CHAPTER 4

532nm PUMPED BBO OPO

Beta barium borate (BBO) has a small acceptance angle which places stringent requirement on the beam quality of the pump source. For oscillation to be observed in BBO crystal, the beam quality should be Gaussian or close to Gaussian profile. Angle tuning of OPOs has been shown to produce a wide spectrum in the entire visible and near-IR region $^{1,3,4}$. This provides an added advantage over temperature tuning in terms of implementation and design. In most cases, conversion efficiency has been limited by the low damage threshold of OPO mirrors. The first observation of BBO optical parametric oscillation was demonstrated by Chen et.al $^1$ using a 532nm pump wavelength from a Q-switched Nd:YAG system at energy of 25mJ with pulse duration of 18ns. The output of the system was about 3mJ with pulse duration of 12ns, and in their experiments the damage threshold was also determined and found to be 7.0 GW/cm$^2$ at the second harmonic wavelength. Further improvement is being made by developing higher quality crystals.
4.1 Straight Cavity Pumping

4.1.1 Experimental Arrangement

The BBO used, manufactured by CASIX, had dimensions of 4x4x12 mm$^3$ and cut at 21$^\circ$ for operation with a pumping source at 532nm. The tuning range of this OPO crystal is between 680nm - 2600nm for the signal and idler waves when pumped at 532nm. In our experiments, the tuning characteristics of the signal wave was carefully studied. The idler waves complements the tuning range of the signal waves in the far infrared but this cannot be investigated at present due to equipment limitations. A Q-switched Nd:YAG laser (Quantel YG-780) with maximum average power of 20 W was employed as the pump source.

The OPO cavity was constructed with two plane mirrors spaced 1.6cm apart. The reflectivities of the mirrors were 99.9% at 694.3nm which also acts as the back mirror of the OPO cavity and the output mirror has 80% reflectivity at the same wavelength. These were the existing Ruby laser mirrors which is available in the laboratory. The experimental setup is shown in Fig. 4.1. The crystal was mounted on a rotary mount with resolution of 5 mins of arc. The BBO was heated to a temperature of about 41°C using a home-made oven prevent deterioration of the crystal quality due to the effect of humidity. Fig. 4.2 is a photograph taken of OPO cavity. Tuning was accomplished by rotating the stage manually. Deviation of the alignment beam at a distance of 49cm from the end face of the crystal allowed us to calculate the external crystal angle. With the known refractive index of the
crystal at the pump wavelength and the external angle, the internal crystal angle can be calculated using Snell's law.

The diameter of beam output from the pump laser was reduced to 2mm to increase the beam intensity of the pumping source. This was done by having a telescope system before the cavity. The Galilean telescope design was used as to reduce telescope length and it comprised of a convex lens and a planoconcave lens of 30mm and 10mm focal lengths, respectively. The OPO was operated with maximum pump energy of 40mJ at a repetition rate of 10Hz. The pump energy was carefully chosen not to exceed 40mJ as not to damage the crystal and this was obtained by having absorbing neutral density filters at the output of the pump source. Fig. 4.3 presents a photograph of the OPO pumping at 532nm second harmonic radiation. Energy measurements of the input pump beam and the output of the OPO were taken using a Ophir NOVA power meter. The output wavelengths of the OPO were measured with a Lamda LS2000 optical multichannel analyser (OMA). This instrument which was fixed to a PTI monochromator enabled us to observe the change in wavelengths as the BBO crystal is tuned over different angles. Pulse shapes of the 532nm and OPO output were obtained by using a fast photodiode (FND-100, EG&G) together with a 2GSa/s digitizing oscilloscope (HP54510A) with input amplifier bandwidth of 300MHz. The overall system provides a system risetime of 1.7ns. The risetime of the FND photodiode is about 0.5ns and the
Fig. 4.1. Schematic diagram of the experimental setup for 532nm pumped BBO optical parametric oscillator
Fig. 4.2  Photograph of the OPO cavity. The BBO crystal is placed in an oven to keep the crystal at a constant temperature.
Fig. 4.3  A photograph showing OPO pumping at 532nm.
system risetime is limited by the input amplifier of the oscilloscope. However, no serious pulse distortions were observed in the measurements.

