Optical Engineering 49(11), 111120 (November 2010)

Utilizing broad gain bandwidth in quantum cascade devices

Miles J. Weida, MEMBER SPIE
David Caffey
Jeremy A. Rowlette
David F. Arnone
Timothy Day, MEMBER SPIE
Daylight Solutions, Incorporated
15378 Avenue of Science, Suite 200
San Diego, California 92128
E-mail: mweida@daylightsolutions.com

Abstract. The utilization of the broad gain bandwidth available from quantum cascade (QC) devices is considered. The performance of homogeneous and heterogeneous QC gain media is explored in an external-cavity configuration. Paradigms for realizing fixed wavelength or broad tuning performance of QC devices are considered. [DOI: 10.1117/1.3505845]

Subject terms: semiconductor lasers; lasers; infrared lasers; infrared spectroscopy.

Paper 100400SSR received May 7, 2010; revised manuscript received Jul. 12, 2010; accepted for publication Aug. 24, 2010; published online Nov. 22, 2010.

1 Introduction

Quantum cascade (QC) devices have become the standard gain media for lasers where high power, room-temperature operation, and continuous wavelength coverage are required in the midinfrared region of 3 to 12 μm. Recently, a tuning range of 432 cm^{-1} was demonstrated[1] for a QC device run in external-cavity mode. Such a broad gain bandwidth is comparable to results achieved with other semiconductor gain media: For example, 596 cm^{-1} of tuning has been demonstrated in near-IR diodes,[2] and 444 cm^{-1} in cryogenically cooled mid-IR Pb-salt diodes.[3] Utilizing the broad gain bandwidth of QC devices is an important consideration in the commercialization of QC-based lasers.

Broad gain bandwidth in a gain medium offers potential advantages in the manufacture of lasers. For fixed-wavelength lasers, a larger offering of wavelengths can be made without having to create multiple gain media.[4] Broad gain bandwidth can be converted into tuning range to access wider spectral ranges.[5] In both cases, however, a method is needed to restrict the laser operation to a single mode or subset of modes that are useful for the application of interest.

Distributed feedback (DFB) structures have been integrated into the QC waveguide to restrict lasing to a narrow wavelength range.[6] This approach has the advantage that an extremely compact single-mode laser can be made with narrow linewidth and low frequency noise.[7] DFB lasers can be used in an intrapulse mode to perform spectroscopy of rotationally resolved gas molecules over a few inverse centimeters.[8] Ultimately, however, DFB QC lasers can only realize broader tuning by changing temperature, which limits their effective tuning range to less than 20 cm^{-1}, not nearly enough to utilize the full gain bandwidth available in QC devices. Moreover, from a manufacturing standpoint, different DFB QC devices have to be stocked for each fixed wavelength, negating the advantage of broad gain bandwidth in manufacturing.

An alternative method, which allows for manufacturing settability of wavelength and broad tuning if required, is an external-cavity configuration. External-cavity QC lasers have been successfully employed to realize both narrow linewidth and broad tuning.[9,10] A typical external cavity arrangement with grating feedback in Littrow configuration is shown in Fig. 1. Here the chief elements of an external-cavity laser are displayed: a QC gain medium, with an antireflection (AR) coated intracavity facet, a collimating optic, and a diffraction grating for wavelength-selective feedback. On the output side, a cavity output coupler is created by the coated or uncoated output facet; fiber or free-space coupling through a collimating lens is possible.

Broad gain bandwidth in the mid-IR creates additional challenges compared to shorter-wavelength regions. For example, the 596 cm^{-1} of tuning demonstrated[2] for near-IR diodes corresponds to a change of only 4.8% of center wavelength about 832 nm. Such a comparison is important, since optical coatings and filter efficiencies are more strongly related to wavelength than to energy spread, whereas energy spread is a more fundamental measure of device physics. The 432 cm^{-1} demonstrated[1] for a QC device around 9.5 μm corresponds to a 39% change in center wavelength. Optical coatings, lens dispersion, and filter efficiencies can change to a much greater degree over this greater fractional change in wavelength.

