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MID-INFRARED LASER SOURCE - Operator's guide

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Director of Research

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8) **ABSTRACT**
A mid-infrared laser source, based on an optical parametric oscillator pumped by a $Nd:YVO_4$ laser at 1.06 µm wavelength, is described. The nonlinear material is periodically-poled lithium niobate (PPLN). The source operates at 20 kHz pulse rate, and the idler wavelength is tunable across the 3.1-3.8 µm region, using 8 different PPLN grating periods on a single crystal. The idler output power is in the range of 1.1-1.4 W, depending on the wavelength, and the corresponding pump-to-idler conversion efficiency is 7-9 %. The beam quality of the idler, given by the M^2-value, is in the range of 1.3-1.7, which is slightly poorer than that of the pump. In addition to describing the laser source and its characteristics, the report also serves as a guide for operation of the system.

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CONTENTS

MID-INFRARED LASER SOURCE - Operator's guide

1 INTRODUCTION

There is currently an urgent military need for efficient tunable laser sources in the 3-5 µm (mid-IR) spectral band. Such sources are key components in directive infrared countermeasure systems against military infrared sensors, such as missile seekers and thermal imagers. Such countermeasure acts may include either deception, dazzling, or destruction of the infrared sensor. FFI has taken interest in this subject, both in order to investigate the vulnerability of Norwegian military sensors to such countermeasures and in order to evaluate the possibility of employing such countermeasures against enemy sensors, such as IR missile seekers.

This report describes a mid-IR source developed for this purpose at FFI. It is based on a primary laser source at 1.06 µm wavelength, which is shifted to the mid-IR region by a nonlinear optical device, called an optical parametric oscillator. The nonlinear material is so-called periodically-poled lithium niobate, which is suitable for generation of mid-IR wavelengths up to about 4 µm. The report meant to serve as a guide for operation of the system.

Section 2 of the report gives a brief introduction to the basic principle of the laser system. An overview of the laser configuration and the functions of the different components is given in Section 3. Section 4 discusses some important laser safety issues, and provides instructions concerning alignment and operation of the system. Some of the measured performance characteristics of the source are discussed in Section 5, and conclusions are given in Section 6. Some details concerning the special type of nonlinear material used in this work are discussed in Appendix A.

2 LASER SOURCE PRINCIPLE

The laser system is based on an optical parametric oscillator (OPO), which converts light from a near-infrared laser at about 1 µm wavelength into light at longer wavelengths by a wavelength mixing process in a nonlinear crystal [1, 2]. The principle is illustrated in Figure 2.1.

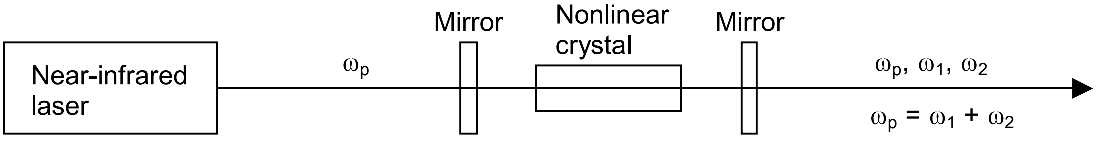


Figure 2.1: Optical parametric oscillator principle.

The near-infrared laser, commonly called the *pump* laser, has frequency ω_p. This frequency is converted in the nonlinear crystal to two new frequencies ω_1 and ω_2, the sum of which is equal to ω_p. The nonlinear process is enhanced by placing the nonlinear crystal into a resonator, which provides feedback and oscillation at one of the new frequencies (thereby the name *optical parametric oscillator*). The oscillating electromagnetic wave is commonly called the *signal* wave, and the other generated wave is called the *idler* wave. In some cases the resonator provides feedback at both of the generated frequencies, and both generated waves are then called signal waves.

The signal and idler frequencies (ω_1 and ω_2) can generally be varied by changing the so-called *phase-matching* condition for the 3 waves in the nonlinear crystal [1]. This is normally achieved by changing the crystal orientation or temperature. The nonlinear material used in the system described in this report is so-called periodically poled lithium niobate (PPLN) [3-5]. Phase-matching in this material is achieved by a special technique, called quasi-phase-matching, which is explained in more detail in Appendix A. This type of phase-matching can generally be obtained if the orientation of the nonlinear crystal material is inverted periodically in the propagation direction of the electromagnetic waves. The spatial period of the inversion will typically be in the range from a few μm up to a few tens of μm. In PPLN the periodic inversion is obtained by applying a periodic electric field, which induces a permanent periodic inversion of the polarity of the ferroelectric domains in the crystal. The spatial period of the inversion grating, together with the crystal temperature, determine the signal and idler frequencies, ω_1 and ω_2, for a given pump frequency, ω_p.

The PPLN crystal used in the system described here is manufactured by Crystal Technology (US). The crystal is 18 mm long, 1 mm wide, and 11.5 mm high. The crystal has 8 different periodic poling gratings, positioned side by side with 0.1 mm spacing along the vertical direction, as illustrated in Figure 2.2. The 1st grating is 1.7 mm high and the 7 other gratings about 1.3 mm high. A pump beam aligned to hit grating number 5 is indicated in the figure.

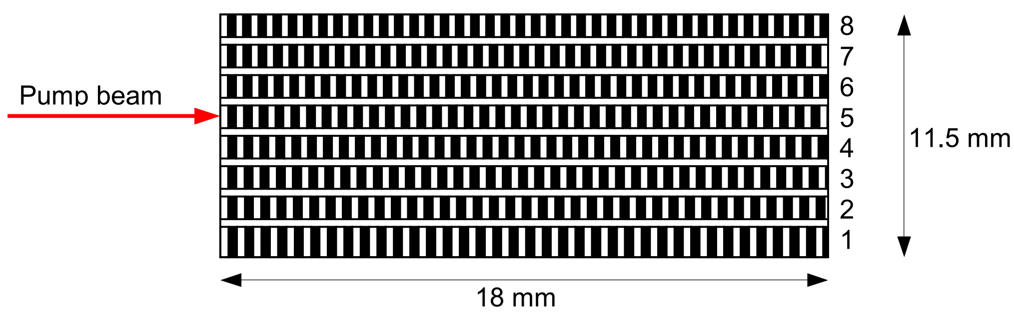


Figure 2.2: PPLN crystal with 8 periodic poling gratings

The grating period varies from 28.5 μm in grating 1 to 29.9 μm in grating 8. This implies that the idler wavelength can be varied from about 3.8 μm to 3.1 μm, for a pump wavelength of 1.064 μm and 190°C crystal temperature, as used in the system described in Section 3 below.

