3.5-THz quantum-cascade laser emission from dual diagonal feedhorns

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***Abstract*—We present antenna-pattern measurements obtained from a double-metal supra-terahertz-frequency (supra-THz) quantum cascade laser (QCL) mounted within a mechanically micro-machined waveguide cavity and dual diagonal feedhorn assembly. With the QCL operating in continuous-wave mode at 3.5 THz, and at an ambient temperature of ~60 K, emission from both laser facets has been simultaneously directed to a suitable supra-THz detector mounted on a multi-axis linear scanner. Comparison of simulated and measured far-field antenna patterns shows an excellent degree of correlation between beamwidth (full-width–half-maximum) and sidelobe content. Furthermore, when compared with unmounted equivalents, very substantially enhanced QCL beam profiles are observed. Our novel device demonstrates the effectiveness of diagonal feedhorns intended for use in future spaceborne Earth-observing supra-THz heterodyne radiometers.**

Index Terms*—*QCL, supra-terahertz, antenna, heterodyne, mixer, local oscillator, waveguide, diagonal feedhorn.

I. Introduction

The Earth's upper atmosphere plays an important role in influencing weather and future climate change. In particular, the mesosphere and lower thermosphere (MLT) are strongly affected by both natural and anthropogenic inputs from the surface, and by solar and space-weather impacts from the space environment above. By measuring the global distribution of chemical species (O, NO, OH) that exist within the MLT, climate models can be enhanced and the prospect of climate change better understood.

Observations within the MLT are best performed by supra-THz high-spectral-resolution heterodyne radiometers as these allow full characterisation of related spectral signatures. In order to avoid the attenuation of Earth's lower atmosphere, and provide global coverage, deployment in space is also required.

II. Radiometer System Concept

The use of THz heterodyne spectral radiometry has been well demonstrated at frequencies below 1 THz. However, developing supra-THz radiometer equivalents, shown schematically in Fig. 1, is very challenging and even more so when space deployment is required. For instance, difficulties must be overcome with respect to the fabrication of suitable heterodyne frequency mixers, local oscillators (LOs) and antennas; efficient radiometer front-end signal coupling between the mixer and the system fore-optics (primary and secondary antenna) is also necessary, as is compliance with small satellite platforms that invariably place demands on permissible system volume, mass and power consumption. Additionally, a supra-THz LO source should ideally be coupled directly with the heterodyne mixing device and within a single package that also provides an accessible free-space output port for supra-THz power monitoring, levelling and frequency stabilisation.

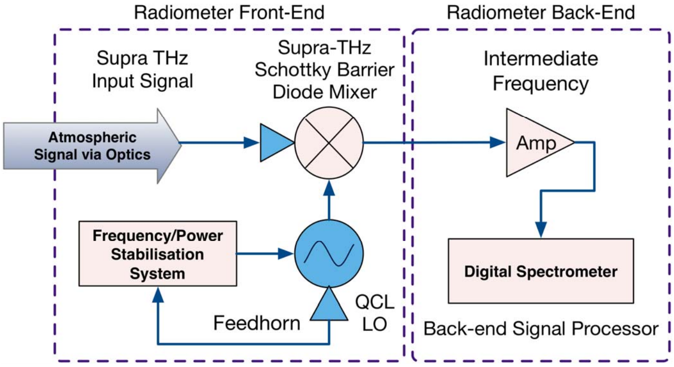

Fig. 1. Supra-THz radiometer schematic

Despite their excellent potential as supra-THz LO sources, quantum-cascade laser (QCL) devices are renowned for exhibiting a poor free-space power distribution, i.e. poor antenna pattern quality. This undesirable feature is particularly apparent when high-performance "double-metal" plasmonic cavities are used to confine radiation within the optical-gain medium [1] and limits QCL effectiveness in wider applications where free-space signal transmission is required. Integration with a mechanically fabricated waveguide and feedhorn antenna structure offers the possibility of enhancing the QCL output signal by constraining it to a propagation mode that results in improved beam quality, and simultaneously allows coupling to a mixer diode mounted within the same waveguide. This provides an attractive solution to the provision of a spaceborne supra-THz LO and radiometer as it serves the purpose of delivering well-controlled signal guidance via a small and robust mechanical assembly, along with the provision of an efficient electromagnetic interface with free-space.

