Interband cascade laser arrays with watt-level continuous-wave optical power

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Abstract

Interband cascade laser arrays with continuous-wave (CW) watt-level output power at room temperature are demonstrated. A three-emitter laser array episide-down bonded on a diamond submount exhibited a CW output power in excess of 1 W at 10. The wall-plug efficiency of the laser array is almost the same as that of a single emitter, indicating that there is little heat accumulation caused by the thermal interference between the emitters in the array structure.

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Introduction: Quantum cascade lasers (QCLs) [1] and interband cascade lasers (ICLs) [2] are important coherent light sources in the mid-infrared spectral range. In the past few decades, great progress have been made in the output power and wall-plug efficiency (WPE) of QCLs [3-5]. Benefiting from the efficient heat dissipation properties of the regrown InP in the buried ridge geometry, a room temperature output power of 5 W has been achieved from a 40-stage QCL [6] and 22% WPE [7] from a 45-stage one in continuous wave (CW) operation. Unlike QCLs, ICLs are much more sensitive to the temperature of the active regions. The characteristic temperature of a typical ICL is in the range of 45-55 K [8], which is on the order of 200 K for a QCL. The low characteristic temperatures are ascribed to the high vertical thermal resistance of the thick InAs/AlSb superlattice cladding layers [9] and the unrealized regrowth of GaSb-based materials required for the buried ridge geometry. As a consequence, it is not feasible to increase the CW output power of an ICL just by increasing the number of cascaded stages.

In fact, the maximum room temperature CW output power of 592 mW so far was reported from a 7-stage ICL with a ridge width of 32 µm and a cavity length of 3 mm by the Naval Research Laboratory [10], which is higher than that from their 10-stage device [11]. In addition to stacking multiple active regions, another way to increase the output power of a semiconductor laser is to arrange monolithically multiple emitters in parallel to form an array. Using this configuration, a CW optical power near 1 kW was obtained from a 980 nm diode laser array [12]. For long wavelengths, a GaSb-based type-I quantum well laser array emitting at 2.3 µm exhibited 18.5 W quasi-CW output power at 18 [13]. In this letter, we demonstrate a 3.4 µm type-II ICL array with CW output power in excess of 1 W at 10, using 3-mm long array chips each containing three emitters.

Device design and fabrication: The laser structure was grown on an n-GaSb (001) substrate in a Riber Compact 21 molecular beam epitaxy system. The growth started from an InAs/AlSb superlattice cladding layer, followed by a 7-stage active region sandwiched by two 0.7 µm GaSb separated confinement layers (SCLs). The growth ended with an InAs/AlSb superlattice cladding layer and a 10 nm heavily-doped InAs cap layer. Both SCLs were uniformly n-doped with GaTe to 8×10^{16}cm^{-3}, trading off the serial resistance against the waveguide loss. The thick upper and lower cladding layers of 1.2 µm and 2.5 µm, respectively, were used to prevent optical leakage into the GaSb substrate and the top metallization. The 7-stage active region applied the carrier rebalanced design [14], with necessary adjustments to shift the emission wavelength to 3.4 µm. The wafer was then processed into 16 µm-wide ridges by contact lithography and wet etching. The distance between each ridge was 400 µm, which is necessary to avoid thermal interference according to our thermal simulation. A SiO_2 layer of 450 nm was used for electrical insulation. A Ti/Au metal stack was e-beam evaporated as the top contact. Then, the substrate was mechanically thinned and metalized by a Ge/Au/Pt/Au bottom contact. The wafer was then cleaved into either 3-mm-long single emitters or arrays with multiple emitters. Al_2O_3/Au high-reflection coatings and $\lambda/4$ Al_2O_3 anti-reflection coatings were deposited on the back and front facets of the lasers.

Laser performance: Single ICL emitters were mounted episide-down on AlN heat sinks and tested in CW mode. The emission spectra were recorded by a Fourier transform infrared spectrometer. The output power was measured by a pyroelectric power meter.

