Tandem PPKTP and ZGP OPO for mid-infrared generation

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ABSTRACT

Efficient laser sources in the 3 - 5 µm wavelength range are needed for directed infrared countermeasures, but also have applications in remote-sensing, medicine and spectroscopy. We present new results on our tandem optical parametric oscillator (OPO) scheme for converting the radiation from a 1.06 µm Nd^{3+}-laser to the mid-infrared. Multi Watt level output power in the 3-5 µm range at 20 kHz pulse repetition frequency is reported. Our setup uses a type I quasi phase-matched PPKTP crystal in a near degenerate OPO to generate 2.13 µm radiation. A volume Bragg grating resonant close to, but not exactly at the degenerate wavelength, is used as a cavity mirror to reduce the bandwidth and ensure singly resonant operation. Both signal and idler from the PPKTP OPO are used to pump a ZGP OPO generating high power radiation in the 3-5 µm region. Using this scheme for each pump photon it is possible to generate four photons for each pump photon, all in the interesting wavelength range, thus enabling high efficiency conversion.

Keywords: OPO, ZGP, mid-infrared, DIRCM, PPKTP, volume Bragg gratings

1. INTRODUCTION

Tunable and broadband laser sources in the 3.5-5 µm wavelength range are an important component in directed infrared countermeasure (DIRCM) systems and several other applications. As direct laser generation at these wavelengths from solid state lasers is difficult due to phonon resonances optical parametric oscillators (OPOs) are commonly used to convert the wavelength of near infrared (IR) lasers to the interesting mid-IR wavelengths. Also many nonlinear optical crystals have absorption problems at these wavelengths, but there are a few exceptions. The material that best combines transparency in the mid-IR with good mechanical thermal and optical properties is Zink-Germanium-Phosphide, $ZnGeP_2$ (ZGP). ZGP however has high absorption in the near IR and needs a pump wavelength for the OPO above approximately 2 µm.

Pumping of OPOs near 2 µm is dominated by Ho-lasers. With the advent of thulium–fiber lasers as pump sources for the holmium lasers this has become a reliable and efficient method for high average power pumping of ZGP OPOs. Another method is to use a near degenerate OPO pumped by a 1.064 µm Nd-laser to generate the 2 µm radiation. The advantage of this is that Nd-lasers are well developed and readily available. As they are used in many other applications dual use of this most expensive component in the system is possible. Until recently these OPOs always used bulk type II KTP ($KTiOPO_4$) crystals where the signal and the idler from the OPO have different polarizations. As the pump for the ZGP OPO needs to be polarized then only one of the components can be used to pump the second OPO stage and half of the possible pump energy has to be discarded. The alternative is to use quasi phase matching (QPM), where all involved waves, pump, signal and idler, can have the same polarization. In this configuration where signal and idler are truly identical at 2.128 µm the phase mismatch will increase slowly as the signal and idler wavelengths move away from degeneracy giving a wide gain bandwidth. As narrow bandwidth of the pump is an important factor for the efficiency of an OPO, a free running near degenerate QPM OPO is not suitable as pump source for a ZGP OPO.

The bandwidth of the radiation generated in an OPO does however not only depend on the gain bandwidth, but also on the cavity feedback. By using a cavity that gives feedback only in a narrow wavelength range the generated bandwidth can be limited to this range. An efficient way to give narrow wavelength feedback is to use a volume Bragg grating (VBG) as one of the cavity mirrors. A volume Bragg grating is a component where the index of refraction along the

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propagation direction is periodically modulated. By controlling the modulation period, the modulation depth and the number of periods the center wavelength, bandwidth and diffraction efficiency of the grating can be controlled.

Narrow bandwidth OPO operation with a VBG was first demonstrated in the near IR by Jacobsson *et al.*[1]. We have subsequently demonstrated operation at 2.0 µm[2,3], and very close to degeneracy at 2.13 µm[4,5] using periodically poled $LinNbO_3$ (PPLN) and KTP (PPKTP). These OPO setups have also demonstrated high efficiency pumping of ZGP OPOs[3-5]. Recently Saikawa *et al.* demonstrated high energy operation using a MOPA architecture with a 5×5 mm aperture PPLN crystal[6].

This paper will give some recent results from experiments on OPOs with volume Bragg gratings and the use of them for pumping a ZGP OPO. It also includes a discussion about factors limiting the efficiency of OPOs where the bandwidth is limited by the cavity feedback.

