Proceedings Paper:

North, N.K, Holstein, J., Horbury, M.D. et al. (7 more authors) (Accepted: 2023) Real-Time Analysis Of THz Quantum-Cascade Laser Signals Using A Field Effect Transistor Array. In: Journal of Infrared, Millimeter and Terahertz Waves. 48th International Conference on Infrared, Millimeter and Terahertz Waves, 17-22 Sep 2023, Montreal, Canada. Springer . (In Press)

Real-Time Analysis of THz Quantum-Cascade Laser Signals using a Field Effect Transistor Array

N. K. North[1], J. Holstein[2], M. D. Horbury[1], H. Godden[1], L. H. Li[1], J. R. Freeman[1], E. H. Linfield[1], H. Roskos[2], A. Lisauskas[2], and A. Valavanis[2]
[1]School of Electronic and Electrical Engineering, University of Leeds, Leeds UK LS2 9JT*t*
[2]Physikalisches Institut, Johan Wolfgang Goethe-Universität, D-60438 Frankfurt am Main, Germany

***Abstract* — We demonstrate real-time analysis of the emission from a 3.4-THz quantum-cascade laser (QCL) source, using an array of nanoscale field-effect transistor devices. We show that THz power can be detected directly up to a modulation bandwidth of 500 kHz, and indirectly via a change in the device threshold, up to a 100-MHz bandwidth.**

I. Introduction

Terahertz-frequency quantum-cascade lasers (THz QCLs) are compact semiconductor sources of narrowband radiation in the ~2–5-THz band. They have been shown to allow high direct-modulation bandwidths, up to >35 GHz [1], potentially underpinning their applications in high-speed wireless communications, real-time gas sensing, or industrial inspection. For example, numerous important atmospheric gas-phase species have strong spectral features in the THz band (e.g., atomic oxygen at ~4.7-THz), and fast tunable-laser spectroscopy techniques could be used to analyze their reaction kinetics on nanosecond-scale timescales. However, fast analysis of THz QCL signals typically requires either complex heterodyne techniques, or cryogenic detectors. THz field-effect transistor (TeraFET) detectors have recently been shown to offer low-noise room-temperature detection of THz QCL signals over kHz bandwidths [2], but the use of a single-element detector with a patch-antenna introduces very high sensitivity to system alignment.

Here, we demonstrate that TeraFET detectors in an array geometry allow real-time acquisition of THz QCL signals directly up to 500-kHz modulation bandwidth, with more relaxed alignment requirements. This can be extended to 100-MHz bandwidth by analyzing the shift in QCL threshold current.

II. Detector Design

The TeraFET detector we applied in this work was fabricated using a commercial 65-nm CMOS process conducted by TSMC (Taiwan Semiconductor Manufacturing Company).

It consists of 64 identical resonant patch coupled TeraFETs (pixels) in parallel readout circuitry, forming a square-shaped array. The pixels' patch antennas were optimized for best performance at 3.4 THz using CST Microwave Studio.

For the experiments, the detector was packaged on a PCB board using epoxy glue. Following this step, a wire-bonding approach was applied to establish electronic connections. In the final packaged assembly, the detector PCB is connected to a second OPA stage. In addition to signal amplification, it enables access to the experimental environment for final readout.

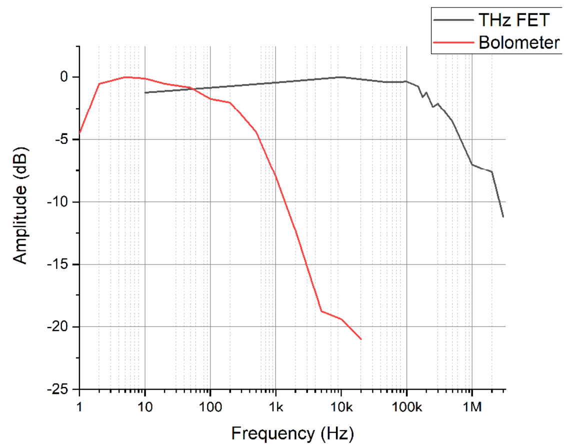

Fig. 1. Frequency response of the TeraFET array (black) and a commercially available helium-cooled silicon bolometer (red) for comparison.

III. QCL Modulation Analysis

A single-mode 3.4-THz QCL was used as the radiation source in this work, which was processed into a semi-insulating surface-plasmon waveguide structure. Although this waveguide configuration limits the QCL modulation bandwidth to <1 GHz, it provides superior far-field beam profile compared with double-metal devices. The QCL was driven using a Wavelength Electronics QCL1000 LAB current source, which was modulated externally using an arbitrary waveform generator. The QCL was mounted inside a ColdEdge closed-cycle cryocooler at an operating temperature of 22 K.

