Advanced Photonics Congress (BGPP, IPR, Networks, NOMA,
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Characterization of Optical Chaos in Mid-Infrared Interband Cascade Lasers: Towards High-Speed Free-Space Applications

O. Spitz,[1] S. Zhao,[1,†] D. A. Díaz-Thomas,[2] L. Cerutti,[2] A. N. Baranov,[2] D. Rontani,[3] and F. Grillot[1,4]

[1] *LTCI, Télécom Paris, Institut Polytechnique de Paris, 19 place Marguerite Perey, Palaiseau, 91120, France*
[2] *IES, Université de Montpellier, CNRS, Montpellier, 34000, France*
[3] *Chair in Photonics, LMOPS EA 4423, CentraleSupélec & Université de Lorraine, Metz, 57070 France*
[4] *Center for High Technology Materials, University of New-Mexico, 1313 Goddard SE, Albuquerque, NM, USA*

[†] *shiyuan.zhao@telecom-paris.fr*

Abstract: We analyze the dynamics features of 4.1 μm optical chaos generated experimentally bya Fabry-Perot interband cascade laser. The numerical simulations we perform with the Lang-Kobayashi model are in good agreement with the experimental findings. © 2021 The Author(s)

1. Introduction

The topic of nonlinear dynamics at mid-infrared wavelengths has attracted attention in the recent years owing to the advantages of mid-infrared light for free-space applications. What makes this optical domain so relevant is that it is less affected by inclement weather than near-infrared wavelengths while conferring stealth, thus paving the way for regular and private communication channels in the transparency windows of the atmosphere [1]. So far, most of the experimental efforts about mid-infrared nonlinear dynamics have focused on quantum cascade lasers (QCLs) because they are renown for the absence of relaxation oscillation. This peculiarity should lead to wide nonlinear dynamics bandwidths of dozens of GHz [2] but experiments have shown much slower dynamics so far [1]. Another semiconductor lasers of interest for mid-infrared dynamics are called interband cascade lasers (ICLs). They are based on an interband structure with broken gaps and exhibit relaxation oscillations [3]. The consequence is that the nonlinear behavior of ICLs is predictable and recent numerical investigations have highlighted multi-GHz dynamics bandwidths [4], which is also what we can achieve experimentally, as shown hereafter. Furthermore, the chaos generated by ICLs shows complex features. The latter are of paramount importance for private communication because it hinders message extraction from an illegitimate receiver, and for chaotic LIDAR [5] as every signal outcome has a unique signature that allows accurate ranging and sensing.

2. Numerical modelling and experimental waveform

The simulation we carry out is based on the Lang-Kobayashi model that is a standard tool for analyzing the nonlinear dynamics of semiconductor lasers under external optical feedback [4]. In this numerical simulation, the relaxation oscillation frequency is set to 1 GHz [3] while the external cavity frequency is set to 15 GHz. This is compatible with our experimental configuration that focuses on a Fabry-Perot ICL in the short-cavity regime, for which the relaxation oscillation frequency is smaller than the external cavity frequency. Experimentally, the output of the laser is stable just above threshold current (72 mA) and the dynamics becomes more and more complex when the bias current is increased to 2.5 times the threshold current (180 mA). This behavior is also observed in our simulation, and one can see in Fig. 1 (a - d) that for a feedback strength of 0.28, the output of the ICL goes from a stable state (72 mA in a)) to period-1 oscillation dynamics (108 mA in b)), to period-doubling oscillation dynamics (144 mA in c)) and finally to developed chaos (180 mA in d)). When the experiment is carried out at 180 mA, the timetrace we record with a 25 GSa/s oscilloscope shows fast nonlinear dynamics (Fig. 1 (e)) with a strange attractor along which the trajectories wrap (Fig. 1 (f)) and an autocorrelation pattern with full width at half maximum of 900 picoseconds and almost no sidelobes (Fig. 1 (g)). This latter characteristic is of paramount importance for applications like chaotic LIDAR because that prevents matching errors during remote detection.

