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OPTICAL RECONFIGURABLE NEURON BY USING THE TRANSVERSE POCKELS EFFECT

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The paper presents a new type of optical neuron, whose weights can be optically changed at any moment. Once being established, the weights are memorized for a period of few days. The structure of the optical neuron comprises a photoelectret as the recording medium of the weights and an optical nonlinear crystal of the type of those that manifest the Pockels effect. The device uses the transverse Pockels effect. The paper describes the structure of the device, as well as the estimated values of its parameters. Moreover, several alternatives of the structure are briefly presented.

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1. Introduction

Today we are assisting at a great interest in the field of optical computing [1 - 3]. This interest is due to the advantages provided by light when used as an information carrier. Among these advantages we mention speed, parallelism of processing and improved connectivity between devices. Moreover, with light beam as information carrier, several types of information processing can be performed, such as analogue computing and integral transforms. A special application of light in information processing is its use in optical neural networks.

The paper describes an all-optical neuron, whose structure is derived from a previous published paper [4]. The present version allows for the integration of the device.

The paper consists in several sections, as follows. Section 2 is devoted to the presentation of a general background in which are presented the main features of artificial neurons, the characetristics of optical neurons, as well as notions about photoelectrets. Section 3 is devoted to the presentation of the optical neuron as regards its structure and evaluated parameters. Its specific features are presented also within this section. The last section of the paper is devoted to conclusions.

We are focusing here only on the device structure and parameters. We are not dealing neither with the technological realisation of it, nor with its applications.

2. Background

An artificial neuron is a device that has a number of ‘n’ inputs and an output, which makes the weighted sum of its inputs and compare this sum with a threshold value, emitting signal if the sound overcomes the threshold etc. The schematic diagram of the device is depicted in Fig. 1. Let X_i (i=1,n) be the value of input ‘i’ while w_i be its corresponding weight. Let Y be the result of the sum. After performing the weighted sum, the device compares the value of Y with a threshold value, Y_0. If

$Y > Y_0$, then the output is activated. The weights, w_i, can be changed, so as the neuron be able to adapt to several input sequences, X_i. The output can be of the ON / OFF type or can be represented by a nonlinear function f(Y).

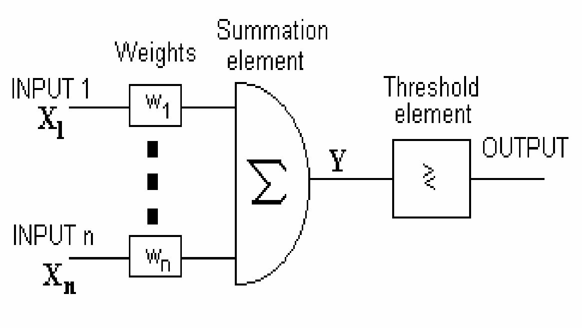


Fig. 1. The schematic diagram of a neuron-type device.

If:

$$Y = \sum_{i=1}^{n} w_i X_i > Y_0 \text{, then} \tag{1a}$$

$$Output \neq 0 \tag{1b}$$

An optical neuron is a device whose inputs and output are optical. The weights are established also by optical means. Usually, the light intensity is used for encoding the information. In this case, X_i are given by the light intensity , Φ_i, entering the input 'i'.

There are two types of optical neurons, depending on the way in which summing is performed. The first type is the non-coherent one, in which the sum in (1a) refers to simple summation of light intensities, Φ_i, as it is in the case of non-coherent light. The second case is the coherent one, in which amplitudes are summed instead of intensities. This latter case creates a dependence of the sum not only on the amplitudes of the incoming beams but also on their relative phase shifts. This feature creates some practical difficulties when making the device, so the former case of non-coherent neuron is usually prefered.

An optical neuron exploits the light features when used in information processing. The most important are speed, the high degree of parallelism in processing and the possibility to make a great number of interconnections between several units. These three features are of basic importance for (artificial) neural networks. Moreover, an optical neuron is not influenced by electromagnetic perturbations.

