Incoherent optical triggering of excitable pulses in an injection-locked semiconductor laser

B. Garbin,[1] D. Goulding,[2,3] S. P. Hegarty,[2,3] G. Huyet,[2,3] B. Kelleher,[2,3,*] and S. Barland[1]

[1]Université de Nice, CNRS UMR 7335, Institut Non-Linéaire de Nice, 1361 Route des Lucioles, 06560 Valbonne, France

[2]Centre for Advanced Photonics and Process Analysis & Department of Applied Physics and Instrumentation, Cork Institute of Technology, Cork, Ireland

[3]Tyndall National Institute, University College Cork, Lee Maltings, Dyke Parade, Cork, Ireland

*Corresponding author: bryan.kelleher@tyndall.ie

Received November 14, 2013; revised January 15, 2014; accepted January 21, 2014; posted January 24, 2014 (Doc. ID 200976); published February 25, 2014

We experimentally study the response of an injection-locked quantum dot semiconductor laser in the excitable regime to perturbations from an external, incoherent laser. We show that excitable pulses may be triggered both for perturbation wavelengths close to that of the quantum dot device and wavelengths detuned even by a few tens of nanometers.

OCIS codes: (140.3520) Lasers, injection-locked; (140.5960) Semiconductor lasers; (190.3100) Instabilities and chaos; (250.5590) Quantum-well, -wire and -dot devices.

http://dx.doi.org/10.1364/OL.39.001254

Excitability refers to the possibility for a system to admit two different responses following an external perturbation to a steady state. In each case, after the response the system returns to its steady state. However, the nature of the return to the steady state depends on the amplitude of the perturbation compared to a certain threshold. Below threshold the system relaxes to the steady state after a transient whose duration is mostly fixed by the perturbation strength. Above the threshold, however, the system undergoes a large and unique trajectory in phase space, which is essentially independent of the details of the perturbation. Excitability was originally observed in biological systems [1] and was an important discovery in the study of the nervous system. Excitability has since been intensively studied in many fields, such as biology [2] and chemistry [3,4], and in various semiconductor laser systems, including a laser with a saturable absorber [5,6], lasers with optical feedback [7], semiconductor ring lasers [8], and lasers with optical injection [9–14].

Among these laser systems, the optically injected laser is the most straightforward configuration admitting the phenomenon. The system has been extensively studied (see [15] for example and references therein) and is known to exhibit a multitude of dynamical phenomena, including excitability, multistability, and chaos. The primary bifurcations leading to phase-locking in the system are saddle-node and Hopf bifurcations. For weak injection strengths the main bifurcation is only of saddle-node form and the physics of the system is well described by the Adler equation [16], one of the prototype equations for excitability [17]. When the slave laser is phase-locked and brought very close to the unlocking boundary (i.e., close to the saddle-node bifurcation), one can observe noise-induced excitable pulses [10,12,18]. It is, however, also of interest to excite such pulses deterministically. Recently in [19] such a deterministic triggering was achieved by applying an external perturbation in two ways: (i) by injecting a pulse in to the pumping current of the slave laser, and (ii) by perturbing the phase of the master laser. In this last case, the perturbation is therefore purely optical, but it is a *coherent* perturbation. Here we show that one can also trigger these pulses in an optically incoherent way by perturbing the locked slave laser with an additional wavelength detuned laser. The ability to trigger pulses in this way may be of interest since the characteristics of the excitable response should be independent of the perturbation that caused it. Thus, once the threshold is exceeded, the detailed characteristics of the perturbation such as the shape, amplitude, and wavelength are not important. Wavelength conversion and pulse reshaping are thus possible applications of such a mechanism.

