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CMOS IMPLEMENTATION OF SPATIO-TEMPORAL FILTERS WITH CELLULAR NEURAL NETWORKS

BY

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Abstract. Cellular Neural Networks (CNN’s) are a type of analog parallel architectures which consist of arrays of identical linear cells identically coupled by means of cloning templates can exhibit spatio-temporal filtering and pattern formation. In this paper we present a transistor level implementation of such a structure and study its behaviour for symmetric templates of first and second order. The roles of the cell structure and the connection template are discussed and models for the spatial modes dynamics are presented.

Key words: CMOS implementation, analog parallel architectures; Cellular Neural Networks; spatio-temporal dynamics; spatial filters.

1. Introduction

Various architectures of Cellular Neural Networks have been and are still studied for their interesting spatio-temporal dynamic behaviors including pattern formation similar to those described in (Turing,1952). The spatio-temporal dynamics in various architectures of CNN’s has been studied for both 1-D and 2-D cases by many researchers (Chua & Yang, 1988; Shi, 1998; Roska,

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1995). These architectures basically consist of an array of identical and identically coupled cells within a neighborhood characterized by its dimension and weights of the interconnection template. The specific feature of some of these architectures is that of being able to exhibit instabilities leading to patterns due to the development and competition of unstable spatial modes. It has been shown that the analysis of such behaviors, useful for filtering applications and in pattern formation, can be made in the case of piecewise linear cells using the decoupling technique (Goraş & Chua, 1995). This technique mainly consists of a change of variable, the new variables being the amplitudes of the spatial modes, dependent on the boundary conditions. In this way, the transformed differential equations corresponding to each spatial mode which are now decoupled may have unstable solutions, the new variables in these equations being the amplitudes of the spatial modes of the array. The competition of the unstable spatial modes will eventually lead to a pattern.

In the unstable case, the two mechanisms that were used to limit the dynamic evolution were the nonlinearity of the cell characteristics or the transient "freezing" before any nonlinearity has been reached. In the last case the CNN behaves as a spatial time variable filter dependent on the moment the transient has been stopped.

2. The Architecture

The principle of the 1D array studied in this paper is based on the architecture shown in Fig. 1. It consists of linear cells represented by admittances coupled by means of voltage controlled current sources (vccs's) over a neighborhood N_r of radius r.

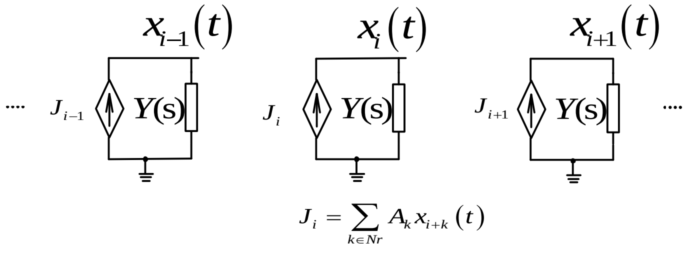


Fig. 1 – Architecture of an 1D array.

The circuit is autonomous, its evolution being determined by the initial conditions. In the following we briefly review the main results on such architectures presented in several papers including (Goraş, 2009). The cells are characterized by admittances of the form:

$$Y(s) = \frac{Q(s)}{P(s)} = \sum_{l=0}^{q} q_l s^l \Big/ \sum_{n=0}^{p} p_n s^n , \tag{1}$$

where $Q(s)$ and $P(s)$ are polynomials in the variable s.

The (coupled) differential equations that describe the circuit are:

$$Y(s)x_i(t) = \sum_{k\in Nr} A_k x_{i+k}(t). \tag{2}$$

The above set of differential equations can be solved using the same decoupling technique as in the algebraic or homogeneous template case. The technique consisting of the change of variable

$$x_i(t) = \frac{1}{M}\sum_{m=0}^{M-1}\Phi_M(i,m)\hat{x}_m(t), \tag{3}$$

where: $\Phi_M(i,m)$ are orthogonal with respect to the scalar product in C^M can be applied as well in the general case presented above.