In the last part of this section, we shall briefly present some basic notions about photoelectrets. A photoelectret is a solid-state material that, if placed in an electric field simultaneously with its illumination, remains electrically charged after the switching-off of both the field and illumination. Unlike ferroelectrics, the electric field of the photoelectret does not represent a spontaneous polarization but it is produced by external means. The photoelectret preserves its their electric polarization from a period of several minutes to several days, depending on the preservetaion conditions such as temperature, humidity, pressure, illumination. An important feature of the photoelectrets is the fact that their surface charge density, σ, given by the electric polarization, depends on the charging light dose, i.e. on the product between the light intensity, Φ_p, used to charge them and the exposure time, t [5]:

$$\sigma = K * \Phi_p * t \tag{2}$$

The constant, K, is dependent on the photoelectret material, the material geometry as well as on the electric field used to charge the photoelectret. Relation (2) holds only for a certain interval of values of the product $\Phi_p t$ [5]. Examples of materials that can be used as photoeletrets are: monocrystalline sulphur, polycrystalline sulphur, polycrystalline telluride, CdS:(Cu, Cl), sensitized

ZnO, anthracene, alkali halides that possess colour centers, AgCl, chalcogenide glasses, etc. A detailed description of these materials can be found in [5].

An important observation is that light used for charging or discharging the photoelectret must have a photon energy greater than or equal with a certain value (a sort of optical band gap), depending on the material.

3. Device structure

The schematic diagram of the optical neuron device is presented in Fig. 2. The device comprises as main parts, the block for input weighting and weights changing and the summation element (a lens). The other elements are the polarizers and the thresholding element. The later element can be an optical thyristor, as that presented in [2] or a tunnel diode, as presented in [6]. We will not present this element because it is already described in the literature [7]. The voltage source depicted in Fig. 2 refers in fact to two voltage sources, as can be seen further in Fig. 3.

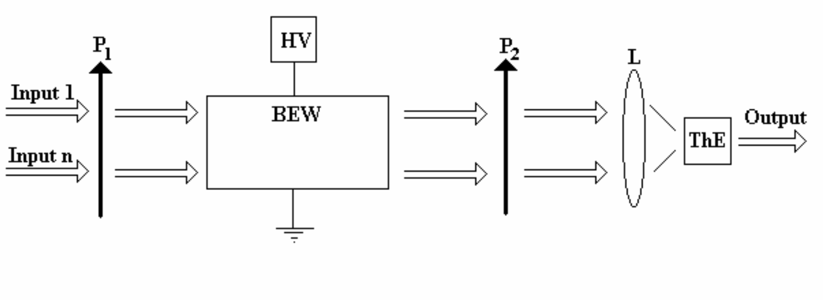


Fig. 2. The schematic diagram of the optical neuron structure. P_1,P_2 - linear polarizes, BEW - block for establising weigths, HV - voltage source, L - convergent lens, ThE - threshold element.

The main unit of the optical neuron is the block for fixing the weigths of the inputs. It is a sandwich structure (Fig. 3) containing an electro-optic crystal, that presents the Pockels effect, and a photoelectret layer. The electro-optic crystal and the photoelectret are separated by a metallic electrode, the whole structure being placed between two other electrodes. The electrode deposited on the photoelectret surface is transparent, in order to allow the light for charging the photoelectret to enter into the material. The sandwich type structure is depicted in Fig. 3, for a single input. The output beams are incident on the summing lens, L, from Fig. 2. The electro-optic crystal is used in the transverse mode of the Pockels effect, i.e. the optic axis is perpendicular to the light propagation direction.

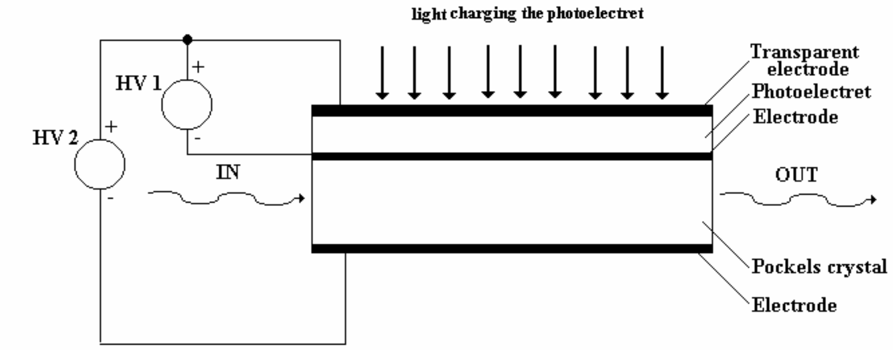


Fig. 3. Structure of the weights establishing part.

