Waveguide-integrated THz Quantum-Cascade Lasers for Atmospheric-Research Satellite Payloads

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***Abstract*—Terahertz-frequency quantum-cascade lasers (THz QCLs) are compact, electrically-driven sources of narrowband radiation in the ~2–5-THz band. Numerous scientifically important gas-phase species within the Earth's upper atmosphere have distinctive spectral features within this band, making QCLs attractive sources for spectroscopic and radiometric atmospheric studies. In this paper, we demonstrate the integration of a QCL with a satellite-compliant cryocooler, precision-micromachined waveguide, a pair of diagonal feedhorns and a Cassegrain telescope, as key steps toward a complete 3.5-THz integrated receiver system.**

***Index Terms*—quantum cascade lasers, terahertz radiation, infrared spectra, receivers, submillimeter wave devices**

I. Introduction

The Mesosphere and Lower Thermosphere (MLT) region of the Earth's atmosphere is a "gateway" between Earth and the near-space environment, in which solar radiation and energetic particles from above interact with natural and anthropogenic inputs from below. This region is of great interest, in part, because its temperature response to "greenhouse gas" concentrations and ozone depletion is an order of magnitude larger than that of the troposphere, thus providing a sensitive indicator of climate change phenomena [1]. However, the principal gas-phase species in the MLT (O, OH, CO, NO etc.) are extremely challenging to observe directly, as their fundamental rotational spectral features lie within the terahertz (THz) band of the electromagnetic spectrum (e.g., O: 4.7 THz; OH: 3.5-THz) and cannot be distinguished using infrared/millimeter-wave instrumentation. Furthermore, conventional THz instrumentation is too large, complex and power-hungry for use in satellite payloads.

To address this need, a low-Earth-obit radiometry satellite, LOCUS (*Linking Observations of Climate, the Upper-atmosphere and Space-weather*) has been proposed [2]. The payload (Fig. 1) includes four receivers in the 0.8–4.7-THz band. The highest frequency channels (3.5-THz and 4.7-THz) employ Quantum-Cascade Lasers (QCLs) as Local Oscillators (LOs). Unlike THz gas lasers or photoconductive antennas, QCLs are ~1-mm-long narrowband semiconductor sources [3], requiring no pump laser or reference oscillator, and yielding continuous-wave output powers up to >100 mW [4] (~2.4 W pulsed [5]).

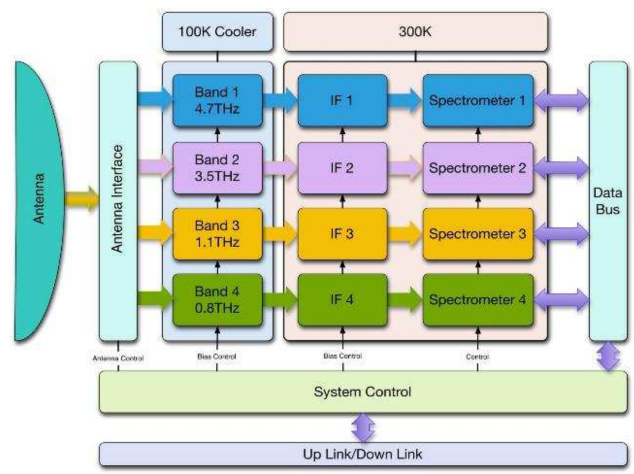

Fig. 1. LOCUS satellite payload system schematic

Although QCL-LOs have been developed for airborne [6] and balloon [7] deployment, these have been based on discrete components, which are too large and fragile for satellite deployment. Here, we demonstrate integration of a QCL-LO with a compact micro-machined waveguide and a pair of diagonal feedhorns, and its operation in a space-compliant cryocooler, with fore-optics in a Cassegrain-telescope configuration.

II. System Architecture

An "elegant-breadboard" system has been developed to demonstrate key LOCUS payload technologies (Fig. 2), on a custom-machined aluminium baseplate. Cassegrain-telescope fore-optics (A,B) yield a compact instrument envelope (< 1 m^3). A 480-mm-diameter diamond-turned concave primary mirror, and 100-mm convex secondary target 2-km atmospheric-layer resolution from 800-km altitude, and project onto a 25-mm-diameter focal plane. The QCL-based receivers are located within a space-qualified < 100-K Stirling-cycle cryocooler (C).

