Periodic and aperiodic pulse generation using optically injected DFB laser

I. Aldaya, C. Gosset, C. Wang, G. Campuzano, F. Grillot and G. Castañón✉

Generation of optical pulse trains using semiconductor lasers has attracted significant attention due to their applications in optical communications and signal processing. A pulse generator based on the nonlinear dynamics of an optically injected distributed feedback laser is presented. The proposed system does not require electrical excitation and can be configured to operate in a periodic or aperiodic pulsation regime by controlling the injection conditions. Experiments show periodic pulsation with a repetition rate of 1.034 GHz and aperiodic pulsation with an average repetition rate of 5.618 GHz.

Introduction: Given its application in soliton-based systems and the possibility to generate high-power spikes [1], optical pulse generation attracted attention soon after the first lasers were fabricated. Optical pulses can be generated using different laser technologies: fibre-ring lasers [2], solid-state lasers [3] and semiconductor lasers [4]. Optical signal processing and communications require compact and low-cost light sources, and consequently semiconductor lasers are more suitable. Therefore, with the goal of implementing an all-optical signal processor, research on pulse generation using semiconductor lasers has regained interest. Periodic optical pulses may be used for sampling in the optical domain and for all-optical clock recovery [5], whereas aperiodic optical pulses have applications in random bit generation [6] and in compressive sampling [7]. Among the different techniques available for generating optical pulses, two have attracted special attention [4]: gain switching [8] and modelocked lasers [9]. Both approaches require external electrical excitation, the former to switch the laser between non-lasing and lasing states, and the latter to stabilise phase locking among modes. An alternative approach exploits the rich nonlinear dynamics of an optically injected laser. In this Letter, we present pulse generation system based on an optically injected distributed feedback (DFB) laser capable of generating both periodic and aperiodic pulse trains without external electrical excitation, simplifying the associated electronics.

By selecting the injection conditions, i.e. frequency detuning ($\Delta\nu$) and the ratio of the power of the injected laser, when operating under free-running condition, to the power of the external light (ρ), the dynamical state of the injected laser can be controlled. Typically, the analysis of nonlinear dynamics of lasers subject to external light injection has been carried out numerically [10] or based on spectral measurements [11]. Even if frequency-domain analysis allows the identification of periodic regimes such as ‘Period 1, Period 2’ and higher orders, it fails to discriminate among non-periodic states. Given the averaging nature of the spectral analysis, chaos cannot be distinguished from some other dynamics such as excitability and bistability, which require time-domain analysis. With the advent of high-speed oscilloscopes, time-domain analysis has become a reality. An analysis of the time series obtained in the negative detuning static boundary revealed different behaviours depending on the value of ρ. In qualitative terms, for a high enough ρ, geometric chaos appeared. For moderate ρ, geometric chaos disappeared to become homoclinic chaos [13] (also denominated by the Shilnikov-type chaos). At even lower ρ, chaos is not present and a dynamical regime characterised by low-frequency periodic peaks appears. Finally, under weak injection, an unbounded-phase limit cycle resulted in ‘Period 1’. For pulse generation only periodic pulsation regime and homoclinic chaos are of interest:

Periodic pulsation: At relative low ρ values, the injected light power is not high enough to generate such complex behaviour but it still excites four-wave mixing (FWM). However, when the frequency detuning between the injected and the cavity resonances is small enough, highly efficient intracavity FWM is present. Even if the injected laser is not locked, the master laser (ML) imprints its phase noise to the slave laser (SL), maintaining the phase condition that increases the FWM efficiency. Additionally, under injection, the ML pulls the SL emission frequency towards its frequency, reducing the frequency detuning and further increasing the efficiency. Since FWM is a coherent process, all the generated components tend to be phase locked, resulting in periodic pulse trains.

Homoclinic chaos (aperiodic pulsation): from the nonlinear dynamics point of view [10], homoclinic chaos appears when the laser trajectory returns to a saddle node point. A small amount of noise forces the system to run out of the equilibrium point and generates a spike [12]. In contrast to geometrical chaos, where peaks with random amplitudes are generated, homoclinic chaos is characterised by a train of pulses with low amplitude noise and a random inter-spike interval (ISI) [12]. This regime has been observed in lasers subject to optoelectronic feedback both in CO_2 [12] and semiconductor lasers [13, 14]. However, to the best of our knowledge, homoclinic chaos has not been reported in optically injected semiconductor lasers.