2. THEORY AND MODELING

2.1 Volume Bragg gratings

In photo-thermo-refractive (PTR) glasses, that are alumo-sodia-silicate glasses doped with silver, cerium and fluorine, a photochemical process initiated by illumination with ultraviolet light can after heat treatment cause a permanent change of the refractive index to occur. By using an interference pattern between two laser beams a sinusoidal modulation can be achieved

$$n = n_0 + n_1 \sin\left(2\pi x / \Lambda\right), \tag{1}$$

where the modulation n_1 is up to 10^{-3} in magnitude. The glasses are mechanically, chemically and thermally (to at least 400°C) stable, have damage thresholds similar to normal mirror substrates and have low absorbtion from the visible up to 2.7 µm. The wavelength of the peak reflectivity is determined by the Bragg condition and is for propagation along the grating vector

$$\lambda_B = 2n_0\Lambda \tag{2}$$

The reflectance bandwidth can be approximated with

$$\frac{\Delta\lambda}{\lambda_B} = \frac{\lambda_B}{2n_0 d} = \frac{\Lambda}{d}, \tag{3}$$

where d is the length of the grating. Bandwidths range from 0.01 nm to a few nm. The peak diffraction efficiency can be calculated by

$$R = \tanh^2\left(\frac{\pi n_1 d}{2n_0\Lambda}\right), \tag{4}$$

and may reach over 99 % reflectivity. The bandwidth and the reflectivity cannot be totally separately controlled, but high reflectivity broadens the bandwidth.

2.2 Narrowband near degenerate OPO considerations

The coupling between different wavelengths satisfying energy conservation in a nonlinear crystal is decided by the phase-matching relation and is most efficient when Δk_{OPO}=0.

$$\Delta k_{OPO} = \frac{2\pi}{c}\left(n_p\nu_p - n_s\nu_s - n_i\nu_i\right) - \frac{2\pi}{\Lambda}. \tag{5}$$

The indices p, s and i represent pump, signal and idler respectively while n is the refractive index and ν=c/λ is the oscillation frequency. The modulation period for the second order nonlinearity in the nonlinear crystal is written Λ. The refractive index decreases for longer wavelengths and can for the relevant range for PPKTP be described by the Sellmeier equation

$$n^2 = A + \frac{B}{1 - C/\lambda^2} + \frac{D}{1 - E/\lambda^2} - F\lambda^2, \tag{6}$$

where A to F are constants given by Fradkin *et al.*[7], whose refractive index values are those that best fit our experimental data. If the pump wavelength is kept fixed it is easily seen from equation (5) that the rate of change of the phase mismatch (with $\partial \nu_i = -\partial \nu_s$ from energy conservation) is

$$\frac{\partial \Delta k_{OPO}}{\partial \nu_s} = -\frac{1}{c}\left(\nu_s \frac{\partial n_s}{\partial \nu_s} + n_s - \nu_i \frac{\partial n_i}{\partial \nu_i} - n_i \right) = \frac{n_{g,i} - n_{g,s}}{c}. \tag{7}$$

At degeneracy in a type I or QPM interaction the group velocities of the signal and idler are equal so that not only the phase mismatch, but also the rate of change of the phase mismatch has a zero at degeneracy. This situation gives a very wide gain bandwidth as we need to move far from degeneracy until higher order effects make a substantial phase mismatch. In a type II interaction on the other hand polarization lifts the degeneracy so that the group indices are not equal and the phase mismatch grows rapidly as the signal moves away from degeneracy. The gain bandwidth is thus much narrower in type II interactions than in type I.

By assuming that the phase mismatch is zero at ν_{s0} and writing $\nu_s = \nu_{s0} + \Delta\nu_s$ we can calculate the bandwidth where the phase mismatch is equal to π after passing through a crystal of length L as

$$\pi = \frac{2\pi L}{c}\left| \left(\nu_{s0} + \Delta\nu_{s+}\right) n\left(\nu_{s0} + \Delta\nu_{s+}\right) - \nu_{s0} n\left(\nu_{s0}\right) + \left(\nu_{i0} - \Delta\nu_{s+}\right) n\left(\nu_{i0} - \Delta\nu_{s+}\right) - \nu_{i0} n\left(\nu_{i0}\right) \right|. \tag{8}$$

Solving this equation numerically with refractive indices from equation (6) we find the half width bandwidth for shift to a shorter wavelength $\Delta\nu_{s+}$. For a 10 mm PPKTP crystal the full gain bandwidth found around degeneracy is $2\Delta\nu_s$=18.6 THz or the range from 2 to 2.28 μm. For the non-degenerate case the gain profile may be asymmetric and the calculation should also be done for $\nu_s = \nu_{s0} - \Delta\nu_{s-}$, and the two half widths added.

By limiting the cavity feedback to a narrow wavelength region the OPO can be kept below threshold except for this wavelength. The slow change of Δk_{OPO} will however also result in a low phase-matching error for cascaded interactions such as the frequency doubling of the signal and idler from the OPO interaction

$$\Delta k_{SHG(\lambda_s)} = 2\pi\left(2\frac{n(\lambda_s) - n(\lambda_s/2)}{\lambda_s} + \frac{1}{\Lambda} \right) = 2\pi\left(\frac{n(\lambda_s)}{\lambda_s} - \frac{n(\lambda_i)}{\lambda_i} + \frac{n(\lambda_p)}{\lambda_p} - \frac{n(\lambda_s/2)}{\lambda_s/2} \right). \tag{9}$$

