Monolithically integrated laser Bragg Q-switch and wavelength converter in a PPLN crystal

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Abstract: We report a periodically poled lithium niobate (PPLN) crystal for both temperature-insensitive laser Q-switching and temperature-tuned wavelength conversion. The PPLN crystal consists of two sections, a 20.3-μm period section functioning as an electro-optic Bragg grating for Q-switching a diode-pumped Nd:YVO₄ laser at 1064 nm and a 31-μm-period section functioning as an optical parametric generator for down converting the generated 1064-nm laser. When driving the PPLN Bragg grating with 170-V voltage pulses, we measured 181 μJ pulse energy at 1064 nm from the Nd:YVO₄ laser pumped by 20.4 W diode power. The 181-μJ pulsed laser was further converted into mid-infrared radiation in the monolithic PPLN crystal with 35% parametric efficiency. The wavelengths were broadly tunable in the range of 1.75-1.88 μm (signal) and 2.7-2.44 μm (idler) via temperature without affecting the performance of the PPLN Bragg Q-switch.

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References and links

1. Introduction

Diode-pumped, Q-switched solid-state lasers are popular sources for producing nanosecond
and high-power laser pulses. Passive Q-switching and active Q-switching are two commonly
seen laser Q-switching techniques. A passively Q-switched (PQS) laser, comprising a
saturable absorber and a laser gain medium, is particularly simple and compact. Active Q-
switching usually adopts an acousto-optic or an electro-optic (EO) scheme to modulate the
laser cavity loss. Compared with a PQS laser, an actively Q-switched laser has advantages in
timing stability and pulse-rate control; however, the drawbacks of an actively Q-switched
laser are usually associated with the additional cost and complexity of a Q-switch driver. An
EO Q-switch [1] is known to have fast switching time and large hold-off ability. For example,
a Pockels cell is a popular EO Q-switch, with which the quality factor of the laser cavity is
tuned through the EO controlled polarization loss. Nevertheless, a typical EO Q-switch needs
driving voltage from a few hundred volts to kilo-volts within a few tens of nanoseconds [1].

Among several EO crystals, lithium niobate is a popular one because of its relatively low cost
and large EO coefficient; in addition, lithium niobate is not only used as an EO crystal but
also used in a variety of nonlinear optical frequency converters. In the past decade,
periodically poled lithium niobate (PPLN) [2] has attracted plenty of attention due to its
unprecedented wavelength conversion efficiency through the so-called quasi-phase-matching
(QPM) technique [3]. By applying the QPM condition to polarization modes, Lu et al. [4]
also demonstrated an EO wavelength filter by rotating the polarization in a PPLN crystal
between crossed polarizers. When Lu’s device works as a transverse-mode modulator, its
half-wave voltage is lowered by a factor of two compared with a conventional lithium niobate
amplitude modulator. Chen et al. [5] employed Lu’s device as an EO Pockels cell in a diode-
pumped, Q-switched Nd:YVO₄ laser cavity. The driving voltage of such a PPLN Q-switched
laser was found to be between 50 and 150 V for a pump power between 1 and 9 W. Chen et al.
[6] further cascaded an EO PPLN Pockels cell to a PPLN wavelength converter in a
monolithic crystal substrate to perform laser Q-switching and optical parametric oscillation in
a Nd:YVO₄ laser. Despite the demonstrated compact size, low-switching voltage, and high
conversion efficiency, the wavelength tuning of the laser device is limited by the single
temperature setting for both PPLNs in a crystal substrate. Therefore, it is desirable to re-invent
a temperature-insensitive laser Q-switch cascaded to a temperature-tuned wavelength
converter for the compact and efficient laser source.

