Tunable Dispersion Compensation of QCL Frequency Combs

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Introduction

Frequency combs are sources of coherent light whose optical spectrum is comprised of many equidistant lines. In quantum cascade lasers (QCL), frequency combs can be generated thanks to the nonlinear optical process Four-Wave-Mixing (FWM) which acts as phase-locking mechanism and ensures the equidistant frequency spacing of the longitudinal cavity modes [1]. If the QCL operates in the comb regime, a very narrow RF beatnote at the cavity roundtrip frequency can be observed in the driving current because the equidistant cavity modes beat with each other. However, FWM is only able to lock the modes efficiently if the dispersion of the QCL caused by waveguide, material and gain is reasonably low. As a consequence of dispersion, a second operating regime called high phase-noise regime is observable where increased amplitude and phase noise of the comb result in a considerably broader RF beatnote. Hence, a method to compensate the intrinsic dispersion of the laser is required in order to increase the fraction of the comb regime in the dynamic range of QCL frequency combs [2, 3].

1. Tunable Gires-Tournois Cavity

We present a novel dispersion compensation scheme that offers the possibility to tune the dispersion without modifying the QCL itself [4]. We place a planar mirror behind the back facet of the laser (Fig. 1a). The mirror forms a Gires-Tournois cavity (GTI) together with the partially reflective back facet. The group delay dispersion (GDD) created by this configuration shows a characteristic shape in frequency space (Fig. 1b). A local minimum is followed by a local maximum at slightly larger wavenumbers. Furthermore, this shape is shifted towards lower wavenumbers as the mirror distance is increased. Hence, the GDD induced by the GTI at a certain wavenumber can be changed from negative to positive and vice versa by moving the mirror. This allows to tune the dispersion of the QCL without permanently modifying it thus enabling a systematic study of the influence of GDD on the generation of frequency combs in one single device.

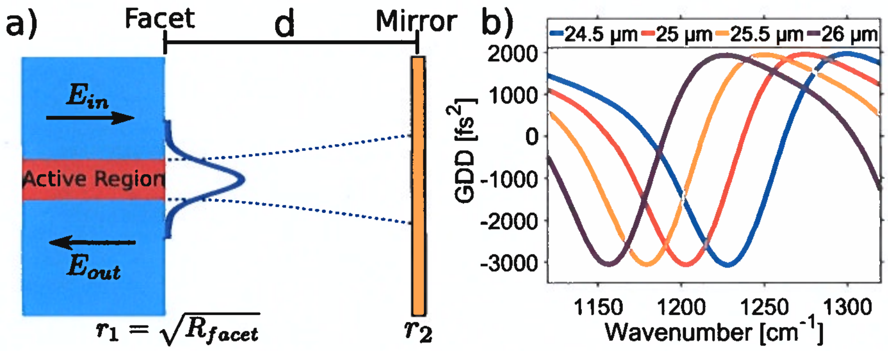

Fig. 1: **a**: Principle of the external Gires-Tournois cavity. A mirror is placed behind the back facet of the QCL and reflects a part of the emitted light back into the waveguide. **b**: Simulation of the GDD created by the GTI at 4 positions of the mirror around d=25 µm. The lateral profile of the waveguide mode is modeled as Gaussian beam with 2.7 µm waist.

2. Results

The cleaved edge of a piece of GaAs (≈30% reflectivity at 8 µm) mounted on a piezo-actuator in closed loop operation is used as mirror. We study the behaviour of a QCL emitting at $\lambda = 8$ µm at several different positions of the mirror located between 23 to 30 µm distance to the facet. At each position, we determine the operating regime of the QCL as function of the driving current by recording the RF beatnote. Furthermore, we measure the GDD and the optical spectrum of the comb at each position.

Fig. 2a shows the influence of the GTI on the total GDD of the laser. At position 1, the GDD created by the GTI enhances the intrinsic GDD of the laser resulting in large negative dispersion of more than -5000 fs^2 at the high energy side of the spectrum. As a consequence, the fraction of the high phase-noise regime in the dynamic range of the QCL is increased at this position compared to the bare device (Fig. 2b). In contrast, the GDD of the GTI cancels out with the laser GDD at position 2 resulting in an extremely low dispersion ($\leq$ 1000 fs^2) over the whole span of the spectrum at 590 mA. As a result, the high phase-noise regime is not observed at this position. Moreover, at position 3 the mirror is approximately 4 µm (i.e., $\lambda/2$) farther away from the facet than at position 1. Since the dispersion induced by the GTI is periodic with the mirror distance (period equal to $\lambda/2$), both the GDD as well as the dynamic range of the QCL show a similar behavior at these two positions. The same holds true for positions 2 and 4.

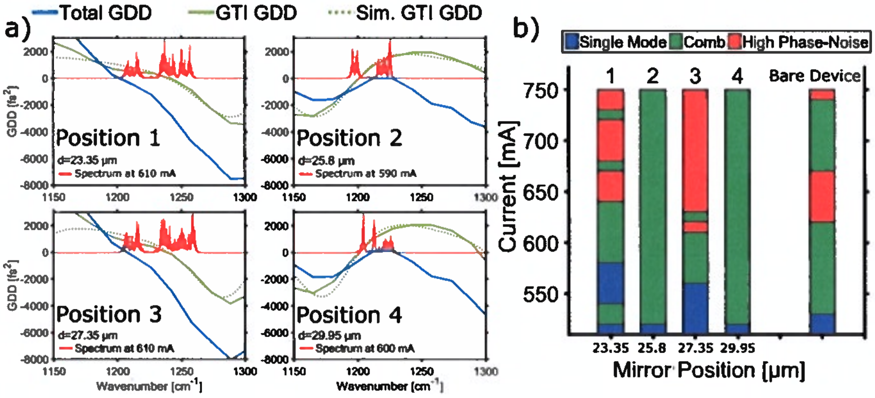

Fig. 2: **a**: Influence of the GTI on the total GDD and the spectrum of the comb. Blue line: total measured GDD. Solid green line: GDD induced by the GTI. Dotted green line: simulated GTI GDD. Red line: optical spectra around 600 mA. **b**: Operating regimes of the frequency comb depending on the driving current above 500 mA at all four characterized positions as well as for the bare device.

In conclusion, we demonstrate a novel dispersion compensation scheme based on a tunable external Gires-Tournois cavity. By tuning the mirror distance, the intrinsic dispersion of the QCL can be either enhanced or decreased by the GTI. At positions where the GTI GDD cancels out with the intrinsic GDD of the QCL, the high phase-noise regime is not observed anymore.

References

[1] A. Hugi, G. Villares, S. Blaser, H. Liu, and J. Faist, "Mid-infrared frequency comb based on a quantum cascade laser," Nature **492**, 229–233 (2012).

[2] G. Villares, S. Riedi, J. Wolf, D. Kazakov, M. J. Süess, P. Jouy, M. Beck, and J. Faist, "Dispersion engineering of quantum cascade laser frequency combs," Optica **3**, 252–258 (2016).

[3] Y. Bidaux, I. Sergachev, W. Wuester, R. Maulini, T. Gresch, A. Bismuto, S. Blaser, A. Muller, and J. Faist, "Plasmon-enhanced waveguide for dispersion compensation in mid-infrared quantum cascade laser frequency combs," Optics Letters **42**, 1604–1607 (2017).

[4] J. Hillbrand, P. Jouy, M. Beck, and J. Faist, "Tunable dispersion compensation of quantum cascade laser frequency combs," Optics Letters **43** (2018).