For boundary conditions of ring type, $\Phi_M(i,m) = \mathrm{e}^{\mathrm{j}2\pi im/M}$ and $\Phi_M(i+k,m) = \mathrm{e}^{\mathrm{j}2\pi km/M}\Phi_M(i,m) = \Phi_M(k,m)\Phi_M(i,m)$. Thus, the action of the spatial operator A on $\Phi_M(i,m)$ gives

$$\sum_{k\in Nr} A_k\Phi_M(i+k,m) = K_{A(m)}\Phi_M(i,m), \tag{4}$$

where

$$K_A(m) = \sum_{k\in Nr} A_k \mathrm{e}^{\mathrm{j}2\pi km/M} = \sum_{k\in Nr} A_k\Phi_M(k,m). \tag{5}$$

It is apparent that $\Phi_M(i,m)$ are eigenfunctions of the spatial operators represented by the A template and the integro-differential operators KA(m) behave as the corresponding spatial eigenvalues which are complex in general and depend on the parameters of the neighborhood and on the mode. The decoupled equations valid for each spatial mode m are

$$Y(s)\hat{x}_m(t) = K_{A(m)}\hat{x}_m(t) \quad m = 0,1,\ldots,M-1, \tag{6}$$

and the characteristic polynomial of the m-th mode is now

$$R(s) = Q(s) - K_{A(m)}P(s). \tag{7}$$

For templates that satisfy $A_k = A_{-k}$, and for a first order neighborhood, $K_A(m)$ has the form:

$$K_A(m) = \sum_{k=1}^{1} A_k \cos\frac{2\pi km}{M} = 2A_1\cos\frac{2\pi m}{M}, \tag{8}$$

and determines the spatial filter characteristic. Thus if A_1 is positive/negative a low-pass/high pass spatial filtering are obtained respectively.

Similarly, for a symmetric second order neighborhood,

$$K_A(m)=\sum_{k=1}^{2} A_k \cos\frac{2\pi km}{M}=2A_1\cos\frac{2\pi m}{M}+2A_2\cos\frac{4\pi m}{M}. \qquad (9)$$

From the above relation it follows that second-order spatial filters can be created by using templates either with first and second-order neighbourhood, or only with second-order neighbourhoods.

For $A_1 > 0$, $A_2 > 0$, low-pass filters or band-pass filters can be obtained while for $A_1 < 0$, $A_2 < 0$, high-pass filters or band-stop filters can be designed.

The practical implementation of the system need a lot of connections and in order to minimize the number of connections for the second-order filters, band-pass and band-stop filters, the first-order connections have been neglected ($A_1 = 0$).

Since the network is designed to be unstable, its dynamics needs to be stopped before any of the cells reaches saturation, so the obtained spatial filter has a selectivity variable in time.

3. Implementation of the Architecture

The network that has been designed contains 16 cells (connected with first and second-order neighbourhoods, like in Fig. 2) and I/O circuits for loading and reading serial voltages on the network capacitors.

Because of the limited number of available pins we have chosen serial loading and reading as solution for loading the network and reading the capacitor voltages of the system, both implemented with the same clock signal and initialisation.

The I/O circuits are composed of two shift registers, one for loading and one for reading capacitors, an output buffer circuit and the bias circuit of OTA’s and comparators.

The network functionality comprise the following steps:

1. network configuration – all OTAs and interconnections between cells are configured; for this step three control signals are necessary;
2. charging the network – capacitors are serially loaded from a digital memory via a D/A converter; for this step two control signals are necessary;
3. processing stage (or free evolution) – the network is designed unstable such that certain spatial modes will be unstable; they will increase with time starting from the initial conditions;
4. freezing the network – the OTA outputs are disconnected from the capacitors, using a command signal, that will remain charged with the filtered spatial signal unconnected;
5. reading output data – reading voltage on capacitors;

Both digital memory and controll signals of the network have been generated using an FPGA with D/A and A/D converters.

