CHAPTER 3

SECOND HARMONIC GENERATION

The OPOs described in this dissertation are pumped by the second harmonic and fourth harmonic radiation of a pulsed Nd:YAG lasers. This chapter covers the second harmonic generation of the fundamental 1064nm radiation. D-CDA and KD*P crystals were used in frequency doubling the supergaussian and multimode output of Nd:YAG lasers. The properties of the nonlinear crystals as second harmonic generators are compared and the beam qualities of the radiation are investigated for efficient pumping of a BBO parametric oscillator. In this work it was found that the beam of the fundamental radiation has to be nearly Gaussian or Gaussian before oscillation in BBO can be observed.

3.1 Review of SHG in Nonlinear Crystals

The first second harmonic generation experiment was performed by Franken et al[1] in 1961 using a ruby laser beam at 694.3 nm that was focused onto the front surface of a crystalline quartz plate emitting an ultraviolet output at 347 nm. The basic result is the demonstration of nonlinear behaviour of the optical material when being subjected to a very high intensity laser beam.

3.1.1 SHG Phase Matching

Phase matched SHG can be achieved in birefringent crystals with an appropriate choice of input beam polarization, direction of polarization and crystal temperature [2,3]. As described in the previous chapter , the two types of phase-matching are referred to as type I and type II phase-matching. For type I phase-matching in negative crystals the propagation direction in the crystal must be at a phase-matching angle θ such that

$$n^{e}_{2\omega}(\theta) = n^{o}_{\omega} \qquad (3.1)$$

For type II phase-matching, a negative birefringent crystal obeys the relation

$$n^{e}_{2\omega}\,(\theta) = (\, n^{e}_{\omega}\,(\theta) + n^{o}_{\omega}\,)\,/\,2 \qquad (3.2)$$

For negative uniaxial crystals such as D-CDA and KD*P, the second harmonic output is always polarized as an e-ray for both types of phase-matching processes. The phase-matched generation of second harmonic radiation can be accomplished by angle tuning or temperature tuning of the nonlinear crystal. In our experiments the tuning of the crystal was performed by adjusting the angle with respect to the fundamental beam.

3.1.2 Output Efficiency

In the regime of small signal gain, the output power of the second harmonic beam is proportional to the input powers. The efficiency of second-order frequency conversion is determined to a large extent by the optical parameters of the nonlinear crystal like the effective nonlinear coefficient, the walk-off (discussed further in section 3.3), the acceptance angle, temperature or angle dependence of the birefringence and the damage threshold . KDP isomorphs are excellent generators for situations involving small peak powers or multi-mode power with high conversion efficiency [11]. D-CDA and KD*P are the two most popular frequency doubling crystals for 1064 nm Nd:YAG lasers. KD*P crystals are excellent second harmonic generators for fundamental beam of Nd:YAG lasers with high peak power and beam quality of TEM_{00} mode. For conversion of low peak power radiation, as in the case of continuous wave (CW) Nd:YAG lasers, and poor fundamental beam quality , D-CDA is normally preferred. D-CDA has a wider acceptance angle and works well with multimode beams. Both D-CDA and KD*P are negative uniaxial crystals,crystallizes in the tetragonal system, space group 42m and is isomorphous with KDP. D-CDA is very hygroscopic compared to KD*P. It has a moderate birefringence (0.016) at 1064 nm and due to its low dispersion angle it allows type I SHG. Phase-matched angle is 81^0 for D-CDA, 37^0 (type I) and 53.5^0 (type II) for KD*P [2,6] .

3.2 Experimentation

D-CDA and KD*P crystals were both used to generate the second harmonic from 1064 nm output of a Q-switched multimode Nd:YAG laser. The multimode fundamental beam is supplied by a Lumonics HY600 laser capable of generating maximum output power of 1.2 J at 8 ns pulse duration.