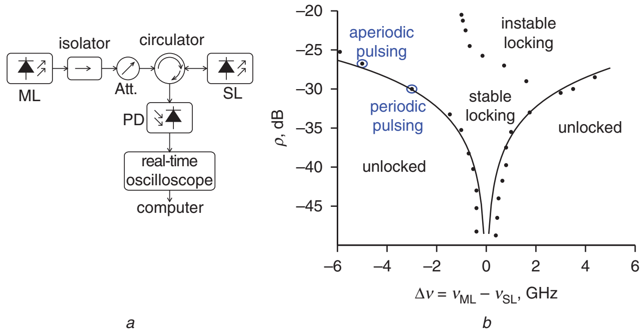

Fig. 1 *Experimental set-up, and locking diagram*

a Experimental set-up
ML: master laser, Att.: optical attenuator, SL: slave laser and PD: photodetector
b Locking diagram showing injection conditions for periodic and aperiodic pulsing regimes

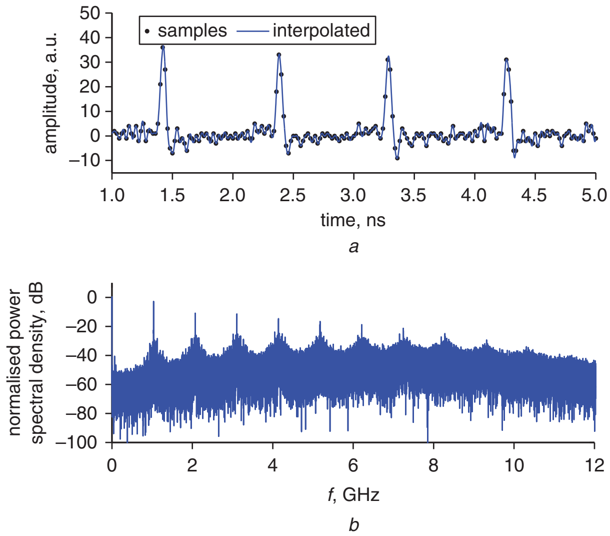

Fig. 2 *Periodic pulsation regime*

a Detailed caption of time series (samples and interpolated curve)
b Normalised spectral density

Experimental set-up: The employed lasers (ML and SL) are index-coupled DFB lasers supplied by Alcatel and they show a threshold current of 10 mA and a frequency–current slope of 1 GHz/mA. The injection experiments are carried out in reflective mode, as shown in the set-up, Fig. 1*a*. The ML is followed by an isolator that prevents reflections from the variable optical attenuator, after which the signal is injected into the SL through the low reflectivity facet. The SL output is redirected by a circulator to a 12 GHz bandwidth photodetector (PD), whose output is sampled at 50 GSps using a Tektronic DPO72004B oscilloscope. The bias current of the SL was kept at 37.5 mA, whereas the driving current of the ML was tuned to control the $\Delta\nu$. It was set at 56 mA for aperiodic pulsing and 52.4 mA for periodic pulsation. Afterwards, the ρ setting was performed through the optical variable attenuator. The measured locking map is shown in Fig. 1*b*, where the SL is considered to be stably locked when the power of the main locked peak is at least 30 dB higher than that of the resonance peak or spurious unlocked peak [15]. Both periodic and aperiodic pulsing regimes were found in the negative detuning boundary between stable locking and unlocked states. At higher power injection ratio, aperiodic pulsing occurred, whereas at lower injection ratio, periodic pulsing regime was observed. The captured time series had 5×10^5 samples, which was the maximum number of samples allowed by the oscilloscope. From these time series, the power spectral density (PSD) was computed and the ISI and peak amplitude analysis were performed offline.

