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OPTOELECTRONIC LOGICAL GATES “AND”, “OR” AND “NOT”

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Optoelectronic AND, OR and NOT logical gates were composed of thin film photoconducting and electroluminescent elements, made of cadmium sulphide and zinc sulphide, respectively, doped with copper, chlorine and manganese. The gates consisted of several photoconducting elements and one electroluminescent element suitably connected and supplied with a sinusoidal voltage. In such circuits the functions of product, sum and negation for input light signals illuminating the photoconducting elements were realized, and the output signal was the light emitted by the electroluminescent element.

Keywords: Optoelectronics; Thin films; Logical gates

1 INTRODUCTION

In measuring systems when converting the signals it is necessary more than once to use various kinds of logical circuits [1] and in the case of utilization of optoelectronic sensors it is convenient if they would also be optoelectronic logical circuits. Each logical function can be realized by adequate connection of elementary gates AND, OR and NOT.

Optoelectronic logical gates have been realized based on thin film photoconducting and electroluminescent elements, adequately connected, so as to realize the asked logical function [2].

Every one of the gates was considered individually and for each of them mathematical models describing static and dynamic characteristics were elaborated. All measurements were also executed individually for every one of the gates.

In Figure 1 the optoelectronic gate AND composed of two photoconducting elements PC connected in series and one electroluminescent element EL is presented. If the elements PC_1 and PC_2 are illuminated with light pulses of intensities L_1 and L_2, the voltage across these elements will be so low that practically all the exciting voltage U will be applied to the electroluminescent element EL, generating its luminance. The light signal emitted by the element EL will therefore fulfil the condition of logical product $B = L_1 \cap L_2$. In this case the

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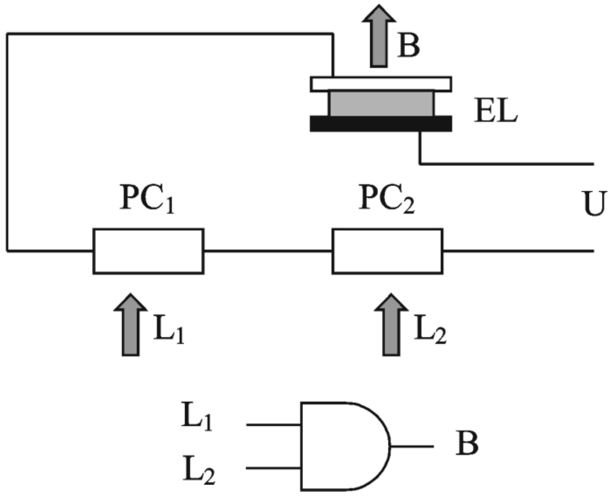

FIGURE 1 Optoelectronic AND logical gate.

impedances of element PC_1 (Z_{PC1}) and of element EL (Z_{EL}) will satisfy the relation: $Z_{PC1} \ll Z_{EL}$.

In Figure 2 a simplified schematic diagram of the OR gate, composed of two PC elements connected in parallel and one EL element is shown.

If one of the elements PC_1 or PC_2 is illuminated with a light pulse of intensity L_1 or L_2, the voltage across this element will be so low that practically all the exciting voltage U will be applied to the electroluminescent element EL, generating its luminance. The light signal emitted by the element EL will therefore fulfil the condition of the logical sum $B = L_1 \cup L_2$. In this case the impedances of element PC_1 (Z_{PC1}) and of element EL (Z_{EL}) will satisfy the relation $Z_{PC1} \ll Z_{EL}$.

In Figure 3 the optoelectronic gate NOT composed of one photoconducting element PC and one electroluminescent element is shown.

