Section 2
ADVANCED TECHNOLOGY DEVELOPMENTS

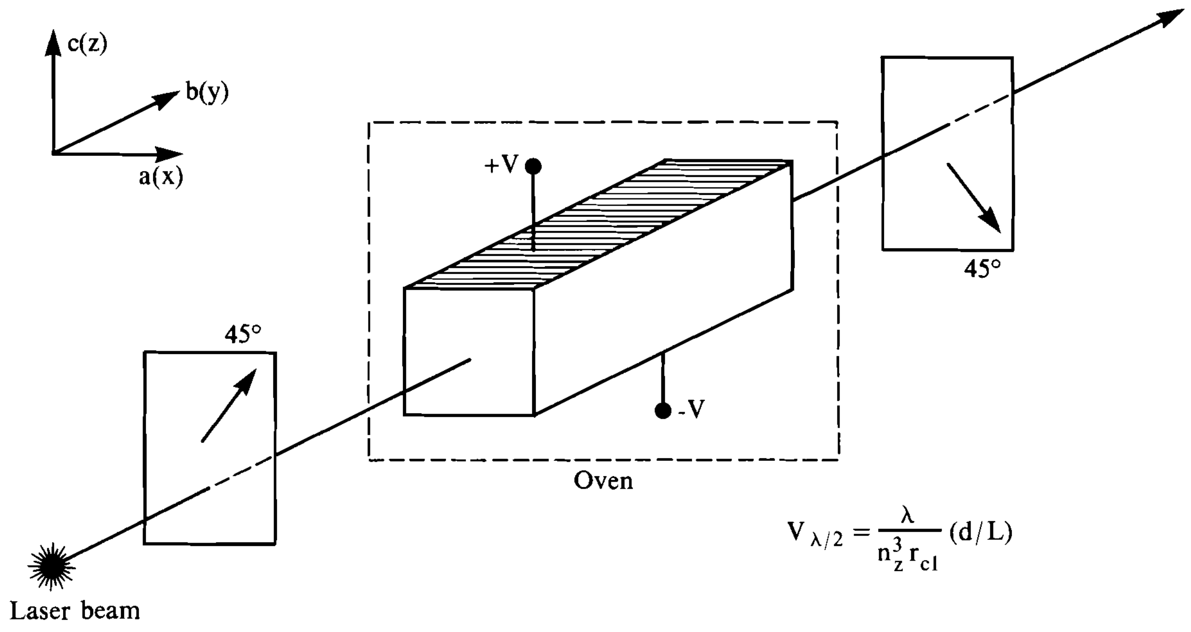
2.A Application of KTP Crystal as an Electro-Optic Amplitude Modulator

Potassium titanyl phosphate ($KTiOPO_4$ or KTP) has become a widely used nonlinear optical crystal because of its superior properties for several nonlinear-optical applications[1] and, in particular, for second-harmonic generation of Nd^{3+}-based lasers.[2] In addition to its well-recognized characteristics, such as high nonlinear coefficients, high-optical-damage threshold, and low insertion loss, it has been shown that KTP has large electro-optical *r* coefficients and low dielectric constants.[3] These unique properties of KTP crystal make it an attractive material for various electro-optic (E-O) applications, especially as an E-O Q-switch and switchout device in regenerative amplifiers. There has been a great deal of interest in the development of a high-peak-power, high-repetition-rate laser system,[4,5] which is of great importance for spectroscopic studies in physics, chemistry, and biological science. Despite its proven superior qualities as a doubling crystal for 1-μm-Nd lasers, only a few other applications have been addressed during the decade following the discovery of this material. In this regard, one of the primary limitations in the application of KTP as an E-O device has been the intrinsic birefringence of this crystal group.

This article discusses the use of temperature-tuned birefringence compensation of KTP and the operation of a KTP Pockels cell at repetition rates of up to 30 kHz. The application of this Pockels cell for high-peak-power laser systems and YLF regenerative amplifiers is also discussed. Our measurements of the KTP device performance have shown that it has a high-polarization-extinction ratio and a low dynamic half-wave voltage and is free from acoustic ringing. All of these properties make it a prospective choice for many extra/intracavity high-repetition-rate electro-optical applications.