In the present paper, the aspects of utilizing broad gain bandwidths of QC devices with external cavities are considered. First, the QC devices and intrinsic performance are discussed. This is followed by a discussion of turning a broad-gain-bandwidth device into a fixed-wavelength laser. The cw tuning performance across the mid-IR is evaluated; then finally the ultimate tuning performance for realizing the greatest extent of the gain bandwidth is considered.

2 QC Devices as Gain Media

The QC devices used in the manufacture of external-cavity lasers can be obtained from a variety of vendors, and come in a variety of designs. Homogeneous gain media have a structure where the QC layers are designed to be nominally identical. Heterogeneous gain media[11] consist of dissimilar QC layers designed to provide gain bandwidth over an extended range. Within these two broad classes are a variety of specific designs, including bound-to-continuum,[12] bound-bound, and proprietary mixtures of the two.

Consider the amplified spontaneous emission (ASE) spectrum recorded with a Fourier transform infrared (FTIR) spectrometer in Fig. 2. This spectrum is from the AR-coated facet of a bound-to-bound homogeneous QC device at 4.3 μm, operated at 15°C. The device is operated in Fabry-Perot (FP) mode, i.e., with no external cavity. Cavity mode structure is

0091-3286/2010/$25.00 © 2010 SPIE

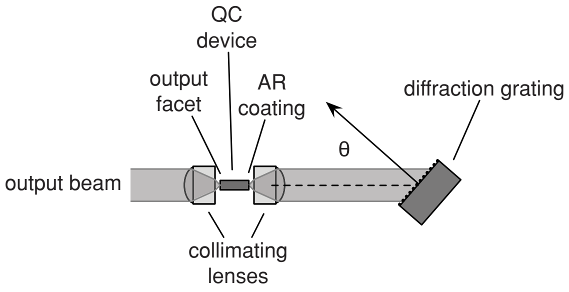

Fig. 1 External-cavity QC laser with grating in Littrow configuration.

absent because of the AR coating on the device. Note the broad width (500 cm^{-1}) of the radiation. The absorptions from atmospheric CO_2 demonstrate that the broad wavelength range covered by this device is ideal for spectroscopy. The curve in Fig. 2 can be taken as a mapping of the gain bandwidth.

How this gain bandwidth translates into useful tuning range is explored by building the QC device into an external cavity with grating feedback in Littrow configuration, as shown in Fig. 1. For these studies, the intracavity facet of the QC device is AR-coated, with reflectivity $<10^{-3}$. The output facet is left uncoated; given the large index of InP-based materials (≈ 3.2), this leads to an output coupling of approximately 30%. The tuning range is determined by operating the QC device at 15°C with maximum output in the region where optical power is increasing linearly with drive current. A spectrometer is used to assess the extent of single-mode tuning. For example, the gain bandwidth in Fig. 2 translates into 150 cm^{-1} of cw tuning, and approximately 200 cm^{-1} of pulsed tuning (5% duty cycle, 100-kHz repetition rate).

The cw lasing spectrum recorded with a FTIR spectrometer for a similar QC device (homogeneous, bound-to-bound) at 5.2 μm is shown in Fig. 3. Here, the device is run in Fabry-Perot (FP) mode, with one facet coated for high reflectance (>95%). As can be seen, the laser is strongly multimode when there is no wavelength selectivity from either a DFB structure or an external cavity with wavelength-selective feedback. The spectral width of the radiation is 50 cm^{-1}, corresponding to a QC device gain in Fig. 2 that is approximately 90% or more of the maximum. This can be contrasted with the external-cavity performance already discussed, where the cw range can be extended to utilize gain bandwidth that is approximately 50% or more of the maximum.

