Quantum Electronics **35** (11) 1071 – 1074 (2005)

PACS numbers: 42.55.Wd; 42.60.Fc; 42.70.Mp; 42.79.Hp
DOI: 10.1070/QE2005v035n11ABEH009851

A LiNbO3 switch for fibre lasers

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***Abstract*. An electro-optical switch (modulator) based on one LiNbO$_3$ crystal and fundamentally thermally stable is investigated. The switch is intended for controlling radiation from laser and luminescence fibre emitters. The operation principle of the modulator is described briefly, its static and pulse characteristics are measured and the temperature behaviour is studied. A switching contrast of 38 dB is obtained at a dc voltage of $U_{\lambda}/2 = 400$ V on a test device connected with isotropic single-mode fibres in the optical switching mode at a wavelength of 1060 nm. The half-wave voltage in the pulsed mode is 800 V.**

Keywords: *electro-optical switch, modulator, LiNbO$_3$, fibre laser.*

1. Introduction

Electro-optical (EO) switches (modulators) with the response time of the order of several nanoseconds are usually employed in fibre optics as *Q* switches in fibre laser cavities or as extracavity pulse shapers of laser and luminescence fibre sources.

Bulk crystal modulators are used for an optical power of tens of watts and higher, when direct application of faster integrated EO modulators is problematic. In fibre optics, such modulators are rigidly connected (coupled) with optical fibres. Naturally, attempts are made at minimising the sizes of the devices, while preserving their main parameters, such as contrast, low control voltages, small values of introduced optical losses, and efficiency in a wide temperature range.

In this study, we describe a small-size EO switch (modulator), in which three components of the standard modulator (polariser, controllable phase element, and analyser) are combined in the same LiNbO$_3$ crystal. The main optical parameters of the modulator (switching contrast, losses, and control voltage) were found to be virtually independent of temperature. The device is intended for operation in the wavelength range λ=1060 ±50 nm.

Switches (modulators), each based on an individual EO crystal, were used quite a long time ago [1, 2]. Unlike the modulator considered here, such switches are usually prepared in the form of controllable electro-optical reflectors executing angular selection of polarised beams. This technique of discrimination was the only reasonable approach for solid-state lasers with relatively large-beam cross sections since the splitting of polarised beams through their parallel separation would require extremely long crystals. Collimated narrow optical beams (of diameter 0.3 – 0.4 mm) are conventionally employed in fibre laser optics. The numerical apertures (NA) of single-mode fibres are usually of the order of 0.1. Even when the beams displaced only by the size of their cross section are introduced into fibres, they do not fall into this numerical aperture and do not propagate along the fibre. This property of fibres makes it possible to use modulators ensuring even small parallel separations of polarised beams. This, in turn, allows one to select a geometry of a crystal prism, which would be equivalent to a plane – parallel plate that does not introduce any angular distortions in principle upon temperature variations. The EO prism used in our switch is based precisely on this concept.

On the contrary, reflector switches [1] exhibit a fairly strong temperature dependence of the angular position of the output beam. These devices are equivalent to a 90° Porro prism, in which the anisotropic expansion of the crystal material modifies the output beam angles upon a change in the 90° apex angle. Anisotropy of the temperature expansion of a uniaxial crystal is due to different values of the thermal expansion coefficient along ($\alpha_{\parallel}$) and across ($\alpha_{\perp}$) the optical axis of the crystal. For LiNbO$_3$, the linear expansion coefficients differ substantially [3]: $\alpha_{\parallel} = 2 \times 10^{-6}$ K^{-1}, $\alpha_{\perp} = 14 \times 10^{-6}$ K^{-1}.

For a reflecting LiNbO$_3$ prism with a rectangular trapezoid as a base, one of whose lateral sides is inclined at an angle of 45° to the base [1], calculations for an ordinary returning beam in a zero field lead to a deviation of about $\pm 3'$ upon a change in the crystal temperature by ±30 °C. The-beam deviations for other reflection-type prismatic switches are even larger and amount to $\pm 5'$ [1]. According to our measurements, such misalignment in single-mode fibre devices result in optical losses from 1.5 to 5.0 dB. For this reason, single-element reflection-type switches are not widely used in commercial lasers operating in a wide temperature range.