In an OPO working close to degeneracy the differences between λ_s and λ_i and between λ_p and $\lambda_s/2$ are small and the phase mismatch will also be small. In the forward pass through the crystal we will see SHG of both the signal and the idler. This is in addition to the normal back-conversion and reduces the effective gain for the signal and idler. In the backward pass there will be SHG of the signal, reducing the feedback in the cavity. A simulation to study the effect of this was made with the OPO simulation engine SISYFOS, developed at the Norwegian Defence Research Establishment[8]. To save time the simulation was done in plane wave geometry. The resonance wavelength of the VBG was varied and the QPM period changed to give optimum phase-matching for that wavelength. The different back-conversion processes will cause a reduction of the conversion efficiency in the OPO and as seen in the left part of Figure 1 the efficiency very close to degeneracy is much lower than with the signal at 2050-2080 nm. The results at low pump energy do not depend on the wavelength as the difference is caused by cascaded nonlinear effects and appear only when there are high peak intensities in the signal and idler.

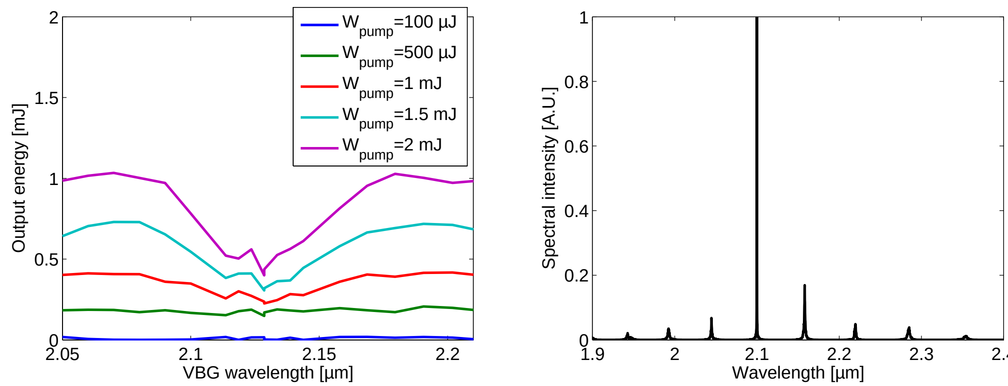

Figure 1. Simulation of near degenerate OPO with VBG. Left output energy as a function of VBG wavelength with a few different pump energies. Right spectrum of the output for one example with a 2100 nm VBG. Note that the wavelength resonant in the cavity has a narrower spectrum and thus the peak looks much higher in the spectrum, even though the difference in energy between signal and idler is small.

Through difference frequency generation (DFG) between the frequency doubled signal and the idler a new frequency will be generated, a process that can be seen as four wave mixing (FWM) through cascaded $\chi^{(2)}$ interactions between the signal and the idler. This new wavelength is for a near degenerate OPO within the gain spectrum and will thus experience single pass optical parametric amplification (OPA) and reach measurable levels as seen in the simulated spectrum in the right part of Figure 1. In most applications it is not a big problem that a few percent of the generated energy is in these unwanted spectral lines. A bigger problem is that the gain for the primary OPO wavelength is reduced.

2.3 Pump spectrum considerations

The phase-matching relation can also be used to study how the efficiency depends on the pump bandwidth. This is a more complicated matter as in a normal OPO both the signal and the idler may adjust to compensate a small change in pump wavelength. The traditional pump acceptance bandwidth is calculated by keeping the signal frequency fixed and seeing how much the pump can vary before the phase mismatch gets too large. The energy conservation is satisfied by the idler changing with the pump. The half width for increasing pump frequency is calculated from

$$\pi = \frac{2\pi L}{c}\left|\left(\nu_{p0}+\Delta\nu_{p+}\right)n\left(\nu_{p0}+\Delta\nu_{p+}\right)-\nu_{p0}n\left(\nu_{p0}\right)-\left(\nu_{i0}+\Delta\nu_{p+}\right)n\left(\nu_{i0}+\Delta\nu_{p+}\right)+\nu_{i0}n\left(\nu_{i0}\right)\right|. \quad (10)$$

It is necessary to also calculate the negative half width as the pump bandwidth will be asymmetric. This equation quite accurately describes the case of OPA of a single frequency signal with a multi mode pump. For a free running OPO it is however not telling the whole story.

By linearizing the expression around the point where we have phase-matching this can be simplified to[9]:

$$\pi > L\left|\left(\frac{\partial k_p}{\partial \omega_p}-\frac{\partial k_i}{\partial \omega_i}\right)\Delta\omega_p\right| = L\left|\left(\frac{1}{v_{g,p}}-\frac{1}{v_{g,i}}\right)\Delta\omega_p\right|. \quad (11)$$

This expression is basically the same as equation (7) but with the pump instead of the signal changing. As long as the group velocities are different the error in this linearization is generally small. The problem with fixing the frequency of the signal wave is however not removed. For a 24 mm long ZGP crystal pumped at 2.128 µm and with signal and idler at 3.7 and 5 µm, respectively, the calculation using the group velocities gives a maximum pump bandwidth of 275 GHz or 4.1 nm.

