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# Waveguide-integrated terahertz-frequency quantum cascade lasers for detection of trace-gas species

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***Abstract*—We demonstrate high-performance THz QCLs lasing at 2.2, 2.53, 3.5 and 4.7 THz, which target absorption lines of water, methane, hydroxyl and atomic oxygen respectively. Reliable single-mode targeting of gas species is obtained through the use of a photonic lattice design. A highly reproducible micro-machined waveguide block yields narrow beam-divergence and enables future integration of a complete THz heterodyne system including local-oscillator, mixer, and feed-horn.**

## I. INTRODUCTION

The terahertz frequency band (1–5 THz) is of significant interest for atmospheric science and astronomy, owing to the strong fundamental rotational modes of relevant gas species in this spectral range. However, there has been a lack of compact, robust and powerful THz sources at these frequencies, which are needed for high resolution heterodyne spectroscopy systems for satellite use. THz quantum-cascade lasers (QCLs) can provide > 1 W optical power [1], with very narrow intrinsic linewidth [2], and as such are highly-promising candidates for local oscillator development. To date, however, their deployment in practical applications has been limited (in part) by the lack of a low-cost, mechanically-robust and reproducible scheme for integration with other THz system components, control and stabilization of the emission frequency, comparably high power, high working temperature and optimization of the far-field beam profile.

We demonstrate a reliable photonic-lattice waveguide design scheme [Fig. 1(left)] for single-mode, continuous wave QCLs, specifically for trace-gas detection [2.2 THz ($H_2O$, $CH_4$), 2.53 THz ($CH_3OH$), 3.5 THz (OH) and 4.7 THz (O)] and present a systematic optimization of their performance. The applicability of these lasers to *in situ* gas sensing is demonstrated.

QCLs have been integrated into precision-micro-machined waveguide blocks [Fig. 1(right)], which have previously been developed to support construction of waveguide-integrated THz mixers. These mechanically-robust blocks yield significant improvement in the far-field beam pattern without degradation in thermal or electrical performance.

## II. PHOTONIC LATTICE QCLS

A set of THz QCLs was fabricated using photonic-lattice waveguides to target the rotational modes of the gas species listed above. In each case, the active region was processed into a gold semi-insulating surface plasmon waveguide using conventional optical photolithography. A photonic lattice structure was etched into the top metallic contact using a focused ion-beam (FIB).

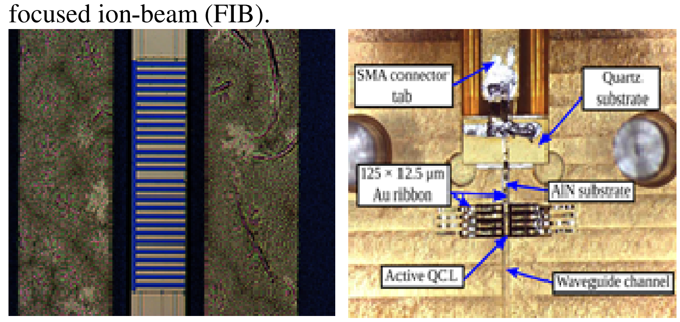


**Fig. 1.** (Left) Single mode QCL, using a photonic lattice waveguide (Right) structure of block-integrated device.

The QCLs were mounted onto a copper heat-sink block in a helium cryostat, and were driven using a dc power supply. The beam was modulated at 185 Hz using an optical chopper, and the radiation was detected using a helium-cooled bolometer using a lock-in amplifier, referenced to the chopper. The emission frequency was measured to ~250 MHz resolution using a custom-made long-path FTIR interferometer.

In each case, single-mode, continuous-wave operation was obtained around the desired operating frequency. Fig. 2 shows the emission frequency of a THz QCL being tuned over the 2.2210−2.2216 THz range as the drive current is varied. Tuning coefficients were found to be −0.1 GHz/K and −7 GHz/A with respect to heat-sink temperature and drive current respectively, which will enable the analysis of the methane absorption line at 2.2212 THz.

