Investigation of β-BaB_2O_4 as a Q switch for high power applications

G. D. Goodno
Department of Physics and Astronomy, The University of Rochester, Rochester, New York 14627

Z. Guo
Xidian University, Xian 710071, People's Republic of China

R. J. D. Miller
Department of Chemistry and Institute of Optics, The University of Rochester, Rochester, New York 14627

I. J. Miller and J. W. Montgomery
Lumonics Inc., Kanata, Ontario K2K 1Y3, Canada

S. R. Adhav and R. S. Adhav
Quantum Technology, Inc., Lake Mary, Florida 32746

(Received 12 September 1994; accepted for publication 10 January 1995)

A beta barium borate (β-BaB_2O_4 or BBO) crystal has been used to electro-optically Q switch both diode-pumped and lamp-pumped Nd:YLF laser systems, resulting in stable, high average power operation. Piezoelectric ringing was found to have negligible effects on the performance of the BBO Pockels cell at repetition rates up to 6 kHz. The high damage threshold and low insertion loss of BBO permitted operation up to average powers in excess of 6 kW/cm^2, which makes a BBO Pockels cell well suited for high power, small mode volume operation, such as in diode-pumped solid state lasers. Based on typical diode-pumped laser parameters, BBO is expected to extend simple compact Q-switched operation of diode-pumped lasers to average powers of 30–100 W.

Since its discovery in recent years, the nonlinear optical crystal beta-barium borate (BBO) has found use primarily as a frequency mixer for harmonic generation and other parametric processes. While BBO is admirably suited for these applications due to its large nonlinear coefficient,[1] it has a smaller linear electro-optic coefficient than other common nonlinear materials such as KTP, KD*P, and $LiNbO_3$.[2] Both the small electro-optic coefficient and the cost of fabricating crystals of sufficient size and quality have limited the use of BBO in electro-optic devices. Despite these drawbacks, BBO shows promise for use as an electro-optic crystal in compact, high-power systems such as diode-pumped solid-state (DPSS) lasers. The small intracavity beam size of most typical diode-pumped laser cavities results in higher peak intensities than in conventional flashlamp-pumped systems of similar average power. Due to these high intensities, optical damage, multiphoton absorption, and/or gray tracking become problematic in intracavity $LiNbO_3$, KD*P, and KTP Pockels cells, limiting both the peak and average powers in pulsed operation. Some of these limitations can be overcome by expanding the intracavity beam diameter or using thermal compensation schemes.[3,4] However, these approaches increase the complexity of the oscillator and decrease the resonator stability. Ideally, one would like an electro-optic material which has a higher damage threshold than the laser gain medium and can support high average powers within a compact laser resonator. BBO represents one such material. For conventional lamp-pumped systems, the typically large intracavity beam diameter causes the half-wave voltage to become prohibitively large in this application.[5] However, for compact diode-pumped systems the small beam size permits the use of small aperture BBO Pockels cells, with commensurate reductions in operating voltages to an acceptable level. BBO has a damage threshold of >20 GW/cm^2,[6] which enables it to withstand the high intensities resulting from the small aperture size. Since BBO is transparent down to 200 nm, little multiphoton absorption should occur at lasing wavelengths in the near IR.[1] In this letter, we report the operation of an intracavity BBO Q switch in two Nd:YLF laser systems, one arc lamp pumped and the other diode pumped, to demonstrate this application.

The electro-optic coefficient for BBO is 2.5 pm/V.[7] For typical laser applications, a 10 nm aperture is usually required. For currently available crystal lengths of 10 mm, an aperture of this size leads to impractically large half-wave voltages of 40 kV at 1053 nm. An obvious solution is to reduce the aperture of the Q switch in a transverse geometry to attain suitably lower half-wave voltages. The BBO crystal used in this study has dimensions $3\times3\times15$ mm^3 (x,y,z). The square xy faces were cut perpendicular to the crystallographic c axis and were antireflection (AR) coated at 1053 nm. Electrodes were deposited on the rectangular yz faces. These crystal dimensions lead to a dc quarter-wave voltage of 4.6 kV in agreement with that expected from the measured electro-optic coefficient.

