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Electromagnetic-field analysis of diagonal-feedhorn antennas for terahertz-frequency quantum-cascade laser integration

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***Abstract*—we present an electromagnetic-field analysis of a terahertz-frequency quantum-cascade laser (THz QCL) integrated with a mechanically micro-machined waveguide cavity and diagonal feedhorn. A hybrid finite-element/Fourier transform approach enables analysis of both the near-field and far-field regions and is shown to agree well with experimental observations. The far-field antenna patterns show enhancement of the beam profile when compared with an unmounted QCL, in terms of beam divergence and side-lobe suppression ratio. Furthermore, we demonstrate integration of the QCL with dual diagonal feedhorns, enabling simultaneous access to both facets of the QCL, underpinning future integration with a satellite-based receiver and frequency-stabilization subsystem.**

I. INTRODUCTION

There is considerable scientific interest in studying the abundance of key gas species (*e.g.*, O and OH) within the mesosphere–lower thermosphere (MLT) region of the Earth's atmosphere, in part because there is a strong indication that these provide a highly sensitive indicator of climate change. The proposed *Linking Observations of Climate, the Upper Atmosphere and Space weather* (LOCUS) satellite aims to observe these gases by limb-sounding from low-Earth orbit to record their emission spectra using four receiver channels in the 0.8–4.7-THz band [1]. The system comprises two novel terahertz-frequency (THz) radiometers, in which THz quantum-cascade lasers (QCLs) will be exploited as local oscillators (LOs) at 3.5 and 4.7 THz, owing to their high THz output power (> 1 mW continuous-wave), narrow intrinsic linewidths (~20 kHz) and compact size (~1 mm). Moreover, they have been integrated successfully into precision-micro-machined waveguide blocks and operated in space-qualified Sterling-cycle cryo-coolers (~60 K) [2]. Key development challenges remain though, including stabilizing the emission frequency of the QCL, and improving the beam-profile and the coupling of THz radiation between the QCL and other system components.

To address these challenges, we have developed a dual-feedhorn integration technique, which enables access to both QCL facets simultaneously. Fig. 1(a) shows the internal structure of a precision micro-machined copper block containing a 3.3-THz QCL mounted in a rectangular waveguide with cross-sectional dimensions of (160 × 80)-µm^2. The waveguide feeds into a diagonal feedhorn with a (1.556 × 1.556)-mm^2 square aperture at either end, enabling the free-space THz emission to be coupled simultaneously to a mixer and a frequency-stabilization subsystem. In addition, the feedhorn has been shown to improve power outcoupling and beam divergence [3], but in order to optimize the far-field beam-profile, an electromagnetic model is needed.

II. SIMULATION METHOD

A hybrid modelling approach has been developed, to enable accurate yet fast simulation: first, an HFSS finite-element model of the field within the waveguide is used to determine the near-field pattern, assuming a constant electric-field excitation across the QCL facet. A 2D Fourier transform is then used to find the far-field pattern, described by a form-factor:

$$\tilde{h}(\theta,\phi) = \iint \tilde{E}_{\mathrm{a}}(x_{\mathrm{a}},y_{\mathrm{a}}) \times \exp[\mathrm{j}k\sin\theta\,(x_{\mathrm{a}}\cos\phi + y_{\mathrm{a}}\sin\phi)]\,\mathrm{d}x_{\mathrm{a}}\mathrm{d}y_{\mathrm{a}} \qquad (1)$$

where (θ,ϕ) are the angles between the antenna and the far-field observation plane in the horizontal and vertical directions respectively, k is the wave vector, and $(x_{\mathrm{a}},y_{\mathrm{a}})$ are respectively the horizontal and vertical coordinates across the antenna aperture. The complex electric field, $\tilde{E}_{\mathrm{a}}$ across the antenna aperture (*i.e.*, the near-field excitation) is obtained from the HFSS simulation. The far-field pattern is found using:

$$\tilde{E}(R,\theta,\phi) = \frac{\mathrm{j}k}{2\pi}\left(\frac{e^{-\mathrm{j}kR}}{R}\right)\tilde{h}(\theta,\phi) \qquad (2)$$

where R is the distance from the antenna to the far-field plane. This hybrid numerical/analytical modelling technique enables a rapid means of optimizing the coupling of THz radiation between the QCL and other system components.

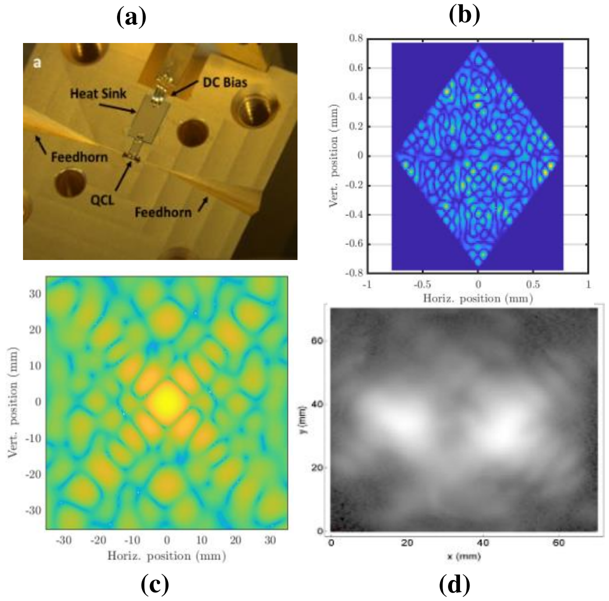

Fig. 1. (a) QCL mounted within a dual-feedhorn waveguide block (b) Simulated beam-profile for the emission from a single feedhorn in the near-field, (c) simulated emission beam-pattern obtained at 70 mm away from the feedhorn aperture, (d) experimental results of the beam-pattern of dual-diagonal feedhorn.