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Received 8 June 2005; revision received 7 September 2005
Kvantovaya Elektronika **35** (11) 1071 – 1074 (2005)
Translated by Ram Wadhwa

2. Optical scheme

Figure 1 shows the optical scheme of an EO modulator switch and the optical paths of polarised waves (rays) in it. The only optical element of such a modulator is a uniaxial $LiNbO_3$ crystal in the form of a long thin rectangular prism of size $1.5 \times 3.5 \times 34$ mm. The prism base has the shape of a parallelogram with lateral sides inclined at an angle of 45°. All four narrow faces of the prism are polished. On two broad base faces oriented at right angles to the x axis, 2.5×27 mm gold electrodes with a chromium sublayer are deposited and a field E_x is applied to them. The optical axis z of the crystal is oriented along the long side of the prism. The ordinary (o) and extraordinary (e) rays, which are incident at right angles to the prism as a single beam, are split spatially in the crystal due to anisotropic total internal reflection at the first 45° face. After this reflection, the o-wave and the o-ray propagate collinearly along the optical z axis, while the e-wave deviates in the crystal through an angle $\sim 2°$ from the axial direction (the e-ray is also deflected almost in the same manner). Upon the application of a half-wave field E_x to a trigonal $LiNbO_3$ crystal of such an orientation, the circular cross section of the optical indicatrix at normal angles to the z axis is transformed into elliptical cross section with axes turned through 45°. As a result, the crystal is transformed into a half-wave plate. The corresponding working half-wave voltage ensuring such a field [4] is described by the relation

$$U_{\lambda/2} = \frac{\lambda}{2N_o^3 r_{22}} \frac{d}{L}, \qquad (1)$$

where λ is the wavelength (1060 nm) of the light being modulated; $N_o = 2.2343$ is the 'ordinary' refractive index of $LiNbO_3$; r_{22} is an element of the EO tensor r_{ik}, whose value is equal to 7×10^{-10} cm V^{-1} at low frequencies and 3.4×10^{-10} cm V^{-1} at high frequencies [4]; $L = 27$ mm is the length of the electrodes; and $d = 1.5$ mm is the separation between the electrodes. Thus, the functions of a polariser, controllable phase element, and analyser (the second output 45° face) are combined in one crystal.

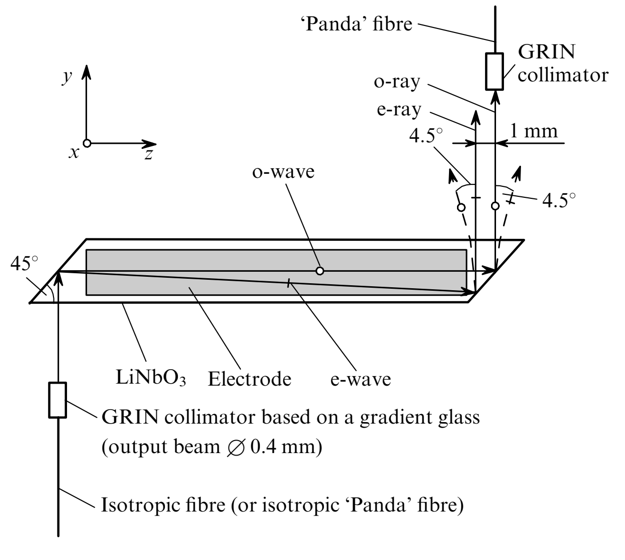

Figure 1. Optical scheme of the switch.

In the absence of the applied voltage across the electrodes, both rays emerging from the crystal are parallel and relatively displaced by ~ 1 mm. Anisotropic thermal expansion leaves the mutually parallel faces unchanged at all temperatures and, hence, the angular parameters of the output rays remain the same and the rays are only displaced parallel to each other. An ordinary ray introduced through the collimator into a single-mode fibre with a numerical aperture NA = 0.1 served as the 'working' ray. The crystal operates as an optical shutter when the control voltage is switched from $U_{\lambda/2}$ to zero. In the absence of an electric voltage, only the o-ray enters the output fibre, which means that the modulator is open. When a voltage $U_{\lambda/2}$ is applied to the crystal, the o-wave emerging from the electric field region is found to be polarised at right angles to its initial polarisation state. This reflects from the output 45° face as an e-wave, and the corresponding ray is deflected in air through an angle $\sim 4.5°$. On the other hand, the primary e-wave, whose path differs from that of the o-wave after the first reflection, is not completely trans-formed into an o-wave. Upon reflection from the output 45° face, it is split into two-waves with orthogonal polarisations, one of which continues to propagate in the same direction, while the other is also deflected in air through an angle $\sim 4.5°$, but in a direction opposite to that in which the late o-wave was deflected. Consequently, none of the rays enters the fibre, i.e., the shutter is closed. Thus, the switching off of this modulator requires an electric bias voltage, which is reduced to zero by an opening pulse of the opposite polarity.

Figure 2 shows a photograph of the experimental version of the instrument. The EO switch connected with microcollimators through single-mode fibres is shown in the upper part of the photograph, while the lower part shows the high-voltage pulse shaper controlled by TTL pulses and fed by a low-voltage dc power supply. The cores of the two electric cables shown in the photograph are connected to the ends of the same electrode. Such a design was used only for estimating the delay time of an electromagnetic wave propagating in the crystal. If the electric pulse fronts have a duration of 2–3 ns or more, it is quite sufficient to use just one cable.

