A Receiver-less Link for Excitable Laser Neurons: Design and Simulation

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***Abstract*—Many-to-one connections are difficult to implement in excitable laser neurons. We design and simulate an O/E/O receiver-less link from photodetector to laser that accepts many spiking inputs (large fan-in) without significant bandwidth degradation.**

I. INTRODUCTION

Recently, there has been a surge of interest in the processing abilities of dynamical lasers [1], [2]. Many of these models have forged a correspondence between biological spiking neurons—commonly modeled in computational neuroscience—and lasers [3]. Implementing these devices in a scalable system, however, requires cascadability, fan-out, and well-isolated input/output ports [4]. These restrictions are problematic for photonic devices with optically injected inputs. Networks would require complex wavelength conversion, sorting and routing, consuming significant energy and space. In addition, devices with direct optical injection have difficulty accepting many inputs simultaneously (large fan-in), which is a critical property in neural network models. These complications would offset many of the advantages of using optical physics over more traditional RF electronic approaches.

We investigate a receiver-less link from photodetector to laser that allows for cascadability and large signal fan-in by temporarily converting the signal to the electronic domain. The junction would allow for processing systems that are both fast (∼GHz) and exhibit dense interconnectivities (∼100 fan-in) in a suitable wavelength division multiplexed (WDM) ring network [5]. This regime of processing is beyond the physical capabilities of electronics and could find use in the complex, real-time processing of the RF spectrum.

This junction was initially part of the structure proposed in [6]. Included here is a much more detailed physical design and simulation of the photodetector and metal junction. We also show that this system emulates a synaptic variable, an important processing parameter in computational neuroscience. We demonstrate that the bandwidth (or synaptic time constant) can be engineered over a wide range via the capacitance of the metal bridge.

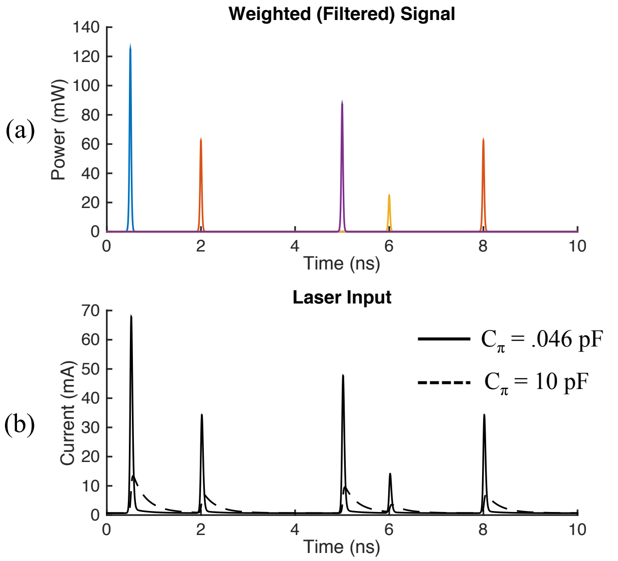

Fig. 1. (a) Pulses from other excitable lasers (FWHM ≈ 40 ps) of various wavelengths that are incident on the photodetector from a WDM network. Each color represents a different wavelength λ_i. It is assumed that the photodetector responsivity profile (.81 A/W) is fairly flat across the spectrum. (b) the resulting current response as it travels into the laser. With low capacitance, the pulses experience only minor distortion, but with large capacitance, the junction acts as a low pass filter (i.e. a large synaptic time constant). A full SPICE model was used for simulation.

II. DESCRIPTION

The design for an excitatory junction [6] connects an N-side photodetector (PD) directly to the N-side of a laser. Multiple pulses of various wavelengths are incident on the photodetector, which provides the role of summation and converts signals to current pulses. A schematic of the junction is shown in Fig. 2, including a superimposed image of the parasitic circuit model. A simulation of multiple input pulses is shown in Fig 1. The laser is pumped with a stable current source I_p, while the PD is reverse biased with a large voltage (>5 V) to offset the influence of I_p. The junction is kept fairly short (∼100s of μm) to avoid transmission line effects. Unlike typical circuit models, current is the dominant information carrier in this receiver-less link.

There is an RC time constant associated with this junction, but since the signal pathway is complex, the resistances and capacitances are not strictly additive. The most influential parameters are the capacitance of the metal wire C_π and the contact resistances R_{PD}, R_L. The metal wire capacitance C_π is the easiest to adjust lithographically, either by modulating the height of the oxide layer or the area occupied by the metal bridge to change the characteristics of the junction. Other RF engineering techniques, such as fabricating adjacent grounding pads to the metal bridge, can further increase the capacitance.