When an input signal L illuminating the PC element is switched on, then the relation $Z_{PC} \ll Z_{EL}$ will be fulfilled, and the voltage across the EL element will be so low that this

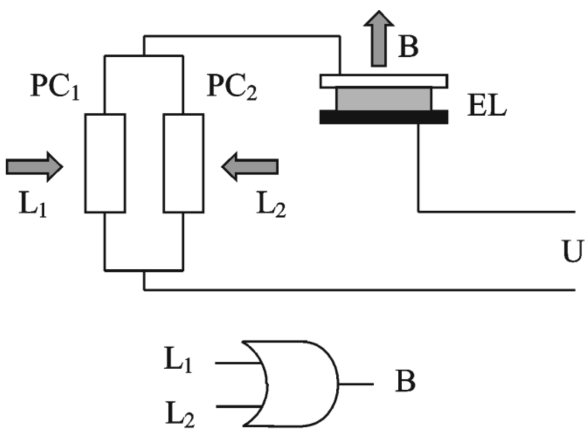

FIGURE 2 Optoelectronic OR logical gate.

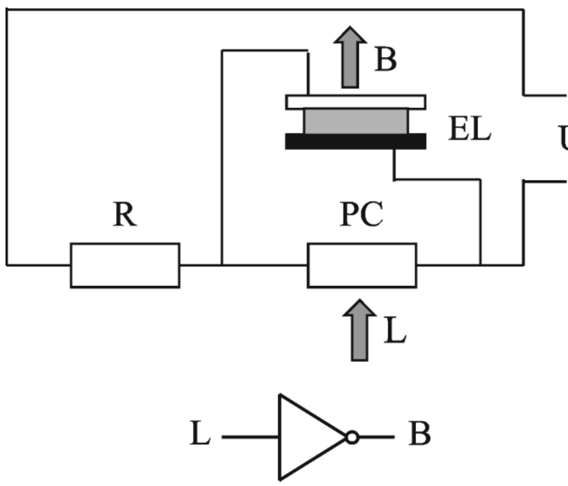

FIGURE 3 Optoelectronic NOT logical gate.

element will stop emitting the light. Thereby the output signal from the element EL will be a negation of the input signal L.

2 MATHEMATICAL MODELS OF LOGICAL GATES

2.1 Model for Dynamic Characteristics of AND Gate

The mathematical model of the AND logical gate was developed with utilization of an equivalent circuit shown in Figure 1.

The instantaneous value of the current i through the elements PC can be represented by the formulae

$$i = u_1^{PC}(G_1^{PC} + G_{01}) \tag{1}$$

$$i = u_2^{PC}(G_2^{PC} + G_{02}) \tag{2}$$

$$i = C^{EL}\frac{d}{dt}u^{EL} + G^{EL}u^{EL} \tag{3}$$

where u_1^{PC} and u_2^{PC} are the instantaneous values of the voltage across PC_1 and PC_2 elements, G_{01} and G_{02} are the "dark" conductances of these elements, u^{EL} is the instantaneous value of the voltage across the EL element, C^{EL} is the capacitance and G^{EL} is the leakage conductance of this element.

Variations of conductance G^{PC} of photoconducting elements PC_1 and PC_2 can be given [3] by the following equations

$$\frac{d}{dt}G_1^{PC} = a_1L_1 - \frac{G_1^{PC}}{\tau_1} \tag{4}$$

$$\frac{d}{dt}G_2^{PC} = a_2L_2 - \frac{G_2^{PC}}{\tau_2} \tag{5}$$

where a_1, a_2, τ_1 and τ_2 are constant quantities for given PC_1 and PC_2 elements.

The voltages across individual elements fulfil the dependence

$$u = u_1^{\mathrm{PC}} + u_2^{\mathrm{PC}} + u^{\mathrm{EL}}. \tag{6}$$

The input signal in the form of luminance B of the electroluminescent element EL can be given [4, 5] by the formula

$$B_t = B_0 \exp(-\gamma t) \exp\left(-\frac{b}{|u^{\mathrm{EL}}|^{1/2}}\right) \tag{7}$$

where B_0, γ and b are constant quantities for the given EL element.

The instantaneous value of voltage u^{EL} can be calculated from Eqs. (1)–(6), and after its insertion into Eq. (7) the instantaneous value of the luminance B_t is obtained.

2.2 Model for Static Characteristics of AND Gate

The conductance of photoconducting elements (Fig. 1) can be given by the formulas

$$G_1^{\mathrm{PC}} = G_{01} + g_1 L_1 \tag{8}$$
$$G_2^{\mathrm{PC}} = G_{02} + g_2 L_2 \tag{9}$$

where $g_1 = a_1 \tau_1$ and $g_2 = a_2 \tau_2$.

