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Broadband mid-IR source based on a MgO : PPLN optical parametric oscillator

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Abstract. **We have designed and tested a broadband fan-out PPLN-based optical parametric oscillator (OPO) pumped by a *Q*-switched Nd:YAG laser (1.064 μm) and operating in the spectral range 2.6–4.2 μm. The optical scheme of the OPO utilises a cylindrical pump beam expander for increasing the effective aperture of the PPLN structure and obtaining broadband generation.**

Keywords: *optical parametric oscillator, MgO : PPLN crystal.*

1. Introduction

The mid-IR spectral range (2–14 μm) is of great interest for a variety of applications. It contains fundamental rovibrational absorption bands of various gases, which allows one to perform remote [1, 2] or local [3, 4] gas analysis of the atmosphere using lasers with mid-IR wavelengths. Water vapour absorption in the atmosphere significantly limits spectral regions in which laser light can pass through an open atmosphere. The main atmospheric transmission windows are located in the ranges 3–5 and 8–12 μm. Laser light propagation is limited by not only water vapour but also atmospheric carbon dioxide, which has broad, strong absorption bands centred near 4.3 and 14 μm.

In the spectral range 8–12 μm, tunable CO_2 lasers are commonly used for various purposes (including gas analysis of the atmosphere). They emit on rovibrational transitions in the range 9.2–10.8 μm [5, 6]. In the range 3–5 μm, wide use is made of optical parametric oscillators (OPOs), quantum cascade lasers (QCLs) and other devices. The development of high-power mid-IR laser sources is of great interest for IR countermeasure applications [7, 8].

A number of applications require high-power broadband mid-IR sources, like a laser Globar. One approach to making such a source is to use an OPO based on aperiodically poled or fan-out periodically poled [9] structures (Fig. 1).

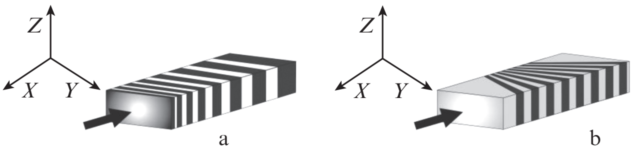

Figure 1. Configurations of (a) an aperiodically poled and (b) a fan-out periodically poled structure.

To obtain a broad spectrum in the range 3–4 μm, Mayer et al. [10] used an aperiodically poled lithium niobate (APPLN) structure (Fig. 1a) pumped by femtosecond pulses. The use of a fan-out PPLN structure (Fig. 1b) as a nonlinear component of an OPO, in combination with a narrow pump beam (1.053 nm) [11, 12], allowed for smooth emission wavelength tuning in the range 2.5–4.5 μm [12] by shifting the structure across the axis of the OPO cavity. Such an oscillator was used in a medical photoacoustic laser gas analyser [13] for clinically monitoring the composition of the gas exhaled by patients [14].

PPLN structures pumped in the 1-μm range are widely used for parametric wavelength conversion to the spectral range 2.1–4.2 μm (idler wave) [15]. The main limitation on the use of PPLN structures for the generation of an increased power of mid-IR light is the rather low optical damage threshold of lithium niobate (~100 MW cm^{-2}). Wu et al [16] described a PPLN OPO pumped by the 1.064 μm Nd : YVO_4 laser line, with a maximum average output power of 9.23 W at 3.82 μm (idler wave).

The purpose of this work was to study a broadband mid-IR (2.6–4.2 μm) OPO using a large-aperture fan-out PPLN structure.

2. Experimental setup

To generate 3-μm light with an increased average power (10 W and above), it is necessary to increase the effective aperture of a PPLN structure and use a higher pump energy (power). To raise the output power at a reduced pump intensity and prevent PPLN damage, Peng et al. [17] used an elliptical pump beam.

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In this study, to generate broadband IR light in the range 2.6–4.2 μm we used a large-aperture (3 × 20 mm) fan-out (Fig. 1b) MgO:PPLN-based OPO pumped by a Nd:YAG laser (1.064 μm). Figure 2 shows a schematic of the OPO. The basic principle underlying the optical scheme of the OPO is that different areas of the aperture with different periods are simultaneously pumped using a cylindrical pump beam expander in front of the OPO cavity input.

