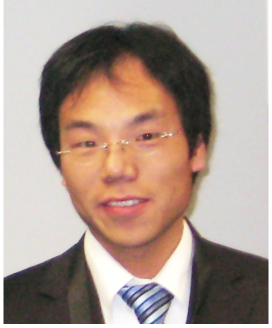
High power quantum cascade ring lasers and possible applications

Yanbo Bai *[a], Steven Slivken, Neelanjan Bandyopadhyay, Quanyong Lu, and Manijeh Razeghi
[a]Center for Quantum Devices, Department of Electrical Engineering and Computer Science,
Northwestern University, Evanston, Illinois 60208

BIOGRAPHY



Yanbo Bai received his M.S. degree in Physics and Ph.D. degree in Electrical Engineering from Northwestern University in 2005 and 2011. He is currently a research assistant professor at Northwestern. Since 2005, he has been with the Center for Quantum Devices. His research holds the current performance records of mid-IR quantum cascade lasers (QCLs) in terms of the output power and wall plug efficiency. He has also been investigating photonic crystals, broad area devices, optical coatings, ring lasers, and terahertz QCLs. He is the recipient of SPIE best student paper award (2008), SPIE optical science and engineering scholarship (2010), IEEE photonics society graduate student fellowship (2010), and Northwestern EECS outstanding Ph.D. thesis award (2011). He is the author of 18 peer reviewed journal publications and 11 conference papers.

TECHNICAL ABSTRACT

Quantum cascade laser (QCL) technology has undergone tremendous development in the last decade [1]. The current state-of-the-art QCL gain medium gives a wall plug efficiency (WPE) of 21% in room temperature continuous wave (cw) operation [2]. This was achieved in conventional edge-emitting devices without intentional spectral and spatial beam quality control. Add-on features, such as one dimensional distributed feedback (1D-DFB) [3], photonic crystal distributed feedback (PCDFB) [4], or ring cavity surface emitting (RCSE) QCLs [5], allow for spectral and/or spatial beam shaping to some extent. However, except for the conventional edge emitting 1D-DFB, which has been demonstrated with watt-level cw operation at room temperature [6], the rest are limited to pulsed mode operation.

According to diffraction principles, the far field divergence is inversely proportional to the size of the emitting aperture in the near field. Therefore, a low divergence beam calls for a large emitting aperture on the device. For edge emitting devices, although the lateral dimension of the emitting aperture can be increased, such as in the case of the PCDFB, the vertical beam divergence is still limited by the thickness of the laser core. An exception is using plasmonics to expand the near field toward the substrate on the edge emitting facet [7], but this technique is still limited by the thickness of the substrate, and has not been proven under cw operation. In comparison, surface emitting devices can make use of a much larger aperture, in some cases the size the entire device. Therefore, they are ideal candidates for extremely directional beams.

However, cw operation of surface emitting QCLs poses a significant challenge. For conventional edge emitting QCLs, cw operation is usually realized with all or some of the following thermal management techniques: thick gold plating, narrow ridge widths, buried heterostructures, epilayer-down bonding, etc. For the RCSE QCL demonstrated in [8], a narrow ridge width has already been implemented. Room temperature cw operation is precluded not only due to a high threshold gain medium, but also the lack of efficient heat removal mechanisms. Considering the small grating size, electroplating of thick gold on top of the device would block the emission. Epilayer-down bonding, on the other hand, is a viable choice for efficient heat removal. With this technique, the heat generating surface is placed in close proximity to the heat sink. As such, the light has to be extracted from the substrate side. Although substrate emitting QCLs have been demonstrated [9-11], no cw operation has been reported. Here, we show substrate emitting quantum cascade ring lasers with high cw power at room temperature. The emission wavelength is around 4.85 μm with a high power output of 0.51 W. Single mode operation persists up to 0.4 W (Fig. 1). Far field exhibits concentric ring features. Modal behavior is analyzed using the coupled mode theory, which suggests that the device operates in an extremely high order mode. Polarization measurement indicates that the beam is azimuthally polarized.

Many applications can be envisioned using the demonstrated high power quantum cascade ring lasers as the building blocks. First, surface emitting devices can be arranged in a two-dimensional array, which is an excellent platform for power scaling, beam combining, and wide range tuning with DFB. Second, the ring laser concept can be

used in the recently developed THz sources based on intracavity difference frequency generation, which allows for a compact room temperature THz source with single mode emission, good beam quality and continuous wave operation. Third, the unique polarization state with high power output may find applications in tight focusing, optical tweezers, and plasmonics.

