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# Polarisation-independent electrooptical switch based on $LiNbO_3$ and $LiTaO_3$ crystals

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*Abstract*. **Two electrooptical switches for nonpolarised narrow beams from fibre laser and luminescent sources are considered. Requirements for crystals, the accuracy of their thermal stabilisation, and tolerances for their manufacturing and adjustment are estimated from the point of view of the maximum switching contrast. A switch based on two $LiNbO_3$ crystals with a control half-wave voltage of $\sim 270$ V, connected with an isotropic single-mode fibre, is tested. It is shown that errors in the adjustment and manufacturing of crystal phase elements can be compensated by a weak controllable heating of one of the crystals.**

***Keywords***: *electrooptical switch, fibre laser.*

## 1. Introduction

Nanosecond electrooptical modulators are commonly used in laser optics as intracavity *Q* switches or extra-cavity pulse shapers for producing optical pulses of the required duration. Electrooptical modulators are usually intended for operation with polarised radiation [1 – 3]. The development of luminescent and laser sources based on isotropic fibres stimulated the elaboration of modulators capable of operating with nonpolarised light without polarisation losses [4, 5].

A polarisation-independent modulator can be fabricated by placing its controllable phase element not simply between two polarisers but between two polarisation dividers [6]. These dividers can be two identical prisms in the form of parallelepipeds made of a birefringent crystal ($CaCO_3$, α-BBO, $YVO_4$, $TiO_2$, etc.). The first prism splits the input nonpolarised beam into two parallel, orthogonally polarised beams, which propagate through a common controllable phase element. Then, the beams enter the second prism, which either combines them again into one beam or separates them even greater, depending on their polarisation states.

We studied two variants of the modulator in the optical switch regime, which had different phase elements. The dependence of the switching contrast (the ratio of the maximum and minimum intensity of light at the modulator output) on the optical quality of crystals, the accuracy of their manufacturing and temperature gradients in electrooptical elements was estimated. The modulators were compared with phase elements made of $LiNbO_3$ and $LiTaO_3$ crystals. A modulator made of two $LiNbO_3$ crystals, rigidly connected through gradient lenses with isotropic fibres, was tested.

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## 2. Optical schemes

In the first variant of the electrooptical switch, two collimated, orthogonally polarised beams propagate along the optical axis of an electrooptical $LiNbO_3$ (or $LiTaO_3$) crystal (Fig. 1). In the second variant, these beams propagate through a controllable phase element consisting of a pair of identical $LiNbO_3$ crystals (Fig. 2). In this case, the beams propagate perpendicular to the orthogonally oriented optical axes (the principle of 'optical thermal compensation' [1]) and their planes of polarisation make angles $\pm 45°$ with these axes.

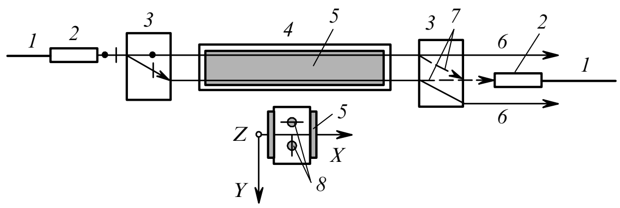


**Figure 1.** Scheme of single-crystal polarisation-independent switch 1: (*1*) input and output isotropic single-mode fibres; (*2*) matching gradient lens; (*3*) polarisation-dividing $CaCO_3$ prism; (*4*) electrooptical $LiNbO_3$ crystal; (*5*) electrodes on the electrooptical crystal; (*6*) path of orthogonally polarised beams in the absence of the control voltage across crystal (*4*); (*7*) path of orthogonally polarised beams (dashed straight lines) in the presence of the control voltage $U_\pi$ across crystal (*4*); (*8*) polarised beams in the cross section of the electrooptical crystal (*X*, *Y*, *Z* are the crystallographic axes of the electrooptical crystal, *Z* is the optical axis).

