Temporal Resolution Enhancement in Quantum-Dot Laser Neurons due to Ground State Quenching Effects

George Sarantoglou[1], **Menelaos Skontranis**[1], **Adonis Bogris**[2], **Charis Mesaritakis**[1]

[1] *Department of Information and Communication Systems Engineering, University of the Aegean, Karlovassi-Samos 83200-Greece*

[2] *University of West Attica, Department of Informatics & Computer Engineering, Ag. Spyridonos 12243, Egaleo - Greece*

email address: cmesar@aegean.gr

Abstract: We present experimental results for an all-optical quantum-dot neuron, biased to a ground-state quenching regime alongside emission from the excited state. This regime, allows reduction of the temporal width of spikes down to 500 ps and enhanced firing rate.

1. Introduction

Photonic neuromorphic computing has emerged during the last years as a promising non-von-Neumann information processing paradigm that incapacitates the limitations inherent to conventional processors when addressing tasks, such as pattern recognition, decision-making and optimization [1]. In particular, multi-section quantum-dot laser (QD), can provide an alternative route to biological isomorphism by emulating both inhibitory and excitatory neurons. This can be achieved by exploiting waveband switching and by encoding neural inhibition and excitation signals as optical emission from the excited (ES) and ground state (GS) respectively [2]. Moreover, in conventional two-section lasers, excitability is achieved under sub-threshold laser biasing, whereas the temporal width of the generated spikes is linked to Q-switching effect [1]. This mechanism leads to spikes with temporal width in the scale of microsecond [1] when typical devices are considered, whereas picosecond spikes have been only demonstrated by micro-lasers at the expense of low emitted power [3].

In this work, we exploit the QD related GS quenching regime [4], so as to trigger significantly faster dynamics compared to typical sub-threshold biasing. In particular, we demonstrate that even a 2 mm long, edge-emitting two-section QD laser when forced to GS quenching, can allow the generation of neural spikes with picosecond duration (500 ps). Typical sub-threshold biasing for the same device lead to spike duration in the microsecond regime. Therefore, GS quenching effects in QD laser neurons provide a two-fold benefit: firstly, allows isomorphic operation to biological neurons [2] and secondly enables faster dynamics compared to typical biasing scenarios.

2. Experimental Setup

The experimental setup is presented in Fig. 1.a. It consists of two InAs/InGaAs Fabry Perot, two-section QD lasers in a master-slave optical injection configuration. The slave laser (SL) acts as the photonic neuron; it is 2 mm long, it contains 5 QD layers into a 440 nm GaAs waveguide surrounded by $Al_{35\%}Ga_{65\%}As$ layer. The master-laser (ML) generates the optical triggering; contains 10 QD layers and is 4 mm long. The gain/absorber ratio for both lasers is set to 85/15, whereas the saturable absorber (SA) is reversed biased in both structures. The temperature of the devices was stabilized through an electro-optic cooler in a closed-control loop. It was set to 33 °C and 20 °C for the ML and SL respectively, so as their optical spectrums to overlap (Fig.1.b). The variable optical attenuator (VOA) allowed the control of the injection strength, whereas a GS pass-band filter was used in order to monitor only this waveband. A photodiode with 6 GHz bandwidth followed by a real-time oscilloscope with 40 Gsa/s data acquisition capability tracked the time evolution of the neurons output, while the optical spectrum was recorded through an optical spectrum analyzer with 0.05 nm resolution.

3. Experimental Results

The ML's SA is set to -3 V and emits GS mode-locked pulses with repetition frequency equal to 20 GHz. The ML's injection current is fine-tuned so as to maximize the spectral overlap between the ML and SL spectrum. The SL is biased as an excitatory neuron [2] with its SA set to -4.5 V; meaning that ML injection of GS perturbations will evoke GS spikes from the SL. In this context, two regimes can be used: The first is below GS threshold (low

