Resonate and Fire Neuromorphic Node based on two - section Quantum Dot Laser with multi-waveband dynamics

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Abstract *We present the experimental results regarding an excitable, two – section quantum dot laser exhibiting resonate and fire dynamics. Moreover, we explore the beneficial role of quantum dot assisted multi – waveband emission in enhancing the firing rate and the temporal resolution of photonic neuromorphic processors.*

Introduction

Spiking Neural Networks have emerged as a promising non – Von-Neumann computational paradigm that successfully overcomes the limitations inherent in traditional architectures. Their significant computational efficiency is attributed to their inherent parallelism and the utilization of the spiking scheme, namely a coding scheme that combines the expressiveness of analogue processing and the robustness of digital encoding [1].

Although CMOS-based SNNs show remarkable computational efficiency, the need to handle a vast amount of interconnections, leads to problems like limited bandwidth, important heat dissipation and high energy footprint. Photonic SNNs overcome these limitations due their high communication bandwidth, ultra-fast dynamics and low cross-talk. For this reason, multiple photonic neuron implementations have appeared in literature based on two-section lasers, optically injected lasers, optical feedback lasers, micro-disk lasers, phase change materials, etc [1 and references therein].

Additionally, in order to mimic various neural motifs with photonic neurons, it is important to emulate various types of neurons. An important distinction is made between integrators and resonators. Integrators encode information strength at their firing rate, whereas resonators are triggered only by inputs with certain repetition frequencies [2]. Resonators act as band-pass filters and can be used for selective communication between neural groups [2]. Although resonators are of high importance in biological literature, this concept has yet to be thoroughly studied in photonic literature apart from the case of an optically injected QW device [3].

In this work, we further explore the neuro-computational capabilities of two – section QD lasers (QD) [4], by presenting results regarding the characterization of a two - section QD laser as a resonator. Moreover, we study for the first time the effect of multi wave-band dynamics at the firing rate and temporal resolution of spike events, revealing their potential role in boosting the performance of photonic neurons.

Experimental Setup

The full – scale experimental setup is shown in Fig. 1. It consists of two $Al_{35\%}Ga_{65\%}As$ Fabry perot, edge emitting, two – section QD lasers, connected in a master (ML) – slave (SL) configuration. The ML has 4 quantum dot (QD) layers and it is 4 mm long. Its role is to trigger the SL with 10 GHz mode – locked pulses generated from the ground state level (GS). The SL has 2 QD layers and it is 2 mm long. It is biased so as to be excitable – being able to generate GS spikes. The gain to SA ratio is 85/15 and it is the same for both lasers. The temperature in each laser is controlled by a Peltier cooler which sets the SL at 20℃ and the ML at 33℃ to achieve optimal matching between the two optical spectra. The strength of optical injection is controlled by a variable optical attenuator (VOA). A photodiode with 6 GHz bandwidth, followed by a real – time oscilloscope with 40 Gsample/s data acquisition capability is used to track the optical output of the SL and an optical spectrum analyzer with 0.05 nm resolution is used to measure the optical spectrum. Also a GS filter is used to record time – traces only from this waveband.

At first only a part of the setup is used, consisting of the solitary SL under various bias conditions in order to determine its neuro-computational properties. Then, the full set-up is employed so as to achieve the triggering of spikes with external optical injection, which is a more application oriented scenario.

Neuro-computational properties of the QD Laser

The neuro-computational properties of a two – section laser can be determined by biasing it below its lasing threshold and observing the transition from resting to Q – switching dynamics with the variation of the gain current (I_{gain}). The isomorphism between neurons and two – section lasers allows for perceiving the Q – switching regime as the spiking regime and the gain current as a parameter similar to the application of DC current in biological neurons [2], [5]

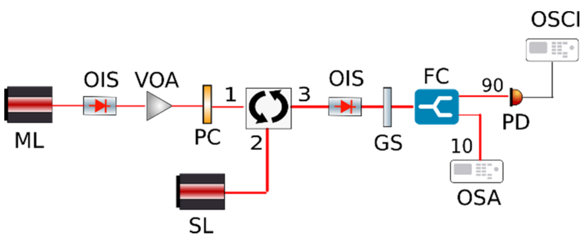

Fig. 1 : Experimental set-up. ML is the master laser, SL the slave laser, VOA the variable optical attenuator, PC the polarization controller, OC the optical circulator, FC the fiber coupler, OSA the optical spectrum analyzer, GSF the ground state pass-band filter, PD the photodiode and OSCI the oscilloscope

In Fig. 2 the power emmitted from the GS and the first excited state (ES) is presented in order to reveal the sub-threshold regions available for different reverse voltage (V_{rev}) biasing. For $V_{rev} \leq 4\,V$, the GS lasing threshold is unique and close to 200 mA. Interestingly, for $V_{rev} > 4\,V$ there exists an additional second threshold for $I_{gain} \approx 400\,\mathrm{mA}$. This lasing threshold is the outcome of complex dual-band dynamics between the GS and ES levels.

