Near-degenerate Volume Bragg Grating PPKTP OPOs in tandem OPO mid-IR sources

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ABSTRACT

We demonstrate that using volume Bragg grating for spectral narrowing of type-I PPKTP OPO the oscillation remains singly resonant very close to degeneracy. Longitudinal mode analysis and possible effects of frequency pulling due to volume Bragg grating dispersion are discussed. Efficient operation of tandem OPOs in the mid-IR is demonstrated.

1. Introduction

Broadband laser sources in the 3.5 to 5 μm wavelength range with ns pulse widths and multi-kHz repetition rates, delivering several W of average power, are important components in e.g. directed infrared countermeasure (DIRCM) systems. So far the sources that best fulfill the demands of the DIRCM application are optical parametric oscillators (OPOs) with ZGP or orientation patterned GaAs crystals. These crystals need to be pumped at wavelengths longer than 2.0 and 1.8 μm, respectively. One way to produce this pump radiation is a degenerate, or near degenerate, OPO pumped by a Nd-laser at 1.06 μm. In early realizations type II interaction in bulk KTP crystals was used for this OPO, and only one of the generated waves was utilized for pumping the second OPO while the other polarization was dumped. The use of type I interaction in quasi-phase matched crystals can improve the system efficiency considerably as in addition to the higher nonlinearity and walk-off free interaction it also enables the use of both signal and idler for pumping the mid-infrared OPO. Near degeneracy the gain bandwidth in a type I configuration, where signal and idler have the same polarization, can however be several hundred nm. This is especially true for quasi-phase matching (QPM) in periodically poled crystals. The efficiency of an OPO depends strongly on the bandwidth of the pump, and it is thus necessary to reduce the bandwidth of the quasi phase-matched OPO if it is to be used for pumping a second OPO.

The spectrum of an optical parametric oscillator is determined by the gain and by the cavity feedback. To obtain a narrow bandwidth from a near degenerate OPO using QPM it is thus necessary to limit the bandwidth of the cavity feedback. The usual methods to reduce the bandwidth of an OPO are by using etalons and gratings in the cavity[1]. This introduces additional losses in the cavity and reduces the overall device efficiency. With the extremely broad gain bandwidth of the near degenerate QPM OPO the etalons are also ineffective in establishing single-mode operation due to the limited free-spectral range of etalons. The use of a volume Bragg grating (VBG) output coupler in an OPO cavity, first demonstrated by Jacobsson *et al.*[2], has been shown to be an efficient way of narrowing the spectrum of an OPO. We have earlier shown narrowband OPO operation near degeneracy with both PPLN and PPKTP crystals[3-6]. Efficient pumping of a ZGP OPO by the combined signal and idler from a periodically poled KTP (PPKTP) OPO with a VBG[5,6] has also been demonstrated.

In this work we demonstrate that using VBG and judicious cavity design the type-I PPKTP OPO can remain single resonant very close to degeneracy, where signal and idler spectra start partially overlapping. The analysis of the signal spectrum reveals well-developed longitudinal modes. Subsequently, it is shown that such a device exhibits periodic cavity coherence resonances, which previously were only observed in over constrained doubly-resonant OPOs[7,8]. To demonstrate the practicality of the near-degenerate PPKTP OPO containing VBG, we show efficient pumping of a ZGP OPO in the 3.5-5 μm region.

1. EXPERIMENTAL SETUP

An experimental setup that will supply us with a mid-infrared source in the lab, and at the same time lets us test the principles of OPOs with VBG output couplers and their use in tandem OPO setups, has been assembled. The pump source was a commercial multi-longitudinal mode $Nd:YVO_4$-laser. After passing an isolator and a power regulating half-wave plate polarizer combination the laser beam was focused in the PPKTP OPO. The PPKTP OPO cavity consisted of a flat dichroic incoupling mirror, the nonlinear crystal and a volume Bragg grating. The PPKTP crystal had a 16 mm long domain grating with 38.85 μm period in a 20x6x1 mm crystal. The surfaces were slightly wedged compared to each other to inhibit monolithic OPO action and were AR-coated. Several different VBGs 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 losses. The physical dimensions of the VBG were 4x3x3 mm. For some of the experiments the VBG was mounted on a translation stage to vary the cavity length. As no surfaces other than the incoupling mirror have their normal parallel to the pump direction the cavity should be perfectly singly resonant with a VBG off degeneracy.

