AN OPTRON WITH DIRECT OPTICAL COUPLING AS A FOUR-TERMINAL NETWORK

PHYSICS

1970

SovietRxiv

Fig. 1. Schematic diagram of an O-optron

Figure 1: Fig. 1. Schematic diagram of an O-optron

Abstract

Full Text

UDC 539.293:621.382/383

PHYSICS

Academician of the Academy of Sciences of the Uzbek SSR É. I. ADIROVICH, D. A. ARONOV, N. YUNUSOV

AN OPTRON WITH DIRECT OPTICAL COUPLING AS A FOUR-TERMINAL NETWORK

1. For the development of optoelectronics and the design of optron devices and systems it is necessary to represent an optron as a four-terminal network, i.e., to find expressions for the Z-, Y-, and h-parameters through the differential characteristics of the optron. In papers ([1–5]), as the differential characteristics of an optron, transfer functions of its components and couplings were introduced: $\alpha = \partial B_1/\partial I_1$—the luminous-efficiency coefficient of the emitter; $\theta = \partial B/\partial B_1$—the light-transfer coefficient of the optical channel; $\beta = \partial I_\phi/\partial B$—the photoeffectiveness coefficient of the light receiver, equal to the quantum efficiency in the case when I_ϕ and B are expressed, respectively, in the number of electrons and in the number of photons; $m = \partial I_2/\partial I_\phi$—the coefficient of division of the photocurrent in the photoreceiver circuit; $K = \partial I_1/\partial I_2$—the current feedback coefficient. For an optron with a photoresistor as the light receiver, $\beta = \gamma V_2$, where $\gamma = \partial G/\partial B$ is the photoconductivity coefficient.

Fig. 1. Schematic diagram of an *O*-optron

It should be noted that the introduction of these differential characteristics, through which it is most convenient to represent the signal regeneration coefficient in an optron with positive feedback ($\mu = \alpha\beta\theta mk$), is, on the one hand, insufficient for expressing all elements of the Z-, Y-, or h-matrices of an optron and, on the other hand, contains excess information characterizing the optron together with the external circuits. Indeed, among the parameters given there is absent, for example, the differential resistance of the light emitter $Z_{\text{em}} = \partial V_{\text{em}}/\partial I_{\text{em}}$, while the expression for $m = 1/(1 + Z_{\text{fpr}}/Z_{\text{n}})$, in addition to the differential resistance of the photoreceiver $Z_{\text{fpr}} = \partial V_{\text{fpr}}/\partial I_{\text{fpr}}$, includes Z_{n}, the load impedance in the external circuit.

For calculating the Z-, Y-, and h-parameters of an electrical amplifier based on an optron with direct optical coupling (*O*-optron) ([6,7]) (Fig. 1), we shall apply the method set forth in general form in articles ([4,5]). In doing so we shall have to change the notation somewhat in comparison with ([4,5]), in order to bring it into correspondence with the standard notation of four-terminal-network theory.

For an optron pair, an injection light-emitting diode—photoresistor, described by the equations

$$\begin{gathered} I_1 = I_1(V_1); \qquad I_2 = I_\phi + I_{\phi 0}(V_2); \\ B_1 = B_1(I_1); \qquad B = B(B_1); \\ I_\phi = G(B\{B_1[I_1(V_1)]\})V_2, \end{gathered} \tag{1}$$

the components of the conductance matrix are equal to

$$\begin{gathered} Y_{11} = \partial I_1/\partial V_1 \big|_{V_2} = Y_{\mathrm{sd}}; \qquad Y_{12} = \partial I_1/\partial V_2 \big|_{V_1} = 0; \\ Y_{21} = \frac{\partial I_2}{\partial V_1}\bigg|_{V_2} = \frac{\partial I_2}{\partial I_\phi}\bigg|_{V_2} \frac{\partial G}{\partial B}\frac{\partial B}{\partial B_1}\frac{\partial B_1}{\partial I_1}\frac{\partial I_1}{\partial V_1} V_2 = \gamma\theta\alpha Y_{\mathrm{s}} V_2; \\ Y_{22} = \partial I_2/\partial V_2 \big|_{V_1} = G + Y_{\phi\mathrm{p}0} = Y_{\phi\mathrm{p}}. \end{gathered} \tag{2}$$

Similarly, we find the Z-parameters

$$\begin{aligned} Z_{11} &= \partial V_1/\partial I_1\big|_{I_2} = Z_{\mathrm{sd}}; & Z_{12} &= \partial V_1/\partial I_2\big|_{I_1} = 0; \\ Z_{21} &= \partial V_2/\partial I_1\big|_{I_2} = -\gamma\theta\alpha Z_{\mathrm{fr}} V_2; & Z_{22} &= \partial V_2/\partial I_2\big|_{I_1} = Z_{\mathrm{fr}}, \end{aligned} \tag{3}$$

and the h-parameters

$$\begin{aligned} h_{11} &= \partial V_1/\partial I_1\big|_{V_2} = Z_{\mathrm{sd}}; & h_{12} &= \partial V_1/\partial V_2\big|_{I_1} = 0; \\ h_{21} &= \partial I_2/\partial I_1\big|_{V_2} = \gamma\theta\alpha V_2; & h_{22} &= \partial I_2/\partial V_2\big|_{I_1} = Y_{\mathrm{fr}}. \end{aligned} \tag{4}$$

Note that the subscript zero denotes the dark values of the corresponding quantities (for example, $Y_{\mathrm{fr}0}$ is the dark differential conductance of the photoresistor).