In both variants, the beams are split and combined by using $CaCO_3$ polarisation-dividing parallelepiped prisms (PDPs) with the angular deflection of the extraordinary e-beam $\delta \approx 6°$.

When the voltage *U*, equal to the half-wave voltage $U_\pi$, is applied to the crystal, each of the beams at the output of the electrooptical crystal(s) changes the azimuth of its plane-polarised state by 90°. In this case, the output PDP

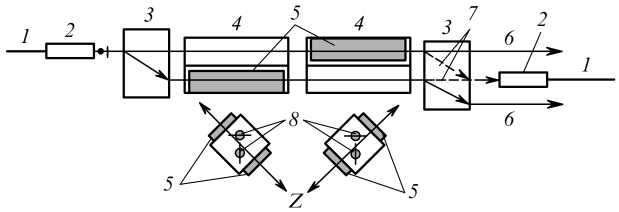


**Figure 2.** Scheme of two-crystal polarisation-independent switch 2: (*1*) input and output isotropic single-mode fibres; (*2*) matching gradient lens; (*3*) polarisation-dividing $CaCO_3$ prism; (4) two identical electrooptical $LiNbO_3$ crystals; (*5*) electrodes on electrooptical crystals; (*6*) path of orthogonally polarised beams in the absence of the control voltage across crystals (*4*); (*7*) path of orthogonally polarised beams (dashed straight lines) in the presence of the control voltage $U_{\pi}$ across crystals (*4*); (*8*) polarised beams in the cross sections of electrooptical crystals (*Z* are optical axis of electrooptical crystals).

combines polarised beams again into a common beam, which is coupled into the output fibre through a gradient lens. For $U = 0$, the polarisation states of the beams do not change, and as a result, the beams become separated even greater behind the output PDP and either are not coupled into the fibre or do not propagate in it due to restrictions imposed by the numerical aperture of the fibre. Both schemes operate by switching on, i.e. the switch is closed in the absence of the control voltage and is open when the voltage is applied. Because the degree of 'closeness' of the switch is not related to the control voltage, this regime provides the maximum switching contrast within the entire spectral band $\Delta\lambda \approx 50$ nm of the commuting light.

## 3. Switching contrast

The influence of the optical quality of crystals, their temperature, the accuracy of their manufacturing and adjustment, and the spectral width of collimated light on the switching contrast was analysed by calculating stationary and electrooptical relative phases and then the intensity of each of the beams [2, 3]. The intensities of the beams at the PDP output were summed. The spectral and temperature variations of the refractive indices, half-wave voltage, and the temperature dependence of the linear dimensions of crystals were taken into account. Weak dispersion and temperature variations of the electrooptical coefficients $r_{ik}$ in the spectral range $\Delta\lambda \approx 50$ nm under study at temperatures $0-50\,^{\circ}$C were neglected. In addition, we assumed that the inhomogeneities of the refractive indices of electrooptical crystals over a small-diameter (0.5 mm) beam cross section were negligibly small.

Let us present the parameters of crystals of the phase element used in calculations. For the $LiNbO_3$ crystal ($T = 0-50\,^{\circ}$C) [7], the linear expansion coefficients along and perpendicular to the optical axis are $\alpha_{\parallel} \approx 0.2 \times 10^{-5}$ K$^{-1}$ and $\alpha_{\perp} \approx 1.4 \times 10^{-5}$ K$^{-1}$, respectively. The dispersion and temperature dependences of the refractive indices $n_{\rm o}(\lambda, T)$ and $n_{\rm e}(\lambda, T)$ of this crystal are taken from [8]. For the $LiTaO_3$ crystal ($T = 0-50\,^{\circ}$C) [9], the coefficients are $\alpha_{\parallel} \approx 0.12 \times 10^{-5}$ K$^{-1}$ and $\alpha_{\perp} \approx 2.2 \times 10^{-5}$ K$^{-1}$. The dispersion dependences of refractive indices of the $LiTaO_3$ crystal in the wavelength range between 1.05 and 1.1 μm were described by the expressions [3]

$$n_{\rm o}(\lambda) \approx 2.13720 - 0.046(\lambda - 1.05),$$

$$n_{\rm e}(\lambda) \approx 2.14107 - 0.048(\lambda - 1.05),$$

where $\lambda$ is measured in micrometres. The derivatives $dn_{\rm o}/dT = 2 \times 10^{-5}$ K$^{-1}$ and $dn_{\rm e}/dT = 5 \times 10^{-5}$ K$^{-1}$ were obtained from the temperature dependences $n_{\rm o}(T)$ and $n_{\rm e}(T)$ [9].

