**Gain recovery dynamics and passive mode locking of THz quantum cascade lasers**

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**Introduction & Motivation**

It is a well-established fact that upon reaching lasing threshold the upper level lifetime of a terahertz (THz) quantum cascade laser (QCL) will rapidly decrease, due to the onset of stimulated emission [1]. These fast dynamics however, do not pose a substantial hurdle for mode locking, since it is only the purely electronic, i.e. *non-radiative*, lifetimes of the upper state which play a role [2]. In this contribution we theoretically investigate the possibility to passively mode lock (PML) terahertz QCLs via a fast saturable absorber (FSA) in a ring cavity geometry. We show that this simple mechanism could yield a periodic train of ultrashort pulses (one pulse per round trip) over a large variation of the experimental parameters, even for *non-radiative* upper level lifetimes as short as 10 picoseconds (ps).

Below threshold the electron transport in THz QCLs is mainly driven by non-radiative transitions such as longitudinal optical (LO) phonon scattering or resonant tunnelling [1]. Pump-probe experimental measurements affirm that in this regime typical lifetimes of the upper laser level are somewhere between 10 and 50 ps for both THz and mid-infrared QCLs [1-3], generally depending on the heterostructure design. Measurements of the same rates when the laser is biased above threshold are difficult since the electron transport is dominated by stimulated emission [2]. However, simple argumentation based on perturbation theory could lead one to expect that slightly above threshold, these numbers would not be drastically different from their sub-threshold values.

Here we show that, assuming soliton propagation inside the cavity, the gain recovery time could be even longer than these sub-threshold non-radiative lifetimes, which could also enable successful PML. To see why, assume a simple two level system, the inversion of which has been saturated by a pulse of sufficient intensity, to some minimal value. *After* the passage of the pulse, the inversion begins its recovery to steady state. Now, the processes that govern this recovery of the gain will be mainly the *non-radiative* scattering processes, mentioned above, since there is no photon density to trigger optical transitions. From a simple rate equations approach, one can easily show that in this scenario the gain recovery time is approximately given by

|  |  |
| --- | --- |
|  | (1) |

where denotes the *non-radiative* lifetime of the inversion, is the inversion at threshold and is the pump parameter (=1 corresponds to pumping at threshold). Importantly, from Eq. (1) we see that could become longer than and that it will strongly depend onto the pump parameter and also the strength of the gain saturation. In the following, we show by simulations that passive mode locking is indeed possible for values of as short as three times smaller than the cavity round trip time ().

**Results**

C:\Users\petz\AppData\Local\Microsoft\Windows\INetCache\Content.Word\ITQWimg.emfUnlike other known PML approaches, where the main ML mechanisms were the Kerr-lensing effect [4] or self-induced transparency mode locking [5], we propose passive mode locking with a fast saturable absorber in a ring cavity THz QCL. The envisaged geometry is one of a microring resonator, similar to the one in Ref. [6], incorporating a gain and an absorber section in a serial fashion as depicted in Fig. 1(a). Both the amplifier and the absorber can be suitably engineered as quantum well heterostructures and are assumed to have the same optical transition energy. Also the absorber is taken to be in a completely non-inverted state, whereas the gain medium is assumed to be pumped to -times above threshold.

Fig. 1: (a) The modelled ring cavity consisting of a gain and absorber section. (b) The envelope optical power spectrum, (c) the intracavity power (left y-axis) and inversion (right y-axis) and (d) the gain recovery time as a function of the pump parameter .

Our calculations, based on the semi-classical Maxwell-Bloch equations [7], show that within this configuration pulse generation could be possible for self-starting, free-running lasers and for a large variation of the input parameters (specifically we observed pulse formation for values of between ps). The mode locked pulse envelope, for the case when ps, its spectrum, together with the gain recovery time calculated from Eq. (1), are depicted in Fig. 1(b)-(d). All other simulation parameters are typical values found in literature and are omitted here for brevity.

**References**

1. H. Choi, et al. "Gain recovery dynamics and photon-driven transport in quantum cascade lasers," *Phys. Rev. Lett.* 100**,** 167401 (2008).
2. B. David, et al. "Gain recovery time in a terahertz quantum cascade laser," *Appl. Phys. Lett.* 108, 081104 (2016).
3. R. P. Green, et al. "Gain recovery dynamics of a terahertz quantum cascade laser," *Phys. Rev. B* 80, 075303 (2009).
4. R. Paiella, et al. "Self-mode-locking of quantum cascade lasers with giant ultrafast optical nonlinearities," *Science* 290, 1739 (2000).
5. C. Menyuk and M. Talkuder, "Self-induced transparency modelocking of quantum cascade lasers," *Phys. Rev. Lett.* 102,023903(2009).
6. G. Fasching, et al. "Subwavelength microdisk and microring terahertz quantum-cascade lasers," *IEEE J. Quant. Electron.* 43, 687 (2007).
7. P. Tzenov, et al. "Time domain modeling of terahertz quantum cascade lasers for frequency comb generation," *Opt. Express* 24, 23232 (2016).