Time Domain Spectroscopy of Mid Infrared Quantum Cascade Lasers

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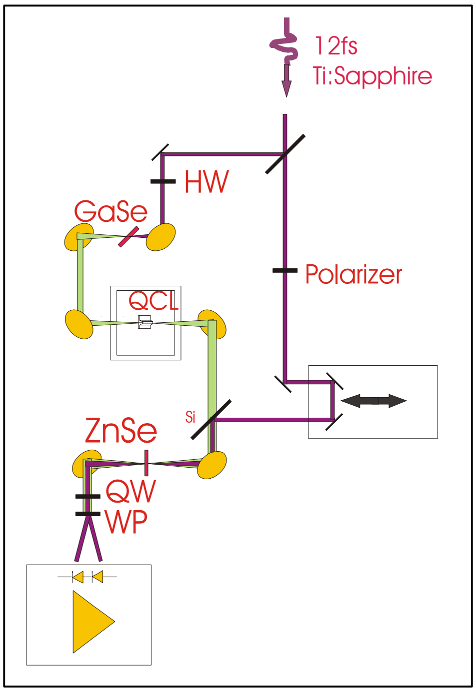
Time domain spectroscopy measurements on quantum cascade mid-infrared laser structures are performed. From these measurements we deduce parameters like wavelength depending losses, modal gain or the gain bandwidth in the spectral domain. Parameters like group refractive index or dispersion can be inferred in the time domain. We also observe thermo optic effects.

Introduction

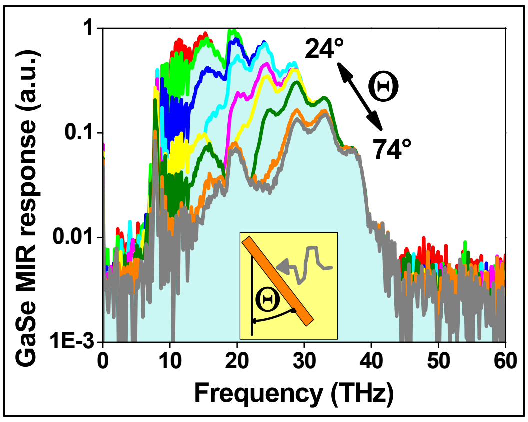
Mid infrared quantum cascade lasers (QCLs) have been under investigation since their invention in 1994 with the aim of increasing their overall performance [1] – [3]. For a deeper understanding of the underlying physics standard device characterization like voltage, current and output power measurements are mostly not sufficient. Quantum Cascade Laser are physical systems composed of a very complex matter structure together with high light field intensities and very high current densities. First results of the dynamics below threshold where observed by Eickemeyer *et al.*. He deduced the gain coefficient in an electrically pumped quantum cascade structure without resonator by measuring the transmission change of a tunable mid-infrared light source [4]. 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 [5]. The scheme of incoherent detection hinders the exploration of operating conditions above threshold because of detector saturation due to the emitting laser light.

Electro Optic Sampling

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. The setup we are using is shown in Fig. 1(a). This has the great advantage that the detection is invariant to the strong light fields of the QCL above threshold. With this technique we are able to achieve a time resolution of 12 fs which allows us detection of frequencies up to 45 THz directly in the time domain. Spectroscopy is done by Fourier transformation of the time domain signal which has the advantage of conserving the phase information besides the amplitude spectrum. As can be seen in Fig. 1(b) the signal to noise ratio is 1000 for the electric field which corresponds to a SNR of 10^6 for the corresponding power.



(a)



(b)

Fig. 1: (a) Sketch of the electro optic sampling setup we are facilitating for measurements on quantum cascade structures; (b) shows the accessible frequency range depending on the phase matching condition

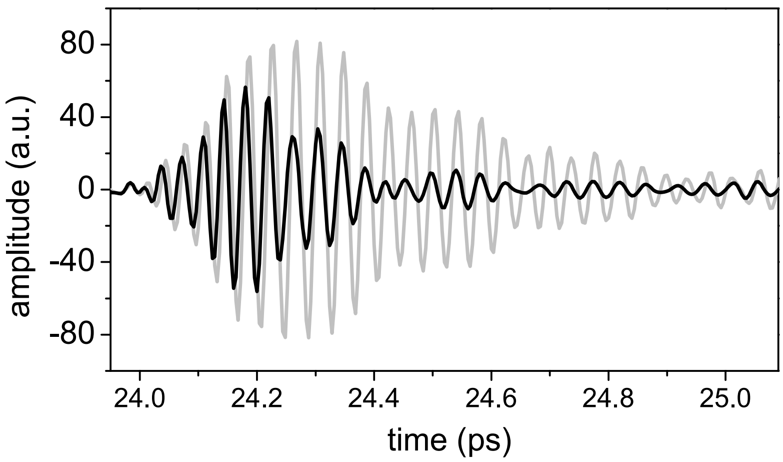


Fig. 2: Pulse response of a mid-infrared pulse coupled through the waveguide of the cold resonator (black), and through the resonator at lasing threshold in cw - operation (grey).

Experimental

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. The laser was mounted on the cold finger of a continuous helium flow cryostat in a way that we can access both facets with a beam of 45° divergence. Figure 2 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 attributed to the change of refractive index due to heating inside the cavity under cw-operation and to the phase shift according to induced gain. The effect of change in refractive index due to changing carrier concentration is much smaller in this case.

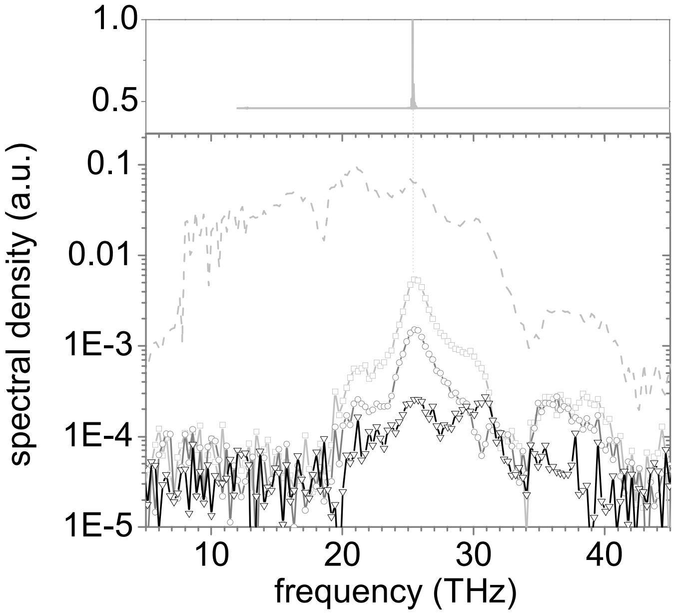


Fig. 3: The lower graph shows the spectral response of the pulse passing through the resonator under conditions of 1% threshold current density (black), 57% (grey), and 120% (light grey). The dashed curve corresponds to the spectrum of the initial mid-infrared pulse. The upper graph shows the emission spectra of the QCL at 110% of the threshold current density.

In the frequency domain shown in Fig. 3 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 due to the surface plasmon confining the light inside the cavity. 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 where emission takes place. We note that this laser emits in 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 artifact 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}.

Conclusion

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.

Acknowledgements

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