Wavelength tuning is achieved by translating the crystal vertically in order to hit different gratings with the pump beam.

The optical parametric oscillator in the system described below has a 3-mirror ring resonator instead of the simple 2-mirror resonator shown in Figure 2.1. This type of resonator has certain advantages related to lack of feedback to the pump laser, reduced problems with thermal effects and optical damage, and reduced back-conversion from the signal and idler to the pump wave.

3 SYSTEM LAYOUT

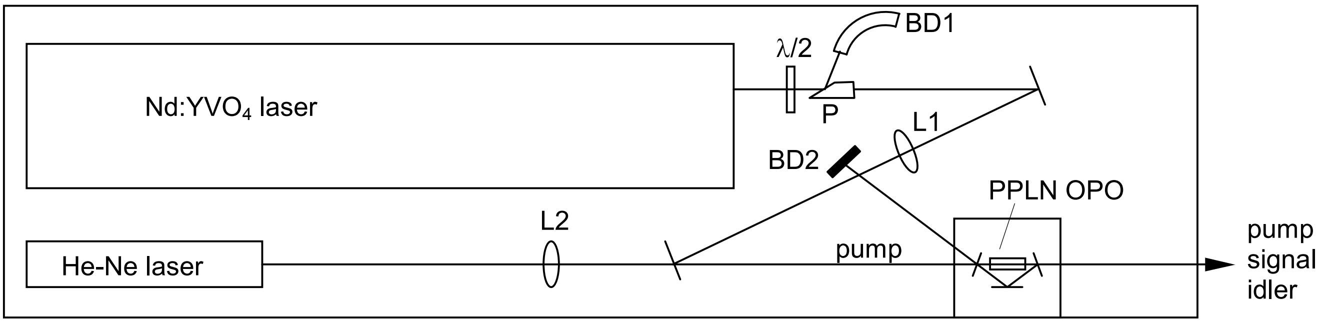


Figure 3.1: System layout: λ/2 – half-wave plate, P - polarizer, BD – beam dumps, L – lenses, OPO – optical parametric oscillator, PPLN – periodically poled lithium niobate (the nonlinear crystal used for wavelength conversion)

The system is mounted on a 0.3 m by 1.2 m breadboard with the optical layout shown in Figure 3.1. The pump laser is a $Nd:YVO_4$ laser (Spectra Physics, Model T80-YPH40-106Q). The laser produces a vertically polarized beam at 1.064μm wavelength, with a good beam quality ($M^2 \approx 1.2$). It can be operated in Q-switched mode over a wide range of pulse rates (1-100 kHz). At 20 kHz pulse rate, which is optimal for the OPO on the breadboard, the laser produces an average output power of 16 W. The pulse length at this pulse rate is 35 ns.

The pump beam passes through the half-wave plate (λ/2) and the horizontal polarizer (P). By rotating the half-wave plate an angle of θ, the plane of polarization is rotated an angle 2θ, hence by rotating the half wave plate an angle of 0-45°, we can adjust the power of the horizontally polarized beam transmitted by the polarizer from 0-16 W. The vertically polarized component of the beam is reflected by the polarizer and directed into a beam dump (BD1). If most of the pump power is directed into the beam dump, it can reach a high temperature and one should therefore avoid touching it.

The horizontally polarized component of the pump is directed to the PPLN OPO by two mirrors and focussed into the PPLN crystal by the lens (L1). L1 has a focal length of f = 300 mm. The focal length and position of L1 are chosen in order to obtain a pump beam waist with a diameter of about 0.5 mm in the center of the PPLN crystal.

The He-Ne laser is used for alignment purposes. It is combined with the pump beam before the PPLN OPO and is aligned to perfectly overlap the pump beam. The lens (L2) is used to focus the He-Ne beam to approximately the same diameter as that of the pump inside the PPLN crystal.

As explained earlier, the PPLN crystal has 8 periodic poling gratings with periods ranging from 28.5 µm to 29.9 µm. When pumped at 1.064 µm, the OPO idler wavelength ranges from approximately 3.8 µm (for 28.5 µm period) to 3.1 µm (for 29.9 µm period), at a typical crystal temperature of 190 °C. The idler wavelength decreases with increasing temperature by 2-3 nm/K, the highest value representing the grating with 29.9 µm period.

The OPO resonator is a 3-mirror ring resonator, as indicated in Figure 3.1. The round-trip geometrical length is about 67 mm, which gives a round-trip time of 0.3 ns. The pump input mirror is flat, with reflectances of 15 %, 100 %, and 13 %, for the pump, signal, and idler waves respectively. The output coupler is also flat, and the corresponding reflectances are 5 %, 76 %, and 9 % (for pump, signal, and idler). The third (folding) mirror is concave with 2 m radius of curvature, and is gold-coated. Some results will also be presented in Section 5, using a flat gold-coated mirror.

Removing the pump and signal beams:

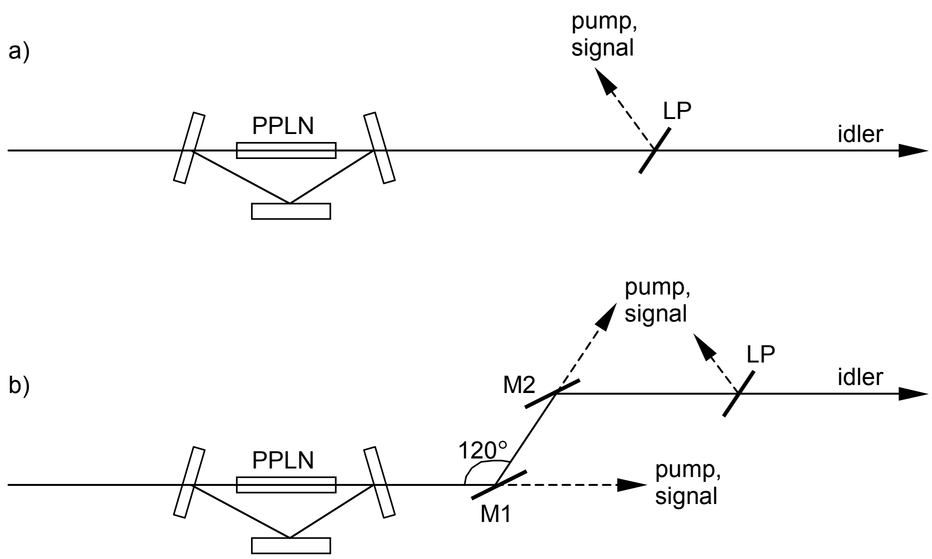


Figure 3.2: Options to remove the pump and signal beams. LP is a Spectrogon LP-2500 long-pass filter. M1 and M2 are two dielectric mirrors (Laseroptik HR4200nm, HT2100nm/0°), with high transmittance for the pump and signal and high reflectance for idler wavelengths above 3.4 µm.

