

High average power KTiOPO_4 electro-optic Q -switch

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We have demonstrated a thermally compensated KTiOPO_4 (KTP) Q -switch with a $10 \text{ mm} \times 6 \text{ mm}$ clear aperture and high contrast ratio. This device showed excellent resistance to thermal depolarization at average power densities as high as 1 kW/cm^2 . Capacitive coupling allowed us to operate the Q -switch for greater than 10^9 shots with no sign of electrochromic damage. © 1995 American Institute of Physics.

The advent of high average power diode pumped solid-state lasers has engendered the need for electro-optic devices which can tolerate both high intracavity fluences and high average powers. Previously, we demonstrated a lithium niobate based Q -switch which could maintain a high contrast ratio at average powers in the kilowatt range.^{1,2} However, the low damage threshold of lithium niobate ($\approx 1 \text{ J/cm}^2$) compromises its reliability in Nd:YAG or YLF lasers, which operate efficiently at saturation fluences comparable to this value. In addition, piezoelectric ringing³ and pyroelectric depolarization⁴ are problems which complicate the use of lithium niobate at high repetition rates and high average powers, respectively. It has been suggested that, because of its higher damage threshold and smaller piezoelectric coupling, potassium titanyl phosphate (KTP) might be superior to lithium niobate as a Q -switch material.⁵⁻⁷ KTP also compares favorably to the other commonly employed Q -switch crystal, deuterated potassium dihydrogen phosphate (KD^*P), having more robust coatings, higher transmission in the $1\text{--}3 \mu\text{m}$ region, and a higher thermal conductivity.

Nonetheless, despite the pioneering work of Refs. 5 and 6, a few applications of KTP as a bulk electro-optic modulator have been reported to date.^{7,8} The salient issue which must be addressed in the design of a practical KTP device is how to handle the effects of finite birefringence. (Since KTP is biaxial, the orientations which exhibit usable electro-optic coefficients are necessarily those which also give rise to substantial birefringence).^{5,6} Thus a single crystal KTP Q -switch will exhibit the thermal and wavelength sensitivity associated with a high order birefringent wave plate. With even modest average powers this makes practical implementation of a single crystal Q -switch problematic since even relatively small temperature changes ($< 1 \text{ }^\circ\text{C}$) can cause significant loss of polarization contrast.⁶

Our approach to this problem is to utilize two identical crystals in a compensating mode. Several possible compensating configurations are shown in Fig. 1. In the device described in this letter, the configuration corresponds to that shown in Fig. 1(a). Configuration 1(b) leads to a higher half-wave voltage, but is convenient for slab lasers where the natural polarization states of the cavity are typically parallel to the slab edges and a quartz rotator would be needed to align the polarization at 45° to the y and z axes if configuration 1(a) were used. In rod lasers, the KTP and quartz rotator crystals can have square apertures, and the entire assembly 1(a) rotated 45° with respect to the laser polarization. Con-

figuration 1(c) is capable of compensating for average temperature changes, but not for thermal gradients caused by laser induced heating, since heat flow is not equivalent in the two crystals.⁹ Thus the marginal advantage in transmission due to the absence of the polarization rotator in Fig. 1(c) is gained at the expense of reduced average power capability. In any case, the three element switch, in principle, should have no greater insertion loss than a typical commercial single crystal KD^*P device with protective windows.

Two crystals of KTP with dimensions $8.2 \text{ mm} \times 10.5 \text{ mm} \times 6.9 \text{ mm}$ oriented along x , y , and z , respectively, were cut from a boule provided by HOYA, Inc. The orientational uncertainty of the cut crystals was ± 15 arc min. The propagation direction was parallel to the x axis and the entrance and exit faces were parallel to ± 5 arc sec and flat to within $\lambda/4$ at $0.633 \mu\text{m}$. These crystals and a quartz 90° polarization rotator were bonded to a ceramic substrate on which gold electrodes were plated to form electrical contacts. The z faces were parallel to the substrate (i.e., $E \parallel z$). Thus the nominal clear aperture of the device was $10.5 \text{ mm} \times 6.9 \text{ mm}$, although in most of our experiments only the central 6 mm diameter region was used.

