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Characterisation of the spectral behaviour of pulsed quantum cascade lasers using a high resolution Fourier transform infrared spectrometer

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Abstract

We present results that describe the evolution of the spectrum of a pulsed quantum cascade (QC) laser. By mapping the temporal characteristics of the light pulse into the wave number domain, we show how the spectral evolution depends on the duration and the quality of the current pulses used to excite the QC laser. © 2001 Elsevier Science B.V. All rights reserved.

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The quantum cascade (QC) laser has the potential to improve both the detection sensitivity and spectral resolution of mid-infrared spectrometers that are currently used for a variety of different spectral measurements [1–3]. The most obvious advantage offered by the QC laser system is the potential ability to operate at or close to room temperature in a continuous-wave manner and major steps have been taken towards the realisation of this goal [4]. To date, however, the majority of spectral measurements made with QC lasers have used pulsed operating conditions, where the duration of the current pulses range from 5 to

200 ns. To fully quantify the behaviour of a pulsed QC laser it is necessary to monitor both the spectral and temporal evolution of the emitted light pulses. The temporal characteristics have been measured by use of infrared detector and oscilloscope combinations that have a time resolution typically ranging from 0.1 to 1 ns [5]. The spectral characteristics, however, have been recorded with medium to low resolution interferometric [6] or dispersive [7] infrared spectrometers. Although this approach has been successful in showing and allowing the partial quantification of both the longitudinal mode structure and the wavelength chirp induced by pulsed operation, little information is available about the detailed spectral evolution of the pulse.

In this paper we show that a high resolution continuously scanning Fourier transform spectrometer (FTS) can be used to probe the spectral

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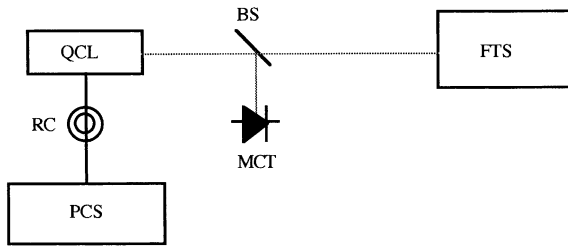


Fig. 1. Schematic of the experimental arrangement: QCL, QC laser; RC, Rowgoski coil; PCS, pulsed current source; BS, beam splitter; MCT, mercury–cadmium–telluride detector; FTS, Fourier transform spectrometer.

behaviour of a QC laser provided that the pulse repetition rate of QC laser is greater than the sampling rate of the spectrometer. We describe how we are able to map the temporal characteristics of the light pulse into the wave number domain and show how the temporal evolution of the current pulse influences the spectral behaviour.

The experimental configuration used to demonstrate the principle of our approach is shown in Fig. 1. The QC laser was a DFB structure (fabricated by Alpes lasers) that was designed to oscillate at a wavelength of $10.2\ \mu\text{m}$. The laser was housed in airtight chamber, and the light was coupled from the chamber through an anti-reflection coated ZnSe window. The QC laser substrate was mounted on a Peltier cooler, which allowed the substrate temperature to be varied between -30°C and $+30^\circ\text{C}$. The temperature of the substrate was stabilised to a level of $\pm 0.01^\circ\text{C}$. The laser was excited by use of an in-house designed pulsed current source. This generated top-hat shaped current pulses with durations ranging from 10 to 200 ns, at repetition rates of up to 100 kHz, and with average currents of up to 10 A. This generator will be described in more detail elsewhere [8]. The amplitude and shape of the current pulse applied to the QC laser were monitored using a Rogowski coil [9] placed between the current source and the QC laser. The threshold current of the QC laser was 3.2 A at a substrate temperature of 0°C . The temporal profile of the resulting light pulses generated by the QC laser was recorded using a high speed mercury–cadmium–telluride (MCT) photovoltaic detector and digital oscillo-

scope, which had a nominal combined temporal resolution of 10 ns. The spectral profile of radiation produced by the QC laser was studied by use of a Bomem DA-3 FTS which had a maximum effective resolution of $0.005\ \text{cm}^{-1}$ (150 MHz). This is significantly higher value than that of the Nicolet ($0.125\ \text{cm}^{-1}$ (3.75 GHz)) that was used in a recent study of the frequency comb produced by a QC laser when operated in a gain-switched mode [5]. The maximum sampling frequency of our FTS is 20 kHz, which is less than the repetition frequency of the current pulses applied to the QC laser (50–100 kHz). As a result the QC laser appears as a quasi-continuous-wave light source when viewed by the FTS.

