Pulsed nanosecond optical parametric generator based on periodically poled lithium niobate

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Abstract

In this paper we report on a pulsed nanosecond optical parametric generator (OPG) of congruent periodically poled lithium niobate (PPLN). The OPG is excited by TEM₀₀ single frequency pulses (duration: 10 ns, repetition rate: 10 kHz) of a Q-switched Nd:YVO₄ laser system. With 7.2 W of average power the OPG generated 1.6 W of signal and 0.76 W of idler radiation. The signal and idler waves are tunable in the range of 1.56–1.64 and 3.34–3.03 μm, respectively, by changing the temperature of the PPLN crystal. Injection seeding with 3 mW of cw 1.580 μm light of a tunable DFB diode laser narrowed the spectral width of the OPG signal wave to less than 140 MHz.

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Spectroscopic methods, such as cavity ring down spectroscopy, photo-acoustic spectroscopy or laser remote sensing, require pulsed-tunable laser light. For these applications pulse durations of 10 ns or less are preferred. In addition, the spectral bandwidth should be as narrow as possible. A Fourier limited bandwidth is in fact highly desirable. Furthermore, the setting of the wavelength should be of high accuracy and of high temporal stability. A high repetition rate (kilo-hertz), high average output power (multi-watt) is also preferred to increase the signal-to-noise ratio and reduce the data acquisition time.

In recent years pulsed optical parametric oscillators and generators (based on periodically poled lithium-niobate (PPLN)) have been developed successfully as reliable sources for the generation of tunable infrared and visible light [1–3]. A main advantage of this material is its high nonlinearity. Yang and Velsko, for example, demonstrated a wavelength-tunable OPO of this material with a repetition rate of 1 kHz [4]. This OPO was non-collinearly phase-matched. A variation of the direction of the pump beam in respect...
to the resonator axis by as much as 24 mrad tuned
the OPO idler wave over a range of 400 cm⁻¹. At
1.5 μm the bandwidth of the signal wave was re-
duced to 158 MHz by injection seeding with cw
diode laser radiation. A main limitation in the
performance of this OPO is, however, the re-
requirement that the wavelength of the seed radia-
tion has to coincide with an OPO cavity mode.

In contrast to the seeding of an OPO, seeded
operation of an OPG is much easier. Since an
OPG has no optical resonator, precise control of
the emission wavelength and its bandwidth is
easily achieved at any wavelength within the
parametric gain profile. This has been demon-
strated in the past by several OPG devices [2,5].
These devices generated average output powers of
less than 200 mW. A main reason for this low
output has been the lack of suitable pump lasers.

OPG pump lasers should meet several require-
ments. The pulse duration, for example, should be
about 10 ns or less in order to obtain a high pulse
power which lowers the OPG’s threshold and in-
creases the conversion efficiency. The aperture of
PPLN is limited at present to about 1 mm or less
due to the fabrication process used for creating the
ferroelectric domains. A scaling of the output
power can thus not be achieved simply by in-
creasing the pump pulse energy, since the power
density would surpass the facet’s damage thresh-
old. Higher average output powers are thus ob-
tained reliably by increasing the pulse repetition
rate. Furthermore, a spatial quality of the laser
beam which is close to the diffraction limit pro-
vides a maximum interaction length inside the
OPG crystal. To allow the use of injection seeding
for narrowing the bandwidth of the OPG radiation
to values as close as possible to the Fourier-limit
[6] the bandwidth of the laser pulses should be of
narrow spectral width.

In this paper we report on a PPLN–OPG which
is excited by a Q-switched, diode-pumped Nd:
YVO₄ oscillator amplifier laser system. This laser sys-
tem provides pulses at 1064 nm with a duration of
less than 10 ns, a repetition rate of 10 kHz and an
average power of 7.2 W. Injection seeding with a
diode-pumped non-planar ring oscillator (NPRO)
reduces the spectral line width to 50 MHz close
to the Fourier-limit. The laser pulses excite a
PPLN–OPG which consists of a 55-mm long
PPLN crystal with a period of the ferroelectric
domains of 29.75 μm. Pumped by laser pulses with
an average power of 6.8 W the OPG provided a
total output power of 2.4 W which corresponds to
a crystal internal conversion efficiency of 47%. At
1580 nm the OPG signal output was narrowed to a
spectral width of 140 MHz by injection seeding
with 3 mW of the emission of a cw DFB-diode
laser.

A schematic of the experimental setup is shown
in Fig. 1. As mentioned above the laser radiation is
generated by a single frequency diode-pumped
Nd:YVO₄ oscillator amplifier laser system. The
laser oscillator is a Q-switched ring laser seeded by
a cw NPRO. The Nd:YVO₄ oscillator was pumped
by 12 W of 808 nm diode laser radiation to pro-
duce 10.5 ns pulses at a repetition rate of 10 kHz
with an average output power of 1.5 W. This ra-
diation is amplified in a longitudinally pumped
Nd:YVO₄ double pass amplifier. The amplified
radiation was emitted in a nearly diffraction lim-
ited beam (M² = 1.2) in 8.5 ns pulses with an av-
erage output power of 7.2 W. The measured
linewidth is 50 MHz which is close to the Fourier-
limit for pulses with a gaussian temporal shape.