4.1.2 Results and Discussions

Initial measurements showed peaks at different wavelengths as the BBO was tuned over a small angle. The crystal was rotated every 5 mins of an arc through 2.0° at pump energy of 15mJ. Results obtained on the OMA as presented in Figs. 4.4(a) and 4.4(b) clearly shows the wavelength range between 680nm-740nm and 730nm-790nm at different tuning angles, with the set of 694.3nm cavity mirrors. These results are shown in two separate ranges because light that enters the monochromator as a point source is dispersed by the grating (1200 lines/mm) and is reflected towards a Photodiode Charge Coupled Device (PCCD) which has a small active surface width of 28.7mm. The PCCD has 2048 pixels that are optically sensitive for light detection and each pixel is 14x300μm in size. Fig. 4.5 shows the tuning curve for the 532nm pumped BBO optical parametric oscillator. Wavelengths spread from 680nm to 790nm were produced over the internal angular range of 0.7° and 2.1°. The photograph in Fig. 4.6 clearly shows the OPO output at these wavelength range. The wavelength range obtained was limited by the reflectance of the mirrors used. A wider spectrum from as low as 680nm to infrared could be achieved with BBO by employing different sets of cavity mirrors.
Fig. 4.4(a) The peaks of the OPO output as the rotary stage was rotated with respect to the input beam direction. The tuning range shown is from 680nm to 740nm.
Fig. 4.4(b)  OPO tuning wavelengths from 745nm to 790nm.
Fig. 4.5  Tuning curve of the OPO with 694.3nm cavity mirrors over the internal crystal angles between $0.7^\circ$ and $2.1^\circ$. 
Fig. 4.6  The photograph showing the OPO output within the wavelength range tuned.
Output energy as a function of input energy is shown in Fig. 4.7. Different neutral density filters were used for variation of the input energy. Threshold is 13.5mJ with slope efficiency of about 1%. This confirms the low energy requirement needed for parametric oscillation in BBO. Also measured in the experiment was the delay between the peak of the 532nm pump pulse and the peak of the OPO pulse. Fig. 4.8 shows the oscilloscope traces of both pulses. From this, the buildup time was found to be 1.9ns. The pulsewidth of the OPO output was 4 ns, shorter compared to the input pulsewidth of 8 ns. Compression of the parametric pulse is because of the number of round trips in the cavity necessary to reach oscillation threshold. The number of round trips was found to be approximately 50 per pulse for a path length of 23.9mm. The output pulsewidth could be reduced by the use of shorter cavities.
Fig. 4.7  Output energy as a function of input energy for the output coupler with 80% reflectivity at 694.3nm.
Fig. 4.8 Oscilloscope traces of the (i) 532nm pump pulse and (ii) OPO pulse.
4.2 Parametric Oscillator With Pump Reflection

Singly resonant oscillators (SROs) whereby only the signal or idler wave resonates (as described in 2.4.3) are more stable than doubly resonant oscillators (DROs) at relatively poorer beam quality. DROs require ideal coherent pump sources for efficient operation. In addition to DROs and SROs the OPO cavity can be extended for a round trip pump wave. Reflecting the pump wave back into the nonlinear crystal could reduce threshold and a higher conversion efficiency would be obtained. In this work a singly resonant BBO OPO is used and results from both single-pass and double-pass configurations are compared.

4.2.1 Experimental setup

A 10mm long BBO crystal was pumped with the second harmonic of a Nd:YAG laser. Fig.4.9 is the schematic diagram of the experimental setup. M₁ and M₂ are flat mirrors that constitute the cavity which was 20mm in length. The reflectivities of the mirrors were 99.9% at 850nm and 80% at 850nm, respectively. M₃ is a flat mirror with maximum reflectivity at 532nm and high transmission at the output wavelength. This mirror was used to return the undepleted portion of the pump beam back into the crystal. The pump beam diameter at the input face of the crystal was measured 2mm corresponding to a maximum intensity of 0.4GW/cm² for this experiment.
Fig. 4.9  A schematic representation of the experimental setup for the BBO OPO with pump reflection.
4.2.2 Results and Discussion

Tuning was achieved by rotating the crystal with energy measurements taken for output at a wavelength of 808nm. The peak at this particular wavelength was detected using an optical multichannel analyser and the energies were measured using a Quantel MP310 power meter. Fig. 4.10 shows the tuning range between 795nm and 895nm. Without the pump reflector, the threshold was found to be 17mJ. Lower energy threshold was attained with mirror $M_3$ placed about 11cm away from the output coupler. With the double-pass configuration the threshold was found to be 12mJ. Fig.4.11 shows the relation between pump energy and output energy of the OPO at 808nm. This result was verified by using the relationship of SRO threshold with power reflection coefficient for the pump beam which is given as

