Time domain spectroscopy of quantum cascade lasers: Gain clamping, spectral narrowing and short pulse circulation

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***Abstract*—We report on the results of time domain spectroscopy measurements on several quantum cascade mid-infrared laser structures. From these measurements we can deduct parameters like wavelength depending losses, modal gain or gain bandwidth in the spectral domain. Parameters like group refractive index or dispersion can be deducted in the time domain.**

We also observe and discuss effects like gain clamping, spectral narrowing, and short pulse circulation.

***Index Terms*—quantum cascade laser, time domain spectroscopy, mid-infrared, gain clamping, modal gain**

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I. Introduction

MID INFRARED quantum cascade lasers (QCLs) have been under investigation since their invention in 1994 with the aim of increasing their overall performance. For a deep understanding of the underlying physics standard device characterisation like voltage, current and output power measurements are mostly not sufficient. Eickemeyer et al. deducted the gain coefficient in an electrically pumped quantum cascade structure without resonator by measuring the transmission change of a tuneable mid-infrared light source

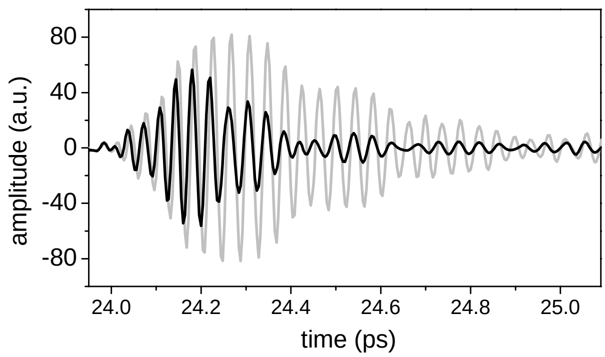

Fig. 1. Pulse response of a mid-infrared pulse coupled through the waveguide of the cold resonator (black), and through the resonator at lasing threshold in cw - operation (grey).

[1]. Later, light of a thermal source was coupled directly through the waveguide of a mid-infrared QCL showing broadband data of gain and losses under current bias close to threshold [2].

Instead of a thermal source we use broadband mid-infrared pulses generated by phase matched difference frequency mixing in a 30 µm thick GaSe crystal. This allows us to detect the transmitted light by coherent detection facilitating the electro optic effect in a 7 µm thick ZnTe crystal. This has the

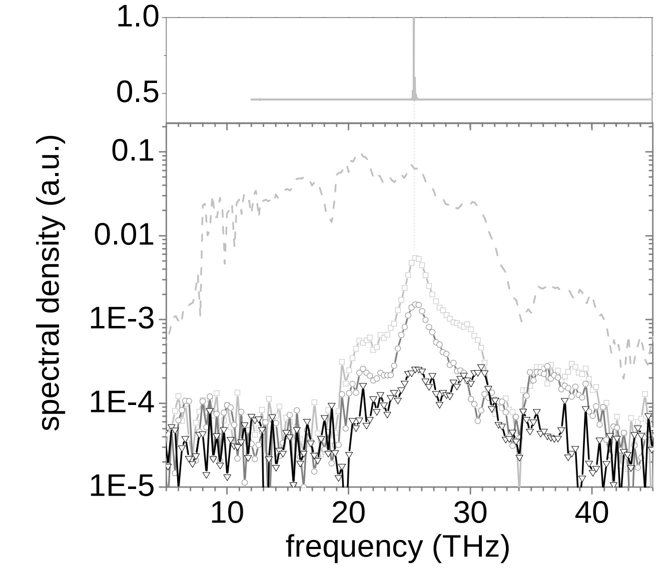

Fig. 2. The lower graph shows the spectral response of the pulse passing through the resonator under conditions of 1% threshold current density (black), 57% (grey), and 120% (light grey). The dashed curve corresponds to the spectrum of the initial mid-infrared pulse. The upper graph shows the emission spectra of the QCL at 110% of the threshold current density.