From consideration of formulas (2), (3), and (4) it is evident that an optocoupler with direct optical coupling is characterized by three parameters: Z_{sd}, Y_{fr}, and $\alpha\theta\gamma$, which can be represented as follows through the elements of the matrices characterizing the optocoupler amplifier stage:

$$\begin{gathered} Z_{\mathrm{sd}} = Z_{11} = h_{11} = 1/Y_{11}; \\ Y_{\mathrm{fr}} = Y_{22} = h_{22} = 1/Z_{22}; \\ \alpha\theta\gamma = h_{21}/V_2 = Y_{21}/Y_{11}V_2 = -Z_{21}/Z_{22}V_2. \end{gathered} \tag{5}$$

Formulas (2), (3), and (4) make it possible to represent an O-optocoupler as a circuit element and, consequently, make it possible to calculate optoelectronic circuits. The equality to zero of the matrix elements Y_{12}, Z_{12}, h_{12} expresses the absence of reverse influence of the output on the input, while the purely optical coupling between the emitter and the photodetector provides electrical isolation, i.e., the possibility of directly matching circuits with different voltage and frequency regimes. The combination in an O-optocoupler of amplifying and isolating properties determines the range of typical problems of optoelectronic circuit engineering.

2. The next problem consists in establishing the relation between the transfer functions of the components and couplings of the optocoupler α, γ, θ, Z_{sd}, and Y_{fr} and the quantities characterizing the materials and structures by means of which these components and couplings are realized. The solution of this problem is necessary both for the purposeful design and technological fabrication of an optocoupler with the required circuit characteristics, and for determining the microparameters of light-emitting diodes, photoresistors, fiber-optic connections, etc., from measurement of the Y-, Z-, or h-parameters of an optocoupler amplifier stage assembled on the basis of these elements.

3. We write the expression for Y_{sd}, taking into account that an injection light-emitting diode is a semiconductor diode with a thick base ($W/L \gg 1$). The small-signal impedance of such a diode is determined, as is known ([8-10]), by the expression

$$Y_{\text{sd}} = \left(\sqrt{1 + j\omega\tau} + j\omega r_i C_b\right) / \left(r_i + r\sqrt{1 + j\omega\tau} + j\omega r r_i C_b\right). \tag{6}$$

Here ω is the frequency of the electrical signal; τ is the lifetime of the injected carriers; r_i and r are, respectively, the differential resistance of the p—n junction and the resistance of the base of the light-emitting diode; C_b is the barrier capacitance of the p—n junction.

We shall calculate the quantity α, assuming that recombination has a monomolecular character and proceeds under conditions of a low injection level (light-emitting diodes, as a rule, are fabricated on the basis of sufficiently strongly doped p- and n-regions ([11,12])). The optical signal generated by

LED, is described by the formula

$$b_1 = \int_0^\infty \frac{p_1(x,t)}{\tau}\, dx, \tag{7}$$

where

$$p_1(x,t) = p_1(0)\exp\left(-\frac{x}{l}\sqrt{1 + j\omega\tau}\right) = \frac{q p_{\text{st}}(0)}{k_0 T}\, i_0 Z_{\text{d}} \exp\left(-\frac{x}{l}\sqrt{1 + j\omega\tau}\right). \tag{8}$$

Here $i_1 = |i_1|e^{j\omega t}$, $p_{\text{st}}(0)$ is the steady-state value of the hole concentration at the injecting contact, and $L = \sqrt{D\tau}$ is the diffusion length of holes in the n-region.

Noting that the product αY_{sd} enters into Y_{21}, from (7) and (8) we find

$$\alpha Y_{\text{sd}} = \frac{qp_{\text{st}}(0)}{k_0 T}\,\frac{\sqrt{D/\tau}}{\sqrt{1+j\omega\tau}}. \tag{9}$$

4. The light-transfer coefficient θ is determined by the geometry of the optical path and by the light losses in it. Since ω is the modulation frequency of the light intensity, which practically does not distort the spectra of carrier frequencies lying in the optical, ultraviolet, and infrared ranges, the complex refractive index of the light-transmitting medium (optical fiber, air, etc.) does not depend on ω, and consequently the modulus θ remains frequency-independent. The phase shift in the optical path may be neglected as long as the wavelength corresponding to the modulation frequency ω (the frequency of the electrical signal transmitted through the optical channel in the optocoupler) is large compared with the optical distance LED—photodetector, i.e., in any case up to frequencies of the order of 1 GHz. Consequently, the light-transfer coefficient θ is a real multiplier, independent of the form of the electrical signal.