$$P_{th}(R) = \frac{[R_{th}(R=0)]}{(1+R)}$$

where $P_{th}$ is the pump threshold and $R$ is the power reflection coefficient for the pump wave. With mirror $M_3$ we assumed $R=100\%$. Without $M_3$, $R=38\%$. From this it is calculated that

$$\frac{P_{th}(R=100\%)}{P_{th}(R=38\%)} = 0.69$$
Fig. 4.10  The spectral range obtained with the OPO using cavity mirrors reflecting at 850nm.
Fig. 4.11  Plot of energy output and input for a single-pass and a double-pass cavity.
Our measurements of threshold energies for two different configurations give the ratio value 12mJ/17mJ = 0.71 which is consistent with our calculation. Although mirror $M_3$ proved efficient in reducing the pump threshold and achieving a relatively higher conversion efficiency, the conversion efficiency is still below 10%. This could be due to the supergaussian beam quality, which is truly not a TEM$_{00}$ beam and output wavelength that did not coincide with the peak reflection band of the cavity mirrors. Nonetheless, our measurements showed that the further extension of the two mirror OPO cavity produced significantly better results.

The pump pulse duration was found to be 8ns and the output pulse was half this duration, that is 4ns. This measurement was taken for a low pump energy of 17mJ and the output wave pulsewidth is expected to increase with increased pump energy $^{10}$.

The output energies for different cavity lengths were also measured. These were done with mirror $M_3$ inserted in the configuration. Lowest threshold is obtained using the shortest cavity. Fig.4.12 is a plot of the output and input energy for three different length cavities. Threshold values increased with longer cavities.

A more efficient 532nm pumped BBO OPO has been demonstrated by extension of a SRO cavity with pump reflection compared to a normal two mirror cavity.
Fig. 4.12  Compared energy curves for different cavity lengths.

Lowest threshold was obtained with the shortest cavity.
4.3 OPO Design With Intracavity Pump Steering Mirror

This section presents a novel cavity design with a pump steering mirror inside the cavity. This cavity greatly reduces the severe requirements placed upon conventional, straight OPO cavity mirrors, with applicability to other OPOs.\(^{14}\)

4.3.1 Cavity Configuration

The pump pulse was obtained from the same Nd:YAG laser used in the previous experiments. The configuration consisted of a pump steering mirror, introduced into a conventional OPO cavity and set at Brewster's angle with respect to the cavity axis, as shown in Fig. 4.13. Bosenberg et al.\(^{14}\) used a pair of pump steering mirrors for fourth harmonic pumping of their BBO OPO. The pump steering mirror is a standard, 532nm, 45° incidence, high reflector (\(\sim 99.9\%\)). This mirror free the cavity mirrors from the requirement of transmitting the intense pump beam. The cavity mirrors used had reflectivities of 99.9% and 80% at 694.3nm. The overall cavity length which is the total spacing between the front and back mirror was measured to be 4.5cm.

Before pumping the OPO cavity, proper and accurate angle measurements had to be taken because the pump beam was not incident on the input mirror but on the 532nm pump steering mirror. This is shown schematically in Fig. 4.14.
Fig. 4.13  The cavity configuration with an intracavity pump steering mirror.
Fig. 4.14  Angles and propagation direction for beam steering in Brewster's angle 532nm pumped OPO.
4.3.2 Experimental Results

The oscillation threshold, for the unoptimized cavity, was measured to be \( \sim 21 \text{mJ} \) from the plot of output energy as a function of pump energy (Fig. 4.15). The pulsewidth of the OPO output was 3.5 ns., as depicted in Fig. 4.16. Oscillation was observed with output at both ends of the cavity. This is expected in such configuration. The inclusion of the pump steering mirror lengthens the cavity and thereby increases the threshold, but this design is a compromise for damage in conventional cavity mirrors.

Modification of the conventional two mirror cavity has a few other advantages. Using this cavity configuration, no filter is required to separate the OPO output from the pump. Two concave mirrors can be used to obtain a more stable resonator without affecting the collimation of the pump beam. This design eliminates the need for intracavity pump beam shaping optics in synchronously pumped OPO. Furthermore, linewidth narrowing elements, such as gratings, prisms and etalons can be easily placed in the cavity.
Fig. 4.15  Energy measurements for the Brewster's angle pumped OPO cavity. The cavity length is about 4.5cm.
Fig. 4.16  The pulsewidth of the OPO which was found to be 3.5ns.
References to Chapter 4


5. Castech-Phoenix Inc. (CASIX) P.O.Box 1103, Fuzhou, Fujian 350014 P.R.China