A simulation allows us to test the dependence of the OPO conversion efficiency on the pump bandwidth. The pump spectrum is described by a Lorentz function and the value given is the FWHM bandwidth. The simulation results (Figure 2) show us that there is no sharp limit but that the conversion efficiency gradually decreases with increasing bandwidth. The notion found in many papers that as long as the pump bandwidth is below the limit found from equation (11) everything is fine thus should be reconsidered. The theoretical expression is however still useful as a scaling for efficiency loss. In the simulated example, a plane wave simulation with parameters similar to the ones used for the theoretical calculation in the last paragraph, three different pump energies were studied. From the data it can be found that there is a both an increase in threshold energy and a decrease in slope efficiency when the pump bandwidth is increased.

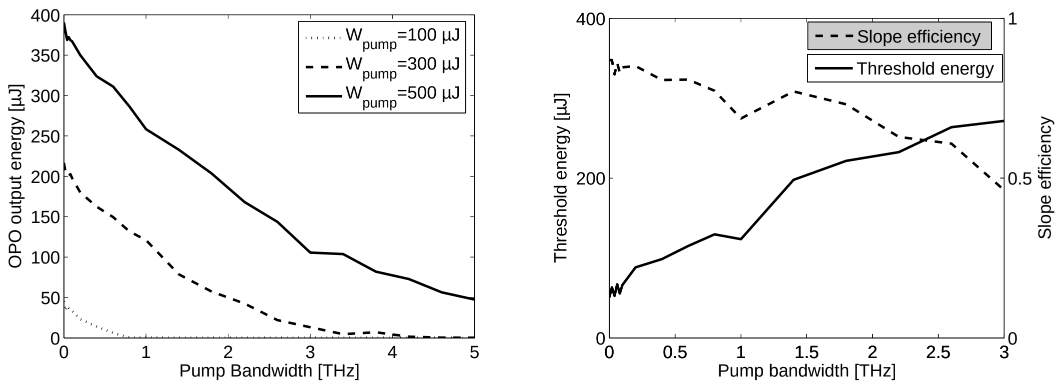

Figure 2. Left: Simulated OPO output energy as a function of pump bandwidth for three different pump energies. Right: Simulated OPO threshold energy and slope efficiency as a function of pump bandwidth.

In our case we have an additional complexity of the pump bandwidth dependence as the pump consists of two components, the signal and idler from the first OPO. The dependence of the efficiency on the separation of the two pump components was simulated. As a comparison the components were also simulated separately. The pump spectrum was simplified compared to the case of a tandem OPO setup; so that both pump components had the same bandwidth and mode separation. The simulation results in Figure 3 compare results with the two pump components used combined or separately. There is a clear increase in output energy when combing the two spectral components, but it decreases as the separation increases. For a detuning from degeneracy of the first OPO in a tandem OPO setup of up to 200 GHz (3 nm) the efficiency reduction compared to a single pump component seems small. The allowable pump separation here is however small compared to the detuning needed in the first OPO to avoid efficiency reduction due to cascaded interactions (Figure 1). For larger detuning the ZGP OPO will work more like two separate OPOs in the same crystal where the pump tuning causes them to have different gain spectra. With a too large detuning there will not be phase matched OPO interaction for both wavelengths at the same crystal angle.

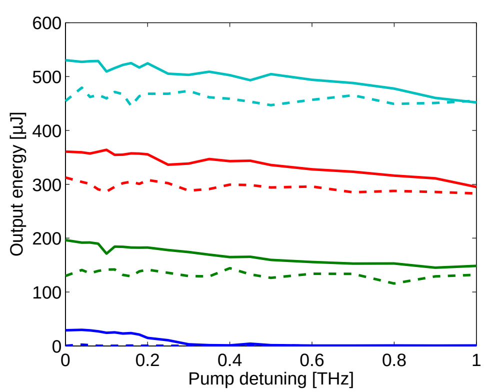

Figure 3. Simulation of OPO with two spectral components in pump as a function of the detuning from degeneracy of the two pump components. Solid lines are for simulations with the combined pump and dashed lines for the two components simulated separately. The total pump energies were 100, 300, 500 and 700 µJ.

3. EXPERIMENTAL SETUP

We have built an experimental setup that will supply us with a mid-infrared source in the lab, at the same time that it lets us test the principles of OPOs with VBG output couplers and their use in tandem OPO setups. In the first generation setup where the results reported here where obtained no consideration has been given to physical size and the setup covers a 1500x600 mm breadboard. A schematic drawing of the OPO part of the setup is given in Figure 4. The laser source is under mechanical redesign to a two-story 900x300 mm breadboard that will fit in our DIRCM testbed. This size is limited by our $Nd:YVO_4$-pumplaser.

