*LASER APPLICATIONS AND OTHER TOPICS OF QUANTUM ELECTRONICS*

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# A wide-aperture Pockels cell with three ring electrodes

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***Abstract*. A wide-aperture Pockels cell based on a DKDP crystal having an optical diameter of 70 mm is studied. Three silver ring electrodes deposited on the side surface of the crystal were used to apply a high-voltage rectangular pulse of variable duration from 50 to 150 ns to the cell. Chains of KT6117A (2N5551) transistors operating in the avalanche regime served as fast electron switches. The duration of the leading and trailing edges of the pulse formed by these switches did not exceed 15 ns. The nonuniformity of the transmission coefficient over the cross section of the cell caused by the inhomogeneity of the electric field inside the crystal was close to 3.5 %.**

***Keywords***: *Pockels effect, electrooptical cell, DKDP crystal.*

**1.** Optical switches based on the longitudinal Pockels effect are used widely in laser technology. In this work, we describe the characteristics of a Pockels cell (PC) used in the four-pass amplifier circuit of the Luch laser setup [1] intended for investigations in the field of controlled thermonuclear fusion. The required aperture (70 mm) of the PC allowed the formation of a longitudinal electric field by using ring electrodes [2] deposited on a cylindrical DKDP crystal. The construction of the PC was mainly determined by its temporal characteristics: the switching time $\tau_f = 10 - 15$ ns, the pulse duration $\tau_i$ (which can be varied from 50 to 150 ns), and the delay $\tau_d = 15 - 20$ ns between the triggering pulse and the high-voltage pulse applied to the PC crystal.

Chains of transistors working in the avalanche mode served as electron switches [3 – 7]. Such switches are fast and reliable. The requirement of controlling the switching time ruled out the use of a cable to form a high-voltage pulse. Two transistor switches, each of which was ‘connected’ to its own ring electrode on the crystal, were used to form the pulse supplied to the cell. The presence of a capacitive coupling (crystal of the cell) between the transistor switches led to parasitic (uncontrollable) actuation of the second switch by the first. The requirement of fast switching ($\tau_f = 10 - 15$ ns) for a comparatively high capacity of the cell ($C = C_c + C' = 80$ pF, where $C_c = 40$ pF is the capacity of the crystal and $C' = 40$ pF is the capacity of the cable connecting the crystal and the switches) made it impossible to use a stabilising capacity to prevent the parasitic switching [8]. The transistor switches were decoupled by using the three-electrode PC (Fig. 1).

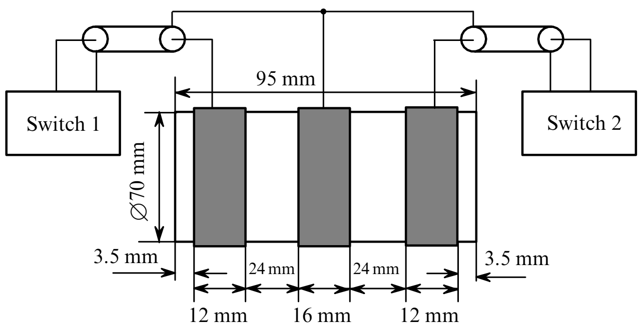


**Figure 1.** A three-electrode Pockels cell.

**2.** It is known [3, 9] that in the avalanche mode, transistor switches are opened in a regulated manner, but are closed spontaneously. Consequently, circuits with transistor switches are used only for creating a voltage drop. In a circuit with three electrodes, the first transistor switch produces a voltage drop (leading edge of a high-voltage pulse) across one of the outer electrodes, while the second switch produces yet another voltage drop (trailing edge) with a certain delay at the second outer electrode. Both voltage drops had the same polarity and consequently a high-voltage pulse of controllable duration was formed between the outer electrodes.

The transistor switch was the eight-stage Arkad’ev – Marx circuit. In turn, each stage comprised six series-connected KT6117A (2N5551) transistors. Such a transistor switch produced a voltage drop of 8 – 9 kV and withstood more than $10^5$ switchings without any apparent deterioration of its characteristics.

**3.** The Pockels cell was made of a DKDP crystal grown at the Institute of Applied Physics, Russian Academy of Sciences, Nizhnii Novgorod. The deuteration of various crystals was varied in the range 90 % – 94 %. To protect the

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crystal from atmospheric effects, its optical surface was covered by a film of the Rozakor organosilicon compound.