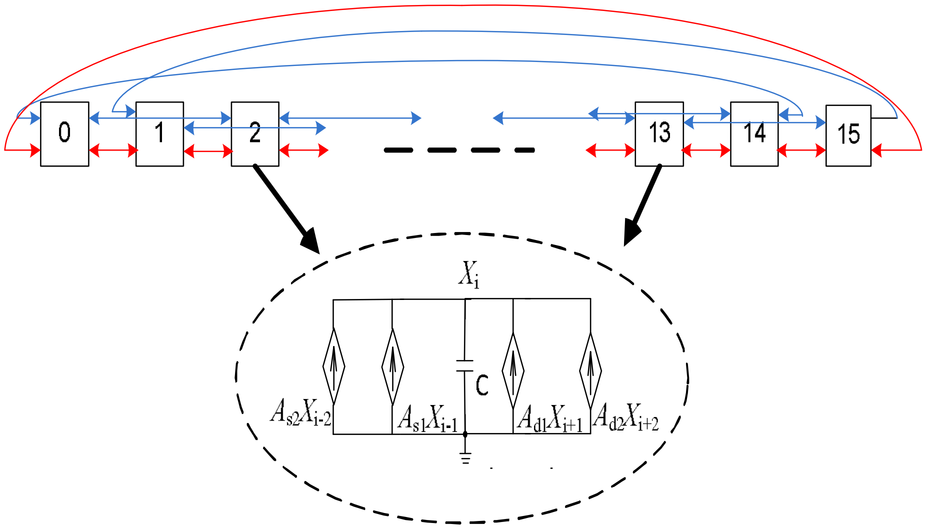


Fig. 2 – Sketch of the 16 cells of CNN.

The voltage controlled current sources have been implemented with OTAs, with transconductances represented by the coefficients A_1 and A_2.

To obtain a minimum occupied area, the chosen OTA's have the simplest structure and the lowest possible power consumption which satisfy a compromise between band, linearity and consumption. A simple structure of an OTA is shown in Fig. 3: to implement a high-pass spatial filter and a band-stop filter, the current sources must have a negative transconductance. That is achieved by inverting the OTA inputs.

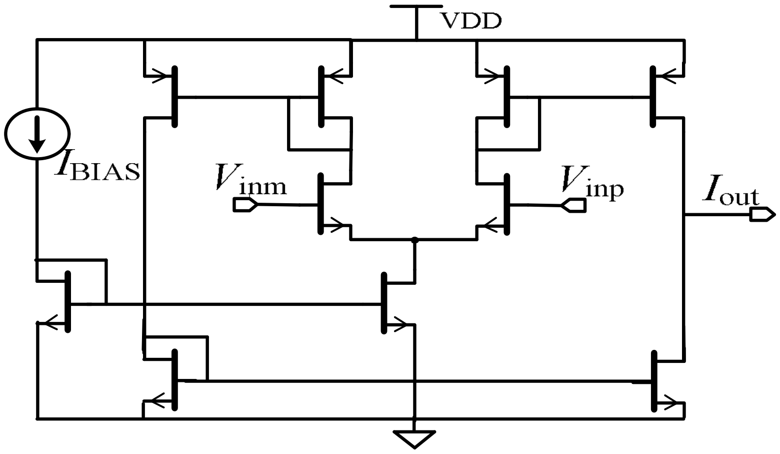


Fig. 3 – OTA used for cells interconnections.

By substituting the voltage controlled current sources with OTAs it follows that 4 OTAs for each cell are necessary, which leads to a rather large occupied area and a higher consumption.

Using first-order connections we can achieve low-pass and high-pass spatial filters. Using only second-order connections, we can obtain band-pass and band-stop filters. Because of the above, we can remove two OTAs and multiplex the connections of the first-order neighbouring cells with the connections of the second-order neighbouring cells.

The cell also contains: a common drain transistor which takes over the voltage by the capacitor and provides it at the output, and a detection circuit of the saturated input of the OTA that can determine the maximum selectivity that is obtained for every type of spatial filter.

The complete schematic of a cell is shown in Fig. 4.