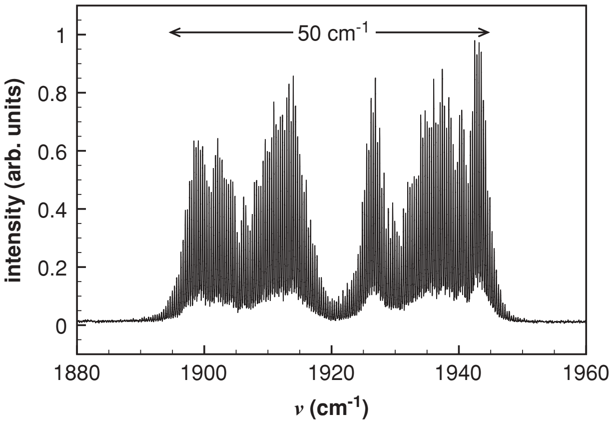

Fig. 3 CW lasing spectrum for a 4.5-mm-long QC device run in FP mode at 15°C. One facet has a high-reflectance coating, and the other is uncoated. Total optical power ~500 mW.

Similar mappings of the gain bandwidth of QC devices can be carried out for heterogeneous devices. Consider the ASE spectrum recorded with a FTIR spectrometer in Fig. 4 for a heterogeneous device. The spectrum indicates broader gain bandwidth, as is to be expected, but with more structure. Heterogeneous devices operated pulsed in FP mode with one facet coated for high reflectance show lasing spectra similar to that in Fig. 3,[1] with the presence of extended structure in the spectrum that indicates broader tunability, but also reveals the heterogeneous nature of the gain. Converting these highly structured self-lasing or FP spectra into broadly tunable spectra with more consistent power as a function of wavelength is one of the strengths of an external-cavity configuration, and is discussed in more detail in Sec. 5. As is discussed later, the tuning ranges demonstrated for heterogeneous devices can be related to the gain bandwidth in Fig. 4. Tuning is observed for room-temperature operation when the gain is approximately 30% or more of the maximum.

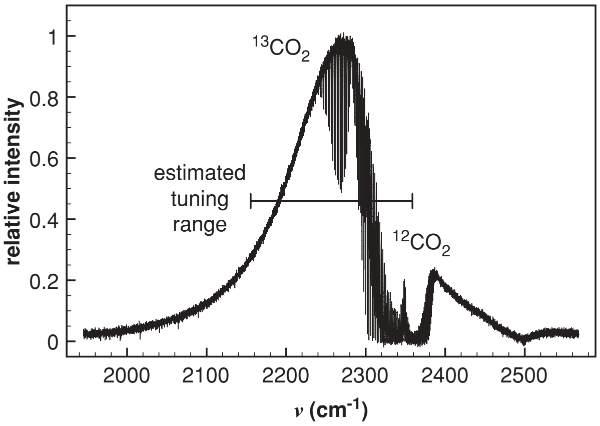

Fig. 2 ASE spectrum from the AR-coated facet of a 3-mm-long QC device run in Fabry-Perot (FP) mode at 15°C. Second facet is uncoated. Estimated tuning range-based on pulsed performance in an external cavity for comparable QC device. Note absorption of light by atmospheric CO_2 isotopologues.

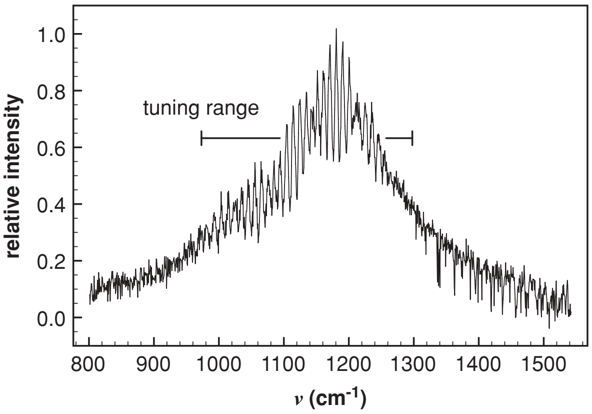

Fig. 4 ASE spectrum for uncoated heterogeneous QC device, 3-mm length. Tuning range realized with pulsed operation (5% duty cycle, 100-kHz repetition rate, 15°C) and grating-tuned external cavity.