3. Experimental results

The main parameter of any modulator is its static characteristic [4]. In order to record this characteristic, we used a stable unpolarised superluminescent emitter based on an isotropic quartz fibre with a Yb^{3+}-ion-activated core pumped by two laser diodes ($\lambda_p = 970$–980 nm). The radiation (with $P_{out} = 10$ mW, $\lambda_{mid} = 1060$ nm, $\Delta\lambda = 10$ nm) was extracted through the endface of a single-mode fibre with a numerical aperture NA = 0.1. This fibre was welded with a similar input fibre of the switch by a Fitel welding machine (the test version of the switch had identical isotropic fibres at both ends). Welding losses did not exceed 0.1 dB. The radiation emerging from the switch was registered at the endface of the fibre using an Anritsu ML9001A precision power meter with a closed input through an operative fibre connector. A constant bias voltage was applied to the switch from a controllable stabilised high-voltage power supply with an output voltage $U_{out} = 0 - 1000$ V (± 0.5 %).

The measured static characteristic of the device was almost identical in shape with the theoretical curve (Fig. 3).

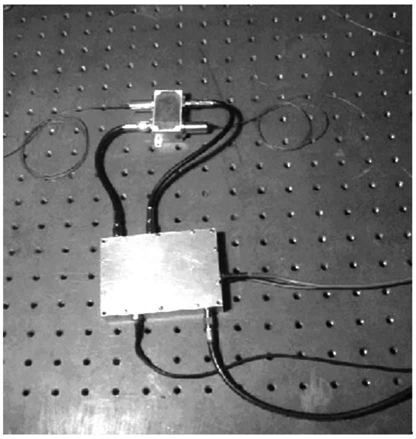

Figure 2. Switch with a block for the formation of high-voltage pulses (the distance between threaded holes in the optical bench is 25 mm).

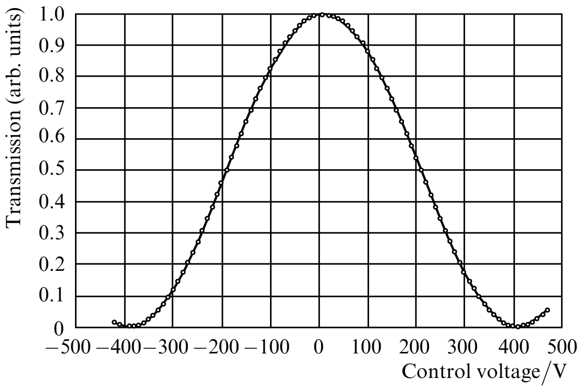

Figure 3. Static modulation characteristic of the switch.

A slight asymmetry in the position of the static characteristic along the abscissa axis (10 − 15 V) can be attributed to misalignment of the prism relative to the input ray.

The static switching contrast (ratio of the maximum and minimum optical powers through the modulator) was measured under the same conditions at zero frequency. The maximum value of the contrast attained at room temperature ($T \approx 20\,^{\circ}\mathrm{C}$) was 38 ± 1 dB under a control half-wave voltage of 400 V. In accordance with formula (1), the theoretical value of this voltage is 377 V for the above-mentioned electrodes and the value of prism thickness.

The total losses introduced in the switch at room temperature for an ordinary ray were 0.5 ±0.1 dB (without taking into account the polarisation losses of 3 dB).

The temperature behaviour of the shutter was studied using the MK240 heat chamber supplied by WTB-binder (the temperature was stabilised with an error not exceeding 0.1 °C). The chamber contained the switch with fibres and electric cables only (without power meter, optical emitter, and bias voltage power supply). The results of measurements presented in Table 1 show that the introduced losses and the switching contrast vary relatively insignificantly in the temperature range from 0 to 55 °C.

Table 1.

Parameters being measured	Modulator casing temperature/°C		
	0	30	55
Holding time at a given temperature/min	30	30	30
Introduced losses/dB	0.4 ± 0.1	0.6 ± 0.1	0.7 ± 0.1
Switching contrast/dB	32 ± 1	35 ± 1	33 ± 1

However, these variations were found to be much larger than the theoretical values. Calculations show that the o-ray emerging from the prism must experience a parallel shift of ±11 μm upon a ±30° variation relative to the room temperature. Such a displacement of the beam can theoretically increase the losses by just 0.02 dB in the output fibre.

We attribute the discrepancy between the experimental and theoretical results to thermal distortion of the shape of the switch casing, whose design in the form of a flat tray open from one side (i.e., asymmetric) was not quite appropriate; the more so, the material of the tray was not invar or super invar, but stainless steel with a linear thermal expansion coefficient of $\sim 10^{-5}$ K^{-1}.

After thermal testing, the modulator was kept at room temperature for about 1 month and the switching contrast was checked again at the same temperature. Its value was found to be 37 dB, indicating that this fundamental parameter was practically restored to its initial value.

