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Abstract: We present results on a 404 nm laser system based on second harmonic generation in a new compact external cavity configuration. We obtain a stable 318 mW cw diffraction limited output from the system with a mode-matched pump power of 630 mW. We observe up to 620 mW SHG, when the cavity is operating in scanning mode. The pump source is an external cavity grating feedback tapered diode laser operating at 808 nm. We find that thermal effects in the nonlinear crystal severely limit the efficiency of the setup with high input powers.

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1. Introduction

Many applications within biomedicine, spectroscopy and optical storage require light sources in the region around 400 nm. Monitoring treatment progression during photodynamic treatment procedures is one such application that requires a high power fiber coupled source. For low power (<100 mW) applications, the GaN based diodes can be used, but high power GaN diodes cannot effectively be coupled into single mode fibers, as they are broad area lasers lasing in several spatial modes.

A straight-forward way to generate high power laser sources in the blue wavelength range would be to frequency double a solid-state laser like the Ti:Sapphire laser system. With the recent development in tapered diode amplifiers [1] a very compact and robust pumping source for frequency doubling has become available around 800 nm. It is more energy efficient to directly double the output from a diode laser, than doubling the output of a diode pumped solid state (DPSS) laser. However the major problem for directly doubling diode lasers has been their poor spatial properties for output powers higher than a few 100 mW. The tapered amplifier design based on external Littrow grating feedback to the diode, has shown output powers up to a few Watts and with only a modest decrease in spatial quality compared to single mode laser diodes [2]. Due to the grating used for feedback, such lasers can be tuned more than 30 nm, while maintaining their spectral properties and power output, making it easy to tune the laser to the phasematching wavelength of a nonlinear crystal, see e.g. [1].

Different nonlinear materials can be used to frequency double the 808 nm output from the diode laser. The borate-group (LBO, BBO, BiBO) all can be used at this wavelength with birefringent phase matching, but they all suffer from walk-off, poor conversion efficiency and requires the use of a high finesse resonator. Quasi phase matched materials like PPLN, PPLT and PPKTP, have recently become available. In these materials the crystal symmetry is intentionally inverted every time the pump and the second harmonic beams are π out of phase. As the propagation direction in the crystal is along a crystal axis, no walk-off is experienced and the use of the largest nonlinear tensor element can be exploited. The symmetry inversion is done by periodically poling the crystal, using a lithographic mask and then applying a high potential across the crystal. Despite having lower absorption and higher nonlinearity than PPKTP both PPLN and PPLT suffer from photorefractivity. Hence we have chosen to use PPKTP in this work. Stoichiometric PPLT (PPSLT) which is resistant to photorefractive effects has recently been introduced, but these crystals are currently not commercially available in thicknesses larger than 0.2 mm, when designed for second harmonic generation of 808 nm light. Such small apertures could increase the losses due to diffraction effects in the resonator. Periodically poled KTP has recently been used to achieve 225 mW at 423 nm [3], 234 mW at 461 nm [4] and 330 mW at 426 nm [5]. In BBO 220 mW at 390 nm [6] has been demonstrated with the use of an external cavity tapered amplifier, employing grating feedback

and etalon stabilization. In LBO 98 mW at 403 nm were obtained [7] using a MOPA diode laser system based on a tapered amplifier.

In this work we successfully double an 808 nm diode laser source by mode matching it to a new, compact external doubling resonator configuration. We obtain an output of 318 mW at 404 nm extracted from the cavity, with a coupled pump power at 808 nm of 630 mW resulting in a conversion efficiency of 50 %. These results are to our knowledge the highest obtained SHG powers so far in PPKTP at this wavelength.