Figures 3–7 present the results of our analysis. Figures 3 and 4 concern the switch containing one crystal (Fig. 1), Figs 6 and 7 describe the parameters of the switch with two crystals (Fig. 2), and Fig. 5 concerns both switches. Figure 3 demonstrates a weak temperature dependence of the switching contrast for electrooptical $LiNbO_3$ and $LiTaO_3$ crystals.

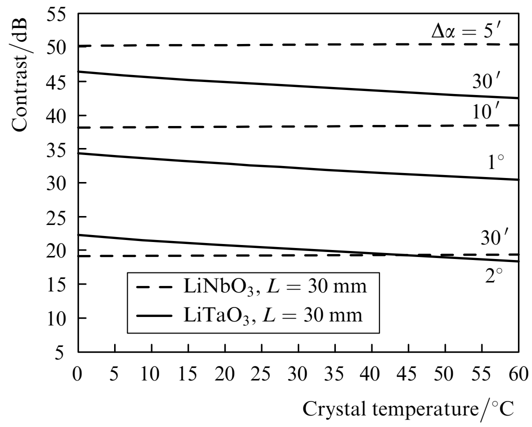


**Figure 3.** Dependences of the switching contrast on the temperature $T$ of the electrooptical crystal, the misalignment angle, and material of the electrooptical phase element of switch 1.

The calculation was performed by assuming that the crystal is optically homogeneous along the light beam path (i.e. $\Delta n_{\rm o} = \Delta n_{\rm e} = 0$) and the optical axis is directed along the normal to the input crystal face. The parameters are the crystal length $L$ and the angle $\Delta\alpha$ of misalignment in air between the incident beam and normal to the input crystal face. Note that the thermal stability of a $LiTaO_3$ prism is noticeably worse than that of a $LiNbO_3$ prism.

An advantage of the electrooptical $LiTaO_3$ prism is that its angular alignment is less critical. Figure 4 shows the dependences of the switching contrast on the misalignment

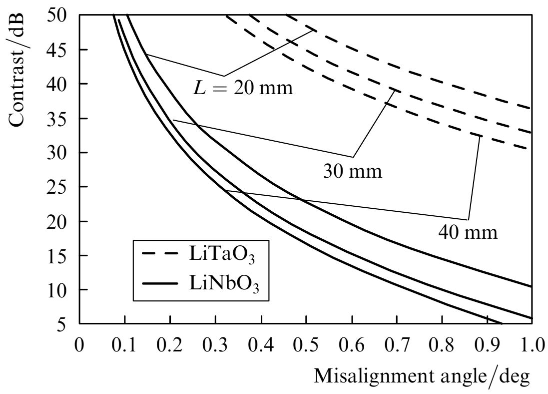


**Figure 4.** Dependences of the switching contrast on the misalignment angle $\Delta\alpha$ of the electrooptical crystal of switch 1 for $LiNbO_1$ and $LiTaO_1$ crystals of different lengths.

angle $\Delta\alpha$ of a collimated beam for electrooptical crystals of different lengths at room temperature 20 °C. For example, to obtain the switching contrast no less than 35 dB for the $LiNbO_3$ prism with the maximum possible but still real length 30 mm, the prism should be aligned with an error of no more than 12′, while in the case of the $LiTaO_3$ prism, it is sufficient to provide an error of 53′ (i.e. $\sim 1°$).