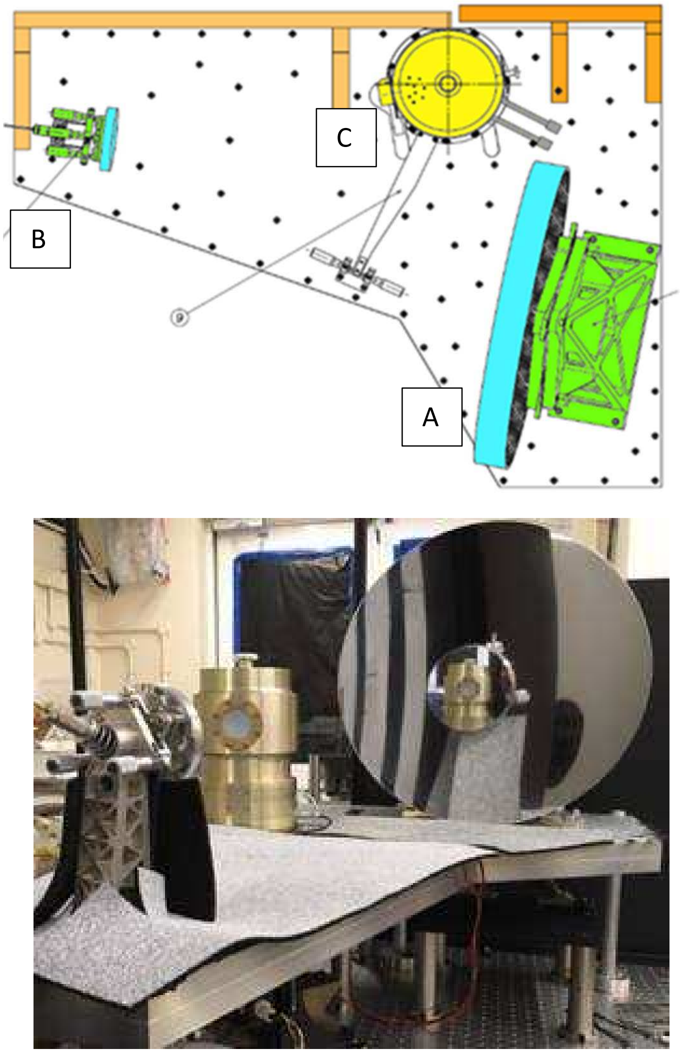

Fig. 2. (Top) Top-down CAD illustration of the LOCUS breadboard system: A, B = telescope optics, C = cryocooler. (Bottom) Photograph of fully-constructed system.

Practical measures for the optical system design included limiting the mirror aperture angle to 60° for compatibility with interferometers for system testing, limiting the bi-conical nature of the secondary mirror to avoid manufacturing complications during polishing, and introducing sufficient tilt into the optical path to allow placement of the cryostat for room-temperature tests.

Within a flight-ready system, the mixer and LO for all channels will be mounted within the cooler. In the present configuration, however, the 3.5-THz LO source under-test has been mounted individually and used as an emitter to test the optical system integration. For the LO, a ~3.5 THz QCL, based on the active region in [8] has been processed into a double-metal ridge waveguide with 75-µm width, and the substrate reduced through mechanical and chemical etching to a thickness of 90 µm. The device was cleaved to a length of 980 µm and diced into a 110 µm-wide chip.

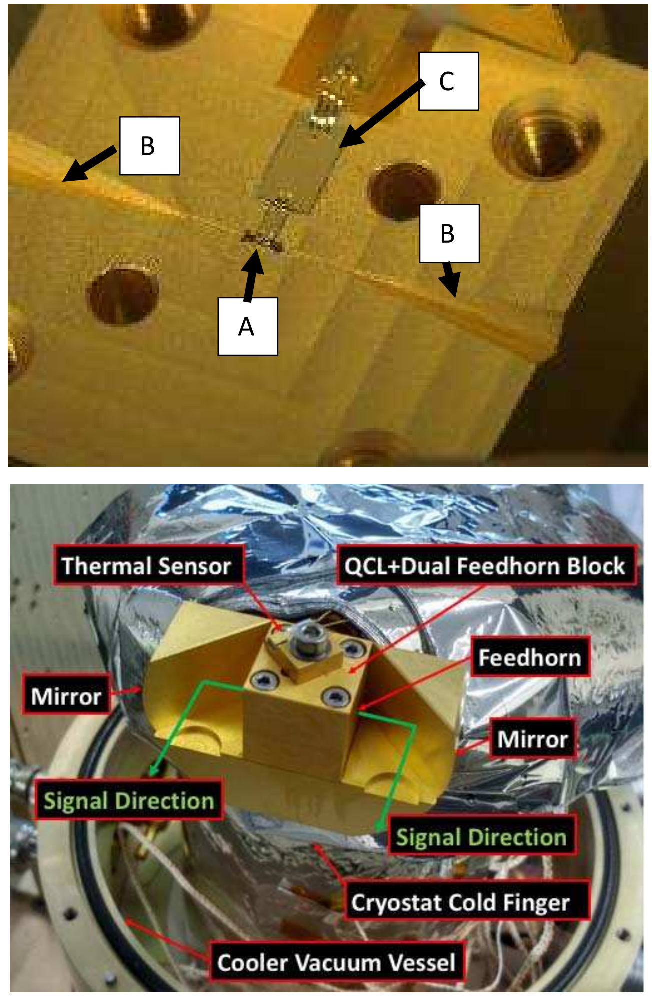

Fig. 3 (Top) Photograph of interior of QCL-LO module, showing (A) a 3.5-THz QCL located within a waveguide channel, (B) a pair of diagonal feedhorns and (C) an electrical interface. (Bottom) Exterior view of complete assembled block, with mirrors attached for beam profiling.

