PROCEEDINGS OF SPIE

[SPIDigitalLibrary.org/conference-proceedings-of-spie](https://spiedigitallibrary.org/conference-proceedings-of-spie)

Mixed type I and II BBO OPO pumped at 355 nm provides good beam quality, bandwidth, and efficiency

Sheng Wu, Vadym Kapinus, Geoffrey A. Blake

Sheng Wu, Vadym Kapinus, Geoffrey A. Blake, "Mixed type I and II BBO OPO pumped at 355 nm provides good beam quality, bandwidth, and efficiency," Proc. SPIE 5337, Nonlinear Frequency Generation and Conversion: Materials, Devices, and Applications III, (14 June 2004); doi: 10.1117/12.547976

SPIE.

Event: Lasers and Applications in Science and Engineering, 2004, San Jose, Ca, United States

Mixed type I and II BBO OPO pumped at 355nm provides good beam quality, bandwidth and efficiency

Sheng Wu, Vadym Kapinus, Geoffrey A. Blake

Division of Chemistry and Chemical Engineering, Caltech 139-74, Pasadena, CA 91125

ABSTRACT

For ns 355nm pumped simple type II BBO OPOs, two problems still remain even after rotated cavity design 1,2. The first problem is that the efficiency is still low. The other problem is the requirement of adjusting the waveplate inserted in the rotated cavity during the wide tuning range. Here, we propose and demonstrate a simple prism rotated cavity¹, which uses both a type I and a type II BBO crystals pumped at 355nm.

Keywords: mixed type I & II BBO OPO

1. Introduction

Nano-second BBO OPO pumped at 355nm continue to receive attention because such OPO could provide broad tunability from deep blue (~400nm) to Mid-IR (3000nm). However, there are some limitations of simple FP cavity BBO OPO device --- for type I BBO OPO, although the efficiency is high and consistent throughout the complete tuning range, the bandwidth is too wide and especially when the wavelength is tuned close to degeneracy; for type II BBO OPO, the bandwidth is consistently narrow over the complete tuning range, but the efficiency drops quickly when tuned to degeneracy and the divergence in the non-phase matching plane becomes very large.

Typical type I BBO OPO efficiency pumped at 355nm, pump energy is 135mJ and over 50% efficiency is possible.

Typical type I BBO OPO bandwidth --- increases to 10s nm at degeneracy

Typical efficiency of a 355nm pumped type II BBO OPO with SHG, note the drop in efficiency when the wavelength approaches the degeneracy (710nm).

The bandwidth of a type II BBO OPO pumped at 355nm could be as narrow as 1cm^{-1} (see the insert). The photoacoustic spectrum of NH_3 shows features under 1cm^{-1} .

Figure 1. typical bandwidth and efficiency curves for type I and type II BBO OPO pumped at 355nm

To overcome the large divergence problem in type II OPO cavities (for both BBO and KTP crystals), Smith et al.^{1,2} proposed and demonstrated that if the type II OPO cavity's resonant wave is rotated 90 degrees geometrically, and the polarization is also rotated 90 degrees with waveplate, then it is possible to significantly reduce the divergence.

This rotated OPO cavity reduces the divergence successfully, but it also introduces extra loss. It works well for KTP crystal because KTP has rather large Deff coefficients in the complete tuning range when pumped at 532nm, but for 355nm pumped type II BBO OPO, the extra loss further limit the efficiency of the type II BBO OPO when the wavelength is tuned to degeneracy.

Here, we propose and demonstrate a simple prism rotated cavity¹, which uses both a type I and a type II BBO crystals simultaneously when pumped at 355nm. We hope that this cavity could improve the efficiency of a type II BBO only OPO, while maintaining the narrow divergence and bandwidth of the type II BBO only OPO.

2. Experimental setup

Figure 2a-2d shows the schematics of the original FP type II only OPO cavity³, the type I only OPO cavity, the rotated type II OPO cavity² and the mixed type I and type II BBO OPO cavity tested here.

In figure 2a and 2b, the rear mirror of the FP cavity is a simple broadband reflective mirror. The type I or type II crystals are rotated inside the FP cavity, and if two crystals are used, they rotated in a counter rotation fashion that cancels the walk-off and refractive displacement.

In figure 2c, the rear mirror of the FP cavity is replaced with a right angle prism (RAP) rotated at 45 degrees from the orthogonal direction, and therefore the resonant wave is rotated 90 degrees. The polarization of the resonant wave, however, is entangled by the RAP, and an additional waveplate is needed to correct the polarization entangle in order to optimize the efficiency.

In figure 2d, is the mixed cavity tested here. The principle is given below.

Figure 2a. Schematic of the original type II BBO only OPO cavity³, the polarization of the 355nm pump is horizontal.

Figure 2b. Schematic of the type I BBO only OPO cavity, with only the type II BBO crystals now replaced by type I BBO crystals and the polarization scheme is now changed.

Figure 2c. Schematic of the type II BBO only OPO cavity with the resonant wave rotated at 90 degrees.