The dependences of the switching contrast on the degree of inhomogeneity of the birefringence of electrooptical crystals with different total lengths $L$ are shown in Fig. 5. The calculations were performed for the beam incident normally on the input face and propagating along the optical axis at $T = 20$ °C. Any additional birefringence $\delta n$ (with respect to the intrinsic birefringence $\Delta n = |n_o - n_e|$ of an ideal crystal) caused by internal stresses in the crystal along the beam propagation path and affecting the relative phase is treated as the birefringence inhomogeneity. This inhomogeneity is manifested in the same way in both modulators, and therefore Fig. 5 concerns both of them. It is easy to see that there exists a rather strict criterion for selecting crystals, especially, at large lengths $L$. For example, to provide the switching contrast of 30 dB for a crystal of length $L = 20$ mm, the admissible inhomogeneity should be $\delta n \approx 5 \times 10^{-7}$(!). In fact, the situation is not so catastrophic, because in practice, by using the angular adjustment of a crystal (if, of course, strong stresses in the crystal are absent), the light beams can be oriented so that the contrast $\sim 30$ dB is achieved even in standard crystals, for example, in a LN-9 $LiNbO_3$ crystal. Preliminary, of course, crystal slabs should be tested for the presence of homogeneous regions (at least by the quality of the conoscopic pattern along the optical axis), be separating the regions where the undistorted conoscopic 'cross' is observed.

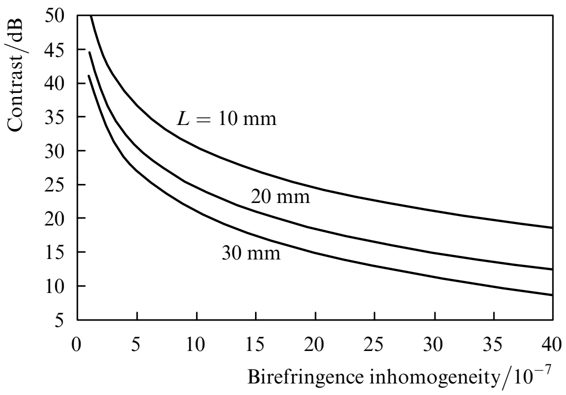


**Figure 5.** Dependences of the switching contrast on the degree of inhomogeneity $\delta n$ of birefringence of $LiNbO_3$ and $LiTaO_3$ crystals for different lengths of the electrooptical phase element in switches 1 and 2.

We found that the switching contrast very weakly depends on the spectral width and the wavelength of light within the band $\Delta\lambda = 50$ nm (the contrast variation was less than 0.1 dB) in both schemes. For a phase element made of a $LiNbO_3$ crystal in switch scheme 1, this is valid for the misalignment angles $\Delta\alpha < 1°$, and for switch scheme 2 – for the difference of lengths of the two crystals $\Delta L < 1$ μm. In other words, according to this 'spectral' parameter for scheme 2, it is sufficient to manufacture crystals with the wedge angle $\sim 5'$ and the error of their angular adjustment can be approximately the same.

Figures 6 and 7 show the dependences of the contrast in optical scheme 2 on the difference $\Delta L$ of lengths of two electrooptical crystals and the difference of their temperatures. Calculations were performed under the following conditions: (Fig. 6) homogeneous crystals have the same temperature, the faces of the electrooptical prism are oriented along crystallographic axes, and light is incident normally on the input face; (Fig. 7) homogeneous crystals have the same length, the faces of the electrooptical prism are oriented along crystallographic axes, and light is incident normally on the input face.

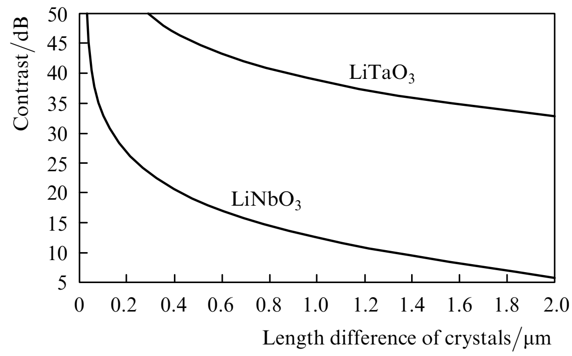


**Figure 6.** Dependences of the switching contrast on the difference $\Delta L$ of lengths of the electrooptical $LiNbO_3$ and $LiTaO_3$ crystals in switch 2.