It is instructive to consider the variability in the degree of gain necessary before lasing is observed for these various devices. Consider, for example, the gain bandwidth and cw lasing discussed in Figs. 2 and 3. The degree of gain (with respect to the gain maximum) necessary for CW lasing shifts from 90% for a device operated in FP mode, to 50% for a frequency-selective external cavity. This is most likely due to the multimode nature of the lasing for the FP device versus the single-mode operation of the frequency-selective external cavity; the overall power levels and lasing threshold with drive current are similar for the two configurations. Since the gain is partitioned among several modes for FP-mode operation, the gain of each individual mode must be higher to realize lasing than in single-mode operation.

The difference in gain between cw and pulsed operation for the device shown in Fig. 2, where approximately 50% and 30% gain are required for single-mode lasing, respectively, can be attributed to the more efficient operation of the device in pulsed mode. For standard pulsed operation conditions of 5% duty cycle at 100 kHz, the active region of the device does not have time to heat to the degree it does in cw operation. Therefore, for the same QC device substrate temperature, the active region will be significantly hotter for cw operation. Since the lasing threshold increases with increasing QC device temperature,[6] this explains the difference in gain needed for cw and pulsed lasing.

3 Fixed-Wavelength and Narrowly Tunable Devices

The broad gain bandwidth of QC devices opens the possibility to manufacture fixed-wavelength lasers over a broad spectral range based on just a few different QC gain media. DFB QC lasers have the disadvantage that if the processing results in a wavelength that is slightly off target, the entire gain device is no longer usable. External-cavity QC lasers can be based on the same gain device over a broad range, and small adjustments can be made to the wavelength filter to reuse gain devices or bring lasers into a specified tuning range.

Two different approaches have been taken to creating fixed-wavelength lasers. In the first, a fixed frequency-selective element is used in the external cavity. In the case of coated optical filters, the accuracy that can be achieved in setting the wavelength is dependent on the quality of the filter. In addition, the typical spectral widths for narrow (30 to 70 cm^{-1}) and ultranarrow ($\sim$10 cm^{-1}) coated notch filters in the mid-IR are such that the resulting lasers are not single-mode. Finer control of the center wavelength can be achieved through frequency-selective elements that can be actively adjusted during manufacturing, such as diffraction gratings and coated étalons. In addition, the notch filters created by these elements can be made narrow enough to ensure single-mode operation. Tests have been conducted as part of this study to determine the degree of wavelength settability achievable with diffraction gratings. The cw wavelength is monitored using a traveling Michelson interferometer while the grating angle is adjusted to maximize power and set wavelength. Wavelength settability of 1 cm^{-1} has been demonstrated with this fixed approach.

An alternative approach to creating a fixed-wavelength laser is to provide for limited tunability after manufacture. Such a scheme allows for finer adjustment of the wavelength to meet the wavelength specifications, with the added complexity of a wavelength-locking servomechanism required in the final application. Limited tuning also allows gas-phase spectroscopy of molecules with narrow spectral features to be performed with these lasers. Limited tuning modules can be built with external cavities based on microelectromechanical systems (MEMS) or on piezoactuated or thermally tunable elements. Figure 5 shows a schematic of a limited tuning module with a MEMS stretchable grating for a tuning element. The MEMS laser in Fig. 5 can be tuned by approximately ±8 cm^{-1} about its center wavelength, as determined by analyzing the lasing emission with a monochromator. Other schemes allow for comparable tuning ranges, allowing the wavelength to be set with extreme accuracy and precision after manufacture.