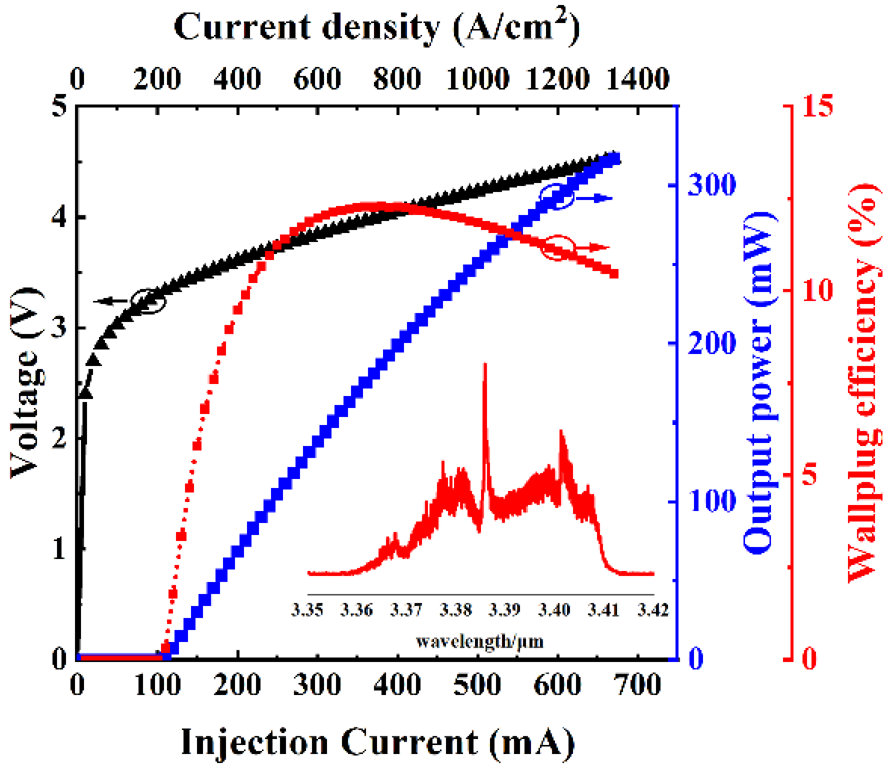

Fig. 1 *Light-Current-Voltage characteristics of a 3-mm-long single ICL emitter with HR/AR coatings in the CW regime at 20°C; inset: the emission spectra at 2*I_{th}.

Figure 1 shows the light-current-voltage (L-I-V) characteristics of a 3-mm-long ICL single emitter with HR/AR coatings. At 20, the threshold current density is 220 A/cm^2 and the slope efficiency near the threshold is 800 mW/A. The maximum WPE reaches 12.3%. These values are close to the previous report on ICLs with the highest CW output power [10]. The CW output power of the single ICL emitter was measured up to 320 mW at the injection current density of 1.35 kA/cm^2, where the WPE is 10.5%. There has been no obvious thermal rollover in the L-I characteristics. As shown in the inset of Fig. 1, the emission spectrum recorded at 2J_{th}injection current density is centered at 3.39 μm, which is consistent with our design.

The three-emitter arrays were mounted epilayer-down on diamond submounts for efficient heat extraction from the laser chips, which were bonded on copper heat sinks. Figure 2 shows the CW L-I-V characteristics of an ICL array sample. Measurements were taken at the heat sink temperature of 10. The threshold current density and the slope efficiency near the threshold are 170 A/cm^2 and 880 mW/A, comparable to the values measured from a single emitter at 10. The output power was measured up to 1.01 W at an injection current of 1.7 A (1.15 kA/cm^2). Again, there is no thermal rollover in the L-I characteristics, indicating a potentially higher maximum output power. The maximum WPE and the WPE at the maximum injection current are 14.4% and 12.9%, respectively.