The primary pump source was a commercial $Nd:YVO_4$-laser (IS4I-E, Edgewave GmbH). During the experiments the laser was always used at full diode pump power and q-switched with 20 kHz pulse repetition frequency (PRF). In this configuration the pulse energy is about 1.4 mJ and the pulse length 6.5 ns. To protect the laser a Faraday isolator was used. A half wave plate (HWP) in a motorized rotation stage and a cube polarizer were used to regulate the pump power to the OPO. A beam sampler reflected part of the power to a monitor detector so that the pump power at the PPKTP OPO could be measured at the same time as the output. After the beam sampler 26 W or 1.3 mJ of pump power was available for the OPO. The beam was focused by a two lens telescope (f=150 mm and f=50 mm) and knife edge measurements around the focus were made. The beam quality was calculated from a parabolic fit of the beam radius and was found to be M^2=1.3 vertically and 1.9 horizontally. To compensate for the slightly astigmatic pump beam a cylinder lens (f_x=500 mm) was used to bring down the beam size in the horizontal direction and make the focuses in the two directions overlap. All lenses were AR-coated. The final beam size in the focus was w_{0x}=200 µm and w_{0y}=230 µm, where $w_{0x,y}$ are the radiuses of exp(-2) power horizontally and vertically, respectively.

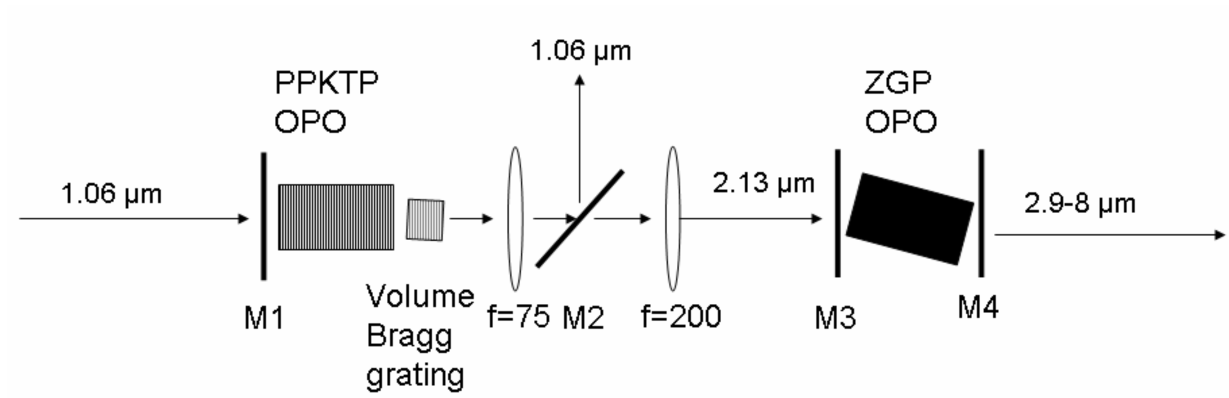

Figure 4. The experimental setup.

The PPKTP OPO cavity consisted of an incoupling mirror (M1), the nonlinear crystal and a volume Bragg grating (VBG). The incoupling mirror was highly reflective for the generated beam and AR-coated for 1.06 µm, but still reflected about 5 % of the pump.

The PPKTP crystal had a 16 mm long domain grating with 38.85 µm period in a 20x6x1 mm crystal. The best performance near degeneracy was found at a temperature of 57°C, but the change with temperature was slow. The surfaces were slightly wedged compared to each other to inhibit monolithic OPO action and were AR-coated. The total air spacing in the cavity was approximately 4 mm.

Several different volume Bragg gratings (Ondax, Inc.) with different resonance wavelengths close to degeneracy were used in the experiments. All of them had nominally 50 % peak reflectance and 0.5 nm (33 GHz) FWHM bandwidth. The surfaces were tilted a few degrees to eliminate broadband feedback and AR-coated to minimize cavity loss. The physical dimensions of the VBG were 4x3x3 mm.

After the PPKTP OPO we placed a dichroic mirror (M2, AR at 2.13 µm, HR at 1.06 µm) at 45 degrees angle of incidence to remove the remaining 1.06 µm pump to protect the ZGP crystal. The 2.13 µm beam was first collimated by an f=75 mm lens and then refocused by an f=200 mm lens to provide a w_0=500 µm focus for the ZGP OPO. The ZGP OPO had an incoupling mirror (M3) that was HR at 3-5 µm and AR at 2.1 µm (91 % transmission). The ZGP crystal (BAE systems) itself was 14x6x6 mm and was cut at 60˚ to the crystallographic C-axis. As phase matching with our pump wavelength is at 54˚ to the C-axis at degeneracy and smaller angles further from degeneracy the crystal was tilted more than 20˚ external angle from plane incidence. The outcoupling mirror (M4) was highly reflecting at 2.1 µm so that the pump was double passed. The reflectance was 85 % in the 3-4.4 µm region and between 10 and 40 % for longer wavelengths. The physical length of the OPO cavity, including the crystal, was approximately 20 mm.

4. RESULTS

Measurements of the output from our PPKTP OPO with a VBG output coupler show very narrow spectral widths. In Figure 5 spectra of the OPO output using three different volume Bragg grating output couplers are shown. As a comparison also a spectrum using an ordinary dichroic mirror output coupler is included. The monochromator measurements show instrument limited linewidths of less than 0.5 nm for the separated signal and idler lines and 0.8 nm for the degenerate spectrum. Fabry-Perot etalon measurements on an earlier setup with a shorter crystal and cavity show a basically single longitudinal mode signal and an idler linewidth of 20 GHz FWHM[5].