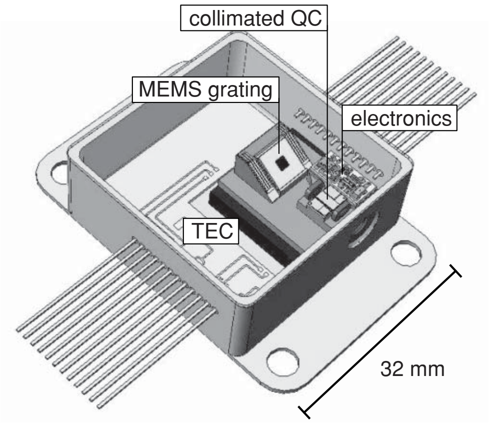

Fig. 5 Schematic of MEMS tunable external-cavity (TEC) QC laser. QC device is 3 mm long. 1-mm-diameter Ge microlenses collimate the light onto a 1-mm-long MEMS grating.

4 Broad Tuning as a Function of Wavelength

Broad gain bandwidth can also be converted into broadly tunable QC lasers for survey spectroscopy or optical characterization. Diffraction gratings remain the most reliable method to create frequency-selective feedback that can be varied over a long wavelength range. Initial studies of tunable external-cavity QC lasers achieved tunability with earlier QC devices that required a degree of cryogenic cooling to operate in cw mode.[9,13] As QC device technology has progressed, removing the need for space-intrusive cryostats, more sophisticated tuning mechanisms have been developed that allow phase-continuous, or mode-hop-free (MHF), tuning.[10] These efforts have been consolidated into a robust commercial package[14] that operates with room temperature QC devices and allows MHF tuning over 100 cm^{-1}, as determined by scanning the tuning mechanism over its mechanical range while monitoring the single-mode lasing wavelength with a FTIR spectrometer.

The broadly tuning cw lasers constructed for the present study have center wavelengths across the mid-IR, allowing an interesting comparison between QC gain bandwidth and tuning. In the lasers constructed for this study, broad cw tuning performance for room-temperature devices has only been demonstrated with homogeneous gain devices, so the comparison excludes heterogeneous gain devices. Broad cw tuning has been observed[15] for heterogeneous devices with careful device design and thermal management, but many

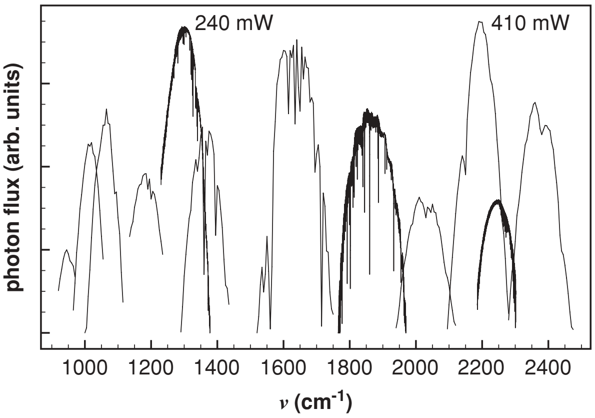

Fig. 6 Demonstrated cw tuning ranges for grating-tuned external cavity lasers based on homogenoeus QC gain devices. The peak powers obtained for two wavelength extremes are indicated.

heterogeneous designs consist of too many QC stages to allow room-temperature cw lasing without thermal runaway.[1]

The relative tuning versus photon flux is compared in Fig. 6 for a broad range of homogeneous QC device lasers constructed for this study. On the vertical axis, photon flux is presented instead of the more traditional power levels. This is meant to compare the performance of devices that have similar numbers of QC layers, but very different wavelengths and photon powers. On the horizontal axis, tuning is presented in energy instead of wavelength, allowing a clearer comparison of fundamental device properties.

The similarity in cw tuning performance across the mid-IR wavelength range is striking. Tuning widths of 100 to 200 cm^{-1} are common. Relating this back to the gain curve in Fig. 2, these QC devices lase for gains greater than approximately 30% of the maximum. This suggests that the energy spread in homogeneous gain media is nearly constant from 4 to 10 μm. The photon fluxes are also comparable for all of these lasers. It would be interesting to compare the photon flux as a function of number of QC layers and current density across this range. The data suggest that the QC devices used for these lasers have comparable quantum efficiencies and number of QC layers.