As indicated in Figure 3.1, the light beam leaving the OPO is a mixture of the pump, signal, and idler waves. Since the idler is the wavelength of interest in this case, the unwanted pump and signal beams have to be filtered out. The two methods shown in Figure 3.2 are used for this purpose:

In option a) a long-pass filter (LP) is used to suppress the pump and signal. The filter consists of a dielectric coating on a Ge substrate. It has a transmittance of 94 % for wavelengths longer than 2.5 μm and a transmittance of less than 0.1 % for wavelengths shorter than 2.5 μm. Most of the pump and signal power is reflected by the filter, but a fraction is also absorbed by the Ge substrate. If the OPO is aligned such that the idler overlaps with the pump, we observe a distortion of the transverse intensity profile of the idler. The reason for this is that the absorbed pump (and signal) leads to local heating such that a thermal lens is created. The thermal lens focuses the part of the idler overlapping with the thermal lens, thereby causing a distortion of the idler. To avoid this, one may use option b).

In option b) two dielectric mirrors (M1 and M2) are inserted into the optical path before the LP-filter. At 60° angle of incidence, the mirrors have a transmittance of about 90 % for pump and signal, and a reflectivity of more than 95 % for wavelengths longer than about 3.4 μm. Thus, most of the pump and signal is removed before the LP-filter, so that the pump-induced thermal lens effect may be avoided. One must note, however, that option b) cannot be used for idler wavelengths shorter than about 3.4μm, since the transmittance of M1 and M2 increases rapidly below this wavelength. There is also a 10 % loss of idler power in option b) compared to option a).

4 LASER SYSTEM SAFETY, ALIGNMENT, AND OPERATION

4.1 Laser safety

The pump source used in the laser system is a very powerful (15-20 W) near infrared (1.064 μm) laser, which poses a serious risk of eye damage (to the retina), severe skin burns, or fire, if proper protection against it is not applied. *Therefore, protective eyewear should always be used by all persons who could possibly be exposed, whenever the pump source is switched on*. In addition to the pump beam, the OPO will generate signal and idler beams at about 1.5 μm and 3-4 μm wavelengths. These beams are also sufficiently powerful to cause burns or fire, but will not penetrate into the eye and cause damage to the retina. *To avoid risk of burns or fire, all beams and reflections should be properly terminated by beam dumps*. In addition, the OPO generates weak green and red beams at 0.532 μm (non-phase-matched frequency-doubling of the pump) and at 0.63 μm (sum-frequency mixing of pump and signal). The LP-filter shown in Figure 3.2 will reflect and absorb all wavelengths generated by the system, except the idler beam, so these beams can easily be terminated inside the laser system itself.

The idler beam is the main output beam from the system and will be used in different types of experiments. The idler power is in the range of 1-1.5 W and poses a risk of burns or fire when focused. Proper care must therefore be taken to prevent such risks by suitable control of the idler beam paths.

For laser safety in general, refer to the safety instruction for work with lasers at FFI: *Verneinstruks for arbeid med laserlys ved Forsvarets forskningsinstitutt*.

It is the responsibility of the person operating the laser system to prevent all risks of injury or damage. The operator must be well aware of all such risks and apply necessary protective measures.

4.2 Alignment

The details of the OPO alignment procedure depends on whether this is the initial alignment of the OPO or a minor adjustment to correct for a misalignment which may have occurred after a period of use or after the system has been moved from one location to another. In any case, the goals of the alignment of the OPO resonator are:

1) To make the signal beam overlap with itself after one roundtrip in the resonator.
2) To make the signal beam overlap with the pump beam inside the PPLN crystal.

Initial alignment:

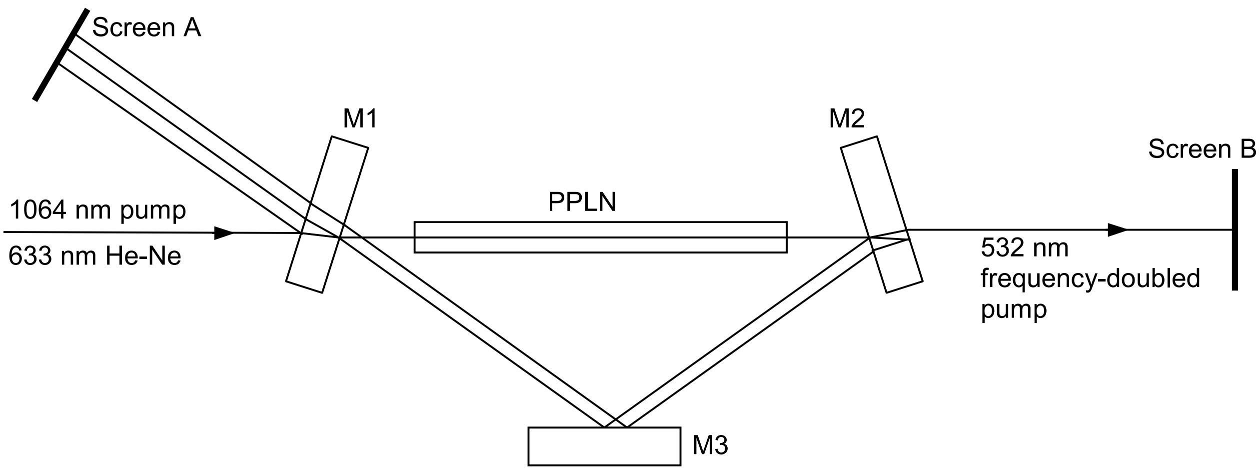


Figure 4.1: Ray diagram used for alignment of the OPO

A ray diagram used for alignment of the alignment of the OPO is sketched in Figure 4.1. Refer also to the system layout shown in Figure 3.1. The following steps are required for the initial alignment of the OPO:

a) The pump must be focused to a suitable waist diameter (0.45-0.5 mm) in the center of the PPLN crystal. Focussing of the pump is done by lens L1 in Figure 3.1. Place a camera in the desired center position of the PPLN. Turn on the pump laser as explained in Section 4.3. Run the pump laser at full power and 20 kHz pulse rate, and attenuate the pump to obtain a suitable intensity on the camera. Suitable attenuation may be obtained by using the half-wave plate and polarizer shown in Figure 3.1, as well additional optical filters. Adjust L1 until the desired waist size and position is obtained. Then adjust the pump and He-Ne beams until they are perfectly overlapping, observing both beams with a camera at different positions along the beam path. Then turn the pump laser off.

