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Tunable intra-cavity SHG of CW Ti:Sapphire lasers around 785 nm and 810 nm in BiBO-crystals

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Abstract: Phasematch curves as well as sensitivity to angular and wavelength misalignment for generation of second-harmonic of 785 nm and 810 nm in BiB₃O₆ crystal was calculated. Measurements were done for intra-cavity CW SHG in a Ti:Sapphire laser. The BiBO crystal was found to be excellent for this application. Temperature dependance was uncritical for both crystals, while power stability was good. Maximum blue output was 53 mW at 392 nm and 100 mW at 405 nm; corresponding to pump-to-blue optical conversion efficiencies of 0.96% and 1.82% respectively.

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1. Introduction

There is a great demand for coherent light sources in the blue (450-400 nm) to UV A (400-320 nm) spectral region. Applications include semiconductor processing, microscopy, and medical technical equipment. Today this spectral region is usually addressed by frequency tripled Nd:YAG lasers, excimer lasers, or gas lasers. However these options only cover a limited number of wavelengths, and it would be preferable to increase the number available. One of the options is doubling Ti:Sapphire lasers, with the possibility of spanning wavelengths from around 325 nm to 525 nm. The scope of this experiment was to test the novel non-linear crystal BiB\textsubscript{3}O\textsubscript{6} (BiBO) in conjunction with frequency doubling of Ti:Sapphire lasers. The BiBO crystal excels by having very high non-linear coefficient – higher than commonly used crystal for frequency doubling to the UV region [1]. In addition BiBO shows good transmission characteristics down to around 286 nm [2]. Until now frequency doubling with BiBO crystal has either been extra-cavity doubling of Ti:Sapphire mode-locked lasers [3, 4, 5], or intra-cavity doubling of CW laser systems at (longer) Nd-wavelengths – SHG of 1064 nm [6, 7], SHG of 946 nm [8], or SHG of 1342 nm [9]. In reference [10] BiBO crystal was utilised for CW SHG of 768 nm in a locked external cavity. The best result for intra-cavity doubling of Ti:Sapphire so far [11] was achieved utilising periodically poled lithium niobate crystals in a uni-directional ring laser to generate 114 mW of power at 403 nm with 4.2 W pump incident at the crystal. However the authors in this reference used a considerably more complicated set-up in a double-bowtie design.

To the best of our knowledge there has been no published references on intra-cavity doubling of CW Ti:Sapphire laser systems utilising BiBO crystal as the non-linear intra-cavity frequency conversion media, except our own [12] where initial results were presented. Here we present calculations on phasematch curves as well as sensitivity to angular and wavelength misalignment for second-harmonic generation of 785 nm and 810 nm respectively BiBO. Tunability, temperature dependance and stability were measured. Maximum blue output was found to be 53 mW at 392 nm and 100 mW at 405 nm; corresponding to pump-to-blue optical conversion efficiencies of 0.96% and 1.82% respectively.

2. Crystal parameters

Utilising the Boyd-Kleinmann equations [13] we calculated the optimal beam waist in the non-linear crystal to be in the order of 15 \(\mu\text{m}\), see table 1. As this was smaller than practical with a standing wave cavity, the set-up was designed to give the smallest possible beam waist at the non-linear crystal position, while maintaining a sufficiently stable set-up and a non-astigmatic beam waist around 60 \(\mu\text{m}\) at the laser crystal position. Walk-off and phasematching angles were estimated utilising the Sellmeier equation given in ref. [2] and the Fresnel equations from ref. [14], with the coordinate system used in ref. [3, 8]. Estimates for optimum beam waist and walk-off as well as crystal data are given in table 1.

A phasematching landscape for doubling of 785 nm using BiBO crystal is shown in Fig. 1. Sensitivity to angular misalignment for crystal 1 is 8.36° FWHM for the \(\phi\)-plane, 0.19° FWHM for the \(\theta\)-plane. For crystal 2 6.82° and 0.12° FWHM for the \(\phi\)-plane and the \(\theta\)-plane respectively. The difference is mainly due to the different lengths of the crystals.
| Crystal | $\lambda_{\text{SHG}}$ | $L \times W \times H$ | $\theta$ | $\phi$ | $\rho$ | $w_{\text{Opt}}$ |
|---------|-----------------|-----------------|---------|-------|-------|-------------|
| 1       | 392.5 nm        | $3 \times 3 \times 3 \text{ mm}^3$ | 149.9°  | 90°   | 61.0 mrad | 12.2 μm     |
| 2       | 404 nm          | $5 \times 3 \times 3 \text{ mm}^3$ | 151.9°  | 90°   | 58.1 mrad | 16.0 μm     |

Table 1. $\theta$ and $\phi$ are phasematch angles at $\lambda_{\text{SHG}}$. $\rho$ is the theoretical walk-off angle. Theoretical phasematch temperature for both crystals are 23°C.