Figure 6 also shows the edges of room-temperature cw performance for QC devices. At wavelength ranges shorter than 4 μm, strain-compensated QC devices[16] have not yet provided the same performance as devices in the 4- to 11-μm range. For wavelengths longer than 11 μm, robust, high-power ($>$50 mW) devices with large gain bandwidth ($>$ 250 cm^{-1}) have been lacking for both fundamental and technical reasons. As the mean transition energy between the upper and lower laser miniband states is reduced in order to achieve longer-wavelength emission, the energy separation approaches that of the longitudinal polar-optical (LO) phonon energy ($\sim$34 meV) for $In_{0.53}Ga_{0.47}As$, the most common material used in forming the quantum wells of QC devices.[17] The energy separation becomes closer to resonance with the LO energy, leading to a dramatic decrease in the upper laser state's lifetime due to the nonradiative phonon-assisted scattering, which reduces the gain and raises the threshold current density.

Furthermore, the dielectric function of the waveguide becomes modified substantially by the effects of surface-plasmon dispersion at the InGaAs/metal contact,[8] as well as from the effects of the reststrahlen band of InGaAs, where the short-wave edge resides in the vicinity of 36 μm.[19] Additional fundamental considerations at longer wavelengths include increased electron-electron scattering,[19] as well as increased free-carrier absorption, which scales quadratically with wavelength in accordance with simple Drude theory. The former reduces the upper laser state's lifetime and thus the gain of the QCL, while the latter raises the gain threshold by adding to the waveguide losses. These effects can be mitigated, but as yet there has not been a more substantial investment of resources to design, fabricate, and characterize device structures optimized for long-wavelength emission.

5 Ultimate Tuning Ranges

QC-based lasers show the greatest promise for miniaturizing and fully commercializing the powerful techniques used in FTIR spectroscopy and imaging. To do so, QC tuning ranges need to be pushed to the maximum; typical FTIR spectrometers acquire from 3 to 16 μm, with extended ranges from 2 to 20 μm. Heterogeneous QC devices have the potential to realize large tuning ranges. State-of-the-art devices have yielded 432 cm^{-1} of tuning in an external-cavity configuration with grating tuning.[1] If comparable tuning ranges can be obtained across the mid-IR, it is estimated[20] that approximately eight different QC devices will be needed to match the spectral range of a typical FTIR spectrometer.

As discussed by Wittmann et al.[15] and Hugi et al.,[1] heterogeneous QC devices rely on combinations of QC stacks that have center wavelengths spaced to cover multiple spectral regions. Care must be taken in the design to ensure adequate gain overlap in wavelength. Active-region and waveguide design is important as well, to ensure appropriate modal overlap. The ability to piece together larger spectral coverage by adding different homogeneous stages together is clear. The disadvantage in this approach is that the number of QC stacks tends to be much larger, making thermal runaway more likely and room-temperature cw operation less likely. In order to utilize the full gain bandwidth of a heterogeneous QC device, it is necessary to run in pulsed mode. Typical conditions of 5% duty cycle and 100-kHz repetition rate offer the best efficiency for room-temperature operation. Running in pulsed mode in an external-cavity configuration results in multimode performance. However, correct cavity design can mitigate this effect to create an effective linewidth of a few tenths of a wave number.[1]

Consider the spectrum of ethyl alcohol in Fig. 7, captured with a broadly tunable heterogeneous device in a grating-tuned external cavity. Such a spectrum can be used to determine the system resolution by comparing the measured linewidths with the predicted values without laser broadening. This analysis shows that the effective full-width half-maximum (FWHM) linewidth for the laser operated in pulsed mode is approximately 0.2 cm^{-1}. The 0.2-cm^{-1} resolution is comparable to that obtained in FTIR spectrometers used for gas phase studies, and allows sharp spectral features of lighter molecules such as H2O, CO2, NH3, and CH4 to be resolved. In addition, the $\geq$300 cm^{-1} of tuning allows the broader spectral features of heavier molecules to be clearly resolved. Even though heterogeneous QC devices that span the full FTIR range have not yet been developed, the wavelength range demonstrated here is sufficient to allow detection of