When a z-direction electric field is applied to a PPLN crystal, the periodic crystal domains
form a diffraction grating through the EO effect. This PPLN grating can be used as an EO
Bragg modulator. Based on this idea, we have recently developed an EO PPLN Bragg Q-
switch that is fairly insensitive to the device temperature and laser wavelength [7]. Given a
laser wavelength and a device length, the half-wave voltage of an EO PPLN Bragg modulator
is 16% lower than that of an EO PPLN Pockels cell [7]. In this paper we demonstrate a
broadly tunable and highly efficient optical parametric generator (OPG) pumped by a low-
voltage Q-switched laser using a PPLN Bragg Q-switch cascaded to a PPLN wavelength
converter. As will be shown below, the output wavelengths of the optical parametric generator
can be widely tuned through temperature variation without affecting the performance of the
monolithically integrated EO Bragg Q-switch.

2. EO PPLN Bragg Modulator

The PPLN crystal used in our Q-switched laser pumped OPG consists of two sections of
different periods along the crystallographic x direction. The transverse width along y direction
is 1.7 cm and the thickness along z direction is 0.78 mm. Both the grating vectors of the two
PPLN sections are in the x direction. The first PPLN has a length of 1 cm in x and a grating
period of 20.3 μm, functioning as a laser Q-switch in the y direction. The second PPLN has a
length of 3 cm in x and a grating period of 31 μm, functioning as an OPG in the x direction.
Below we first show the performance of the laser Q-switch as a Bragg modulator.
In Fig. 1(a), a laser beam is diffracted by a Bragg grating according to the Bragg condition, 

\[ 2\Lambda \sin \theta_B,m = m \lambda_0 / n \]

where \( m \) is the diffraction order, \( \lambda_0 \) is the incident laser wavelength, \( n \) is the average refractive index of the Bragg grating, and \( \Lambda \) is the grating period. To form a Bragg grating, we coated both the positive and negative \( z \) surfaces of the crystal with metal electrodes and applied a voltage to them. The EO-induced periodic refractive-index modulation in the PPLN crystal forms a grating along \( x \). For a 20.3-\( \mu \)m grating period, the Bragg angle is 0.68° for \( m = 1 \) at 1064 nm. Although the EO PPLN Bragg modulator is insensitive to temperature [7], the diffraction efficiency is affected by the laser beam size. When a laser beam is tightly focused, the angular spectrum of the laser becomes broader. We used a \( z \)-polarized continuous-wave Ytterbium fiber laser at 1064 nm with \( M^2 \sim 1.1 \) to measure the diffraction efficiency of the PPLN Bragg grating as a function of the applied voltage for various laser beam sizes. Figure 1(b) shows the transmittance of the PPLN Bragg modulator at 1064 nm along the 0th-order direction versus the applied voltage for different laser beam waist radii at the center of the crystal. Reduced transmittance corresponds to increased diffraction loss. Due to the stress induced refractive-index change between adjacent ferroelectric domains [8], the peak transmittance of the curve is slightly shifted away from the zero-voltage point. It is seen that the transmission curves vary with the applied voltage with a half-wave voltage of 170 V. The measured half-wave voltage agrees well with the theory [7]. The poor diffraction efficiency for a small radius beam is attributable to its broad angular spectrum, within which some laser energy is not matched to the Bragg condition. Since the refractive-index change is proportional to the applied voltage, scattering loss due to high-order Fourier components of the square-wave PPLN grating becomes significant at high voltages. When using this Bragg modulator as a laser Q-switch, as will be shown below, we chose a laser-mode radius of 150 \( \mu \)m to avoid beam clipping in the 0.78 mm thick crystal aperture and yet to provide \(-50\% \) diffraction loss at the first minimum of the transmission curve.

