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# Frequency combs enabled by Bloch gain in quantum cascade lasers

Nikola Opačak, Sandro Dal Cin, Johannes Hillbrand, Benedikt Schwarz
Institute of Solid State Electronics, TU Wien, Gußhausstraße 25, 1040 Vienna, Austria

Optical frequency combs have historically relied on the emission of short pulses. However, a novel type of combs with an almost constant intensity is recently appearing in many laser types – among which is the quantum cascade laser (QCL) [1]. Here, we present our theoretical framework which self-consistently models every aspect of the laser operation – from the bandstructure and carrier transport to the spatio-temporal evolution of the laser field. Using it, we show that a considerable Bloch gain – a nonclassical phenomenon predicted by Bloch in the 1930s – is present in any operating laser. The influence of Bloch gain on the laser intracavity dynamics is analytically included through a single population-dependent parameter $b$. This allows an intuitive implementation in a master equation approach to study comb formation in QCLs [2]:

$$\begin{aligned}\left(\frac{n}{c}\partial_t \pm \partial_z\right)E_\pm = \frac{g(P)}{2}\frac{1+ib}{1+i\xi}\left[E_\pm - \tilde{T}_2\partial_t E_\pm + \tilde{T}_2^2\partial_t^2 E_\pm\right] - \frac{g(P)T_g}{2T_1 I_s}\Big[|E_\mp|^2 E_\pm - (\tilde{T}_2+\tilde{T}_{\mathrm{g}})|E_\mp|^2\partial_t E_\pm \\ -(\tilde{T}_2 + T_{\mathrm{g}})E_\pm E_\mp \partial_t E_\mp^* - \tilde{T}_2 E_\pm E_\mp^* \partial_t E_\mp\Big] + i\frac{k''}{2}\partial_t^2 E_\pm + i\beta\left(|E_+|^2 + |E_-|^2\right)E_\pm - \frac{\alpha_w}{2}E_\pm.\end{aligned} \tag{1}$$

Using our new insights, we will demonstrate that the Bloch gain induces an asymmetry in the spectral profile of the optical gain. This explains the experimentally obtained non-zero values of the linewidth enhancement factor in QCLs along with its linear dependence on the driving current. Moreover, Bloch gain in QCLs with ultrafast gain recovery induces a substantial Kerr nonlinearity, which is two orders of magnitude larger than the bulk values. The resonant Kerr nonlinearity provides coherent coupling between the amplitude and the phase of the laser field, which serves as a locking mechanism. We show that in Fabry-Pérot QCLs this results in frequency-modulated combs with a linear frequency chirp. In accordance with this, Bloch gain serves as an efficient locking mechanism and explains how to obtain comb formation over the entire bias range [3]. In ring cavity QCLs, the Bloch gain is able to induce a single-mode instability by tuning the laser in the phase turbulence regime [4]. This can lead to the formation of locked spatial patterns that are related to dissipative Kerr solitons, paving the way towards active Kerr combs.

## References

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