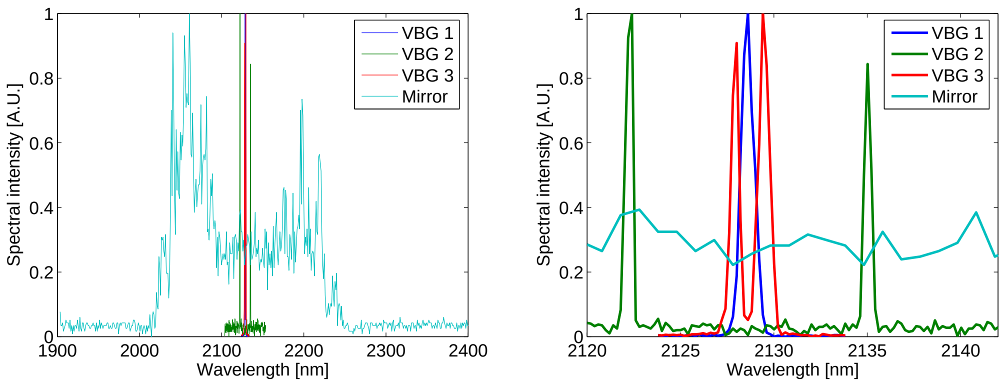

Figure 5. Measured spectra with three different volume Bragg gratings and with a broadband mirror. The two graphs show the same spectra at different scales.

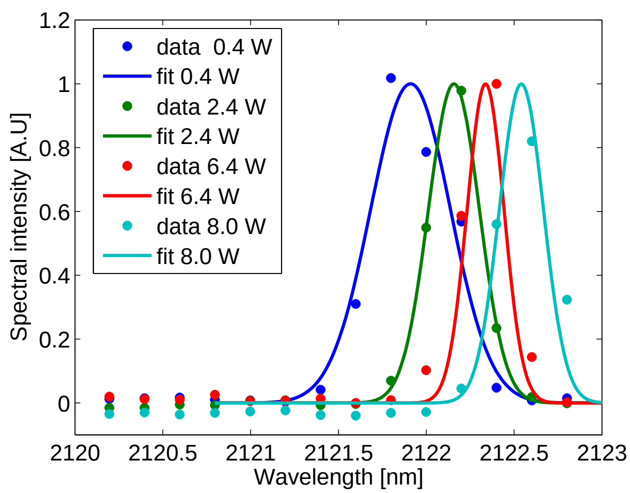

Figure 6. Spectra of the OPO signal for different output powers with measured points and fitted Gaussian profiles.

There is a shift of the spectrum towards degeneracy as the output power increases. This can be explained by heating of the VBG. Blau et al. found a shift of the reflectance peak of 0.0234 nm/°C at 2479 nm[11]. The shift should be proportional to the modulation period in the grating and hence the wavelength so that we should have a gradient closer to 0.020 nm/°C with our grating. The observed shift of 0.6 nm should thus correspond to a temperature increase of 30°C. The temperature of the grating was not measured, but the mount felt warm to the touch. From the not quite resolving monochromator measured points Gaussian fits were made to determine the central wavelengths of the signal at different output powers. A few of these measurements with fitting functions are shown in Figure 6. A least square fit to the function

$$\lambda = \lambda_0 + a \times P_{pump} + b \times P_{OPO} \tag{12}$$

was then made for the determined wavelengths. The result was a=-0.0014 nm/W and b=0.080 nm/W. The negative influence of the pump power is clearly a result of measurement errors, but the magnitude of this pump power induced shift is very much smaller than the OPO output power induced shift. The specific values are very much depending on the heat transfer of the VBG mount, but the measurement gives the information that the absorption at 2.1 µm is much higher than the absorption at 1.06 µm.

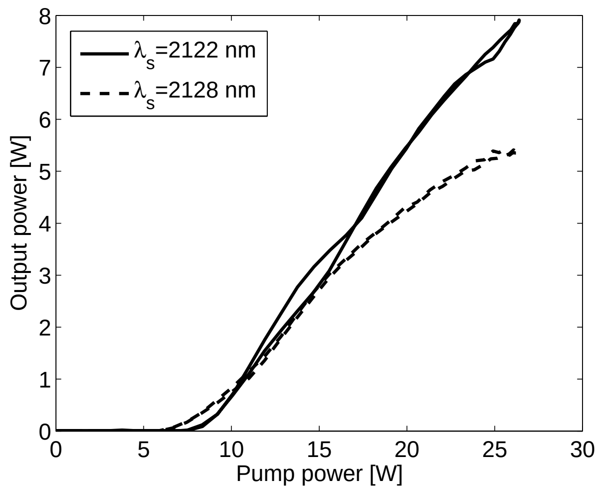

Figure 7. Output power as a function of pump power for two different VBG outcouplers, one very close to degeneracy and one 7 nm from degeneracy. The pump power was varied by rotating the half wave plate by 90° so that the pump power first increased and then decreased, hence the double lines.

