Artificial optoelectronic spiking neurons with laser-coupled resonant tunnelling diode systems

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Abstract:* *We report a spiking artificial optoelectronic neuron based on a resonant tunnelling diode (RTD) coupled to a photodetector (receiver) and a vertical cavity surface emitting laser (VCSEL, transmitter). We experimentally realize this O/E/O system, and demonstrate optical spiking with a well-defined, adjustable excitability threshold.

Keywords: resonant tunneling diode, VCSEL, excitability, photonic neuron, neuromorphic photonics

I. INTRODUCTION

Over the recent years, application-specific computing hardware has been gathering growing research interest. While the conventional von-Neumann digital CPU is Turing complete, its architecture is not optimal for every kind of computation. This is significant for fields such as artificial intelligence (AI) and deep learning (DL), where specialized hardware such as GPUs and tensor cores offer significant increases in computational performance. By going beyond the von-Neumann paradigm, neuromorphic engineering represents one of such unconventional, novel approaches for AI-tailored chips. By taking inspiration from the workings and structure of biological brains, it holds the promise of energy efficient and high speed execution of AI algorithms. In particular, realization of such systems in the optical domain offers benefits such as increased bandwidths, wavelength-divison multiplexed signalling or even passive computation through physical light-matter interaction. These advantages, together with advancements in PICs and the growing significance of AI, make neuromorphic photonics into a rapidly growing field, with wide array of photonic systems being investigated for use in such brain-inspired systems [1], [2].

II. RTD-BASED ARTIFICIAL OPTOELECTRONIC NEURONS

We report on a spiking optoelectronic artificial neuron based upon a resonant tunnelling diode (RTD) coupled to photosensitive and light emitting elements, which we refer to as PRL (photodetector-RTD-laser, Fig. 1(a)). RTDs are capable of operating at up to THz bandwidths at room-temperatures and may exhibit complex neuron-like dynamics, including excitability and spiking [3], which can be utilized for photonic spiking neural networks (SNNs) [4]. The AlAs/InGasAs RTD used in this work exhibits a highly nonlinear, *N*-shaped *I*-*V* characteristic with negative differential resistance (NDR), starting at approx. $900\,\mathrm{mV}$ (see Fig. 1b). Biasing the device near the NDR (at $880\,\mathrm{mV}$, dashed line in Fig. 1b) and perturbing it with small electrical pulses results in all-or-nothing spiking responses by the RTD. To enable operation with optical signals, the perturbations are provided by a photodetector. Furthermore, the electronic spiking signals from the RTD are converted to the optical domain via bias (RF) modulation of an off-the-shelf VCSEL. It has been previously show that VCSELs are very promising candidates for neuromorphic photonic applications thanks to ultrafast spiking [5], ability to encode and rate-code information into spikes [6], [7] and perform functional tasks such as pattern recognition [8] and image edge-feature detection [9].

Figs. 1(c-f) demonstrate the activation of large amplitude, ns-long excitable responses in the PRL node in response to short optical input perturbations ($3\,\mathrm{ns}$ long pulses). These voltage pulses shown in Fig. 1(c) are produced by an arbitrary waveform generator and encoded into the intensity of the optical input signal input to the PRL by using a Mach-Zehnder modulator. It is clearly visible that the PRL node exhibits a very well-defined excitable threshold for all-or-nothing spiking responses. By varying the RTD bias voltage U_S (Figs. 1(d-f)), the threshold for spike firing can be adjusted, meaning that the amplitude of spikes that is sufficient for spike triggering is different as well. Fig. 1(d) shows operation furthest from the threshold, while Fig. 1(f) shows operation closest to the threshold. Therefore, we confirm the existence of excitability in the PRL node,

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as well as a well-controlable excitable threshold and operation of the node in an O/E/O architecture, defining an artificial optoelectronic spiking neuron with optical I/O terminals. We will also present our experimental findings demonstrating the successful performance of the reported optoelectronic neuron in different tasks, i.e. coincidence detection and XOR logic operation, using spiking signals for operation. Furthermore, we achieved spiking with refractory period $T_{ref} \approx 90\,\mathrm{ns}$, defining the upper limit of node spiking rate $\frac{1}{T_{ref}} \approx 10\,\mathrm{MHz}$. With spiking speed determined by the optoelectronic circuit parameters, further optimization is expected to yield spiking in PRL nodes at >GHz rates, as highlighted by recent numerical studies [4].