The slave laser is single-mode quantum dot semiconductor laser based on InAs, with a side mode suppression ratio greater than 30 dB and emitting at approximately 1300 nm. The stability diagram of the device under optical injection was similar to that found in [20]. The output from the slave laser is coupled via a polarization-maintaining lensed-fiber. Two lasers were injected into the cavity of the slave laser. The first is the master laser, a commercial single-mode tunable device with a linewidth lower than 100 kHz, tunable by steps of 0.1 pm. The second is the detuned perturbing pulsed laser, a Fianium commercial mode-locked laser, tunable by steps of 0.1 nm, with pulse spectral width of about 10 nm. The polarization of each injection device is controlled using manual fiber polarization controllers and aligned with that of the slave. The two injection lasers are combined using a 90/10 coupler and injected into port one of an optical circulator (with an isolation greater than 30 dB) in order to obtain unidirectional coupling from the master to the slave.

The light is injected into the slave by connecting the lensed-fiber directly to port two of the circulator. Port three of the circulator was then connected to an optical filter centred on the slave laser wavelength with about 2 nm bandwidth in order to remove the transmitted part of the perturbing laser since this transmission served to greatly obscure the detection of the excitable response. The output of the optical filter was connected to a 12 GHz bandwidth real-time digital oscilloscope (Agilent

0146-9592/14/051254-04$15.00/0

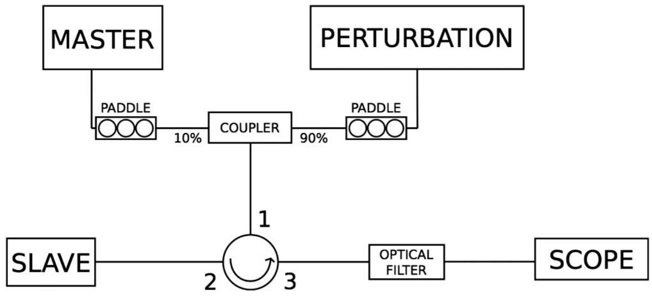

Fig. 1. Schematic of the experimental setup.

DSO91204A, 40 GS/s sampling rate) via a 12 GHz bandwidth photodetector. The experimental setup used is shown in Fig. 1.

Experimentally we have access to three control parameters: the injected power, the pumping current of the slave laser, and the detuning Δ (defined as the master frequency minus that of the slave). The threshold current of the slave laser was 28 mA and the experiment was carried out using a current of 36 mA (approximately 1.3 times threshold). Both the pump current of the slave laser and the injection strength were kept constant throughout the experiment. For sufficiently low injection power the bifurcation leading to the phase-locking is of saddle-node form for both signs of the detuning. In the locked state the slave laser is synchronized to the master both in frequency and in phase, with a fixed phase difference between the two lasers. Outside the locking region both the intensity and phase of the slave laser oscillate. For high injection strengths the locking bifurcation changes to Hopf form and the excitable behavior is no longer obtained. The present work is focused on the behavior near the negative detuning boundary and for sufficiently low injected power to have a saddle-node bifurcation.

As detailed previously, very close to the unlocking boundary noise-induced excitable pulses can be observed. Figure 2 shows an example of a noise-induced excitable pulse. The shape and amplitude of the pulse are inherent to the excitable nature of the pulse and will also hold for the optically triggered pulses.

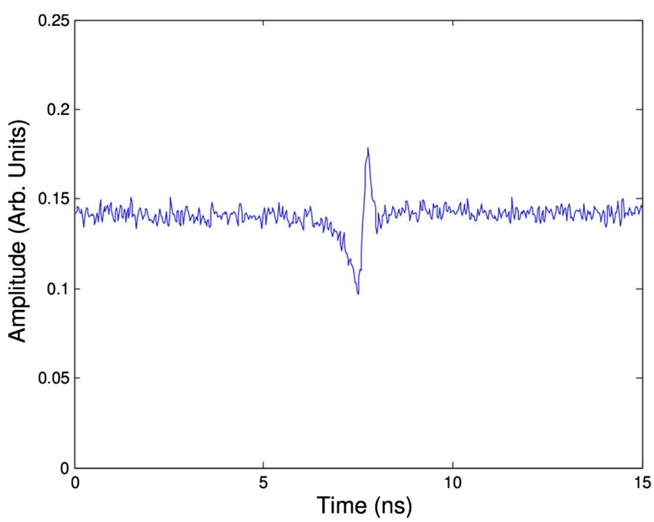

Fig. 2. Noise-induced intensity pulse for $\Delta \approx -800$ MHz.

