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Waveguide-integration and packaging of terahertz quantum-cascade lasers for Earth observation instrumentation

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***Abstract*—We demonstrate a range of schemes for the integration and packaging of terahertz quantum-cascade lasers (THz QCLs) for satellite applications. This includes embedding within precision-micromachined waveguide/diagonal feedhorn modules, enabling near-Gaussian far-field emission, and photonic integration with power modulators. We present an analysis of solder-mounting and packaging on device performance and show that modulation bandwidths exceeding 4 GHz can be obtained through integration with robust coplanar RF waveguides.**

I. INTRODUCTION

TERAHERTZ-FREQUENCY quantum-cascade lasers (THz QCLs) are compact, yet powerful sources in the 2–5-THz band of the electromagnetic spectrum. They are attractive for applications in space and atmospheric science, as local oscillators both for radiometric gas observations, and wideband communications. To date, THz QCLs have been deployed for measurement of mesospheric/lower thermospheric atomic oxygen [O] in aircraft [1] and balloon-based spectrometers [2]. However, QCLs present challenges for satellite deployment, including poor far-field power coupling, long-term power drifts, and impedance mismatch with RF electronics. We present progress in packaging and integration of QCLs to address these issues.

II. RESULTS

A precision-micromachining and electroless plating approach has been used to define rectangular hollow waveguides within copper split-block structures (Fig. 1, left). This kind of waveguide is well-established in the microwave/millimeter-wave band, and is defined by the IEEE 1781.1–2012 standard [3]. The low-frequency cut-off is given by

$$f_{\mathrm{c}} = \frac{c}{\sqrt{\varepsilon_r}} \times \frac{1}{2a}$$

Where ε_{r} is the relative permittivity within the waveguide ($\varepsilon_{\mathrm{r}} = 1$ for a hollow guide), a is the width of the waveguide and c is the speed of light. In this standard, a width:height ratio of 2 is specified.

We have integrated THz QCLs at frequencies from 2.1–5.0 THz into such waveguides. At the lower-frequency end, fundamental waveguides can be produced, with $(130{\times}65)$-$\mu\mathrm{m}^2$ channels meeting the IEEE WM-130 standard recommended for 1.4–2.2 THz propagation. This enables single-mode and near-Gaussian laser emission at 2.1 THz [4]. The inclusion of a photonic-integrated racetrack resonator structure also enables stabilization of long-term power drifts [5].

However, at higher frequencies it becomes challenging to couple radiation from the QCL facet into narrow fundamental

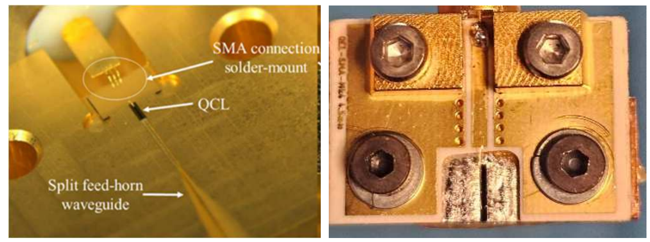

Fig. 1. (left) microscope image of interior of QCL waveguide module, showing bonding to the electrical contact and optical coupling into a rectangular metallic waveguide and diagonal feedhorn. (right) photograph of THz QCL bonded electrically to a coplanar RF waveguide.

waveguides. For example, the WM-56 standard for 3.3–5.0 THz devices would require a (57×29)-$\mu\mathrm{m}^2$ channel, which is comparable with the dimensions of the laser facet. As such, a wider (and hence over-moded) 300 μm channel allows much lower insertion loss, and we demonstrate that >5 mW continuous-wave output powers are achievable for 3.4-THz and 4.7-THz QCLs.

A diagonal feedhorn structure has been integrated with these waveguide geometries and yields far-field emission with up to 84% of the power radiated in the fundamental Gaussian mode. In practice, this enables $< 8^{\circ}$ full-width half-maximum divergence in a single-lobed beam.

An alternative packaging scheme has been developed, in which a THz QCL is electrically bonded to an RF coplanar waveguide (Fig. 1, right). This enables a modulation bandwidth greater than 4 GHz, underpinning future wideband communications applications.

We also present a thermal analysis of soldering schemes for cryogenic packaging. In this case, we analyze the QCL performance using a first order lumped-element thermal model for the offset between the temperature of the QCL active region and the heatsink:

$$T_{\mathrm{AR}} - T_{\mathrm{HS}} = R_{\mathrm{th}} P$$

Here, R_{th} is the thermal resistance and P is the time-averaged electrical heating within the active region. This heating power can be determined directly using $P = IV\gamma$, where I and V are the drive current and terminal voltage of the laser respectively, and γ is the duty-cycle of the pulsed electrical power supply.

Since the active-region temperature cannot be probed directly, we use the laser terminal voltage as a thermometric property. Fig. 2 shows a typical recorded thermometric calibration with the QCL operating at low electrical duty-cycle such that internal Joule heating is negligible.

This enables the internal temperature of the laser to be estimated under higher duty-cycle operation through measurement of the laser terminal voltage. A range of solder materials and techniques have been analyzed, with indium

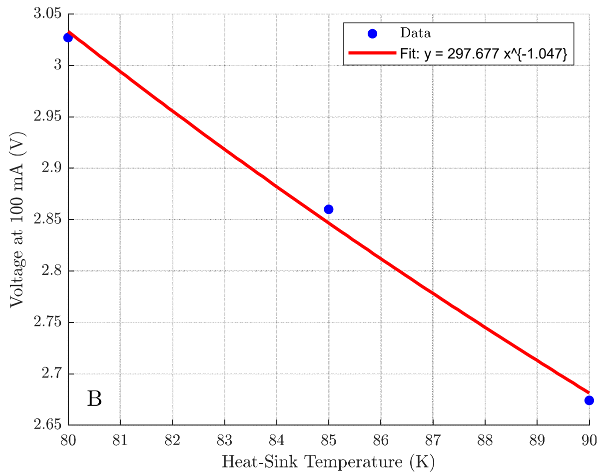

Fig. 2 Thermometric analysis of QCL terminal voltage as a function of heat-sink temperature under low-duty-cycle operation.

providing the best thermal performance, when used with an organic acid flux.

III. Summary

Micromachined waveguides and RF integration of THz QCLs provide improvements in far-field beam quality and modulation bandwidth. This will underpin future development of local oscillators for satellite-borne radiometry and communications systems.

Data availability

All data relevant to this work is contained within the manuscript.

Author contributions

MS: Investigation, Resources; SSK: Investigation; ND: Investigation; AB: Investigation; NKN: Investigation; NB: Resources, Investigation; EVN: Investigation; IK: Resources; YH: Resources; LHL: Resources; EHL: Funding acquisition; BA: Funding acquisition, Methodology; HW: Funding acquisition, Methodology; PGH: Funding acquisition, Methodology; PD: Supervision; JRF: Funding acquisition, Supervision, Methodology; BNEL Funding acquisition, Methodology, Investigation, Supervision; AV: Writing — original draft, Funding acquisition, Methodology, Investigation, Supervision.

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