The necessity of using three electrodes instead of two in the PC raised a serious problem of obtaining a uniform transverse distribution of electric field in the crystal. This distribution has been studied in detail for a cylindrical crystal with two ring electrodes [2, 10, 11]. According to [11], the radial nonuniformity $\delta t$ of the transmission coefficient in a two-electrode cell was less than 1.5 % when the ratio of crystal length $L$ to its diameter $D$ was 1.3.

Figure 1 shows the position and size of the silver electrodes deposited on a z-cut DKDP crystal of diameter 70 mm and length 95 mm. Crystals of desired diameters and lengths were prepared with an accuracy of $\delta D = \pm 0.1$ mm and $\delta L/L = \pm 5\,\%$, while the position and size of the electrodes were maintained within an accuracy of $\delta l = \pm 0.5$ mm.

The electric field inhomogeneity in the PC crystal was studied by supplying a high dc voltage to it. For this purpose, the cell was placed between crossed polarisers (Glan prisms). The transmission coefficient $t$ of the cell was determined at the 1.064-μm wavelength of a Nd : YAG laser. The diameter $d = 2$ mm of the laser beam was small enough to allow the evaluation of $t$ at various points $r = (x, y)$ of the crystal cross section by scanning the beam.

According to Ref. [10], the PC transmission coefficient is described by the expression

$$t(r) = \sin^2 \frac{\pi}{2} \frac{u(r)}{u_{\lambda/2}}. \qquad (1)$$

Here, $u(r)$ is the potential difference between points at the opposite faces of the crystal with transverse coordinates $x$, $y$ $[r = (x^2 + y^2)^{1/2}]$, which depends on the voltage $U$ across the PC electrodes and $u_{\lambda/2}$, the half-wave voltage across the crystal [12], is a parameter determined by the lasing wavelength $\lambda$ and the properties of the DKDP crystal being used (including the degree of its deuteration [13]). Assuming that $u$ and $U$ are related linearly, it is convenient to rewrite expression (1) in the form

$$t(r) = \sin^2 \frac{\pi}{2} \frac{U}{U_{\lambda/2}(r)}, \qquad (2)$$

where $U_{\lambda/2}(r)$ is the voltage across the PC electrodes for which the potential difference $u$ between the end faces of the crystal at a given point $r$ of the crystal cross section is equal to the half-wave voltage $u(r) = u_{\lambda/2}$. For definiteness, we will call the quantity $U_{\lambda/2}(r)$ the effective half-wave voltage. The following relation holds between $u(r)$ and $U_{\lambda/2}(r)$:

$$U_{\lambda/2}(r) = U \frac{u_{\lambda/2}}{u(r)}. \qquad (3)$$

Thus, we have two methods based on expressions (1) and (2) for finding the transverse distribution of the electric field inside a crystal. In the first case, by measuring the distribution $t(r)$ for a fixed voltage $U$ across the crystal electrodes, we determine the distribution of the quantity $u(r)/u_{\lambda/2}$ or of the effective half-wave voltage $U_{\lambda/2}(r)$ using expressions (1) or (2). In the second case, by measuring the voltage across the crystal electrodes for which the transmission coefficient $t$ attains its maximum value at a given point on the cross section, we determine the distribution $U_{\lambda/2}(r)$. Our measurements have shown that the second method is more accurate and convenient, but more time consuming.

Knowing the distribution $U_{\lambda/2}(r)$, we can use expression (2) to find the distribution $t(r)$ over the crystal cross section for any voltage across the electrodes. This allows us to minimise the inhomogeneity of the quantity $t(r)$ in the voltage $U$. Note that to improve the accuracy of measurements, we determined the quantity $1 - t(r)$ by placing the PC between parallel polarisers.

**4.** The transmission coefficient $t(x, y)$ of the PC and the distribution $U_{\lambda/2}(r)$ were determined with a step of 2 – 5 mm over the entire cross section of the crystal (first method). In the second method, the distribution $U_{\lambda/2}(r)$ was determined with the same step along the crystallographic axes $X$ and $Y$. To avoid crowding of the figures, we shall present below only the averaged or selected typical curves. These curves were obtained by displacing the probe beam along the $X$ or $Y$ axis. Most of the distributions $U_{\lambda/2}(r)$ presented here were obtained by the second method.