It is well known that the application of a current pulse to a QC laser results in a wavelength chirp, which is almost linear [3,10]. This mapping between the time and frequency response of the QC laser combined with the resolution offered by the FTS has allowed the characterisation of the spectral output from the pulsed QC laser as a function of current pulse shape, current pulse duration, current amplitude and substrate temperature, at a resolution that has not been reported to date. A direct consequence of this is that we have been able to observe non-linear spectral dynamics as the current pulse is applied to the QC laser that, to our knowledge, has not been previously reported.

The initial measurements made on the spectral performance of the QC laser were made with a substrate temperature of 5°C , current pulses of 106 ns duration and 4.4 A amplitude at a repetition frequency of 50 kHz. With the FTS set to give spectral resolutions of $1\ \text{cm}^{-1}$ (30 GHz) and $0.1\ \text{cm}^{-1}$ (3 GHz), the spectral output appeared to be single frequency as shown in Fig. 2(a) and (b). It can be seen that even with a resolution of $0.1\ \text{cm}^{-1}$, the resolution of most commercial FTSs (see Fig. 2(b)), it is impossible to obtain much information about the structure of the pulse. There was no evidence of any spectral sidebands at the cavity longitudinal mode spacing. As the spectral resolution of the FTS was increased to $0.03\ \text{cm}^{-1}$, it was found that there was significant structure within the spectral envelope (see Fig. 3). The oscillatory variation in the spectral output, as shown in Fig. 3, was attributed to the damped oscillations

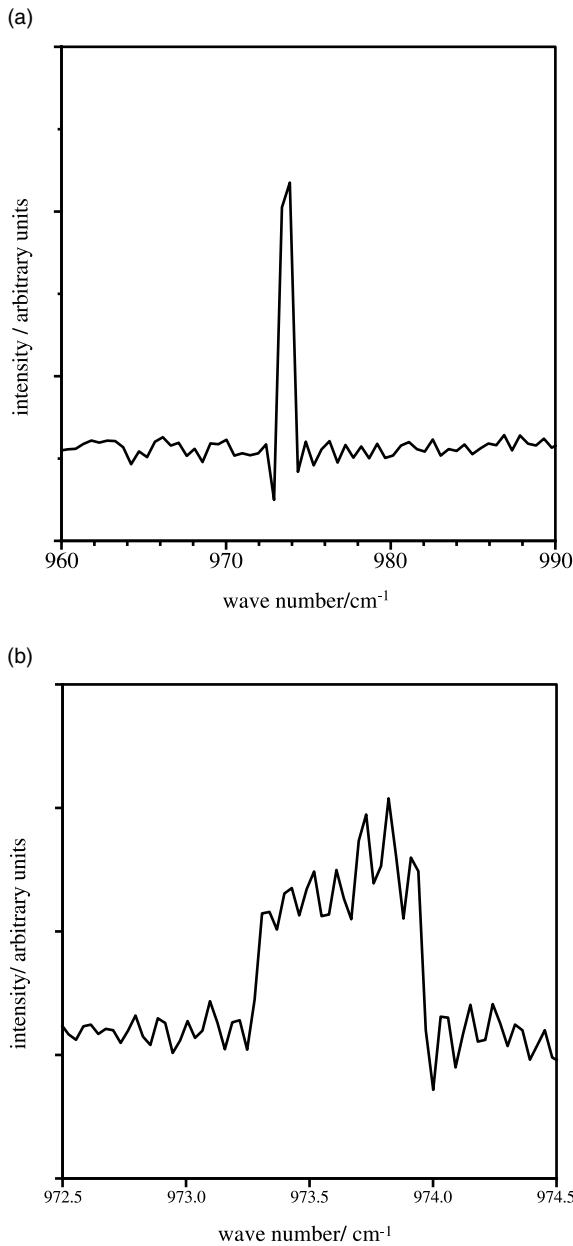


Fig. 2. Spectral output from QC laser using low FTS resolution: resolution set to (a) 1 cm^{-1} and (b) 0.1 cm^{-1} .

present on the driving current pulse (see Fig. 4(a)), which are due to the current source and the QC laser not being correctly impedance matched (see also Ref. [3]).