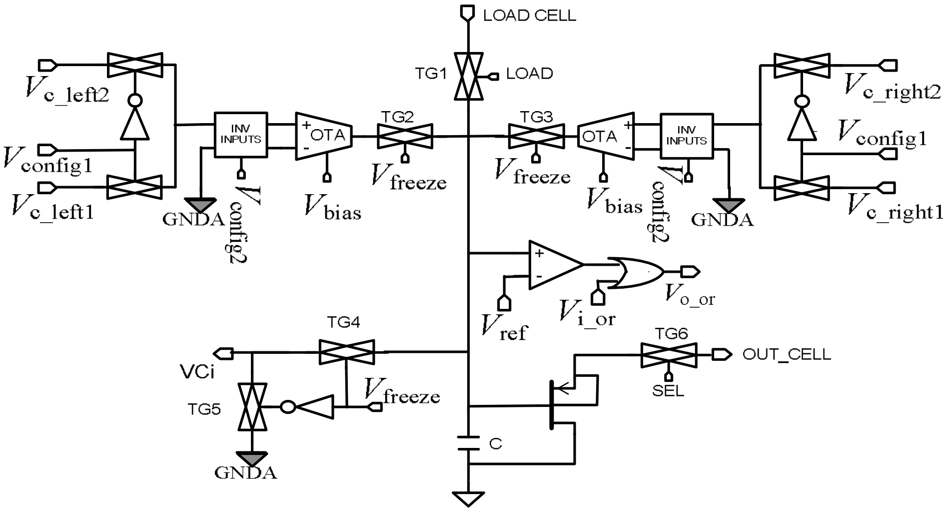


Fig. 4 – The CNN cell.

The network was implemented using AMSH18A6 technology and is part of the first implementation using the ARPIC (Academic Research Platform for Integrated Circuits) platform.

The area occupied by a cell is 231 × 96 µm and the area occupied by the entire network of test is 1,055 × 705 µm (Fig. 5). Most of the cell area is occupied by OTAs, capacitors and interconnection paths. A negligible area is occupied by the control block.