III. RESULTS AND ANALYSIS

Fig. 1(b) and (c) show the simulated near-field and far-field (at 70-mm) beam patterns respectively for a single feedhorn. The simulation results for the experimentally fabricated feedhorn and WM-130 rectangular QCL waveguide, predict a 4.04° far-field divergence and 17.5-dB side-lobe suppression, (*c.f.*, ~5.1–8.0° experimental value). Since an over-moded waveguide has been used, this yields a highly non-uniform near-field profile. However, the *far-field* pattern exhibits a well-defined central lobe, similar to that of an ideal feedhorn. This indicates that the beam pattern is only weakly dependent on the QCL waveguide. This has been investigated further by changing the dimensions of both the waveguide and the diagonal horn in the model.

Table 1 shows the beam-divergence angle and side-lobe ratio calculated for feedhorns with varying aperture sizes. Results are shown both at the near-to-far-field transition zone (at 70-mm) and within the far-field region ($2D^2/\lambda$) at 830-mm.

Figure 2(a) shows an inverse-exponential relationship between the aperture size and the beam divergence, for feedhorns fed by a WM-130 waveguide, whereas Figure 2(b) shows that the divergence of a 1.556-mm feedhorn is only weakly dependent on the feed-waveguide dimensions.

Table 1. Beam divergence and side lobe ratio for a diagonal feedhorn with varying aperture size, fed by a WM-130 rectangular waveguide.

	Aperture size (mm)			
	0.389	0.778	1.167	1.556
	Transition zone at 70-mm			
Divergence (degree)	18.4	8.43	5.69	4.04
Side lobe ratio (dB)	23.7	18.4	18.9	17.5
	Far-field region at 830-mm			
Divergence (degree)	18.6	8.81	5.84	4.30
Side lobe ratio (dB)	27.5	18.4	21.2	17.5

IV. CONCLUSION

We have presented a hybrid analytical/numerical electromagnetic model of a THz QCL coupled with a rectangular waveguide and a diagonal feedhorn, enabling rapid simulation of the impact of device geometry on the near- and far-field antenna patterns. The calculated far-field divergence has been shown to depend only weakly on the geometry of the rectangular QCL waveguide, and is therefore close to that of an ideal feedhorn, simplifying the optical design of the receiver system. The divergence angle can be reduced by increasing the feedhorn aperture size, albeit at the expense of increased side-lobe content in the far-field pattern. The simulation could be improved further through the inclusion of an accurate electromagnetic model of the QCL itself, underpinning future waveguide-integration design of the receiver system.

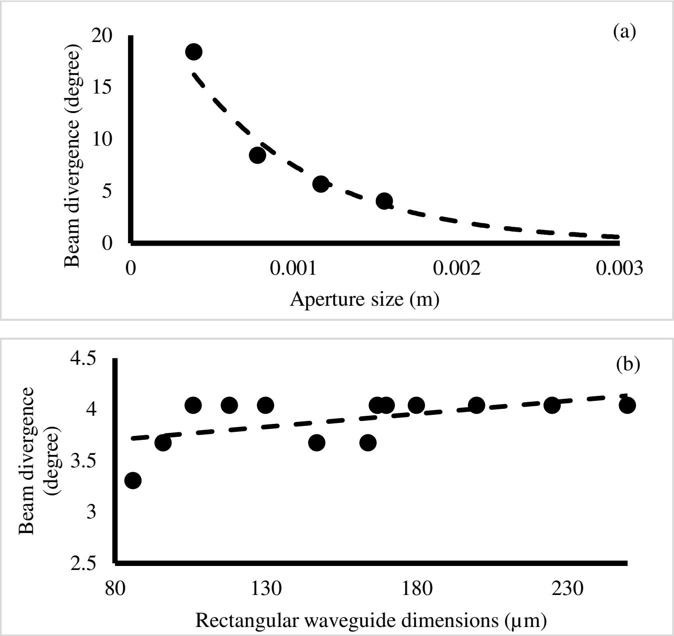

Fig. 2. Relationship between beam divergence and (a) aperture size of a diagonal feedhorn fed by a WM-130 waveguide and (b) rectangular waveguide width, when feeding a 1.556-mm feedhorn. Circles show simulation results, and dashed lines show exponential and linear fittings to the data for each subfigure, respectively.

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REFERENCES

[1] S. P. Rea *et al.*, 'The Low-Cost Upper-Atmosphere Sounder (LOCUS)', in *26th international symposium on space terahertz technology*, Cambridge, MA, 2015.

[2] A. Valavanis *et al.*, 'Mechanically robust waveguide-integration and beam shaping of terahertz quantum cascade lasers', *Electronics Letters*, vol. 51, no. 12, pp. 919–921, Jun. 2015.

[3] B. N. Ellison *et al.*, '3.5 THz quantum-cascade laser emission from dual diagonal feedhorns', *Int. J. Microwave Wireless Technol.*, pp. 1–9, May 2019.