The perturbations in our system are short pulses generated by the Fianium laser. This laser has a repetition rate of about 20 MHz, which is sufficiently low compared to the carrier decay time to avoid other unwanted effects. The perturbation is centered at 1288 nm, approximately 10 nm from the peak of the slave laser. Since the detuning between the perturbing laser and the slave laser is so large, the perturbation only affects the carriers and any optical phase of the perturbing laser can be ignored.

The detuning between the master and slave devices was set so that the system was close to the negative detuning unlocking boundary but sufficiently far away so that noise-induced pulses were not obtained. Figure 3(a) shows the response of the slave laser under a perturbation without the generation of an excitable pulsation. The perturbation itself is not visible in the output time series due to the optical filter. The linear response is essentially composed of one deep trough followed by a single small intensity ring. Figure 3(b) shows the response of the slave laser in the case where an excitable pulse has been generated. The initial response is the same as that of Fig. 3(a). However, this time it is followed by an excitable pulse showing the same features as the noise-induced pulse shown in Fig. 2. Figures 3(a) and 3(b) were obtained using the same control parameters showing that for certain perturbation amplitudes the perturbation can either promote an excitable pulse or indeed fail to do so. In an idealized noise-free system this could not occur. However, in a real system with noise, such behavior is not surprising. Nonetheless, one should expect that as the perturbation is increased the number of excitable pulses generated should also increase. The ideal excitable "all-or-nothing" response is replaced with something akin to an "efficient-or-inefficient" response, which has been theoretically analyzed in [21]. In order to verify this we examined the response of the system under different perturbation amplitudes. Three excitable responses are shown in Figs. 4(a)–4(c), acquired for progressively increasing amplitudes of the

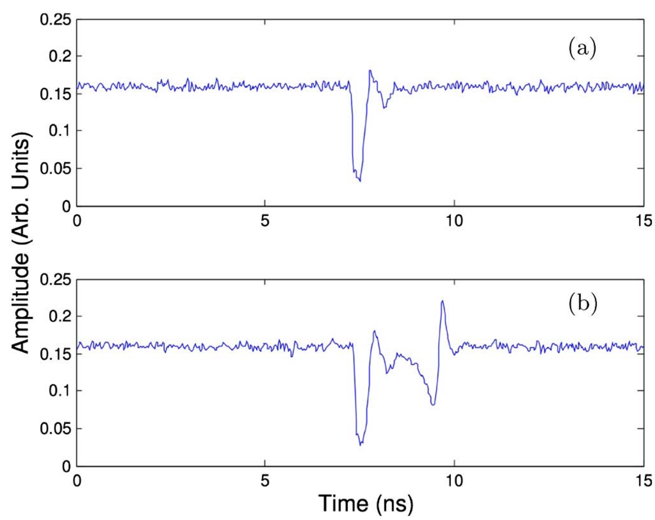

Fig. 3. (a) Response of the system to the perturbation taken for a perturbation of 1.6 (Arb. Units); (b) response of the system taken for a perturbation of 1.6 (Arb. Units) generating an excitable pulse. $\Delta \approx -750$ MHz in both cases.