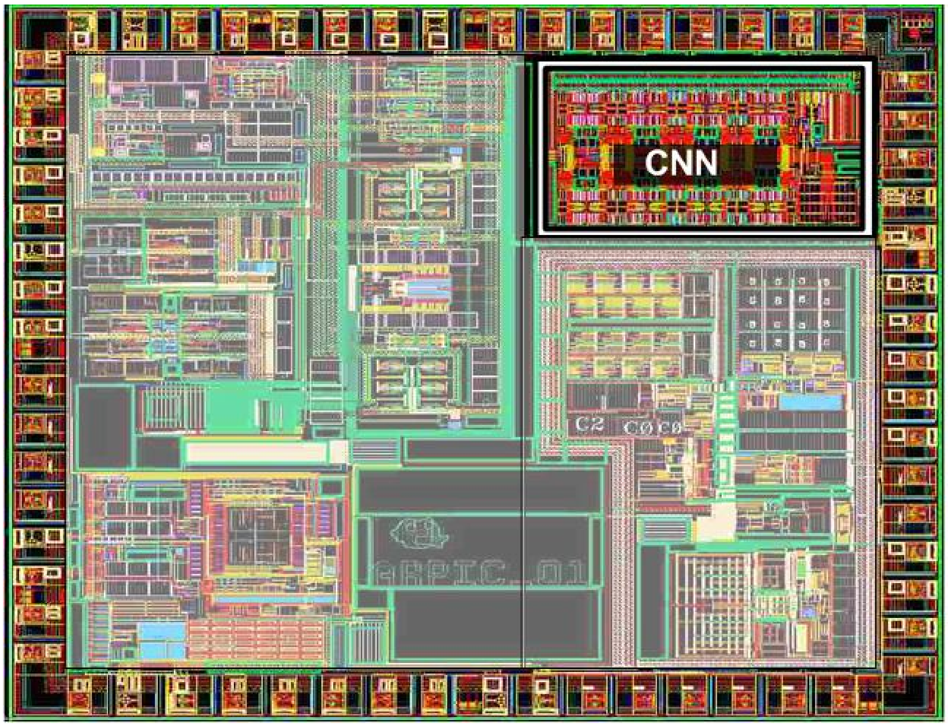


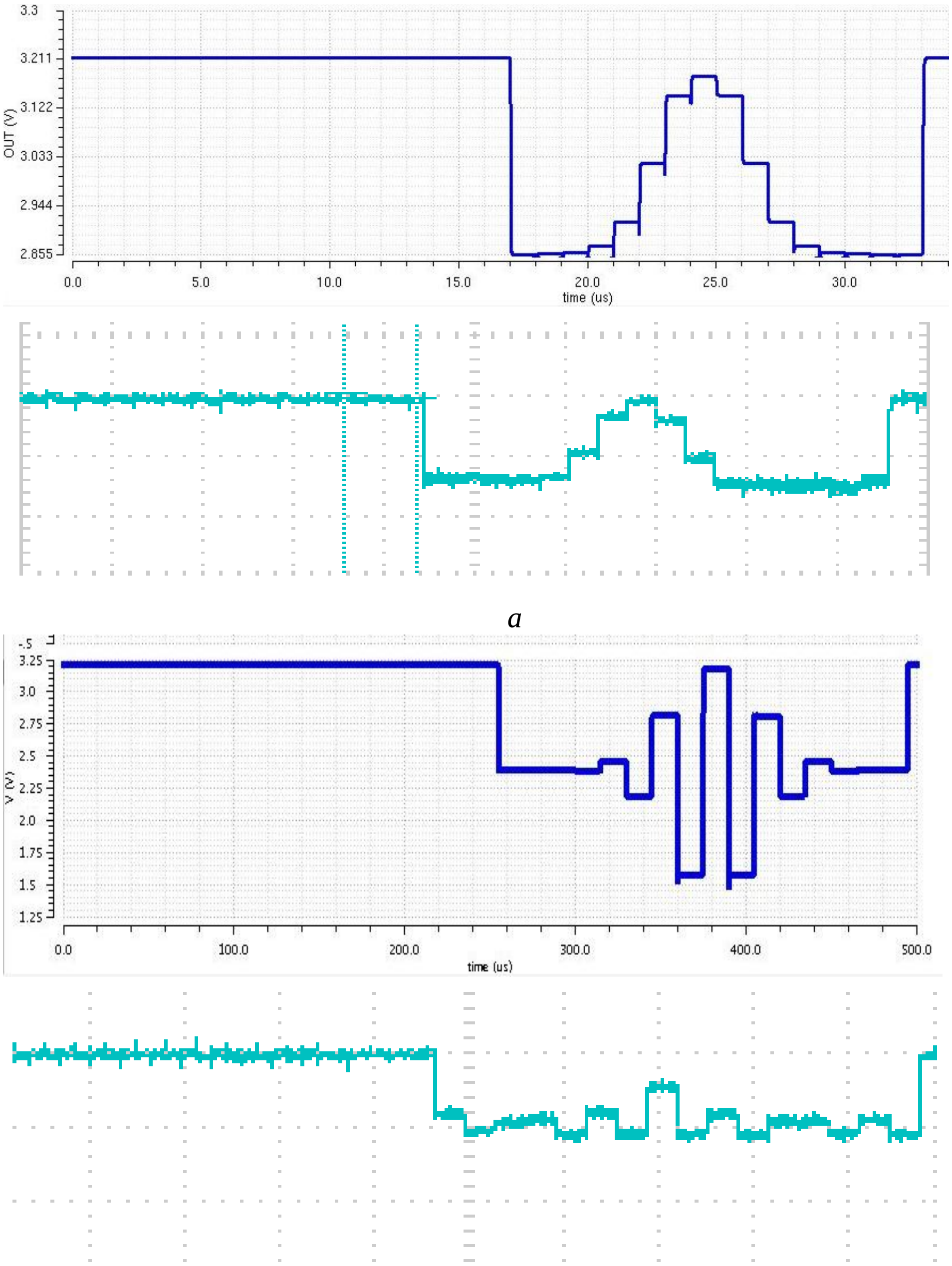
Fig. 5 – Layout of the CNN in the test integrated circuit.

4. Simulation and measurement results

To highlight the frequency characteristic of a spatial filter, the network was loaded with an impulse of amplitude of 150 mV, applied on the capacitor of the 8th cell. Thus the 8th cell will have an initial state equal to 150 mV, the rest of the cells will have their initial states equal to 0.

