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Dean, P, Valavanis, A, Scheuring, A et al. (10 more authors) (2012) Ultra-fast sampling of terahertz pulses from a quantum cascade laser using superconducting antenna-coupled NbN and YBCO detectors. 2012 37th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz). 1 - 2 . ISSN 2162-2027

https://doi.org/10.1109/IRMMW-THz.2012.6380341

Ultra-fast sampling of terahertz pulses from a quantum cascade laser using superconducting antenna-coupled NbN and YBCO detectors

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Abstract—We demonstrate the ultra-fast detection of terahertz pulses from a quantum cascade laser (QCL) using superconducting NbN and YBCO detectors. This has enabled both the intrapulse and interpulse dynamics of a THz QCL to be measured directly, including interpulse heating effects on sub−µs timescales.

I. Introduction and Background

THE most commonly employed detectors for terahertz (THz) quantum cascade lasers (QCLs) rely on incoherent thermal detection of radiation. Owing to the slow time-constants of thermal processes (typically ~ms), such schemes are sensitive only to the total pulse energy during typical pulsed QCL operation. This slow detector response precludes investigation of intrapulse and interpulse dynamics, including interpulse heating effects. Yet the current requirement for cryogenic cooling of THz QCLs has led to great interest in analyzing their thermal properties. Such studies generally infer the internal temperature from changes in the emission power [1]. However, heat-extraction occurs on τ∼1 µs time-scales [2] that cannot normally be resolved.

We report the ultra-fast detection of QCL pulses using superconducting NbN and YBCO detectors with response times of ~165 ps [2] and ~45 ps [3], respectively. The intrapulse dynamics are interpreted in terms of the time-dependent driving current, enabling the true power-current relationship for the QCL to be determined. We show that this transfer function differs from that obtained using slow thermal detectors that respond only to the integrated pulse energy. We also present direct observations of pulse-to-pulse degradation in the emitted power, which enables calculation of time-constants for heat extraction, as well as the thermal resistance and anisotropic thermal conductivity of THz QCLs.

II. Intrapulse Dynamics

The QCL used for this work was based on a three-well resonant-phonon depopulation scheme emitting at ~3.1 THz, processed into a semi-insulating surface plasmon ridge waveguide. The detector elements consisted of NbN or YBCO micro-bridges fabricated on a sapphire substrate and embedded into a planar log-spiral antenna. The detectors were operated below the critical temperature and driven onto the superconducting transition by a constant bias voltage. A 500 MHz real-time oscilloscope was used to monitor the detector output following 40 dB of amplification in the bandwidth 0.1–400 MHz.

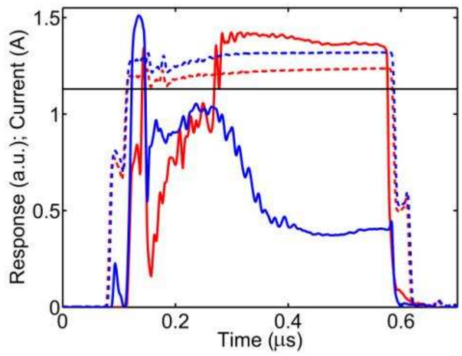

Fig. 1. (a) NbN detector responses (solid) to a THz QCL driven by 500-ns current pulses of different amplitude (dashed). The horizontal black line indicates the current value at threshold for this QCL.

Fig. 1 shows exemplar NbN detector responses to a 500-ns driving pulse of low duty cycle, for which the recorded current pulses are also shown. We have confirmed that these dynamic responses can be correlated directly to the time-dependent amplitude of the current pulses. As can be seen, the shape of the THz pulse reacts strongly to small changes in the driving pulse, giving rise to drastically different pulse shapes. Using the correlation between the instantaneous detector output and driving current measured under a range of driving conditions we have obtained the true power-current relationship for the QCL, as shown in Fig. 2. For comparison the response obtained using a germanium bolometer, which responds only to the pulse energy, is also shown. This measurement demonstrates the inaccuracy of the power-current relationship measured with the bolometer under pulsed operation.