At a frequency of 3.5 THz, however, the dimensions of both waveguide and feedhorn challenge mechanical fabrication techniques. Thus, the viability of a diagonal feedhorn and waveguide combination as a supra-THz antenna and propagation medium requires demonstration. To achieve this step, we have integrated a QCL within a mechanically micro-machined waveguide cavity that incorporates a diagonal feedhorn at each end. This new device extends a previously reported result [2] in which a QCL device was integrated with a larger over-sized waveguide and single diagonal feedhorn. In addition to using reduced waveguide and feedhorn dimensions that approach fundamental-mode operation, our novel dual feedhorn allows signal emission from each facet of the QCL to be propagated into free-space and the resulting antenna patterns to be measured.

III. Quantum Cascade Laser

QCLs offer very considerable advantages as direct supra-THz signal sources. Although cryogenic operation is required, typically below 100 K, they are highly compact (mm-scale) and rugged structures that are biased from a single direct current (dc) power supply as opposed to harmonically multiplying a lower-frequency source. They also directly generate sufficient supra-THz output power, typically at the milliwatt level, to 'pump' a semi-conductor mixer diode, and thus provide a source of heterodyne radiometer LO power with an inherent narrow spectral emission signature.

Formed from a bandgap engineered semiconductor structure, the QCL used in this experimental work is based on a GaAs/AlGaAs phonon-assisted "hybrid" design [3]. The active region of the device has been grown using molecular-beam epitaxy and processed into a 1-mm-long Au–Au ridge-waveguide structure, as described previously in [1]. The unmounted device operates in continuous-wave (cw) mode at heat-sink temperatures up to 86 K, with collected power in excess of 0.4 mW. It is important to note that the true output power of the unmounted laser is substantially larger than the measured value, as the coupling efficiency of radiation into the detector is limited by the poor beam quality.

IV. Integrated QCL, Waveguide and Dual Feedhorn

The QCL was integrated into a waveguide cavity with a cross-section dimension of (0.16×0.08) mm^2. The waveguide was machined into a copper block by using a precision mill. Two identical diagonal feedhorns with an across-diagonal aperture of (1.56×1.56) mm^2 and a slant angle of 7.5º were also machined into the same block at each end of the waveguide. After machining, the block was gold plated to prevent corrosion and to improve thermal heat sinking to a cryogenic cooler. Bias connection to the QCL was achieved through the use of a standard SMA connector and a series of wire bonding steps that also included a stage of heat sinking. Fig. 2a, shows the fabricated cavity and feedhorn structure with a QCL placed in the waveguide.

V. Experimental System and Method

In order to achieve the necessary electron population distribution within its multilayer bandstructure, the QCL must be cooled to a low ambient temperature. To achieve this, the integrated QCL and feedhorn block was attached to the 'cold finger' of a Stirling cycle cooler and operated at ~60 K in a cw mode. Two plane mirrors inclined at 45º to the signal propagation axis were machined into a gold-plated copper subcarrier and directed each feedhorn output through a single 1-mm-thick supra-THz semi-transparent vacuum window made from high-density polyethylene. Fig. 2b shows the complete assembly mounted in the cooler.