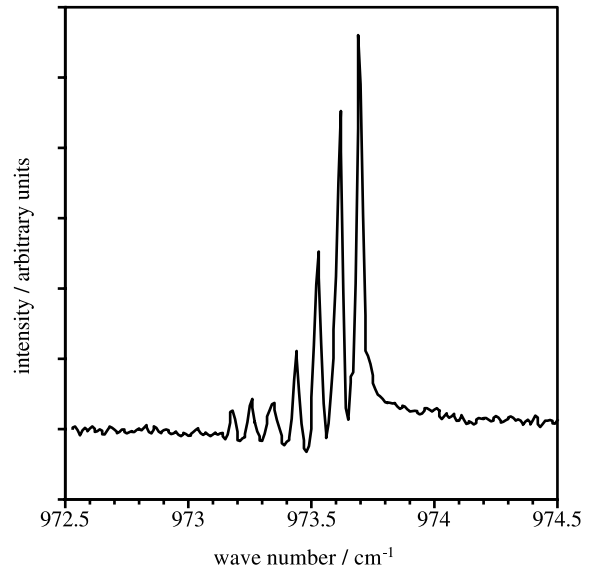


Fig. 3. Spectral output from QC laser with FTS resolution set to 0.03 cm^{-1} . This resolution is just sufficient to allow the modulation of the pulse envelope to be clearly seen.

It is also evident from Figs. 3 and 4(b) that there is a linear mapping of the pulse temporal profile into the wave number domain, as the amplitude modulation seen on the temporal profile of the pulse is mirrored in the amplitude variation with wave number of the pulse spectrum that is recorded via the FTS. The linear correspondence between the pulse duration and wavelength-up-chirp is further verified by reference to Fig. 5(a). From this graph the rate of change of wave number, as a function of pulse duration, was determined to be $6.1 \times 10^{-3} \text{ cm}^{-1}/\text{ns}$ (183 MHz/ns). Furthermore this pulse induced wavelength change appears to be, within the accuracy of our measurement, independent of the substrate temperature. This wavelength change is due to the local heating induced in the QC laser structure by the applied current pulse. Fig. 5(b) shows the wavelength change as a function of the duty cycle of the applied pulse at a range of different substrate temperatures whilst Fig. 5(c) shows the temperature induced wavelength-up-chirp. From this plot it was found that the rate of change of wave number as a function of temperature was $7.6 \times 10^{-2} \text{ cm}^{-1}/\text{K}$ (2.3 GHz/K). Finally, by placing two

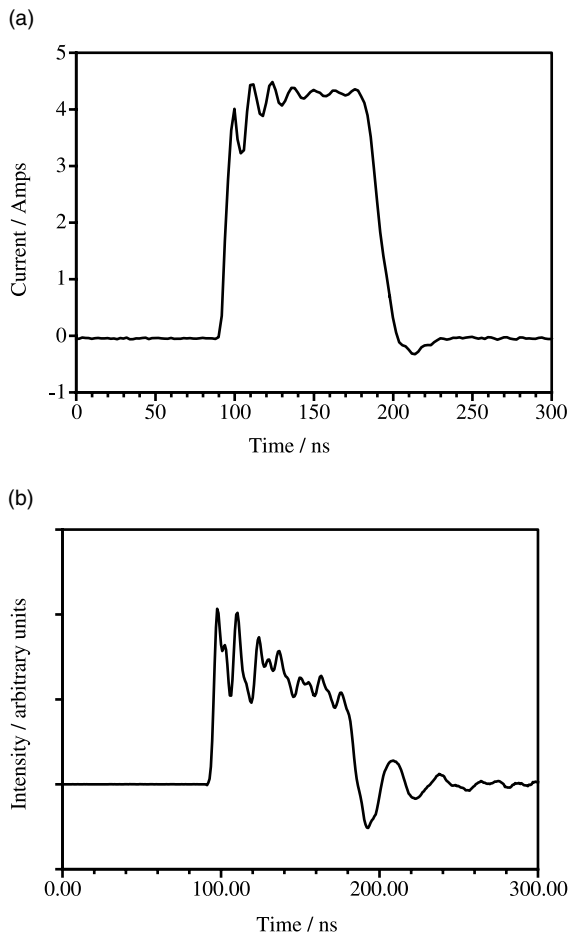


Fig. 4. (a) Temporal response of the current pulse used to drive the QC laser as measured with the Rowoski coil. (b) Temporal output from the QC laser measured using a fast photovoltaic MCT detector.