The sensitivity to changes in the wavelength for crystal 1 was calculated, assuming angles and temperature fixed at the design parameters for SHG, to be 2.1 nm FWHM. For crystal 2 the FWHM of the wavelength acceptance was 1.5 nm.

3. Set-up

To achieve the small beam waist size at the non-linear crystal, and a beam waist in the laser crystal of around 60 μm, a 5-mirror W-type cavity was designed, as shown in Fig. 2.

M1 is a plane mirror, highly reflecting (HR) between 680–880 nm and anti-reflecting (AR) at 532 nm. M2 and M3 have similar coatings to M1 but are concave with a radius of curvature of -100 mm. M4 and M5 are HR between 750–850 nm, AR between 375–425 nm, and concave with a radius of curvature of -50 mm. Between M1 and M2 a single plated Brewster-angle
birefringent filter (BRF) allowed for tunability. Between M2 and M3 a beam waist \((V \times H \, 56 \, \mu m \times 65 \, \mu m)\) was formed, wherein a \(10 \times 3 \times 3 \, \text{mm}^3\) Brewster-angled Ti:Sapphire laser crystal, Titanium doping 0.15 atomic percent, was mounted in a water cooled holder. Between M4 and M5 a smaller waist was formed, in which the non-linear crystals were placed. M5 was mounted on a translation stage to be able to adjust the beam waist in the non-linear crystal by changing the length between M4 and M5. Beam waists at the non-linear crystal position were calculated to be in the order of 20 to 25 \(\mu m\). The non-linear crystals were mounted in a temperature controlled holder on a \(\text{XYZ}\phi\theta\) translation stage. The Ti:Sapphire crystal was pumped by a 532 nm laser (Coherent Verdi V-5) through mirror M3. Position and spot size of the pump laser were adapted by means of a periscope and a focusing lens with a focal length of 100 mm, the latter being mounted on a translation stage. To ease the initial alignment an extra plane mirror M6 (partially reflecting between 680-880 nm, transmission 3 %) was placed between mirrors M3 and M4, making a shorter, more easily aligned cavity. The output from this shorter cavity was then used to visually align the mirrors M4 and M5, whereafter M6 was removed from the cavity.

4. Results

Utilising a filter to block any leaking fundamental light from reaching the detector the blue generated power was measured after mirror M4. It was assumed that the power of the blue light generated in each direction was of equal level, thus the measurement data have been multiplied by two and corrected for filter transmission before being presented here. In all measurements the laser was run with the maximum available pump power (5.5 W) – except for the power-slope measurement.

The blue output spot after the out coupling mirror was found to be elliptical even for circular focussing of the fundamental in the BiBO crystal. This is likely caused by the highly anisotropic angular acceptance for the \(\theta\) and \(\phi\) planes together with the tight focussing of the fundamental in the BiBO crystals.

The bandwidth of the fundamental was measured to be 0.85 nm FWHM at 785 nm and 810 nm, with the resolution of the spectrometer being 0.7 nm FWHM.

For crystal 2 the fundamental wavelength was set to 810 nm instead of the 808 nm the crystal was cut for, as the laser was running better at 810 nm. The crystal was then temperature tuned to phase match at 810 nm instead of 808 nm.