For $V_{rev} \leq 4.5\,V$ and low gain current, the transition from resting to spiking dynamics is characterized by opto-thermal spikes with temporal width in the micro-second time scale and firing rate in the KHz regime. These pulsations, which have been observed in the past also in single section QD devices [6], suffer from very low temporal resolution and firing rate and consequently they are not examined in this work.

For $V_{rev} = 5\,V$, the transition from the resting to spiking dynamics is due to the Q – switching mechanism. This transition is illustrated in Fig. 3 for three representative gain current conditions. For I_{gain} = 218 mA (Fig. 3 a), the system is in its resting state. For 219 mA (Fig. 3 b) spontaneous emission triggers random spike events. For 220 mA (Fig. 3 c) the system fully enters at the spiking regime. The RF spectrum (Fig. 3 d) in all three cases reveals a peak at 17.6 MHz whose power increases with gain current. The small – amplitude oscillations of 17.6 MHz at 218 mA and the generation of spike events synchronized to this frequency are related to a transition from resting to pulsating dynamics via a Hopf bifurcation [7], which in neural theory is linked to a resonate and fire dynamics [2]. Consequently, when the SL is biased close to 218 mA, it acts as a resonator which is sensitive to inputs with repetition frequency that is an integer multiple of 17.6 MHz. Moreover, 17.6 MHz is the maximum firing rate for this bias condition. Similar results are observed for $V_{rev} = 5.5,\ 6\,V$ and low gain current.

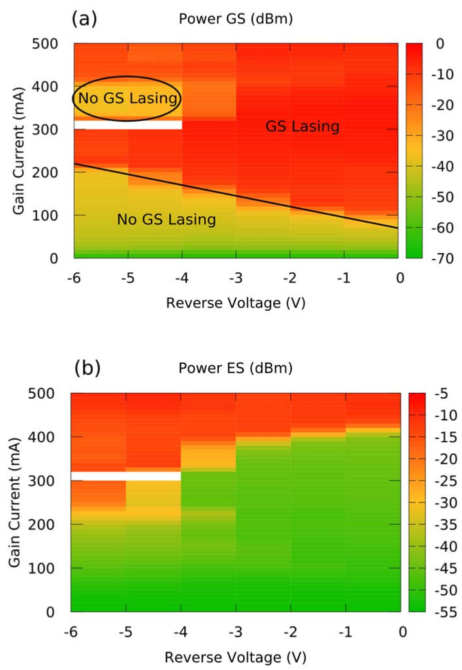

Fig. 2: The effect of gain current and reverse voltage bias on GS (a) and ES (b) power.

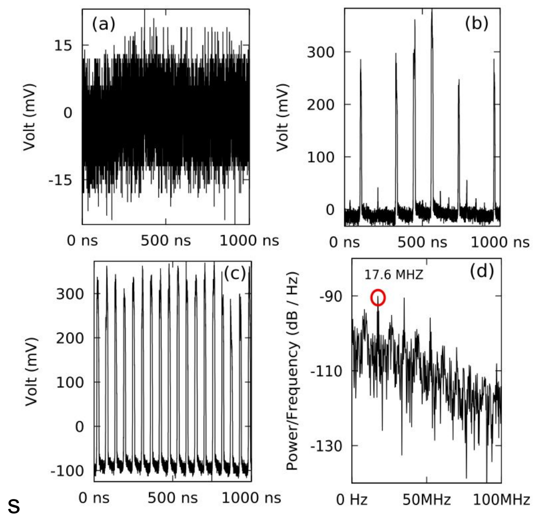

Fig. 3 : Transition from resting to spiking dynamics for the solitary SL laser biased at 5 V reverse voltage. (a) resting state ($\mathbf{I_{gain}}$ = 218 mA), (b) noise – triggered spikes ($\mathbf{I_{gain}}$=219 mA), (c) spiking regime ($\mathbf{I_{gain}}$ = 221 mA). (d) The RF spectrum for $\mathbf{I_{gain}} = \mathbf{219\ mA}$.