The divergence of the beam is 1 mrad. Fig. 3.1(a) shows the schematic setup for the observed SHG using KD*P which was later replaced with the D-CDA crystal. The KD*P crystal comes from Quantum Technology, U.S.A and the D-CDA from Lumonics Ltd., U.K. Dimensions of the KD*P crystal is 10 x 10 x 30 mm^3 and was placed on a rotary mount enabling rotation about the X or Y axis. The crystal axis was adjusted to be at 45^0 to the vertically polarized input beam. Tuning of the crystal about the horizontal axis produced maximum SHG output at the phase-matched angle. The fundamental 1064 nm was separated from the output using a Pellin Broca prism placed after the crystal. A Gentec MP 310 power meter measures the 532 nm beam generated by the KD*P crystal. The same set-up was used for the SHG measurement with the D-CDA crystal. The crystal has dimensions of 10 x 10 x 25 mm^3. A 1064 nm absorptive filter after the output of the second harmonic crystal was found not effective in blocking the infrared. Therefore a pair of dichroic mirrors with reflectivity at 532 nm and transmittance at 1064 nm was added to the experimental set-up.

SHG of KD*P crystal (Quantel SA, France) was also performed with a supergaussian beam from a Quantel Nd:YAG laser (YG-780). Supergaussian profiles, which are bell-shaped and considerably flatter in the centre than a Gaussian curve are obtained with resonators using variable reflectivity mirrors. This type of resonator substantially increases the mode volume in the active laser medium while at the same time preserving good diffraction and propagation properties of the output beam [13]. The Q-switched system generates 6 ns pulses of 1064 nm radiation with energies up to 140 mJ. Divergence of the supergaussian beam is 0.5 mrad. The 25 mm long crystal was mounted on a motorized stage and rotated every 0.1^0 over the phase-matching angle. The experimental set-up is as shown in Fig. 3.1(b). A infrared filter which blocks the 1064nm fundamental radiation and allows the 532nm beam to pass through was placed in the path of the output. Neutral density filters were used for attenuation of the input power incident on the crystal. Conversion efficiency was calculated from the measured pulse energies of the 532 nm output.

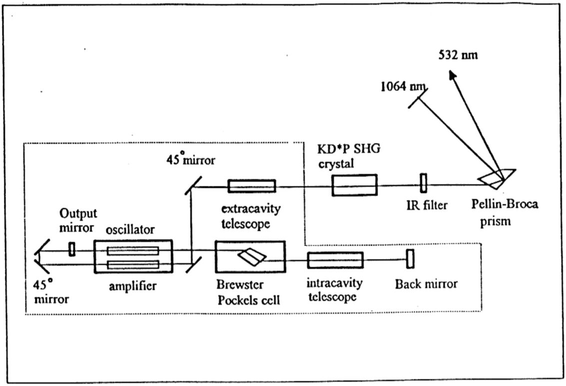

Fig. 3.1(a) Schematic diagram of the experimental setup for SHG in KD*P using a multimode Nd:YAG laser source.

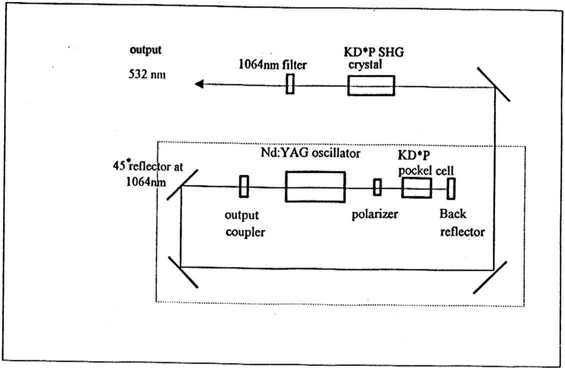

Fig. 3.1(b) The experimental setup for SHG in KD*P using a supergaussian 1064nm radiation of a Nd:YAG laser.

