Mid-infrared quantum cascade laser arrays with electrical switching of emission frequencies

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We present a design of quantum cascade laser arrays made of ridge-waveguide devices in which the emission frequency can be electrically switched between several specified values. Our approach relies on fabricating multiple independently-biased distributed feedback grating sections along the laser ridge waveguides. Switchable single-mode lasing from the laser facet is achieved by balancing the injection pumping of the different grating sections. Our method provides a robust solution that can increase the tuning bandwidth of the quantum cascade laser arrays without increasing the size of the array emission aperture. © 2018 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/). https://doi.org/10.1063/1.5046782

Compact broadly-tunable electrically-pumped semiconductor mid-IR sources are highly desired for a wide range of sensing and spectroscopy applications. Quantum cascade lasers (QCLs) are currently the only semiconductor lasers capable of providing broadly-tunable output across the entire mid-infrared spectral range (mid-IR, 3-15 µm) at room temperature. An active region of a single mid-IR QCL can be designed to produce a gain bandwidth up to ~600 cm⁻¹,³⁻⁵ covering a significant portion of the mid-IR molecular fingerprint region. Single-mode tuning of such a device allows one to identify chemical compounds by their mid-IR absorption ‘fingerprint’. Broadband single-mode tuning of mid-IR QCLs has thus been a subject of intense research.

The best results in terms of tuning range have been achieved using external cavity (EC) setups.⁵,⁶ EC systems, however, are bulky, mechanically complex and require high-quality broadband anti-reflection coating on the laser cavity as well as precise optical alignment among the external optical elements in the setup. In contrast, a monolithic broadly-tunable mid-IR QCL source has a number of advantages over EC setups, including compact size, mechanical robustness, and high tuning speed. Multi-segment QCLs with sampled distributed feedback (DFB) gratings have demonstrated single-mode frequency output tuning over 200 cm⁻¹ based on the Vernier principle.³,⁷,⁸ However, such devices often suffer from poor mode selectivity and require complex fabrication.

Linear arrays of DFB QCL devices are the most straightforward and robust solution to produce a compact broadly-tunable single-mode QCL source.⁹⁻¹² A typical DFB QCL array source consists of an array of DFB lasers with different wavelengths processed from the same QCL wafer. Both edge-emitting⁹,¹⁰ and surface-emitting¹¹,¹² DFB QCL array sources have been demonstrated.

Unlike the EC QCL sources and tunable QCLs based on the Vernier principle, the spatial position of light emission from the QCL arrays varies with frequency.⁹⁻¹² This situation, however, is acceptable for a wide range of applications, as long as the sample and the detector size are sufficiently large.⁹⁻¹² Nevertheless, as the number of the lasers in the array increases to cover broader frequency range, the array size becomes too large for practical applications. We note that one can produce overlapping beams for the emission from the laser array using spectral beam combining with a suitable diffraction

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However, the beam combining system makes the laser setup nearly as bulky and complex as the EC setup.

Here we present a robust method that can increase the tuning bandwidth of the QCL arrays without increasing the size of the array emission aperture. Unlike QCL arrays where each laser emits one wavelength, the lasers presented here can be electrically switched between several predetermined frequencies. To achieve that, we fabricate multiple independently biased sections with different DFB gratings in ridge-waveguide QCLs as shown in Fig. 1. In this scheme, a single QCL ridge can now emit two, three, or more different frequencies, depending on the bias configuration. Individual DFB-QCL tuners with multiple emission has been shown previously. Here we further combine this approach with a standard serial QCL array configuration to produce a QCL array with a broad tuning range. We demonstrate two QCL arrays that cover the spectral range from 1000 cm$^{-1}$ to 1100 cm$^{-1}$ with a 5 cm$^{-1}$ frequency step. The first one is a 10-laser array with each of the lasers capable of switching between 2 different emission wavelengths and the second one is a 7-QCL array with each of the lasers capable of switching between 3 different emission wavelengths.

We achieve reliable control of the emission frequency of all lasers in the array using high spatial localization of the optical intensity of the DFB mode in the DFB grating section. This happens in strongly-coupled DFB lasers with $\kappa L > 2$, where $\kappa$ is the DFB grating coupling strength and $L$ is the grating length. In this case, electrical pumping of a specific DFB section in our multi-section devices will excite the DFB laser mode of that section. The feedback from the cleaved facets, which are uncoated in case of our devices, may distort the mode distribution and mode localization in the DFB lasers. However, even in the presence of facet reflections, the distribution of the optical intensities along the waveguide of our multi-section devices remains dissimilar for different DFB modes and we are able to configure our laser bias to excite a specific DFB emission line as discussed below. We note that we have recently successfully used a similar approach to balance the gain for the two DFB modes in order to achieve dual-color emission in QCLs designed for intra-cavity difference-frequency generation.