The voltage source, HV1, is used for charging the photoelectret. The HV2 voltage source applies a voltage across the whole structure when neccessary. In some cases only HV2 voltage source can be used both for charging the photoelectret and applying a constant voltage across the whole structure.

Details on the electro-optic crystals that present the Pockels effect can be found in reference [8].

Here we present an estimation of some of the device parameters. The detailed computations are presented in [9]. Let ε_f and d_f be the electric permittivity and, respectively, the thickness of the photoelectret layer, while ε_N and d_N are the same respective parameters for the electro-optic crystal. Let σ_f be the surface charge density of the photoelectret and V_0 the voltage applied to the whole structure (by HV2 voltage source). It results that the voltage, V_N, induced across the electro-optic crystal is [4]:

$$V_N = \frac{V_0 - \frac{\sigma_f}{\varepsilon_f} d_f}{1 + \frac{\varepsilon_N d_f}{\varepsilon_f d_N}} \tag{3}$$

If the polarizers P_1 and P_2 are parallel, then the transmission, T, of the system is given by [8]:

$$T = \cos^2\left(\pi \frac{V_N}{V_{\pi/2}}\right) \tag{4}$$

where $V_{\pi/2}$ is the half-wave voltage of the electro-optic crystal in the transverse Pockels effect mode. In the case of perpendicular polarizers, the $\cos^2$ in (4) is replaced by $\sin^2$. Let $V_{\lambda/2}^{(0)}$ be the half-wave voltage of the crystal when used in longitudinal mode of the Pockels effect and $V_{\lambda/2}$ the half-wave voltage in the transverse mode. Let l_N be the length of the electro-optic crystal. Then one can obtain [8]:

$$V_{\lambda/2} = V_{\lambda/2}^{(0)} * \frac{d_N}{l_N} \tag{5}$$

Let us now consider that for each channel '*i*' we have a certain value of the surface charge density $\sigma_f^{(i)}$ and thus a specific value T_i of its transmission. Let Φ_{0i} be the light intensity applied at the input '*i*' of the device and Φ_i the intensity value leaving the weighting element. It results that [4]:

$$T_i = \cos^2\left(\frac{\pi}{V_{\pi/2}} * \frac{V_0 - \frac{\sigma_f^{(i)}}{\varepsilon_f} d_f}{1 + \frac{\varepsilon_N d_f}{\varepsilon_f d_N}}\right) \tag{6}$$

and:

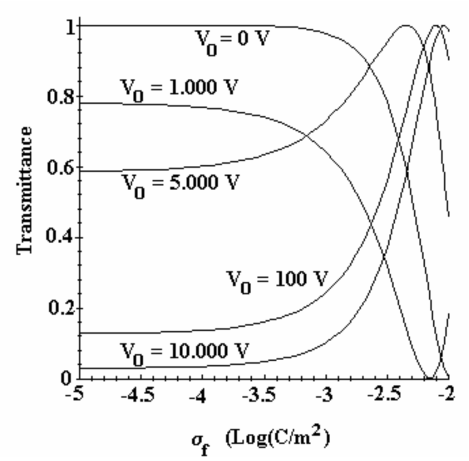
$$\Phi_i = T_i * \Phi_{0i} \tag{7}$$

The net intensity sum, Φ_{tot}, applied to the threshold element is:

$$\Phi_{tot} = \sum_{i=1}^{n} T_i * \Phi_{0i} = \sum_{i=1}^{n} \Phi_{0i} * cos^2\left(\frac{\pi * l_N}{V_{\lambda/2}^{(0)} * d_N} * \frac{V_0 - \frac{\sigma_f^{(i)}}{\varepsilon_f} d_f}{1 + \frac{\varepsilon_N d_f}{\varepsilon_f d_N}}\right) \tag{8}$$

From (8) it is seen that, for a given crystal and geometry, Φ_{tot} depends on the surface charge density values $\sigma_f^{(i)}$ of the each input as well as on the overall voltage, V_0, applied from the external voltage source. Thus, there are two degrees of freedom for controling the device output.