We compared the distributions $U_{\lambda/2}(r)$ obtained for the same ⌀30 × 40-mm crystal with two [Fig. 2, curve (*1*)] and three [Fig. 2, curve (*2*)] electrodes. In the two-electrode geometry, the electrode size and arrangement were the same as in Ref. [11]. Note that curve (*1*) is close to the corresponding curve obtained in Ref. [11]. The nonuniformity $\delta t$ of the transmission coefficient over the crystal cross section did not exceed 1.5 % and 3.5 % for two- and three-electrode PCs respectively, which is in good agreement with the data presented in Fig. 2.

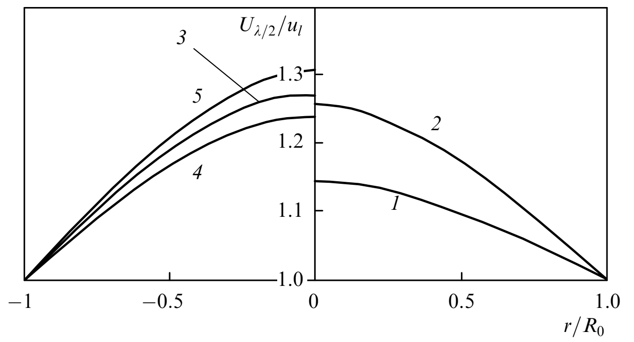


**Figure 2.** Radial dependences of the normalised effective half-wave voltage $U_{\lambda/2}(r/R_0)/u_l$ obtained for the same crystal in two- and three-electrode geometry respectively, [curves (*1*), (*2*)], the dependence averaged over all the crystals (curve 3), and the dependences obtained for specific crystals and differing most strongly from the averaged dependence [curves (*4*), (*5*)].

Only three-electrode version of the PC was used in subsequent experiments. We determined the distribution $U_{\lambda/2}(r)$ for three ⌀30 × 40-mm crystals and four ⌀70 × 95-mm crystals. The fitting curve was drawn through experimental points for each crystal by the least squares method

$$U_{\lambda/2}(r) = \frac{u_l(1 + c)}{1 + c(r/R_0)^p}. \qquad (4)$$

Here, $R_0$ is the crystal radius; $u_l$, $c$ and $p$ are the fitting parameters; and $u_l = U_{\lambda/2}(r = R_0)$. The standard deviation of the quantity $U_{\lambda/2}(r)$ from the experimental data did not exceed 100 V. The values of fitting parameters averaged over all the seven crystals were $c = 0.271 \pm 0.021$, $p = 1.96 \pm 0.16$, and $u_l = 6.40 \pm 0.17$ kV. The averaged curve $U_{\lambda/2}(r)$ obtained this way is shown in Fig. 2 together with the 'extreme' curves, i.e., the dependences for specific crystals differing most strongly from the averaged curve. For a two-electrode PC [Fig. 2, curve (*1*)], the fitting curve parameters [expression (4)] are $c' = 0.146$ and $p' = 1.7$.

**5.** By using expression (4), we can easily formulate the criterion or conditions under which the nonuniformity of the transmission coefficient $t(r)$ of the PC over the crystal cross section is minimum. The voltage $U_0$ across the electrodes of the crystal must satisfy the condition

$$U_0 = (1 - \Delta_0)U_{\lambda/2}(r = 0)$$

or

$$U_0 = (1 + \Delta_0)U_{\lambda/2}(r = R_0), \qquad (5)$$

where $\Delta_0 = c/(2 + c)$. At the point $r_0/R_0 = 2^{-1/p} \simeq 0.7$ of the crystal cross section, the quantity $t(r = r_0) = 1$. The latter condition is more convenient for determining the optimal voltage $U_0$ across the crystal. For $U = U_0$, the maximum nonuniformity of $t(r)$, according to (2), is

$$\Delta t_{\max} = [1 - t(r)]_{\max} = \sin^2\frac{\pi}{2}\Delta_0 = \sin^2\frac{\pi}{2}\frac{c}{2 + c}. \qquad (6)$$

According to this relation, $\Delta t_{\max} = 3.5\,\%$ for three electrodes ($c = 0.271$) and 1.1 % for two electrodes ($c = 0.146$).

**6.** The inhomogeneity of real DKDP crystals, caused by the internal stresses, for example, leads to a violation of relation (1), and the parameter $t(r) \neq 0$ even for $u(r) = 0$. While discussing the crystal inhomogeneity in this work, we will mean just this kind of a nonuniformity leading to a distortion of the characteristic birefringence pattern in a uniaxial crystal.

