Time resolved photocurrent measurements of terahertz QCLs

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***Abstract*—We have used a two beam, time resolved photocurrent technique to study the gain recovery time in a terahertz quantum cascade laser. We find that the recovery time is ∼45 ps, and does not change significantly with current density.**

Quantum cascade lasers (QCLs) were first demonstrated in 1994 [1] and extended to the terahertz spectral region in 2002 [2]. As well as their intriguing application potential, they are interesting from a physical point of view because the light emission has its origins in an intersubband transition. A zero linewidth enhancement factor has been predicted for these devices, because the laser levels consist of parallel subbands, and it has also been suggested that the fast electron scattering times of intersubband transitions will lead to a fast gain recovery time, and novel laser dynamics [3]. In designs of THz QCLs where the depopulation of the lower laser level is based on scattering of electrons into a miniband, the energy separations between the energy levels of interest are less than an LO phonon energy, meaning that only electrons with high wavevector k can lose energy by LO phonon emission. For this reason, it might be expected that the characteristic relaxation times in these devices may differ significantly from those in mid-IR QCLs.

To gain some insight into the dynamics of THz QCLs we have used a time resolved photocurrent technique. We used a terahertz QCL designed to emit at ~ 94 μm wavelength, which had a waveguide designed for low optical confinement, facilitating the coupling of light into the cavity. The two end facets were polished at 45° to suppress lasing. This prevented the clamping of population inversion at laser threshold, allowing measurements to be made over a wider range of inversion values. Measurements were carried out at the FELIX free electron laser (FEL) facility which can provide a sequence of short pulses (∼10 ps), tunable in the THz region. The FEL radiation was split into two co-polarised and collinear beams of equal intensity which could be delayed relative to each other.[4] A variable attenuator allowed the FEL power to be varied over a range of 38 dB. Measurements were carried out at low temperature, with the device biased using a constant voltage source. The photocurrent was measured by amplifying the voltage drop across a 1 ohm series resistor, and visualised on an oscilloscope. Figure 1 shows the power dependence of the photocurrent signal observed at an FEL wavelength of 94 μm, approximately equal to the laser transition energy. This was measured at a current density within the normal operating regime of the QCL and shows a very good fit to the expression for the saturation of an inhomogeneously broadened transition (shown as a solid line).

Figure 2 shows the photocurrent measured as a function of the QCL bias, which seems to fall into two regimes; we attribute the observed photocurrent to different mechanisms in each regime. In the higher current regime the measured photocurrent increases with drive current, following the increase of the population inversion in the device. We believe that the photocurrent here arises from the depletion of the upper laser level, possibly due to stimulated emission caused by the arrival of the FEL pulse. As expected, the photocurrent starts decreasing again above the current value for maximum gain (i.e. maximum injection in the upper laser level). At very low currents, the device instead acts as a detector, since the

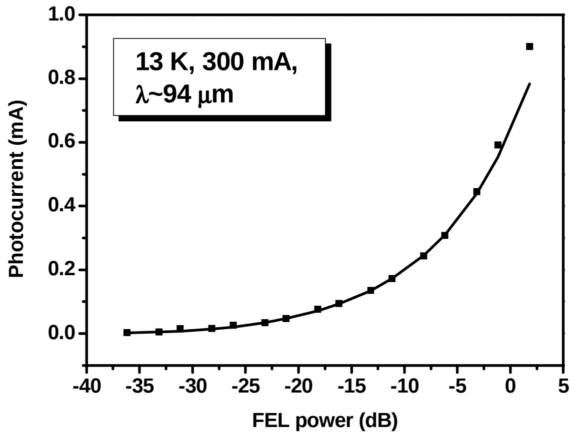

Fig. 1. Power dependence of the measured photocurrent. Symbols denote the measured data, while the solid lines shows a fit of the data to the saturation expression for an inhomogeneously broadened transition. In this figure 0 dB attenuation corresponds to a micropulse energy of ∼0.8 μJ.

energy levels are not yet correctly aligned for laser operation [5], as one can see from the lower part of the figure where the measured I-V characteristic are shown.

Figure 3 shows the gain recovery times measured at different QCL currents. In the high current regime the decay time is approximately constant, to within the experimental error. When scanning the optical delay line, the measured decay times are produced by the following mechanism. The first pulse arrives at the same, and stimulates the emission of photons, reducing the population of the upper laser level, and causing a small transient increase in the device current. If the second pulses arrives after a long time delay, the population of the upper laser level will have recovered, and so the induced photocurrent will be the same as that caused by the first pulse. Because the measuring electronics are too slow to discriminate between the effects of the two beams, what we actually see is a single transient, double the size of that measured when just one beam is incident on the sample. However, when the time delay between the two FEL pulses is small, the upper laser level population is still below its steady-state value, and the current transient due to the second pulse will be smaller. Hence we observe a reduction in the photocurrent at short delay times, as seen in the inset to figure 3. With the exception of the two lowest current data points, at 50 and 100 mA, the measured gain recovery time is approximately constant, to within the experimental error. Possible reasons for these two anomalous data points will be discussed.

In summary, we have used a time resolved photocurrent technique to measure the gain recovery time of a terahertz QCL. It is found to be almost unchanged for current densities where the device is expected to be lasing.

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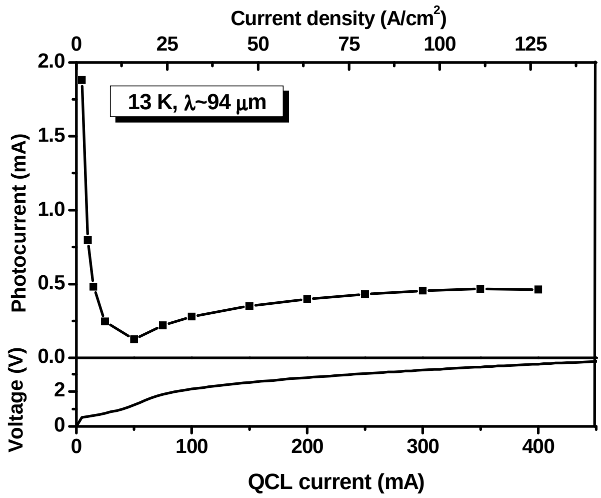

Fig. 2. (Upper part) Current dependence of the photocurrent measured at 5 dB attenuation. (Lower part) I-V characteristic measured from the device.

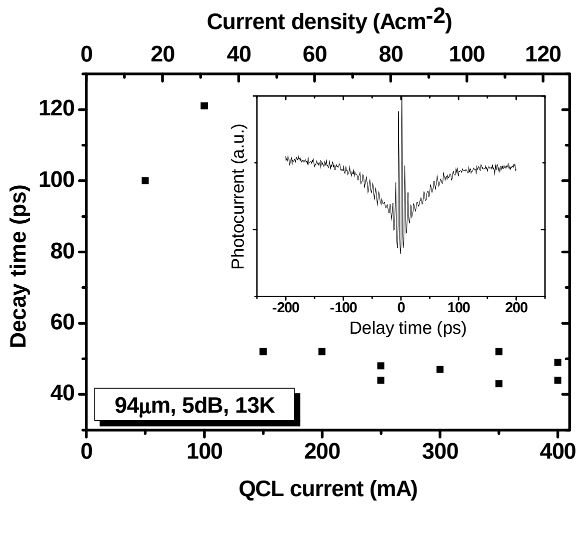

Fig. 3. (Inset) A typical trace of the measured photocurrent against delay time. The very sharp peaks close to zero delay are a consequence of interference between the two beams. (Main part) Decay times measured at different QCL current levels.