The dependence of T on σ and V_0 is depicted in Fig. 4a, while in Fig. 4b is depicted the dependence of T on d_N and σ_f. Fig. 4c depicts the dependence of T on d_f, for d_N = 2 mm. For Fig. 4a the parameters are $\varepsilon_f = 9\varepsilon_0$, $\varepsilon_N = 7\varepsilon_0$, l_N = 10 cm, d_f = 4 μm, d_N = 2 mm, $V_{\lambda/2}^{(0)}$ = 13 kV, while for Fig. 4b the same parameters are $\varepsilon_f = 9\varepsilon_0$, $\varepsilon_N = 7\varepsilon_0$, l_N = 10 cm, d_f = 4 μm, V_0 = 0 V (ε_0 is the vacuum permittivity).



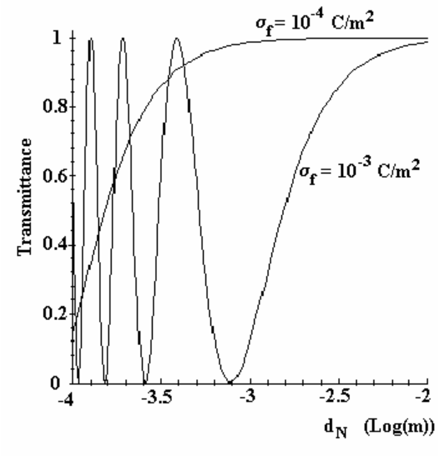


Fig. 4a. The dependence of transmittance on V_0 and σ_f. Fig. 4b. The dependence of transmittance on d_N and σ_f

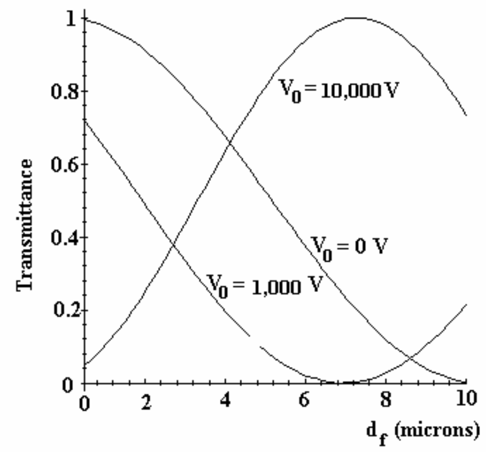


Fig. 4c. The dependence of transmittance on d_f, for d_N = 2 mm.

The voltage, V_{phot}, induced by the photoelectret is:

$$V_{phot} = \frac{\dfrac{\sigma_f}{\varepsilon_f} d_f}{1 + \dfrac{\varepsilon_N d_f}{\varepsilon_f d_N}} \tag{9}$$

Fig. 5 depicts the dependence of V_{phot} on the photoelectret and electro-optic crystal thickness respectively, for a surface charge density $\sigma_f = 10^{-8}$ C/cm^2 and for $\varepsilon_f = 9\varepsilon_0$, $\varepsilon_N = 7\varepsilon_0$.

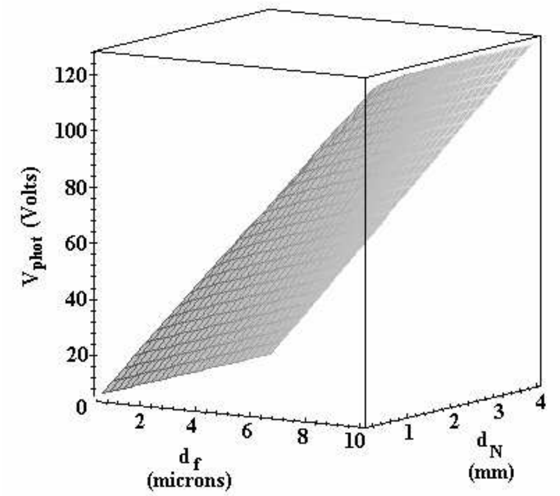


Fig. 5. The dependence of V_{phot} on the photoelectret and electro-optic crystal thickness.

In Fig. 6 it is represented the dependence of V_{phot} on the decimal logarithm of σ_f and on the photoelectret thickness, for a thickness of the nonlinear medium equal to 2 mm.