The dependence $U_{\lambda/2}(r)$ determined by the first and second methods may become nonsymmetric relative to the crystal centre $r = 0$ due to crystal inhomogeneities. This is especially typical of large crystals. For example, Fig. 3 shows the dependence $U_{\lambda/2}(r)$ obtained for a $\varnothing 70 \times 95$ mm crystal along the crystallographic axis $X$ [curve (*1*)]. Comparing this curve with those presented in Fig. 2, we find that crystal inhomogeneities may in fact conceal information about the transverse profile of the electric field formed in the crystal.

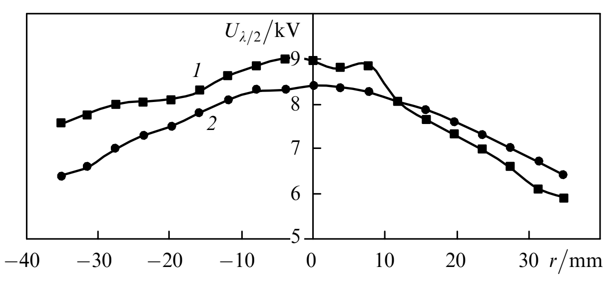


**Figure 3.** Radial dependences of the effective half-wave voltage $U_{\lambda/2}$ obtained by the second method [curve (*1*)] and by the modified second method [curve (*2*)].

We modified the second method for determining the dependence $U_{\lambda/2}(r)$. First we determined the transmission coefficient $t\,(U = 0) = t_0$ of the PC in the absence of voltage across the crystal. After this, voltage was applied across the crystal so that the condition $t(U_0) = 1 - t_0$ was satisfied instead of the condition $t(U_0) = 1$, where $U_0$ was assumed to be equal to $U_{\lambda/2}(r)$. Note that the condition $t(U_0) = 1 - t_0$ is satisfied for two different voltages $U_{01}$ and $U_{02}$. However, the choice between these two voltages can be made easily with the help of the condition of continuity of the function $U_{\lambda/2}(r) = U_0(r)$. Curve (*2*) presented in Fig. 3 was plotted for the same crystal as curve (*1*), but by using the modified second method. Curve (*2*) obtained this way is symmetric relative to the crystal centre. It coincides to a reasonably high degree of precision with the curves $U_{\lambda/2}(r)$ obtained by the second method in a crystal with insignificant inhomogeneities. As a matter of fact, the effective electric potential $\bar{U}$ leading to the same depolarisation of the radiation transmitted through the crystal as the mechanical stress (inhomogeneity) was determined at a given point $r$ of the crystal cross section by the modified second method. After this, the quantity $U_{\lambda/2}(r)$ is taken into account while determining $\bar{U}$. The dependences $U_{\lambda/2}(r)$ presented above were obtained by the modified second method if the crystal inhomogeneity $t_0$ exceeds the value $\bar{t_0} = 0.003$. Note that $\bar{t_0} = 0.003$ corresponds to $\bar{U} \sim 250$ V.

**7.** It was mentioned in Section 3 that the transverse electric field distribution in a crystal, characterised by the dependence $U_{\lambda/2}(r)$, was determined by two methods. The error $\delta U$ in determining $U_{\lambda/2}(r)$ by the second method depends on the voltmeter (a C196 static kilovoltmeter) used for measurements and on the stability of dc voltage from the power supply. In our experiments, $\delta U \leqslant 100$ V. The 'accuracy of measurement' of $U_{\lambda/2}(r)$ by the first method was determined by the quality of the crystal. Figure 4 shows the radial dependence $U_{\lambda/2}(r)$ of the effective half-wave voltage obtained in one of the crystals $\varnothing 70 \times 95$ mm and the fitting curve constructed for these data with the help of expression (4). In this case, the standard deviation $\delta U = 0.6$ kV. It is more difficult to take into account the inhomogeneities using the first method than by using the modified second method.

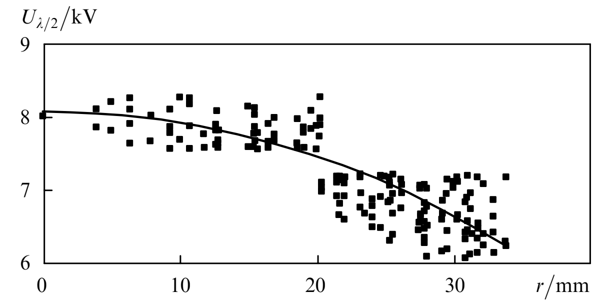


**Figure 4.** Radial dependence (squares) of the effective half-wave voltage $U_{\lambda/2}$ obtained by the first method in one of the investigated crystals ($\varnothing 70 \times 95$ mm). The solid curve is the best fit by expression (4).

