Optoelectronic III-V nanowire implementation of a neural network in a shared waveguide

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***Abstract*—Neural node components consisting of III-V nanowire devices are introduced. This allows for the construction of a small footprint specialized neural network. A broadcasting strategy is developed which removes the need for inter-node wiring. As a model system, an insect brain navigational circuit is chosen and successfully emulated using the introduced nodes and network architecture. The results are based on electronic transport simulations in each device as well as finite-difference time-domain simulations for the broadcasting of optical signals.**

***Index Terms*—neural network, III-V nanowire, phototransistors**

I. Introduction

A large energy expenditure, as well as a complexity issue in bio-inspired processing networks, are the large number of inter-component connections [1], [2]. Optical communication is in principle superior for this task since information can be transmitted quickly and at low energy cost. However, the large footprint of regular optoelectronic devices prevents technologies like neuromorphic photonics [3] to realize their full potential.

In this work we design a neural network with nanoscale nodes, allowing the whole network to be placed inside a single shared waveguide. Broadcasting of optical signals is used to transmit information both among the nodes inside each layer (in case of recurrent connections) and to subsequent layers. The weights needed to define the neural network are set by the system geometry. This strategy allows us to remove all inter-device wiring or waveguiding and drastically reduce the total footprint.

This work was supported by the Swedish Research Council (VR) and NanoLund FutureThemes. SH was supported by the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program (grant agreement no. 714599).

II. Model system and methods

As an interesting test case we implement an insect brain navigational circuit. Such a circuit has recently been described in great detail in [4], where a recurrent computational neural network was constructed to demonstrate its functionality, following closely the insect brain anatomy. This network was shown to be able to navigate using path-integration. Here we demonstrate a successful implementation of this circuit using our novel communication strategy and nanoscale components.

The node component that we propose is based on III-V nanowire technology. It is capable of receiving, weighing and adding optical signals, processing the electronic result through a non-linear activation function, and finally outputting a resulting optical output signal. A schematic drawing is presented in Fig. 1a) where a branched nanowire is shown. This type of structures has already been realized using nanowire bottom-up growth [5]. Doping design as well as heterostructure engineering can be used to accommodate the subcomponents of each device: two npn phototransistors on the wide part of the nanowire and one LED on the branch, as detailed in Fig. 1a). The npn phototransistors act as photodetectors for incoming signals [6], while the LED produces the resulting output signal. Each transistor is operated in a floating base configuration and can be made sensitive to different wavelengths by bandgap engineering. We show how the circuit formed by the subcomponents effectively acts as a nonlinear activation function with shape being close to sigmoidal.

We model the transport of electron and holes of each subcomponent using a drift-diffusion equation with thermionic boundary conditions, to accommodate for the heterojunctions. A model representation is then made of both the transistors and

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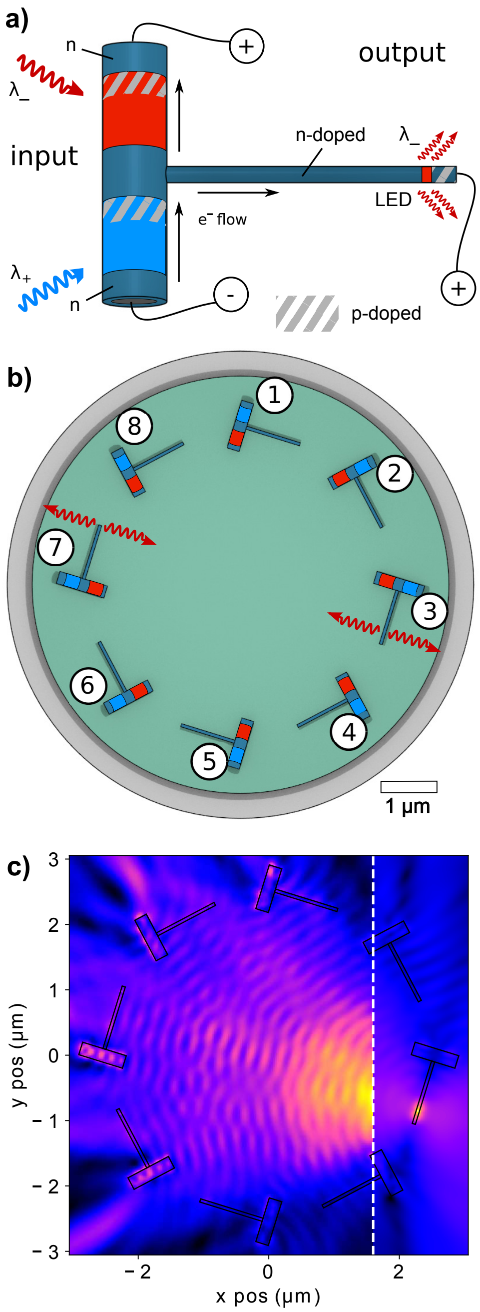

Fig. 1. a) III-V nanowire node component. The color (blue and red) indicate low bandgap regions sensitive to absorption of the input signals. By dopant engineering two npn phototransistors are defined in the wide part of the nanowire and an LED in the branch. b) Drawing to scale of the network part consisting of 8 nodes. The nodes transmit output signals both inwards and outwards. c) FDTD modeling results. Intensity distribution inside the shared waveguide for a signal emitted by device 3 at 830 nm. The dashed white line indicates logarithmic scaling of the values on its right-hand side.

the nanowire LED. This allows us to map the whole device of connected subcomponents onto a circuit model that we solve using standard software (LTspice).

For this test case, we choose the most central part of the circuit described in [4], consisting of 8 nodes in a ring configuration similar to our proposal shown in Fig. 1b). This recurrent layer is a heavily interconnected part of the navigational circuit: Each device is coupled with individual weights to all other nodes in the ring, as well as to the next layer in the neural network (not included in this work). This requires a large number of interconnections which is elegantly solved by our broadcasting communication strategy. All devices transmit their output signals into the shared waveguide, both inwards towards its layer peers and outwards to drive the signal through the subsequent layers of the neural network of [4].

III. Results

For the nanoscale node device, the circuit simulations yielded activation functions that were in close agreement to the ones used in [4] for the specific nodes in the ring configuration.

To calculate the geometric weights, the emission and absorption of devices in the network of Fig. 1b) was simulated using a finite-difference time-domain (FDTD) approach [7]. In Fig. 1c) we exemplify our results by showing how the fields for a signal at 830 nm are distributed from a dipole emitter located in the branch of device 3. The opposite device 7, has the largest weight and that a gradual decline in coupling strength is expected for the devices closer to the emitter. These features are in good correspondence to the requirements described in [4].

As a final test, we replaced the activation functions and the weights of the computational model of [4] with those extracted from the modeling of our implementation here. We show that the navigational circuit functions well after these modifications.

IV. Conclusions

In this work we present an optically connected neural network with nanoscale nodes. The nodes are standalone units with nonlinear activation functions that receive and output optical signals. These small nodes allow us to place the whole network inside a shared waveguide which removes the need to inter-device wiring or waveguiding and drastically reduces the total footprint. We show that the performance of these components is sufficient for the task of navigation, and that the power efficiency is on par with biological neural circuits.

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