The root-mean-square value of the voltage U_{EL} across the EL element when supplying the circuit with a sinusoidal alternating voltage is described by the formula

$$U_{\mathrm{EL}} = U \left| \frac{Y_{\mathrm{PC}}}{Y_{\mathrm{PC}} + Y_{\mathrm{EL}}} \right| \tag{10}$$

where

$$Y_{\mathrm{EL}} = G^{\mathrm{EL}} + j2\pi f C^{\mathrm{EL}} \cong j2\pi f C^{\mathrm{EL}}, \tag{11}$$
$$Y_{\mathrm{PC}} = \left(\frac{1}{G_{01} + g_1 L_1} + \frac{1}{G_{02} + g_2 L_2} \right)^{-1}. \tag{12}$$

The average value of the luminance B when supplying the circuit with the voltage of frequency f can be calculated from the dependence

$$B = B_0 \exp\left(-\frac{\gamma}{4f}\right) \exp\left(-\frac{b}{U_{\mathrm{EL}}^{1/2}}\right). \tag{13}$$

Utilizing the formulas (10), (11) and (12) the dependence (13) can be given in the form

$$B = B_0 \exp\left(-\frac{\gamma}{4f}\right) \exp\left[-\frac{b}{U^{1/2}} (1 + x_1^2)^{1/4}\right] \tag{14}$$

where

$$x_1 = 2\pi f C^{\mathrm{EL}} \frac{G_{01} + G_{02} + g_1 L_1 + g_2 L_2}{(G_{01} + g_1 L_1)(G_{02} + g_2 L_2)}. \tag{15}$$

Generally it can be assumed that $G_{01} = G_{02}$, $g_1 = g_2$ and that we use, in case of logic one, the same values of input signals ($L_1 = L_2 \gg 0$). The input signals can also take the values equal to zero (logic zero).

When $L_1 \gg 0$ (logic one) and $L_2 \gg 0$, then $g_1 L_1 \gg G_{01}$; $g_2 L_2 \gg G_{02}$. Then

$$x_1 \cong 2\pi f C^{\mathrm{EL}} \frac{2}{g_1 L_1} \tag{16}$$

and

$$B \cong B_0 \exp\left(-\frac{\gamma}{4f}\right) \exp\left(-\frac{b}{U^{1/2}}\right) \tag{17}$$

as for usually used frequencies (about 500 Hz) $g_1 L_1 \cong g_2 L_2 \gg 2\pi f C^{\mathrm{EL}}$, *i.e.* $x_1 \ll 1$.

The input signal B therefore takes a relatively high value, which corresponds to logic one.

If the input signal $L_1 = 0$ and $L_2 \gg 0$, then $g_2 L_2 \gg G_{02}$. Then

$$x_1 \cong \frac{2\pi f C^{\mathrm{EL}}}{G_{01}} \gg 1 \tag{18}$$

as $2\pi f C^{\mathrm{EL}} \gg G_{01}$. Thereby the output signal B will assume a relatively low value, which corresponds to logic zero.

It will be similarly for the case $L_1 \gg 0$, $L_2 = 0$, since then

$$x_1 \cong \frac{2\pi f C^{\mathrm{EL}}}{G_{02}} \gg 1 \tag{19}$$

i.e. the value of the signal B will also correspond to logic zero.

If $L_1 = 0$ and $L_2 = 0$, then

$$x_1 \cong \frac{4\pi f C^{\mathrm{EL}}}{G_{01}} \gg 1, \tag{20}$$

therefore also in this case we will have the logic zero.

Thus the layout presented in Figure 1 realizes the function of logical product.

2.3 Model for Dynamic Characteristics of OR Gate

The mathematical model of an OR logical gate has been elaborated based on the equivalent circuit given in Figure 2.