3. Complimentary analysis of the experimental time series

In order to confirm the chaos nature of the aforementioned experimental waveform at 180 mA, further investigation is required. The nonlinear analysis of the intensity time series is carried out first through embedding techniques [6],

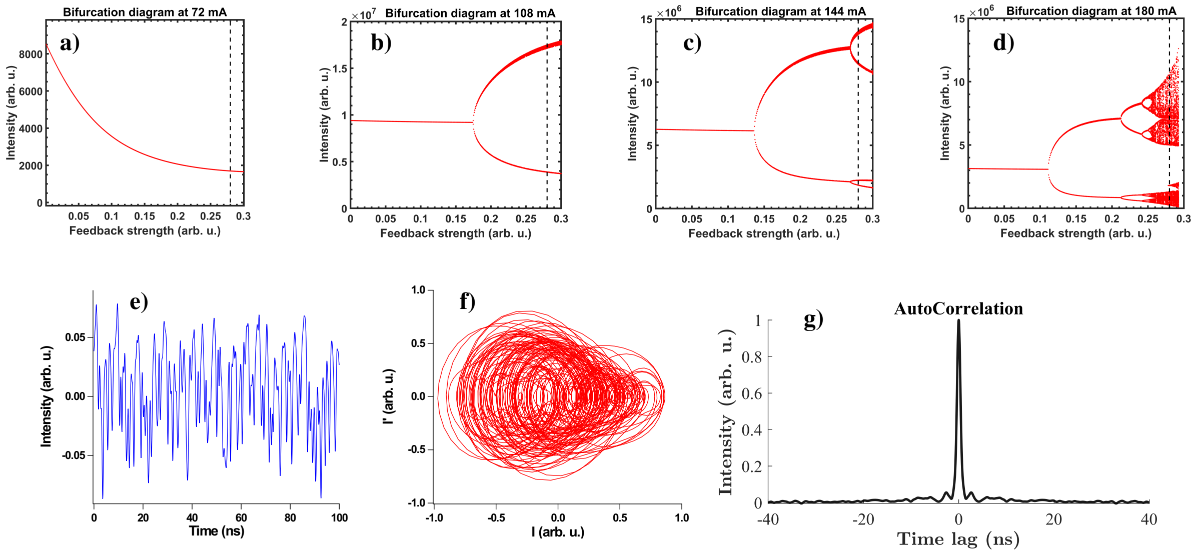

Fig. 1: Non-linear dynamics of the ICL under study emitting around 4.1 μm. Top row corresponds to dynamics modelling and bottom row corresponds to experimental results. (a - d) bifurcation diagrams when increasing bias current from 72 mA to 180 mA. For a feedback strength of 0.28 (black vertical dashed line), the larger the current, the more complex the dynamics. e) experimental waveform at 180 mA showing chaos with typical fluctuation timescale in the range of nanoseconds. f) phase portrait for the aforementioned waveform where one can see chaos attractors. g) autocorrelation function confirming that optical signal is independent of any previous outcome.

with a denoising filtering step that preserves all the relevant spectral features associated with the dynamics [7]. Embedding time-delay is set to $\tau_e = 40\Delta t$ (which was evaluated using delayed mutual information) and dimension is set to $d_E = 8$ (based on false-nearest neighbor technique with a residual proportion of false neighbors $< 0.5\%$). To assess the presence of chaos, we use two statistical methods. We first perform a modified $0-1$ chaos test [8]. This test builds upon initial data sample in order to create auxiliary variables forming a 2D map. The next step consists of estimating the growth rate K of the time-averaged mean-square displacement evaluated from the map. If $K = 0$, then the dynamics are considered regular, and if $K = 1$, it is considered chaotic. We compile 50,000 samples from our filtered time series and find $K = 0.9974$. In parallel, chaos titration with additive noise is also performed [9]. This method compares one-step predictions given respectively by optimal nonlinear Wiener-Volterra series and a linear autoregressive model when an increasing amount of synthetic noise is added to the original data. The noise level (in percent of the initial data variance) that leads to optimal accuracy of the linear predictive model is called noise limit (NL). In this framework, if $NL > 0$, we can conclude in the presence of strong nonlinearity in the system and hence chaos. Using the same number of samples as in the $0-1$ chaos test, considering a maximum degree $d = 2$, memory depth $\kappa = 10$, and subsampling factor of 10, we find that $NL = 50.8\%$.
Based on these two statistical analyses, we can conclude on the evidence of chaos dynamics in the time series produced by our laser system. This complements the information given by the chaotic attractor and the autocorrelation pattern, which overall makes this optical chaos very promising for fast, remote applications in the mid-infrared.

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This work is supported by the French Defense Agency (DGA), the French ANR program under grant ANR-11-EQPX-0016, the European Office of Aerospace Research and Development (FA8655-22-1-7032). This work was also supported in part by the Chair in Photonics.

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