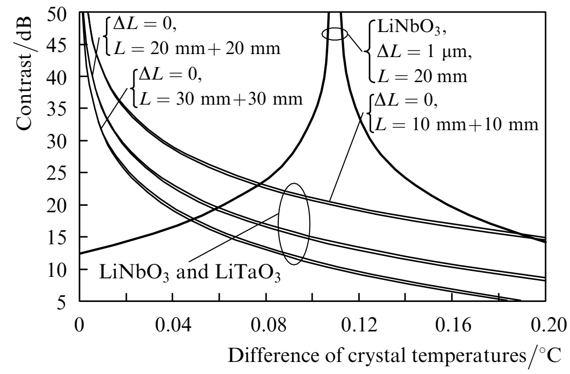


**Figure 7.** Dependence of the contrast of switch 2 on the temperature difference $\Delta T$ of electrooptical crystals, their total length, and the difference of their lengths $\Delta L$ along the beam propagation path.

It is easy to see that, to obtain the required contrast, for example, no less than 30 dB in the case of $LiNbO_3$ crystals, the requirements for the equality of their lengths are quite rigid ($\Delta L < 0.15$ μm). If an optician polishes a crystalline block with a square cross section glued, for example, from 100 crystals of cross section $2 \times 2$ mm each, this requirement on the 20-mm base means that the angular tolerance for the common wedge is of the order of 1.5″ (!). Only in this case the lengths of the first and last samples from a series of 10 crystals will differ by no more than 0.15 μm. Therefore, it is reasonable to manufacture a small number of crystals, for example, four crystals placed within a $2 \times 2$ square and enclosed in low-cost optical 'parasitic' cases of a large size. However, in this case the manufacturing of high-quality samples will be also a quite complicated problem because the admissible wedge is still quite small ($\sim 7.5''$).

This problem can be solved by the temperature adjustment of the contrast. Figure 7 demonstrates a strong dependence of the latter on the difference $\Delta T$ of temperatures of crystals. The required temperature difference $\Delta T$ can be simply obtained by slightly heating the plated electrodes of one of the crystals. This can be done, for example, with the help of low-power resistors glued to the electrodes. Figure 7 illustrates the dependence of the contrast on $\Delta T$ for roughly manufactured $LiNbO_3$ samples with $\Delta L = 1$ μm. One can see that $\Delta T \sim 0.10 - 0.12\,^{\circ}C$ provides the contrast exceeding 30 dB. Obviously, such a temperature difference $\Delta T$ should be maintained accurate to a few hundredths of a degree, i.e. the device design should provide the temperature stabilisation at this level even when the common temperature of crystals changes due to temperature variations in the environment. Such a task is not too complicated. Relatively massive electrodes are required in a closed housing made of a material with a high heat conduction and a high heat capacity. The problem can be also solved by using automatic thermal stabilisation with the help of thermal sensors.

As follows from Fig. 6, the tolerances for the length difference $\Delta L$ for the $LiTaO_3$ crystals are more than an order of magnitude milder than those for $LiNbO_3$ crystals.

Thus, the results of our calculations show that the effect of errors in the manufacturing and adjustment of electrooptical samples, and in some cases of optical inhomogeneities, can be considerably weakened by the angular and temperature 'adjustment' of crystals.

By using the known parameters of crystals (Table 1), we present (in Tables 2 and 3) the calculated values of static voltages $U_\pi$ for two schemes of the modulator-switch at a wavelength of 1.06 μm and the interelectrode distance $d =$ 2.2 mm [2, 3].

