cascade laser (QCL)[1,2] as compact and convenient device is the most promising candidate due to its novel operation principle and attainable performance. Up to now, spectral coverage has been demonstrated from 1.2–5.0 THz (when operated without the assistance of external magnetic field)[3]. However, their operation temperature is still limited in the cryogenic range[4], leading to considerable interest to raise it into thermoelectric coolers' range. At the same time, for application requirement, higher output power is always another most important research goal. High power operation based on resonant-phonon (RP) active region design has been reported[5]. However, considered fault-tolerant space when grown by molecular bean epitaxy (MBE), the bound-to-continuum (BTC) structure is more robust than the RP structures[6]. In this work, we demonstrate high power operation of THz QCLs operating at about 3 THz based on BTC active region structure. What's more, we firstly introduce THz QCL array by monolithically integrated technology to obtain higher output power.

The active region unit, based on $GaAs/Al_{0.15}Ga_{0.85}As$ material system, builds BTC transition similar to that in Ref. [7], is grown by EPI Gen II solid source MBE on a semi-insulating GaAs substrate. The growth started with 0.8-μm highly-doped (Si, 2.5×10^{18} cm^{-3}) GaAs cladding, followed by 120 periods of chirped superlattice active region unit with the actual thickness of 14.37 μm. Finally, a 0.2-μm highly-doped (Si, 5×10^{18} cm^{-3}) GaAs was grown as the top contact layer. The sample was then processed into 1.5-mm-long semi-insulating surface-plasmon devices with 125- and 225-μm widths as described in Ref. [8] except the Bragg gratings, followed by deposition of $Al_2O_3/Ti/Au/Ti/Al_2O_3$ as high-reflection coating on the rear facet. Figure 1 shows optical microscope photographs of single device and integrated THz QCL array (two devices).

For measurement, the devices were soldered onto the Cu heat-sinks and wire-bounded. The packaged laser bars were then mounted to the cold finger of a liquid helium flow cryostat. An f/2.0 Winston cone with an exit diameter of 8.2 mm was used to collect light from the facet. For pulsed light power measurement, the emission was collected by a calibrated thermopile powermeter (Model 3A-NOVA II, OPHIR, Israel) with the detection aperture of 9.5 mm at a distance of about 41 mm. The calculated collection efficiency was to about 22%.

Figure 2 shows the pulsed output power and voltage as functions of current (L-I-V characteristics) of the single

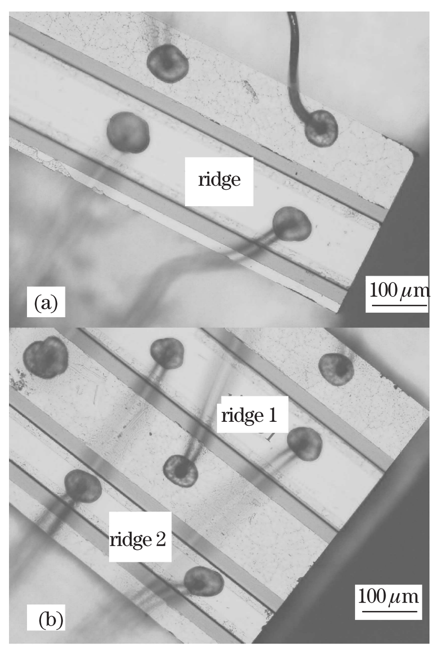

Fig. 1. (Color online) (a) Optical microscopy top viewport of single device with 225-μm-wide ridge. (b) Optical microscopy top viewport of integrated THz QCL array composed of two devices with 125-μm-wide and 225-μm-wide ridges.

225-μm-wide device at different operating temperatures. By applying pulse width of 2 μs and a repetition rate of 5 kHz, the lasing ceased at a heat-sink temperature of 87 K with a collected optical power of 0.9 mW (uncorrected by the collection efficiency). The collected peak optical power at 10 K exhibits a value of 30.1 mW (137 mW, after correction by the collection efficiency of 22%) with a threshold current density of J_{th}=247.5 A/cm^2.

In Fig. 3, we plot the L-I-V characteristics of the two device arrays. It's obviously that the total peak output power raised up to 48 mW (218 mW after correction), just as the addition of two devices. The heat cross-disturbance between the two devices may hinder the heat dissipation in some degree. As a result, the highest operation temperature is a little lower compared with single device.

The performance comparison of the array and the single device were shown in Figs. 4 and 5. Figure 4 shows the relationship between threshold current density and heat-sink temperature in pulsed mode. For all temperatures, the average threshold current densities of array are lower than that of single device. By fitting the temperature dependence of threshold current density with an exponential function $J_{\mathrm{th}}=J_0+J_1\exp(T/T_0)$, the characteristic temperature of T_0=20.7, 24.7 K were obtained, respectively. The relatively lower T_0 of the array also

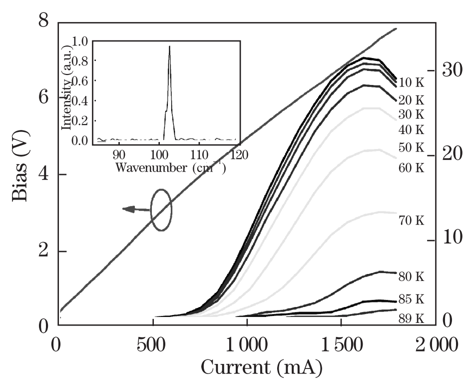

Fig. 2. (Color online) Pulsed L-I-V characteristics of a 1.5-mm-long and 225-μm-wide device at different operating temperature. The optical output power values presented here only corrected by the transmission of the polyethylene window (0.75). The insert shows the lasing spectrum of the device at 10 K.