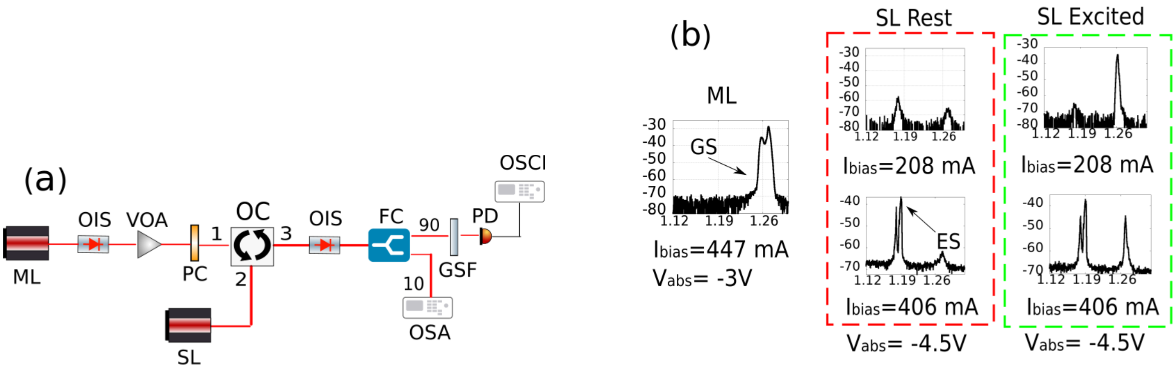

Fig. 1: (a) Experimental set-up. ML is the master laser, SL the slave laser, VOA the variable optical attenuator, PC the polarization controller, OC the optical circulator, FC the fiber coupler, OSA the optical spectrum analyzer, GSF the ground state pass-band filter, PD the photodiode and OSCI the oscilloscope, (b) Optical spectrum of GS mode-locked optical injection in a solitary SL, biased in both the low current (208 mA) and high current (406 mA) injection regime for V_{abs} = -4.5 V.

gain currents) as in typical two-section approaches and one involving higher injection current, where GS lasing is suppressed due to GS quenching (Fig. 1.b). Typical time traces of these two regimes are shown in Fig. 2.a, where the injection strength is set equal to -7 dBm for both cases. It is evident that the number of generated spikes increases, while spike duration is radically reduced in the second regime. Fig. 2.c-d illustrate the amplitude of the spike events and the firing rate as a function of the injection strength in the GS quenching regime. A steep activation threshold is observed for injection strength equal to -13 dBm. The amplitude of the generated spikes remains relatively constant (all-or-nothing events [1]). The firing rate increases as a function of the injection strength up to 30 MHz for -7 dbm (rate - encoding scheme [1]).

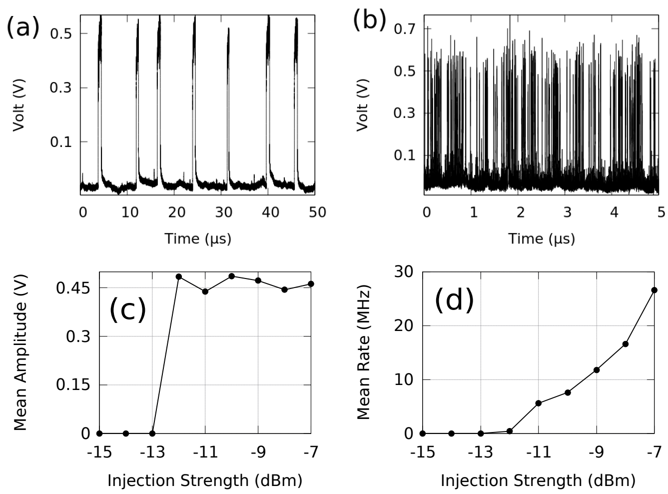

Fig. 2: Time traces of the triggered SL for (a) I_{bias} = 208 mA and (b) I_{bias} = 406 mA. The reverse bias at the SL's SA is -4.5 V and the optical injection comes from the mode-locked ML with I_{bias} = 447 mA and V_{abs} = -3 V. The injection strength is equal to -7 dBm. (c) The mean amplitude and (d) the mean firing rate for increasing injection strength in the case of SL with I_{bias} = 406 mA and V_{abs} = -4.5 V .

In order to observe the effect of GS quenching on the temporal resolution of the spikes, we computed the mean full width at half maximum (FWHM) of the spike events (Fig. 3) versus the reverse voltage at the SA. In particular, in Fig. 3.a, for reverse bias lower than 5 V, GS quenching was not detected (typical sub-threshold laser) resulting to broad neural spikes FWHM ¿ 600 ns (Fig. 3.a). The presence of GS quenching (increasing bias from 4.5 V to 5 V) led to the reduction by two orders of magnitude of the FWHM. In Fig. 3.b, the injection current is further increased so as to achieve a sub-threshold GS regime (quenching) alongside ES lasing. In this case, FWHM is close to 1 ns for 4.5 V and 5 V and reaches picosecond values for 5.5 V and 6 V. Increasing the reverse bias in this case had a relatively weak impact on the FWHM, as opposed to the low current injection case (Fig. 3.a). It is worth mentioning, that FWHM values as low as 500 ps were detected for high current injection (Fig. 3.c).