b) Put the OPO assembly in its desired position, and observe the He-Ne spot on the input and output faces of the PPLN with an eye piece (the *pump laser must be turned off* during this operation!!). Adjust the OPO assembly with the translation- and tilt-mount until the He-Ne spot is centered in the input and output apertures of the desired PPLN grating. The reflected He-Ne beam should then propagate back along the incoming beam direction.

c) Place screen A as shown in Figure 4.1. Adjust mirrors M1 and M2 (M3 is fixed) in order to obtain the He-Ne beam reflection pattern indicated in the figure on screen A. There may be up to 4 intense spots on the screen, 2 reflections from the outer and inner side of M1 and 2 reflections from M2 (in the current set-up the reflected beam from the outer side of M2 is clipped by the PPLN mount before reaching the screen). With perfect alignment, the reflections from the inner sides of both mirrors should overlap on the screen, as indicated. Make fine adjustments of M1 and M2 to make the two reflections overlap perfectly, independent of the distance between M1 and screen A. The OPO may now be sufficiently well aligned to oscillate when pumped at full pump power.

d) Switch on the PPLN heater, and set the temperature to 190°C. Put a power meter in front of the OPO in order to monitor the pump power. Turn on the pump laser as explained in Section 4.3. Run the pump laser at full power and 20 kHz pulse rate. Adjust the half-wave plate shown in Figure 3.1 so that the pump power in front of the OPO is as low as possible. Then remove the power meter.

e) Place the LP-filter shown in Figure 3.2a at the output of the OPO (about 50 cm away) and put a power meter after the filter to measure the idler output. The reflected pump beam from the LP-filter must be blocked by a suitable beam dump. Increase the pump power slowly up to 15 W by adjusting the half-wave plate, while observing the power meter readout to see if the OPO starts to oscillate. If the OPO starts oscillating, then make vertical and horizontal tilt adjustments of M2 to maximize the idler power before increasing the pump power to the nominal value of 15 W. Finally, adjust both M1 and M2 to maximize the idler output, by

systematically “jogging” the tilt angle of both mirrors, first in the vertical- and then in the horizontal direction: First, make a small vertical tilt of M1 away from the current optimal position, causing a small drop in the idler power. Then tilt M2 to maximise the power again. If this leads to a higher idler power than the initial value, then repeat this step as many times as necessary until the idler power reaches a maximum. If the idler power decreases in the first step, then start by tilting M1 in the opposite direction. Then repeat the procedure in the horizontal direction.
The idler power should now be in the range of 1.1-1.4 W, depending on which PPLN gating is used (refer to the test results in Section 5).

f) If the OPO does not oscillate at 15 W pump power, then make small tilt adjustments of M2 in the vertical direction to search for oscillation. The horizontal adjustment is less critical and should not be touched before a vertical search has been tried. If the OPO starts oscillating, then optimise the idler power as explained under e).

g) If oscillation is still not obtained, a separate check of the alignment can be made by observing the weak beam of green light generated by frequency-doubling of the pump in the PPLN. This beam will perfectly overlap the pump and can be observed on screen B, as shown in Figure 4.1. For perfect alignment of M1 and M2, the part of the green beam which has passed one round-trip around the resonator should perfectly overlap the part which is coupled out directly through M2. Adjust M1 and M2 and observe the overlap on screen B. An extra check may also be made by observing the green and red spots on Screen A. Then remove screen B and adjust the pump power to 15 W. If necessary, make a small vertical tilt adjustment of M2 to make the OPO oscillate. Then optimise the idler power as explained under e). If the OPO does not oscillate after these alignment steps, parts of the alignment procedure will have to be repeated with improved accuracy.

Minor alignment adjustments:

After some time of use, or after the system has been moved, it may occur that the OPO becomes misaligned. This is usually indicated by a decrease in the idler output power. If the drop in idler power is small, one may be able to optimise the resonator by adjusting mirror M2 only. Note again that the output power is more sensitive to adjustments in the vertical direction than in the horizontal direction. For a larger misalignment, one may have to adjust both M1 and M2 by the jogging procedure explained under step e) above.

Note also that a drop in output power may have other explanations, such as contamination or damage to optical surfaces, or a drop in output power from the pump source.

Changing the PPLN grating period:

As explained earlier, the idler wavelength may be changed by using another grating on the PPLN crystal. Such a change is achieved by displacing the entire OPO assembly vertically. Small displacements up to 2-3 mm are achieved by adjusting two screws on the mount which carries the OPO assembly. Larger displacements require adjustment of the height of the posts that carries the mount. After such a change of grating, it is important to ensure that the pump beam is well centered in the input aperture of the new grating. This is checked by observing the spot of the He-Ne alignment beam on the input and output faces of the PPLN crystal, as explained under step b) above. Make sure that the He-Ne beam is reflected back along the direction of the incoming beam. After changing the grating it will usually be necessary to re-optimize the mirror alignment. Usually, the OPO will oscillate after a small adjustment of M2, and may reach full power without adjusting M1. If the power is lower than desired, one may have to adjust both M1 and M2 by the jogging procedure explained under step e) above.