KTP is a biaxial crystal with an orthorhombic structure (point group mm^2). The crystallographic directions *a,b,c* correspond to the optic axes x,*y,z*, with *c* being the polar axis. The KTP crystal used in this work was grown using the hydrothermal technique and was cut normal to the principle crystal axes with dimensions $4 \times 8 \times 4$ mm^3 (x,y,z). The *y*-faces were optically polished and Ar coated at 1.053 μm, and the electrodes were deposited on the *z*-faces with ~500 Å of sputtered gold. From consideration of KTP's mm^2-point symmetry, light-amplitude modulation for a beam propagating along the *y* axis requires the beam to be polarized 45° relative to the *x* axis with the electric field along the *z* (polar axis) direction. Figure 45.19 shows the KTP Pockels-cell layout. The phase retardation Γ for light propagation in a KTP crystal of length *l* is relative to the voltage $V_z = E_z d$ across the electrodes by

$$\Gamma = -\frac{2\pi}{\lambda} l\left(n_z - n_x\right) + \frac{\pi}{\lambda} n_z^3 r_{c1} V \frac{l}{d} , \tag{1}$$



$$V_{\lambda/2} = \frac{\lambda}{n_z^3 r_{cl}} (d/L)$$

Fig. 45.19
KTP amplitude modulator (Pockels cell) configuration. The crystal is housed in a temperature-controlled oven, and a transverse field is applied along the *z* axis of the crystal.

where $r_{c1} = r_{33} - (n_1/n_3)^3 r_{13}$ is the effective E-O coefficient for amplitude modulation in the y direction. It is important to note that the first term is in fact an arbitrary static birefringence of the crystal, and it has to be compensated for. The conventional method of compensation, in which a $\lambda/4$ wave plate is placed behind the KTP in the double-pass scheme,[6] is not proper for E-O application as it compensates for both static- and electric-field-induced retardation.

Here we report the compensation for the static birefringence by tuning the KTP crystal temperature. This approach takes advantage of the thermal index of refraction changes ($\Delta n_x = 1.1 \times 10^{-5}\,°C^{-1}$, $\Delta n_z = 1.6 \times 10^{-5}\,°C^{-1}$) and the thermal expansion ($\alpha_y = 0.9 \times 10^{-5}\,°C^{-1}$) of KTP.[1] With the temperature dependence included, the static, field-independent, birefringence term in Eq. (1) can be written

$$\Gamma_{\text{static}} = -\frac{2\pi}{\lambda}(l_o + \Delta l)\left[(n_{zo} + \Delta n_2 \Delta T) - (n_{xo} + \Delta n_x \Delta T)\right], \quad (2)$$

i.e.,

$$\Gamma_{\text{static}} = -\frac{2\pi}{\lambda} l_o (n_{zo} - n_{xo}) \left[1 + \left(\frac{\Delta n_z - \Delta n_x}{n_{zo} - n_{xo}} + \alpha_y\right)\Delta T\right], \quad (3)$$

where l_o, n_{zo} and n_{xo} are values at room temperature, and $\Delta l = \alpha_y l \Delta T$. From Eq. (3) it is obvious that the static birefringence can be temperature tuned to $2n\pi$, so it will have no effect on the modulation.

Assuming the constants used in Eq. (3) are temperature independent, we can easily estimate the period of two adjacent minimums to be $\Delta T = 13°C$ ($\lambda = 0.633\ \mu m$). Experimental studies of the temperature dependence of the crystal birefringence are shown in Fig. 45.20. For these studies, the KTP Pockels cell was housed in a temperature-controlled oven with 0.1°C sensitivity. The temperature-tuning measurements were done using a HeNe laser with a PMT detector, while the KTP Pockels cell was placed between two crossed calcite polarizers. Compensation for the crystal birefringence is achieved at temperature intervals of 12°C, which is in good agreement with the calculated value. At this point, the contrast ratio is ~2000:1 (limited by the polarizers). This contrast ratio is sufficient for most laser applications and demonstrates the high degree of compensation possible using this simple approach.