For $V_{rev} = 5\,V$ and high gain current, the dynamical transition is again via a Hopf bifurcation, meaning that the neuron acts as a resonator. However, the RF peak is equal to 150 MHz - one order of magnitude higher. This increase can be linked to the increase of ES emision and the dual– waveband dynamics that are responsible for the second GS threhsold [8]. For $\mathrm{V_{rev}} = 4.5, 5.5, 6\ \mathrm{V}$ and high gain current similar qualitative and quantitative results are observed.

Neural excitation of the QD laser with optical triggering

The SL, after its characterization is triggered by the ML which produces GS mode – locked pulses. In Fig. 4, the output of the SL for $\mathrm{V_{rev}} = 5\ \mathrm{V}$, when biased at (a) 218 mA and (b) 409 mA is presented for injection power equal to -9 dBm. Additionally, we examine the effect of ES emission on temporal resolution. This is accomplished, by triggering the SL with GS mode-locked pulses from the ML and measuring the mean full width at half maximum (FWHM) of the generated spikes, for various bias conditions (Fig. 5). Close to the low current lasing threshold (Fig. 5 a), the increase of reverse bias causes a radical decrease starting from 604 ns at 4.5 V, down to 860 ps at 6 V. For $V_{rev} \geq 5\ V$, emission from ES lasing is observed close to the low current GS threshold due to the increase in unsaturated losses. Close to the high current lasing threshold (Fig. 5 b), the ES emission near the GS threshold is enhanced due to higher current injection and an important overall reduction of the temporal width is observed, which weakly varies with V_{rev} , thus revealing the role of ES emission in reducing the temporal width. For $\mathrm{V_{rev}} = 5.5\ \mathrm{V}$, values as low as 500 ps (Fig. 5 c) are observed, which are remarkably close to the state – of – the art FWHM of 200 ps [9].

Conclusion

We provided experimental results from a two – section QD laser operating as a resonator neuron. The contribution of ES emission on the processing speed and the temporal resolution is also investigated by exploiting an extra gain current GS lasing threshold accompanied by increased ES emission. This threshold, which is observed for high reverse voltage, appears due to complex multi-waveband dynamics. The increased ES emission in the second threshold leads to an increase by an order of magnitude of the processing speed (firing rate) and a decrease of the temporal width down to 500 ps. These benefits originating from ES emission, which is enhanced for smaller cavities [10] render the QD laser as a promising candidate for ultra-fast spike processing.

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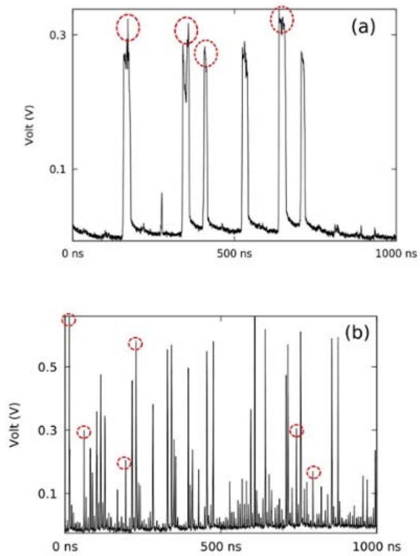

Fig. 4 : Spike events generated by triggering the SL biased at 5 V and (a) 218 mA, (b) 409 mA with mode –locked pulses from the ML biased at 3 V and 400 mA with mean power equal to – 9 dBm. The circles point at the amplitude of various spike events

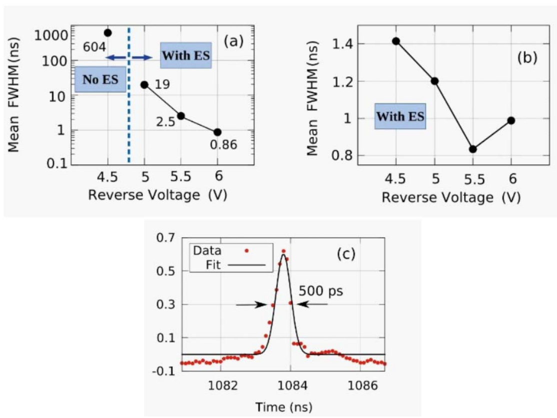

Fig. 5 : Temporal width of spike events as a function of the reverse voltage for SL biased at (a) the low gain current threshold, (b) the high gain current threshold. (c) A spike event with 500 ps temporal width for $\mathbf{I_{bias} = 407\ mA}$ and $\mathbf{V_{rev} = 5.5\ V}$.

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