Based solely on the efficiency of the AR coatings and crystal scattering losses, the intracavity insertion loss is expected to be less than 2%. The contrast ratio of BBO between crossed polarizers at 488 nm was found to be $>1500:1$, such that significant depolarization losses should also not be a problem. However, the small crystal aperture leads to diffraction losses and strain near the crystal edges which could likewise significantly increase the insertion losses. We tested the BBO resonator with an intracavity beam diameter of 500 μm and found the insertion loss to be 6% using standard Findlay-Clay analysis.[8]

The above result demonstrates the applicability of using small aperture BBO Q switches in DPSS laser systems. One

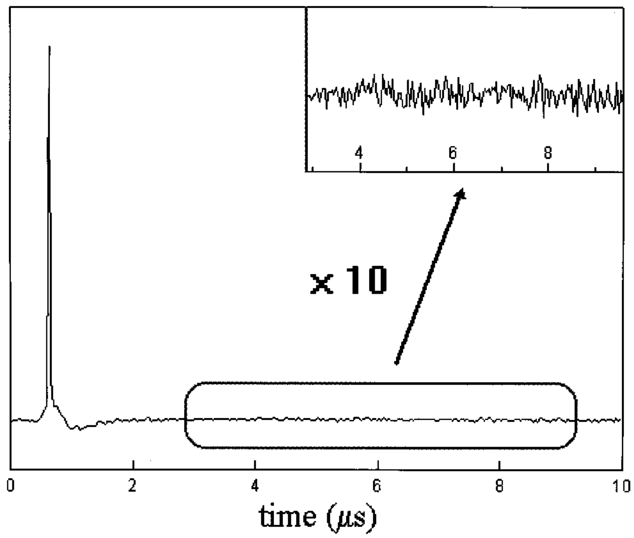

FIG. 1. Pulse switched from a cw HeNe beam at 632 nm. No acoustic ringing is evident above the signal-to-noise ratio (>100:1).

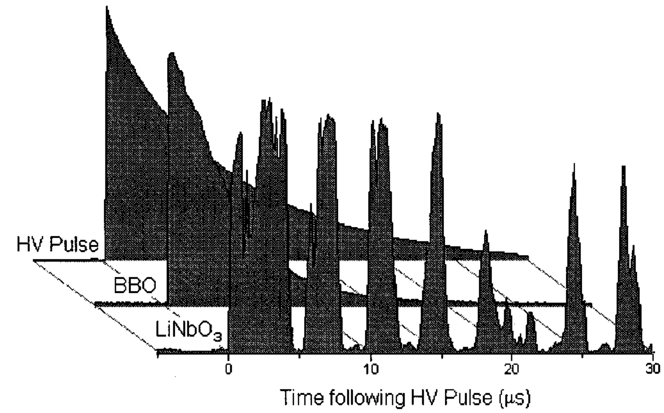

FIG. 2. Qualitative comparison of acoustic ringing in BBO and $LiNbO_3$. The intensity transmitted through the $LiNbO_3$ Pockels cell varies greatly due to piezoelectric effects, whereas the light transmitted through the BBO Pockels cell follows the decay of the applied high voltage pulse with no evident acoustic ringing.

of the important features of DPSS systems is the high gain which permits high repetition Q-switched operation. In this regard, electro-optic Q switching is preferred over acousto-optic Q switches as electro-optic Q switching enables the production of much shorter pulses than acousto-optic due to the intrinsically faster Q switching and associated pulse buildup times of electro-optic devices. Acousto-optic rise times are limited by the acoustic transit time across the optical beam diameter (usually >100 ns), whereas electro-optic materials are primarily limited by the crystal capacitance and RC circuit considerations (usually <10 ns). BBOs extremely low capacitance (<1 pF) will permit high repetition rate switching with rise times on the order of 100 ps or less. The higher peak power with electro-optic Q switching is an important design consideration for nonlinear frequency conversion of the laser fundamental to visible and UV wavelengths.