3. Experimental Setup for Simultaneous Laser Q-Switching and Wavelength Conversion

Figure 2 shows the schematic of the Nd:YVO\(_4\) laser pumped OPG with an EO PPLN Bragg Q-switch cascaded to a PPLN wavelength converter. Along the grating vector direction, the first 1-cm section has a grating period of 20.3 \( \mu \)m functioning as a Bragg laser Q-switch and the second 3-cm section has a period of 31 \( \mu \)m functioning as a wavelength converter. The ±z
surfaces of the first 1-cm PPLN section were coated with 50-nm thick NiCr electrodes, on which a voltage was applied to form a Bragg grating during the high-loss state of laser Q-switching. Because of the small Bragg angle, the 1064-nm laser pulse was generated along a direction nearly perpendicular to the grating vector of the PPLN Bragg modulator. The 1064-nm laser pulse was then bent 270 degrees external to the Nd:YVO_{4} laser cavity and focused into the center of the OPG PPLN. The four side faces (±y and ±x surfaces) of the PPLN crystal were optically polished and coated with anti-reflection dielectric layers at both 1064 nm (reflectance R<0.2%) and 1600 ~ 2000 nm (R<1%). To tune the OPG output wavelengths, the PPLN crystal was installed in an oven controlled within 0.1 °C. We used a 20.4-W fiber-pigtailed diode laser at 808 nm to pump a 9 mm long, a-cut, 0.25-at.% Nd-doped YVO_{4} crystal through a set of one-to-one imaging coupling lenses. The low Nd doping level in the YVO_{4} crystal avoids thermally induced fracture at high pump power. An a-cut Nd:YVO_{4} crystal has the advantage of generating a linearly polarized output for pumping the OPG PPLN. The Nd:YVO_{4} crystal was wrapped in an indium foil and embedded in a water-cooled copper housing to dissipate excess heat. The two end surfaces of the Nd:YVO_{4} crystal were optically polished and coated with antireflection layers at both 808 and 1064 nm. The 1064 nm Nd:YVO_{4} laser cavity was formed by a flat high reflection (HR) mirror M1 at 1064 nm (R>99.8% at 1064 nm) and an output coupler (OC) with a 200-mm radius of curvature (ROC) and 30% output coupling at 1064 nm. The distance between M1 and the upstream surface of the Nd:YVO_{4} crystal is 1 mm and that between M1 and the upstream y surface of the EO PPLN Bragg Q-switch is 44 mm. The total cavity length of the 1064-nm laser is around 88 mm.

During operation, we first set the temperature of the crystal oven to room temperature and applied a −170V DC bias voltage to the EO PPLN Bragg modulator. To Q-switch the laser, we superimposed a +170 V voltage pulse with a 500 ns pulse width and a 1-kHz pulse rate to the Bragg modulator. When the laser incidence angle was matched to the Bragg condition of the EO PPLN Bragg modulator, the laser started to generate Q-switched pulses. We used a double-convex lens with a 75-mm focal length (\( f = 75 \) mm) after the output coupler to collimate the 1064-nm output pulses and two 1064-nm HR mirrors to direct the 1064-nm beam into the same PPLN crystal in the x direction. Another \( f = 75 \) mm double-convex lens was used to focus the 1064-nm laser beam down to 80-μm laser waist radius at the center of the OPG PPLN. The 1064-nm pumped OPG generated appreciable green-laser power through...
non-phase-matched second harmonic generation in the OPG PPLN crystal. Since photorefraction induced by the green laser in the EO PPLN Q-switch could cause power instability in the 1064-nm laser cavity [5, 6], we first let the 1064-nm laser go through the EO PPLN Bragg Q-switch and then through the OPG PPLN when pumping the OPG.

4. Result and Discussion

Figure 3 shows the measured output energy of the 1064 nm pulse versus diode pump power when the PPLN Bragg Q-switch was operated at 1 kHz and kept at room temperature. After overcoming the pump threshold at about 5.5 W, the Q-switched 1064-nm laser generates pulse energy that steadily increases to 180 μJ/pulse at 20.4-W diode power. The peak output power at 1064 nm was 22.5 kW with a laser pulse length of 8 ns. The laser pulse energy was reduced about 15% when we increased the Q-switching rate to 10 kHz. The relatively short upper state lifetime of a Nd:YVO₄ laser would allow the Q-switched Nd:YVO₄ laser to operate at a pulse rate up to 50-100 kHz with high efficiency. However, high peak power at 1064 nm is desirable for pumping the OPG. For this proof-of-principle experiment, we chose to operate the Nd:YVO₄ laser at 1 kHz and used the maximum pulse energy of 180 μJ/pulse to pump the down-stream OPG. Due to losses in the optical components between the 1064-nm output coupler and the OPG, the 180 μJ pulse energy was slightly reduced to 172 μJ at the entrance of the OPG.