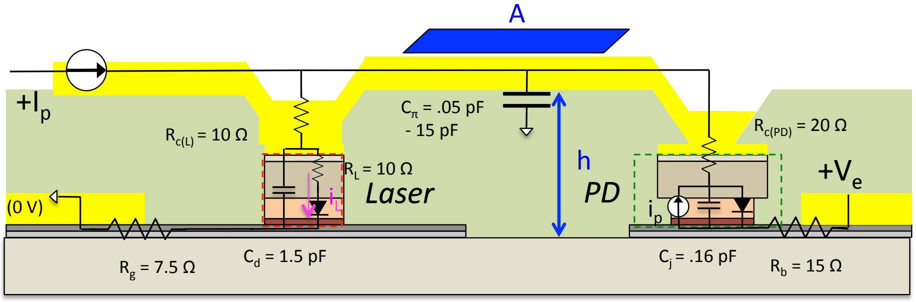

Fig. 2. Schematic of photodetector laser system with equivalent circuit model of the wire junction. Inputs of multiple wavelengths are incident on the photodetector, generating an input current i_p. This travels across the metal junction, injected as current i_L in the laser. $R_c(L)$, $R_c(PD)$ are the contact resistances, R_L is the active region resistance, C_j the junction capacitance, and R_b, R_g are drain resistances. The wire capacitance C_π can be adjusted based on the the height h of the oxide layer and area A of the wire bridge.

A common first order model for synaptic dynamics is [7]:

$$\frac{ds}{dt} = -\frac{s}{\tau} + I(t)$$

where $I(t)$ is the input, τ is the time constant and $s(t)$ is the synaptic variable. A neuron will typically sum signals from multiple synapses $s_i(t)$ and receive them as inputs. This behavior takes place independently of temporal integration in the soma. The synaptic time constant thus has a correspondence with this circuit's RC time constant.

Various synaptic variables are useful for different processing contexts. For example, short time constants are necessary for spike-timing recognition, while longer synaptic variables find use in spike-frequency models [8]. A junction that can be designed with different time constants would be important for the emulation of these diverse behaviors.

III. RESULTS AND DISCUSSION

Simulations were performed using an equivalent circuit model of the signal pathway. Multiple incident pulses with full width half maximums (FWHMs) of 40 ps (based on [6]) are shown in Fig. 1. The PD is assumed to have a flat responsivity of .81 A/W. As seen by the impulse responses in Figure 1(b), the junction is simple enough to be characterized by a single synaptic (or RC) time constant. As shown in Fig. 3, if the junction is optimized with low capacitance, through i.e. a thick ($\sim$5 μm) oxide layer, the input pulses experience only minor distortion ($\sim$30 ps time constant), suitable for correlative temporal processing. Nonetheless, a junction with significant capacitance (i.e. $C_\pi = 15$ pF with a thin oxide layer of $\sim$.2 μm and RF engineered capacitance) leads to an increase in the effective synaptic variable to $\sim$600 ps, large enough for neural rate encoding models [8].

We have described, designed, and simulated an optoelectronic junction that can accept many inputs with a lithographically controllable bandwidth, playing the analogous role of a synapse in biological neural network. It allows both (i) large fan-in and (ii) the emulation of a synaptic variable. Through a detailed physical model, we have investigated fabrication and design, showing that the synaptic variable can be adjusted by changing the capacitance of the metal bridge. An optoelectronic synapse solves many of the problems associated with scalability, and may provide a basis for the formation of practical, integrated laser neural networks.

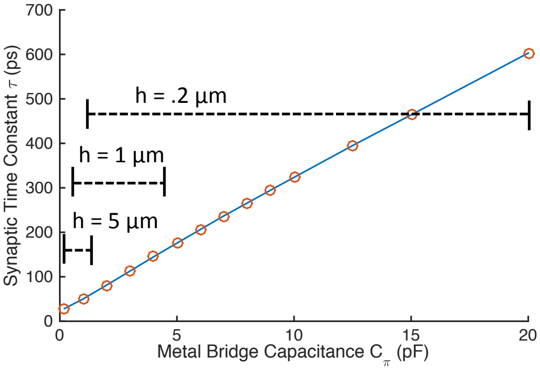

Fig. 3. Synaptic (RC) time constant as a function of metal bridge capacitance, simulated using the full circuit model. A small capacitance ($\sim$.05 pF) can be achieved with a thick oxide layer ($\sim$5 μm) and small area wire junction (.01 mm^2). A large ($\sim$20 pF) capacitance can be achieved via a thin oxide layer ($\sim$.2 μm) and RF engineered capacitance. Also shown are the ranges of capacitances that can be achieved with different heights (.2 μm, 1 μm, 5 μms) assuming an areal range of .01 to an effective RF engineered area of .12 mm^2. The time constant can be engineered from 30 ps → 200 ps.

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