3.3 Results and Discussion

Fig.3.2 shows the measured second harmonic power as a function of external angle of the KD*P crystal pumped with the multimode source. Comparison with the results obtained using D-CDA (Fig.3.3) shows smaller angular mismatch in KD*P. This mismatch is due to the angular divergence from the phase-matched direction. Smaller mismatch is advantageous in type II SHG over type I SHG because angular alignment and thermal control becomes less critical. Double refraction and angular acceptance in the nonlinear interaction need to be considered in phase matching. An extraordinary wave propagating in a crystal is doubly refracted at an angle from its phase velocity direction. This angle φ , known as the walk-off angle can be calculated from the formula [3]

$$\varphi = \tan^{-1} \left[(n^{o}_{\omega}/2) \{ (n^{e}_{2\omega})^{-2} - (n^{o}_{2\omega})^{-2} \} \sin 2\theta_m \right] \qquad (3.3)$$

where θ_m is the phase matching angle.

The half angular acceptance width inside the nonlinear crystal of length l is given by

$$\delta\theta = \lambda_{\omega} / l (n^{o}_{2\omega} - n^{e}_{2\omega}) \sin \theta_m \qquad (3.4)$$

The external acceptance angle is therefore

$$\delta\theta_{ext} = n_{\omega}\, \delta\theta \qquad (3.5)$$

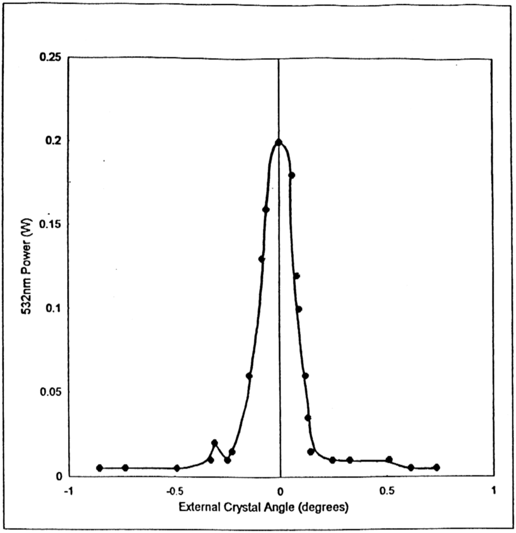

Fig. 3.2 The 532nm second harmonic output as a function of the external crystal angle showing angular mismatch from the phase matching condition in KD*P.

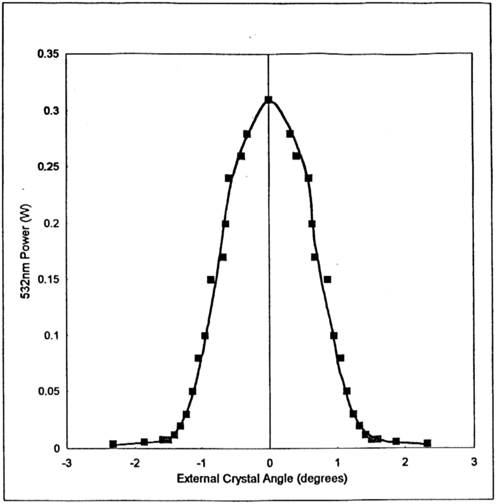

Fig. 3.3 The second harmonic output as a function of the external crystal angle for D-CDA.

Using the formula, the calculated acceptance angle of the D-CDA is 10.8 mrad with beam walk-off of 2.4 mrad. A walk-off angle of 17 mrad and acceptance angle of 1.4 mrad was calculated for the 30 mm long KD*P doubler. Angular acceptance of the D-CDA is about six times greater than that for KD*P (type II) crystal of the same length [6]. This large angular acceptance in D-CDA permits beam focusing with expected improvement in SHG efficiency. It also makes this crystal more suitable for SHG of a multimode high power radiation.