The performance characteristics were measured for a reference device with similar characteristics, which was mounted in a continuous-flow helium cryostat and driven in continuous-wave mode using a dc power supply. The emitted power was monitored using a pyroelectric detector, which was calibrated against a photoacoustic THz power meter. A peak operating temperature of 86 K and a maximum collected output power (at 10 K) of ~0.4 mW were recorded. The emission spectrum was recorded using a Fourier-Transform Infrared (FTIR) spectrometer and a helium-cooled bolometric detector. A principal emission peak at 3.31 THz was found to dominate the spectrum, with ~15 dB side-mode suppression.

A separate QCL was subsequently solder-mounted within a precision micro-machined 130-µm-wide × 75-µm-deep channel within an oxygen-free copper enclosure (Fig. 3, top), and ribbon-bonded to an integrated SMA connector. A second, symmetrical copper section was attached above the QCL to form a rectangular waveguide enclosure around the device.

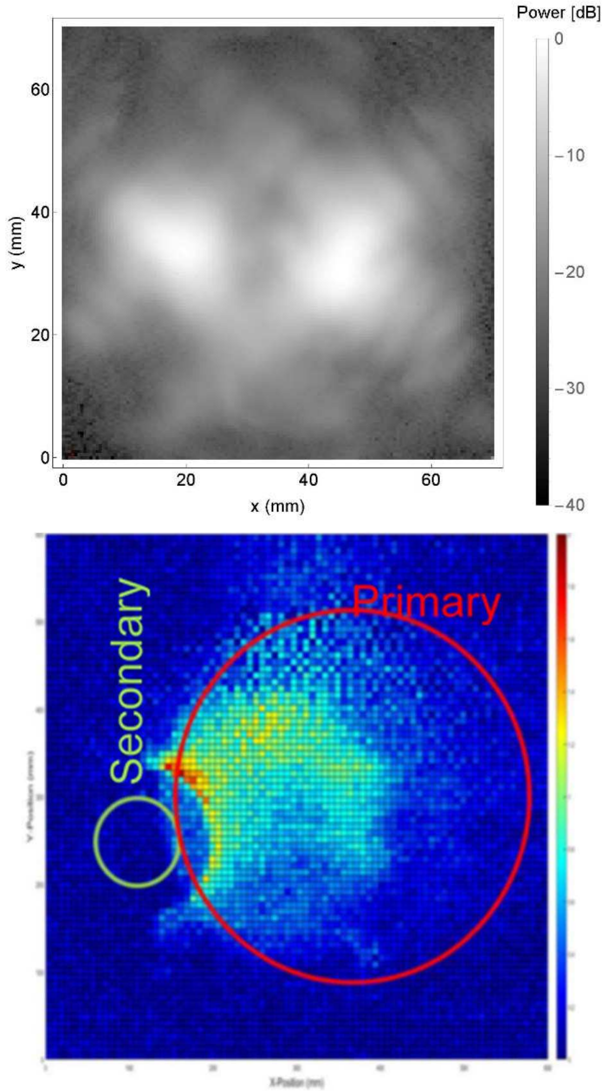

Fig. 4. THz power profiles (Top) for dual-feedhorn QCL module and (Bottom) for near-field of telescope optics.

In contrast to previous work [9], a single QCL ridge has been used, and a diagonal feedhorn has been integrated into each end of the waveguide structure. This improves free-space radiation coupling and provides access to radiation from both facets of the QCL simultaneously. This enables simultaneous coupling to the receiver, and a frequency-stabilisation subsystem.

III. THz Beam Characterisation

The QCL block was mounted within the cryocooler (Fig. 3, bottom) and driven using a dc current source. The cryocooler provide sufficient heat-lift (3 W) at the optimal QCL bias and maintained a stable ~60 K. The THz output power was measured using a photoacoustic power meter as > 8 mW.

A pair of reflectors was used to direct all radiation onto a measurement plane, and a beam profile [Fig. 4(Top)] was obtained using a raster-scanned Golay detector (4-mm aperture) at 70-mm from the QCL. Two symmetrical main lobes were observed, corresponding to each feedhorn, with a near-Gaussian pattern with 5–8° divergence, representing a significant improvement above an unmounted QCL [10] (~120° divergence). Fig. 4(Bottom) shows the beam profile from a single feedhorn, successfully propagating along the Cassegrain optics, with slight obscuration by the secondary mirror.

IV. Conclusion

We have demonstrated integration of a 3.5-THz QCL with a bi-directional waveguide/feedhorn module, and operation in a space-compliant cryocooler. Beam propagation has been demonstrated using Cassegrain fore-optics, representing a key step towards the first fully-integrated QCL-based THz receiver. The dual-feedhorn configuration will underpin frequency-stabilized LO development, enabling high-resolution radiometry.

Acknowledgment

We acknowledge the RAL Millimeter-wave Group Precision Development Facility for fabrication of the waveguide and feedhorns. Funding was provided by the European Space Agency (General Support Technology Programme Contract 4000114487/15/NL/AF), the UK Centre for Earth Observation Instrumentation (CEOI) (contract RP10G0435A03), and the Royal Society (Wolfson Research Merit Award WM150029).

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