2. SHG setup

The laser source shown in Fig. 1 consists of a tapered amplifier laser diode with grating feedback in a Littrow configuration, similar to the one reported on in [1]. The length of the ridge section is 1 mm, and the tapered section is 3 mm long with a taper angle of 4°. The tapered amplifier laser diode used in this work has a wider waveguide structure perpendicular to the active region, allowing for a more efficient coupling to the external cavity [8], as the vertical divergence angle is lowered to 15° (FWHM) compared to 18° in the previous work. The thicker waveguide results in an increased threshold current, but still allows for the laser diode to be operated at 3 A and a temperature of 20 °C delivering 1.4 W of output power. The laser is operating in a single frequency mode less than 1 MHz (instrument resolution) in bandwidth, and has a free spectral range of 10 GHz. The wavelength changes slightly over time, resulting in an effective bandwidth of ~20 MHz during 1 second, and is believed to be due to minute temperature fluctuations in the tapered amplifier laser diode itself, changing the optical path length and thereby the lasing frequency. The beam quality parameter M^2 was measured for the laser after its front collimator to be <1.3 for both axes.

As the tapered amplifier laser diode is sensitive to feedback, an optical isolator providing >33 dB of isolation is placed in front of the laser. A half-wave plate is used before the isolator which in combination with the polarizing beam splitter in the isolator can be used to reduce the power of the beam. The tapered amplifier laser diode is operated in constant conditions all the time, as the beam astigmatism and hence the subsequent mode matching to the doubling resonator will change with a change in supplied diode current.
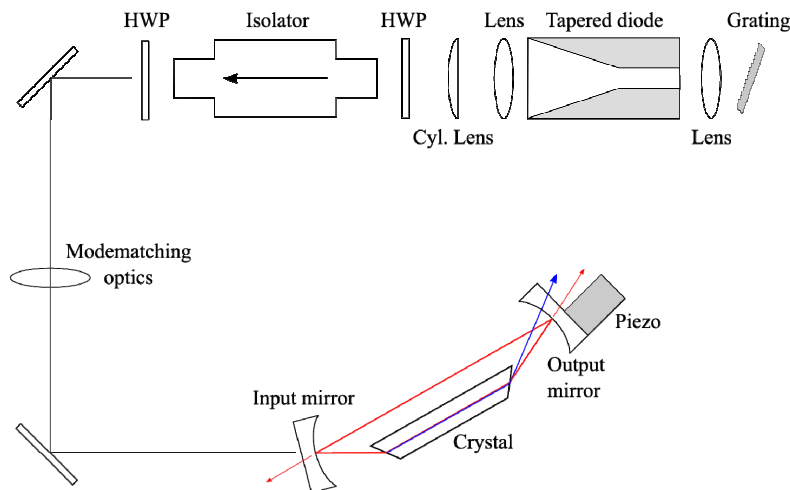
Fig. 1. Sketch of the experimental setup. The laser source is shown in the top right. HWP, half-wave-plate; Modematching optics, 4 cylindrical lenses (not drawn).

After the beam has passed through the isolator, waveplates and mode matching lenses, 1160 mW is available for coupling into the external doubling cavity. The laser wavelength was tuned to 808.5 nm as that allowed the PPKTP crystal to be operated at 55 °C. In order to achieve this a small oven was introduced in the resonator without sacrificing compactness.

Despite the temperature being lower than 80 °C at which the greytracking is minimized [9], no greytracking was observed in the experiments.

The external doubling cavity consists of two concave mirrors of equal radius of curvature and the nonlinear PPKTP crystal. This design was chosen to minimize the roundtrip length in order to increase the acceptance bandwidth of the resonator. The input coupler is 83% reflective and both mirrors have a radius of curvature of 51.8 mm. The output mirror is more than 99.8% reflecting for the pump beam, and has 96% transmission for the second harmonic beam. Both mirrors were anti-reflection coated for both wavelengths at their other facet. In order to adjust the roundtrip length of the resonator, the output mirror is mounted on a piezo used in the electronic locking. The optical length of the resonator is 177 mm, resulting in a free spectral range of 1.69 GHz.