For effective operation at high repetition rates, it is highly desirable that the crystal be relatively free from acoustic ringing. When subjected to high voltage pulses, piezoelectric effects can give rise to acoustic waves in the crystal which impair the performance of the Pockels cell by continuing to modulate the crystal birefringence through the elasto-optic effect long after the high voltage pulse is applied. $LiNbO_3$, in particular, is notorious for suffering from piezoelectric ringing, and a $LiNbO_3$ Pockels cell typically cannot be run at repetition rates above a few kHz without some means of attenuating these resonances.[9,10] With this issue in mind, we looked for piezoelectric ringing effects in the BBO crystal. A beam from a cw HeNe laser was passed through the BBO Pockels cell sandwiched between two crossed polarizers. The BBO was switched to its half-wave configuration at the HeNe lasing wavelength of 632 nm with a 6.2 kV, 20 ns electrical pulse. As shown in Fig. 1, the ratio of the electrically switched pulse to subsequent noise is >100:1. This noise was still present with the laser beam blocked and is due to dark current from the PMT used. Any piezoelectric effects which may have occurred were obscured by the dark current, and were certainly less than 1% of the switched pulse. Another indicator of the low piezoelectric coupling is that the ac half-wave voltage was found to be within 10% of the dc half-wave voltage.

A more dramatic demonstration of the relative merits of BBO for high fidelity Q-switch applications is shown in Fig. 2, where BBO is directly compared to a standard $LiNbO_3$ Pockels cell. Both Pockels cells were switched to their quarter-wave configurations with the same Pockels cell driver at the appropriate quarter-wave voltage. No attempt was made to damp any acoustic resonances in either crystal. As shown in Fig. 2, the pulse switched by the BBO Pockels cell cleanly follows the applied 2 μs voltage pulse, while the $LiNbO_3$ suffers enormously from piezoelectric ringing after a few microseconds. Both Pockels cells were operated at repetition rates up to 6 kHz with no discernable change in performance.

The other important feature of BBO electro-optics is their very low absorption and associated laser-induced thermal birefringence. Due to the low absorption, very little optical heating will occur at operating wavelengths in the visible and near IR. We increased the temperature of the BBO crystal with a heater jacket in a range from 25 to 50 °C and observed that both the contrast ratio and the half-wave voltage changed by approximately 0.1%/°C. Therefore, even in the event of laser absorption the small thermal anisotropy minimizes the problems associated with crystal heating. Apart from the high intrinsic damage threshold, this natural property makes BBO an attractive candidate for high power applications. This is especially true in visible to near UV wavelengths, where the half-wave voltage is reduced and where other electro-optic materials, KTP in particular, suffer from gray tracking[11] and associated depolarization losses which can limit their utility in Pockels cells despite otherwise meritorious characteristics.[12] For Q-switched operation in which pulses longer than 10 ns are produced, KTP and BBO have comparable power handling capabilities.[12] However, problems with two photon absorption below 500 nm and ion conductivity make KTP less desirable for operation at wavelengths less than 1 μm. In this regard, BBO has superior properties and can be constructed to have acceptable

TABLE I. Performance of BBO Q-switched lasers. $(I_{avg}, I_{peak}) \equiv$(average, peak) intracavity intensity at the crystal.