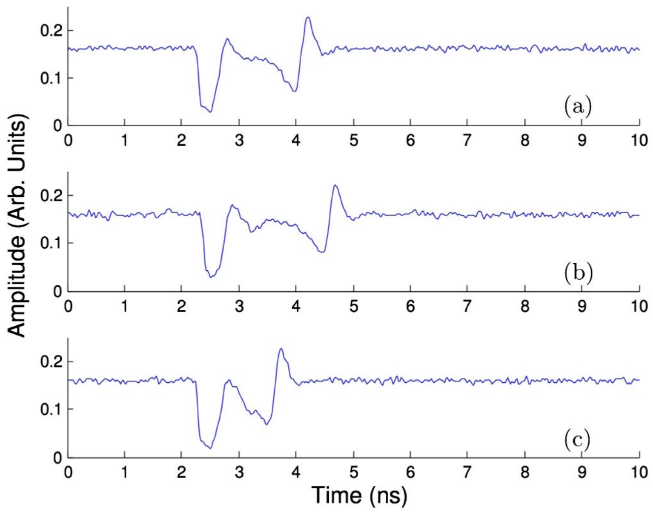

Fig. 4. Excitable responses of the system for $\Delta \approx -750$ MHz and perturbation strengths of (a) 1 (Arb. Units), (b) 1.6 (Arb. Units), (c) 2 (Arb. Units).

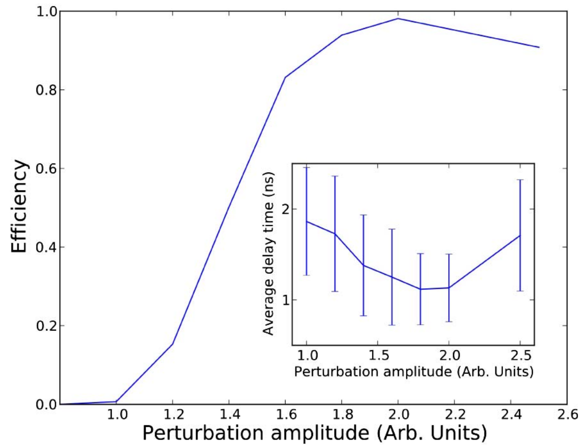

Fig. 5. Efficiency curve for varying perturbation strengths. For each strength the efficiency is defined as the ratio of the number of successful generations of an excitable pulse to the total number of perturbations. Each point corresponds to more than 5000 perturbations. The inset shows the delay between the perturbing pulse and the excitable response.

perturbation. The only difference observed in the three responses is the variation of the delay time between the perturbation and the excitable pulse. The delay time varies significantly for each perturbation strength, as shown in the inset of Fig. 5, suggesting that stochastic effects are important in this respect.

Figure 5 shows an efficiency curve for the system. The efficiency is defined as the ratio of the number of triggered excitable pulses to the number of perturbations injected into the system. The appearance of a threshold is clearly visible, although our perturbation does not reach a hundred percent efficiency. We believe that the decrease in efficiency for sufficiently high perturbations is related to the suboptimal trajectory in phase space caused by the perturbation. The direction in phase space of the perturbation cannot be arbitrarily controlled and for high amplitudes, rather than pushing the system along the Adler circle it pushes it away from the circle and thus the trajectory back to the fixed point is not necessarily along the excitable path.

A notable observation was the presence of several rare events of double pulse responses caused by only one perturbation for high perturbation strengths (including the last two points of Fig. 5). These may be related to two things. One is the presence in the perturbation of the ring, which also grows with perturbation strength. This ring may eventually be strong enough to promote an excitable pulse itself. The second possibility is the presence of an additional degree of freedom (arising from increased dimensionality and analogous to an inertial term in a mechanical excitable system [22]), potentially giving rise to a deterministic, multipulse trajectory in the system involving two (or indeed more) rotations in phase space induced by the presence of homoclinic bifurcations [10,11,13,15,23].

We also examined the influence of the perturbation wavelength on the efficiency. The shape of the response was almost unchanged and indeed excitable responses were obtained over a wide range of wavelengths but as the detuning between the perturbing pulse and the slave laser was increased the requisite perturbation strength also increased. The efficiency was reduced and reached a maximum of 0.35 at a perturbation central wavelength of about 1240 nm.

In conclusion, the triggering of excitable pulses in an all-optical manner has been demonstrated with an optically injected laser. As well as being of interest for purely nonlinear dynamics, it served as an experimental proof of a new technique for pulse reshaping and wavelength conversion. Further studies are required using different perturbing pulse shapes and characteristics.