Due to specific features of the PPLN fabrication process (high coercive fields), the thickness of periodically poled lithium niobate structures should not exceed 3–5 mm. At a pulse duration of ~10 ns, MgO:PPLN experiences optical damage at a rather low energy density: ~1 J cm^{-2}. This factor restricts pump beam focusing. At the same time, using a wide aperture of a MgO:PPLN structure (3 × 20 mm in our case) allows the pump beam area to be increased by more than six to ten times. Thus, the use of a stripe structure of the nonlinear element and a similar pump beam cross section makes it possible to raise the pump pulse energy (power), with no optical damage to the nonlinear element, and allows the power (energy) of the converted IR light to be increased by several times relative to classic systems that employ circular pump beams.

In our experiments, we used a fan-out MgO:PPLN structure (Labfer, Ltd., Russia) [18] 3 × 20 × 50 mm in dimensions. Its period in the width direction (*Y* coordinate) gradually varied in the range 27.42–32.5 μm. The polished end faces of the structure had an antireflection coating with a centre wavelength of 1.5 μm. The structure was placed on a motorised linear precision translation stage (Standa), which ensured a gradual transverse displacement of the structure relative to the *Y* axis of the OPO cavity. A similar fan-out MgO:PPLN structure was used by Karapuzikov et al. [13] to make a combined OPO with smooth spectral tuning in the range 2.5–4.5 μm. As shown earlier [11, 12], the optimal fan-out MgO:PPLN length is 40–50 mm.

The pump source used was a repetitively pulsed LQ 215 *Q*-switched Nd:YAG laser (1.064 μm). It generated pulses with an energy from 20 to 180 mJ at a repetition rate of 20 Hz. The pulse duration was ~6 ns. The beam diameter at the laser output was about 8 mm, and the beam quality factor was $M^2 \approx 2.5$.

The optical scheme of the OPO (Fig. 2) utilised two lens telescopes. One of them consisted of spherical lenses L1 (f = 174 mm) and L2 (f = −111 mm) and served to form a pump beam of ~2.8 mm diameter. In this configuration, the OPO operated like in a previous study [12]. The other telescope, consisting of cylindrical lenses L3 (f = −50 mm) and L4 (f = 300 mm), ensured a 6$^{\times}$ pump beam expansion along the *Y* (horizontal) axis, without changing the beam size along the *Z* (vertical) axis. As a result, essentially all the aperture of the structure (3 × 20 mm) was used for pumping.

In our experiments, we used a double-pass pumped singly resonant OPO configuration on the signal wave. The input/output OPO mirror used was a flat mirror (M5) on a ZnSe substrate, with a high transmittance at 1.064 μm ($T \approx 99\%$) and in the range 2–12 μm ($T \approx 85\%$–90%) and a reflectivity near 90% at the signal wavelength (1.15–1.8 μm). The back mirror (M6) had a gold coating produced on a flat silicon substrate. The idler wave was outcoupled using a dichroic mirror (M4) with high reflectivity ($R \approx 99.9\%$) near 1.064 μm and high transmittance in the spectral range 2–4 μm.

The idler and signal waves obtained as a result of parametric conversion in the MgO:PPLN structure left the cavity as a broad elliptical beam through mirror M5 and passed through the dichroic mirror (M4). The idler wave was separated [in energy (power)] measurements] by a filter (F) with a high transmittance (~90%) in the spectral range 2–4 μm and high reflectivity (~99%) in the range 1.3–1.8 μm.

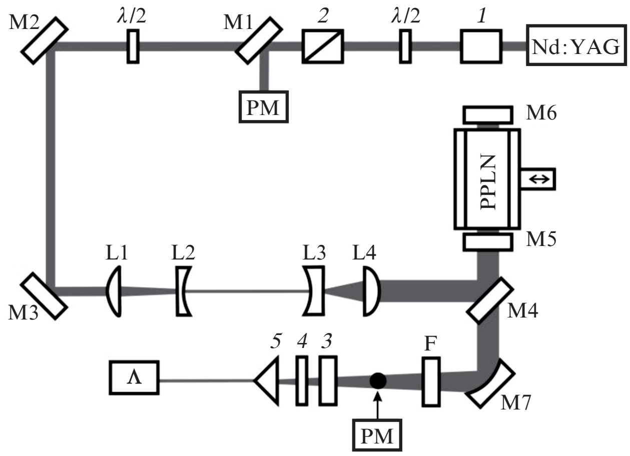

Figure 2. Schematic of the OPO:
(Nd:YAG) pump laser; (λ/2) half-wave plate; (M1–M7) mirrors; (PM) energy (power) meter; (L1, L2) spherical lenses; (L3, L4) cylindrical lenses; (PPLN) large-aperture fan-out MgO:PPLN structure; (F) filter; (L) spectrometer; (*1*) Faraday optical isolator; (*2*) polariser; (*3*) attenuator; (*4*) diffuser; (*5*) collimator.