After the PPKTP OPO we used a dichroic mirror to remove the remaining 1.06 μm pump and then refocused the beam in the ZGP OPO. The ZGP crystal was 14x6x6 mm and cut at 60° to the crystallographic C-axis. As phase matching with our pump wavelength occurs 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 cavity consisted of two flat dichroic mirrors, coated for singly resonant operation, but with some residual idler reflection, and double passage pumping.

2. EXPERIMENTAL RESULTS

Compared to the case of a PPKTP OPO with a mirror output coupler where we measure radiation over a 200 nm wide region we can reduce the spectral width by a factor of more than 200 to a spectral width of 25 GHz (0.4 nm) for the signal and 45 GHz (0.7 nm) for the idler. The spectral width is measured as the regions where the amplitude in the Fabry-Perot etalon setup exceeds the noise. The FWHM values are hard to define but are about half of this. In Figure 3 the spectra are shown, with evident modes for the signal and a nearly continuous spectrum for the idler. There might be modulation of the idler on unresolved frequency scales, something that has been observed in shorter cavities. Similar measurements carried out for a VBG resonant so close to degeneracy that the signal and idler cannot be separated, show a total spectral width of 80 GHz (1.2 nm). Even in this case the OPO cavity modes are well developed primarily on the signal-side of the spectrum corresponding to the reflectivity bandwidth of the VBG (0.5 nm).

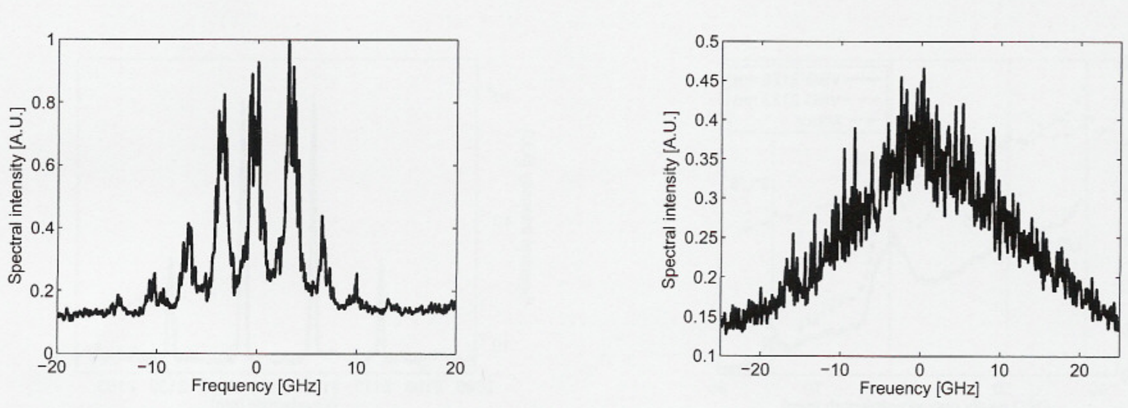

Figure 3. Spectrum of signal (left) and idler (right) of PPKTP OPO measured with a scanning Fabry-Perot etalon. The output coupler was a volume Bragg grating resonant close to 2122 nm.

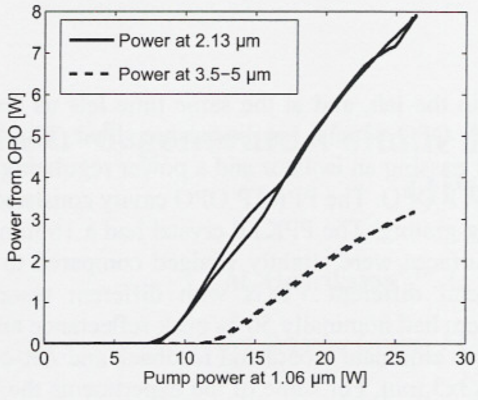

Figure 4. Output power from the tandem OPO. The output power was measured for both increasing and decreasing pump power, showing minimal hysteresis.