At a wavelength of $\lambda = 1.053\ \mu m$ the effective E-O coefficient is $r_{c1} = 28.6$ pm/V for a dc field (low frequency) and 27.0 pm/V for a fast-pulsed field (i.e., high frequency).[3] The theoretical half-wave voltage obtained from the second term of Eq. (1) for our sample crystal size of $4 \times 8 \times 4\ mm^3$ is 2900 V and 3200 V, respectively. Measurements of the half-wave voltage of this KTP crystal were accomplished using a 100-MHz, mode-locked, YLF laser. A synchronized 10-ns, high-voltage electric pulse is applied to the crystal from a microwave triode-based driver to switch out one of the pulses in the 100-MHz pulse train after the second polarizer. An experimental half-wave

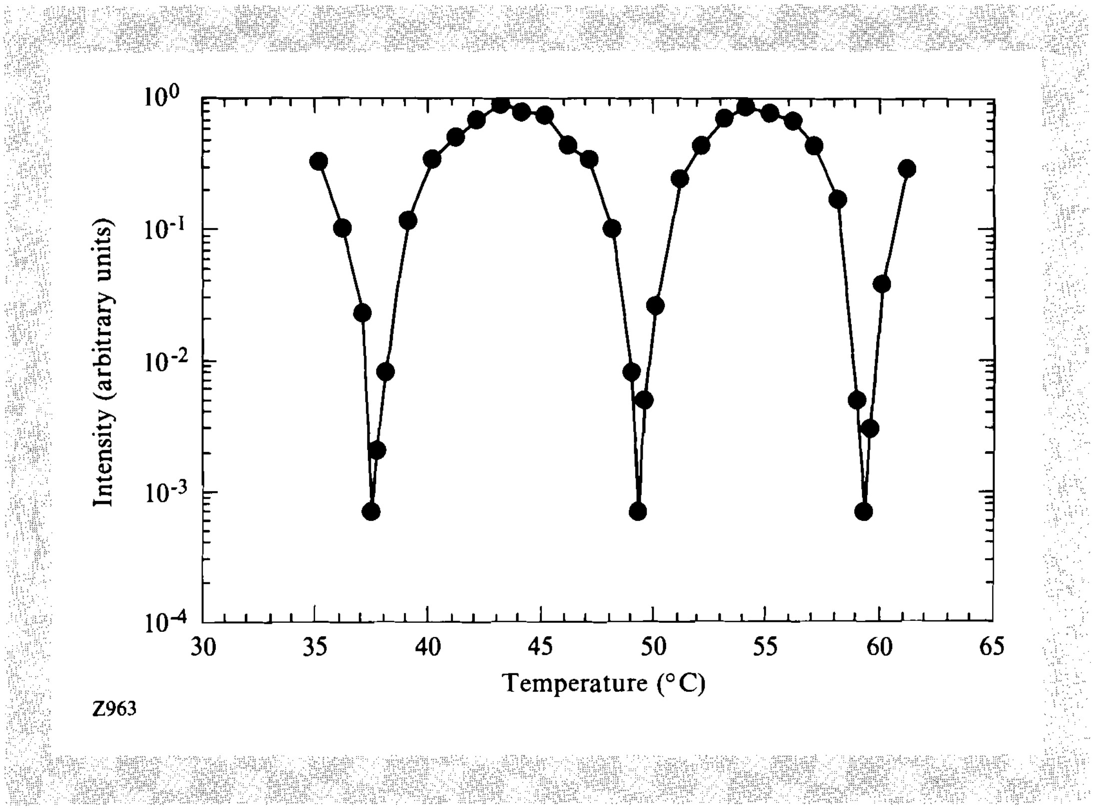


Fig. 45.20
Transmission versus temperature of the KTP Pockels cell sandwiched between crossed polarizers in the absence of an electric field at $\lambda = 633$ nm.

voltage of 3200 V is obtained with 99% single-pulse switchout, confirming the theoretical value. This is about the same as the dc half-wave voltage of a typical $9 \times 9 \times 25$ mm^3-$LiNbO_3$ crystal, but 30% to 40% less than the dynamic half-wave voltage of $LiNbO_3$.[7] The dynamic half-wave voltage is the important criteria for Q-switch applications. In addition, the acoustically induced birefringence generated through piezoelectric coupling during the applied field was found to have an insignificant effect on the performance of the KTP Pockels cell (Fig. 45.21). Based on both low half-wave voltage and lack of piezoelectric-induced parasitics, we have successfully demonstrated the operation of this KTP Pockels cell, working up to a 30-kHz repetition rate, limited only by our 10 kV/10 mA-HV power supply.