To measure the Nd:YAG pump pulse power (energy), a small part of the pump beam (4.4%) was reflected from mirror M1 (flat quartz plate mounted at 45°) to a Thorlabs PM100D/ES120C power meter (PM). For OPO idler pulse energy (power) measurements, the power meter was placed after the filter (F) (the black circle in Fig. 2).

Spectral parameters of the idler and signal waves were measured by a computer-interfaced NIRQuest512 spectrometer. The beam was launched into the spectrometer using a collimator and optical fibre (the filter was then not used). To prevent damage to the spectrometer, an attenuator and diffuser were added to the scheme (Fig. 2). The monitor of the computer showed the current OPO signal wavelength, which was then used to determine the idler wavelength.

3. Experimental results

In our experiments, first the MgO:PPLN structure was mapped as described previously [19] in order to determine the OPO idler wave intensity distribution throughout the aperture of the structure (Fig. 3). To this end, the structure was scanned in the *YZ* plane (across the cavity axis) in 0.2-mm steps using two Standa computer-controlled motorised single-axis linear translation stages. During the mapping process, the cylindrical beam expander was not used, and the pump beam was focused into the structure by an auxiliary lens (f = 100 mm) to give a beam of ~0.5 mm diameter at the input of the structure. The OPO idler wave intensity distribution (Fig. 3) consisted of a total of ~1000 data points. The maximum efficiency of pump conversion to the idler wave corresponds to a maximum quantum efficiency η = 17.7%, so the intensity scale in Fig. 3 is normalised to this value.

As seen in Fig. 3, there is an extremely uneven OPO idler wave intensity distribution. The highest intensity is observed near the left edge of the structure under study, where the period of the structure is largest (~32.5 μm) and the idler wavelength is ~3 μm. As the pump beam moves to the right, the period of the structure decreases to 27.42 μm, which is accompanied by an increase in idler wavelength to about 4 μm. The reduction in the idler wave intensity as the pump beam moves from left to right is due to the decrease in parametric conversion efficiency in the MgO : PPLN structure under study because of the increase in idler wavelength. A change in wavelength from 3 to 4.2 μm (by 40%) reduces the conversion efficiency by a factor of 1.7, but the results presented in Fig. 3 demonstrate a substantially larger decrease (by almost one order of magnitude), which can be accounted for in terms of the spectral transmission of the MgO : PPLN structure [18] and the specifics of the dielectric coatings on the OPO cavity mirrors.

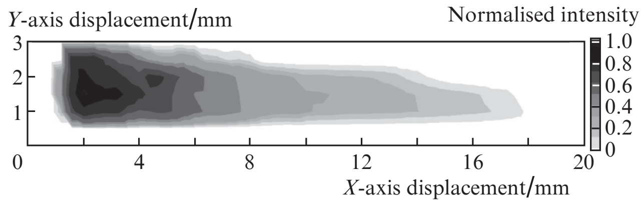

Figure 3. OPO idler wave intensity distribution over the aperture of the fan-out MgO : PPLN structure.

Figure 4 shows idler wave emission spectra of the OPO measured with the cylindrical pump beam expander. The aperture of the dichroic mirror (M4), mounted at 45°, prevented us from using the entire width (20 mm) of the structure, placed in the OPO cavity. The horizontal pump beam width at the OPO cavity input was ~14 mm, so in our experiments we were able to pump only some parts of the aperture of the structure.

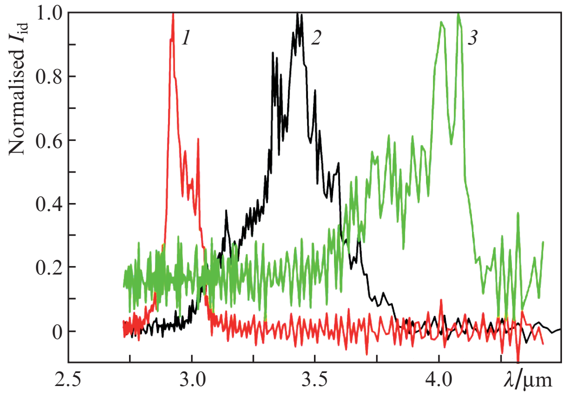

Figure 4. Idler wave emission spectra, I_{id}, of the OPO at different transverse positions of the large-aperture fan-out MgO : PPLN structure.