The crystal is a Brewster cut 30 mm long PPKTP crystal (Raicol Crystals), with a poling period of 3.5 μm. This will allow the crystal to operate in 1st order for SHG at 808nm. The crystal acts both as a nonlinear converter and as a refractive element, thus, reducing the number of reflective surfaces in the resonator to a minimum. The crystal is placed in a small copper heatsink, lined with indium foil to increase the thermal conduction between the heatsink and the crystal. Due to the effective linewidth of the laser, it is necessary to keep the finesse of the doubling cavity relatively low in order to have effective coupling of the pump laser to the cavity and, hence, to have stable operation in terms of SHG output. A long crystal was chosen to increase the roundtrip losses, both the passive absorption losses but more importantly the nonlinear conversion losses. A long crystal will also allow for looser focusing of the pump beam and still achieve high conversion efficiency. Earlier reports [3, 4] on blue generation in KTP has shown considerable absorption in the blue wavelength region and associated large thermal effects.

The crystal is placed equidistant from the two mirrors in order to obtain a non-astigmatic resonator mode. But due to the Brewster cut facets of the crystal and the off-axis reflections in the spherical mirrors, the beam will still be elliptic inside the resonator. Hence a trade off has to be made between having a circular focus inside the PPKTP crystal and having a circular harmonic output beam. For crystals with no birefringence the use of a circular beam optimizes the conversion efficiency, whereas elliptical focusing can advantageously be used with birefringent crystals like BiBO [10].

The resonator was designed to have a waist size in the crystal of 100 μm (in-plane) by 75 μm (out-of-plane). This waist size is about 4 times as large as the optimal waist size given by Boyd-Kleinman theory [11] of 27 μm, but was chosen to minimize the thermal effects in the crystal, and was experimentally found to provide the highest cw conversion efficiency.

In our setup we have chosen to let the beam propagate directly from the input mirror to the crystal, see Fig. 1. The advantage of this configuration is that the generated blue beam will exit the resonator through the piezo-mounted mirror, along with a very small fraction of the circulating pump, making it easy to separate the two beams.

The Gaussian stability [12] defined as the half-trace of the ABCD roundtrip matrix was -0.91 and -0.85 in the in-plane and out-of-plane directions respectively for the geometry presented here. This is quite close to the stability limit, but in anticipation of thermal effects in the crystal, it was found that an induced thermal lens in the crystal would move the resonator further into the stable region.

The passive roundtrip losses of the cavity were calculated from the measured losses of each component. The absorption loss from passing through the crystal combined with the two Brewster reflections was measured to 3.2% away from phasematching, and at low incident power in order to make the nonlinear contribution negligible. The transmission peaks in scanning mode, along with the piezo voltage are shown in the left part of Fig. 2. The distance between two peaks is the free spectral range FSR. The ratio between the FSR and the FWHM width of a resonance peak is the finesse of the resonator. For our setup the finesse was found to be 31 in agreement with the expected roundtrip loss of 20% away from phasematching. The best fit to the data corresponds to a roundtrip loss of 4%. The FWHM of the resonance peaks is a measure of the acceptance bandwidth of the resonator. With no loss to second harmonic

generation the resonator has a bandwidth of 55 MHz. This bandwidth increases when the crystal is phasematched, due to additional losses from the nonlinear process, making it easier to couple the laser into the resonator effectively. The absorption of the blue light in the crystal was not measured, it is estimated from [3, 4, 13] to be in the range of 10-20%/cm.
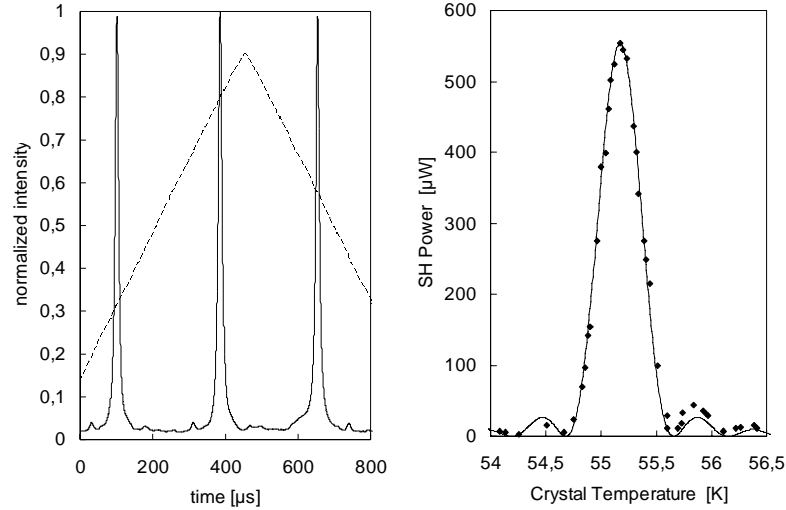

