DETECTION OF 2.2–3.5 TERAHERTZ RADIATION USING A QUASI-OPTICALLY-MOUNTED PLANAR SCHOTTKY DIODE

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ABSTRACT

Practical supra-terahertz (1–5 THz) heterodyne radiometry systems require compact local oscillator and mixer components, which are suitable for robust waveguide integration. We demonstrate detection of radiation emitted by quantum cascade lasers at frequencies between 2.2 and 3.5 THz using room-temperature quasi-optically mounted planar Schottky diodes. These diodes are more readily integrated into waveguides than point-contact diodes, do not require the cryogenic environment of hot-electron bolometers and offer potentially better noise performance than superlattice devices.

Key words: Terahertz radiation; quantum cascade lasers; Schottky diodes.

1. INTRODUCTION

Heterodyne radiometry systems, operating in the "supra-terahertz" (1–5 THz) frequency band, have potentially widespread applications within satellite-borne and ground-based instrumentation [1]. These include the detection of trace-gas species including atomic oxygen (4.7 THz), hydroxyl radicals (3.5 THz), methanol (2.56 THz) and methane/water (2.2 THz). A range of THz-radiometry instrumentation has been proposed for future satellite missions, including the Low-Cost Upper Atmospheric Sounder (LOCUS) [2], which will enable the mapping of the high-energy atomic oxygen chemistry in the mesosphere and lower thermosphere [3].

Satellite-borne supra-THz radiometry systems require high powered and compact THz-frequency sources, and sensitive mixer/detector technology, which are suitable for tight optical and electronic integration. A range of compact THz mixer technologies have been demonstrated to date. However, all of these are fundamentally limited, to some extent, in terms of their suitability for satellite-borne operation. Conventional point-contact Schottky mixers can operate at frequencies in excess of 3 THz at room temperature [4], and superlattice devices [5] have been demonstrated at either room temperature or at cryogenic temperatures but present a challenge for waveguide integration. Hot-electron bolometers can detect similar THz frequencies under cryogenic cooling [6], but are highly sensitive to temperature and therefore cannot be integrated thermally with a high-powered THz source. Their ∼4 K operational temperature requirement is also undesirable from a space-operation perspective.

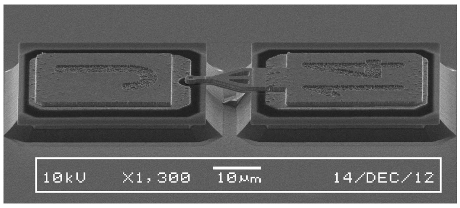

Figure 1. A scanning electron microscope image of a planar airbridged GaAs Schottky diode similar to the devices used in this work

In this paper, we report the detection of free-space radiation, emitted by quantum cascade laser (QCL) sources [7], in the 2.20–3.50 THz frequency range using a quasi-optically-mounted room-temperature planar airbridged Schottky detector. Devices with this geometry are mechanically robust, can readily be packaged and integrated quasi-optically with other THz components, and offer potentially higher signal-to-noise ratio (SNR) than superlattice based devices.

2. PLANAR SCHOTTKY DIODES

The detector used in this work is based on an airbridged GaAs Schottky diode of a type similar to devices used in sub-harmonically pumped heterodyne mixers, as required for Earth observation at sub-THz frequencies. A scanning-electron microscope image of such a diode is shown in Fig. 1. The ∼1-μm-diameter diode is defined with metallic pads on a GaAs chip. This is flip-chip connected across the the feed-points of a planar gold bow-tie

Table 1. Emission frequency and maximum time-averaged output power of THz QCLs when driven by a 10-kHz, 20% duty-cycle pulse train.

Frequency [THz]	Power [mW]
2.20	0.8
2.56	1.8
2.75	1.3
3.05	7.6
3.50	1.3

antenna that has been photolithographically defined on a high-resistivity silicon substrate. Incoming THz radiation is focussed onto the antenna by a hyperhemispherical silicon lens, also made from high-resistivity silicon.

The diode was forward-biased using a constant-current source, and the rectified signal is capacitively coupled to a low noise operational amplifier for preamplification. This amplifier limits the response time of the receiver to ≤ 1 µs; the intrinsic response time of the Schottky diode is well below 1 ns.