An instantaneous value of the current through the PC_1 element can be described by the equation

$$i_1 = u^{\mathrm{PC}}(G_{01} + G_1^{\mathrm{PC}}) \tag{21}$$

where u^{PC} is the instantaneous value of the voltage across this element, G_{01} is the "dark" conductance, and G_1^{PC} is the instantaneous value of conductance of this element. Analogically for the PC_2 element it can be written

$$i_2 = u^{\mathrm{PC}}(G_{02} + G_2^{\mathrm{PC}}). \tag{22}$$

The instantaneous value of the current through the EL element is described by the equation

$$i^{\mathrm{EL}} = C^{\mathrm{EL}} \frac{\mathrm{d}}{\mathrm{d}t} u^{\mathrm{EL}} + G^{\mathrm{EL}} u^{\mathrm{EL}} \tag{23}$$

where u^{EL} is the instantaneous value of the voltage across this element, C^{EL} is the capacitance, and G^{EL} is the leakage conductance of the element.

As $i^{\mathrm{EL}} = i_1 + i_2$ and $u = u^{\mathrm{EL}} + u^{\mathrm{PC}}$, thus

$$C^{\mathrm{EL}} \frac{\mathrm{d}}{\mathrm{d}t} u^{\mathrm{EL}} + G^{\mathrm{EL}} u^{\mathrm{EL}} = (u - u^{\mathrm{EL}})(G_{01} + G_{02} + G_1^{\mathrm{PC}} + G_2^{\mathrm{PC}}). \tag{24}$$

The variations in time of the conductances G_1^{PC} and G_2^{PC} can be described [3] by the equations

$$\frac{\mathrm{d}}{\mathrm{d}t} G_1^{\mathrm{PC}} = a_1 L_1 - \frac{G_1^{\mathrm{PC}}}{\tau_1} \tag{25}$$

$$\frac{\mathrm{d}}{\mathrm{d}t} G_2^{\mathrm{PC}} = a_2 L_2 - \frac{G_2^{\mathrm{PC}}}{\tau_2} \tag{26}$$

where a_1, a_2, τ_1 and τ_2 are constant values for given PC_1 and PC_2, whereas L_1 and L_2 are illuminations of these elements and they make the input signals. From the set of Eqs. (24)–(26), the voltage u^{EL} can be calculated, and after its insertion [4, 5] into the formula

$$B_t = B_0 \exp(-\gamma t) \exp\left(-\frac{b}{|u^{\mathrm{EL}}|^{1/2}}\right) \tag{27}$$

the instantaneous value of luminance B_t of the electroluminescent element EL is obtained, the quantity B_t being the output signal. B_0, γ and b are constant values for the given element.

2.4 Model for Static Characteristics of OR Gate

The conductance of photoconducting elements (Fig. 2) can be described by the relations

$$G_1^{\mathrm{PC}} = G_{01} + g_1 L_1 \tag{28}$$

$$G_2^{\mathrm{PC}} = G_{02} + g_2 L_2 \tag{29}$$

where $g_1 = a_1 \tau_1$ and $g_2 = a_2 \tau_2$.

The root-mean-square value when the circuit is supplied with a sinusoidal voltage (with root-mean-square value U and frequency f) can be described by the formula

$$U_{\mathrm{EL}} = U\left|\frac{Y_{\mathrm{PC}}}{Y_{\mathrm{PC}} + Y_{\mathrm{EL}}}\right| \tag{30}$$

where

$$Y_{\mathrm{EL}} = G^{\mathrm{EL}} + j2\pi fC^{\mathrm{EL}} \cong j2\pi fC^{\mathrm{EL}} \tag{31}$$

and

$$Y_{\mathrm{PC}} = G_{01} + G_{02} + g_1L_1 + g_2L_2. \tag{32}$$

The mean value of the luminance B, when the circuit is supplied with a voltage of frequency f, can be calculated from the dependence

$$B = B_0\exp\left(-\frac{\gamma}{4f}\right)\exp\left(-\frac{b}{U_{\mathrm{EL}}^{1/2}}\right). \tag{33}$$

Utilizing the formulas (30), (31) and (32) the dependence (33) can be given in the form

$$B = B_0\exp\left(-\frac{\gamma}{4f}\right)\exp\left[-\frac{b}{U^{1/2}}(1 + x_2^2)^{1/4}\right] \tag{34}$$

where

$$x_2 = \frac{2\pi fC^{\mathrm{EL}}}{G_{01} + G_{02} + g_1L_1 + g_2L_2}. \tag{35}$$

Generally it can be assumed that $G_{01} = G_{02} = G_0$ and $g_1 = g_2 = g$. Furthermore it is assumed that in the case of a logic one the same values of input signals ($L_1 = L_2 \gg 0$) are used, and for logic zero $L_1 = L_2 = 0$.

