Influence of time-delayed feedback on the dynamics of temporal localized structures in passively mode-locked semiconductor lasers

T. Seidel¹, A. Bartolo³, N. Vigne¹, A. Garnache¹, G. Beaudoin⁵, I. Sagnes⁵, M. Giudici³, J. Javaloyes², S. V. Gurevich¹, M. Marconi³

1. Institute for Theoretical Physics & Center for Nonlinear Science (CeNoS), University of Münster, Schlossplatz 2, 48149 Münster, Germany
2. Dpt. de Física, Universitat de les Illes Balears & IAC-3, Campus UIB, E-07122 Palma de Mallorca, Spain
3. Université Côte d’Azur, Centre National de La Recherche Scientifique, Institut de Physique de Nice, F-06560 Valbonne, France
4. Institut d’Electronique et des Systèmes, UMR5214, University of Montpellier, 34000 Montpellier, France
5. Centre de Nanosciences et de Nanotechnologies, CNRS, Université Paris-Saclay, UMR 9001, 91120, Palaiseau, France

We analyze both theoretically and experimentally the impact of optical feedback on the dynamics of external-cavity mode-locked semiconductor lasers (VECSELs) operated in the long cavity regime [1]. In particular, by choosing certain ratios between the cavity round-trip time and the feedback delay, we show that feedback acts as a solution discriminator that either reinforces or hinders the appearance of one of the multiple harmonic arrangements of temporal localized structures. For the theoretical modeling, the delayed differential equation model [2] is extended by a term describing the optical feedback. Denoting by \( A \) the amplitude of the optical field, \( G \) the gain, and \( Q \) the saturable losses, the model reads

\[
\frac{\dot{A}}{A} = \sqrt{\kappa} \exp \left[ \frac{1 - i\alpha}{2} G(t - \tau_c) - \frac{1 - i\alpha}{2} Q(t - \tau_c) \right] A(t - \tau_c) - A(t) + \eta e^{i\Omega} A(t - \tau_f), \\
G = g_0 - \Gamma G - e^{-Q} (e^{\tau_f} - 1) |A|^2, \\
Q = q_0 - Q - s (1 - e^{-Q}) |A|^2,
\]

where \( t \) has been normalized to the SA recovery time, \( g_0 \) is the pumping rate, \( \tau_c \) the round-trip time in the cavity, \( \eta \) the feedback rate, \( \Omega \) the feedback phase and \( \tau_f \) the round-trip time in the feedback loop.

In the absence of the optical feedback such a laser can generate so-called harmonic mode-locked solutions denoted by HML\(_n\), where \( n \) is the number of equally spaced pulses per round-trip. The optical feedback induces that each pulse is followed by a train of small copies of itself. The size and position of this echo can be controlled via the feedback rate and the delay time, respectively. When an echo is placed close to the leading edge of another pulse, the pulse experiences less amplification by the gain medium as it is already depleted by the echo. This interaction can lead to the destruction of the main pulse. In consequence, the system settles on a solution where pulses and echos are well-separated and thus, do not interact. This mechanism is visualized in Fig. 2 where a HML4 and HML2 are exposed to optical feedback and therefore, the output changes to a HML3 and fundamental mode-locked solution, respectively. This behavior was also observed in the experiment. In the further steps, a detailed bifurcation analysis is conducted where the influence of the position of the echo is investigated [3]. Further parameters, such as the linewidth enhancement factors, also play an important role in the dynamics of the system. Various interesting regime including a global bifurcation in form of a satellite instability where found. Close to this global bifurcation, the system is shown to be excitable.

References

[1] A. Bartolo, T. Seidel, N. Vigne, A. Garnache, G. Beaudoin, I. Sagnes, G. Huyet, M. Giudici, J. Javaloyes, S. V. Gurevich, and M. Marconi, “Manipulation of temporal localized structures in a VECSEL with optical feedback,” Opt. Lett. 46, 1109-1112 (2021).
[2] A. Vladimirov and D. Turaev, “Model for passive mode locking in semiconductor lasers,” Phys. Rev. A 72, 033808 (2005).
[3] T. Seidel, J. Javaloyes, and S. V. Gurevich, “Influence of time-delayed feedback on the dynamics of temporal localized structures in passively mode-locked semiconductor laser” Chaos 32, 033102 (2022).