Frequency comb generation using actively mode-locked interband cascade lasers

Benedikt Schwarz[1,*], **Johannes Hillbrand**[1], **Maximillian Beiser**[1], **Anne Schade**[2], **Hermann Detz**[1], **Maxwell Andrews**[1], **and Sven Höfling**[2]

[1] *Institute of Solid State Electronics, TU Wien, Floragasse. 7, A-1040 Wien, Austria*

[2] *Technische Physik, Physikalisches Institut, University Würzburg, Am Hubland, D-97074 Würzburg, Germany*

[*] *Contact Email: benedikt.schwarz@tuwien.ac.at*

Miniaturized sensors will lead to a potential breakthrough in mid-infrared technology and applications, however, their implementation beyond prototype experiments is still a major challenge in science and technology. In this work, we demonstrate a frequency comb source based on actively mode-locked interband cascade lasers (ICL), thereby solving two current issues connected to on-chip miniaturization. First, the dual comb scheme will enable the implementation of chip-scale high resolution spectrometers without the need of any movable parts. Second, by utilizing ICLs, we move to a technology with a much smaller power requirement and thermal dissipation to enabling battery driven miniaturized sensors in future. At the same time, ICL technology allows straightforward on-chip detection capabilities [1].

Mode-locked interband cascade laser

ICLs rely on interband transitions in quantum wells based on a type-II broken gap alignment, which serves as an elegant solution to overcome the laser emission wavelength limit due to the material band-gap. ICLs can be seen as a mix of quantum cascade lasers (QCLs) and heterostructure band-gap lasers, offering the possibility to combine the best features of both worlds. The cascading principle and the fast intersubband transport for fast carrier injection origins from QCLs, while the interband transition enables much longer upper state lifetimes, which is key to achieve fundamental mode-locking.

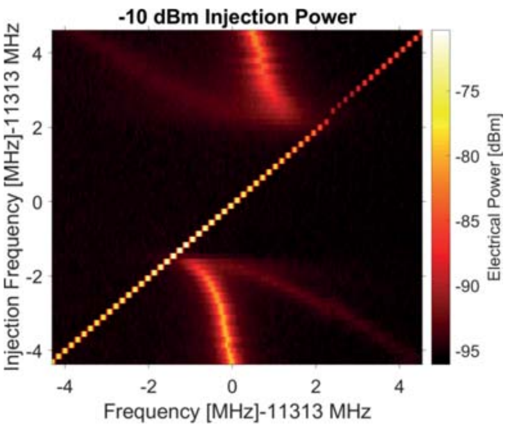

Fig. 1: Beatnote map showing the injection locking range, indicated by range where the broad beatnote vanishes (left).

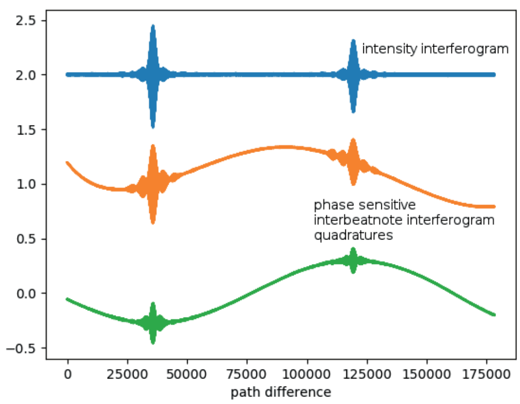

Fig. 2: Intensity and SWIFTS quadrature interferograms recorded with an RF QWIP.

Optical frequency combs are light sources whose spectra consist of a number of equally spaced modes. Using two combs with a slightly detuned spacing, one can simultaneously down-convert the entire laser spectrum to the RF domain using a fast detector, where it can be analyzed by state-of-the-art FPGA based electronics.

Frequency combs based on QCLs were one of the first compact source in the mid-infrared [2] and their large potential for spectroscopic applications is already evident [3, 4]. Continuing this successive path, we demonstrate a frequency comb based on mode-locked ICLs including an adequate proof. We utilize a two-section device consisting of a long gain and a short absorber section that is optimized for RF injection. Active modulation of the short absorber section allows control over the cavity loss and, together with the long upper state lifetime of ICLs, enables to lock the modes of the cavity to obtain picosecond pulse emission. Figure 1 shows the RF beatnotes of the ICL in presence an injected RF signal that is swept past the cavity round-trip frequency.

SWIFTS to proof mode-locking

How can we proof mode-locking? First, let us start with the proof that it is a frequency comb (phase locking). Observing a narrow beatnote at the round trip frequency can serve as a first indication that at least some of the modes emitted by the laser posse a fixed phase relation. However, due to the limited signal to noise ratio it remains unclear how many modes are locked. In presence of a large group delay dispersion, unlocked modes produce a wide beatnote and potentially are hidden below the noise floor.

A much better technique is the so called intermode beat spectroscopy [2]. Thereby, an interferogram of the optical beatnote signal is recorded using a fast detector and a RF spectrum analyzer. It allows to measure the spectrally resolved coherence and thus is a perfect technique to proof frequency comb generation. In order to proof mode-locking we go one step further and apply a phase sensitive technique to obtain both the amplitude and phase of the beating between each pair of frequency comb lines. The quadratures of the interbeatnote interferogram as well as the intensity interferogram are shown in figure 2. Also referred to as shifted wave interference Fourier transform spectrum (SWIFTS) [5], this method allows the reconstruction of the time domain signal emitted by the laser and thus gives a clear proof that our laser is a fundamentally mode-locked frequency comb. This method thus is as an alternative to intensity autocorrelation techniques using two-photon absorption or second order non-linear generation.

Conclusion

We demonstrate an actively mode-locked ICL by gain/loss modulation including an adequate proof. The laser round-trip frequency is synchronized to an external source, which will simplify further comb stabilization. Using SWIFTS we are able to study the spectrally resolved coherence and phase. It enables the reconstruction of the time domain signal emitted by the laser and gives a clear proof of picosecond pulse generation by a mode-locked ICL.

References

[1] H. Lotfi, L. Li, S. M. S. Rassel, R. Q. Yang, C. J. Corrége, M. B. Johnson, P. R. Larson, and J. A. Gupta, “Monolithically integrated mid-IR interband cascade laser and photodetector operating at room temperature,” Applied Physics Letters **109**, 151111 (2016).

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

[3] G. Villares, A. Hugi, S. Blaser, and J. Faist, “Dual-comb spectroscopy based on quantum-cascade-laser frequency combs,” Nature Communications **5**, 5192 (2014).

[4] https://irsweep.com.

[5] D. Burghoff, Y. Yang, D. J. Hayton, J.-R. Gao, J. L. Reno, and Q. Hu, “Evaluating the coherence and time-domain profile of quantum cascade laser frequency combs,” Optics Express **23**, 1190 (2015).