Maximum 532 nm energy of 20 mJ was achieved in the type II SHG with KD*P. The fundamental 1064 nm input energy at this phase-matched angle is 190 mJ. Power density of the fundamental wavelength was restricted to 0.17 GW/cm^2 as not to damage the crystal whereas higher output was observed with D-CDA as the input intensity was increased up to 0.46 GW/cm^2. Relation of the second harmonic output and fundamental input energy is almost linear for both KD*P and D-CDA as plotted in Figs. 3.4(a) and 3.4(b) respectively. Lower threshold of ~5 mJ was obtained in our experiment with D-CDA compared to a value of ~20 mJ in KD*P. The SHG energy curve clearly shows proportionality of input and output at low conversion limit. Fig.3.5(a) and 3.5(b) gives the energy conversion efficiency as a function of input power density for KD*P and D-CDA respectively. Conversion efficiency of about 30 % was calculated for D-CDA with the maximum output energy of 160 mJ at 520mJ pump energy.

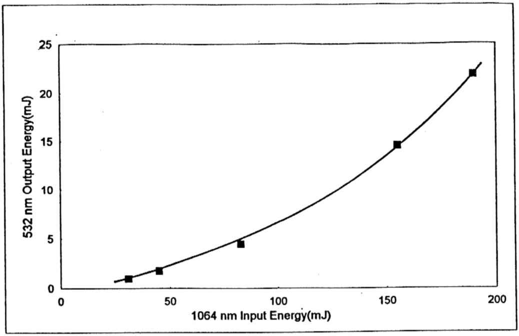

Fig. 3.4(a) Dependence of output energy to the fundamental energy of a multimode laser for KD*P.

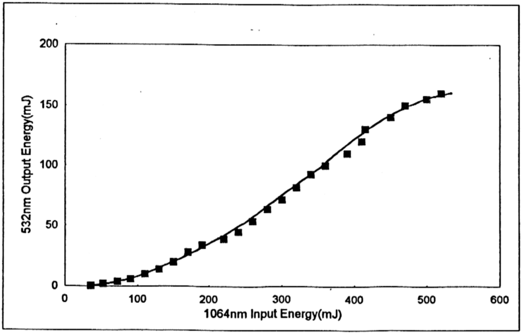

Fig. 3.4(b) Dependence of 532nm output energy to the 1064nm pump energy of a multimode laser radiation for D-CDA.

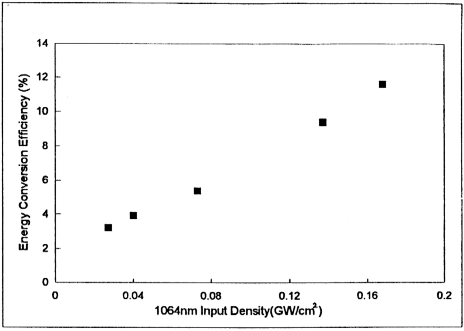

Fig. 3.5(a) Conversion efficiency curve for SHG of a multimode 1064nm radiation using KD*P.

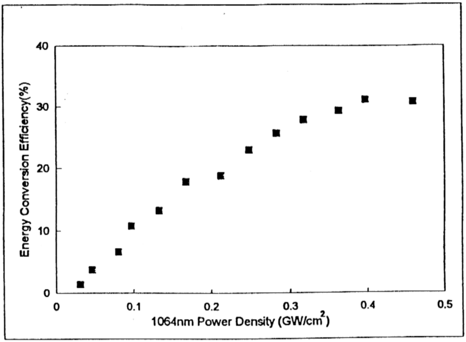

Fig. 3.5(b) Conversion efficiency for SHG of a multimode radiation using D-CDA crystal.

Efficiency of ~12% was obtained for KD*P, less than the 18% efficiency obtained for D-CDA at the same input energy of 190mJ. This indicates that D-CDA is relatively more efficient and suitable for frequency doubling of high power radiation with multimode beam quality because of its higher angular acceptance than KD*P. Focusing of the beam is permissive for further improvement in the harmonic efficiency. The main disadvantage in using D-CDA doubler is that it is very hygroscopic and therefore requires an oven to keep it at a constant temperature, that is about 60^{0}C.

