Electro-optic periodically poled lithium niobate Bragg modulator as a laser Q-switch

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We report an electro-optic Bragg modulator using a periodically poled lithium niobate (PPLN) crystal. We measured a half-wave voltage of 160 V when transmitting a 1064 nm laser through a 14.2 mm long, 780 μm thick, 20.13 μm period PPLN crystal at the Bragg angle. We also demonstrated a Q-switched Nd:YVO_4 laser using such a PPLN Bragg modulator as its Q-switch, producing 7.8 ns, 201 μJ pulses at a 10 kHz repetition rate when pumped by a 19.35 W diode laser at 808 nm. © 2007 Optical Society of America

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Diode-pumped Q-switched lasers are popular sources for generating nanosecond and high-power laser pulses. In general there are two Q-switching schemes, active Q-switching and passive Q-switching. Compared with a passively Q-switched laser, an actively Q-switched laser is advantageous in handling a wider range of laser power and in controlling the Q-switch timing. However, an actively Q-switched laser usually requires a RF driver if an acousto-optic (AO) Q-switch is used or a pulsed high-voltage driver if an electro-optic (EO) Q-switch is used. An AO Q-switch is usually a Bragg cell that can be fairly insensitive to the laser's polarization. On the other hand, an EO Q-switch is usually a Pockels cell that controls the polarization loss of a laser cavity. For fast Q-switching, the EO switching is the preferred scheme due to the much faster response in the EO effect.

Lithium niobate is known to be an excellent nonlinear optical material. In the past 10 years, periodically poled lithium niobate (PPLN) has drawn much attention for quasi-phase-matched (QPM) nonlinear frequency conversion.[1] Electro-optic tuned PPLN wavelength converters were demonstrated to be useful for wavelength tuning and optical signal modulation.[2–4] In particular, a PPLN crystal alone can be made into an EO polarization rotator[5] at a phase-matched laser wavelength when an electric field is applied along the crystallographic y direction. Previously, we have successfully employed such a PPLN Pockels cell as a laser Q-switch with a switching voltage as low as ~100 V.[6] For clarity we replot in Fig. 1(a) the PPLN Pockels cell as a laser Q-switch. The PPLN Pockels cell consists of a quarter-wave plate and an EO PPLN crystal having the same crystal orientation as a typical PPLN wavelength converter. We further demonstrated efficient intracavity wavelength conversion by cascading such a PPLN Pockels cell with a PPLN wavelength converter in a Q-switched Nd:YVO_4 laser.[7] Despite the low switching voltage and excellent integrated QPM performance, the PPLN Pockels cell was sensitive to temperature and generated appreciable green-laser power at 532 nm in the Nd:YVO_4 laser, both due to the QPM structure in the PPLN. It is desirable to have a "green-free" and temperature-insensitive laser Q-switch that still retains the advantages of low switching voltage and excellent integrated QPM performance. In this Letter, we report such a laser Q-switch using a novel EO PPLN Bragg modulator.

The laser Q-switch reported in this Letter is also a PPLN crystal applied with an electric field along the crystallographic z direction, except that the laser propagation direction is along the Bragg angle direction of the PPLN grating. Therefore the PPLN crystal is an EO Bragg modulator capable of introducing time-dependent diffraction loss into a laser cavity. Figure 1(b) illustrates this laser Q-switch in a diode-pumped Nd:YVO_4 laser. The PPLN Q-switch is applied with a voltage at the low-Q state of the laser