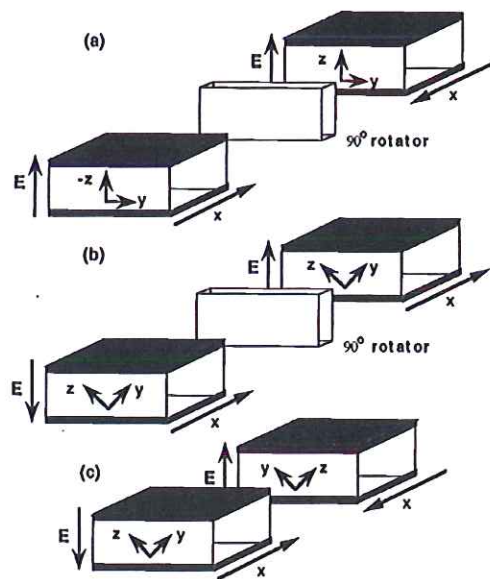


FIG. 1. Compensated Q -switch designs: (a) is the arrangement utilized in this letter; (b) and (c) are alternative designs.

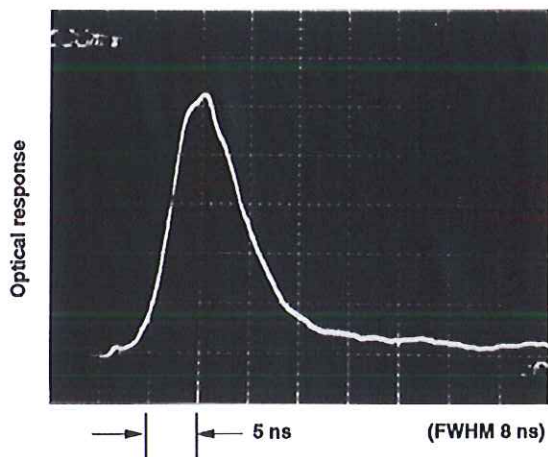


FIG. 2. Oscilloscope trace of 8 ns FWHM Q -switched pulse produced using the KTP modulator.

The KTP crystals were antireflection coated with a dual wavelength coating to facilitate measurements at both 0.633 and 1.06 μm . As a result, the one way insertion loss of the three crystal assembly was 2.5% at 1.06 μm , significantly higher than could be expected if coatings optimized for 1.06 μm alone were used. The depolarization losses at 0.633 and 1.06 μm were 1.8% and 0.6% (contrast ratios of 55:1 and 160:1, respectively) integrated over the entire clear aperture. The rather low contrast ratios are a consequence of residual strain in the KTP crystals, and not due to angular misalignments of the crystals and rotator.

Since KTP exhibits electrochromism when subjected to a dc electric field,¹⁰ we used a blocking capacitor (6 kV, $C=0.04 \mu\text{f}$) in series with the crystals. This arrangement is similar to that used to prevent electrode migration and subsequent fogging in KD*P Pockels cells.¹¹ This has allowed us to Q -switch repetitively for greater than 10^9 shots (3 kV, 1 μs long pulses at 2.5 kHz continuously for 1 week) without any noticeable darkening of the crystals. The measured optical rise time of the Q -switch was ≈ 15 ns, limited by the rise time of the high voltage pulser used for our experiments.

We demonstrated Q -switching operation in a low repetition rate diode pumped Nd:YLF laser similar to that described in Ref. 12. An 806 nm diode array with a 500 μs long pulse end pumped a 2 cm long Nd:YLF rod. A 60% reflectivity output coupler was used. The Q -switch assembly was rotated 45° to the plane of polarization of the laser. A quarter-wave plate is used to achieve standoff, and a high voltage pulse was applied to the device for Q -switching. As calculated, an effective quarter wave voltage of 1.6 kV was determined by maximizing the output energy of the laser. With a cavity length of 28 cm we obtained 50 mJ of Q -switched output at 1.047 μm in an 8 ns full width at half-maximum FWHM pulse, shown in Fig. 2. The depolarized energy rejected by the polarizer during Q -switching was measured to be 1.1% of the output energy. The angular alignment sensitivity of the KTP Q -switch was not noticeably higher than that of a commercial KD*P Pockels cell. The unit could be tilted by nearly 10 mrad before a change in

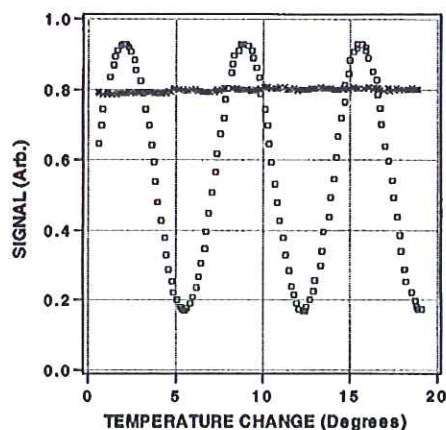


FIG. 3. Compensation for average temperature changes in the Q -switch. \times =compensated; \square =uncompensated.

depolarization signal was noticeable. We also note that no spectral narrowing of the YLF laser was necessary,⁸ as the compensated design has a wavelength bandwidth of nearly 1 nm.

