

Solitonic Neural Network: a novel approach of Photonic Artificial Intelligence based on photorefractive solitonic waveguides

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Abstract. Neuromorphic models are proving capable of performing complex machine learning tasks, overcoming the structural limitations imposed by software systems and electronic neuromorphic models. Unlike computers, the brain uses a unified geometry whereby memory and computation occur in the same physical location. The neuromorphic approach tries to reproduce the functional blocks of biological neural networks. In the photonics field, one possible and efficient way is to use integrated circuits based on soliton waveguides, ie channels self-written by light. Thanks to the nonlinearity of some crystals, propagating light can write waveguides and then can modulate them according to the information it carries. Thus, the created structures are not static but they can self-modify by varying the input information pattern. These hardware systems show a neuroplasticity which is very close to the one which characterize the brain functioning. The solitonic neuromorphic paradigm this work introduces is based on X-junction solitonic neurons as the fundamental elements for complex neural networks. These solitonic units are able to learn information both in supervised and unsupervised ways by unbalancing the X-junction. The storage of information coincides with the evolution of structure that changes plastically. Thus, complex solitonic networks can store information as propagation trajectories and use them for reasoning.

1 Introduction

Neuromorphic science was developed to reproduce the learning mechanism typical of the biological brain [1]. Relying on a logic of parallel computation, the brain in fact can carry out an extremely large number of calculations while requiring very low energy [2]. It is also able to carry out learning and storage operations contextually: learning a piece of information means processing and storing it through structural geometric changes [1]. In recent years, we have shown how photorefractive crystals, due to their saturating nonlinear refractive index, are able to offer a learning strategy that is very close to the biological one [3]: learning and storing become two contextual operations that take advantage of the plasticity of the refractive index.

2 Episodic Solitonic Recognition

A soliton X junction is the intersection between two waveguides self-written by two laser beams that do not diffract (spatial solitons) within a material with saturating nonlinearity (as Lithium Niobate). Based on intensities of the writing beams, the structure of the solitonic neuron could be balanced (symmetric) or unbalanced (asymmetric): in the first case (figure 1a) a third beam, the information signal beam, is divided perfectly 50/50 in both output channels (figure 1b). In the second case, the intensity of one beam is higher compared to the other, therefore the junction is unbalanced in favour of one of the two outputs, as shown in figure 1(c). Information processing in a nonlinear manner was successfully accomplished in thin layers of Lithium Niobate as shown in Figures 1d-e (balanced solitonic neuron) and 1f (unbalanced solitonic neuron).

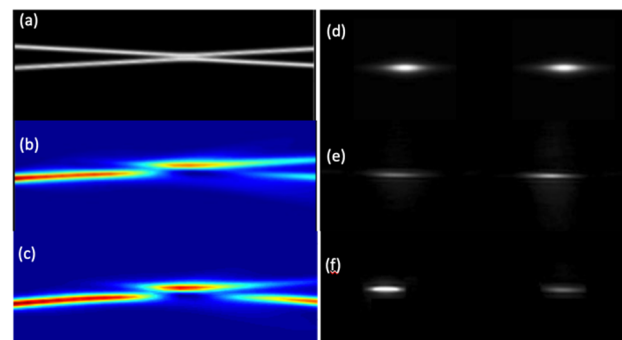


Fig. 1. X-Junction solitonic neuron: (a) shows a simulated symmetrical structure (out of scale) according to which (b) the signal is equally splitted towards both outputs. If the X-Junction is not symmetrical, (c) the majority of signal follows the higher refractive index contrast channel. It is reported the light distribution on output face of the crystal for balanced writing beams (d), for balanced signal beam (e) and for unbalanced signal beam (f).

This type of neuron is capable of both supervised and unsupervised learning [4], and, just as is the case with biological neurons [5], it constitutes the fundamental unit of complex learning systems: Solitonic Neural Networks (SNNs). We have recently shown that the plasticity of the refractive index of certain nonlinear crystals allows these networks to self-modify their structural geometry in accordance with received information. In this way, each memory is saved in the form of a change in refractive index. An SNN network is able to learn and recognize according to what modern psychology calls episodic intelligence [6].

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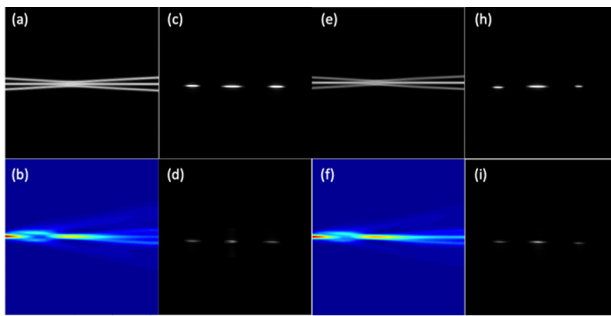


Fig. 2. A balanced 3x3 solitonic neuron (a); the signal light is equally split towards all the three outputs (b). Experimental balanced 3x3 solitonic neuron (c) and signal propagation inside of it (d) (light at the output face of the crystal). If the central channel is highlighted (e), then almost all the light from the side channels collapses into it (f). Experimental results of unbalanced 3x3 solitonic neuron.

Starting from these structures, it is possible to build more complex solitonic neural systems in which the neuron is characterized by a larger number of channels. We have shown theoretically that this configuration makes it possible to lower the amount of energy required to switch output channels [7].

This new type of neuron is similar to the previous 2-channel X-Junction with the addition of a further channel in the centre between the two pre-existing ones, as shown in the fig.2. The central channel can be used as a control to turn off and on the neuron itself: by increasing the intensity of its writing beam above a threshold value, the light collapses into it, stopping propagation in the other two. If the intensity is zero, however, one returns to the two-channel case. For intermediate values, it is possible to distribute the information signal in all three channels.

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