4.3 System operation

When the system has been well aligned, it can be turned on and operated according to the following simple procedure:

a) Turn on the PPLN crystal heater. The crystal temperature should reach a stable temperature of about 190° C before operating the OPO.

b) Activate the pump laser as follows:
Switch on the water-cooling unit and the power supply. The pump laser is controlled by a computer program "t80". Start the program by typing "t80" and then ENTER to start the program in DOS. Press F1 to enter the monitor screen and then CTRL+PAGE UP to switch the diodes on. The diode currents will automatically be set to the nominal values for maximum laser output power. Let the diode temperatures stabilize at the nominal temperature values (displayed on the screen). Finally, insert the shutter deactivation knob on top of the laser head to transmit the pump beam from the laser head. The half-wave plate controlling the pump power to the OPO should normally be set in a fixed position for 15 W pump power, and need not be adjusted before turning the laser on.

5 EXPERIMENTAL RESULTS

This section summarizes some of the measured performance characteristics of the OPO.

In the first OPO experiments, the resonator folding mirror, M3, was a flat gold-coated mirror. This mirror was damaged during the experiments and was replaced by another gold-coated mirror with 2 m radius of curvature. The curved mirror is used in the present version of the device. Unless otherwise stated, the results presented below have been obtained with the flat M3.

A fairly extensive experimental investigation has been carried out, including measurements at different pulse rates, measurements for different PPLN grating periods, measurement of idler wavelength as a function of PPLN temperature and pump power, and measurement of idler beam quality.

5.1 Idler output energy and power

Figure 5.1 shows the measured idler pulse energy as a function of pump energy for 3 different pulse rates, 5, 10, and 20 kHz. The PPLN grating period was 29.1 µm (grating # 4) and the temperature 190 °C, yielding an idler wavelength of about 3.52 µm. The idler energy values are corrected for a 12 % loss in the optical filter and mirrors, which were used to block the remaining pump and the signal at the OPO output (see Figure 3.2b).

There seems to be no significant dependence on pulse rate, indicating that there is little influence from thermal effects, which might arise from a small residual absorption at any of the wavelengths involved. Note that there is a variation in average pump power from 3.75 W (at 5 kHz) to 15 W (at 20 kHz) at the highest pulse energy. It should be remarked that it was generally necessary to make small adjustments of the resonator alignment in order to maximize the idler energy, as the pump power was raised from threshold and up to the maximum value. This was achieved by a small tilt adjustment of M2. The adjustment was particularly critical close to the pump threshold.

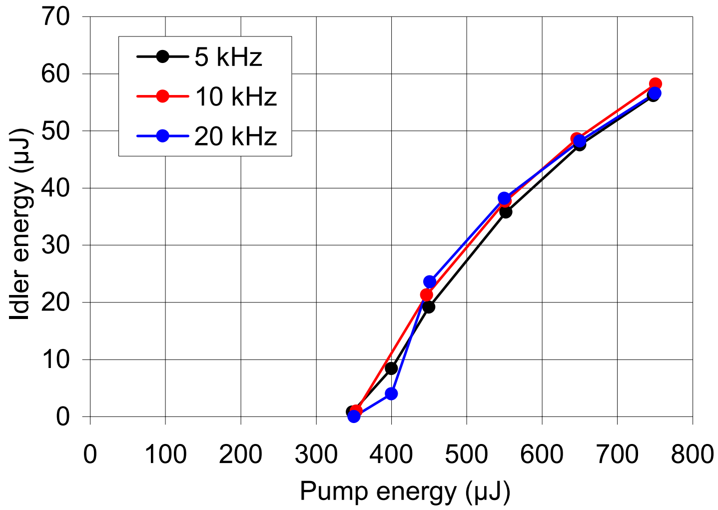


Figure 5.1: Idler pulse energy as a function of pump energy at different pulse rates.

Similar experiments were performed with 3 of the gratings on PPLN crystal (grating 1, 4, and 8) with 29.9 µm, 29.1 µm, and 28.5 µm periods, yielding 3.11, 3.52, and 3.77 µm idler wavelength at 190 °C crystal temperature. As in Figure 5.1, we found that there was little dependence on the pump pulse rate. Results obtained with the 3 gratings are shown in

Figure 5.2 for 20 kHz pulse rate. The average idler output power is shown as a function of the pump power. As mentioned above, it became necessary to change mirror M3 (from flat to 2 m radius of curvature) during the experiments, and the data shown in the figure have therefore not all been obtained under exactly the same experimental conditions. However, this seems to have relatively little influence, at least at the highest pump powers, where the curves at 3.52 µm wavelength converge to approximately the same value for both mirrors. There are some inconsistencies near threshold (i.e. the lower threshold at 3.52 µm than at 3.11 µm with the curved M3), but this may have been due to small differences in the OPO alignment. At the maximum pump power we observe an increase in the idler output power for decreasing idler wavelength. This dependence is expected, due to the increasing idler photon energy and assuming an approximately constant number of idler photons per pulse.

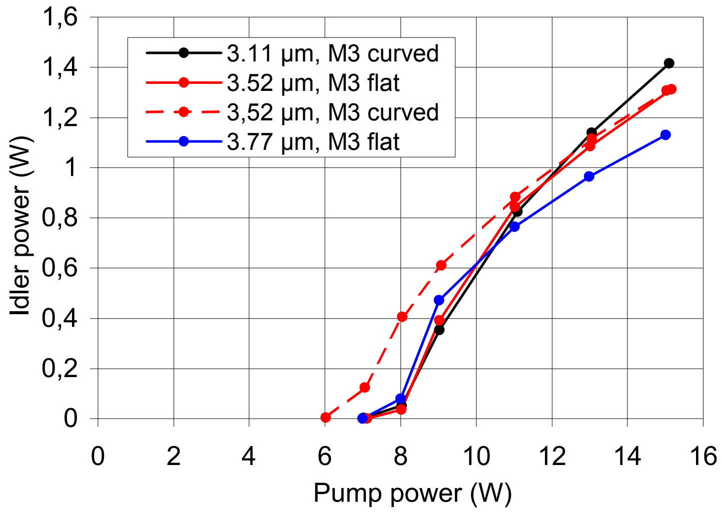


Figure 5.2: Measured idler power as a function of pump power. The measurements were made at 20 kHz pulse rate. The curved M3 had a 2 m radius of curvature.