The insensitivity of the contrast ratio of the compensated KTP Q -switch to changes in *average* temperature is demonstrated in Fig. 3. In this experiment, the Q -switch was placed in a thermally regulated mount between parallel polarizers whose polarization directions were 45° to the z axis of the KTP crystals. The signal transmitted through the polarizers was measured as a function of the mount temperature. The change in retardation with temperature of a single crystal KTP Q -switch with an equivalent half-wave voltage was simulated by removing the quartz rotator. Clearly, the compensated design has a temperature bandwidth at least an order of magnitude greater than a single crystal device.

To test the behavior of the compensated Q -switch under high average power conditions, where significant thermal *gradients* can occur, we placed the device inside the resonator of a cw lamp pumped Nd:YAG welding laser, as shown schematically in Fig. 4. The welding laser beam, which heats the Q -switch crystals is approximately 6 mm in diameter.

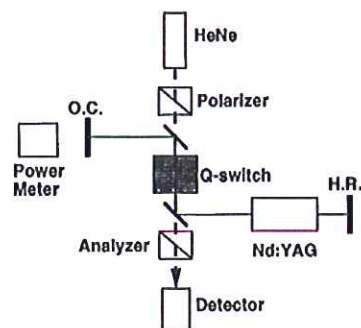


FIG. 4. Experimental arrangement used for measuring Q -switch depolarization caused by average power loading. O.C.=output coupler; H.R.=High reflector.

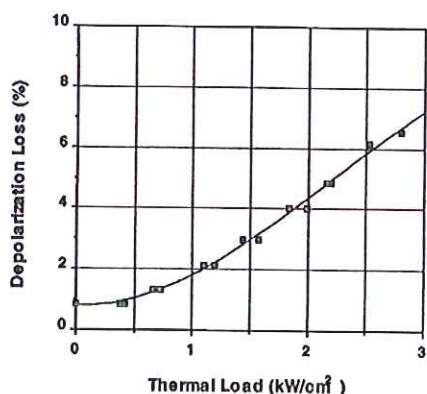


FIG. 5. Depolarization loss observed in the KTP Q -switch as a function of the $1.06 \mu\text{m}$ irradiance.

Dichroic mirrors allow a beam-expanded HeNe laser to be used to probe the depolarization of the Q -switch over its full clear aperture. Although the measurements are made at $0.633 \mu\text{m}$, the results are converted to an equivalent depolarization at $1.06 \mu\text{m}$ by the equation:

$$\% \text{Depol} (1.06 \mu\text{m}) = \% \text{Depol} (0.633 \mu\text{m}) * (0.633/1.06)^2,$$

which is valid for small losses $>15\%$). The result, shown in Fig. 5 implies that at an average power loading of 3 kW/cm^2 (approximately 1 kW circulating intracavity average power), the aperture integrated depolarization loss at $1.06 \mu\text{m}$ is less than 7% . The depolarization observed in an equivalent uncompensated Q -switch (again simulated by removing the quartz rotator and rotating the analyzing polarizer) shows almost two full excursions from maximum to minimum contrast over the same power range, implying an average temperature rise of around 10°C . At each power level this average temperature effect could be nulled out by the use of a Babinet compensator placed before the analyzer. The residual depolarization was then due to the thermal gradients across the KTP crystals. At the 3 kW/cm^2 level, this residual depolarization was approximately 30% in the uncompensated Q -switch.

We anticipate that KPT electro-optic modulators in the configurations shown in Fig. 1 will enable a number of applications, in addition to the Q -switching of very high average power Nd:YAG or YLF oscillators. For example, the fast rise time and small piezoelectric response also facilitates implementation of the pulse transmission mode of operation which could be used to generate short ($\approx 5 \text{ ns}$) pulses.¹³ Another possible application is the Q -switching of midinfrared Tm or Er:YAG lasers. The long wavelengths (2.02 and $2.9 \mu\text{m}$, respectively) at which these lasers operate precludes the use of KD*P, while their large saturation fluences ($>10 \text{ J/cm}^2$) make it difficult to use lithium niobate.

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