If $L_1 \gg 0$ (logic one) and $L_2 = 0$, then $gL_1 \gg G_0$ and $x_2 \cong (2\pi fC^{\mathrm{EL}})/(gL_1)$. For commonly used frequencies (about 500 Hz) $gL_1 \gg 2\pi fC^{\mathrm{EL}}$, *i.e.* $x_2 \ll 1$. Then

$$B = B_0\exp\left(-\frac{\gamma}{4f}\right)\exp\left(-\frac{b}{U^{1/2}}\right), \tag{36}$$

that is to say the output signal takes a relatively high value, which corresponds to logic one on the output.

It will be similar when $L_1 = 0$ and $L_2 \gg 0$, since $x_2 \cong (2\pi fC^{\mathrm{EL}})/(gL_2) \ll 1$, and also when $L_1 = L_2 \gg 0$, since $x_2 \cong (2\pi fC^{\mathrm{EL}})/(g(L_1 + L_2)) \ll 1$.

For $L_1 = L_2 = 0$, $x_2 \cong (2\pi fC^{\mathrm{EL}})/(2G_0) \gg 1$, since $G_0 \ll 2\pi fC^{\mathrm{EL}}$. Then the output signal B will assume a relatively low value, which corresponds to logic zero. Thereby the system given in Figure 2 realizes the function of logical sum.

2.5 Model for Dynamic Characteristics of NOT Gate

A mathematical model of the NOT gate has been elaborated based on the equivalent circuit shown in Figure 3.

The instantaneous value of the current i^{PC} through a photoconducting element PC can be written by the formula

$$i^{\mathrm{PC}} = u^{\mathrm{EL}}(G_0 + G^{\mathrm{PC}}) \tag{37}$$

where u^{EL} is the instantaneous value of the voltage across the PC element (also across the electroluminescent element EL), G_0 is the "dark" conductance, and G^{PC} is the instantaneous conductance of the element PC illuminated by a light of intensity L.

The instantaneous value of the current i^{EL} through the element EL is described by the dependence

$$i^{\mathrm{EL}} = C^{\mathrm{EL}} \frac{\mathrm{d}}{\mathrm{d}t} u^{\mathrm{EL}} + G^{\mathrm{EL}} u^{\mathrm{EL}} \tag{38}$$

where C^{EL} is the capacitance, and G^{EL} is the leakage conductance of this element.

As the current through the resistance R is equal to the sum of currents i^{PC} and i^{EL}, thus

$$\frac{1}{R}(u - u^{\mathrm{EL}}) = C^{\mathrm{EL}} \frac{\mathrm{d}}{\mathrm{d}t} u^{\mathrm{EL}} + G^{\mathrm{EL}} u^{\mathrm{EL}} + u^{\mathrm{EL}}(G_0 + G^{\mathrm{PC}}) \tag{39}$$

where $u - u^{\mathrm{EL}}$ is the voltage across the resistance R, and u is the instantaneous value of the voltage supplying the circuit under consideration.

A change in time of the conductance G^{PC} can be described by the relation

$$\frac{\mathrm{d}}{\mathrm{d}t} G^{\mathrm{PC}} = aL - \frac{G^{\mathrm{PC}}}{\tau} \tag{40}$$

where a and τ are constant values for the given PC element.

From Eqs. (39) and (40) the instantaneous value of the voltage u^{EL} can be calculated, and after inserting [4, 5] into the formula

$$B_t = B_0 \exp(-\gamma t) \exp\left(-\frac{b}{|u^{\mathrm{EL}}|^{1/2}}\right) \tag{41}$$

a dependence is obtained which defines the instantaneous value B_t of the element EL, this quantity being the output signal (the input signal is the illumination L).