The laser pulses are focused at the center of the
OPG–PPLN crystal to a intensity waist of 130 μm.
The period of the ferroelectric domains in the
PPLN crystal is 29.75 μm, the crystal’s size is
55 mm × 8 mm × 0.5 mm. The end facets were cut
and polished with a wedge angle of 5° with respect

![Fig. 1. Schematic of the Nd:YVO₄-pumped PPLN–OPG system. The seed source was a DFB diode laser. ISO, optical isolator; HWP, halfwave plate; VA, variable attenuator; L1–L3, spherical lenses; L4 and L5, cylindrical lenses.](image-url)
to the domain walls. The wedged facets prevent feedback of laser and OPG radiation into the crystal by Fresnel reflections. The crystal was placed in an oven which allowed to vary and control the temperature of the crystal within the range of 25–250 °C.

Figs. 2(a) and (b) show the dependence of the total-, signal- and idler-power on average pump power. This dependence is shown for both the seeded and unseeded operation. In these measurements the OPG was operated at a wavelength of the signal radiation of 1.580 nm. This wavelength requires a crystal temperature of 168 °C.

The OPG threshold, which is defined (in agreement with [7]) by the detection of an OPG output pulse energy of 0.1 μJ, required a pump pulse energy of 160 μJ in the unseeded case. From this value we estimate in a plane wave approximation an effective nonlinear coefficient $d_{\text{eff}}$ of 15 pm/V. This result is in good agreement with the value of 17 pm/V reported in [1]. Near the OPG threshold, the estimated single pass gain for parametric fluorescence exceeds a value of $10^2$ for a 55-mm crystal length. For the maximum pump power of 6.8 W the OPG emitted a total output power of 2.4 W. This output consisted of 1.63 W of signal- and 0.76 W of idler-radiation. These output powers were determined by taking the losses in the beam separating optical elements into account. These losses were further increased for both the pump and OPG pulses by Fresnel reflections at the uncoated crystal facets. Considering these losses at the crystal facets, the crystal internal conversion efficiency is 47%. The ratio between the power of the signal and idler wave is 2.14, which is in good agreement with the theo-

![Graph](image-url)

Fig. 2. Average OPG output power vs. average pump power for unseeded operation (a) and for seeded operation (b).

![Graph](image-url)

Fig. 3. (a) OPG signal wavelength vs. crystal temperature for pumping at 1064 nm. The grating period of the OPG crystal was 29.75 μm. The solid line represents the calculated signal wavelength using the dispersion equation of [8]. (b) Bandwidth (FWHM) of the signal wave vs. signal wavelength. The wavelength was tuned by varying the crystal temperature. The solid line is the high gain bandwidth calculated for a 55-mm long PPLN crystal with a maximum gain of $\Gamma \ell = 12$. 
Theoretical value of 2.06 given by the ratio of the quantum energy of the signal and idler photons.

The wavelengths of the OPG signal and idler waves were tunable in a range of 1.56–1.64 μm and in the range of 3.34–3.03 μm, respectively. As seen in Fig. 3(a) this tuning was achieved by changing the crystal temperature from 140 to 250 °C. The measured wavelengths were in good agreement with theoretical values calculated by using the dispersion equation reported in [8].

Fig. 3(b) shows the spectral width of the signal wave for unseeded operation as measured at different wavelengths. The measured spectral widths are compared with values derived from the calculated high gain bandwidth of single-pass parametric amplification [7]. It should be noted that the low gain approximation is not valid for the investigated PPLN–OPG since the parametric gain exceeds a value of $G' = 12$. The high gain causes a broadening of the gain profile calculated in the low gain limit by a factor of 3.3.

In addition to the output power and the spectral width the spatial quality of the OPG output is of special interest. Fig. 4 shows the measured beam quality (in values of $M^2$) as a function of the pump power. At threshold the $M^2$-value was measured in the direction perpendicular ($M^2_x$) and parallel ($M^2_y$) to the polarization of the pump beam. Therefore $M^2_x$ corresponds to the beam quality in the $y$-axis of the crystal and $M^2_y$ to the $z$-axis. At a pump power of 1.65 W the values of $M^2_x$ and $M^2_y$ are 1.2 and 1.6, respectively. The slight difference in the two values could be caused by distortions in the domain structure of the PPLN crystal and by photorefractive effects. For higher pump power, the values of $M^2_x$ and $M^2_y$ increased to 2.4 and 3.0, respectively.

