

Nonlinear Dynamics in Semiconductor Ring Lasers: From Phase Turbulence to Solitons

Original

Nonlinear Dynamics in Semiconductor Ring Lasers: From Phase Turbulence to Solitons / Piccardo, M.; Schwarz, B.; Columbo, L. L.; Prati, F.; Lugiato, L.; Brambilla, M.; Gatti, A.; Silvestri, C.; Gioannini, M.; Kazakov, D.; Opacak, N.; Beiser, M.; Hillbrand, J.; Wang, Y.; Belyanin, A.; Capasso, F.. - ELETTRONICO. - (2021), pp. 1-1. ((Intervento presentato al convegno 2021 Conference on Lasers and Electro-Optics Europe and European Quantum Electronics Conference, CLEO/Europe-EQEC 2021 tenutosi a Munich, Germany nel 21-25 June 2021 [10.1109/CLEO/Europe-EQEC52157.2021.9542382]).

Availability:

This version is available at: 11583/2952580 since: 2022-01-26T14:14:17Z

Publisher:

Institute of Electrical and Electronics Engineers Inc.

Published

DOI:10.1109/CLEO/Europe-EQEC52157.2021.9542382

Terms of use:

openAccess

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

Publisher copyright

IEEE postprint/Author's Accepted Manuscript

©2021 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collecting works, for resale or lists, or reuse of any copyrighted component of this work in other works.

(Article begins on next page)

Nonlinear Dynamics in Semiconductor Ring Lasers: From Phase Turbulence to Solitons

Marco Piccardo^{1,2}, Benedikt Schwarz³, Lorenzo L. Columbo⁴, Franco Prati⁵, Luigi Lugiato⁵, Massimo Brambilla⁶, Alessandra Gatti⁷, Carlo Silvestri⁴, Mariangela Giovannini⁴, Dmitry Kazakov², Nikola Opacak³, Maximilian Beiser³, Johannes Hillbrand³, Yongrui Wang⁸, Alexey Belyanin⁸, Federico Capasso²

1. Center for Nano Science and Technology, Fondazione Istituto Italiano di Tecnologia, Milano, Italy

2. Harvard John A. Paulson School of Engineering and Applied Sciences, Harvard University, Cambridge, MA, USA

3. Institute of Solid State Electronics, TU Wien, Vienna, Austria

4. Dipartimento di Elettronica e Telecomunicazioni, Politecnico di Torino, Torino, Italy

5. Dipartimento di Scienza e Alta Tecnologia, Università dell'Insubria, Como, Italy

6. Dipartimento di Fisica Interateneo and CNR-IFN, Università e Politecnico di Bari, Bari, Italy

7. Istituto di Fotonica e Nanotecnologie IFN-CNR, Milano, Italy

8. Department of Physics and Astronomy, Texas A&M University, College Station, TX USA

The recent study of ring quantum cascade lasers [1,2] (QCLs, Fig. 1a) revealed a new laser instability. It is triggered by phase turbulence akin to the wave instabilities that occur in other nonlinear systems such as fluids, superconductors and Bose-Einstein condensates. The choice of the ring geometry took inspiration from Kerr combs [3], that are commonly generated in passive ring microresonators and have attracted great attention within the photonics community in the last years thanks to their rich physics.

In this contribution we show that similar physics can occur in ring QCLs, that are active media and do not require an external optical pump. These new laser frequency combs are characterized by bell-shaped optical spectra exhibiting a sech^2 envelope—a characteristic commonly seen in microresonator Kerr combs. The behavior of the laser is explained by rewriting its governing equations in the form of the complex Ginzburg-Landau equation—one of the most famous nonlinear equations in physics [1].

To prove further the connection with Kerr combs, we propose a generalization of the well-known Lugiato-Lefever equation (LLE) [4], unifying the description of the spatiotemporal dynamics in nonlinear passive and active cavities with cubic nonlinearity (Fig. 1b-d). This model makes it possible to connect for the first time from a formal viewpoint Kerr microresonators and QCLs in terms of spontaneous optical frequency combs generation. Our comprehensive description also captures the physics of a hybrid device, a unidirectional ring QCL driven by an external coherent field [5]. The new system shows a wealth of spatiotemporal dynamics ranging from phase and amplitude turbulence to the self-generation of highly correlated dissipative patterns, such as Turing rolls and localized cavity solitons.

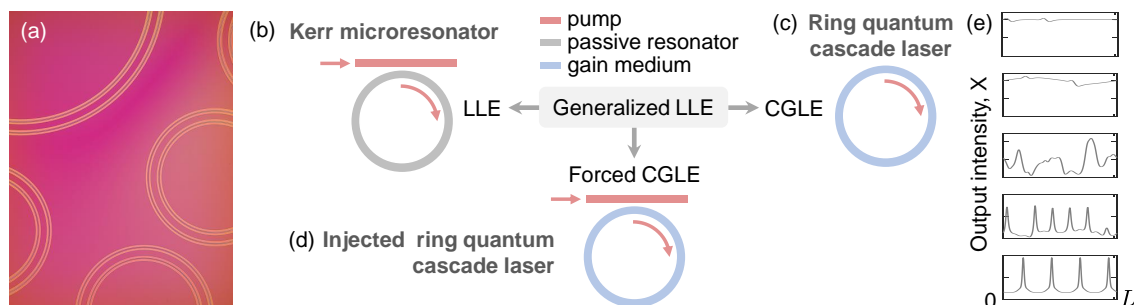


Fig. 1 (a) Microscope image of fabricated ring quantum cascade lasers. (b)–(d) The generalized Lugiato-Lefever equation unifies three distinct active/passive optical systems with cubic nonlinearity. (e) Localized structures emerging from phase instability, phase turbulence, amplitude turbulence, filamentation, and cavity solitons, when the ring laser transitions from free-running to externally driven.

References

- [1] M. Piccardo, B. Schwarz, D. Kazakov, M. Beiser, N. Opacak, Y. Wang, S. Jha, J. Hillbrand, M. Tamagnone, W. Chen, A. Zhu, L. Columbo, A. Belyanin, and F. Capasso, “Frequency combs induced by phase turbulence”, *Nature* **582**, 360–364 (2020).
- [2] B. Meng, M. Singleton, M. Shahmohammadi, F. Kapsalidis, R. Wang, M. Beck, and J. Faist, “Mid-infrared frequency comb from a ring quantum cascade laser”, *Optica* **7**, 162 (2020).
- [3] T. J. Kippenberg, A. L. Gaeta, M. Lipson, and M. L. Gorodetsky, “Dissipative Kerr solitons in optical microresonators”, *Science* **361**, eaan8083 (2018).
- [4] L. Columbo, M. Piccardo, F. Prati, L.A. Lugiato, M. Brambilla, A. Gatti, C. Silvestri, M. Giovannini, N. Opacak, B. Schwarz, F. Capasso, “Unifying frequency combs in active and passive cavities: Temporal solitons in externally-driven ring lasers”, arXiv:2007.07533 (2020)
- [5] F. Prati, M. Brambilla, M. Piccardo, L. Columbo, C. Silvestri, G. M., A. Gatti, L. Lugiato, and F. Capasso, “Soliton dynamics of ring quantum cascade lasers with injected signal”, *Nanophotonics* **10**, 195 (2020)