2.6 Model for Static Characteristics of NOT Gate

The conductance of the element PC (Fig. 3) can be defined by the dependence

$$G^{\mathrm{PC}} = G_0 + gL \tag{42}$$

where $g = a\tau$.

The root-mean square value of the voltage U^{EL} across the element EL, when the circuit is supplied with a sinusoidal voltage, will be described by the formula

$$U_{\mathrm{EL}} = U\left|\frac{Z_C}{Z_C + R + RG^{\mathrm{PC}}Z_C}\right| \tag{43}$$

where

$$Z_C = R^{\mathrm{EL}} - j\frac{1}{2\pi f C^{\mathrm{EL}}} \cong -j\frac{1}{2\pi f C^{\mathrm{EL}}}.$$

The mean value of the luminance B, when the circuit is supplied with a sinusoidal voltage of frequency f can be described with the dependence

$$B = B_0 \exp\left(-\frac{\gamma}{4f}\right)\exp\left(-\frac{b}{(U_{\mathrm{EL}})^{1/2}}\right) \tag{44}$$

and using the dependences (42) and (43) the formula (44) takes the form

$$B = B_0 \exp\left(-\frac{\gamma}{4f}\right)\exp\left[-\frac{b}{U^{1/2}}(1+x)^{1/4}\right] \tag{45}$$

where $x = (2\pi f C^{\mathrm{EL}} R)^2 + R^2(G_0 + gL)^2 + 2R(G_0 + gL)$.

The resistance R should be selected for $(2\pi f C^{\mathrm{EL}} R)^2 \ll 1$ as well as for $R \gg (gL)^{-1}$ and $R \ll 1/G_0$.

Furthermore the value of the input signal ($L \gg 0$ – logic one) should be such that $gL \gg G_0$. Then, if the input signal $L \gg 0$, $x \cong R^2(gL)^2 + 2RgL \gg 1$, *i.e.* the output signal B will reach a relatively low value, which corresponds to logic zero.

If the input signal $L = 0$, then $x \cong R^2G_0^2 + 2RG_0 \ll 1$, and

$$B \cong B_0 \exp\left(-\frac{\gamma}{4f}\right)\exp\left(-\frac{b}{U^{1/2}}\right) \tag{46}$$

that is to say the output signal will reach a relatively high value, corresponding to logic one. Thereby the proposed system will realize the NOT function.

3 INVESTIGATION RESULTS

The photoconducting elements PC were prepared on a glass substrate with a transparent In_2O_3(Sn) electrode deposited previously. The In_2O_3(Sn) layer was made by reactive ionic sputtering in a diode circuit in an oxygen atmosphere, and on this layer the photoconducting CdS layer [6] was then evaporated under vacuum. Next the CdS layer was recrystallized by its annealing in CdS powder with Cu^{2+} and Cl^- ions. The second electrode of the PC element was an indium layer evaporated under vacuum on a photoconducting CdS(Cu,Cl) layer.

The electroluminescent elements (EL) were also produced on a glass substrate, on which a transparent In_2O_3 electrode was previously deposited. Next on this electrode the electroluminescent ZnS(Cu,Cl,Mn) layer [7] was evaporated under vacuum. The parent substance for the evaporation was a zinc sulphide powder with copper, chlorine and manganese admixtures

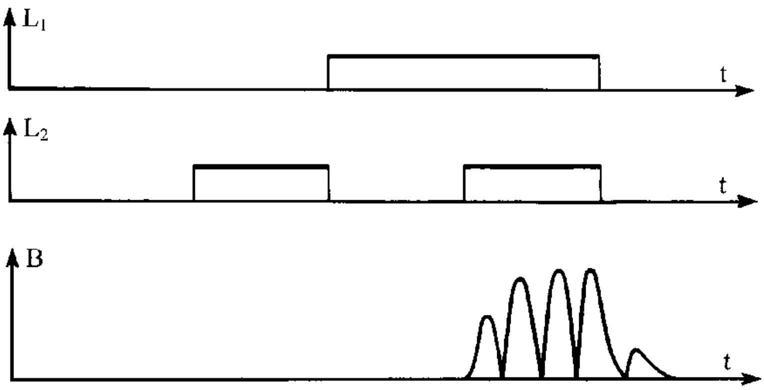

FIGURE 4 The time dependence of the output signal $B(t)$ and the input signals $L_1(t)$ and $L_2(t)$ for the AND logical gate.

introduced previously. On the ZnS(Cu,Cl,Mn) layer an insulating SiO_X layer and then a second electrode, an aluminium layer, were evaporated under vacuum.