The same superluminescent emitter was used for pulse testing of the switch. High-voltage pulses (whose amplitude and repetition rate could be varied) with a controlled bias, which were triggered by TTL signals, were used as the control signals. The pulse parameters were as follows: repetition rate 0 − 20 kHz, trapezoidal shape with fronts of 4 − 6 ns, FWHM 13 ns, and amplitude 300 − 900 V.

The half-wave voltage in the pulsed mode was double the value of $U_{\lambda/2}$ in the static mode; this is due to the absence of the secondary piezoelectric effect at high frequencies due to finite velocities of acoustic waves in the crystals. For pulse fronts of 4 − 6 ns, the fastest longitudinal acoustic wave in LiNbO$_3$ (propagating at a velocity of $\sim$7 km s^{-1}) traverses a distance of about 35 μm, which is much shorter than the distance (1500 μm) between the electrodes. This voltage doubling is fully in accord with the halving of the EO coefficient r_{22} at high frequencies (see above).

Figure 4 shows an oscillogram of an optical pulse formed by a modulator from continuous radiation with a pulse repetition rate of 5 kHz. Upon an increase in the pulse repetition rate beyond 20 kHz, the switching contrast deteriorated steadily and reached a value of 6 dB for a

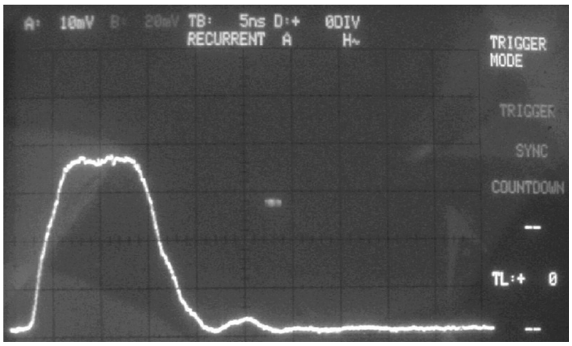

Figure 4. Oscillogram of the optical pulse shape (with a sweep of 5 ns div^{-1}).

repetition rate of 50 kHz. The deterioration in the contrast is due to the high-voltage pulse shaper that did not ensure the required pulse amplitudes at these frequencies.

It is clear from the optical diagram of the rays (see Fig. 1) that the modulator switch can also be used for 'switching on' if it is closed in the absence of control voltage and open when a voltage $U_x = U_{\lambda/2}$ is applied to it. For this purpose, the formerly deflected o-ray should be used as the working ray (in Fig. 1, it is the extreme right ray shown by a dashed curve). This ray should be introduced to the receiving fibre when a voltage $U_{\lambda/2}$ is applied to the switch. A poor thermal stability is a significant drawback of this approach. Calculations (taking into account the thermal expansion coefficient as well as the temperature dependences of the refractive indices of $LiNbO_3$ taken from [5]) show that the e-ray (formerly o-ray) emerging from the prism will be deviated further through an angle of about $\pm 1.8'$ upon a temperature variation of just $\pm 5\,^{\circ}C$ in the crystal. It was found in experiments that when such a beam enters the fibre in a device adjusted at room temperature, it will suffer additional losses of ~ 0.4 dB. As the crystal temperature varies by $\pm 15\,^{\circ}C$, the angular deviation increases to $\pm 5.7'$ and the losses become as high as ~ 5 dB. Thus, the switch of such a configuration can operate either in laboratory conditions or under thermal stabilisation of its casing.

4. Conclusions

We have studied an electro-optical amplitude modulator, which differs from traditional devices in the following features:

(i) it contains only one EO crystal, which combines the functions of a polariser, Pockels cell, and analyser and, hence, is characterised by minimum optical losses and simple design;

(ii) it is characterised by a low sensitivity to the spectral width of radiation being modulated (a static contrast of 38 dB was obtained in the experiment for $\Delta\lambda \approx 10$ nm; the theoretically admissible value for this contrast is $\Delta\lambda \approx 50$ nm);

(iii) at low pulse repetition rates, the device has a half-wave voltage $U_{\lambda/2} \approx 400$ V, which is relatively low for the chosen scheme of the EO interaction and is close to the theoretical value of 377 V; in the pulsed mode, this voltage is twice as high , which can be explained by the absence of the secondary piezoelectric effect at high repetition rates;

(iv) it is characterised by a high thermal stability in the case when the scheme of the EO interaction corresponds to the 'closed' state in the presence of the bias voltage;

(v) it can be used for operation without a bias voltage (i.e., can be opened by an electric pulse); however, in this case the device can be used only under laboratory conditions in view of its high temperature sensitivity;

(vi) it can be used not only in fibre optics, but also as an attenuator and switch for narrow (~ 1 mm) laser beams.

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