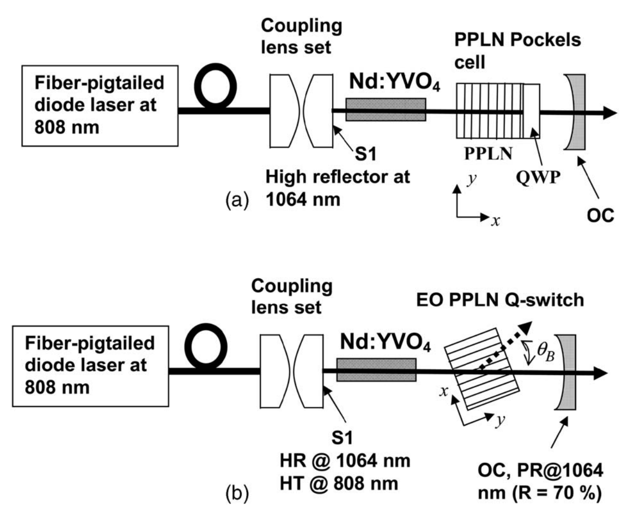

Fig. 1. Schematic of the actively Q-switched Nd:YVO_4 laser using (a) a PPLN Pockels cell and (b) an EO PPLN Bragg modulator as a laser Q-switch. The laser cavity is formed by the surface S1 and the output coupler (OC). In (b), the Bragg angle θ_B is exaggerated for clarity. QWP, quarter-wave plate; HR, high reflection; HT, high transmission; PR, partial reflection.

cavity until a quick switch-off of the voltage to generate a Q-switched laser pulse. Under a z-component electric field E_z, the refractive-index change in the crystal domain of a PPLN crystal is given by

$$\Delta n_{o,e} = -\frac{n_{o,e}^3 r_{13,33} E_z s(x)}{2}, \quad (1)$$

where n_o and n_e are the ordinary and extraordinary refractive indices, respectively; r_{13} and r_{33} are the relevant Pockels coefficients for ordinary and extraordinary incidence waves, respectively; and $s(x) = \pm 1$ denotes the sign of the domain orientation of the PPLN crystal as a periodic function of x. Since r_{33} is much larger than r_{13} for lithium niobate, the extraordinary wave is the preferred incidence wave for this PPLN Bragg modulator. For what follows, we only consider an incidence wave with extraordinary polarization. Resembling a Bragg grating, such an EO grating functions as a beam deflector for a light incident at the Bragg angle $\theta_{B,m} = \sin^{-1}[m\lambda_0/(2n\Lambda)]$, where m denotes the diffraction order, λ_0 is the laser wavelength in vacuum, n is the average refractive index of the grating, and Λ is the grating period. Since diffractions at $m = \pm 1$ are usually most significant, in the following we concentrate our discussion on $m = \pm 1$ diffractions. For a sinusoidal index variation in a grating, the diffraction efficiency of a transmission grating can be derived by following the same analysis for a Bragg cell, given by[8]

$$\eta = I_d / I_{in} = \sin^2(\gamma L/2), \quad (2)$$

where I_{in} and I_d are the incidence and diffraction intensities of a laser, respectively; L is the length of the grating; and $\gamma = 4\pi\delta n/\lambda_0$ for a sinusoidal index amplitude δn in the grating. By taking Fourier decomposition to the square-wave index profile in the EO PPLN grating, it is straightforward to show that $\delta n = 2\Delta n/\pi$ from the first Fourier coefficient. The high-order components in the Fourier decomposition are important only for a larger Δn or equivalently when the PPLN is applied with a large electric field. We should point out that plane-wave, small-angle, and slowly-varying-envelope assumptions were made in deriving Eq. (2). The half-wave voltage of an EO PPLN Bragg modulator, V_π, can be defined to be the voltage satisfying $\gamma L = \pi$ in Eq. (2). From Eqs. (1) and (2), the half-wave voltage for an extraordinary incident wave is calculated to be

$$V_\pi = \frac{\pi}{4} \frac{\lambda_0}{r_{33} n_e^3} \frac{d}{L}, \quad (3)$$

where d is the electrode separation in the z direction.