Fig. 2. *Left*: The scanning peaks when the system is operated away from phasematch. The dashed line is the supplied voltage to the piezo. The measurements are done of the leaked pump beam through the piezo mirror. *Right*: The temperature tuning curve with a fitted sinc[2] function. The used pump power is 200 mW. The FWHM value of the fitted sinc[2] is 0.44 K.

Both facets of the crystal are Brewster cut for the pump wavelength in order to minimize the roundtrip losses. Due to the quasi phase-matched nature of the crystal, the polarization of the second harmonic beam is the same as that of the pump beam and, hence, the second harmonic will not experience the large losses commonly observed with Brewster cut crystals used with birefringent phase matching. A Fresnel loss of 1.3% of the second harmonic when exiting the crystal is expected due to the material dispersion. The Brewster interface will separate the pump and second harmonic spatially, removing the need for a dichroic mirror or other separator of the pump and second harmonic. The results presented here have not been corrected for the losses of the output mirror and the absorption and reflection losses of the crystal.

3. Experimental results

In order to characterize the performance of the resonator, the piezo-mounted mirror was set to sweep the cavity in and out of resonance. The second harmonic beam exiting from the cavity was detected behind a colored glass filter to avoid saturation of the photo diode, and filtering off any diffuse or stray reflected pump. The pump leaking through the HR coated folding mirror, and the reflected input beam from the input mirror were detected simultaneously. The leaked pump power is directly proportional to the intracavity circulating power, and when calibrated with a known source, or if the transmission of the mirror is known, the circulating power in the resonator can be deduced. The relationship between the coupled, generated and circulating powers can be deduced following [14, 15]

$$T_1 P_{in} = P_c \left[1 - \left((1-L)(1-T_1)(1-\eta P_c) \right)^{\frac{1}{2}} \right]^2 , \qquad (1)$$

with T_1 as the transmission of the input coupler, P_{in} and P_c the coupled power and the circulating power and L the total passive roundtrip loss excluding the loss from the input coupler. η is the single pass conversion efficiency defined by $P_{2\omega} = \eta P_\omega^2$.

The single pass conversion efficiency of the crystal was measured by blocking the beam in the resonator between the two mirrors only allowing for single pass operation, after mode matching of the resonator. This allows for the same mode to be used in the crystal as when the crystal is used on resonance. As the resonator functions as a spatial filter, the resulting mode in the crystal when on resonance will be slightly different. We have disregarded this effect as the low finesse indicates that only a small number of passes (7-10) of the beam will occur and, hence, the spatial filtering will be incomplete. The fact that 80-85% of the beam can be coupled into the resonator when on resonance, also shows that the pump source beam must be close to the supported Gaussian mode of the resonator. The single pass conversion efficiency η was measured to 1.38 %/W for the 30 mm long crystal. This should be seen in comparison with the value 0.83 %/W·cm measured in a 10 mm long crystal from the same supplier, but was in the latter case focused for optimal single pass generation [1].

By varying the temperature and hence the phasematching, the temperature bandwidth can be measured. The experimental results are shown in the right part of Fig. 2, along with a fitted sinc^2 function. The FWHM of this fitted function is the temperature bandwidth and was found to be 0.44 K. An effective length of the crystal can be defined as [16, 17]

$$L_{eff} = \frac{1.39\lambda}{\pi\Delta T_{FWHM}} \left[\left(\frac{\partial n_{2\omega}}{\partial T} - \frac{\partial n_\omega}{\partial T} \right)\bigg|_{T=T_{pm}} - \alpha(n_{2\omega} - n_\omega) \right]^{-1} \tag{2}$$