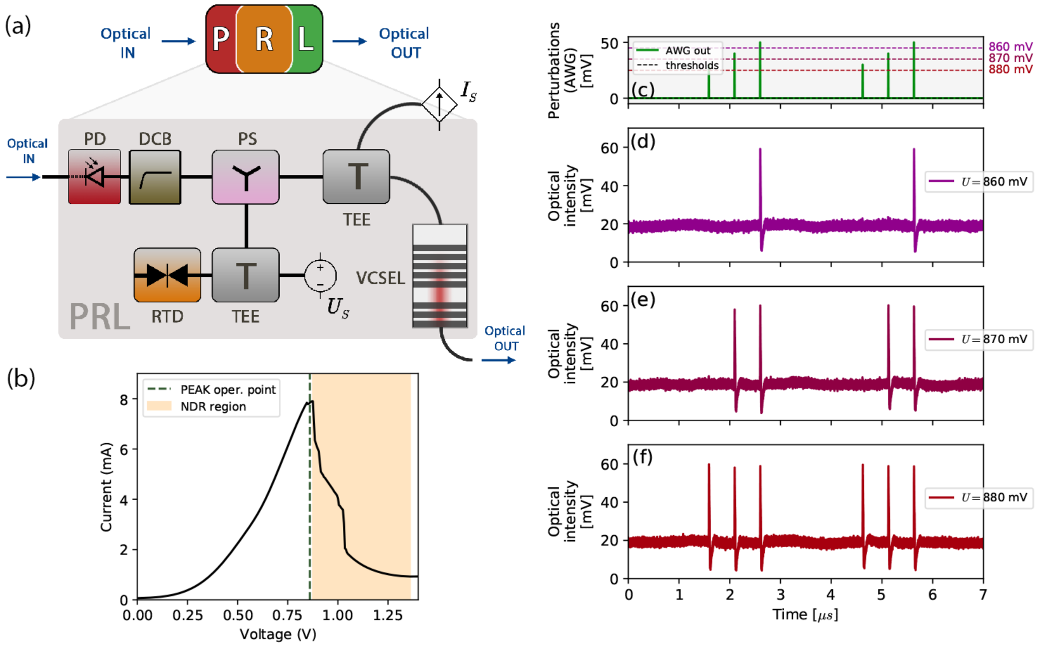

Fig. 1. (a) Electronic circuit layout of the PRL node, with the RTD coupled to a $1550\,\mathrm{nm}$ VCSEL (additional bias I_S) and PD (750-1650 nm photodetector); DCB - DC block; PS - power splitter; TEE - bias tee. (b) The highly nonlinear N-shaped *I-V* of the RTD. (c) Train of input perturbations (shown as the source waveform), that are used to modulate the optical input into the PRL. For various bias values of (d) $860\,\mathrm{mV}$, (e) $870\,\mathrm{mV}$ and (f) $880\,\mathrm{mV}$, we can see how the steady state of the RTD is gradually shifted closer to the *I-V* peak (threshold), resulting in spike activation with lower amplitude input perturbations.

III. SUMMARY

We report a spiking O/E/O neuron based on a PD-RTD-VCSEL system. We experimentally validate the existence of a well-defined, controllable spike firing threshold in this system. Our demonstrated approach readily permits optical interlinking, offering exciting prospects for implementations in photonic spiking neural networks for light-enabled neuromorphic computing.

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