The spectrum of the unseeded OPG signal wave is shown in Fig. 5 on a logarithmic scale for three different pump powers. In these measurements the temperature of the crystal oven was kept constant at 168 °C. With increasing pump power the spectrum broadens and its shape becomes more and more non-symmetric. As the pump power is increased, the OPG signal and idler wave bandwidth increases with a corresponding shift to longer wavelengths for the signal and shorter wavelengths for the idler. The increase in bandwidth can be attributed to non-collinear phase matching at higher pump power. The non-collinear phase matching causes a spectral shift of the generated parametric radiation to longer wavelengths [9]. Furthermore, non-collinear phase matching shortens the interaction length between the pump, signal and idler waves. This lowers the overall parametric gain for the more divergent components of the generated OPG radiation. This indicates an increase of the temperature of the crystal within the area of the focused pump radiation by absorption of laser and OPG radiation. The
wavelength shift observed for an increase of the laser power from 2 to 6 W corresponds to an increase of the crystal internal temperature by about 5 °C.

The broad spectral emission of the OPG could be reduced to a narrow spectral line by using the method of injection seeding. The source of the required narrowband cw seed radiation was a low power distributed feedback (DFB) diode laser with an emission wavelength of 1.580 μm. The diode laser was mounted on a temperature controlled copper plate. The seed radiation was spatially matched to the pump beam by a combination of spherical and cylindrical lenses. An optical isolator with an extinction ratio of ~40 dB prevented feedback from the OPG facets into the diode laser. A half wave plate was used to rotate the polarization of the seed laser to match the polarization of the OPG signal wave.

When driven by a current of 100 mA, the DFB diode laser generated a maximum output of 5.8 mW in an almost diffraction limited beam ($M^2 = 1.2$). Under these conditions, the seeded spectral linewidth was 10 MHz (Fig. 6(a)). The wavelength of the DFB-laser radiation was tuned by changing the diode current or temperature. Changing, for example, the diode temperature from 15 to 40 °C, the output wavelength was tuned from 1.579 to 1.582 μm. This tuning range is well within the amplification bandwidth of the PPLN. Temperature tuning of the diode’s wavelength is, however, a rather slow process with limited accuracy. Fast wavelength tuning (with tuning rates of up to $10^5$ GHz/s) is possible within a range of 25 GHz by varying the diode current. With a seed power of 3 mW the injection seeding reduced the OPG threshold by 200 mW to about 1.4 W. Simultaneously, the output power of the seeded OPG (Fig. 2(b)) was increased by a small amount.

In Fig. 7, the temporal profile of the pump pulse is shown for a pump power of 1.6 W, a power which is close to the threshold of the unseeded OPG. In this case no depletion of the laser pulse is observed. With injection seeding pump depletion is detected, however, in the central part of the laser pulse. At a pump power of 6.8 W the total output of the seeded OPG is 2.5 W (see Fig. 2(b)). This output corresponds to a total crystal internal conversion efficiency of 49%. The internal efficiency of the seeded OPG is thus (compared to unseeded operation) higher by only 2%.

The spectrum of the signal radiation of the seeded OPG is shown in Fig. 8 for three different...
Pump powers (which are identical to those used in the measurements shown in Fig. 5). For a pump power of 2 and 4 W the seeding controls completely the spectral bandwidth of the OPG signal wave. At higher pump powers a small amount of broadband OPG radiation is emitted in particular at longer wavelengths. Although the power of this broadband OPG radiation is lower than 20 dB compared to the seeded narrowband emission, it clearly indicates the presence of inhomogeneous gain broadening caused by non-collinearly phase-matched parametric amplification.

The spectral bandwidth of the seeded OPG output was measured using a scanning Fabry–Perot interferometer (S-FPI) with a free spectral range of $\Delta \nu_{FSR} = 2$ GHz. A sampling method was used to determine the bandwidth. The scanning frequency was low compared to the 10 kHz laser repetition rate. Each of the lines shown in Fig. 6(b) represent different OPG pulses. For the 10 ns duration of a single pulse the mirror separation of the scanning S-FPI is static. The envelope of the power of consecutive pulses in the pulse train transmitted by the S-FPI thus represents the spectral line width of the pulsed OPG radiation. The bandwidth of the OPG signal radiation measured in this way was 140 MHz.

In conclusion we have demonstrated a powerful nanosecond PPLN–OPG pumped by a single frequency Nd:YVO₄ oscillator power amplifier laser system. The laser system operates at a repetition rate of 10 kHz with an average power of 7.2 W. The OPG output power was 1.63 W at the signal wave and 0.76 W at the idler wave. The maximum total conversion efficiency was as high as 47%. The signal wavelength was tunable from 1.56 to 1.64 μm by changing the temperature of the crystal in the range from 140 to 250 °C. The beam quality factor $M^2$ of the OPG output was less than 3 although the OPG was pumped four times above threshold. The spectral width of the generated OPG radiation was narrowed to 140 MHz by injection seeding the OPG crystal with the cw radiation of a DFB diode laser. Due to the reliable, frequency stable operation of the DFB diode laser the seeded OPG provides powerful radiation with well controlled wavelength and narrow spectral width. Because of the high spectral and spatial quality, the short pulse duration and the high repetition rate the infrared OPG radiation should be well suited for many spectroscopic applications which require pulsed-tunable laser light.

References