The output power was measured for two different output couplers and is shown in Figure 7. The pump power was varied by rotating a half wave plate by 90°, so that the slope efficiency was measured both for increasing and decreasing pump powers. The system paused 5 s at each position before recording the measurement. As there is very small difference between the increasing and decreasing pump power this seems to be enough for thermal stabilization. As expected from the theoretical discussion and the simulations in section 2.2 we see better efficiency away from degeneracy. Very close to degeneracy the OPO suffers from severe back conversion and cascaded nonlinear effects and the slope efficiency drops gradually starting already at threshold. The output of the near degenerate OPO can also be influenced by the thermal drift of the VBG wavelength. When the power increases the resonance moves even closer to degeneracy and the cavity may become doubly resonant. As is common in multi-longitudinal mode OPOs the threshold is not very well defined as for some pulses spikes will reach threshold but for other pulses the pulse shape is smoother and no conversion occurs. Following the linear slope of the power curve down to zero output power we find a threshold of 8.2 W or 410 µJ. For the case where signal and idler are separated by 13 nm we see a slope efficiency of 46 % with very low roll off. The maximum output power in this measurement was 7.9 W corresponding to 30 % conversion efficiency.

When using the grating that reflects the degenerate wavelength we find very clear resonance peaks of increased output power when the OPO and laser roundtrip times match or have a fractional relation as described by Arisholm et al.[10]. Unlike with a mirror output coupler we see significant power instability with matched resonator lengths with the degenerate VBG OPO. For a matched cavity length we see a standard deviation of 15 % of the average power and peak to peak variations of up to 54 % of the average power with shifts on a timescale of 10 s. The pulse to pulse variation was not measured, but the measurement was made with a thermopile sensor with 2 s response time. When trying to find a position where the lengths were unmatched we found a standard deviation that was 2.8 % of the average power. The pump power was higher for the unmatched case, to compensate for the lower efficiency. The measurement for the length matched cavity was started during a period of high power so the average power during the whole measurement was in the end slightly lower than for the unmatched case, but the highest short term power was still measured with the length matched cavity.

The increased variation of output powers may be caused by the clusters formed in the spectrum that were reported by Arisholm[10]. Small changes to the cavity phase caused by thermal or mechanical variations that in a mirror OPO would cause a translation of the clusters could here move them away from the feedback and change which modes are allowed to oscillate.

We used two lenses to refocus the output beam from the PPKTP to the ZGP OPO, a first lens that gave an approximately collimated beam and a second lens to focus the beam to a suitable size. The knife edge scans that were used to measure the focus can also be used to estimate the beam quality. Our measured values were M^2=1.9 and 2.1 horizontally and vertically, respectively.

The ZGP OPO gave a maximum output power of 3.18 W with the signal in the range 3.7 to 4 µm and the idler at 4.5 to 5 µm. The output power curve and the spectrum are shown in Figure 8. The spectrum shows double peaks in the signal and idler because the two components in the pump that are separated by 13 nm phase match to slightly different wavelengths at the specific crystal angle that was used. Tuning of the spectrum was possible with only a small reduction of the output power. The slope efficiency just above threshold was 27 % with respect to the pump power at 1.06 µm and the conversion efficiency was 12 % at full power. The PPKTP OPO output power could not be measured with the ZGP OPO in place, but measurements during alignment indicate that maximum 8 W of 2.1 µm pump power was available so that the conversion efficiency from 2.1 µm to the mid-IR would be 40 %.

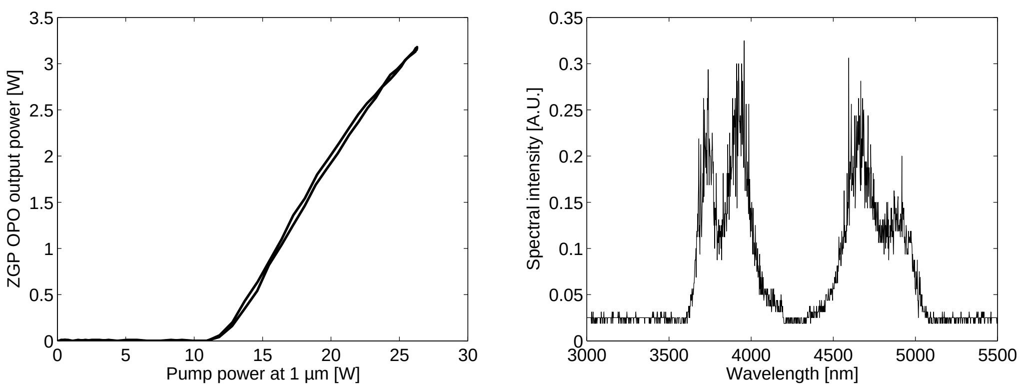

Figure 8. Output power and spectrum for the ZGP OPO pumped by the PPKTP OPO.

