Actively $Q$-switched Nd:YVO$_4$ laser using an electro-optic periodically poled lithium niobate crystal as a laser $Q$-switch

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We demonstrate a low-voltage and fast laser $Q$-switching by using an electro-optic periodically poled lithium niobate (EO PPLN) crystal. The half-wave voltage measured from the EO PPLN crystal was 0.36 V × $d$ (μm)/$L$ (cm), where $d$ is the electrode separation and $L$ is the electrode length. When a 13-mm-long EO PPLN was used as a laser $Q$ switch at 7-kHz switching rate, we measured an ~12-ns pulse width and ~0.74-kW laser pulses at 1064-nm wavelength from a diode-pumped Nd:YVO$_4$ laser with continuous 1.2-W pump power at 809-nm wavelength. © 2003 Optical Society of America

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A class of $Q$-switched lasers employs a fast intracavity polarization rotator for switching the laser polarization between high- and low-loss laser modes. The two loss modes can be established by using a polarization-dependent loss element such as a Brewster plate or a polarization-dependent laser gain medium such as a Nd:YVO$_4$ crystal. An electro-optic (EO) birefringence crystal may rotate laser polarization and can be used as a laser $Q$ switch. For example, lithium niobate, KDP, and KTP crystals are usually the crystal materials for Pockels cells in $Q$-switched lasers. Among those EO crystals, lithium niobate has a relatively large EO coefficient. Specifically, when it functions as a transverse amplitude modulator with the same ratio of electrode separation to electrode length, $d/L$, a lithium niobate crystal has a half-wave voltage 1.3 lower than that for a KTP crystal and 5.7 times lower than that for a KDP single crystal at 633-nm wavelength under the best crystal arrangement.

In the past few years the advancement of periodically poled lithium niobate (PPLN) has permitted high-efficiency nonlinear optical frequency conversion by use of the quasi-phase-matched technique. Recently, the EO effect of a PPLN crystal has been investigated. In particular, Lu et al. described a quasi-phase-matched condition in an EO PPLN polarization rotator similar to that in a PPLN laser frequency converter. Although a proof-of-principle experiment was cited in Ref. 8 in which a 1-mm-long Czochralski-grown EO PPLN crystal was used to obtain a polarization rotation angle that was 20% of the theoretical prediction, we demonstrate in this Letter a much-improved electric-field-poled EO PPLN crystal for use as a laser $Q$ switch in an actively $Q$-switched Nd:YVO$_4$ laser.

An EO PPLN crystal consists of a periodic domain structure in a $z$-cut lithium niobate substrate with each domain behaving as a half-wave plate. Accordingly, the EO PPLN has a grating period $\Lambda$ given by

$$\Lambda = 2mL_c = m\frac{\lambda_0}{n_o - n_e},$$

where $m$ is an odd integer, $L_c = \lambda_0/[2(n_o - n_e)]$ is the half-wave retardation or the coherence length of the EO PPLN crystal, $\lambda_0$ is the laser vacuum wavelength, and $n_0$ and $n_e$ are the refractive indices of the ordinary and extraordinary wave in lithium niobate, respectively. When an electric field is applied to the crystallographic $y$ direction, the crystal axis rotates a small angle of

$$\theta = \frac{r_{51}E_y}{1/n_o^2 - 1/n_e^2} s(x),$$

in the $y$–$z$ plane, where $r_{51}$ is the relevant Pockels coefficient, $E_y$ is the electric field in the $y$ direction, and the sign functions are $s(x) = +1$ and $s(x) = -1$ along $x$ for the $+z$ and $-z$ domain in the PPLN, respectively.

As a result, the polarization of a $z$-polarized input light is rotated by an angle of $4\pi\theta$ at the output after traversing $N$ domain periods in an EO PPLN crystal. From Eq. (1) and expression (2), the half-wave voltage, defined to be the voltage required for rotating a $z$-polarized input wave by 90°, is equal to

$$V_{\pi,PPLN} = \frac{\pi\lambda_0}{8} \frac{(n_o + n_e)}{r_{51}n_e^2} \frac{d}{L},$$

where $d$ is the electrode separation in $y$ and $L$ is the electrode length in $x$. Compared with the half-wave voltage of a lithium niobate transverse amplitude modulator between crossed polarizers, given by

$$V_{\pi,LN} = \frac{\lambda_0}{r_{33}n_e^3 - r_{13}n_o^3} \frac{d}{L},$$

$V_{\pi,PPLN}$ is only approximately half of $V_{\pi,LN}$ for a given $\lambda_0 d/L$, if we choose $n_o = 2.286$, $n_e = 2.200$, $r_{13} = 9.6$, $r_{33} = 30.9$, and $r_{51} = 32.6$ pm/V at 633-nm wavelength.