The idler wave emission spectra of the OPO in Fig. 4 were obtained at three transverse positions of the structure relative to the cavity axis. Curve *1* corresponds to the leftmost position of the structure according to the map in Fig. 3, which ensures the highest efficiency of parametric conversion at an idler wavelength of ~3 μm. Curves *2* and *3* correspond to the central and rightmost positions of the structure. The highest idler pulse energy (power) was observed in spectrum *1*, centred near 3 μm. Spectrum *3*, centred near 4 μm, has the lowest intensity, so after normalisation its hash differs markedly from that of the other spectra. The full width at half maximum of spectrum *1* is ~150 nm and that of spectrum *2* (centred at 3.5 μm) is about 300 nm. Note that the severe spherical aberrations in the cylindrical lenses lead to an intensity redistribution along the light propagation line, reducing the intensity in the centre of the line and raising it in the peripheral parts. Note also that the use of Powell lenses instead of the cylindrical lenses in this configuration will ensure a more uniform pump intensity distribution along the light propagation line.

In Fig. 5, the measured average OPO idler wave power corresponding to spectrum *1* in Fig. 4 is shown as a function of pump power. The maximum average idler wave power is 0.206 W (at a pump power of 1.679 W), which corresponds to a conversion efficiency of 12.3%. Quantum efficiency is 34.68% and slope efficiency is 11.7%. It is seen that the relation is almost linear, with a weak tendency toward saturation at pump powers of up to 1.7 W. This leads us to conclude that, even at an energy density 17 times as high as the threshold, there is no pump saturation.

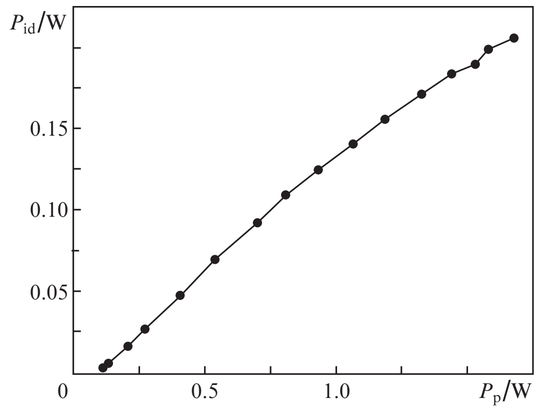

Figure 5. Average OPO idler wave power P_{id} as a function of pump power P_p for the spectrum centred near 3 μm.

The highest output pulse energy of the OPO corresponds to a pump energy density of 0.21 J cm^{-2}, which is a factor of 4.76 lower than the damage threshold of the PPLN structure. Therefore, the pump pulse energy can be increased by about a factor of 4.5, which will correspond to 78 times the generation threshold of the OPO. When a PPLN structure is used in a double-pass pumped singly resonant OPO configuration, the pump energy density usually does not exceed 70% of the damage energy density of the crystal. In the present experiment with the large-aperture PPLN structure, the pump energy density (at 1.064 μm) was a factor of 5–6 lower than in experiments that use conventional pump beams with a circular cross section. This means that it is possible to raise the pump energy (power) and energy density to a level comparable to that in previously reported experiments [19].

It should be noted that, to raise the idler pulse energy, PPKTP or PPKTA periodic structures, which have a much higher damage threshold (~1 GW cm^{-2}) than does lithium niobate, can be used as nonlinear elements of OPOs. In addition, PPKTP structures can operate in a 1 μm pumped OPO at emission wavelengths of up to ~3.3 μm, and PPKTA structures, up to about 5 μm [20]. Note that effective nonlinearity is 14.2 pm V^{-1} in PPLN structures, 10.8 pm V^{-1} in PPKTP and 10.3 pm V^{-1} in PPKTA [20].

4. Conclusions

The use of an OPO with a stripe structure of its nonlinear element and a cylindrical pump beam expander allows the average power of near- to mid-IR laser frequency converters to be raised by several times relative to systems that employ circular pump beams. The reduction in the energy density on the nonlinear element is due to the increase in the effective aperture of the element, which improves the reliability of the system and increases the service life of the OPO.

The use of a fan-out PPLN structure as a nonlinear element allows one to make multi-frequency OPOs in the range 2.6–4.2 μm, with the possibility of simultaneous generation of a broad frequency spectrum in the mid-IR region (sort of a laser Globar) when the entire aperture of the nonlinear element is pumped. Using Powell lenses instead of the cylindrical lenses in the pump beam expander, one can obtain a more uniform pump intensity distribution over the entire aperture of the crystal, which will lead to an increase in average power in the spectral range 2.6–4.2 μm.

To raise the idler pulse energy, PPKTP or PPKTA periodic structures, which have a much higher damage threshold (~1 GW cm^{-2}) than does lithium niobate, can be used as nonlinear elements.

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