5. DISCUSSION

We have shown 63 % improvement, from 1.95 to 3.18 W, of the mid-IR output power from our tandem OPO setup compared to our earlier results[5]. The improvement was to a large degree caused by the change of the repetition frequency from 10 to 20 kHz which allowed us to use a longer crystal with the same aperture without bulk crystal damage and also increased the pump average power. Another factor in increasing the conversion efficiency from 10 to 12 % was the realization that near degenerate OPOs with broadband gain and bandwidth limiting by the cavity suffer an efficiency penalty from SHG of the signal and idler, and that this is worse the closer to degeneracy the OPO is operated. The efficiency of the PPKTP OPO should increase as the separation of signal and idler increases. On the other hand the efficiency of the ZGP OPO should decrease as the two pump wavelengths cease to interact because of pump tuning separating the spectral peaks in the mid-IR. This trade-off has not yet been optimized and there might be some additional efficiency gain possible here.

The spectrum of the ZGP OPO does not show significant clustering, and it is therefore probable that the roundtrip times of the two OPOs are not matched. Matching of the cavity length should increase the ZGP OPO efficiency as the idler reflectivity is significant. Further means of optimizing the efficiency would be to use a ZGP crystal where phase-matching can be obtained at plane incidence and by optimization of the focusing of the pump beam.

One effect of moving away from degeneracy at 2.13 µm is that the mid IR spectrum becomes wider because of the pump tuning in opposite directions for the two pump components for the ZGP OPO. Depending on the application this may actually be desirable, but sometimes there is a need for a single pump wavelength to produce a reasonably narrow spectrum in the second stage. In this case truly degenerate operation of the first OPO is needed. Our results indicate that there in this case exists a trade off between efficiency and power stability because of instabilities when the round trip times of the pump laser and the degenerate narrowband OPO are matched. Further investigation is needed to characterize and understand this trade-off.

In conclusion we have demonstrated an OPO using a volume Bragg grating output coupler with 30 % conversion efficiency to two narrow bandwidth spectral lines separated by 13 nm near degeneracy. The output from this OPO was used to pump a ZGP OPO to give 12 % conversion efficiency from 1 µm to the 3.5 to 5 µm range. The system ran at 20 kHz and produced 8 W at 2.13 µm and 3.2 W in the mid-IR.

REFERENCES

[1] Jacobsson, B., Tiihonen, M., Pasiskevicius, V. and Laurell, F. "Narrowband bulk Bragg grating optical parametric oscillator," Opt. Lett. 30(17), 2281-2283 (2005).

[2] Henriksson, M., Sjoqvist, L., Pasiskevicius, V. and Laurell, F., "Narrow linewidth 2 µm optical parametric oscillation in periodically poled $LiNbO_3$ with volume Bragg grating outcoupler," App. Phys. B 86(3), 497-501 (2007).

[3] Henriksson, M., Tiihonen, M., Pasiskevicius, V., and Laurell, F., "$ZnGeP_2$ parametric oscillator pumped by a linewidth-narrowed parametric 2 µm source," Opt. Lett. 31(12), 1878-1880 (2006).

[4] Henriksson, M., Tiihonen, M., Pasiskevicius, V. and Laurell, F., "Mid-infrared ZGP OPO pumped by near-degenerate narrowband type-I PPKTP parametric oscillator," App. Phys. B 88(1), 37-41 (2007).

[5] Henriksson, M., Sjoqvist, L., Tiihonen, M., Pasiskevicius, V. and Laurell, F., "Tandem OPO systems for mid-infrared generation using quasi phase-matching and volume Bragg gratings," Proc. SPIE 6738, 673805 (2007).

[6] Saikawa, J.; Miyazaki, M., Fujii, M., Ishiszuki, H. and Taira, T., "High-energy, broadly tunable, narrow-bandwidth mid-infrared optical parametric system pumped by quasi-phase-matched devices," Opt. Lett 33(15), 1699-1701 (2008).

[7] Fradkin, K., Arie, A., Skliar, A, and Rosenman, G., "Tunable midinfrared source by difference frequency generation in bulk periodically poled $KTiOPO_4$," App. Phys. Lett. 74(7), 914-916 (1999).

[8] Arisholm, G., "Quantum noise initiation and macroscopic fluctuations in optical parametric oscillators," J. Opt. Soc. Am. B 16(1), 117–127 (1999).

[9] Arisholm, G., Rustad, G. and Stenersen, K., "Importance of pump-beam group velocity for backconversion in optical parametric oscillators," J. Opt. Soc. Am. B 18(12), 1882-1890 (2001).

[10] Arisholm, G., Lippert, E., Rustad, G. and Stenersen, K., "Effect of resonator length on a doubly resonant optical parametric oscillator pumped by a multilongitudinal-mode beam," Opt. Lett. 25(22), 1654-1656 (2000).

[11] Blau, P., Pearl, S., Fastig, S. and Lavi, R., "Single-Mode Operation of a Mid-Infrared Optical Parametric Oscillator Using Volume-Bragg-Grating Cavity Mirrors," IEEE J. Quant. Elec. 44(9), 867-871 (2008).