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Mid-Infrared Frequency Combs based on Single Section Interband Cascade Lasers

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Abstract. In this work we show Frequency Comb (FC) and short pulsed operation of mid-infrared Interband Cascade Lasers (ICLs) in a single long section. This is through the use of an adapted ultrafast Quantum Well Infrared Photodetectors (QWIPs), and correlating the microwave beatnotes with high resolution spectra of the ICL. In particular, we will show active mode-locking (ML) of single -section ICL that does not require RF optimisation of the ICL device and highlight its temporal characteristics using Shifted Wave Infrared Fourier Transform Spectroscopy (SWIFTS) analysis to reconstruct the intensity in the time domain.

1 Introduction

Interband Cascade Lasers (ICLs) are semiconductor lasers emitting in the mid-wave infrared (MWIR 3-6 µm). They are practical laser sources for IR spectroscopy (through dual-comb or others techniques as detailed in references [1,2]). ICLs provide milliwatts of output powers with low electrical power requirements, offering complimentary performances to quantum cascade lasers (QCL). Recent work has shown that these ICLs can operate as frequency combs (FC) [3,4,5,7]. However, these works have emphasised the use of double section cavities for FC operation, optimized for RF injection/extraction or to control the lifetime in a section. Here we show that this is not entirely necessary and single section ICLs can be modelocked when the group velocity dispersion is reduced at long wavelengths.

2 ICL Active Mode Locking

We realized a 4mm long single section ICL operating at a wavelength of 4.1 µm, with its emission detected with a fast InP-based QWIP (response > 20 GHz), designed and operating at the same wavelength. Both structures operate at room temperature. The QWIP and ICL are mounted on RF coplanar waveguides for a high frequency response. Measuring a narrow BN, electrically on the ICL or optically on the QWIP, is a preliminary measurement to determine if the ICL is operating in a FC regime.
Figure 1 shows the electrically measured BN, and where the intensity of the BN as a function of ICL pump current is investigated, showing a narrow BN over tens of milliamps.
Figure 2 shows the BN with the ICL current fixed at 153 mA (1.5xI_{th} *where* I_{th} *is the laser threshold*) and the entire section modulated close to the free running intermodal beat frequency (9.872 GHz). With a power injection of 17dBm, the laser BN can be pulled to the modulation, highlighting that the laser can be actively mode-locked.

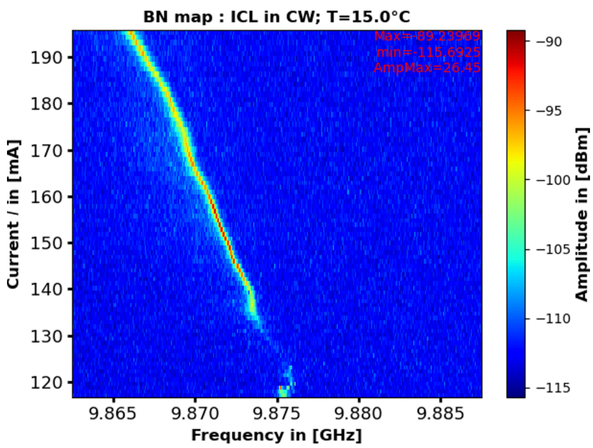

Figure 1:Electrically measured BN map; RBW=300Hz

In this particular temperature and applied current configuration the locking range is shown to be ~ 2.4 MHz, despite the device not being entirely optimised for RF injection or extraction. We then applied the SWIFTS (**S**hifted **W**ave **I**nfrared **F**ourier **T**ransform **S**pectroscopy) [6] method to reconstruct the electrical field in the time domain.