Oscillator configuration	Repetition rate (Hz)	I_{avg} (kW/cm^2)	I_{peak} (MW/cm^2)	Avg. output power (W)	QS pulse energy (mJ)	Pulse width (ns)
Lamp-pumped QS	500	2.8	31	2.7	5.2	550
	2000	6.7	19	6.2	3.2	550
Lamp-pumped MLQS	200	1.0	1200	0.95	4.8	0.5[a]
	6300	5.8	220	5.5	0.9	0.5[a]
Diode-pumped QS	200	⋯	⋯	1.5	7.5	16

[a]Mode-locked pulse width estimated from a 20 GHz photodiode and 50 GHz Tektronix sampling scope; Q-switched pulse envelope=550 ns.

half-wave voltages for operation at wavelengths less than 1 μm; whereas the lower half-wave voltage and low absorption of wavelengths between 1.2 and 4 μm make KTP the more attractive material between the two for high power operation in the infrared.

To determine the operational limits of the power handling capabilities of BBO, a number of cavity configurations with various average and peak powers were tested. These results are summarized in Table I. In this regard, we were most interested in determining the operational limit of BBO under the high intensity conditions of a high power diode-pumped laser resonator. A quasi-cw diode-pumped oscillator was studied at a pulse repetition rate of 200 Hz. The average power of the diode-pumped laser exceeded 1.5 W with the same cavity used to determine the insertion loss. Stability and laser performance were identical to acousto-optic Q switching the same cavity. By going to low output couplers, the intracavity power was increased to 25 W with no change in laser stability or slope efficiency which would have otherwise indicated thermal problems. To further test the high average power capabilities of BBO, the crystal was also tested in an arc lamp-pumped Nd:YLF laser constructed from a Quantronix Model 116 head. The Pockels cell was positioned near a beam waist (beam diameter $\approx$1 mm) inside the oscillator to increase the intensity at the crystal and to avoid clipping the beam due to the small aperture. We obtained stable pulses ($<$4% peak-to-peak variation) with an average power density at the crystal of 6.5 kW/cm^2. To demonstrate the performance of BBO at high peak intensities, we simultaneously mode-locked and Q-switched (MLQS) the lamp-pumped Nd:YLF, resulting in peak intracavity intensities $>$1 GW/cm^2. The output power and stability were within 10% of the purely Q-switched case. This observation indicates that BBO does not suffer from multiphoton induced thermal or photorefractive problems which have limited the use of both $LiNbO_3$ and KTP in short pulse regenerative pulse amplification. The only observed problem was that the AR coating damaged at peak intensities $>$1GM/cm^2 but the crystal itself was undamaged.

The above results indicate that BBO is well suited for Q-switching diode-pumped lasers. The average circulating power in the lamp-pumped resonator during QS operation was approximately 50 W. Assuming a typical value of 50% for the output coupling of a QS DPSS laser, one would expect 25 W average QS output power to be easily obtainable. Based on extracavity tests of power handling and induced crystal birefringence, we anticipate that average output powers approaching 100 W can be achieved. For higher peak power applications ($>$1 GW/cm^2) we are currently investigating the use of high damage threshold sol-gel coatings. Improvements in the growth of BBO should enable the use of longer crystals which will reduce the half-wave voltage and also allow the use of Brewster cut faces to eliminate AR coating limitations in power handling capabilities for external use.

In summary, we have demonstrated the use of a BBO Pockels cell and pointed out its suitability for use in Q-switched diode-pumped solid-state lasers due to its many superior properties, which include high power handling capability, transparency over a broad range of harmonics of near-IR wavelengths, high contrast ratio, negligible acoustic ringing, and low insertion loss for a small aperture device. In addition to these properties, the low dispersion of BBO eminently suits it for applications in short pulse regenerative amplifiers. We have demonstrated that a BBO Q switch enables extremely high peak and average power pulsed operation of a conventional lamp-pumped laser. Extrapolating the intracavity powers achieved in the lamp-pumped laser to DPSS systems indicates that a BBO Pockels cell will make 25 W average power Q-switched operation feasible.

This work was supported by the NSF Science and Technology Center for Photoinduced Charge Transfer at the University of Rochester (Grant No. CHE-9120001), a Phase I S.B.I.R. award on topic No. SDI-093-014 (QTI), and contractual support from the Naval Air Warfare Center under Contract No. 62269-93-R-0569 (QTI).

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