We also raised the temperature of the PPLN crystal from room temperature to 200°C and found no degradation in the output pulse energy shown in Fig. 3. This temperature-insensitive feature of the PPLN Bragg Q-switch permits tuning of the OPG output wavelengths while keeping a stable pump power from the 1064-nm laser. The 31-μm period of the OPG PPLN crystal is phase matched to a signal wavelength of 1753 nm and an idler wavelength of 2707 nm for a pump wavelength of 1064 nm at 100 °C. Figure 4 shows the 1753-nm signal pulse energy versus 1064-nm pump energy with 28.7% slope efficiency. The maximum signal pulse energy reached 37.4 μJ with 172-μJ pump energy at 1064 nm. The overall parametric efficiency from the 1064-nm pump to the signal and idler is 36%, corresponding to an effective nonlinear coefficient of 16 pm/V.

The temporal profiles of the pump and signal pulses were measured by a fast InGaAs detector. Figure 5 shows a 4-ns pulse width for the signal wave at 1753 nm when the OPG
was pumped by 172-μJ energy at 1064 nm. The inset shows the pump pulse before entering and after exiting the OPG PPLN. The exponential gain of the parametric amplification process strongly depleted the 8-ns pump pulse and generated a shortened 4-ns signal pulse. For 37.4-μJ signal energy, the generated peak signal power was 9.35 kW.

Fig. 5. The temporal profile of the OPG signal pulse with 172-μJ pump energy at 1064 nm. The inset shows original and depleted pump pulses before and after the OPG PPLN. The exponential gain in the parametric amplification process strongly depletes the 8-ns pump pulse and generates a shortened signal pulse.

Fig. 6. Temperature tuned parametric wavelengths (filled dots) and the correspondingly measured parametric conversion efficiency. The solid line is the theoretical curve calculated from the published Sellmeier equation [9].

A major improvement of the demonstrated PPLN laser device compared with that in Ref. [6] is its broad wavelength tuning through temperature. Figure 6 shows the tuned wavelength (filled circle) and the corresponding parametric efficiency (open circle) as a function of the PPLN crystal temperature. The wavelength tuning agrees well with the theoretical curve (solid line) calculated from the published Sellmeier equation for congruent lithium niobate [9]. Throughout the whole tuning range, the OPG output power stayed fairly constant, because the 1064-nm Q-switched pulse energy was insensitive to the temperature variation in the PPLN Q-switch. The measured parametric efficiency was around 35% for the tuning range of 1.75-1.88 μm (signal) and 2.7-2.44 μm (idler).

5. Conclusion

In conclusion, we have successfully integrated an EO PPLN Bragg Q-switch and an optical parametric generator into a monolithic PPLN crystal, and demonstrated simultaneous laser Q-switching and parametric wavelength tuning with 35% parametric conversion efficiency. When driving the EO PPLN Bragg Q-switch with a 170-V, 500-ns voltage pulse at 1 kHz, we obtained 181-μJ pulse energy at 1064 nm from the 20.4-W diode pumped Nd:YVO₄ laser. The Q-switched laser pulse at 1064 nm was re-injected into the PPLN OPG monolithically integrated to the PPLN Bragg Q-switch. While generating stable output power, the OPG wavelengths were tunable in the range of 1.75-1.88 μm (signal) and 2.7-2.44 μm (idler) through temperature variation in the PPLN crystal. Our work demonstrated for the first time a continuously tuned optical parametric device cascaded to a laser Q-switch in a monolithic PPLN crystal.

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