Figure 2d. Schematic of the mixed type I and type II BBO OPO cavity.

2.1. Working principle of a mixed type I and type II BBO OPO cavity

- Pump beam will have horizontal polarization, and pass through a type I and type II crystal both have vertical rotation axis, i.e. horizontal phase matching direction.
- Broadband idler radiation generated by type I crystal will have vertical polarization , and after passing through the RAP prism and reflected back, it will have horizontal polarization, and will only have a narrow band of the radiation amplified **when** passing through the type II crystal, which has a narrow bandwidth of acceptance.
- Narrowband idler radiation generated in type II crystal will have horizontal polarization , and after passing through the RAP prism and reflected back, it will have vertical polarization, and only this narrow band will be amplified efficiently when passing through the type I crystal.
- Narrowband and broadband **signal** radiation all have vertical polarization, and after passing through the RAP prism and reflected back, it will have horizontal polarization and could not act as seed for further amplification. Therefore **signal** could not be the resonant wave.

The process works in fashion like below –

- During the first incoming pass of the pump beam, in the type I crystal, broadband (BB) parametric radiation (PD) is generated for both signal with vertical polarization and idler with vertical polarization.
- In the type II crystal, only narrowband (NB) of the BBPD signal from the first type I crystal could only be amplified, all signal have vertical polarization; and this process also generate some NB idler with horizontal polarization.
- At the output mirror, ~95% of the signal and idler in step 2 are lost due to transmission at the output mirror.
- At the type II crystal again, same process of step 2 repeats.
- At the type I crystal, the BB & NB part of signal with vertical polarization and BB idler with vertical polarization also got amplified (there are also some NB idler with vertical polarization generated as a result of the NB part of the signal).

Note now that idler with horizontal polarization part is still purely narrowband (NB).

- At pump input coupler mirror, about 20% of all the signal and about 20% of all the BB idler with vertical polarization are lost (they all have vertical polarization, and experience a ~5% 30° AOI Fresnel loss each surface at the mirror plus loss induced by HR355 coating); and about 5% of the narrowband idler with horizontal polarization are lost due to HR355 coating.
- After the RAP prism, all the remaining BB signal now have horizontal polarization which are no longer useful for parametric amplification when passing through the type I and II crystals, and they experience another 95% loss at the output coupler and another 30% loss at the pump input coupler (pass twice as p-polarized and twice as vertical polarized $0.70 * 0.05 * 0.70$ only ~2% left for the BB signal) before they have the correct polarization for amplification in type I crystal again. *We hope that such BB loss could suppress the BB power.* If necessary an optional long pass filter in front of the RAP could be added to completely block the signal.
- After the RAP prism, all **remaining** BB idler now has horizontal polarization. There is only ~10% loss at the pump input coupler mirror, but there is no amplification in the type I crystal because the polarization does not match in type I crystal. Now only a NB of the BB idler could be amplified in the type II crystal due to its small acceptance of bandwidth, generating also NB signals with vertical
- polarization, and after transmission loss at the output mirror, only the NB of the idler and signal could be amplified in the type II crystal again and the returning NB signal could also get amplified efficiently in type I crystal, generating NB idler and signal with vertical polarization. While ~95% of the BB idler are lost due to transmission at the output mirror and experience no amplification in the returning trip. *This process only amplifies NB idler in the type II crystal and also NB signal in the type I crystal, while suppress BB idler (also about 2% left after round trip before seeing amplification again).*
- And after RAP prism, all the *pure NB idler now have vertical polarization*, after 20% loss at the pump input coupler, they now could be amplified in the type I crystal, and also generate lots of NB signal. Then in the type II crystal, only the NB signal generated in type I crystal could be further amplified, generating more NB signal with vertical polarization and NB idler with horizontal polarization. *In this process only more NB idler and signal are amplified.*

Seems that this design could generate NB radiation efficiently in the type I and type II crystals, while suppress BB radiation (with 2% left for each round trip). 90-degree image rotation also reduces the divergence of the type II only OPO and therefore only output with circular small divergence is generated. The downside is that the idler polarization purity will be compromised ---- vertical vs. horizontal ~ gain difference between the type I and type II (for the same crystal length, it is about 1.5:1 in the blue to 9:1 in the red); and the signal's polarization will also be compromised to some extent --- vertical vs. horizontal ~ 40:1 (2~3%, $5\% * 0.7 * 0.8$).

However, there is a complication when we consider the polarization entanglement because of RAP used to rotate the polarization of the resonant wave. At the each face of the total internal reflection, because the polarization is not orthogonal to the surfaces, the phase delay for each polarization is not integers of π , and therefore the polarization after the RAP is entangled. Figure 3 shows the polarization rotation simulation for different wavelength wave after RAP 90 degree rotation.

Because of this entanglement, it is still necessary to include a half waveplate in order for the above scheme to work for the mixed crystal OPO cavity.

Figure 3. Polarization rotation for a lightwave passing through the RAP which rotates the wave by 90 degrees, the two legs of the RAP is coated with Al metallic coating.