In our experiment, we fabricated a 1.42 cm long, 1 cm wide, and 780 μm thick PPLN crystal. The grating period of the EO PPLN crystal was 20.1 μm, corresponding to a Bragg angle of 0.7° for $m = 1$ at 1064 nm. The Bragg angle θ_B in Fig. 1 is exaggerated for clarity. The $\pm z$ surfaces of the PPLN crystal were coated with 500 nm thick metal electrodes, and the $\pm y$ surfaces were antireflection (AR) coated at 1064 nm. We first measured the diffraction efficiency of the PPLN crystal by using a continuous-wave laser at 1064 nm with a 110 μm laser radius. This laser radius is approximately the same as the mode radius of the Nd:YVO_4 cavity in Fig. 1. The incidence laser was prealigned to have an incidence angle equal to the Bragg angle. Figure 2 shows the measured transmittance of the zero-order beam versus applied voltage at 30 and 100 °C. It is seen from the curves that the diffraction loss of this EO grating is fairly insensitive to temperature, because the far-field divergence angle of the incident laser beam (3 mrad) is much larger than the change of the Bragg angle (~20 μrad) when the crystal temperature is varied from 30 to 100 °C. On the other hand, the PPLN Pockels has a typical temperature acceptance bandwidth of ~1 °C cm due to the QPM condition for polarization rotation. The transmittance of the zero-order beam indeed has a characteristic voltage period predicted by Eq. (2). The slight offset of the transmittance peak from the zero voltage is due to the stress-induced refractive index change[9] at the PPLN domain boundaries. In the measurement, we used a fairly small laser radius to simulate the small mode size in the Nd:YVO_4 laser cavity. The broad angular spectrum of the incidence laser prevented us from obtaining 100% diffraction efficiency at $\gamma L = \pm \pi$ predicted by the plane-wave model Eq. (2). However, when we used a more collimated, large-radius incidence beam, the measured diffraction efficiency approached 100%. As will be shown below, it is not necessary to have 100% diffraction loss for holding a Q-switched laser at the low-Q state. In Fig. 2, the diffraction loss is increased at high voltage, because high-order scatterings from the square-wave grating are more significant when Δn becomes large under high voltage. From Fig. 2, the measured half-wave voltage is about 160 V, which gives a normalized half-wave voltage of 0.29 V × d (μm)/L (cm). This normalized half-wave voltage is about 16% lower than that demonstrated for a PPLN Pockels cell[7] at the same wavelength. From Eq. (3) the calculated

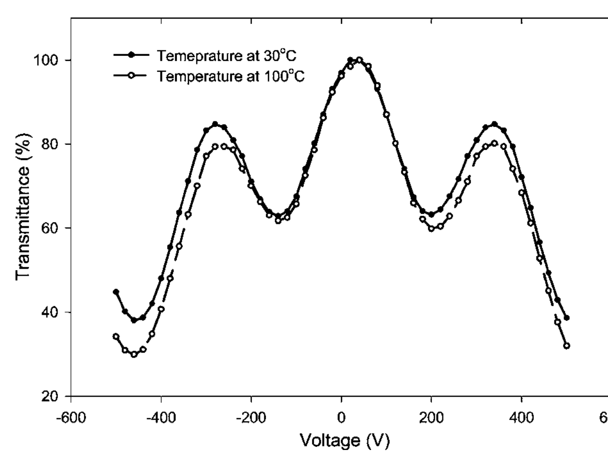

Fig. 2. Transmittance of a continuous-wave 1064 nm laser through the EO PPLN Bragg modulator at the zero-order direction as a function of applied voltage on the modulator. The half-wave voltage is 160 V. The increased diffraction loss at high voltage is due to high-order scatterings of the square-wave grating.

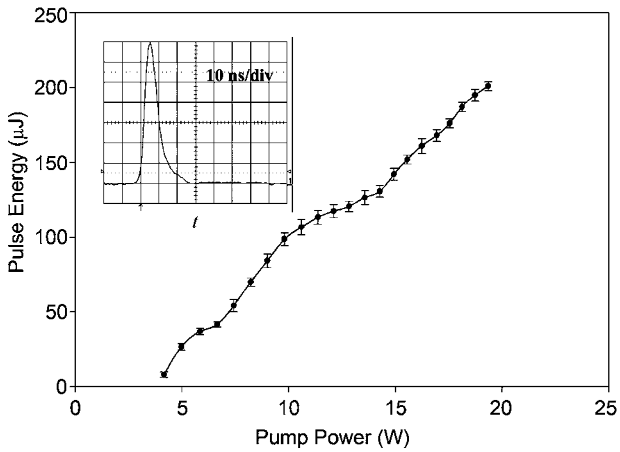

Fig. 3. Output pulse energy of the actively Q-switched Nd:YVO_4 laser versus pump power. With 19.35 W pump power at 808 nm, the 1064 nm laser pulse has an energy of 201 μJ and a width of 7.8 ns, corresponding to a laser peak power of 26 kW. The inset shows the measured temporal profile of the Q-switched laser pulse.

