ON THE THEORY OF THE REGENERATIVE OPTRON

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Fig. 1

Figure 1: Fig. 1

Fig. 2

Figure 2: Fig. 2

Abstract

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ON THE THEORY OF THE REGENERATIVE OPTRON

1. In papers ([1]-[3]) a theory was given of the EO$^+$-optron (an optron with direct electrical and positive optical feedback) based on a light-emitting diode and a photoresistor, under certain particular assumptions about the ampere-lux and lux-ohmic characteristics of its components. In the present work a general theory is developed, free of these restrictions. Its results are presented in a form that makes possible an engineering calculation of the optron, as well as of its components and connections. In particular, it is shown that almost independent control of the three characteristic points I_0, I', and I'' is possible (Fig. 1a), i.e., construction, from given optron components, of an optron with a required current-voltage characteristic (I-V characteristic).

Fig. 1. *a*—qualitative form of the characteristic of a regenerative optron; *b*—I-V characteristic of an EO$^+$-optron, the circuit of which is shown in Fig. 2 (solid lines—theory; points—experimental data)

Fig. 2. EO$^+$-optron. Inside the four-terminal network is shown the circuit of the electrical connection implemented in the optron studied by us

2. The complete system of equations for the optron consists of the equations of its components

$$I = GV'; \qquad G = G(B); \qquad IV' < W,$$

$$V_1 = V_1(I_1); \qquad B_1 = B_1(I_1); \qquad I_1 V_1 < W_1 \tag{1}$$

and the equations of the connections

$$B = B(B_1); \qquad I_1 = I_1(I). \tag{2}$$

Here G is the conductance of the photoresistor; B_1 is the radiation intensity of the light-emitting diode; B is the illumination of the photoresistor; W and W_1 are the maximum-

possible values of the dissipated power, respectively, in the photoresistor and the light-emitting diode. The meanings of the remaining quantities are explained by Fig. 2.

3. Noting that $V = V' + V''$ and denoting by r the input resistance of the matching amplifier, we find that, for the existence in an EO+-optron of a section of the current-voltage characteristic with negative differential resistance ($dV/dI < 0$), it is necessary and sufficient that, in some range of values of I, the inequality

$$\frac{dG}{dI} \geqslant \frac{G}{I}(1 + rG). \tag{3}$$

be satisfied.

The dependence of the conductance G of the photoresistor on the current I passing through it is of a complicated nature and is due to the fact that, owing to the direct electrical coupling, I affects the current I_1 flowing through the light-emitting diode. Depending on I_1, the brightness of the radiation of the light-emitting diode B_1 changes; correspondingly, the illumination of the photoresistor B changes, which ultimately leads to a change in its conductance G. Mathematically the dependence of G on I may be represented in the form of the following composite function

$$G = G(B\{B_1[I_1(I)]\}). \tag{4}$$

Consequently,

$$\frac{dG}{dI} = \frac{dG}{dB}\frac{dB}{dB_1}\frac{dB_1}{dI_1}\frac{dI_1}{dI} = \gamma\theta\alpha k, \tag{5}$$

where γ, θ, α, and k are, respectively, the differential coefficients of the photoconductivity of the photoresistor, of the light transmission of the optical path, of the luminous efficiency of the emitter, and of the current amplification of the matching stage.

Substituting the value of dG/dI from (5) into (3), we arrive at the inequality

$$\alpha\gamma\theta kI/G \geqslant 1 + rG, \quad (6)$$

which coincides with the condition for the existence of a section of negative resistance on the current-voltage characteristic of an EO+-optron, obtained earlier for the particular case in which all differential coefficients are constant [(1–3)]. The breakaway points I_0 and I' are determined from the equation

$$\alpha\gamma\theta kI/G = 1 + rG. \quad (7)$$

In order that the switching of the optron be accompanied by a significant change of current in the photoresistor circuit, it is necessary that the decisive role in the circuit impedance be played by the resistance of the photoresistor $1/G$, and not by the input resistance of the matching stage r. Consequently, with proper matching of the stages one should have $rG \ll 1$, i.e., inequality (6) may be written approximately in the form

$$\alpha\gamma\theta kI/G \geqslant 1, \quad (8)$$

in any case in the neighborhood of the first breakaway point.

Noting that $\alpha\gamma\theta = dG/dI_1$, we rewrite inequality (8) in the form

$$dG/dI_1 \geqslant G/kI. \quad (9)$$

Let us consider this condition separately for linear and nonlinear electrical coupling.

4. For a linear coupling between the currents I and I_1 ($k = \text{const}$) we obtain the expression

$$dG/dI_1 \geqslant G/I_1, \quad (10)$$

which characterizes a photoresistor that, under the given conditions of illumination by the light-emitting diode, is independent of the values of the current I flowing through the photoresistor. This makes it possible, from the lux-ohmic characteristic of the photoresistor $G(I_1)$, measured with the light-emitting diode and the photoresistor circuits electrically decoupled, to determine the position of the first breakaway point of the optron I_0 (Fig. 3), corresponding to

$$dG/dI_1 = G/I_1. \quad (11)$$

The values of the current and voltage at this point can be controlled by changing the optical coupling in the optocoupler (the distance between the components; the use of fiber optics, etc.), which affects the form of the function $G(I_1)$, and also by changing the gain coefficient k, since $I_0 = I_{10}/k$.