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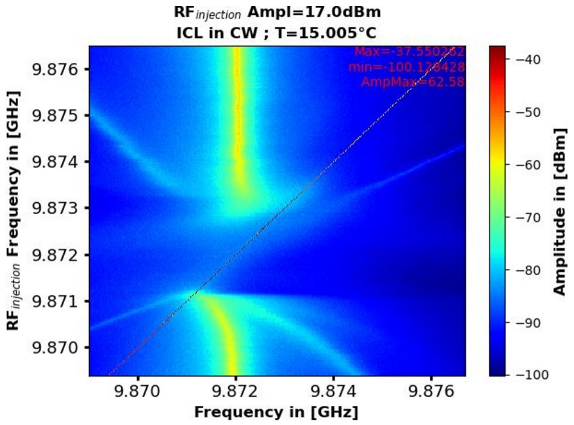

Figure 2:RF injection with frequency sweep: active ML map

3 Time-domain characterization

The ICL is thermally stabilized by a low noise controller and driven using a low noise current driver. Two RF generators and the fast lock-in amplifier are synchronized by 10MHz clock to demonstrate active modelocking and pulse generation. One part of first RF generator (RF1) is used to injection lock ICL, the second part of the RF1 and a part of RF2 are mixed together to generate a MHz down converted signal, which is used as a reference for the lock in amplifier. The Interferometric signal is measured on the fast QWIP and an FTIR. For each step of mirror of the FTIR, the RF part is extracted, amplified by a LNA and down converted to the MHz region with second part of RF2. The lock-in amplifier records the quadrature (X, Y) demodulated signals. In the case when the amplitude of injected RF signal is close to 0 dBm, the ICL can be considered to be free running. Indeed, as explained in [6, 7] a small RF injection power permits to stabilise the frequency of the BN without effecting its temporal characteristics, making it robust against optical feedback, which can dramatically perturb the intermodal coherence of the laser.

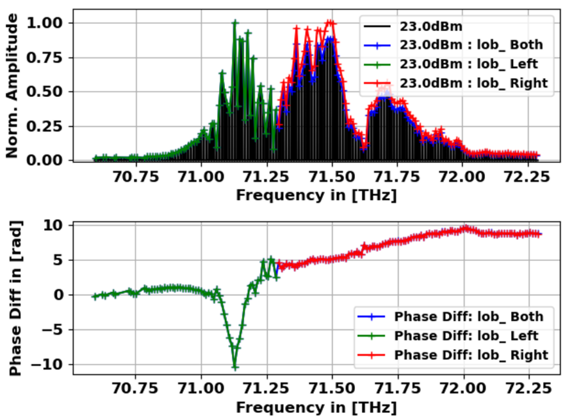

Figure 3:Optical Spectrum & Phase Difference from SWIFTS

Figure 3 shows an example SWIFTS measurement when the laser is actively ML at 10°C base temperature. The current is 186mA which is 2.35x*Ith*. The RF modulation frequency is same as the ICL BN (9.872391GHz) and a high modulation amplitude is used here (23dBm) for active ML. Figure 3(a) shows high resolution spectra (from AC part). Figure 3(b) shows the phase difference between each adjacent modes. Different part of the spectrum can be isolated as well as their contribution to the temporal form. The phase difference for the red part of spectrum is close to 2π. From this part of the spectrum, the temporal trace in the cavity is reconstructed. Figure 4 show the non-normalized intensity. From the reconstructed time traces for the red part of the spectrum, we observe the formation of short pulses. The contribution of the green part of the spectra is less compared to the overall temporal response, as shown in Figure 4. In summary, Figure 3 & 4 highlights the formation of pulses with a linearly chirped instantaneous frequency (not shown here).

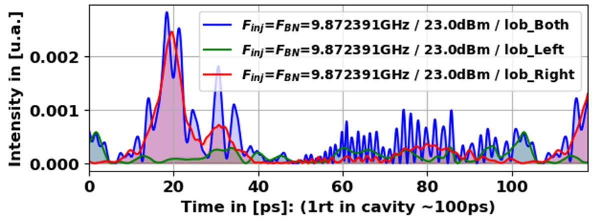

Figure 4:1 round trip temporal trace ~100ps.

4 CONCLUSION

We have demonstrated active ML of a single section ICL showing that this can be used to demonstrate comb operation, without the need of double section or RF contacts/optimization. The temporal characterisation of ICL show a chirped pulse generation with a relatively low RF injected power <200mW. These results will also be compared to Maxwell-Bloch simulations in the free running and actively mode-locked cases, and the role of the gain recovery time that is much longer than in quantum cascade lasers.

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