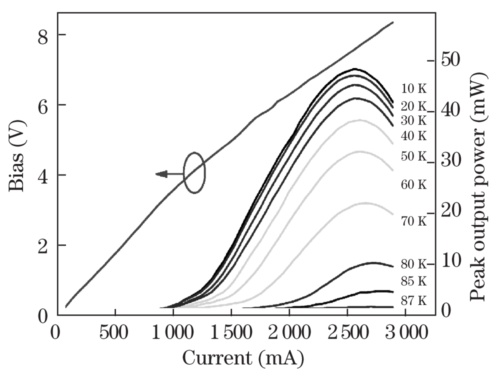

Fig. 3. (Color online) Pulsed L-I-V characteristics of a THz QCL array composed of two 1.5-mm-long devices with 125- and 225-μm width at different operating temperatures. The optical output power values presented here only corrected by the transmission of the polyethylene window (0.75).

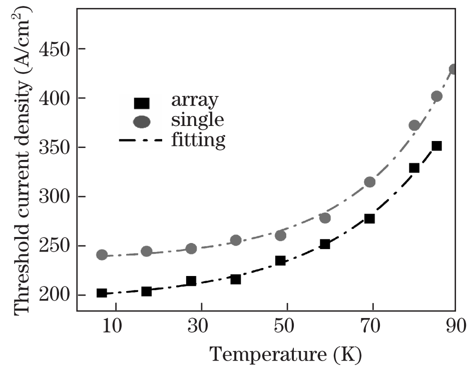

Fig. 4. (Color online) Threshold current density as a function of heat-sink temperature for single device and array. The dash lines are the exponential fitting of the measurement data (points).

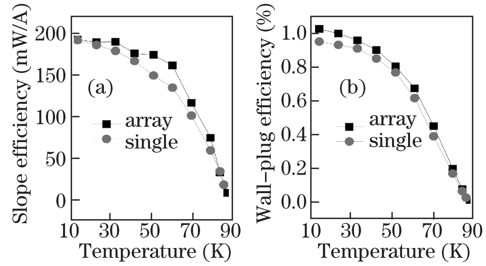

Fig. 5. (Color online) (a) Slope efficiency and (b) wall-plug efficiency as functions of heat-sink temperature for single device and array. The collection efficiency of 22% is considered in these data.

indicates the effect of heat cross-disturbance.

The slope efficiency at various heat-sink temperatures were shown in Fig. 5(a). Corrected with the factor of 22%, the maximum value of about 191 mW/A at 10 K for both array and single device were obtained. The slope efficiency of the laser with the rear facet is coated can be expressed as

$$\frac{\mathrm{d}P}{\mathrm{d}I}=\frac{h\nu}{e}N_{\mathrm{p}}\frac{\alpha_{\mathrm{m}}}{\alpha_{\mathrm{m}}+\alpha_{\mathrm{w}}}\eta_i,$$

where $h\nu$ is the photon energy, e is the elemental electronic charge, N_{p} is the number of cascade period, α_{w} is the waveguide loss, $\alpha_{\mathrm{m}}=-\ln(R_1\cdot R_2)/2L$ is the mirror lass, and η_i is the internal quantum efficiency of each period. As the array is composed of two similar device except the ridge width, the slope efficiency should be close. Our results are mainly in accord with the expected while the array show a little better than the single device between 20 and 80 K.

Wall-plug efficiency (WPE), defined as the division of the total output optical power by the input electrical power, was depicted in Fig. 5(b). It is obviously that the array behaves better than the single device until they exhibit the same value above 85 K. The maximum value of 1.02% was obtained from the array.

In conclusion, we demonstrate high output power THz QCLs at based on BTC active region structure. Also, we introduce monolithically integrated THz QCL array to obtain higher output power. The array composed of two devices shows better performance than single device. It is the first attempt to improve the output power by integrating the devices and the results shows cheerful prospect. In future, we will investigate more about THz QCL array.

This work was supported in part by 100 Talents Program of Chinese Academy of Sciences (No. 1731110000012), the National Natural Science Foundation of China (Nos. 60736031, 60806018, and 60906026), and the Special-Funded Program on National Key Scientific Instruments and Equipment Development (No. 2011YQ13001802-4). The authors would like to thank P. Liang, Y. Hu, and L. Jiang for their help in the processing.

References

1. J. Faist, F. Capasso, D. L. Sivco, C. Sirtori, A. L. Hutchinson, and A. Y. Cho, Science **264,** 553 (1994).
2. S. Kumar, Chin. Opt. Lett. **9,** 110003 (2011).
3. S. Kumar, IEEE J. Sel. Top. Quant. Electron. **17,** 38 (2011).
4. S. Fathololoumi, E. Dupont, C. W. I. Chan, Z. R. Wasilewski, S. R. Laframboise, D. Ban, A. Mátyás, C. Jirauschek, Q. Hu, and H. C. Liu, Opt. Express **20,** 3866 (2012).
5. B. S. Williams, S. Kumar, Q. Hu, and J. L. Reno, Electron. Lett. **42,** 89 (2006).
6. X. Qian, N. Chandrayan, S. R. Vangala, W. D. Goodhue, A. A. Danylov, J. Waldman, C. Baird, R. H. Giles, and W. E. Nixon, Proc. SPIE **8261,** 82610K (2012).
7. J. Q. Liu, J. Y. Chen, F. Q. Liu, L. Li, L. J. Wang, and Z. G. Wang, Chin. Phys. Lett. **27,** 104205 (2010).
8. J. Y. Chen, J. Q. Liu, F. Q. Liu, L. Li, L. J. Wang, and Z. G. Wang, Electron. Lett. **46,** 1340 (2010).