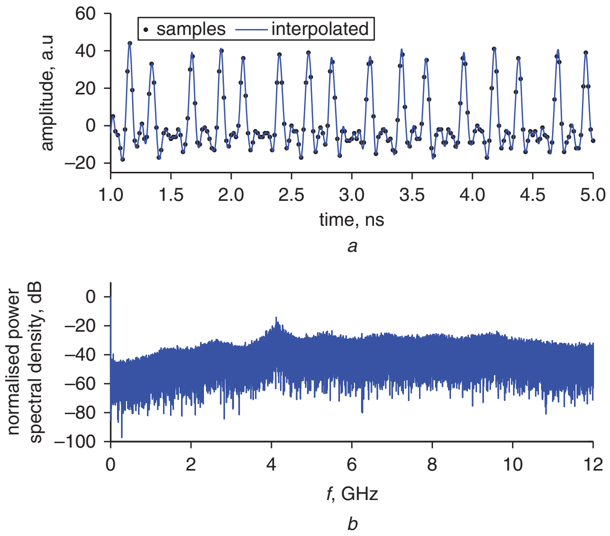

Fig. 3 *Aperiodic pulsation regime*

a Detailed caption of time series (samples and interpolated curve)
b Normalised spectral density

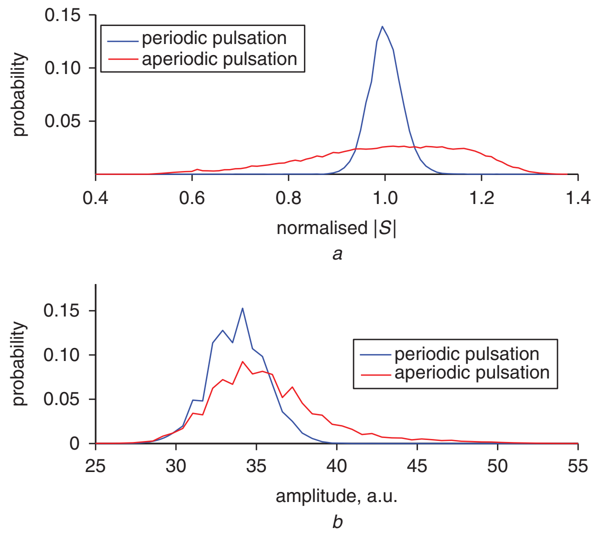

Fig. 4 *Pulse characterisation*

a Probability of normalised ISI for periodic and aperiodic pulsing regimes
b Probability of pulse amplitude for periodic and aperiodic pulsing regimes

Results: Fig. 2*a* shows a detail of the time series obtained when the injection conditions were set to $\Delta\nu = -3.5$ GHz and $\rho = -30.2$ dB. From the time series, the repetition rate was measured to be 1.034 GHz and the half-maximum full-width pulse width was 40 ± 20 ns, which is limited by the PD bandwidth. The periodicity can be appreciated in the PSD, Fig. 2*b*. The power of the frequency peaks decreases as the frequency increases, which is attributed to the combined effect of decreasing FWM efficiency and the bandwidth limitation imposed by the PD.

A detailed view of the time series and the PSD for aperiodic pulse generation is shown in Figs. 3*a* and *b*, respectively. The injection conditions were set to $\Delta\nu = -5.1$ GHz and $\rho = -26.5$ dB. It is clear that the ISI is not constant but that spikes occur at random times, with an average repetition rate of 5.618 GHz. The lack of periodicity is confirmed by the continuum spectrum in Fig. 3*b*.

We then characterised the generated periodic and aperiodic pulses. Fig. 4*a* shows the distribution of the ISI normalised to its average value. From Fig. 4*a*, it is clear that the periodic pulsation regime results in an ISI distribution with significantly lower jitter than the aperiodic pulsation regime. The periodic pulsation regime showed a more stable amplitude, as can be seen in Fig. 4*b*. This can be attributed to the more complex nature of the homoclinic chaos compared with the periodic pulsation regime, leading to more irregular trajectories.

Conclusion: In this Letter, we have presented a pulse generator based on an optically injected DFB laser capable of generating periodic and aperiodic pulse trains. Experimental results reveal that the proposed system can be used to generate periodic pulse trains with a repetition rate of 1.03 GHz and aperiodic pulse trains with a repetition rate of 5.6 GHz.