We assume, that the substantial decrease of the temporal width is related to the presence of ES emission when GS is below its lasing threshold - GS quenching. This effect is analogous to the reduction of the temporal width of GS mode-locked pulses due to ES emission [5]. For low current injection, GS quenching along with increased reverse bias result in a significant reduction of the spikes duration. For high current injection, the enhanced ES emission reduces the temporal width to sub-nanosecond values, whereas the role of reverse bias is significantly reduced. Consequently, GS quenching seems to play an important role to the decrease of the temporal width down to picosecond durations.

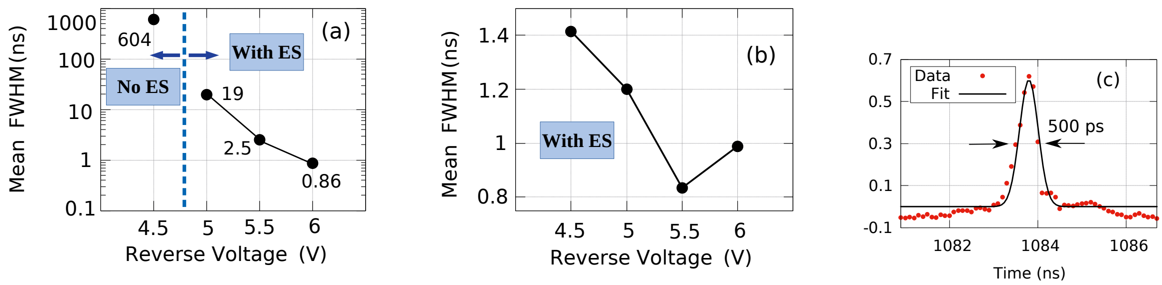

Fig. 3: The mean FWHM of the spike events measured (a) for SL biased below the first GS threshold (the numbers on the graph indicate the measured FWHM) and (b) in the GS quenching regime. (c) A spike event with 500 ps FWHM, for SL with $V_{abs} = -5.5$ V and $I_{bias} = 407$ mA.

4. Conclusion

In this work, we provide experimental results concerning the effect of the GS quenching on the temporal width of spike events generated by a 2 mm long, all-optical excitatory edge emitting QD laser neuron. In the presence of ES emission (GS quenching), spike events with picosecond durations have been recorded (500 ps). In the abscence of ES emission, the duration of the pulses was in the microsecond scale. Picosecond spike durations have been achieved until now only for two-section microcavities. These results, combined with the fact that ES emission is enhanced in short cavities [4] and that volume miniaturization reduces the pulse duration [6], renders the QD laser a promising choice for ultra-fast cognitive processing.

5. Acknowledgements

This project has received funding from the Hellenic Foundation for Research and Innovation (HFRI) and the General Secretariat for Research and Technology (GSRT), under grant agreement No 2247 (NEBULA project). The authors would like also to thank the members of the photonic technology laboratory in the department of Informatics and Telecommunications at the University of Athens for hosting the experimental activities of the NEBULA project.

References

1. Prucnal, P. R., Shastri, B. J., de Lima, T. F., Nahmias, M. A., & Tait, A. N. (2016). ”Recent progress in semiconductor excitable lasers for photonic spike processing”. Advances in Optics and Photonics, 8(2), 228-299.
2. Mesaritakis, C., Kapsalis, A., Bogris, A., & Syvridis, D. (2016). ”Artificial neuron based on integrated semiconductor quantum dot mode-locked lasers”. Scientific reports, 6, 39317.
3. Erneux, T., & Barbay, S. (2018). ”Two distinct excitable responses for a laser with a saturable absorber”. Physical Review E, 97(6), 062214.
4. Röhm, A., Lingnau, B., & Luedge, K. (2014). ”Understanding ground-state quenching in quantum-dot lasers”. IEEE Journal of Quantum Electronics, 51(1), 1-11.
5. Rafailov, E. U., Cataluna, M. A., & Sibbett, W. (2007). ”Mode-locked quantum-dot lasers”. Nature photonics, 1(7), 395.
6. Spühler, G. J., Paschotta, R., Fluck, R., Braun, B., Moser, M., Zhang, G., ... & Keller, U. (1999). ”Experimentally confirmed design guidelines for passively Q-switched microchip lasers using semiconductor saturable absorbers”. JOSA B, 16(3), 376-388.