4.1. Crystal 1

![Fig. 3. Left: Temperature scan for 785 nm doubling process, optimised at 23 C. Right: Temperature scan for 810 nm doubling process, optimised at 38 C.](image-url)
Tuning the laser to 785 nm a temperature scan of the non-linear crystal was made. Results are shown in Fig. 3 left. We were not able to reach higher output at temperatures higher than 23 C. Temperatures lower than 23 C were not accessible as the mount could not cool the crystal below this temperature. The temperature dependence was found to be low, scanning the temperature a few degrees around 23 C did not lead to a significant change in blue output. FWHM of the measured temperature dependence curve was estimated to be around 60 C, an order of magnitude broader than previously published results [6]. The theoretical value of the conversion efficiency was calculated to be $6.4 \times 10^{-5} \text{ W}^{-1}$, which is close to the maximum measured value of $6.2 \times 10^{-5} \text{ W}^{-1}$ at 23 C. Due to problems measuring the intracavity field through the very high reflecting mirror M1 the measured value is connected with some uncertainty. This result compares favourably to the value measured in ref. [8] ($5.4 \text{ W}^{-1}$), where a 10.4 mm long crystal was utilised for doubling of 946 nm. After resetting the temperature of the BiBO crystal to its design temperature at 23 C a power-slope measurement was done. Threshold for laser action and blue generation was approximately 2.25 W of green pump power. The graph in Fig. 4 shows the generated blue power plotted as a function of the pump power. During this measurement the highest blue generated output at 392 nm was recorded at about 53 mW.

![Graph](image.png)

Fig. 4. Slope efficiency plot of the blue SHG output against pump power – as selected on the pump laser power supply. Solid line is trend line.

In Fig. 5 is shown the tunability of the laser with the crystal optimised for frequency doubling of 785 nm light. For every measurement point the set-up was realigned including phase matching of the BiBO crystal by angular tuning. The dip around 390 nm may be caused by mode-hop due to a slight birefringent filter-effect of the Ti:Sapphire crystal. This may also count for the narrow dip at 392 nm. Tunability is found to be in the range of 386.6 nm to 394.7 nm, which corresponds to ref. [3], who measures 375-435 nm. It should be observed, though, that they utilise a 1.4 mm thick crystal for extra-cavity doubling of a femtosecond laser.

The stability was measured over the course of an hour by recording the blue output as well as the red leak every two seconds. The average blue power generated during the measurement was 40.0 mW, with a standard deviation of 3.23 mW corresponding to 8.1%. Other references report fluctuations in the same range [6, 8]. The power level in this measurement was below maximum due to problems with damage to the BiBO coatings at maximum power. The power level was lowered by increasing the beam waist in the BiBO crystal slightly.
4.2. Crystal 2

First measurements done were temperature tuning scans. Temperature dependence was found to be higher for the 5 mm crystal 2 than for the 3 mm crystal 1 around the optimum phasematch temperature – as expected, still within our scan limits of 24 to 72 C the output did not drop below half of maximum power, see Fig. 3 right. Power output at 405 nm was highest at 36 C.

Stability measurements were performed for the 405 nm generation similar as for the 392 nm generation. The stability proved to be excellent, with a standard deviation 2.66 mW at an average output of 93.3 mW corresponding to 2.9%. By fine tuning of the set-up the blue generated 405 nm power could be upped to 100.4 mW. The higher blue output obtained at 405 nm was mainly due to the BiBO crystal being longer. Using a similar set-up we see no problems in reaching 100 mW in 392 nm as well.

Recordings of tunability and power slope were not made due to catastrophic failure problems with the coatings on this BiBO crystal causing it to crack and sputter where the fundamental field passed it, severely increasing scattering losses after short time at maximum power. Others have reported similar problems [8].

5. Conclusions

Phasematching angles, as well as sensitivities to angular and spectral misalignment were calculated. A maximum of 53 mW at 392 nm and 100 mW at 405 nm was measured corresponding to pump-to-blue conversion efficiencies of 0.96% and 1.82% respectively. Highest fundamental-to-blue conversion coefficient was measured to $7.0 \times 10^{-5}$ W$^{-1}$ at 392 nm. Temperature dependence was found to be very low, with FWHM of the acceptance estimated to be about 60 C for the 3 mm crystal. Both blue wavelengths proved to be stable over longer time spans, where again 810 nm doubling was the superior performer. Further comparisons could unfortunately not be made due to problems with the coatings on the crystal.

BiBO was found to be a preferable material for efficient CW- intra-cavity SHG in the blue region of light for Ti:Sapphire lasers. The low requirements for temperature stability greatly simplifies the set-up, with the broad spectral acceptance lessening the demands for line-narrowing filters and etalons.