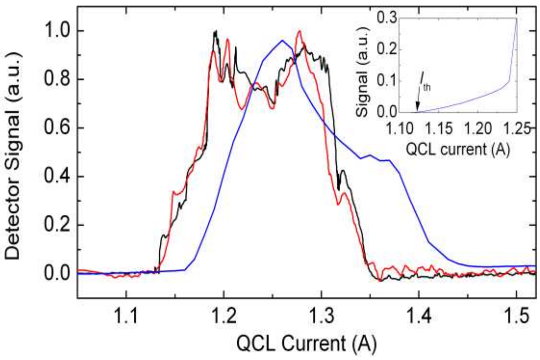

Fig. 2. Power-current relationships obtained using superconducting NbN (black) and YBCO (red) detectors, and a germanium bolometer (blue).

III. Intrapulse Dynamics and Heating

Pulse-to-pulse degradation of the emitted power, arising from Joule heating of the QCL, has also been studied. Fig. 3(a) shows the NbN detector response (average amplitude within each pulse) for a QCL driven by a 1-ms long pulse-train of 500 ns pulses of varying repetition rate, using a fixed heat-sink temperature, T_H=15 K. It can be seen that the THz power decreases in successive pulses, and more severely for higher repetition rates (duty cycles), as a result of the QCL not being able to return to thermal equilibrium with the heat sink.

The effect of active-region (AR) temperature, $T_{AR,}$ upon the THz power was measuring with a Ge bolometer; a continuous 1-kHz pulse-train was used, such that $T_{AR}\approx T_H$. The AR temperature variation was then inferred for the rapidly-repeating pulse trains in Fig. 3(a) by comparison with the low-duty-cycle data. Fig. 3(b) shows the extracted AR temperatures for each pulse train, along with a regression to the form $T_{AR} = T_\infty + (T_H - T_\infty)\exp(-t/\tau)$, where τ is a material-specific thermal time-constant for average heating in the material, and T_∞ is the final, quasi-equilibrium temperature. This functional form represents a general solution of the one-dimensional heat equation for a bulk solid with temperature-independent material properties. The temperature can be seen to increase over the length of the pulse train, with a larger final temperature at high repetition rates. Values of T_H increase from 25 K at 100-kHz repetition up to 49 K at 500 kHz. Values of τ were found to be between 0.29 and 0.46 ms in each case.

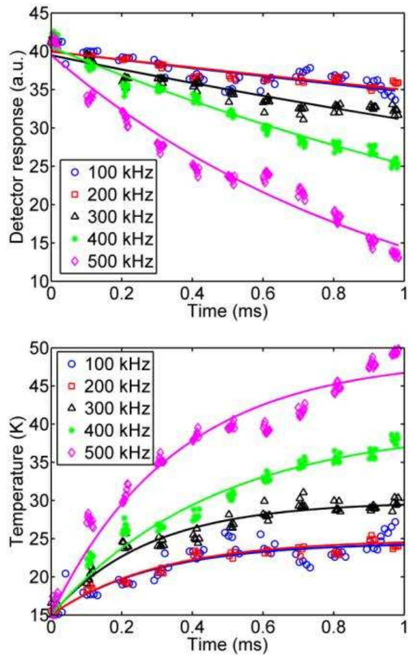

Fig. 3. (a) Detector response to a QCL driven by a pulse train of 500 ns pulses with varying repetition rate. (b) Time-dependence of the QCL active region temperature deduced from (a).

IV. Conclusion

Direct detection of THz QCL pulses using superconducting detectors enables the observation of intrapulse and interpulse dynamics. We have measured the true power-current relationship for a QCL from the correlation between instantaneous driving current and detector response. Interpulse heating effects have also been studied, from which the thermal properties of QCLs can be [have been?] obtained.

Acknowledgments

We are grateful for support from the EPSRC, the Royal Society, the Wolfson Foundation, and the European Research Council grants 'TOSCA' and 'NOTES'. This work was partly supported by the German Federal Ministry of Education and Research (Grant Nos. 05K2010 and 13N12025) and by DFG Center for Functional Nanostructures.

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