If at different moments in time we “freeze” the network and calculate the discrete Fourier transform of the cell’s states, we obtain the frequency characteristic of the filter at different moments in time. Thus we obtain the spatial-temporal character of the network. “Freezing” the network after an evolution duration of 300 ns, so that none of the cells reaches saturation, at the buffer’s output we obtain the voltages from the capacitances of the cells connected in series that are synchronised with the clock signal so that after each period of clock the voltage provided is that on a certain capacitance.

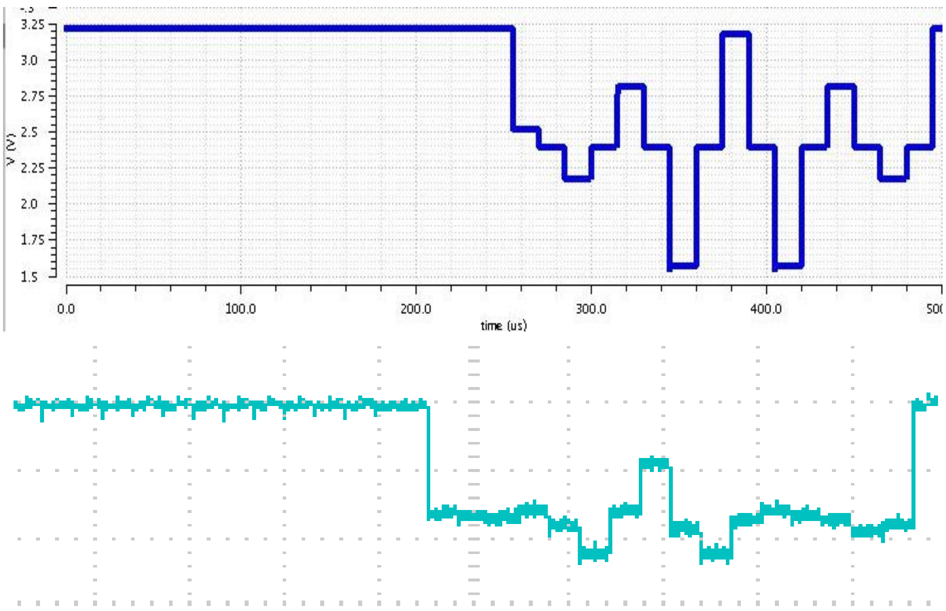
The simulation and measurement results are comparatively presented in Fig. 6 for low – pass filter and high – pass filter and in Fig. 7 for band – pass filter and band – stop filter. The obtained spatial frequency characteristics are presented in Fig. 8.



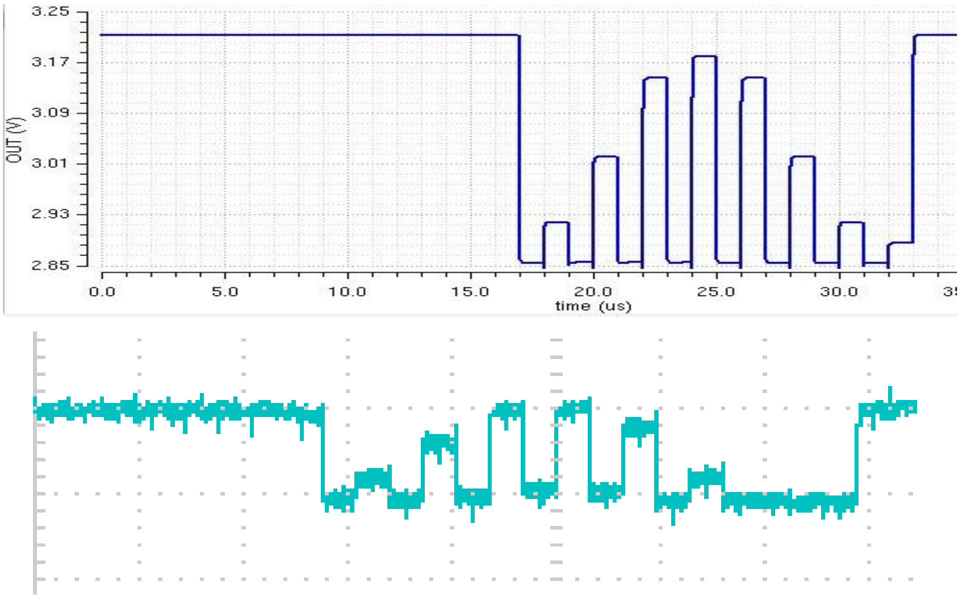
a

b

Fig. 6 – Simulation *vs*. measurement for spatial filters: *a* – low – pass filter, *b* – high – pass filter.