27 November 2014
doi: 10.1049/el.2014.3927
One or more of the Figures in this Letter are available in colour online.

I. Aldaya, G. Campuzano and G. Castañón (*Tecnológico de Monterrey, Monterrey, Mexico*)

✉ E-mail: gerardo.castanon@itesm.mx

C. Gosset, C. Wang and F. Grillot (*Telecom ParisTech, Paris, France*)

References

1 Haus, H.: 'Mode-locking of lasers', *IEEE J. Sel. Top. Quantum Electron.*, 2000, **6**, (6), pp. 1173–1185
2 Richardson, D., Nilsson, J., and Clarkson, W.: 'High power fiber lasers: current status and future perspectives [invited]', *J. Opt. Soc. Am. B*, 2010, **27**, (11), pp. 63–92
3 Pekarek, S., Klenner, A., Südmeyer, T., Fiebig, C., Paschke, K., Erbert, G., and Keller, U.: 'Femtosecond diode-pumped solid-state laser with a repetition rate of 4.8 GHz', *Opt. Express*, 2012, **20**, (4), pp. 4248–4253
4 Rafailov, E., and Avrutin, E.: 'Semiconductor lasers: fundamental and applications (Chapter 5: Ultrafast pulse generation by semiconductor lasers)' (Series in Electronics and Optical Materials, (Woodhead Pub., Cambridge, UK, 2013)
5 Smith, K., and Lucek, J.: 'All-optical clock recovery using a mode-locked laser', *Electron. Lett.*, 1992, **28**, (19), pp. 1814–1816
6 Kanter, I., Aviad, Y., Reidler, I., Cohen, E., and Rosenbluh, M.: 'An optical ultrafast random bit generator', *Nat. Photonics*, 2010, **4**, pp. 58–61
7 Li, Y., Dai, Y., Xu, K., Wu, J., Ji, Y., and Lin, J.: 'Integrated multifrequency recognition and downconversion based on photonics-assisted compressive sampling', *IEEE Photonics J.*, 2012, **4**, (3), pp. 664–670
8 Chen, S., Yoshita, M., Ito, T., Mochizuki, T., Akiyama, H., and Yokoyama, H.: 'Gain-switched pulses from InGaAs ridge-quantum-well lasers limited by intrinsic dynamical gain suppression', *Opt. Express*, 2013, **21**, (6), pp. 7570–7576
9 Avrutin, E., Marsh, J., and Portroi, E.: 'Monolithic and multi-GHz mode-locked semiconductor lasers: constructions, experiments, models and applications', *IET Proc. Optoelectron.*, 2000, **147**, (4), pp. 251–278
10 Wieczorek, S., Krauskopf, B., Simpson, T., and Lenstra, D.: 'The dynamical complexity of optically injected semiconductor lasers', *Elsevier Phys. Rep.*, 2005, **416**, pp. 1–128
11 Simpson, T., Liu, J., Huang, K., and Tai, K.: 'Nonlinear dynamics induced by external optical injection in semiconductor lasers', *Quantum Semiclassic Opt.*, 1997, **9**, pp. 765–784
12 Arecchi, F., and Meucci, R.: 'Stochastic and coherence resonance in lasers: homoclinic chaos and polarization bistability', *Eur. Phys. J. B*, 2009, **69**, pp. 93–100
13 Lin, F., and Liu, J.: 'Nonlinear dynamical characteristics of an optically injected semiconductor laser subject to optoelectronic feedback', *Opt. Commun.*, 2003, **221**, pp. 173–180
14 Al-Naimee, K., Marino, F., Ciszak, M., Meucci, R., and Arecchi, F.: 'Chaotic spiking and incomplete homoclinic scenarios in semiconductor lasers with optoelectronic feedback', *New J. Phys.*, 2009, **11**, (11), pp. 1–11
15 Naderi, N., Pochet, M., Grillot, F., Terry, N., Kovanis, V., and Lester, L.: 'Modeling the injection-locked of a quantum dash semiconductor laser', *IEEE J. Quantum Electron.*, 2009, **15**, (3), pp. 563–571