Late Breaking Results with Ultra Broad Tuning in External Cavity Quantum Cascade Lasers

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BIOGRAPHY

Timothy Day: is a cofounder of Daylight Solutions and serves as the CEO and CTO for the company. Daylight Solutions is a manufacturer of advanced molecular detection and imaging products, serving markets that include Industrial Process Control, Medical Diagnostics, Defense and Security, and Fundamental Research using mid-IR lasers and sensor systems. Dr. Day has over 20 years' experience in both technical and business management in the photonics industry. He has led engineering, research, product development, manufacturing, and marketing operations. He started his career as a cofounder of New Focus, where he served from 1990 through 2004. During his time at New Focus, he was involved in all aspects of the company's history, concluding with his work on the sale of the company to Bookham Technology PLC for $338M. While at New Focus he also contributed to the raising of over $500M though public and private equity offerings. From 1990 to the present, while at New Focus and Daylight Solutions, Dr. Day has developed extensive patent and product portfolios and transferred numerous products into production, both onshore and overseas.

TECHNICAL ABSTRACT

The mid-IR portion of the electromagnetic spectrum (~3-20 µm) is a feature-rich spectroscopic region. Most molecules have fundamental vibrational transitions in this region that are typically 30-1000 times stronger than overtones or combination bands that occur in the more easily accessible visible and near-infrared portion of the spectrum. Molecules with absorption bands in the mid-IR are of interest for a wide range of applications, from environmental monitoring to defense and security to bio-medical diagnostics. Many of these applications benefit from a source with broad tuning across the mid-IR range.

Quantum Cascade Lasers (QCLs), invented in 1994 [1], have become the standard gain media for lasers where high-power, room temperature operation and continuous wavelength coverage are required in the mid-IR. A key figure of merit for users and for success in commercial applications is the 'cost per wavenumber', and critical to improving this figure is increasing the gain bandwidth from individual QCLs as well as accessing the gain bandwidth in an efficient manner. For QCLs to achieve the promise of miniaturizing and fully commercializing the powerful spectroscopic and imaging techniques in the mid-IR, QCL tuning ranges need to be pushed to the maximum.

Many researchers have demonstrated ever increasing bandwidths by modifying the structure of the quantum wells in the cascade. Designs have evolved from bound-to-bound energy levels that typically permit tuning of 5-10% of the center wavelength to the use of continuum states (B-C, C-B) that have demonstrated tuning over 25% of the center bandwidth [2,3,4]. The state-of-the art in broadband QCL gain media is achieved using heterogeneous structures, where quantum wells with different structures are combined within the same chip[5].

Many spectroscopic applications require a controlled emission from the QCL, with both a narrow linewidth and broad wavelength tuning. One approach to controlling the linewidth and frequency of a QCL is to grow a Bragg Reflector epitaxially onto the surface of the waveguide. By controlling the temperature of the gain chip, this Distributed Feedback (DFB) system can be caused to tune with narrow linewidth over a limited frequency range (~ 5-15 cm^{-1}) [6,7]. Multiple DFBs can be combined on a device to expand the tuning range [8]. Much more of the available gain bandwith may be exploited with even narrower linewidth by employing an External Cavity. Over 525 cm^{-1} of single mode tuning from a single QCL chip at 4.2 microns has been achieved, representing tuning of 22% of the center bandwidth [9].

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Late-breaking results exceeding tuning over 40% of the center wavelength will be presented. The rapid evolution in tuning range achieved from a single QCL in an external cavity is shown by the chart in Figure 1.