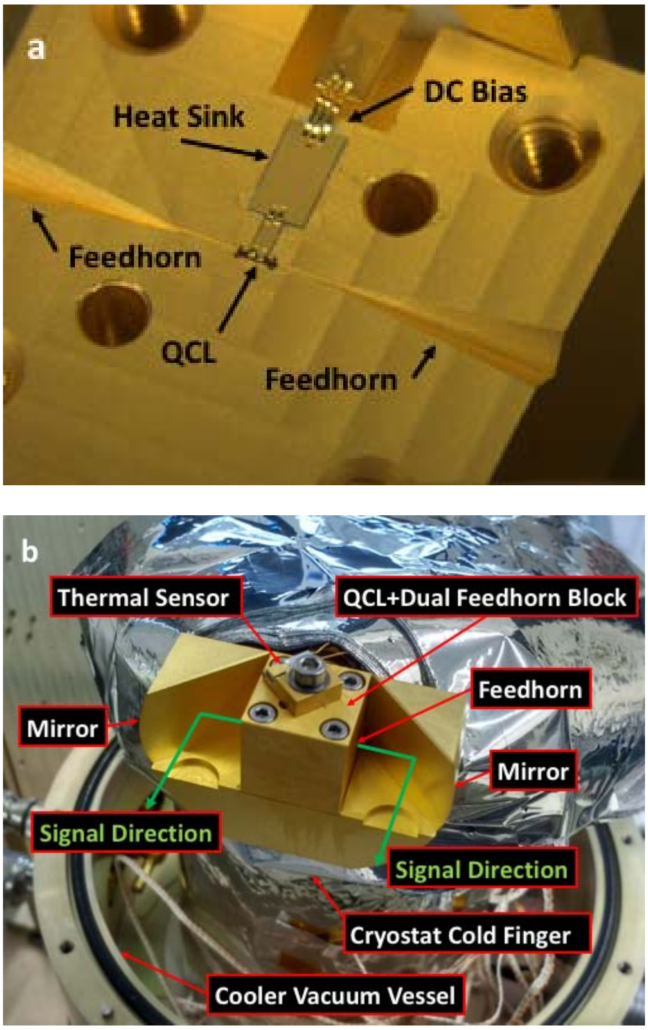

Fig. 2. a) QCL, waveguide cavity and dual feedhorn structure; b) QCL, feedhorn block and mirrors mounted on the cold finger. Window not shown.

An unpolarised Golay detector [4] mounted on a two-dimensional linear scanning system was used to measure the supra-THz emission intensity, as shown in Fig. 3. With the detector located approximately 70 mm away from the feedhorn apertures, and thus in the antenna far-field, a series of discretely sampled intensity measurements were made in a rectangular coordinate reference plane orthogonal to the direction of signal propagation. The inherent Golay input signal entrance aperture was 3 mm in diameter, and could be reduced via the insertion of aperture stops, though at the expense of reduced signal-to-noise. A measurement step interval of 0.5 mm was used in both scan axes to ensure adequate spatial sampling. With a combined measurement integration and dwell time of 0.5 seconds, the typical time required to complete a full scan was 3 hours.

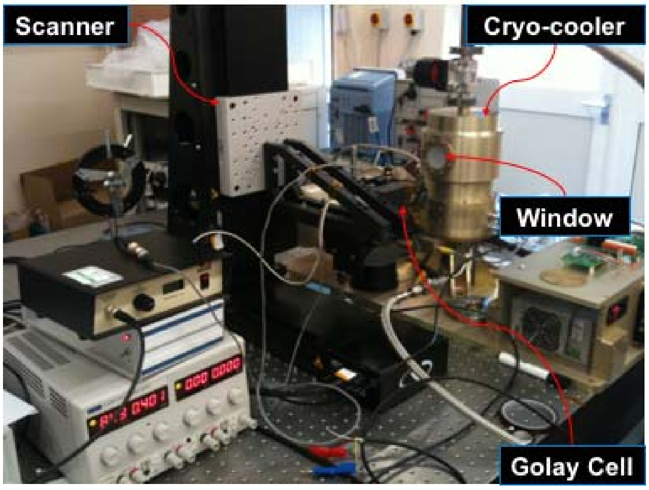

Fig. 3. System used to measure far-field 3.5-THz dual diagonal feedhorn antenna patterns.

VI. Simulation and Measurement Comparison

A software model of the diagonal feedhorn expanded single aperture electric fields into Gauss–Hermite modes [5], as shown in Fig. 4a. Comparison with measured 3.5-THz feedhorn antenna patterns, Fig. 4b, obtained using the experimental arrangement shows good correlation. For example, bright central maxima and regions of undulating intensity located on two 45° planes that correspond to sidelobes are clearly visible for each beam. Additionally, the measured full-width–half-maximum (FWHM) beamwidths, as shown in Fig. 5., are close to the simulated value of 5°. The larger (8°) discrepancy apparent in one axis of one beam is likely due to imperfections in the feedhorn fabrication or misalignment of the separate block halves. Mutual interference effects due to the coherent nature of the QCL emission are also present within the measured pattern.

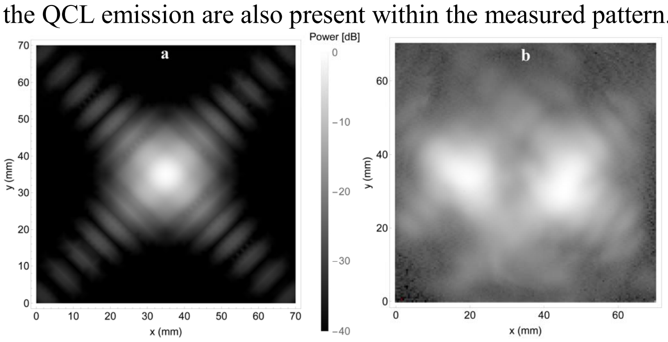

Fig. 4. a) Simulated single 3.5 THz feedhorn pattern; b) Measurement of the dual feedhorn QCL device at 3.5 THz. The scan extent in each case is (70×70) mm^2 and the Golay detector aperture was 3 mm diameter. The power scale applies to both images.