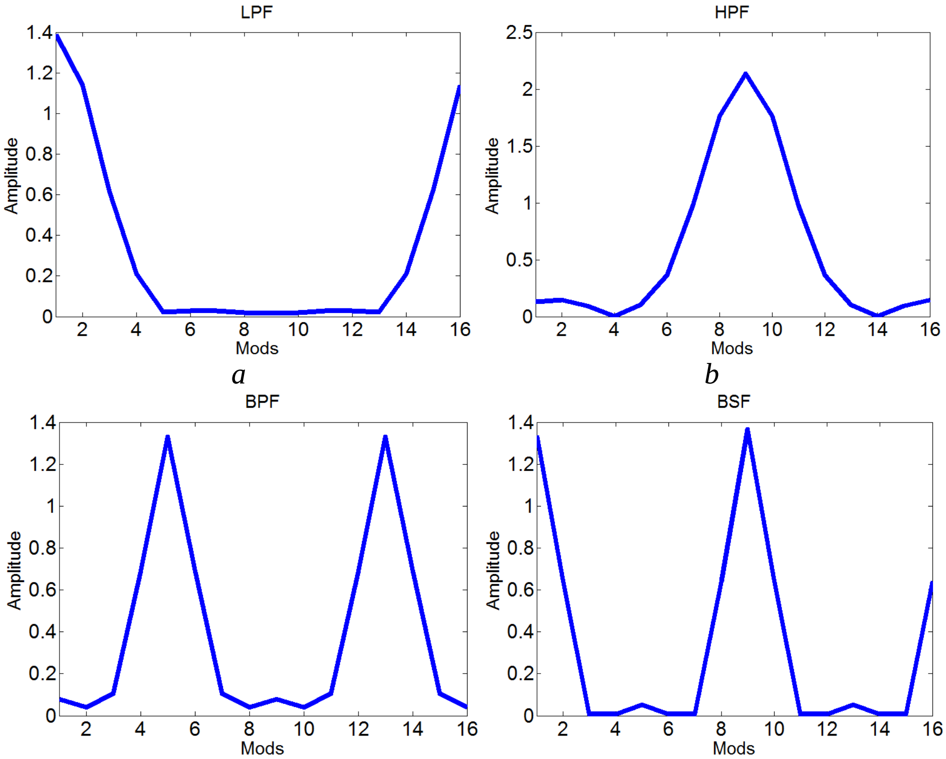


a



b

Fig. 7 – Simulation *vs.* measurement for spatial filters: *a* – band – pass filter, *b* – band –stop filter.



a *b* *c* *d*

Fig. 8 – Spatial frequency characteristics obtained for spatial filters: *a* – low – pass filter, *b* – high – pass filter, *c* – band – pass filter, *d* – band – stop filter.

5. Conclusions

In this paper we have presented several results regarding the dynamics of a spatial-temporal filter, based on a parallel analogic architecture of CNN type. The 1D architecture with 16 cells has been implemented using 0.18 μm CMOS technology and different types of spatial-temporal filtering could be obtained. Measurement confirmed with good precision transistor level simulations.

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IMPLEMENTAREA CMOS A FILTRELOR SPAȚIO-TEMPORALE CU REȚELE NEURALE CELULARE

(Rezumat)

Rețelele Neurale Celulare (CNN) sunt arhitecturi analogice paralele de prelucrare a semnalelor ce pot realiza diverse tipuri de filtrări spațio-temporale. Se propune o arhitectură de rețea neurală celulară, în care celulele sunt conectate cu vecinătăți de ordin unu şi doi, implementată la nivel de tranzistor in tehnologie 0.18 CMOS ce poate realiza filtrari spațiale de tip trece jos şi trece sus, respectiv trece bandă şi opreşte bandă.