5.2 Idler wavelength measurements

In Figure 5.3 we show the measured idler wavelength as a function of the PPLN temperature for the 3 grating periods. The results are in good agreement with phase-matching calculations using the most recent published data for the Sellmeier coefficients of PPLN [6]. It can be added that for all 3 gratings we observed a wavelength shift of approximately 4 nm when the average pump power was changed from 5 W (500 µJ at 10 kHz) to 15 W (750 µJ at 20 kHz). This wavelength shift corresponds to a temperature change of 1.5-2 K in the PPLN crystal, which is most probably due to a small absorption at one or more of the wavelengths involved. A rough estimate indicates that an absorption coefficient on the order of 0.003/cm for the pump and signal could lead to such a temperature increase.

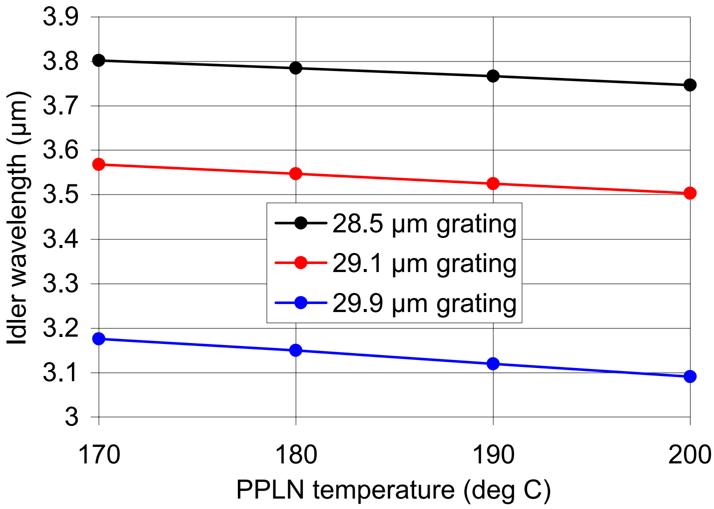


Figure 5.3: Temperature dependences of idler wavelength for 3 different PPLN gratings. The data were taken at 20 kHz pump pulse rate and 15 W average pump power. The wavelengths measured at 10 kHz pulse rate and 5 W average pump power were approximately 4 nm larger for all 3 gratings

5.3 Beam quality measurements

Measurements have been performed in order to determine the beam quality of the idler beam under different operating conditions. The measurements were made by focusing the idler beam to a waist diameter of a few 100 µm and measuring the beam profile with a pyroelectric camera (Spiricon, model Pyrocam I) at a number of axial positions at both sides of this waist. For every position, a Gaussian beam profile was fitted to the measured profile in both transverse directions (x and y), and the beam diameter (2ω) at each position was defined as the FW1/e^{2}M diameter of the fitted Gaussian profile. The measured fitted beam radius, ω(z), was then plotted as a function of the axial position, z, and the beam quality given by the commonly used parameter, M^2, was then found by fitting the following function to the measured data:

$$\omega(z) = \omega_0 \left[1 + \left(M^2 \frac{z}{z_0} \right)^2 \right]^{\frac{1}{2}} \qquad (5.1)$$

where ω_0 is the beam radius at the waist position, z=0, and z_0 is the Rayleigh length defined by:

$$z_0 = \frac{\pi \omega_0^{\ 2}}{\lambda} \qquad (5.2)$$

where λ is the idler wavelength.

An example of such a fit for the beam radius in the x-direction at 3.11 µm idler wavelength, with 15 W pump power at 20 kHz pulse rate, is shown in Figure 5.4. A summary of the M^2 values measured under different conditions is given in Table 5.1. It is not clear, however, how the results should be interpreted. The beam quality is fairly good under all conditions, and some of the variations may have been caused by variations in the OPO alignment. The M^2 values are in the range of about 1.3-1.7, i.e. somewhat poorer than the beam quality of the pump (≈1.2). The data for 3.52 µm wavelength seem to indicate that there is an improvement in the beam quality for increasing average pump power, at least for a given pulse rate. In general, the beam quality will be affected by the overlap of the pump beam and the resonator mode of the signal. This, in turn, will be determined by the mirror distances and curvatures, by thermal lens effects (increasing with increasing pump power), and by gain guiding effects (increasing with increasing pump pulse energy). In addition, back-conversion may lead to reduced beam quality at high pump pulse energies. The measurement at 3.11 µm is the only one taken with the curved M3 mirror, and this seems to have resulted in a slightly poorer beam quality.

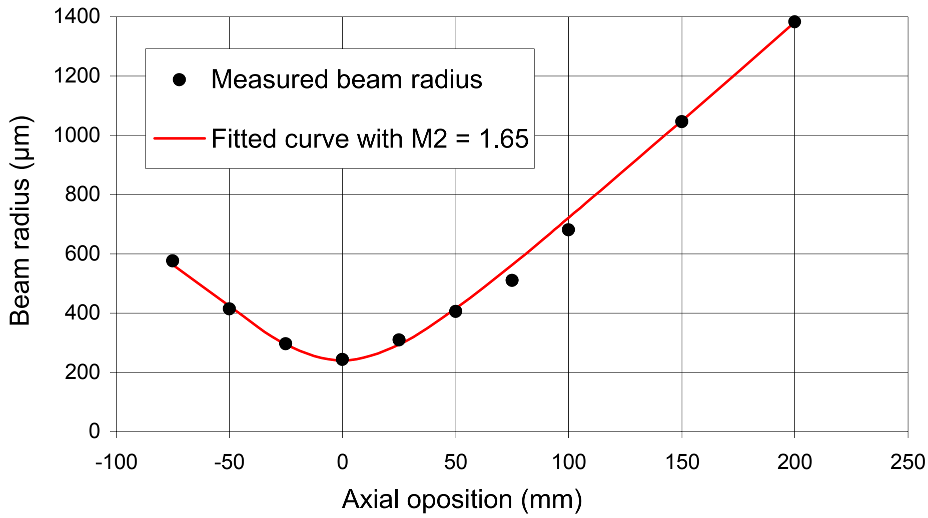


Figure 5.4: Fit of function (4.1) to the measured beam radius in the x-direction for 3.11 µm idler wavelength, 15 W pump power, and 20 kHz pulse rate. The best fit is obtained for a beam quality M^2=1.65, and a beam waist radius ω_0 =240 µm.

Wavelength (µm)	Pump power (W)	Pulse rate (kHz)	M_x^2	M_y^2
3.11	15	20	1.65	1.66
3.52	14	20	1.27	1.32
	9	20	1.57	1.60
	3.5	5	1.43	1.72
	2.25	5	1.66	1.77
3.77	14	20	1.41	1.49

Table 5.1: Measured beam quality. The uncertainty in the measured values is approximately +/-0.1.