Given the agreement with single beam simulation, we believe that the QCL signal is propagating in a fundamental transverse electric (TE_{10}) mode within the waveguide, i.e. in the same mode used to excite the feedhorn simulation model.

The results obtained represent a very substantial improvement in QCL output beam quality. This, in turn, demonstrates that a waveguide and diagonal feedhorn combination offers a very effective means of propagating a supra-THz QCL output signal.

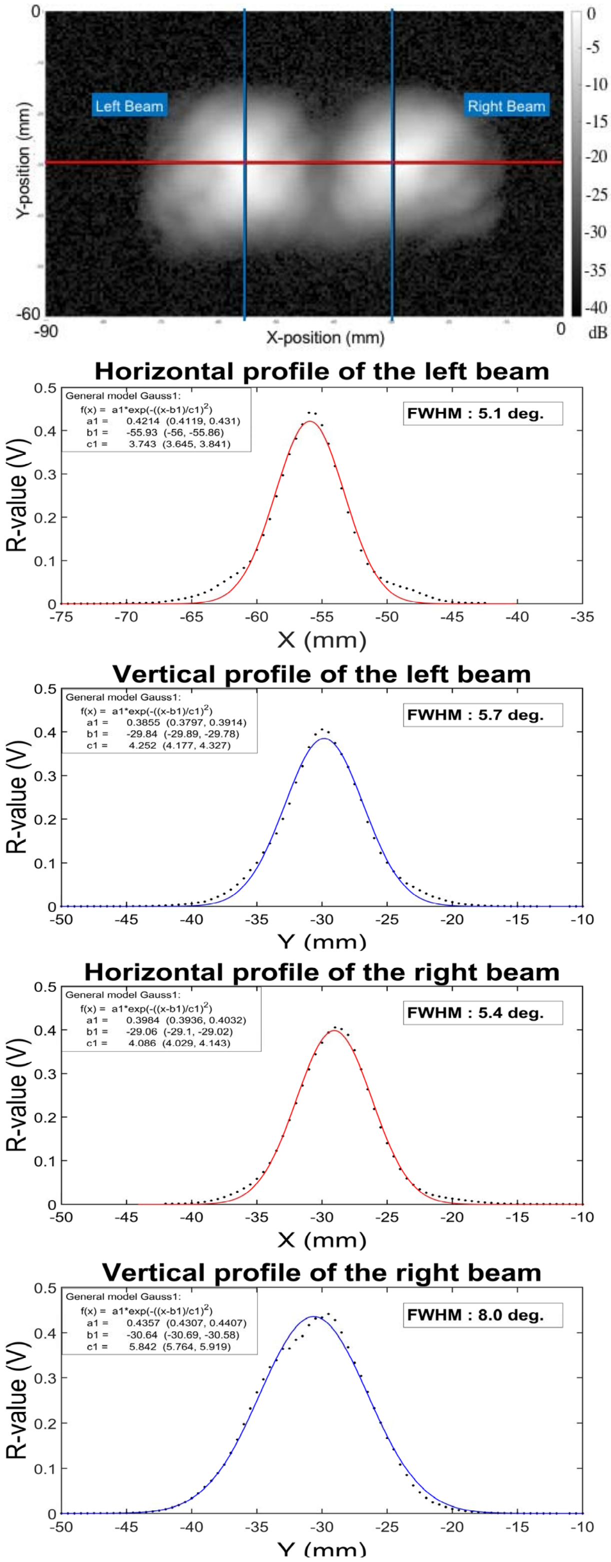

Fig. 5. Uppermost image: 3.5THz QCL dual beam profile sampled with a 2 mm diameter Golay detector aperture. Corresponding horizontal and vertical antenna beam profiles measured across each diagonal feedhorn output (left and right beam) are shown in the lower images and with a Gaussian fit profile superimposed. In most cases the beam FWHM is in close agreement with the simulated value of 5°.

VII. Conclusions

A 3.5-THz QCL has been integrated with a waveguide and a dual diagonal feedhorn structure. This novel device has been used to test the effectiveness of a diagonal feedhorn and has demonstrated a very superior QCL beam profile when compared with unmounted devices. We believe that this suggests a fundamental propagation mode is present within the waveguide. We also believe that this work represents an important step towards the development of a spaceborne supra-THz heterodyne radiometer for Earth observation.

Acknowledgements

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