Figure 1(a) shows the schematic of a single ridge-waveguide device with multiple DFB sections. For the 10-QCL array, the front DFB sections in devices are designed for long wavelength operation from 1003 cm$^{-1}$ to 1048 cm$^{-1}$ with a 5 cm$^{-1}$ spacing between the adjacent lasers. The back DFB sections are designed for short wavelength operation from 1053 cm$^{-1}$ to 1098 cm$^{-1}$ with the same 5 cm$^{-1}$ spacing. For the 7-QCL array, the front, middle, and back DFB sections in the array are designed for emission from, approximately, 1000 cm$^{-1}$ to 1030 cm$^{-1}$, from 1035 to 1065 cm$^{-1}$, and from 1070 to 1100 cm$^{-1}$, respectively, with an approximately 5 cm$^{-1}$ spacing between the adjacent lasers.

The metal contacts for the different DFB sections are electrically isolated from each other. Our current injection scheme is shown in Fig. 1(b). All DFB sections of the laser are connected to the

![Diagram](image)

**FIG. 1.** (a) Schematic of a ridge-waveguide QCL with multiple electrically-isolated DFB sections designed for emission at wavelengths $\lambda_1, \ldots, \lambda_n$. (b) Schematic of biasing of the device in (a) using a single current pulser and multiple radio-frequency attenuators. The pumping condition to select a particular wavelength $\lambda_m$ is shown.
same current pulser through individual radio-frequency (RF) attenuators that control the bias currents of the individual DFB sections.\textsuperscript{20}

The arrays are fabricated from a QCL heterostructure grown by IQE, Inc. The laser heterostructure is similar to that of the devices reported in Ref. 21. Devices were grown on an n-doped InP substrate. The growth commenced with a 200-nm-thick InGaAs current injection layer (n-doped to $7 \times 10^{17}$ cm$^{-3}$), followed by a 3-mm-thick InP lower cladding layer (n-doped to $1.5 \times 10^{16}$ cm$^{-3}$). A 4-µm-thick In$_{0.53}$Ga$_{0.47}$As/In$_{0.52}$Al$_{0.48}$As active region was grown next, based on the design reported in Ref. 21. The top cladding layer of our lasers consists of a 3-mm-thick InP (n-doped to $1.5 \times 10^{16}$ cm$^{-3}$), followed by a 100-nm-thick heavily-doped InP layer (n-doped $3 \times 10^{18}$ cm$^{-3}$) and terminated with a 10-nm-thick In$_{0.53}$Ga$_{0.47}$As contact layer (n-doped to $2 \times 10^{19}$ cm$^{-3}$).

The wafer was processed into arrays of ridge-waveguide QCLs with two or three DFB sections. First, the surface DFB gratings were fabricated by e-beam lithography and dry etching following the approach reported in Refs. 21, 22, 23. The specific grating design and coupling strength in our devices was similar to that of the devices reported in Ref. 21 ($\kappa \approx 25$ cm$^{-1}$). The grating periods were from 1.4 µm to 1.6 µm and the grating duty cycle was 50%. Then, each QCL waveguide with a ridge width of 22 µm was defined by photolithography and dry etching. Metal contacts were deposited on top of the DFB gratings separated by a 300 µm gap. The top 100-nm-thick heavily doped InP layer and the In$_{0.53}$Ga$_{0.47}$As contact layer were removed in the gap between the two metal contacts to prevent current spreading between the DFB sections.\textsuperscript{20,24}

Figure 2(a, b) shows the schematic and a scanning electron microscope image of a 10 ridge-waveguide QCL array with two 1.2 mm-long DFB sections separated by a 300 µm gap per laser waveguide. The devices are cleaved to have facets at the end of the front and back DFB sections, making the total cavity length of the devices in the array of approximately 2.7 mm. The laser facets are left uncoated. The devices are indium-soldered in an epi-up mounting configuration on copper heatsinks for testing with an orientation such that their DFB sections for longer wavelength $\lambda_1$ are facing the detection setup.

Devices are tested at room temperature with 70 ns current pulses at 40 kHz repetition frequency. Output power is collected from the front facet and is measured using a thermophile power meter. The power measurements are corrected for an estimated 70% collection efficiency of our optical setup. Fourier-transform infrared spectrometer (FTIR) is used for spectral measurements.