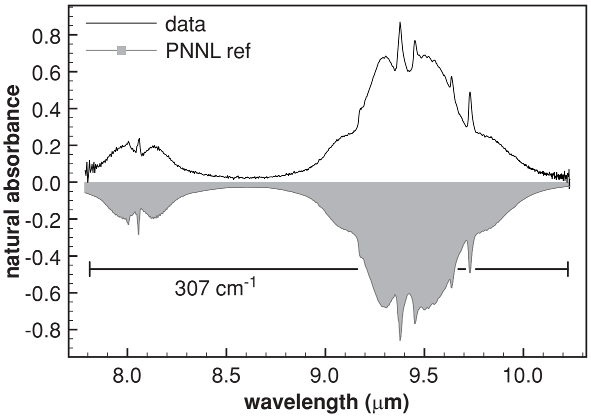

Fig. 7 Spectrum of gaseous ethyl alcohol captured with rapidly tuned, pulsed external-cavity heterogeneous QC laser. Path length 1.3 m, concentration 900 ppm, spectral acquisition time 8 ms. Inverted reference spectrum from PNNL database.[21]

heavier gas phase molecules, and to allow for multicomponent detection.

It is anticipated that pulsed, external-cavity QC lasers will be the only viable means to realize the full tuning ranges available with heterogeneous QC devices. Prototype instruments based on rapidly tuned diffraction gratings have yielded spectral sweeps of 307 cm^{-1} on time scales of less than 10 ms, relevant for capturing atmospheric spectra without suffering the effects of turbulence.[21] Additional work using MEMS tuning devices holds the promise of broadly tunable mid-IR lasers with miniature form factors and resolutions sufficient for condensed phase studies.

6 Conclusions

The broad gain bandwidths available from QC devices match the spread in energies available from other semiconductor devices, with the added complexity of broader bandwidth with respect to center wavelength. The ASE spectra from homogeneous and heterogeneous QC devices can be analyzed to estimate lasing performance as a function of wavelength. For room-temperature operation, lasing can be supported when the gain is approximately 30% or more of the maximum. External-cavity methods can effectively utilize broad gain bandwidth in the manufacture of both fixed-wavelength and broadly tunable lasers. The broad cw tuning performance of homogeneous QC gain media in a grating-tuned external cavity is strikingly similar across the mid-IR, both in spectral width and in generated photon flux. The pulsed tuning performance with heterogeneous QC devices in an external cavity shows the greatest promise for realizing the ultimate tuning ranges available with these broad-gain-bandwidth devices.

