IEEE Transactions on THz Science and Technology – revisions list

**Reviewer: 1**

Recommendation: **Minor Revision**

How significant is this work? : **The work is interesting and is relevant to the community, especially for research into broadband QCL operation and dual-comb spectroscopy.**

Additional comments and suggestions for the author: (attachment)

**Review of “Analysis of operating regimes of terahertz quantum cascade**

**laser frequency combs”**

The manuscript report a theoretical study on comb degradation mechanisms in THz QCLs. The authors present a detailed model, and discuss the effects of various comb degradation mechanisms. They use their model to simulate a reduction in SHB through a selective decrease in the reflectivity of one of the mirrors in the cavity, and the resulting enhancement of comb-like operation without the requirement for any group velocity dispersion compensation. The work is interesting and is relevant to the community, especially for research into broadband QCL operation and dual-comb spectroscopy. This work is suitable for publication in IEEE Transactions on Terahertz Science and Technology after some minor corrections. My comments are as following:

1. Sentence construction in:
   1. abstract: “Specifically, it has been pointed out that four wave mixing (FWM) is the main comb formation process and group velocity dispersion (GVD) is the main comb degradation such”
   2. page 3, line 13, left column: “Unfortunately, this not always occurs ndue to the competition of FWM with various comb-degradation….”
2. Page 3, line 10, right column: Are the reflectivities arbitrarily chosen to be only 5%?
3. Page 5, line 45, right column: “How fast should this gain recovery time be?” I would prefer avoiding interrogative sentences.
4. Figure 3. What are the reflectivity of the mirrors? (Mode 10 is the strongest, may be specify this is the caption).
5. Figure 3(f) the optical powers in modes <3.8 THz are less than 10% of the total power. Can the authors comment in the possible reasons for this? Also, it might be better to replot the spectral plots in logarithmic scales. The various elements in plots 3(f) are barely discernible.
6. Figure 4(c), 5(c): Can the authors comment as to why the optical power in modes <3.8 THz is greater than those > 3.8 THz, unlike in Fig. 3(c)?

**Reviewer: 2**

Recommendation: **Minor Revision**

Comments: **The manuscript should be published after the authors have considered the points addressed above.**

Additional Questions:

The Transactions on Terahertz Science and Technology accepts new and original articles describing significant work and/or ideas not found elsewhere in the literature. Is this work a new and original contribution in the areas of Terahertz science, technology or applications?: **It is a relevant contribution in the area of THz Science, which extends on the work published in Optics Express.**

How significant is this work? **: It is of relevance for scientists interested in nonlinear Laser dynamics in QCLs**

Additional comments and suggestions for the author:

The authors mention that they probe the system with a pulse, which is running through the structure. Why does the intensity not drop in time for non-ideal reflectivity in Fig 5?

Minor details:

- epsilon and q\_0 in Eq(1) are undefined

- in Section V the authors refer to chaotic fluctuations. Do they mean irregular or chaoticity in the sense of dynamical systems with positive Lyapunov exponents?

Revision work done so far CHECKLIST:

**Introduction**:

* Remove paragraph on temperature performance. <- not referenced and mentioned any further in the text.
* Substitution of the word “chaotic” with “non-deterministic” throughout the text in order to avoid confusion and chaos theory (as recommended by Reviewer 2).
* Added a sentence relating our results to the publication [T. S. Mansuripur et. al., “*Singlemode instability in standing-wave lasers: The quantum cascade laser as a self-pumped parametric oscillator*,” Phys. Rev. A, vol. 94, p. 063807, 2016*],* which is highly relevant to our work but was only discovered by the authors AFTER the submission was made. Consecutively we also added a new citation to this publication.
  + Before:
    - We further show that upon suppression of SHB, one can recover the comb character of the laser, albeit over a reduced spectral bandwidth.
  + After:
    - We further show that upon suppression of SHB, one can recover the comb character of the laser, albeit over a reduced spectral bandwidth. This result also corresponds to recent experimental findings affirming that single-mode instabilities, introduced by spatial hole burning, yield an incoherent "dense" emission spectrum, when the QCLs is driven a little above threshold [12].

**Model**:

* Defined, and *q*0 as suggested by Reviewer 2. Paragraph 5 of this section was modified accordingly:
  + Before:
    - Further, we have denoted with *n* the background refractive index, with *c* the velocity of light in vacuum and with …
  + After:
    - Further, is used denote the 1' 3 detuning, *n* the background refractive index, *c* the velocity of light in vacuum, *q*0 the elementary charge and…”

**Mode proliferation mechanisms**:

* Changed the colours in Fig. 1 to be more suitable for grayscale printing.
* Modified paragraph 4 from this section to clarify the choice of bias (11 kV/cm) in our simulations. This modification was necessitated by several comments from Reviewer 1, who inquired about the dependence of the power distribution of the lasing modes on the applied bias. The corresponding sentence was modified as follows:
  + Before:
    - In both cases, the simulations were based on the THz QCL from [4], biased at 11 kV/cm.
  + After:
    - In both cases, the simulations were based on the THz QCL from [4], biased at 11 kV/cm, which is approximately the bias aligning the injector and the upper laser levels, i.e. [11].

