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New Developments in Solid State Physics

Abstract Book

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Theory of frequency modulated combs in semiconductor lasers

Theory of frequency modulated combs in semiconductor lasers

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Optical frequency combs represent laser sources whose optical spectrum consist of a set of equidistant modes with an unambiguous phase relationship. From the Fourier analysis, it is clear that any laser output which is periodic over time will result in a comb spectrum and based on the nature of that output, frequency comb sources can be distinguished into two groups. First is the amplitude modulated (AM) combs, where the laser emits periodic, short pulses with a Gaussian spectrum and constant phases and this was the conventional way to form frequency combs, historically speaking. The other kind is the frequency modulated (FM) combs, which have started to increase in popularity recently, because they can be formed intrinsically, requiring no additional elements, unlike the AM combs. It is known from experimental data that FM combs are dominantly frequency modulated with almost constant output power and a unique linear-like pattern in the phase differences between adjacent modes (Figure 1(a)), which corresponds to a chirp of the instantaneous frequency [1]. This can be explained due to the fact that carrier population in the laser is able to follow modulations of the intra-cavity field to a certain extent. This effect, known as population pulsation (PP), has been shown to result in a parametric losses, lowering the effective gain that the laser experiences. Hence, the laser mitigates any modulations of the field intensity in order to prevent strong PPs and their induced parametric losses, resulting in the formation of an FM frequency comb. This is the main reason why no self-starting AM frequency combs have been reported. A chirp in intermodal phase differences splayed over a range of 2π, which is shown on Figure 1(a), satisfies the requirements of eliminating the PP and forming FM combs. However, so far it was not clear why this particular phase pattern is preferred over many other solutions which would also minimize PPs, e.g. sinusoidal frequency modulated output with a Bessel spectrum.

We have developed an appropriate theoretical model in order to simulate the intra-cavity dynamics and the process of FM mode locking of fast gain lasers along with the reproduction of the crucial linear chirp in the intermodal phase differences [2]. This was done (Figure 1(b)) by utilizing a model based on spatio-temporal coupled density matrix and Maxwell equations (Maxwell-Bloch) employing the slowly varying envelope approximation. In order to obtain a chirp, additional terms need to be incorporated to account for complex interplay between the optical nonlinearities and the group velocity dispersion present in the cavity. We show that it is exactly the interplay of these two effects that governs the process of phase locking inside the QCL, since their inclusion in the model leads to excellent agreement with the experiments. Furthermore, we study the effect of group velocity dispersion on the cavity mode dynamics on its own, which has been neglected in previous research. Lastly, to gain some intuition in the process of mode locking, we were able to derive a laser master equation capable of explaining the underlying physics. By doing so, we have replaced the entire system of Maxwell-Bloch equations with a single equation.

In order to simulate an adequate number of cavity roundtrips (around 50 000) for a thorough study, a highly efficient numerical implementation of the equations was required. Hence, the main body of the code is parallelized and implemented on a GPU. This resulted in a decrease in the calculation time by more than two orders of magnitude compared to a parallel implementation on a CPU.

[1] J. Hillbrand, A. M. Andrews, H. Detz, G. Strasser, and B. Schwarz, *Nat. Photon.*, 13, 101 (2019).
[2] N. Opačak, and B. Schwarz, to appear in Phys. Rev. Lett. (2019) *submitted.* arXiv:1905.13635v2

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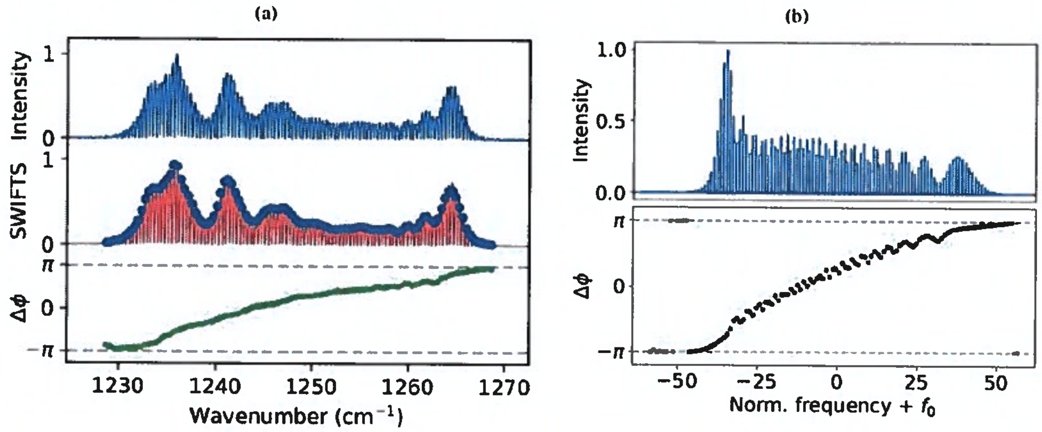

Figure 1: Intensity spectrum of the cavity modes and the phases of the intermode beatings between adjacent comb lines taken from: (a) measured data taken from [1]; (b) developed model, frequency is normalized to the roundtrip frequency [2].