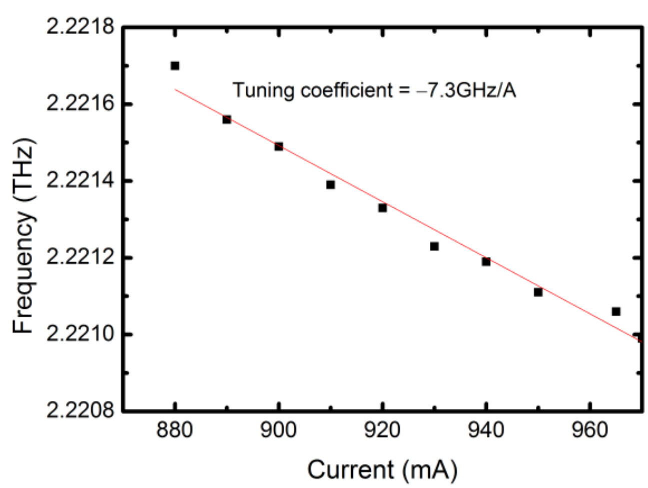


**Fig. 2.** Current tuning of a single mode 2.22 THz QCL

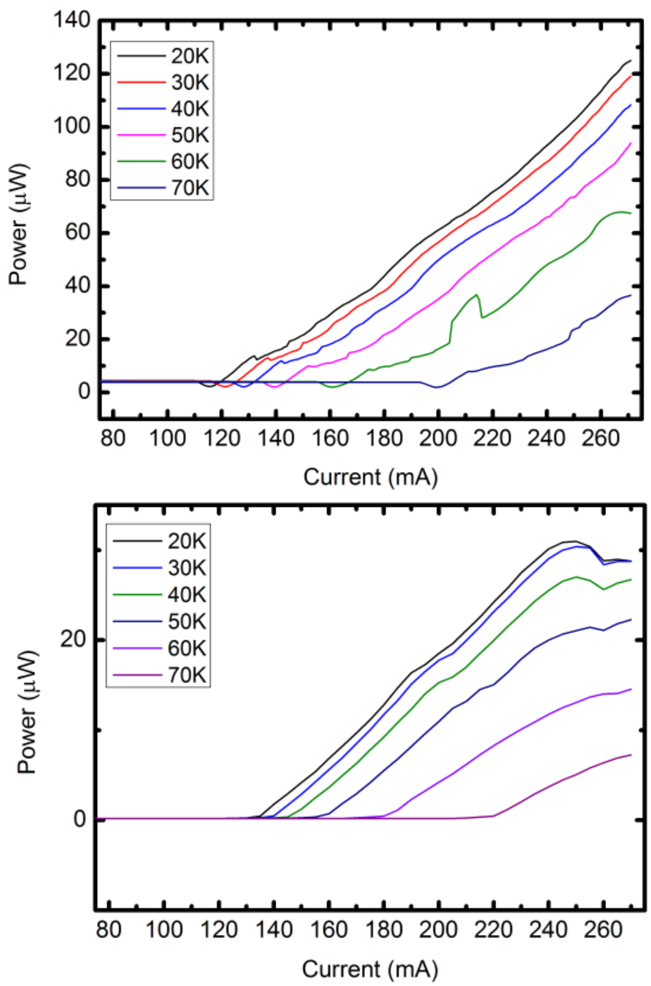


**Fig. 3.** THz QCL temperature performance of (top) the unmounted QCL, and (bottom) the waveguide-integrated QCL.

## I. QCL INTEGRATION

A robust integration scheme was developed, in which a QCL was mounted into a micro-machined copper block [3], as shown in Fig. 1(right). A multi-mode 3.5-THz QCL was used for this preliminary study. An array of these devices was fabricated in a double-metal Au waveguide configuration, and was mounted into a cavity within the waveguide block using a layer of indium foil to ensure a good thermal contact. The facet of the central QCL within the array was aligned with a 300×150 $\mu m^2$ over-moded rectangular waveguide channel (selected for ease of integration), with the other devices being left unused. An Au ribbon bond was used to form an electrical contact between the top of the QCL, and an integrated high-frequency SMA connector. Additional ribbon bonds were used to secure the QCL array into the block, and ensure good thermal contact.

The waveguide-integrated QCL, and an equivalent unmounted device were characterized in terms of their emission power, threshold current and thermal performance. Fig. 3 shows that there is no significant change in threshold current (~20 mA) after integration, compared with the unmounted device, and the maximum operating temperature was found to change from 80 K to 77 K, thus demonstrating good thermal and electronic integration of the QCL. The reduction in output power is attributed to the use of a wide (over-moded) waveguide channel in this preliminary structure, which is optimized for ease of fabrication rather than for optical coupling. We anticipate a significant improvement in out-coupled radiation power in subsequent iterations, which will also include a micro-machined diagonal feedhorn.

The far-field beam profile of the waveguide integrated device was measured by scanning a Golay detector with a 1-mm diameter aperture linearly outside the QCL cryostat. Fig. 4 shows that an approximately Gaussian beam pattern is obtained, with a full-width at half-maximum < 20°. This is a significant improvement compared with the ~120° beam widths that are typically obtained using unmounted double metal QCLs. Furthermore, the spatial "ringing" and anisotropy that are commonly associated with double-metal QCLs have also been removed.

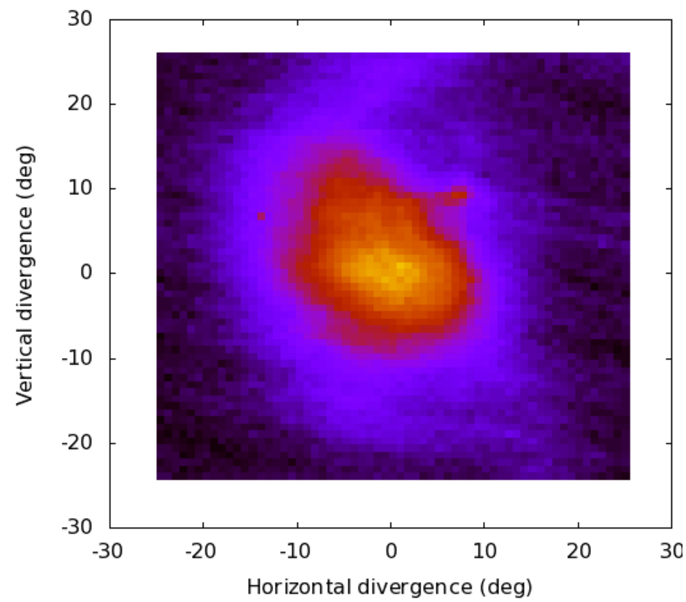


**Fig. 4.** Far-field beam profile of integrated double-metal QCL

## III. SUMMARY

We have developed single-mode THz QCLs using a photonic lattice waveguide scheme and demonstrated a robust, highly-reproducible and low-cost packaging scheme, which significantly improves the far-field beam profile. We will demonstrate the applicability of these devices to measurements of gas absorption line-shapes of key atmospheric gas species.

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