**8.** We also studied the dynamic characteristics of a PC with transistor switches. For this purpose, a 500-ns pulse from a free-running Nd : YAG laser first passed through the PC placed between two parallel polarisers, and then was directed at an LFD-2A avalanche photodiode. In the middle of the laser pulse, a high-voltage pulse of duration $\sim 120$ ns and amplitude $U_0$ was supplied to the PC. During these 120 ns, the PC was locked and the laser pulse did not reach the photodiode. The electric pulse from the photodiode was recorded with a video camera from the screen of a C1-104 oscilloscope with a bandwidth of 500 MHz, and the image was stored and processed (Fig. 5). The processing of oscillograms showed that, other conditions remaining the same, the durations (at the 0.1 – 0.9 level) $\tau_f$ and $\tau_b$ of the leading and trailing edges of the pulse were determined mainly by the capacitance of the PC. For the $\varnothing 30 \times 40$-mm crystals ($C_c = 18$ pF), $\tau_f = 7.9 \pm 0.7$ ns and $\tau_b = 8.1 \pm 0.6$ ns. The corresponding values for the $\varnothing 70 \times 95$-mm crystals ($C = C_c + C' = 80$ pF) were $\tau_f = 14.8 \pm 0.5$ ns and $\tau_b = 15.6 \pm 1.1$ ns. The delay between the external triggering pulse and the high-voltage pulse supplied to the PC was varied in the range 10 – 25 ns depending on the specific triggering circuit. The delay instability did not exceed 3 ns.

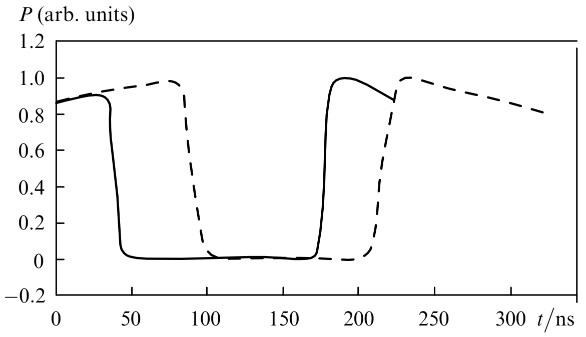


**Figure 5.** Oscillograms of pulses from a free-running laser transmitted through a $\varnothing 30 \times 40$-mm PC (solid curve) and a $\varnothing 70 \times 95$ mm PC (dashed curve).

**9.** Thus, we have presented in this work the results of investigation of the three-electrode PCs developed at the Institute of Applied Physics, Russian Academy of Sciences, Nizhnii Novgorod and controlled by fast electron switches. The latter are based on avalanche transistors. We used the 90 % – 94 % deuterated DKDP crystals of sizes $\varnothing 30 \times 40$ mm and $\varnothing 70 \times 95$ mm in the PC. The transmission coefficient of the PC, which was determined by the Fresnel losses, was 90 % at a wavelength of 1.064 μm. For zero voltage across the electrodes in a PC, the aperture-averaged contrast was more than 100. The contrast was measured as the ratio of energies of the light pulses passing through a PC placed between two parallel and crossed polarisers. The radiation energy incident on the PC was maintained at a constant level. The nonuniformity of the transmission coefficient $t(r)$ over the cross section of the PC due to a nonuniformity of the electric field in the crystal did not exceed 3.5 %. The real value of the nonuniformity of $t(r)$, determined by the nonuniformity of the electric field as well as the PC crystal inhomogeneity, varied in the range 4 % – 12 %.

A high-voltage pulse with an amplitude of about 8 kV (half-wave voltage), whose duration was controlled in the range 50 – 150 ns, was formed in the crystal with the help of an electric circuit. The leading front duration of the pulse did not exceed 14.8 ns, while the duration of the trailing edge was within 15.6 ns. The electronic switches for each of the seven cells prepared for investigations withstood more than $10^5$ switchings without a noticeable deterioration of the characteristics of the high-voltage pulse.

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