different germanium etalons between the laser and the FTS, we have recorded the etalon fringes related to the wavelength-up-chirp. The fringes generated using the shorter of these etalons, with a fringe spacing of 0.05 cm^{-1} have a similar period to the intensity oscillations of the pulse amplitude. However, the shorter period 0.02 cm^{-1} oscillations produced using the longer etalon are clearly shown in Fig. 6. The final trace, Fig. 6(c) shows the ratio of the pulse with and without the etalon. The quality of the resultant fringe pattern demonstrates that this method of ratioing will allow a high resolution spectrum to be recorded directly

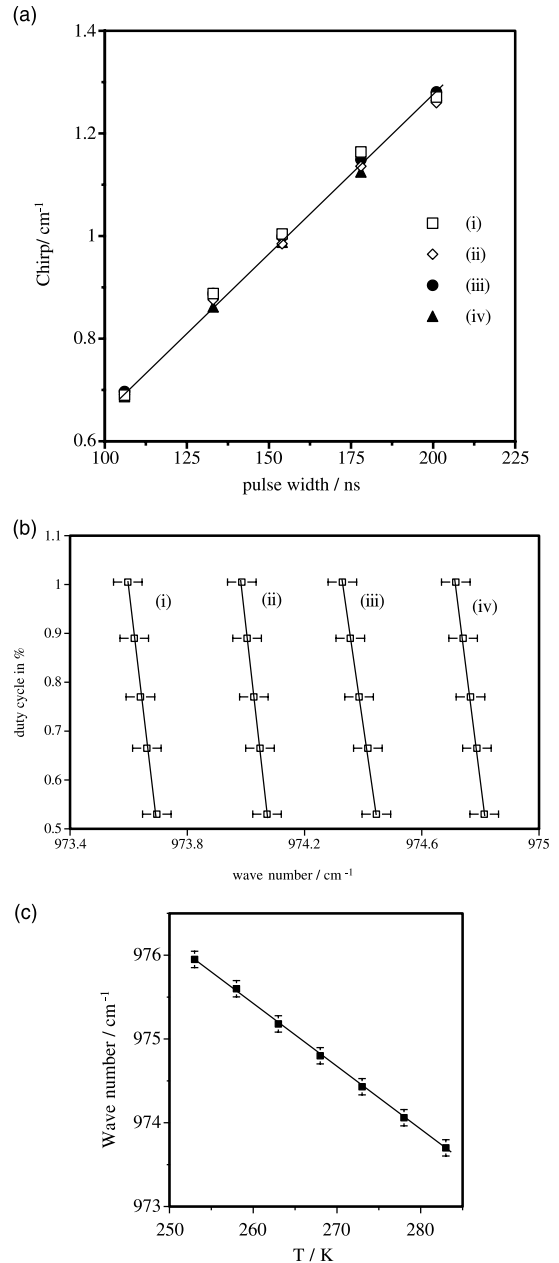


Fig. 5. Wave number tuning as a function of current pulse duration and substrate temperature. (a) Wave number chirp as a function of pulse width, using a current of 4.4 A and a repetition rate of 50 kHz. This is recorded at temperatures of (i) 268 K, (ii) 273 K, (iii) 278 K and (iv) 283 K. (b) Wave number variation with both duty cycle and substrate temperature, the other conditions are given in (a). (c) Temperature tuning of the device, at a pulse width of 106 ns and a 50 kHz repetition rate, using an interferometer resolution of 0.03 cm^{-1} .

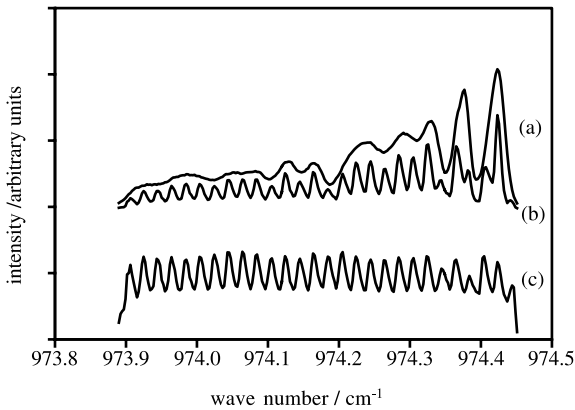


Fig. 6. Wave number tuning produced by a 100 ns current pulse observed via the 0.02 cm^{-1} fringe pattern of a solid Ge etalon. The resolution of the FTS was 0.005 cm^{-1} : (a) without etalon, (b) with etalon, (c) etalon fringes obtained by ratio of (b)/(a).