2.2. Test setup

We tested the above system with a pump laser which pumps out 135mJ at 355nm, it operates in both seeded and unseeded mode. The mixed OPO cavity uses one piece of type I BBO crystal of length 15mm, and one piece of type II BBO crystal of length 12mm. The bandwidth of the OPO is measured with a Burleigh WA4500 wavemeter which has two resolution modes. Unfortunately, the wavemeter's modes do not measure the bandwidth well when the bandwidth is around 1cm-1, which our mixed OPO cavity or a type II only OPO cavity is supposed to produce when the pump is seeded. So, the ultimate resolution has to be verified with another etalon, or with real spectrum test. However, based on the past results of type II only cavity, we are able to make some preliminary conclusion about the results from the wavemeter.

3. Results and Discussion

3.1. Oscillation characteristics

We expect that the OPO will not operate when the type I and type II crystals are tuned to different gain wavelength positions, even when the pump intensity is quite high. Without a waveplate before the RAP, the oscillation threshold of the cavity when the two crystals are detuned is indeed much higher than the type I BBO OPO cavity with a flat reflective mirror --- about 3~4 times higher. However, it still lases when the pump intensity is strong enough, and the output beam quality is quite poor (divergence is larger) when compared to a type I OPO cavity with flat rear mirror. The poor quality is a result of the polarization entanglement.

When a waveplate is inserted in front of the RAP and tuned to the right angle, we are able to completely shut down the type I BBO crystal oscillation even when the pump intensity is about 6 times the operation threshold of a type I BBO cavity with flat rear mirror. Then, we the type II BBO crystal is tuned to match the gain band with the type I crystal, the cavity lases again --- confirming the design principle of the mixed OPO cavity.

3.2. Bandwidth characteristics

The bandwidth of the mixed OPO cavity follows the principle proposed above, even when the waveplate is not inserted. Figure 4 shows the bandwidth at 670nm when the pump laser is unseeded and seeded. The unseeded bandwidth is close to 4cm^{-1} , which is similar to a type II only cavity. The seeded bandwidth is shown to be 2cm^{-1} , but the actual bandwidth is expected to be close to 1cm^{-1} based on past experience with a type II only cavity.

Figure 4a. The bandwidth of the mixed cavity when unseeded.

Figure 4b. Bandwidth of the mixed cavity when pump is seeded.

3.3. Beam divergence characteristics

The divergence of the mixed OPO cavity is also reduced significantly in the non-phase matching plane, which used to be fast expanding when approaching the degeneracy. Figure 5 shows the image of the signal and idler at 701nm and 719nm, the distance is 2 meters from the output. We see that the divergence is reduced, and the majority of the energy is concentrated in the round center beam. The divergence is estimated to be around 0.5mrad in both directions. Note that this image is taken without the waveplate, and therefore there is the scattered background beams which has large divergence. But, the intensity is much weaker.

Figure 5. Beam shape taken at 2m at 701nm signal.

3.4. Efficiency

The efficiency of the mixed cavity is also improved, we could now easily cover 710nm degeneracy with usable amount of energy and since the divergence is reduced by more than an order of magnitude, the usable band of the mixed OPO could now easily cover the complete range. Figure 6 shows the typical energy output of the mixed OPO cavity.

Figure 6. Relative energy output of the mixed OPO cavity

4. Discussions

The above results confirms the principle of the mixed cavity that we proposed. However, there is still the need to use the waveplate because of the polarization entanglement. The above results for bandwidth, divergence and relative energy are taken without a waveplate. We will present results when the waveplate is used.

5. Conclusions

We observed narrow bandwidth across the tuning range --- the same as a simple type II BBO OPO, i.e. $\sim 4\text{cm}^{-1}$ when pump is unseeded and $\sim 1\text{cm}^{-1}$ when seeded. We also observed improved efficiency, small divergence and circular output beam. We could now easily cover the 710nm $\sim$ 630nm range where before type II BBO OPO have low efficiency and large divergence^{2,3}. The divergence is as narrow as 1mrad for unseeded pump and 0.5mrad for seeded pump laser. These parameters match those for dye lasers.

The added benefits also include easy calibration of tuning wavelength and no extra components except the two crystals that need rotation in the complete tuning range.

REFERENCES

1. Darrell J. Armstrong and Arlee V. Smith, Demonstration of improved beam quality in an image-rotating optical parametric oscillator OPTICS LETTERS Vol. 27, 40-42, (2002)

2. G. Anstett, G. Göritz, D. Kabs, R. Urschel, R. Wallenstein, A. Borsutzky: Appl. Phys. B Reduction of the spectral width and beam divergence of a BBO-OPO by using collinear type-II phase matching and back reflection of the pump beam 72, 583–589 (2001)
3. S. Wu, G.A. Blake, Z. Sun, J. Ling, Simple, high-performance type II b-BaB₂O₄ optical parametric oscillator Appl. Opt. 36, 5898 (1997)