Nanosecond periodically poled lithium niobate optical parametric generator pumped at 532 nm by a single-frequency passively Q-switched Nd:YAG laser

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We report an efficient, visible, nanosecond optical parametric generator of periodically poled lithium niobate pumped at 532 nm by a frequency-doubled, diode-pumped, passively Q-switched, single-mode Nd:YAG laser with 90-μJ pulse energy. The signal radiation is tunable from 637 to 593 nm. The maximum signal-conversion efficiency is 23%. Optical parametric amplification of a He–Ne laser at 632.8 nm is also studied. © 1999 Optical Society of America

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The theories of parametric interaction,[1] parametric fluorescence, and optical parametric amplification have been studied for more than 30 years.[2–4] For optical parametric generation (OPG), i.e., amplification of parametric fluorescence to a macroscopic power level, very high pump intensities are required that are often above the optical damage threshold of the nonlinear material. The development of materials with a high optical damage threshold, such as β-barium borate[5] and lithium borate,[6] and progress in ultrafast pulse generation have lead to many practical applications of OPG. When picosecond pulses are used, the useful length and therefore the nonlinear coupling of the nonlinear crystal are limited by group-velocity mismatch among the three interacting waves. With a diffraction-limited pump beam the nonlinear coupling and therefore the OPG threshold are given by a pulse energy that does not vary with the pulse duration.[7]

When nanosecond (ns) pulses are used to pump an optical parametric generator, the optimum crystal length is typically several meters, which is longer than the practical limits set by crystal growth or beam walk-off owing to birefringence, resulting in lower nonlinear gain. Therefore the OPG threshold is more difficult to achieve, because the pump energy is limited by the optical damage threshold of the nonlinear crystal. Usually this problem is overcome by use of multiple passes of the pump beam through the crystal.[8]

Periodically poled lithium niobate (PPLN) provides a novel nonlinear material with an exceptionally high effective nonlinear coefficient of 17 pm/V, eight times greater than the corresponding value for β-barium borate.[9] The large group-velocity mismatch of PPLN, which results in a submillimeter interaction length for femtosecond pulses, is not an issue with ns pulses.[10] Zayhowski demonstrated PPLN to be a suitable material for a compact ns optical parametric generator by use of a passively Q-switched Nd:YAG laser at 1064 nm and a close-coupled PPLN crystal.[11]

In this Letter we report on an optical parametric generator based on PPLN and pumped at 532 nm by a frequency-doubled, diode-pumped, single-frequency Nd:YAG laser. Optical feedback owing to surface reflection was avoided by use of strongly wedged (5°) PPLN crystals. Gain broadening was observed, in agreement with theoretical prediction. With temperature tuning and the use of different quasi-phase-matching (QPM) periods ranging from 10.1 to 11.8 μm, the optical parametric generator covered a spectral range of 637 to 593 nm (signal wave) and 3.2 to 5.1 μm (idler wave). OPG is a very simple method to generate widely tunable infrared and visible ns light pulses, which have various applications in spectroscopy. Moreover, OPG can provide a compact, stable, and coherent tunable light source.

The pump laser was a passively Q-switched Nd:YAG laser operating at 1064 nm, similar to one reported in Ref. 12. The laser consisted of a 4-mm-long Nd:YAG crystal and a 3-mm-long Cr^{4+}:GSGG saturable absorber (with an unsaturated transmission of 56% at 1064 nm). The laser produced pulses of 172-μJ energy at a repetition rate of 1.1 kHz, with a pulse duration of 2.5 ns. Stable single-frequency operation was obtained by careful alignment of the laser cavity and the saturable absorber. To generate the 532-nm second harmonic we focused the laser radiation in a 7-mm-long type II KTP crystal. A pulse energy of 90 μJ at 532 nm was produced at the maximum pulse energy of the fundamental (52% efficiency). The green beam was 1.2 times diffraction limited. After it passed through a dichroic separator, the second-harmonic radiation was focused into the PPLN optical parametric generator crystal to a beam waist of 60 μm.

Two different types of PPLN crystal were used in the OPG setup. The first crystal, with a uniform 10.5-μm QPM period, was 55 mm long, 8 mm wide, and 0.5 mm thick. The second crystal had the same length and thickness and contained 30 channels with different

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QPM periods from 10.1 to 13 μm in 0.1-μm steps, each step having an aperture of 0.5 mm × 0.5 mm. The end facets of both crystals were uncoated and wedged with an angle of 5° with respect to the QPM domain walls, which prevented oscillation induced by surface reflection.