The richness of functional couplings in the optocoupler opens up a great variety of possibilities for controlling the positions of the points I' and I'' independently of I_0. First, these points may be fixed by choosing a definite value of r. Other conditions being equal, decreasing r shifts them into the region of larger currents, and increasing r into the region of smaller currents (see (7)). Among the optocouplers in which the region of negative differential resistances is limited by the load r connected in series with the photoresistor is, in particular, the optocoupler considered in (1–3).

Fig. 3. Determination of the characteristic points of the current-voltage characteristic from the curve of the dependence of the conductivity of the photoresistor in the optocoupler on the current flowing through the light-emitting diode. *a*—with linear electrical coupling; *b*—with nonlinear electrical coupling

Fig. 4. The simplest nonlinear characteristic of an electrical-coupling cascade in an optocoupler

The position of the second breakdown point also depends on the form of the functions $G(B)$, $B(B_1)$, and $B_1(I_1)$. If at least one of them has a tendency toward saturation, then the course of the curve $G(I_1)$ for $I_1 > I_{10}$ will have the form shown in Fig. 3a. In this case both breakdown points I_0 and I' (the beginning and end of the region of negative resistances on the current-voltage characteristic of the EOE-optocoupler) are determined from condition (11). Noting that the magnitude of the voltage at the points I_0 and I'' is the same ($V_0 = I_0/G_0 = I_{10}/kG_0$; $V_0 = I''/G'' = I_1''/kG''$), we see that the point I'' in this case also lies directly on the characteristic $G(I_1)$ (Fig. 3a).

5. For $G(I_1)$ of the form shown in Fig. 3b, control of the form of the current-voltage characteristic is possible by producing a nonlinear electrical coupling in the optocoupler. Then inequality (9) takes the form

$$\frac{dG}{dI_1} = \frac{G}{I_1} \frac{I_1/I}{dI_1/dI}, \tag{12}$$

whence it follows that a sublinear coupling shifts the first breakdown point toward larger values, while a superlinear coupling shifts it toward smaller values of I. We shall show that, by creating in the optocoupler an electrical coupling with a prescribed form of the dependence $k(I)$, one can control over wide limits the form of its current-voltage characteristic and, moreover, ensure fulfillment of the conditions for thermally stable operation. In the present communication we shall show this using the example of a matching amplifier whose characteristic $I_1(I)$ has the form shown in Fig. 4.

For a given value of I_{10}, determined by the properties of the components of the opto-

and by the optical coupling between them (see Fig. 3a), the position of the first breakdown point I_0 is fixed by specifying k on the linear section of the characteristic $I_1(I)$.

Let I'' be the required value of the current amplitude of the jump. Then the corresponding value of the photoconductor conductance G_m is found as V_0/I''. From this G_m, using the characteristic $G(I_1)$, we find the corresponding value of the LED current I_{1m} (Fig. 3b). Thus, by specifying the required values of the current-conversion coefficient on the linear section ($k = k_0$) and of the LED saturation current ($I_1 = I_{1m}$), we completely determine the shape of the characteristic of the matching amplifier (Fig. 4).

The position of the second breakdown point ($I = I'$) is determined from (12) by equating the right- and left-hand sides of this expression. It is easy to see that, in a piecewise-linear approximation of the characteristic, the value I' coincides with the kink point, while for a smooth curve it lies in the transition region from the linear section of the characteristic $I_1(I)$ to the saturation region; moreover, this transition region can be made sufficiently narrow.

With respect to thermal stability, the heat dissipation in the photoconductor at $I = I''$ is most critical. Writing the dissipated power in the form $I''V_0$ and noting that $V_0 = I_0 G_0$, and $I_0 = I_{10}/k$, we arrive at the following inequality for the gain coefficient in the region of the linear section of the electrical-coupling characteristic as the condition for thermal stability of the optoelectronic device:

$$k \geq I_{10} I'' G_0 / W. \tag{13}$$

Within the limits of fulfillment of this inequality, the position of I_0 and I' can be controlled by changing k.

6. The simple characteristic shown in Fig. 4 is convenient for explaining the results of the theory, but it does not provide complete decoupling of the positions of the points I_0, I', and I''. Greater freedom in forming the required current–voltage characteristic for the given EO+-optron is provided by electrical coupling that is also nonlinear in the region preceding saturation. Such an optron was assembled and investigated by us. Its components were a GaAs LED and a specially developed silicon photoconductor. Such photoconductors were fabricated by us on the basis of n-type silicon, in which the donor centers are partially compensated by zinc atoms ([4,5]). In the investigated optrons, photoconductors with dark resistance from $\sim 5 \cdot 10^2$ to $5 \cdot 10^4$ ohms were used. The electrical coupling was implemented by means of a cascade on a single MP-13 transistor (Fig. 2), and, as follows from the theoretical consideration carried out, this cascade provides not only matching of the currents of the LED and the photoconductor, but also the possibility of controlling the shape

of the current-voltage characteristic of the optron for given properties of its components and an unchanged optical coupling. Figure 1b presents a series of current-voltage characteristics of this optron for different values of the parameters R_1 and R_2 of the electrical-coupling cascade, confirming the correctness of the conclusions drawn above.

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Note: Figure translations are in progress. See original paper for figures.