half-wave voltage is 151 V for r_{33}=30.3 pm/V, and n_e=2.156 at 1064 nm.[10] The r_{33}=30.3 pm/V is linearly interpolated from the bulk values at 633 and 3390 nm.[11] The somewhat higher value of the measured half-wave voltage could be attributable to the intrinsic difficulty in fabricating an exact 50% domain-duty-cycle PPLN crystal. For example, a 10% deviation from the ideal 50% duty cycle of the QPM structure can already account for the increased half-wave voltage.

To further demonstrate the EO PPLN Bragg modulator as a low-voltage laser Q-switch, we installed the PPLN grating into a Nd:YVO_4 laser according to Fig. 1. The pump source was a 20 W diode laser at 808 nm, pigtailed by a multimode silica fiber with an 800 μm core diameter and a 0.18 numerical aperture. The 808 nm laser was coupled from the fiber output to the center of the Nd:YVO_4 crystal through a set of coupling lenses with a one-to-one imaging ratio. The Nd:YVO_4 crystal is a 9 mm long, a-cut 0.25 at % Nd-doped YVO_4 crystal with its end surfaces coated with AR layers at both 1064 and 808 nm. The side surfaces of the Nd:YVO_4 crystal was wrapped in an indium foil and mounted in a water-cooled copper housing to dissipate excess heat. In Fig. 1, the S1 surface of the coupling lens is high-reflection coated at 1064 nm ($R>99.8\%$) and high-transmission coated at 808 nm ($T>90\%$). The concave side of the output coupler has a radius of curvature of 200 mm and is partial-reflection coated at 1064 nm ($R\sim 70\%$). The flat side of the output coupler is AR coated at 1064 nm ($R<0.2\%$). The distance between S1 and the upstream crystal surface is 1 mm, and that between S1 and the upstream surface of the EO grating is 44 mm. The total cavity length is 88 mm. The laser polarization direction is aligned along the z direction of the PPLN crystal.

In operation, we first biased the EO PPLN grating with a −140 V DC voltage and drove the EO PPLN grating with +140 V, 300 ns voltage pulses at 10 kHz. Figure 3 shows the measured Q-switched pulse energy versus the diode pump power. At 19.35 W pump power, the Q-switched output pulse at 1064 nm has 201 μJ energy and 7.8 ns width, corresponding to a peak power of 26 kW. The error bar in the plot shows that the pulse-to-pulse energy jitter was less than 5% over the range of our measurement. The inset shows the temporal profile of the Q-switched output pulse. In our experiment, we did not observe any noticeable change on the laser performance when we heated the EO PPLN grating from room temperature to 180 °C. In addition, we observed almost no green-laser power produced from the non-phase-matched second-harmonic generation in the EO PPLN grating.

In conclusion, we have successfully demonstrated an EO PPLN grating as a Bragg modulator with a normalized half-wave voltage of 0.29 V $\times d$ (μm)/L (cm) at 1064 nm wavelength. When driving the EO PPLN Bragg modulator with a 140 V, 300 ns voltage pulses at 10 kHz in a diode-pumped Nd:YVO_4 laser, we produced 7.8 ns, 25.8 kW Q-switched laser pulses with 19.35 W diode pump power. Since the laser propagated nearly perpendicular to the PPLN grating vector, the non-phase-matched second-harmonic generation at 532 nm was very much reduced in the laser cavity. The performance of the EO PPLN Q-switch is insensitive to temperature, which is beneficial to the integration of multifunction PPLN crystals in a monolithic lithium niobate substrate for various laser applications.

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