6 CONCLUSIONS

A mid-infrared OPO, based on PPLN as the nonlinear optical material and a $Nd:YVO_4$ laser as the pump source, has been developed. The idler wavelength is tunable across the 3.1-3.8 µm region, and the idler output power at 20 kHz pulse rate is in the range of 1.1-1.4 W, depending on the wavelength. The corresponding pump-to-idler conversion efficiency is in the range of 7-9 %. The beam quality of the idler is high (M^2 = 1.3-1.7), only slightly poorer than that of the pump.

The source has operated reliably in our laboratory for several months, requiring only minor mirror alignment adjustments in order to maintain maximum output power. It is a convenient source for use in laser countermeasure tests against military infrared sensors, and is currently used for that purpose at FFI.

References:

[1] R W Boyd (1992):
"Nonlinear Optics", Academic Press, San Diego

[2] G Arisholm and G Rustad (1997):
"A review of theory and materials for optical parametric oscillators in the infrared", FFI/RAPPORT-97/02589 (FFI internal report)

[3] M Yamada, N Nada, M Saitoh and K Watanabe (1993): " First-order quasi-phasematched $LiNbO_3$ waveguide periodically poled by applying an external field for efficient blue second-harmonic generation", Appl Phys Lett, Vol 62, 435-6

[4] L E Myers, R C Eckhardt, M M Fejer, R L Byer, W R Bosenberg and J W Pierce (1995): "Quasiphasematched optical parametric oscillators in bulk periodically poled $LiNbO_3$", J Opt Soc Am B, Vol 12, 2102-16

[5] L E Myers and W R Bosenberg (1997): "Periodically poled lithium niobate and quasi-phase-matched optical parametric oscillators", IEEE J Quantum Electron, Vol 33, 1663-72

[6] D H Jundt (1997): "Temperature-dependent Sellmeier equation for the index of refraction, n_e, in congruent lithium niobate", Opt Lett, Vol 22, 1553-5

[7] M M Fejer, G A Magel, D H Jundt and R L Byer (1992):
"Quasiphasematched second harmonic generation: Tuning and tolerances",
IEEE J Quantum Electron, Vol 28, 2631-54

[8] E Lallier, M Brevignon and J Lehoux (1998):
"Efficient second-harmonic generation of a CO_2 laser with a quasi-phase-matched GaAs crystal", Opt Lett, Vol 23, 1511-13

[9] L A Eyres, P J Tourreau, T J Pinguet, C B Ebert, J S Harris, M M Fejer, L Becouarn, B Gerard and E Lallier (2001): "All-epitaxial fabrication of thick, orientation-patterned GaAs films for nonlinear optical frequency conversion", Appl Phys Lett, Vol 79, 904-6

[10] H Karlsson and F Laurell (1997): "Electric field poling of flux grown $KTiOPO_4$", Appl Phys Lett, Vol 71, 3474-6

[11] G T Kennedy, D T Reid, A Miller, M Ebrahimzadeh, H Karlsson, G Arvidsson and F Laurell (1998): "Near- to mid-infrared picosecond optical parametric oscillator based on periodically poled $RbTiOAsO_4$", Opt Lett, Vol 23, 503-5

[12] W R Bosenberg, A Drobshoff, J I Alexander, L E Myers and R L Byer (1996): "93% pump depletion, 3.5-W continuous-wave, singly resonant optical parametric oscillator", Opt Lett, Vol 21, 1336-8

Appendix

A QUASI PHASE-MATCHING BY PERIODIC POLING IN PPLN

A.1 Quasi phase-matching

For the nonlinear conversion to be efficient it is required that the relative phase of the interacting beams remains constant as they propagate through the nonlinear medium [1]. This is generally referred to as the *phase-matching requirement*. Due to dispersion (the refractive index of the medium changes with frequency), this requirement cannot generally be satisfied in isotropic media. Therefore, nonlinear conversion devices are normally based on anisotropic materials, where phase-matching can be achieved by choosing different polarizations for the interacting waves; so-called birefringent phase-matching. This method of phase-matching not only restricts the number of available nonlinear materials. It also restricts the allowed propagation directions and polarizations in such a way that the resulting effective nonlinear susceptibility is generally far below the optimal value for a given material. In addition, unless phase-matching can be achieved for propagation along one of the crystal axes (so-called noncritical phase-matching), there will also be a spatial walk-off between the beams, which limits the interaction distances and tends to distort the beam profiles. Finally, even for birefringent materials, it is not always possible to achieve phase matching for a given set of pump and signal frequencies, even if these frequencies are all within the crystal's transparency range.

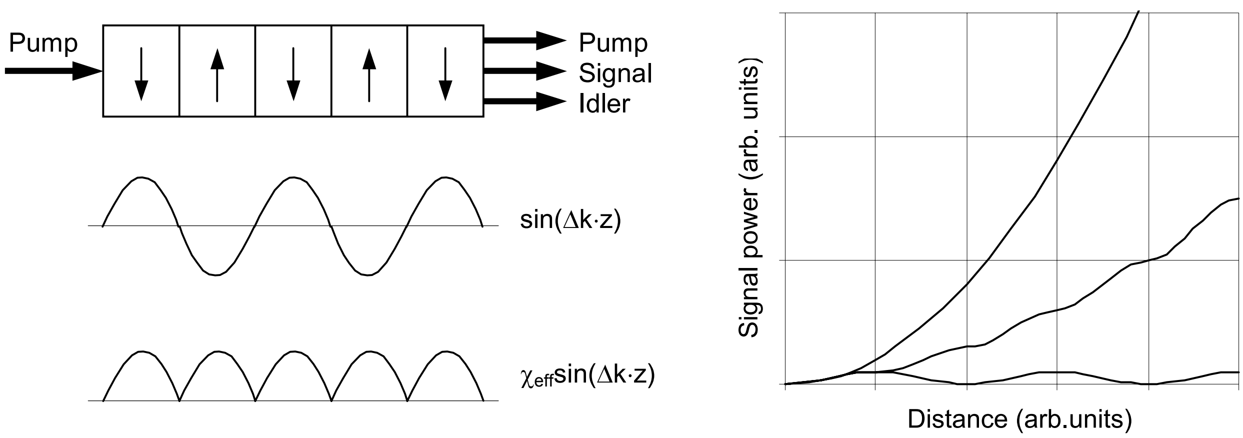


Figure A.1: Principle of quasi phase-matching (QPM). Left: QPM-material where the crystal orientation is inverted for every half-period of the driving term sin($\Delta k{\cdot}z$) in the coupled wave equation, where Δk is the bulk phase mismatch. The effective driving term χ_{eff}sin($\Delta k{\cdot}z$) is thereby rectified. Right: Signal growth through the material (middle curve – with QPM, lower curve – bulk material with phase mismatch Δk, upper curve – bulk material with $\Delta k=0$).