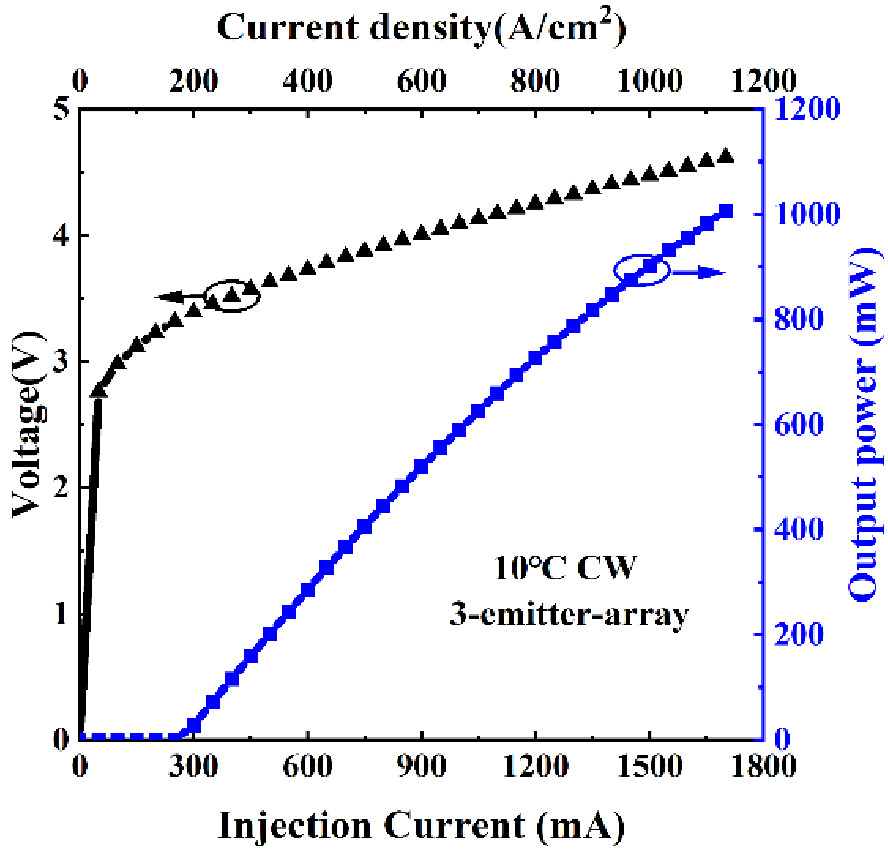

Fig. 2 *Light-Current-Voltage (L-I-V) characteristic of an ICL array with 3 emitters in CW operation at the heat sink temperature of 10°C.*

Figure 3 compares the WPE versus current curves measured from a single emitter and a three-emitter array at 10, respectively. The two curves overlap when the injection current densities are lower than 500 A/cm^2, and deviate slightly as the current density increases. For the single emitter sample, the maximum WPE and the WPE at the maximum current are 15% and 13.6%, respectively. These values are only 0.6% higher than that of the 3-emitter array sample, indicating efficient heat extraction from the

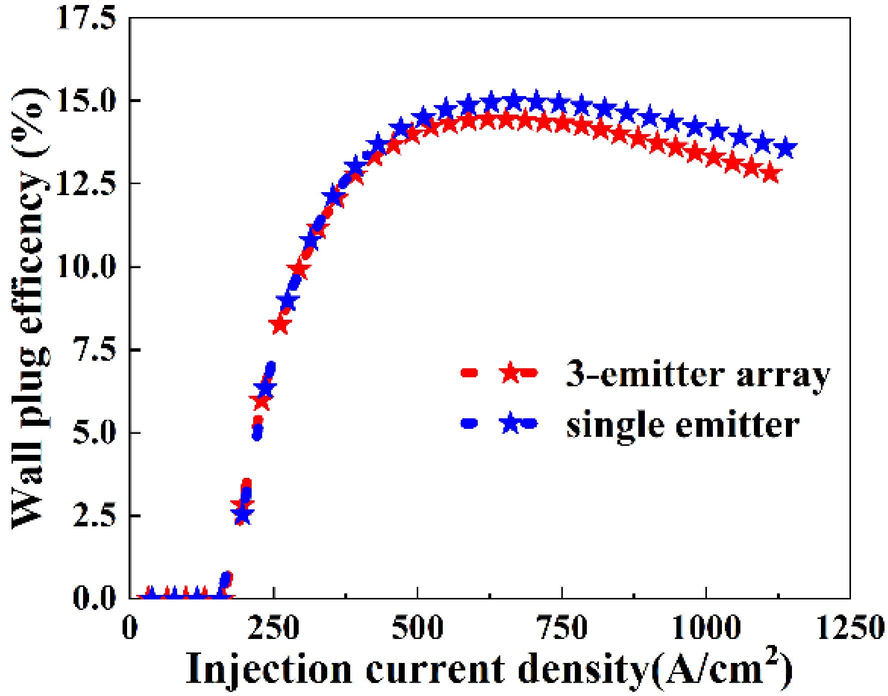

Fig. 3 *Wall-plug efficiency comparison between single emitter against 3-unit ICL array.*

active region and low heat interference between each emitter in our array structure design.