5. We shall calculate the photoconductivity coefficient γ of the photoresistor here for the case of linear photoconductivity, neglecting, for simplicity, surface recombination of the electrons and holes excited by light. Using for the photogeneration function of nonequilibrium carriers the relation $\Gamma(x) = \eta k B e^{-kx}$ (η is the quantum yield, k is the absorption coefficient, B is the intensity of the incident light), from the continuity equation for the distribution of electrons and holes in the photoconductor we obtain

$$\tilde{p} = \tilde{n} = \frac{\eta k b L_\omega^2}{D_p(1-k^2L_\omega^2)}\left[\frac{kL_\omega\left(e^{-kd}\operatorname{ch} x/L_\omega - \operatorname{ch}(d-x)/L_\omega\right)}{\operatorname{sh} d/L_\omega} + e^{-kx}\right], \tag{10}$$

where $L_\omega = \mathcal{L}/\sqrt{1+j\omega\tau'}$, $\mathcal{L} = \sqrt{D_p\tau'}$ is the diffusion length; d is the length of the photoresistor in the direction of incidence of the light.

Taking into account that

$$g \equiv \left.\frac{\partial G}{\partial B}\right|_{V_2} b = \frac{h}{l}q(\mu_n+\mu_p)\int_0^d \tilde{p}\,dx$$

(l is the interelectrode distance, h is the thickness of the illuminated sample, μ_n and μ_p are the mobilities of electrons and holes), for the quantity γ we find

$$\gamma \equiv \frac{g}{b} = \frac{h}{l} q(\mu_n + \mu_p) \frac{\eta}{D_p} (1 - e^{-kd}) \frac{\mathcal{L}}{1 + j\omega\tau'}. \quad (11)$$

The second differential parameter of the photoresistor, Y_{fr0}, is its complex dark conductance, which in the general form may be written as

$$Y_{\text{fr0}} = 1/R_{\text{fr0}} + j\omega C_{\text{fr0}}. \quad (12)$$

6. Analogously to the consideration carried out above, circuit theory can be developed for optocouplers with photodetectors of other types (photodiodes, phototransistors, etc.), for which the stationary values of β were calculated in ([4,5]).

It should be noted that even under the simplifying assumptions made above, the theoretical expressions for the characteristics of an optocoupler, α, γ, etc., are complicated for engineering calculations. For the development of optoelectronics and the search for methods of fabricating optocouplers with the required properties, it is highly important to find approximate formulas, similar to how this was done in transistor electronics ([13–16]).

Physical-Technical Institute named after S. V. Starodubtsev Academy of Sciences of the Uzbek SSR Tashkent

Received 18 II 1970

REFERENCES

1. E. I. Adirovich, A. G. Vishnevetskii et al., DAN, **186**, 799 (1969).

2. E. I. Adirovich, N. Yunusov, Izv. AN UzSSR, ser. fiz.-matem. nauk, **13**, No. 3, 39 (1969).

3. E. I. Adirovich, P. I. Knigin et al., DAN, **186**, 1037 (1969).

4. E. I. Adirovich, D. A. Aronov, N. Yunusov, Fiz. i tekhn. poluprovodnikov, **3**, No. 9, 1395 (1969).

5. E. I. Adirovich, D. A. Aronov, N. Yunusov, Izv. AN UzSSR, ser. fiz.-matem. nauk, **13**, No. 6 (1969).

6. E. I. Adirovich, Sborn. Mikroelektronika, Vol. 1, p. 75, M., 1967.

7. E. I. Adirovich, Izv. vyssh. uchebn. zaved., Radioelektronika, **11**, 679 (1968).

8. V. Shockley, *Theory of Electronic Semiconductors*, IL, 1953.

9. E. I. Adirovich, A. N. Gubkin, B. D. Kopylovskii, Tr. Fiz. inst. im. Lebedeva AN SSSR, **20**, 126 (1963).

10. G. E. Pikus, *Fundamentals of the Theory of Semiconductor Devices*, Nauka, 1965.

11. B. M. Vul, V. S. Vavilov et al., FTT, **8**, 3, 908 (1966).

12. N. S. Dubrovskaya, S. S. Meskina et al., Fiz. i tekhn. poluprovodnikov, **3**, No. 12, 1834 (1968).

13. R. D. Middlebrook, *Introduction to the Theory of Transistors*, M., 1960.

14. E. I. Adirovich, A. Yu. Gordonov, Sborn. *Semiconductor Devices and Their Application*, Vol. 4, p. 39, 1960.

15. I. P. Stepanenko, *Fundamentals of the Theory of Transistors and Transistor Circuits*, M.–L., 1963.

16. A. Ya. Fedotov, *Fundamentals of the Physics of Semiconductor Devices*, M., 1969.

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