Optoelectronic logical gates AND and OR (Figs. 1 and 2) were supplied with sinusoidal voltage U with equal values of amplitude (280 V) and frequency (500 Hz). The input signals were two rectangular light pulses with the same intensities ($L_1 = L_2 = 20$ lx), and the output signal was the luminance B of the electroluminescent cell EL.

The NOT gate (Fig. 3) was also supplied with sinusoidal voltage (with amplitude 280 V and frequency 500 Hz), the input signal was a rectangular light pulse with intensity L, illuminating the PC element, and the output signal was the luminance of the EL element.

For the AND and OR gates the dependence on time of the output signal $B(t)$ (Figs. 4 and 5) at various combinations of input signals L_1 and L_2 was measured.

For the NOT gate the dependence on time of output signal (Fig. 6) was measured, at input signal $L = 0$ and $L \neq 0$.

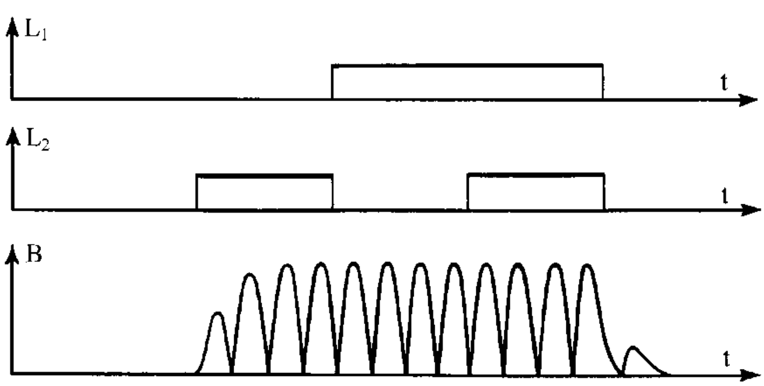

FIGURE 5 The time dependence of the output signal $B(t)$ and the input signals $L_1(t)$ and $L_2(t)$ for the OR logical gate.

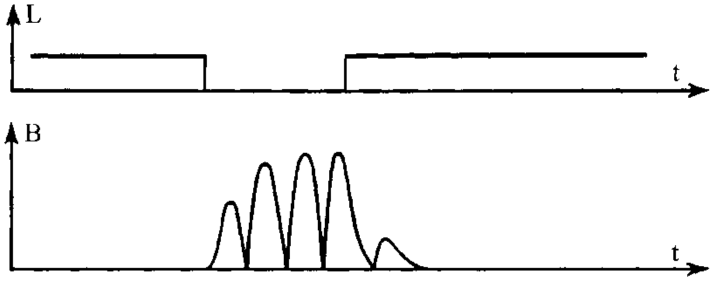

FIGURE 6 The time dependence of the output signal $B(t)$ and the input signal $L(t)$ for the NOT logical gate.

4 CONCLUSIONS

As results from the analysis of proposed mathematical models and carried-out measurements, the optoelectronic systems composed of photoconducting and electroluminescent elements can act as logical gates AND, OR and NOT. For each of the gates the output signals in the form of the luminance of electroluminescent element EL have the character of a periodic function with frequency equal to the doubled frequency of the voltage U supplying the circuit.

The characteristics calculated based on elaborated models have shown a good conformity with the results obtained from the measurements.

Furthermore, on the grounds of carried-out investigations, for each of the gates optimum values of parameters, of supplying voltage and of the levels of input signals can be determined.

As is well known, each logical function can be realized by adequate connection of simple gates AND, OR and NOT, from which much greater functional blocks, having an application in digital techniques, can be constructed.

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