**Table 1.** Electrooptical coefficients and principal values of refractive indices of $LiNbO_3$ and $LiTaO_3$ crystals.

| Crystal | $n_o$ | $n_e$ | $r_{13}$/m V$^{-1}$ | $r_{33}$/m V$^{-1}$ | $r_{22}$/m V$^{-1}$ |
|---|---|---|---|---|---|
| $LiNbO_3$ | 2.2343 | 2.1553 | $8.6 \times 10^{-12}$ | $30.8 \times 10^{-12}$ | $7 \times 10^{-12}$ |
| $LiTaO_3$ | 2.1367 | 2.1406 | $7.9 \times 10^{-12}$ | $35.8 \times 10^{-12}$ | $1 \times 10^{-12}$ |

**Table 2.** Control half-wave voltage $U_\pi$ for single-crystal scheme 1.

| Crystal | $U_\pi$/V | | |
|---|---|---|---|
| | $L = 20$ mm | $L = 30$ mm | $L = 40$ mm |
| $LiNbO_3$ | 747 | 498 | 373 |
| $LiTaO_3$ | 5976 | 3984 | 2988 |

**Table 3.** Control half-wave voltage $U_\pi$ for two-crystal scheme 2.

| Crystal | $U_\pi$/V | | |
|---|---|---|---|
| | $L = 10$ mm + 10 mm | $L = 20$ mm + 20 mm | $L = 30$ mm + 30 mm |
| $LiNbO_3$ | 549 | 274 | 183 |
| $LiTaO_3$ | 425 | 213 | 142 |

## 4. Experiment

We assembled a prototype of thermally compensated scheme 2 with two standard electrooptical LN-9 $LiNbO_3$ crystals of the same size (2.2 × 2.2 × 20 mm). Two pairs of crystal samples manufactured in a common block were tested. The wedge of each of the samples did not exceed 1′. The alignment error of crystallographic axes was within ±15′. Crystal slabs were preliminary visually studied for homogeneity by the quality of the conoscopic pattern in polarised light of a He–Ne laser by scanning the focal waist over the slab cross section. The most homogeneous regions were used for manufacturing electrooptical prisms.

Nonpolarised radiation was obtained from a 1.064-μm, 10-mW luminescent fibre source ($\Delta\lambda = 0.01$ μm) with the output power stabilised within ±0.5 %. On the end faces of the input and output isotropic fibres (with the numerical aperture NA = 0.1) the gradient lenses were placed, which collimated a Gaussian beam to a diameter of 0.4 mm. Gold electrodes with a chrome sublayer were deposited on electrooptical crystals, and 2-mm-thick brass electrodes were then pressed against them. A 0.25-W resistor glued to the centre of upper electrodes of each of the crystals provided the temperature adjustment. Prisms made of uniaxial calcite crystals ($L = 10$ mm) were used as polarisation dividers. The modulator was placed into a brass housing with 1.5-mm-thick walls. In the absence of the housing, the angular adjustment of a pair of electrooptical crystals with respect to the incident collimated beams could be performed.

The static characteristic of the modulator is almost ideal (Fig. 8). The values of the half-wave control voltage $U_\pi$ measured many times fall in the range $270 \pm 5$ V, in accordance with the preliminary estimate. The maximum static switching contrast obtained for the best pair of $LiNbO_3$ crystals was ~ 34 dB, while this contrast for another pair of electrooptical crystals having a greater control voltage was ~ 23 dB. The 34-dB contrast was achieved either by the angular adjustment of a pair of electrooptical crystals as a whole or by heating one of the crystals in the pair (which was selected experimentally). In the first case, the result was less stable because the housing was removed to perform adjustment. The modulator without the housing was sensitive to any convection motions of the air, while the housing eliminated this effect.