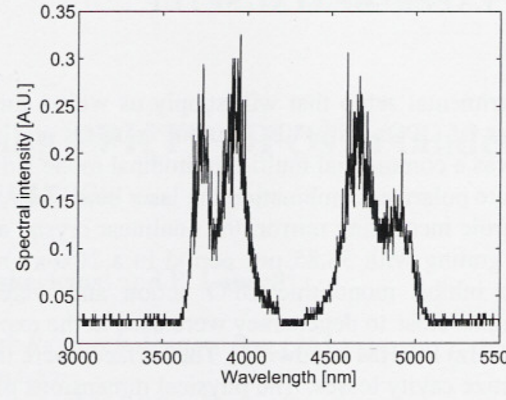

Figure 5. Spectrum from the ZGP OPO tuned for maximum power.

The output power from the PPKTP OPO running the pump laser at 20 kHz pulse repetition frequency with a VBG resonant at 2122 nm is shown in Figure 4. By linear extrapolation we find the PPKTP OPO threshold of 8.2 W or 410 μJ and 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. All of this power is used to pump the ZGP OPO and the output power in the 3.5-5 μm region reaches 3.2 W with a spectrum shown in Figure 43. The ZGP OPO is tunable with a slight reduction of the efficiency. The slope efficiency was 27 % with respect to the pump power at 1.06 μm and the conversion efficiency was 12 % at full power.

During the optimization of the PPKTP OPO it was found that the energy increased at certain cavity lengths. Further examination revealed that increased output power, evident in Figure 4, coincides with the cases where there is a fractional dependence between the roundtrip times in the pump laser and OPO cavities. Previously such periodic efficiency enhancement were only reported in over constrained doubly-resonant OPOs pumped with multimode beams[7,8]. Compared to the reference measurement using a partially reflecting mirror as output coupler the output energy enhancement is however more evident with the VBGs. The enhancement with a perfectly singly resonant cavity is also as strong as in the degenerate cavity, while Rustad *et al.* only reported a small effect in singly resonant cavities from simulations[8]. This suggests that a separate explanation is required for the narrow-band singly-resonant OPO cavities with VBG.

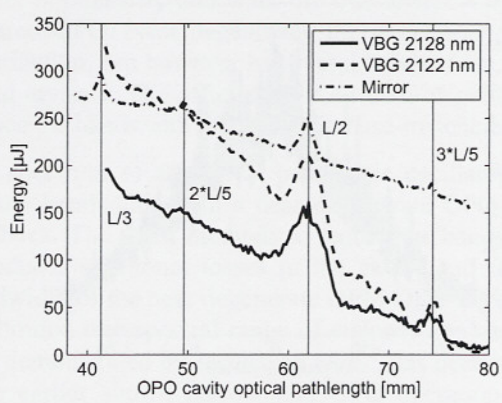

Figure 6. Output energy from PPKTP OPO when changing the cavity length with different output couplers. Vertical lines mark fractional relations between cavity lengths.

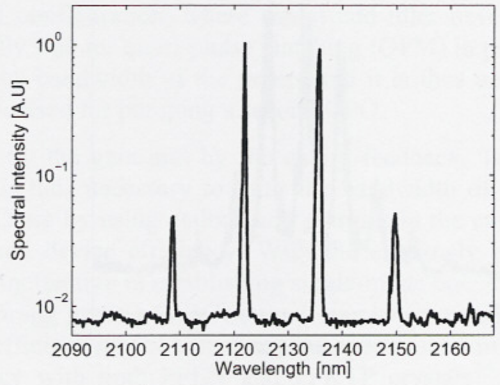

Figure 7. Spectrum from PPKTP OPO showing secondary peaks generated by four wave mixing of signal and idler.

One unwanted effect when using external bandwidth narrowing in parametric interactions with wide gain bandwidth is that four wave mixing (FWM) through cascaded $\chi^{(2)}$-interactions, via second harmonic generation of signal and idler, with subsequent parametric amplification is also phase matched and the FWM peaks may reach macroscopic levels. In this work around 5 % of the output energy was observed in these peaks and contributed little to the pumping of the ZGP OPO (Figure 5).

3. DISCUSSION

We have demonstrated that considerable spectral narrowing of near degenerate OPOs using quasi phase-matched nonlinear crystals can be achieved with volume Bragg gratings. The spectra contain only a few longitudinal modes, and even single mode operation is possible with the right combination of VBG bandwidth and cavity length. We have also shown that the generated radiation can be used for efficient pumping of a ZGP OPO, and have reached 3.2 W output power with 12 % conversion efficiency from 1.06 μm to the mid-IR. Further optimization should be possible.

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