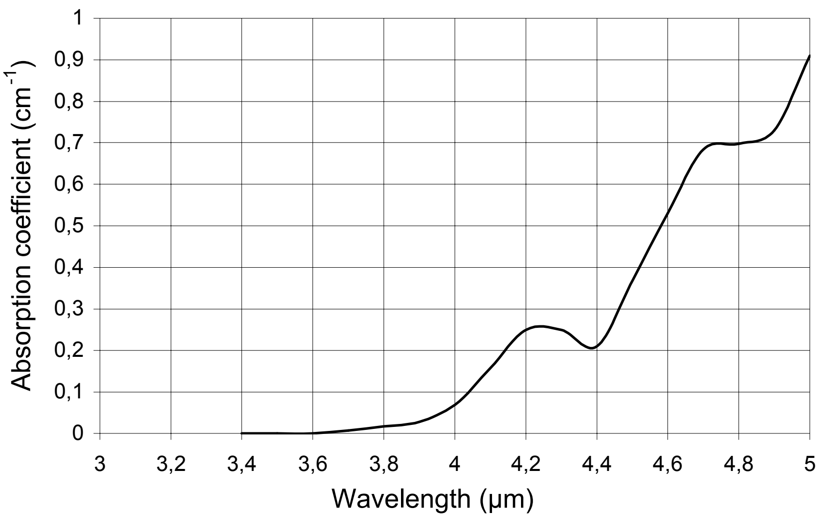
A solution to these problems is to employ so-called quasi-phase-matching (QPM), as illustrated in Figure A.1. In QPM-devices it is common to choose a beam propagation direction in the crystal, as well as polarizations, which lead to maximum nonlinear susceptibility and zero walk-off. In a normal nonlinear material, this would mean that the phase-matching condition could not be satisfied, and the energy would be transferred periodically forth and back between the pump and the signals through the crystal, with a resulting negligible energy conversion. The trick played in QPM-devices is to invert the crystal orientation for every half-period of these oscillations. This is equivalent to changing the sign of the nonlinear susceptibility for every half-period, or, equivalently, to change the phase in the driving term in the coupled wave equations by π. The net effect is that the energy transfer oscillations are rectified, such that energy is always transferred from the pump to the signals in all half-periods [7].

A.2 Methods of quasi phase matching

One method of achieving QPM is to use a stack of thin plates of the bulk material, where the crystal orientation is reversed from plate to plate. This has been done with GaAs, where a large number of plates have been bonded together by diffusion bonding [8]. The problem has been that the QPM-period is typically very short (tens of µm), so that a large number of plates are needed in order to obtain a sufficient interaction length and sufficient gain. The optical loss through all the bonded interfaces thereby becomes a major limitation. Recently, another technique has been invented, where a QPM crystal can be grown directly on a substrate on which the crystal orientation has been altered periodically by a special patterning technique [9]. This technique holds promise for efficient production of QPM crystals, but substantial development work is still required before this can become a practical method. The most successful method of producing QPM crystals has been applied to ferroelectric materials. In such materials the periodic inversion of the crystal orientation is achieved by periodically reversing the polarity of the ferroelectric crystal domains. This can be achieved by applying a high-voltage pulse across a bulk crystal, on which a lithographically defined periodic electrode pattern has been deposited. This method was first successfully applied to lithium niobate ($LiNbO_3$), and such QPM material is commonly denoted periodically poled lithium niobate (PPLN) [3-5]. The periodic poling technique has later also been applied to other materials, such as KTP (PPKTP) and RTA (PPRTA) [10, 11].

A.3 Properties of periodically poled lithium niobate (PPLN)

PPLN is transparent for wavelengths up to about 4 µm, as shown in Figure A.2. For idler wavelengths above approximately 3.7 µm the increasing absorption leads to increased optical loss and, for high average powers, also to heating, thermal lensing, and thermally induced phase mismatch. With the PPLN crystals used in this work, the maximum available idler wavelength is about 3.8 µm, so there is relatively little heating caused by absorption of the idler. In fact, a small residual absorption at the pump and signal wavelengths probably contributes more than the idler to heating of the crystal.



Figur A.2: Absorption spectrum for PPLN [5]

The main advantages of PPLN over standard bulk $LiNbO_3$ are the lack of spatial walk-off and the high optical nonlinearity, which stems from the optimal choice of propagation direction and polarization. The effective nonlinear coefficient is about 17 pm/V [5]. The high gain implies that high conversion efficiency can be obtained for quite modest pump intensities, which means that problems with optical damage can be reduced. In fact, the gain is so high that efficient operation can be obtained even for cw-pumped singly resonant OPOs [5, 12]. One problem with $LiNbO_3$ in general is the susceptibility of the material to photorefractive effects, which tend to destroy the optical quality of the crystal when it is pumped by high intensity 1.06 µm radiation. The problem is caused by the presence of a small amount of (non-phase-matched) frequency-doubled pump light (at 532 nm), which is absorbed by impurities in the crystal. The common method of suppressing the photorefractive damage is to heat the crystal during OPO operation. The required operation temperature for PPLN is typically in the range of 150-200 °C, and is generally highest for cw-operation [5]. The alternating ferroelectric domain polarity, as well as the high nonlinearity, give PPLN an advantage over bulk $LiNbO_3$ with respect to photorefractive effects [5].

PPLN is available from commercial sources in 0.5 mm and 1 mm thickness and crystal lengths up to 50 mm. The longest crystals are used for cw-pumping, where the gain is much smaller than with Q-switched pulse pumping. Commercial vendors typically offer crystals with a number of different grating periods on the same crystal, each grating being approximately 1 mm wide. The different grating periods yield different signal and idler wavelengths for a given pump wavelength and crystal temperature.

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