The first measurements were taken with the single-QPM-grating PPLN crystal. We placed the crystal in an oven and heated it to 150 °C to avoid photorefractive damage. Phase matching was obtained at a signal wavelength of 627 nm. The OPG threshold, which we defined as detection of OPG pulse energy of 0.1 μJ (following Ref. 13), was reached at a pump energy of 13 μJ, as can be seen from Fig. 1. From this pulse energy we calculated an effective nonlinear coefficient d_{eff} of 12 pm/V by use of a plane-wave approximation. This value is similar to results reported for short-period PPLN crystals.[14] The single-pass gain exceeds a value of 10^{12} for the amplification of the parametric fluorescence at the OPG threshold. The highest pump-to-signal conversion efficiency, 23%, was obtained at a pump energy of 33 μJ. At higher pump energies, backconversion and nonlinear absorption of the pump radiation in the PPLN crystal reduced the conversion efficiency. An average signal output power of 12 mW was obtained at an average 532-nm pump power of 97 mW, at a repetition rate of 1.1 kHz. To measure the idler power we inserted a GaAs filter into the optical parametric generator's output beam. The maximum detected idler power was 2 mW at 3.5 μm. The signal beam had an M^2 value of 3.5.

The multigrating PPLN crystal was used to demonstrate broad tunability of the OPG output. Figure 2 shows the tuning range for a constant temperature of 150 °C. By changing the QPM period from 10.1 to 11.8 μm, we were able to tune the signal output from 637 to 593 nm. The corresponding idler wavelength ranged from 3.2 to 5.1 μm. By adjustment of the temperature of the PPLN crystal from 150 to 200 °C, we achieved continuous tuning throughout the entire wavelength range of the OPG device. The OPG threshold generally remained constant for idler wavelengths with low absorption in the PPLN crystal (Fig. 3).

The spectral output of the optical parametric generator was measured with a spectrometer composed of a 1-m monochromator and a CCD array. The resolution of the spectrometer was 0.012 nm. Figure 4 shows the signal bandwidth of the optical parametric generator as a function of the signal wavelength. The signal bandwidth varied from 0.15 nm at a signal wavelength of 637 nm to 0.32 nm at 593 nm. The theoretical curve is calculated for the corresponding single-pass parametric process, taking into account that the approximation as a sinc function is not valid any more because it can be applied only in the low gain limit. Even when the OPG is pumped at threshold, the approximate parametric gain Γl (where Γ is the gain coefficient and l is the crystal length) is 15, resulting in spectral broadening of the gain curve by a factor of 3 (FWHM) compared with the low-gain limit.[13] Note that no cluster effects can

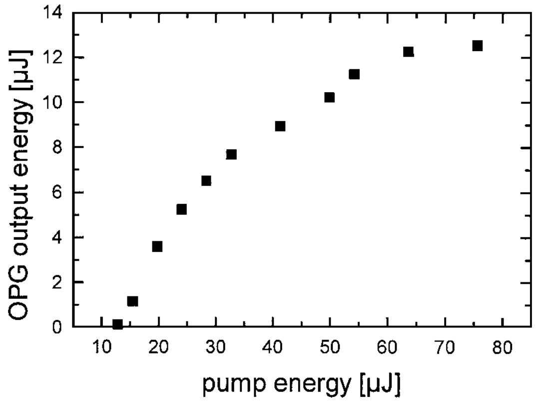

Fig. 1. Signal-pulse energy for the single-grating crystal ($\Lambda = 10.5$ μm, $T_{\mathrm{crystal}} = 150$ °C). The signal wavelength was 627 nm.

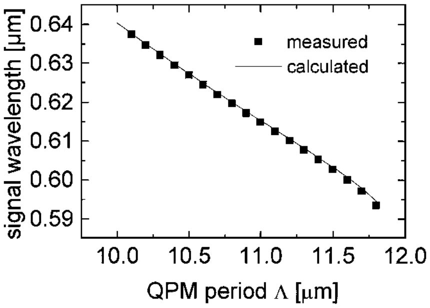

Fig. 2. Tuning range of the OPG for a constant temperature of 150 °C for grating periods from 10.1 to 11.8 μm. The solid curve represents the signal wavelengths calculated with the Sellmeier equations given in Ref. 15.