Keywords: quantum cascade lasers, ring lasers, substrate emission, high power

*y-bai@northwestern.edu; http://cqd.eecs.northwestern.edu/

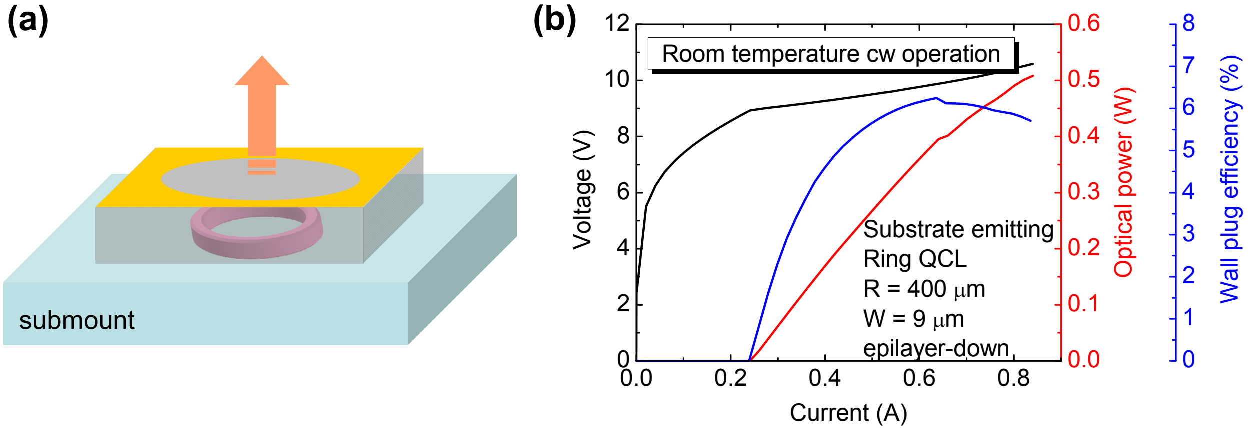


Fig. 1 (a). Schematic for the substrate emitting quantum cascade ring laser epilayer-down bonded to an AlN submount. (b). Voltage, power, and wall plug efficiency as a function of current in room temperature cw operation for the substrate emitting quantum cascade ring laser.

References

[1] Razeghi, M., "High-Performance InP-Based Mid-IR Quantum Cascade Lasers," IEEE J. Sel. Top. Quantum Electron., 15, 941-951 (2009).

[2] Bai, Y., Bandyopadhyay, N., Tsao, S., Slivken, S., and Razeghi, M., "Room temperature quantum cascade lasers with 27% wall plug efficiency," Appl. Phys. Lett., 98, 181102 (2011).

[3] Faist, J., Gmachl, C., Capasso, F., Sirtori, C., Sivco, D. L., Baillargeon, J. N., and Cho, A. Y., "Distributed feedback quantum cascade lasers," Appl. Phys. Lett., 70, 2670-2672 (1997).

[4] Bai, Y., Darvish, S. R., Slivken, S., Sung, P., Nguyen, J., Evans, A., Zhang, W., and Razeghi, M., "Electrically pumped photonic crystal distributed feedback quantum cascade lasers," Appl. Phys. Lett., 91, 141123 (2007).

[5] Mujagic, E., Schartner, S., Hoffmann, L. K., Schrenk, W., Semtsiv, M. P., Wienold, M., Masselink, W. T., and Strasser, G., "Grating-coupled surface emitting quantum cascade ring lasers," Appl. Phys. Lett., 93, 011108 (2008).

[6] Lu, Q. Y., Bai, Y., Bandyopadhyay, N., Slivken, S., and Razeghi, M., "2.4 W room temperature continuous wave operation of distributed feedback quantum cascade lasers," Appl. Phys. Lett., 98, 181106 (2011).

[7] Yu, N. F., Fan, J., Wang, Q. J., Pflugl, C., Diehl, L., Edamura, T., Yamanishi, M., Kan, H., and Capasso, F., "Small-divergence semiconductor lasers by plasmonic collimation," Nat. Photonics, 2, 564-570 (2008).

[8] Mujagic, E., Nobile, M., Detz, H., Schrenk, W., Chen, J. X., Gmachl, C., and Strasser, G., "Ring cavity induced threshold reduction in single-mode surface emitting quantum cascade lasers," Appl. Phys. Lett., 96, 031111 (2010).

[9] Lyakh, A., Zory, P., D'Souza, M., and Botez, D., "Substrate-emitting, distributed feedback quantum cascade lasers," Appl. Phys. Lett., 91, 181116 (2007).

[10] Maisons, G., Carras, M., Garcia, M., Parillaud, O., Simozrag, B., Marcadet, X., and De Rossi, A., "Substrate emitting index coupled quantum cascade lasers using biperiodic top metal grating," Appl. Phys. Lett., 94, 151104 (2009).

[11] Maisons, G., Carras, M., Garcia, M., Simozrag, B., and Marcadet, X., "Directional single mode quantum cascade laser emission using second-order metal grating coupler," Appl. Phys. Lett., 98, 021101 (2011).