Using the supergaussian output of a Q-switched Nd:YAG laser in a type II SHG KD*P, angular mismatch was smaller (see Fig. 3.6) when compared to the SHG of the same process using the multimode fundamental beam. SHG in KD*P in this experiment produced higher 532 nm output and greater energy conversion. Fig. 3.7(a) shows the relation of input and output energies with threshold energy of 10 mJ. Maximum output of 145 mJ was achieved with the crystal in the phase-matched direction. Conversion efficiency of 44 % was obtained with an intensity of 0.28 GW/cm^2 as shown in Fig. 3.7(b). The SHG efficiency is higher in KD*P using a supergaussian beam compared to using a multimode source, with no degradation in beam quality. The variable reflectivity coating of the output coupler provides a greater mode overlap efficiency with the active laser medium and the output having a nearly Gaussian profile. The supergaussian profile, being in shape somewhere about half way between rectangular and Gaussian, combines the advantages of both profiles. The soft smoothing of the tails avoids the build up of pronounced diffraction while the main portion of the beam diameter is at almost constant intensity resulting in a wide overlap with the gain medium and consequently an efficient energy extraction [13].

We have compared the frequency doubling characteristics of D-CDA and KD*P in terms of mode structure, beam divergence and acceptance angle dependence. D-CDA is shown to be more suitable for SHG of a multimode radiation but SHG of a supergaussian source in KD*P produced a conversion efficiency which is about 26% higher than the former. This is one of the reasons we chose to pump a BBO OPO with the second harmonic of the supergaussian source besides the mode and beam quality that this type of resonator provides.

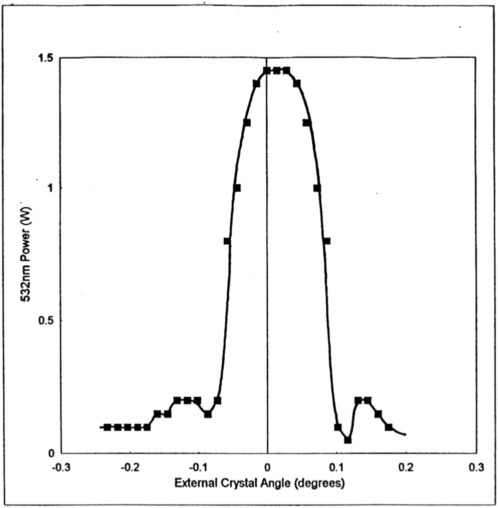

Fig. 3.6 The second harmonic output as a function of the external crystal angle in KD*P SHG of a supergaussian fundamental beam.

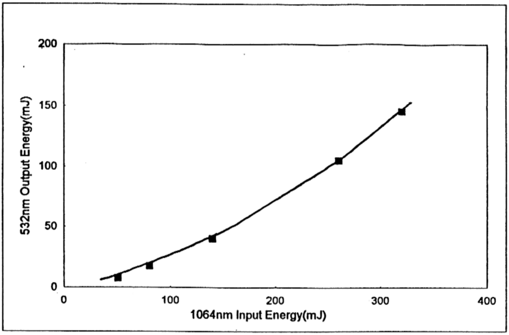

Fig. 3.7(a) Dependence of second harmonic output to input energy for KD*P SHG of 1064nm supergaussian source.

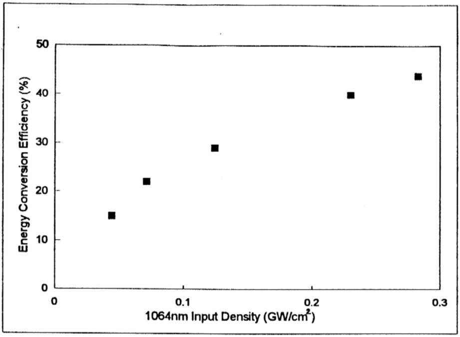

Fig. 3.7(b) Conversion efficiency curve for KD*P SHG of a fundamental supergaussian laser source.

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