Conclusion: We have demonstrated watt-level ICL arrays operating at 10 in CW operation. The CW output power from a single 16 μm-wide and 3-mm-long ridge emitter reached 320 mW at 20. For an array sample containing three emitters, the maximum WPE of 14.4% was achieved at 10, which is close to the value of 15% measured from a single emitter sample, indicating that the array structure design effectively suppressed thermal interference between the emitters.

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References

1. Faist, J., Capasso, F., Sivco, D. L., et al.: 'Quantum cascade laser', *Science* , 1994,**264** , pp. 533–556
2. Yang, R.Q.: 'Infrared laser based on intersubband transitions in quantum wells', *Superlatt. Microstruct.* , 1995, **17** , pp. 77–83
3. Lyakh, A., Maulini, R., Tsekoun, A. et al.: '3 W continuous-wave room temperature single-facet emission from quantum cascade lasers based on nonresonant extraction design approach', *Appl. Phys. Lett.* , 2009, **95** , p. 141113.
4. Bai, Y., Slivken, S., Darvish, S. R., et al.: 'Room temperature continuous wave operation of quantum cascade lasers with 12.5% wall plug efficiency', *Appl. Phys. Lett.* , 2008, 93(2): p. 021103.

5. Maulini, R., Lyakh, A., Tsekoun, A., et al.: ‘High average power uncooled mid-wave infrared quantum cascade lasers’, *Electron. Lett.* , 2011, **47,** pp. 395-397
6. Bai, Y., Bandyopadhyay, N., Tsao, S. et al.: ‘Room temperature quantum cascade lasers with 27% wall plug efficiency’, *Appl. Phys. Lett.* , 2011, **98** , p. 181102.
7. Wang, F., Slivken, S., Wu, D. H., et al.: ‘Room temperature quantum cascade lasers with 22% wall plug efficiency in continuous-wave operation’, *Opt. Express* , 2020, **28** (12), pp. 17532-17538.
8. Meyer, J., Bewley, W. W., Canedy, C. L., et al.: ‘The interband cascade laser’, *Photonics* , 2020, **7** (3), p. 75
9. Zhou, C., Vurgaftman, I., Canedy, C. L., et al.: ‘Thermal conductivity tensors of the cladding and active layers of antimonide infrared lasers and detectors’, *Opt. Mater. Express* , 2013,**3** (10), pp1632-1640
10. Canedy, C. L., Abell, J., Merritt, C. D., et al.: ‘Pulsed and CW performance of 7-stage interband cascade lasers’, *Opt. Express* , 2014, **22** (7): p. 7702-7710.
11. Kim, M., Bewley, W. W., Canedy, C. L., et al.:’ High-power continuous-wave interband cascade lasers with 10 active stages’,*Opt. Express* , 2015, **23** (8), pp. 9664-9672.
12. Li, H., Towe, T., Chyr, I., et al.: ‘Near 1 kW of continuous-wave power from a single high-efficiency diode-laser bar. *IEEE Photon. Technol. Lett.* , 2007, **19** (13), pp. 960-962.
13. Shterengas, L., Belenky, G. L., Gourevitch, A., et al.: ‘High-power 2.3-μm GaSb-based linear laser array’, IEEE Photon. Technol. Lett., 2004, **16** (10), pp. 2218-2220.
14. Vurgaftman, I., Bewley, W. W., Canedy, C. L., et al.: ‘Rebalancing of internally generated carriers for mid-infrared interband cascade lasers with very low power consumption’, Nat. Commun., 2011,**2** , p. 585.