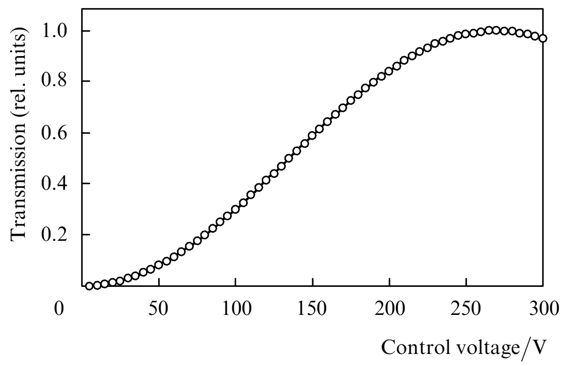


**Figure 8.** Experimental static characteristic of the polarisation-independent electrooptical switch with a controllable double-$LiNbO_3$ crystal phase element.

Figure 9 demonstrates the adjustment of the modulator by heating one of the crystals in scheme 2. The figure shows the dependence of the switching contrast on the heating power for two angular orientations of a pair of electrooptical crystals with respect to the incident beams. The curves in Fig. 9 correlate with the calculated curves in Fig. 7. The curves in both figures have extrema at the nonzero differences of optical paths (obtained either due to different length of the crystals or due to the misalignment of wedge-like samples).

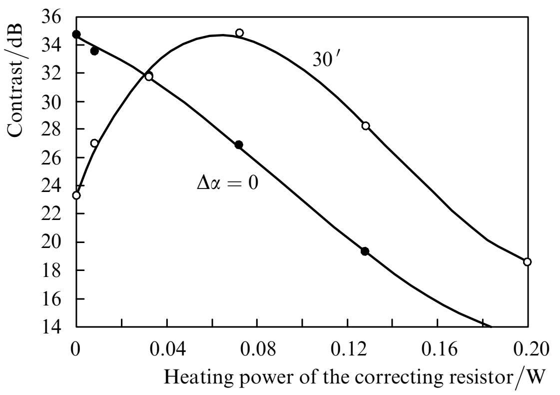


**Figure 9.** Adjustment of the contrast of switch 2 by heating one of the electrooptical crystals.

## 5. Conclusions

Our study has shown that polarisation-independent $LiNbO_3$ and $LiTaO_3$ crystal modulators are quite real. The aperture restrictions imposed by the necessity to transmit simultaneously two beams through an electrooptical crystal, by preserving low control voltages, assume the use of modulators only to modulate small-diameter beams. A Gaussian light beam collimated by a gradient lens and emitted by the end face of a single-mode fibre is ideal from this point of view. Thus, the modulators can be successfully used for *Q*-switching of isotropic fibre laser cavities and rapid extra-cavity commutation of nonpolarised radiation of fibre lasers or near-IR luminescent sources.

The guaranteed contrast in modulators made of standard-quality crystals (i.e. without a special selection) exceeds 20 dB. The stable contrast exceeding 30 dB can be obtained in modulators with phase elements made of selected optically homogeneous crystals.

The design of a modulator consisting of two electrooptical crystals can be quite simple (i.e. without any adjusting elements) because the maximum contrast of the modulator can be achieved by slightly heating one of the crystals.

The $LiNbO_3$ crystals can be used in both schemes of the electrooptical interaction considered above. The $LiTaO_3$ crystals, which require high control voltages during the propagation of light along the optical axis, are appropriate for use only in the ‘thermally compensated’ scheme with two crystals. In this scheme, $LiTaO_3$ crystals are undoubtedly preferable than $LiNbO_3$ crystals from the point of view of a simpler technology of manufacturing electrooptical samples and a lower accuracy of the angular adjustment of nonideal ‘wedge-like’ samples. In other respects (thermal stability, the requirement of a high optical quality), $LiTaO_3$ crystals have no advantages. Moreover, we assume that the possibility of thermal adjustment of the modulator equalises the chances of both these crystals.

The scheme of the switch in Fig. 1 is as a whole somewhat more thermally stable than that in Fig. 2. At the same time, the control voltage in the scheme in Fig. 2 is approximately 1.4 times lower, and this voltage can be further reduced by increasing the lengths of both crystals without the drastic deterioration of their optical quality. Such an operation is complicated for a single-crystal modulator because the growth of optically homogeneous long crystals involves severe technological problems.

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