3. THZ QUANTUM CASCADE LASERS

The THz QCL radiation sources are based upon a set of GaAs/AlGaAs semiconductor heterostructures, which were grown upon semi-insulating GaAs substrates using molecular-beam epitaxy. The designs of the QCL gain media were selected to target molecular emission/absorption lines at 2.20, 2.56, 2.75, 3.05 and 3.50 THz. The devices were processed into semi-insulating surface-plasmon waveguides using optical lithography and were mounted onto the cold-finger of a helium-cooled cryostat at 10 K. The QCLs were biased using a pulsed (10 kHz, 20% duty cycle) current source, which was electrically gated by a 30-Hz modulation envelope. The emitted THz radiation was collimated and focused outside the cryostat using a pair of off-axis paraboloidal mirrors. The THz power was adjusted by varying the current supplied to the QCLs and was measured using a calibrated photoacoustic power meter, which was positioned at the beam-focus. The maximum time-averaged output power of each QCL was found to be between 0.8 and 7.6 mW, as shown in Table 1.

4. DIODE CHARACTERISATION

The detector was characterised at each frequency by systematically adjusting the respective QCL emission power, and recording the video response of the Schottky detector using both an oscilloscope and a lock-in amplifier, which were referenced to the 30-Hz current-modulation envelope. Fig. 2 shows the time-domain response of the detector at 2.56-THz. The rise-time and fall-time of the detector are negligible compared with the length of the pulse. The detector voltage varies significantly during the

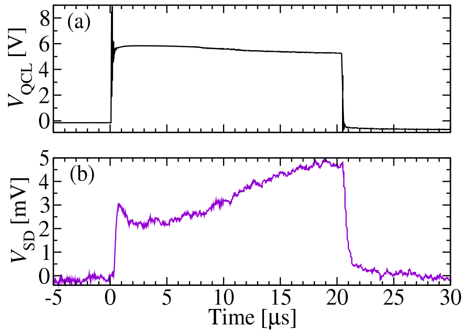

Figure 2. (a) The time-domain voltage signal measured across the 2.56-THz QCL in response to a single current pulse, corresponding to its peak emission power. (b) The corresponding baseline-corrected response of the detector.

'plateau' of the pulse, in response to the intra-pulse time-variation of the THz QCL emission power. As discussed in our previous work [8], this time-variation is principally caused by the variation in the QCL bias voltage during the pulse, although Joule-heating effects are also significant [9].

Fig. 3 shows the time-averaged detector response as a function of the measured (time-averaged) 2.2-THz QCL emission power. The dotted line in the plot shows a linear fit to the data, and indeed the detector response was found to be linear over the full investigated range of THz powers, at all frequencies.

Fig. 4 shows the responsivity (without correction for optical coupling) of the detector as a function of THz frequency. A peak value of $0.460\,\mathrm{V\,W^{-1}}$ was determined at a frequency of 2.56 THz. The responsivity was found to exceed $0.070\,\mathrm{V\,W^{-1}}$ at all frequencies in the 2.2–3.50 THz range. This figure is lower than the state of the art, primarily because the device diameter is larger than the optimal size for supra-THz operation. Additional losses are attributed to the flip-chip mounting approach. Work is currently underway to produce and characterise smaller diameter diodes.

5. CONCLUSION

In conclusion, we have demonstrated the generation and detection of radiation in the 2.2–3.5 THz range using compact QCL sources and a planar Schottky diode detector. Future work will aim to demonstrate frequency downconversion of THz signals using this detector geometry, with QCLs as local oscillators. Both the planar Schottky diode and QCL technologies used in this work have been demonstrated independently to be suitable for waveguide integration [10], and will underpin the development of complete module-integrated heterodyne radiometry systems.

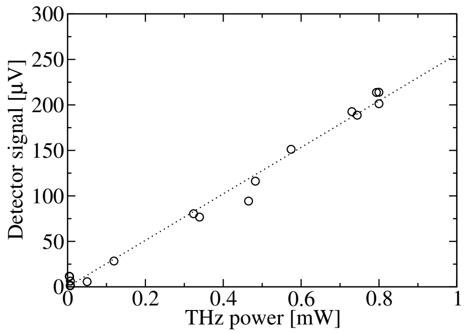

Figure 3. Time-averaged detector response at 2.2 THz as a function of the time-averaged THz QCL power.

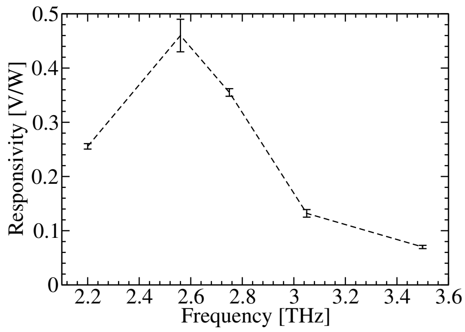

Figure 4. Detector responsivity as a function of THz frequency. The dashed line is a guide for the eye. Error bars show the fitting-uncertainty in the relationship between detector signal and power.

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