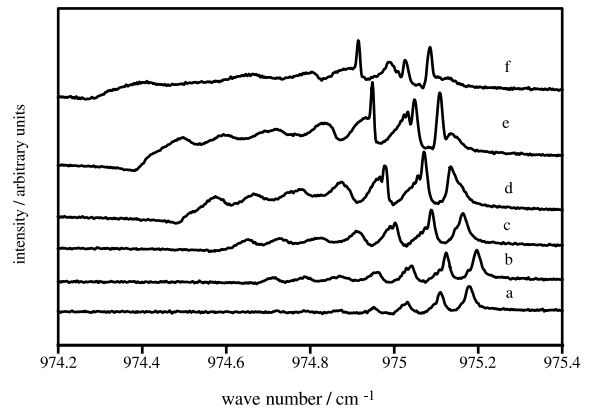


Fig. 7. Variation of the pulse structure as a function of increasing the amplitude of current pulse. The pulse width was 106 ns at a repetition rate of 50 kHz. The Michelson interferometer resolution was 0.006 cm^{-1} . The currents (A) used are (a) 3.6, (b) 3.8, (c) 4, (d) 4.4, (e) 4.8 and (f) 5.2.

using a pulsed laser spectrometer. We have also shown that the use of a 200 ns pulse will give almost 1 cm^{-1} of useful tuning. It is noted both by Namjou et al. [10] and by Kosterev et al. [3] that when a variable pedestal of sub-threshold current is added to produce laser tuning, the wave number chirp is partly quadratic. However, in the present experiments this approach to tuning has not been used, and as a result the tuning appears to approximate to linear behaviour over a tuning range of 0.6 cm^{-1} .

The FTS spectrum offers more information about the dynamics of the laser than our temporal measurement scheme, since Fig. 3 clearly shows that the QC laser “turns off” between successive current spikes. This feature was investigated in a more detail by increasing the resolution of the FTS $6 \times 10^{-3} \text{ cm}^{-1}$ (180 MHz) and varying the amplitude of the current supplied to the laser. The pulse duration was fixed at 106 ns, the repetition rate was 50 kHz and substrate temperature was -10°C . The data obtained from this study are shown in Fig. 7. As the current pulse amplitude increased the spectral structure changes from the almost regular damped oscillatory behaviour seen in Fig. 3, to a pattern in which there is significantly more spectral structure (cf. Fig. 6(a) and (f)). Initially as the amplitude of the current pulse is increased the oscillating frequency associated with the first

spectral spike shifts to a higher frequency, which is attributed to the fact that the laser reaches threshold earlier in the current pulse and so the effects of local heating due to the current pulse are not so dominant. As the current is further increased the first spectral spike appears to downshift in frequency and this spike, together with subsequent spikes, start to show significant structure. The origin of these features is not fully understood at present, but is thought to arise from a combination of the modulation of the gain inside the QC laser induced by the modulation on the current pulse, and the carrier injection dynamics. These processes are the subject of on going numerical modelling and will be reported on at a later date.

In conclusion we have shown that a high resolution continuously scanning Fourier transform infrared spectrometer may be used as a very sensitive probe of the spectral/time dependence of the output pulse of a single mode QC laser driven via a high repetition rate, short pulse power supply. The use of a high repetition rate source obviated the need to use a time resolved Fourier transform instrument. Furthermore, the resolution of the high resolution scanning FTS is much greater than that of commercially available time resolved FTS [11]. Hence the use of a FTS for studying the pulse

duration induced wavelength-up-chirp behaviour is currently only possible via the method described in this paper. Although Namjou et al. [10] and Kosterev et al. [3] have shown that the wavelength-up-chirp behaviour may be measured by deconvolution of the observed line shape of the absorption lines of a trace gas, the use of the FTS allows this behaviour to be measured over a wider wave number region. It has also been pointed out to us by the referee that a high resolution scanning Fabry–Perot interferometer can also be used to measure wavelength-up-chirp. Whilst this is true, and can provide higher resolution for a narrow wave number scan, the advantages of the FTS are the direct measurement of the absolute wavelength of the QC laser, and also the wider wave number range over which the measurements can be made. We have recently exploited this property to obtain the high resolution spectrum of a multi-longitudinal mode laser over a 20 cm^{-1} wave number interval [12].

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