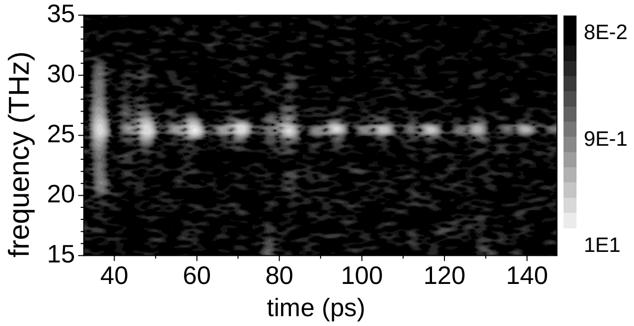

Fig. 3. Shows an intensity plot of the spectral density of a broad band (8 -50 THz) pulse coupled into the resonator of a QCL above threshold. White color corresponds to high intensity and black to lo intensity. After transmission of the first pulse at 32 ps, we observe several reflections of the circulating pulse.

great advantage that the detection is invariant to the strong light fields of the QCL above threshold. For our first studies we used an InGaAs/AlInAs/InP quantum cascade laser cleaved into 495 µm long and 21 – 23 µm broad ridges emitting at 25.5 THz. Figure 1 shows the time response of a broadband 100 fs long pulse coupled through the cavity of the QCL. We clearly see the long lasting oscillations in the case of a bias current at lasing threshold (grey) compared to the response of the cold resonator (black). This corresponds to an enhancement due to gain. The phase shift between these two signals is mostly attributed to the change of refractive index due to heating inside the cavity under cw-operation. The effect of change in refractive index due to changing carrier concentration is much smaller in this case.

In the frequency domain shown in figure 2 we can see three curves corresponding to the spectral response at bias currents of 1%, 57%, and 120% of the threshold current density. The cut off at 19 THz is attributed to the cut off of the lowest TM mode in the resonator. With increasing current density a peak around 25.5 THz is forming reaching its maximum height and staying constant above threshold current density. The gain peaks at the same frequency were emission takes place. We note that this laser emits on multiple Fabry-Perot modes. This might be a reason why we do not observe any sings of spectral-hole burning at the emission frequency which we would expect from inhomogeneous broadening. The gain bandwidth is 1.75 THz. Above the cut off frequency a broadband replica of the initial spectral pulse shape overlaps the gain peak, which is an artefact due to the phase shift caused by heating. The difference in transmission between the operation at zero bias current and at threshold current at the emission frequency leads to a modal gain of 9.04 dB or 42 cm^{-1}. Using a reflectivity of 0.3 we deduct the waveguide losses to 17.7 cm^{-1}, which is in good agreement with the number of 17.1 cm^{-1}, deducted from the threshold current densities of different resonator lengths. The calculated value for this waveguide with a Drude absorption model leads to 16.4 cm^{-1}.

Figure 3 is an intensity plot utilizing a Fast Fourier Transformation with a 2048 point (8.1 ps length) Hamming window function. The current bias density was 105% of the threshold current density. The reflections appearing every 11.4 ps correspond to a group refractive index n_{gr} = 3.45. In agreement with theory the spectral width of the reflections narrows due to the spectral shape of the gain. However some very interesting questions arise since the amplitude of these reflections is decreasing. In fact it decreases faster with higher current densities and emission power. At the moment we believe that the actual amplitude at the emission frequency is not decreasing, but the phase of the light is changing due to phase noise resulting in a lower amplitude in our coherent detection. The origin of this phase noise is still subject of discussions.

In conclusion we showed feedback of spectrally resolved broadband parameters like gain, waveguide- and mirror losses, over the whole range of operating conditions, together with additional time domain information we can provide essential information to characterize and to understanding the physics in a quantum cascade structure.

REFERENCES

[1] F. Eickemeyer, R. A. Kaindl, M. Woerner, and T. Elsaesser, “Large electrically induced transmission changes of GaAs/AlGaAs quantum-cascade structures”, APL 76, 3254 (2000)

[2] D.G. Revin, L. R. Wilson, J.W. Cockburn, A.B. Krya, J.S. Roberts and R.J Airey, “ Intersubband spectroscopy of quantum cascade lasers under operating conditions”, APL 88, 131105 (2006)