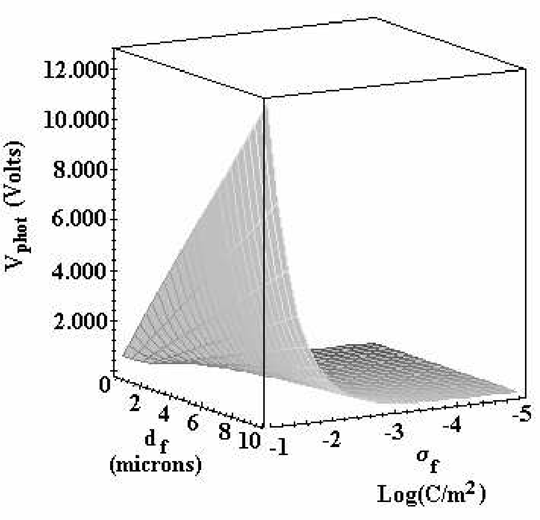


Fig. 6. The dependence of V_{phot} on the decimal logarithm of σ_f and on the photoelectret thickness.

The energy dissipated for charging the photoelectret is of the order of 600 pJ/μm^2 [4].

We mention that the inputs or some of the inputs can be applied also on the photoelectret, in place of the beam used to charge the photoelectret. The situation is depicted in Fig. 7. In this case, the input light can either charge or discharge the photoelectret, depending on its initial state (discharged, respectively charged) and external voltage (non-zero or short-circuit). This way of functioning is useful in some applications. Of course, a suplimentary light source is necessary for producing the output beam. If the photoelectret is initially charged, then its charging is made with another beam, applied on the same position with the input. This case is not, however, represented in Fig. 7.

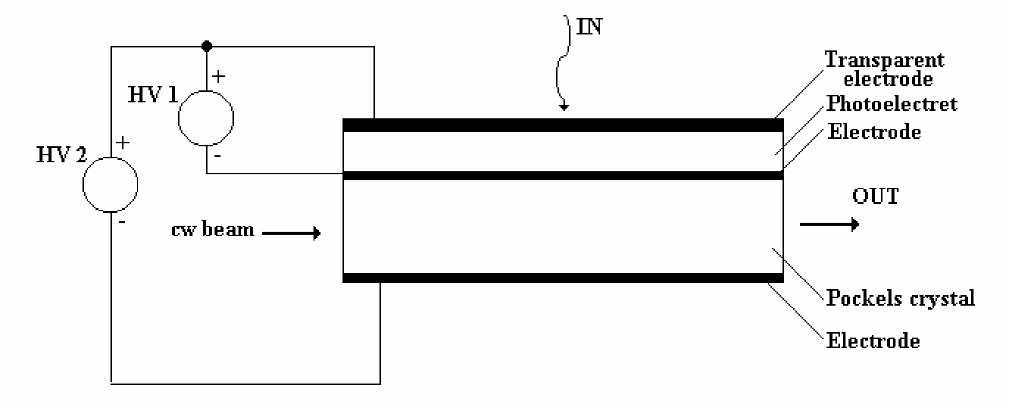


Fig. 7. An alternative structure of the weights establishing part.

The following features are important when using the transverse Pockels effect for making an optical neuron: a) the miniaturization of the device, the only important factor being the ratio between thickness and length from Eq. (5); b) the decrease of the surface charge density necessary for controling the device. For example, if $d_N = 10\ \mu m$ and $l_N = 1$ mm, $V_{\lambda/2}$ reduces to several tens of volts.

Usually, in present day neural networks, a number of a few tens of artificial neurons are used for designing the network. This implies that a volume of approximately 10 cm x 10 cm x 10 cm is occupied by the processing unit. If the nonlinear crystal can be made as thin as 1 μm, the volume reduces to 1 cm x 1 cm x 1 cm, almost the same as a present day microprocessor (considering also its cooler). Thus, a neural network based on artificial optical neurons seems feasible also from the point of view of miniaturization.

Another aspect must be discussed also. As presented in Fig. 3, the number of the device inputs is fixed by construction. This is due to the intermediate electrode present in the structure. If this electrode is discarded, then the number of inputs can be varied without the need of changing the structure. But in this case, the situation depicted in Fig. 7 cannot be applied at all. However, there are many applications in which the situation with a variable number of inputs is prefered against the situation presented in Fig. 7.

4. Conclusion

We have presented an all-optical neuron based on the transverse Pockels effect. This type of neuron allows for the miniaturization of the device, a feature that is important for practical applications. We have presented the dependence of the device main parameters on the geometry and material parameters. Usually, such type of device has a fixed number of inputs. By slightly changing the structure, the number of inputs can be varied from one application to another, without changing the device. The presented structure is versatile, a feature that opens up a wide range of applications.

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