**Comb degradation mechanisms**:

* Modified a sentence in paragraph 6 of the text due to a semantic error.
  + Before:
    - In free-running QCLs, due to their broadband nature and ultrafast carrier dynamics [12], there will be a strong competition between FWM and dispersion, the outcome of which will determine the free spectral range
  + After:
    - In free-running QCLs, due to their broadband nature and ultrafast carrier dynamics [9], there will be a strong competition between FWM and dispersion, the outcome of which will determine the emission spectrum of the device.
* Changed the colours in Fig. 2 to be more suitable for grayscale printing.

**Time evolution of the multimode spectrum:**

* Replot Fig. 3,4 and 5 with the optical power plots in log-scale, as recommended by Reviewer 1.
* Add corresponding beatnotes to figure 3 for ease of comparison with figures 4 and 5 and modified the caption accordingly.
* Modified paragraph 3 of this section in order to resolve the confusions implied by Reviewer 1 regarding why the lasing modes in the high frequency part of the spectrum are stronger than those in the lower part of Fig. 3. Detailed theoretical explanation is included into the appendix.
  + Before:
    - The results are summarized in Fig. 3. A quick comparison …
  + After:
    - The results are summarized in Fig. 3. Note that for these simulations the laser was biased at 10.8 kV/cm, which is when the injector level is energetically below the upper laser level (i.e. < 0). In appendix A we show how this leads to lasing predominantly of the high frequency part of the spectrum, in comparison to the case when the laser is biased at 1’<-> 3 resonance, when both spectral lobes are approximately equally strong. A quick comparison …
* Remove the last paragraph of this section due to the fact that the appearance of a frequency-doubled beatnote in Fig. 5, is not relevant to the comparisons made to the rest of the simulation!
  + Before:
    - Secondly, in Fig. 5(c) we can notice a very strong and narrow beatnote at the second harmonic of the linear cavity’s round trip frequency frt at approximately 15.8 GHz. This is also not so surprising, since due to the unidirectionality of the field propagation, only contributions from the left-to-right propagating signal are sufficiently strong, and thus the effective round trip time is halved.
  + After:
    - XXX

**Appendix A:**

* Added a dedicated appendix onto the bias dependence of the dominant lobe in the emission spectra. The addition of this section was necessitated by several comments made by Reviewer 1.
* Reviewer 1 comments:
  + Are the reflectivities arbitrarily chosen to be only 5%?
    - Clarification added: “Importantly, here we set the left and right amplitude reflectivities to only 5%, chosen to be sufficiently low as to ensure the elimination spatial hole burning from the simulation and thus isolate FWM as the only mode proliferation mechanism.”
  + “How fast should this gain recovery time be?” I would prefer avoiding interrogative sentences.
    - The sentence was corrected to: “The order of magnitude of the gain recovery time needed, in order to suppress SHB, can be calculated directly. For value of *p*=2, for example, and a value of  THz, this ps, which is unfortunately too fast to be realistic.”
  + Figure 3. What are the reflectivity of the mirrors? (Mode 10 is the strongest, may be specify this is the caption )
    - Mirror reflectivities are 100% in both cases. This as well as an indication that mode 10 is the strongest one, are now added in the figure caption. The caption of Figure 3 was corrected accordingly.
  + Figure 3(f) the optical powers in modes <3.8 THz are less than 10% of the total power. Can the authors comment in the possible reasons for this? Also, it might be better to replot the spectral plots in logarithmic scales. The various elements in plots 3(f) are barely discernible.
    - Added the theoretical explanation in the appendix.
  + Figure 4(c), 5(c): Can the authors comment as to why the optical power in modes <3.8 THz is greater than those > 3.8 THz, unlike in Fig. 3(c)?
    - Added the theoretical explanation in the appendix.
* Reviewer 2 comments:
  + The authors mention that they probe the system with a pulse, which is running through the structure. Why does the intensity not drop in time for non-ideal reflectivity in Fig 5?
    - Unlike our simulations in Sections III and IV, section V presents simulation results from “long-time” simulations of self-starting free running THz QCL. For those scenarios instead of probing the system with a pulse, we start with zero electric field envelope and let the system evolve until it settles to steady state. Furthermore, in order to produce the plots of Fig. 5, we sample the electric field envelope at a fixed point inside the cavity, which we have chosen to be immediately before the right facet, i.e. we record f(x=L,t) for each t, which is before the out-coupling has occurred therefore there is not drop in intensity in time for that case.

* + and *q*0 in Eq. (1) are undefined.
    - The text was corrected as follows: “Further, is used denote the 1' 3 detuning, *n* the background refractive index, *c* the velocity of light in vacuum, *q*0 the elementary charge and…”
  + In Section V the authors refer to chaotic fluctuations. Do they mean irregular or chaoticity in the sense of dynamical systems with positive Lyapunov exponents?
    - We have replaced the word chaotic with the word irregular as we are not sure whether this is indeed a manifestation of chaos in the mathematical sense of the word.