A pair of off-axis parabolic mirrors collimated the QCL output and focused the radiation into the detector, which was mounted on a motorized XYZ stage for alignment. The detector signal was recorded in the time-domain using an oscilloscope. The direct-detection bandwidth of the detector was characterized by applying a 200-mA current modulation to the QCL bias and recording the amplitude of the detector signal as a function of modulation frequency. Fig. 1 shows that an approximately flat frequency response was observed up to a 3-dB cut-off frequency of 500 kHz, compared with the ~400 Hz bandwidth achievable using a commercial helium-cooled silicon bolometer.

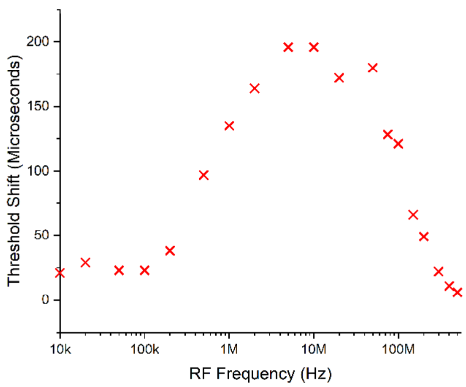

Fig. 2. Reduction in switch on time of the QCL plotted against the modulation frequency.

An alternative measurement scheme was used to confirm that the detected signal was not limited by the modulation bandwidth of the QCL itself. Here, the laser driver output was set slightly lower than the threshold current of the QCL. A slow (230 Hz) current ramp was applied to the modulation input of the driver, such that the QCL bias was swept periodically above the lasing threshold, and the TeraFET array was used to record the time at which THz emission occurred. An additional 1-V-amplitude modulation was applied to the QCL using a Keysight RF generator connected to a bias-T on the electrical input to the cryocooler. This additional fast modulation shifted the time at which the lasing threshold was exceeded.

Fig. 2 shows this effect as a function of the RF signal frequency. At frequencies <300 kHz, the high-pass input to the bias-T filters the RF signal, and the QCL switch-on is only affected weakly. However, a strong modulation effect is seen at higher frequencies, with a 3 dB cut-off at 200 MHz. This confirms both that the single-metal QCL ridge is capable of modulation well beyond the cut-off point seen in Fig. 1, and that the TeraFET detector can provide an indirect means of detecting fast QCL modulation through a change in the time-averaged emission power.

IV. Summary

A TeraFET detector array has been shown to provide a significant improvement in THz signal bandwidth, compared with a commercially available, cryogenically cooled bolometer. Although a detector array, in principle, has poorer signal-to-noise ratio than a single detector with a patch-antenna, it is far more tolerant to shifts in system alignment and mechanical vibrations. We have shown that a ~500 kHz detection bandwidth is achievable at room temperature, which presents significant advantages for future applications development. For example, gas-phase reaction-kinetics studies become accessible on the microsecond scale. Alternatively, large sample sizes would be achievable within imaging or static spectroscopic applications, which can be averaged to increase the SNR.

Acknowledgments

This work was supported financially by the Deutsche Forschungsgemeinschaft INTEREST Priority Programme (SPP 2314) and UK Research and Innovation (Future Leader Fellowship MR/S016929/1).

Data Availability

The data associated with this paper are openly available from the University of Leeds Data Repository http://doi.org/10.5518/1320.

Author Declarations

Conflict of interest

The authors have no conflicts to disclose.

Author contributions

N. K. North: writing — original draft; data curation; investigation (lead); methodology (equal); visualization. J. Holstein: investigation (supporting); methodology (equal). M. D. Horbury: investigation (supporting); methodology (equal). H. Godden: investigation (supporting). L. H. Li: resources; investigation (supporting). J. R. Freeman: funding acquisition (supporting); conceptualization (supporting); methodology (equal). E. H. Linfield: funding acquisition (supporting); conceptualization (supporting). H. Roskos: funding acquisition (lead); conceptualization (supporting). A. Lisauskas: funding acquisition (supporting); conceptualization (lead); methodology (equal); supervision (equal). A. Valavanis: writing — review & editing; funding acquisition (supporting); conceptualization (supporting); methodology (equal); supervision (equal).

References

[1] P. Gellie *et al.*, 'Injection-locking of terahertz quantum cascade lasers up to 35GHz using RF amplitude modulation', *Opt. Express*, vol. 18, no. 20, pp. 20799–20816, 2010, doi: 10.1364/OE.18.020799.

[2] J. Zdanevičius *et al.*, 'Field-Effect Transistor Based Detectors for Power Monitoring of THz Quantum Cascade Lasers', *IEEE Trans. Terahertz Sci. Technol.*, vol. 8, no. 6, pp. 613–621, Nov. 2018, doi: 10.1109/TTHZ.2018.2871360.