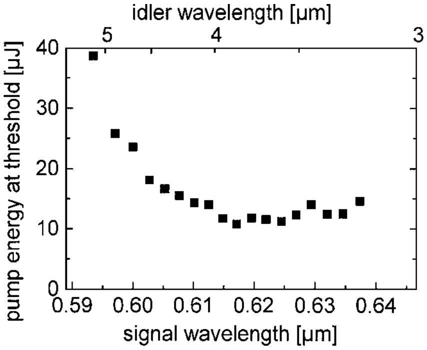

Fig. 3. OPG threshold as a function of the signal wavelength. The OPG output was tuned by translation of the PPLN crystal so that the pump passed through the QPM grating with a period ranging from 10.1 to 11.8 μm.

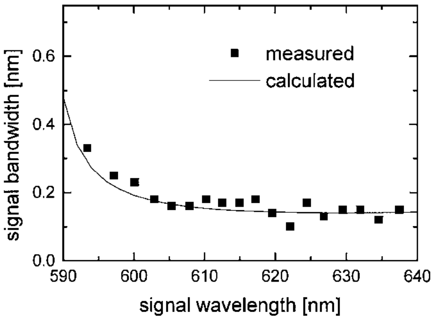

Fig. 4. Signal bandwidth of the PPLN optical parametric generator pumped at 532 nm. The solid curve represents the theoretical bandwidth (FWHM) for single-pass parametric amplification.

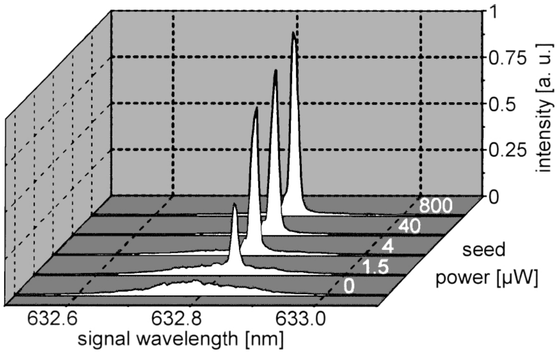

Fig. 5. Spectra of the PPLN OPG at 623.8 nm ($\Lambda = 10.2\ \mu$m, $T_{\text{crystal}} = 177.5\,°$C) injection seeded with radiation from a He–Ne laser. The pump energy was 52 μJ, corresponding to four times the OPG threshold.

be seen in the spectral output of the optical parametric generator. However, in earlier experiments with crystals that had parallel or minimally wedged end facets, a structured spectral output was observed owing to double resonance of the signal and the idler waves.

A strong reduction of the OPG bandwidth was obtained with injection seeding. The radiation of a He–Ne laser was focused and matched to the 60-μm waist of the pump beam. A spectral overlap of the optical parametric generator output and the 632.8-nm radiation of a He–Ne laser was obtained by operation of the optical parametric generator with a 10.2-μm period at 177.5 °C. The spectrum of the OPG as a function of He–Ne seed power is given in Fig. 5. A minimum seed input power of 40 μW is required for complete elimination of the OPG background. At seed input powers less than 40 μW, the optical parametric generator emitted a broadband background. The bandwidth of the seeded OPG signal output was analyzed with an air-spaced plane-mirror Fabry–Perot spectrometer (with a free spectral range of 3.75 GHz and a finesse of 50) and a two-dimensional CCD camera. From the Fabry–Perot ring pattern we measured a bandwidth of 400 MHz for the injection-seeded OPG signal radiation. When the resolution of the spectrometer is taken into account, this value is close to the Fourier limit of 300 MHz for the OPG pulses.

In conclusion, we have demonstrated a PPLN-based optical parametric generator pumped by the second harmonic of a passively Q-switched Nd:YAG laser. The generator's signal output was tunable from 637 to 593 nm, corresponding to an idler wavelength range of 3.2 to 5.1 μm. The bandwidth of OPG ranged from 0.15 to 0.32 nm, in agreement with theory. A further bandwidth reduction was achieved with injection seeding. A minimum of 40 μW or cw He–Ne laser radiation was required for complete suppression of the OPG background. Although the device's performance was limited by (nonlinear) 532-nm absorption, the large parametric gain permits the simple setup of compact frequency converters. Future research will focus on the combination of cascaded parametric processes on one PPLN crystal.

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