We fabricated a 1.3-cm-long, 1-cm-wide, and 0.5-mm-thick 14-μm-period PPLN crystal by using the electric-field-poling technique. The PPLN crystal is phase matched to the first-order EO QPM condition, given by Eq. (1), for a 1064-nm laser wavelength at 35.4 °C. After polishing the two laser faces, we engraved two trenches in the crystal, each 1.3 cm long in the $x$ direction, 120 wide in the $y$ direction, and 400 μm deep from the $+z$ surface. Figure 1 shows a cross section of the PPLN $x$ surface, in which the left portion is a photograph of the trench. A NiCr metal layer of an estimated 550-nm thickness was
Sputtered to the trench surface to form electrodes with a separation of \( d = 1 \) mm. To measure the half-wave voltage at 1064-nm wavelength, we installed the PPLN crystal in an oven between two polarizers with their transmission axes aligned parallel to the PPLN \( z \) axis. Figure 2 shows the transmitted laser power versus the applied voltage on the electrodes. From the figure, it is straightforward to deduce a half-wave voltage of 280 V or a normalized half-wave voltage of 
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\frac{0.36 \times \frac{d}{H}}{L} \text{ cm} \quad \text{with} \quad d = 1000 \, \mu\text{m} \quad \text{and} \quad L = 1.3 \, \text{cm}. 
\]
According to Ref. 9, the \( r_{32} \) coefficient is reduced by a factor of 1.26 when the laser wavelength is varied from 633 nm to 1.15 \( \mu \text{m} \). If a similar reduction factor is applied to the \( r_{51} \) coefficient, the theoretical half-wave voltage calculated from Eq. (3) is 235 V, which is \(-16\%\) smaller than the measured value. The discrepancy is attributable to the intrinsic difficulty in obtaining the exact 50% domain duty cycle in the electric-poling process. Figure 3 shows the temperature tuning curve with 280 V applied to the EO PPLN crystal. The measured 34.5 °C phase-matching temperature and 1.3 °C temperature bandwidth are in reasonable agreement with the calculated 35.4 °C phase-matching temperature and 1.7 °C temperature bandwidth.

To take advantage of the low half-wave voltage, we constructed a Q-switched Nd:YVO\(_4\) laser by using the EO PPLN polarization rotator as a laser Q switch. The gain medium, with a 3 mm × 3 mm laser aperture and 1-mm length, was an \( a \)-cut Nd:YVO\(_4\) crystal with 2-at. % Nd\(^{3+}\) doping. The pump laser was a fiber-coupled diode laser at 809-nm wavelength. On the pump side, the crystal was coated with a high-reflection dielectric layer with reflectance >99.9% at 1064-nm wavelength and an antireflection layer at 809 nm. The output coupler was a 20-cm radius-of-curvature concave mirror with 87% reflectance at 1064-nm wavelength. The laser cavity length was \(-4\) cm. The EO PPLN crystal used in the Nd:YVO\(_4\) laser was the same as the one characterized above except that the downstream end was polished to have an incomplete domain period for use as a quarter-wave plate. Both \( x \) surfaces of the EO PPLN crystal were antireflection coated at 1064-nm wavelength. The optic axis of the EO PPLN was aligned with that of the Nd:YVO\(_4\) crystal so that the laser gain is the highest without \( E_y \) in the EO PPLN. When a voltage is applied to the EO PPLN, the \( z \)-polarized input light from the gain medium is rotated, ideally, by 90° after completing a forward and backward trip through the EO PPLN and the downstream quarter-wave plate. Therefore, the EO PPLN functions as a 45° polarization rotator when a voltage of 140 V is applied to it. However, to achieve laser Q switching, full 90° round-trip polarization rotation is usually unnecessary and a switching voltage much less than 140 V is possible. For example, Fig. 4 shows the continuous-wave (CW) performance of the Nd:YVO\(_4\) laser with and without a 100-V voltage applied to the EO PPLN crystal. Without the applied voltage, the...
Nd:YVO$_4$ laser had a CW threshold of 400-mW pump power, attributable to the high output coupling loss (13%). With a 100-V voltage applied to the EO PPLN crystal, the laser's CW threshold was increased to ~1.4-W pump power as expected from the polarization rotation effect.

To show laser $Q$-switching operation, we drove the EO PPLN by using a 7-kHz, 100-V voltage pulser with a 300-ns pulse width. At 1.2-W pump power, we measured 60-mW average power or 0.74-kW peak power with 8.6-$\mu$J pulse energy in an 11.6-ns laser pulse width. Figure 5 shows the $Q$-switched laser pulse from our measurement. The slow rise time (>100 ns) and high-frequency noise from our voltage pulser prevented us from high-repetition-rate and closer to optimized operation. We also suspect that the quarter-wave plate in the monolithic PPLN was not ideal. The laser performance can be further improved by using a more carefully fabricated or an electric-field controlled quarter-wave plate in the downstream cavity. Nonetheless, the low-voltage EO $Q$-switched operation of a Nd:YVO$_4$ laser was unambiguously confirmed in the experiment. Such a low switching voltage together with the use of a high-gain laser medium (Nd:YVO$_4$) has helped to reduce the transient elasto-optic ringing effect that is due to the piezoelectric response of lithium niobate.

In conclusion, we have successfully demonstrated an actively $Q$-switched Nd:YVO$_4$ laser by using a low-voltage EO PPLN crystal as a laser $Q$ switch. We measured a normalized half-wave voltage of 0.36 V $\times$ $d$ ($\mu$m)/L (cm) at 1064-nm wavelength, where $d$ is the electrode separation and $L$ is the electrode length. When driving the EO PPLN crystal by a 100-V and 300-ns voltage pulse at 7 kHz in a diode-pumped Nd:YVO$_4$ laser, we obtained 11.6-ns, 0.74-kW $Q$-switched laser pulses at 1.2-W pump power.

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