References

1. A. Hugi, R. Terazzi, Y. Bonetti, A. Wittmann, M. Fischer, M. Beck, J. Faist, and E. Gini, “External cavity quantum cascade laser tunable from 7.6 to 11.4 μm,” *Appl. Phys. Lett.* **95**, 061103 (2009).
2. D. Wandt, M. Laschek, K. Przyklenk, A. Tünnermann, and H. Welling, “External cavity laser diode with 40 nm continuous tuning range around 825 nm,” *Opt. Commun.* **130**(1–3), 81–84 (1996).
3. J. Butler, R. Reeder, and K. Linden, “Mesa-stripe Pb1-xSnxSe tunable diode lasers,” *IEEE J. Quantum Electron.* **19**(10), 1520–1525 (1983).
4. T. Day, C. B. Thompson, and J. Lee, “Widely tunable laser technologies: meeting the needs of tomorrow’s networks,” in *Optoelectronic Interconnects, Integrated Circuits, and Packaging, Proc. SPIE* **4652**, 186–196 (2002).
5. F. K. Tittel, D. Richter, and A. Fried, in *Solid-State Mid-Infrared Laser Sources*, I. T. Sorokina and K. L. Vodopyanov, Eds., pp. 445–516, Springer-Verlag, Berlin (2003).
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. J. B. McManus, D. D. Nelson, J. H. Shorter, R. Jimenez, S. Herndon, S. Saleska, and M. Zahniser, “A high precision pulsed quantum cascade laser spectrometer for measurements of stable isotopes of carbon dioxide,” *J. Mod. Opt.* **52**(16), 2309–2321 (2005).
9. A. C. Peng, H. Q. Le, S. S. Pei, W. Y. Hwang, B. Ishaug, J. Um, J. N. Baillargeon, and C. H. Lin, “Grating-tuned external-cavity quantum-cascade semiconductor lasers,” *Appl. Phys. Lett.* **78**, 2834 (2001).
10. G. Wysocki, R. F. Curl, F. K. Tittel, R. Maulini, J.-M. Bulliard, and J. Faist, “Widely tunable mode-hop free external cavity quantum cascade laser for high resolution spectroscopic applications,” *Appl. Phys. B Photophys. Laser Chem.* **81**, 769–777 (2005).
11. C. Gmachl, D. L. Sivco, R. Colombelli, F. Capasso, and A. Y. Cho, “Ultra-broadband semiconductor laser,” *Nature (London)* **415**, 883–887 (2002).
12. R. Maulini, M. Beck, J. Faist, and E. Gini, “Broadband tuning of external cavity bound-to-continuum quantum-cascade lasers,” *Appl. Phys. Lett.* **84**(10), 1659–1661 (2004).
13. G. Luo, C. Peng, H. Q. Le, S. S. Pei, H. Lee, W. Y. Hwang, B. Ishaug, and J. Zheng, “Broadly wavelength-tunable external cavity mid-infrared quantum cascade lasers,” *IEEE J. Quantum Electron*. **38**, 486 (2002).
14. M. Pushkarsky and D. F. Arnone, “Continuous wavelength tunable laser source with optimum positioning of pivot axis for grating,” U.S. Patent, No. 7, 733,925 (2010).
15. A. Wittmann, A. Hugi, E. Gini, N. Hoyler, and J. Faist, “Heterogeneous high-performance quantum-cascade laser sources for broad-band tuning,” *IEEE J. Quantum Electron.* **44**(11), 1083–1088 (2008).
16. J. Faist, F. Capasso, D. L. Sivco, A. L. Hutchinson, S.N. G. Chu, and A. Y. Cho, “Short wavelength ($\lambda \sim 3.4\mu$m) quantum cascade laser based on strained compensated InGaAs/AlInAs,” *Appl. Phys. Lett.* **72**(6), 680–682 (1998).
17. T. P. Pearsall, R. Carles, and J. C. Portal, “Single longitudinal-mode optical phonon scattering in Ga sub(0.47)In sub(0.53)As,” *Appl. Phys. Lett.* **42**(5), 436–438 (1983).
18. A. Tredicucci, C. Gmachl, F. Capasso, A. L. Hutchinson, D. L. Silvco, and A. Y. Cho, “Single-mode surface-plasmon laser,” *Appl. Phys. Lett.* **76**(16), 2164 (2000).
19. R. Colombelli, F. Capasso, C. Gmachl, A. L. Hutchinson, D. L. Sivco, A. Tredicucci, M. C. Wanke, A. M. Sergent, and A. Y. Cho, “Far-infrared surface-plasmon quantum-cascade lasers at 21.5 μm and 24 μm wavelengths,” *Appl. Phys. Lett.* **78**(18), 2620 (2001).
20. M. J. Weida, P. Buerki, E. Takeuchi, and T. Day, “External-cavity QCLs broaden capabilities for molecular detection,” *Laser Focus World* **46**(4), 58–62 (2010).
21. W. W. Harper, J. D. Strasburg, P. M. Aker, and J. F. Schultz, “Remote chemical sensing using quantum cascade lasers,” Pacific Northwest National Lab. Report PNNL-14525, U.S. Dept. of Energy (2004).

Biographies and photographs of the authors not available.