Figure 3(a-b) plots the spectra and the output peak power for the two mid-IR frequencies selected by the DFB gratings for the device #10 (the 10th laser of the array). This device performance is typical for all other lasers in the array. Panels 3(a) and 3(b) show the output power of the long ($1/\lambda_1 \approx 1048$ cm$^{-1}$) and short ($1/\lambda_2 \approx 1098$ cm$^{-1}$) wavelengths, respectively, as a function of current density through the front and back sections of the device. Mid-IR interference bandpass filters are used to separate the optical powers of the two emission frequencies. As indicated in Fig. 3(a), the entire 2-dimensional (2D) current map can be divided into three partitions: 1) $\lambda_1$ lasing only, 2) $\lambda_2$ lasing only and 3) both wavelength lasing. Insets in Figs. 3(a) and 3(b) show the emission spectra of the laser for all three scenarios, respectively. Due to the spectral variation of the laser gain and changes in the spatial distribution of the DFB mode intensity due to wavelength-dependent

![FIG. 2. (a) Schematic of a 10-QCL array with two DFB sections in each of the laser ridge-waveguide (only two ridges are shown). (b) Scanning electron microscope image of the front facet of the fabricated QCL array.](attachment:figure2.png)
phase of the feedback from the cleaved facets,\textsuperscript{18,19} the 2D power dependence of the two DFB modes is different from device to device. Nevertheless, single mode lasing of the long and short wavelengths can be realized in all devices with 100\% yield and with the sidemode suppression ratio of over 20 when the RF attenuators are configured to provide the maximum current density to one DFB section and the minimum current density in the other DFB section. We note that these two situations correspond to the upper left and lower right corners of the 2D plots shown in Fig. 3.

The dependence of the emission spectra of the devices on the current densities through the DFB sections in Fig. 3 is similar to that observed in Ref. 20 and can be understood from the fact that the intensities of the mid-IR modes for $\lambda_1$ and $\lambda_2$ are localized in the front and back DFB grating sections, respectively. Thus, increase in the bias current of the front (back) section is expected to predominantly increase the round-trip gain of the DFB mode at long (short) wavelength.

Figure 4 plots the lasing spectra of the entire 10-ridge array obtained under pumping conditions that select a specific emission frequency for each of the lasers in the array. 2D-bias-mapping results similar to that shown in Fig. 3 were used to select a proper bias condition for the single mode emission in each laser device in the array. The emission of the array can be switched between 20 different wavelengths, which reduces the array spatial extent by a factor of 2, compared to QCL arrays.
FIG. 5. Normalized mid-IR emission spectra (solid, dashed, and dotted lines and the left axis) and the power output (stars and the right axis) for every emission frequency from the 7-QCL array with three DFB sections per device. Solid lines represent emissions selected by the front DFB sections ($\lambda_1$), dashed lines represent emissions selected by the middle DFB sections ($\lambda_2$), and dotted lines represent emissions selected by the back DFB sections ($\lambda_3$) in the array. The emission spectra and powers are recorded for the biasing configuration that corresponds to the maximum output power for a particular single-frequency emission.

with single-color devices. The maximum output power for each emission wavelength is plotted in Fig. 4. The output powers of the wavelengths selected by the back DFB sections are typically lower than those of the wavelengths selected by the front DFB sections since the back-section DFB mode needs to travel through a 300-µm-long unpumped gap section and a 1.2-mm-long front DFB section pumped below threshold.

The method to switch the laser emission wavelength in the multi-section DFB devices can be extended to QCLs with more than two DFB grating sections. To demonstrate that, we fabricated QCL array with 3 DFB grating sections per device. The 3-section devices consist of three 1.3-mm-long grating sections separated by 300 µm gaps, resulting in a total cavity length of 4.5 mm for each of the lasers in the array. Device processing and biasing is similar to that of the 2-section devices. Figure 5 shows the spectra and max output power of an array of seven 3-section devices. This array covers the same spectral range as the previous 10-device array and single mode emission is achieved for all design wavelengths.

To summarize, we demonstrated a simple and robust method to increase the spectral coverage of mid-IR QCL arrays using wavelength switching of the individual lasers in the array. Our approach can be also used to make individual wavelength-switchable ridge-waveguide QCLs for multi-species sensing and spectroscopy. Switchable single mode lasing with 100% yield is demonstrated for all processed devices.

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