BK gratefully acknowledges the support of the Irish Research Council and Campus France. This work was conducted under the framework of the Irish Government's Programme for Research in Third Level Institutions Cycle 5, National Development Plan 2007-2013 with the assistance of the European Regional Development Fund. SB and BG gratefully acknowledge funding from Région Provence Alpes Côte d'Azur and Campus France through grant numbers DEB 12-1538 and 29872PF.

References

1. A. L. Hodgkin, A. F. Huxley, and B. Katz, J. Physiol. **116**, 424 (1952).
2. A. L. Hodgkin and A. F. Huxley, J. Physiol. **117**, 500 (1952).
3. E. Neumann and J. Bernhardt, Annu. Rev. Biochem. **46**, 117 (1977).
4. L. Kuhnert, K. I. Agladze, and V. I. Krinsky, Nature **337**, 244 (1989).
5. J. L. A. Dubbeldam, B. Krauskopf, and D. Lenstra, Phys. Rev. E **60**, 6580 (1999).
6. M. A. Larotonda, A. Hnilo, J. M. Mendez, and A. M. Yacomotti, Phys. Rev. A **65**, 033812 (2002).
7. M. Giudici, C. Green, G. Giacomelli, U. Nespolo, and J. R. Tredicce, Phys. Rev. E **55**, 6414 (1997).
8. L. Gelens, S. Beri, G. Van der Sande, G. Verschaffelt, and J. Danckaert, Eur. Phys. J. D **58**, 197 (2010).
9. S. Wieczorek, B. Krauskopf, and D. Lenstra, Phys. Rev. Lett. **88**, 063901 (2002).
10. D. Goulding, S. P. Hegarty, O. Rasskazov, S. Melnik, M. Hartnett, G. Greene, J. G. McInerney, D. Rachinskii, and G. Huyet, Phys. Rev. Lett. **98**, 153903 (2007).

11. O. Vaudel, N. Péraud, and P. Besnard, Proc. SPIE **6997**, 69970F (2008).
12. B. Kelleher, D. Goulding, S. P. Hegarty, G. Huyet, D.-Y. Cong, A. Martinez, A. Lemaâitre, A. Ramdane, M. Fischer, F. Gerschütz, and J. Koeth, Opt. Lett. **34**, 440 (2009).
13. B. Kelleher, C. Bonatto, G. Huyet, and S. P. Hegarty, Phys. Rev. E **83**, 026207 (2011).
14. S. Barland, O. Piro, M. Giudici, J. R. Tredicce, and S. Balle, Phys. Rev. E **68**, 036209 (2003).
15. S. Wieczorek, B. Krauskopf, T. B. Simpson, and D. Lenstra, Phys. Rep. **416**, 1 (2005).
16. R. Adler, Proc. IRE **34**, 351 (1946).
17. P. Coullet, D. Daboussy, and J. R. Tredicce, Phys. Rev. E **58**, 5347 (1998).
18. S. Wieczorek and D. Lenstra, Phys. Rev. E **69**, 016218 (2004).
19. M. Turconi, B. Garbin, M. Feyereisen, M. Giudici, and S. Barland, Phys. Rev. E **88**, 022923 (2013).
20. T. Erneux, E. A. Viktorov, B. Kelleher, D. Goulding, S. P. Hegarty, and G. Huyet, Opt. Lett. **35**, 937 (2010).
21. F. Pedaci, Z. Huang, M. van Oene, S. Barland, and N. H. Dekker, Nat. Phys. **7**, 259 (2010).
22. P. Coullet, J. M. Gilli, M. Monticelli, and N. Vandenberghe, Am. J. Phys. **73**, 1122 (2005).
23. B. Krauskopf, K. Schneider, J. Sieber, S. Wieczorek, and M. Wolfrum, Opt. Commun. **215**, 367 (2003).