One of the motivations for this work was to find an alternative material to replace the commonly used $LiNbO_3$ Pockels cell. $LiNbO_3$ crystal has several drawbacks, such as strong acoustic ringing and a moderate-optical-damage threshold when used as an intracavity device. Our work has shown KTP to be a strong candidate for the high-peak-power, high-repetition-rate application. To demonstrate this, a KTP Pockels cell was used as a cavity dumper for regenerative pulse amplification and Q-switch operation of a YLF resonator. In regenerative pulse amplification, the pulse output was limited to 0.5 mJ at a 2.5-kHz repetition rate by the crystal aperture. In this mode of

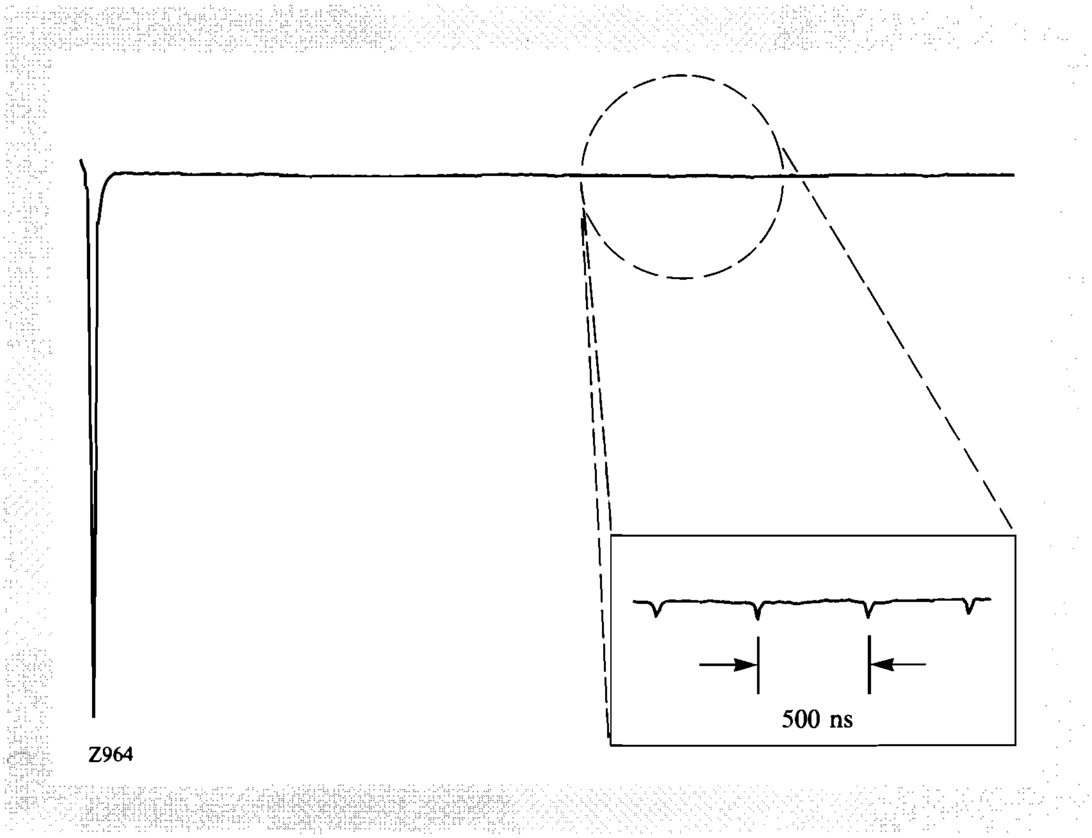


Fig. 45.21
Single-pulse switchout from a 100-MHz pulse train at 1053 nm. The almost complete absence of acoustic ringing is evident from the insert.

operation, the crystal developed some thermal-lensing problems. The thermal lensing did not have a significant effect on the output power but did affect the stability of the laser. This problem should be reduced by using low-temperature, hydrothermally grown crystals that have fewer defects than the high-temperature-grown crystal used in this study.

In conclusion, we have developed a temperature-tuned birefringence-compensated KTP Pockels cell capable of working at a tens-of-kilohertz repetition rate. Applications of this device for high-peak-power, high-repetition-rate Q-switching and regenerative-pulse amplification have also been demonstrated. Our work has shown that KTP has promising potential for various E-O modulation applications other than its major role as a doubling crystal.

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