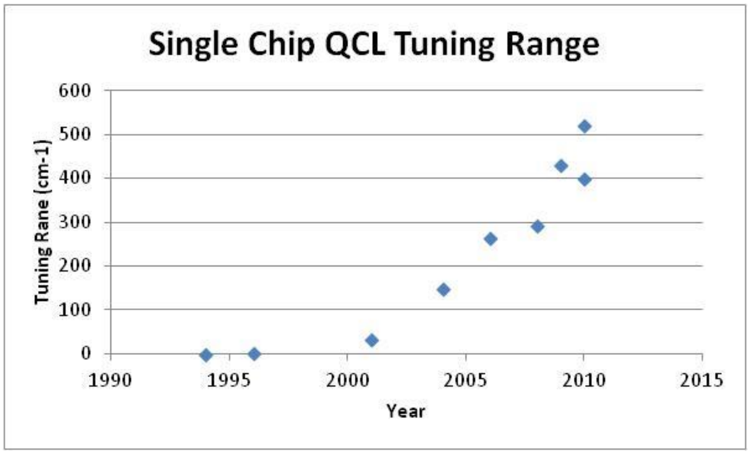

Figure 1: Chart demonstrating the rapid evolution in tuning range achieved by a single QCL in an external cavity.

Even with this impressive tuning of 40% of the center bandwidth, practical instruments that access the mid-IR may still require multiple QCLs. For these applications, combining multiple external cavity lasers in a single instrument allows a further reduction in the cost per wavenumber. This allows much of the electronics and mechanical elements to be shared within the instrument. Up to 4 QCLs have been combined in a single instrument, allowing much of the mid-IR wavelength range to be accessed from a single instrument. Further improvements in QCL tuning range will reduce the number of gain media required, further reducing the cost per wavenumber, and will allow QCLs to find commercial success in a range of applications.

References:

[1] Faist, J., Capasso, F., Sivco, D.L., Sirtori, C., Hutchinson, A.L., Cho, A.Y. "Quantum Cascade Laser," Science, (264), pg. 553 (1994).

[2] Faist, J., Beck, M., Aellen, T., "Quantum-cascade Lasers Based on a Bound-to-Continuum Transition", Appl. Phys. Lett., 78 (2), pg. 147 (2001).

[3] Fujita, K., Edamura, T., Furuta, S., Yamanishi, M., "High-Performance, Homogeneous Broad-Gain Quantum Cascade Lasers Based on Dual-Upper-State Design," Appl. Phys. Lett. 96 (24), pg. 241107 (2010).

[4] K. Fujita, S. Furuta, A. Sugiyama, T. Ochiai, A. Ito, T. Dougakiuchi, T. Edamura, and M. Yamanishi, Appl. Phys. Lett. **98**, 231102 (2011).

[5]. C. Gmachl, D. L. Sivco, R. Colombelli, F. Capasso, and A. Y. Cho, "Ultra-broadband semiconductor laser," *Nature (London)* **415**, 883– 887 (2002).

[6] C. Gmachl, A. Straub, R. Colombelli, F. Capasso, D. L. Silvco, A. M. Sergent, and A. Y. Cho, "Single-mode, tunable distributed-feedback and multiple-wavelength quantum cascade lasers," *IEEE J. Quantum Electron.* **38**(6), 569–581 (2002).

[7] S. Bartalini, S. Borri, P. Cancio, A. Castrillo, I. Galli, G. Giusfredi, D. Mazzotti, L. Gianfrani, and P. De Natale, "Observing the intrinsic linewidth of a quantum-cascade laser: Beyond the Schawlow-Townes limit," *Phys. Rev. Lett.* 104, 083904-083901–083904-083904 (2010).

[8] Lee, Benjamin G., Mikhail A. Belkin, Christian Pflügl, Laurent Diehl, Haifei A. Zhang, Ross M. Audet, Jim MacArthur, David P. Bour, Scott W. Corzine, Gloria E. Hofler, Federico Capasso. "DFB quantum cascade laser arrays." IEEE Journal of Quantum Electronics 45(5): 554-565 (2009).

[9] Caffey, D., Radunsky, M.B., Cook, V., Weida, M., Buerki, P.R., Crivello, S., Day, T. "Recent results from broadly tunable external cavity quantum cascade lasers," Proceedings of the SPIE, Volume 7953, pp. 79531K-79531K-11 (2011).

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