where $\alpha = 11\times10^{-6}\,\text{K}^{-1}$ [18] is the thermal expansion and $n_\omega, n_{2\omega}$ are the indices for the pump and the second harmonic, respectively. By inserting the indices $n_\omega = 1.845$ and $n_{2\omega} = 1.965$ and their temperature derivatives from [19] the result for a 30 mm crystal is 0.37 K. The temperature-bandwidth of our crystal shows that the effective length is 25 mm. The conversion efficiency can directly be found from the temperature tuning by using the fact that 200 mW of pump power was incident on the crystal and 553 µW of second harmonic was generated, resulting in 1.38 %/W.
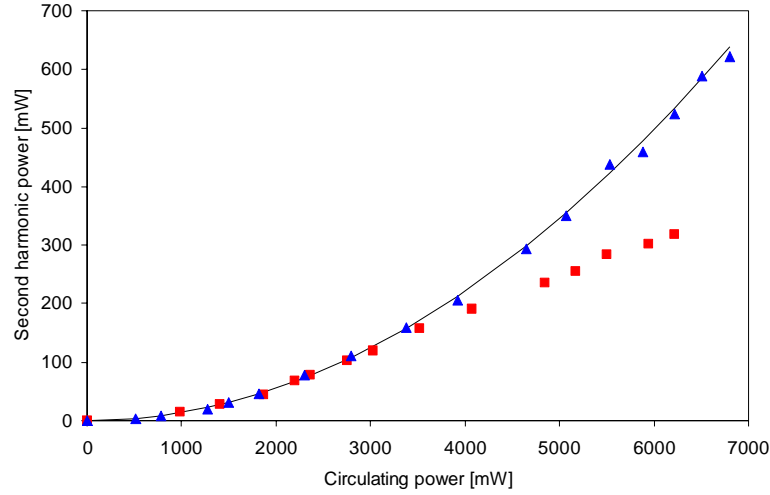
Fig. 3. The second harmonic power measured after the output coupler. The red squares are measured in continuous wave mode; blue triangles are scanning mode results. Solid line is the predicted results based on 4% roundtrip loss, and a single pass conversion efficiency of 1.38%/W.

The generated blue power when scanning the cavity and in cw operation are shown in Fig. 3, respectively, as a function of the circulating power in the cavity. The solid line is the expected SH power based on the measured single pass efficiency, and a roundtrip loss for the resonator of 4%, excluding the input coupler. It is seen that the results when scanning are in good agreement with the expected values. The cw values are not following the same trend, but deviates for circulating powers larger than 4 W to values lower than for the scanning mode of operation. This behavior is believed to be caused by the heating of the crystal associated with the absorption of the circulating pump and the generated blue light. The thermal lens formed inside the crystal will dynamically change the eigen-mode of the resonator, resulting in a different mode match than for the cold cavity. This will lower the coupling efficiency, and thereby reduce the circulating power. In turn this will also change the single pass conversion parameter, as this parameter is dependent on the spatial mode in the crystal. Due to the small acceptance bandwidth (0.44 K) of the crystal, the part of the crystal that is phasematched will decrease as the temperature gradient inside the crystal increase. Using a long crystal allows for looser focusing and thereby lowering the absorbed intensity, thus reducing the temperature gradient.

The beam quality parameter M^2 for the second harmonic beam was measured, using the $1/e^2$ criterion, to ~1.15 for both axes. The beam was measured in cw mode at maximum blue power, with the polarization lock on.

In scanning mode it was possible to mode match 81% of the input beam resulting in a maximum coupled power of 930 mW. This dropped to 630 mW of coupled power when switching to cw mode lowering the mode matching efficiency to 54 %.

The effective nonlinearity d_{eff} of the PPKTP crystal can be found from the relation between second harmonic power and pump power [17]

$$P_{2\omega} = \frac{16\pi^2 d_{eff}^2}{\varepsilon_0 c \lambda_\omega^3 n_\omega n_{2\omega}} P_\omega^2 L h \qquad (3)$$

where the Boyd-Kleinman focusing parameter h can be found in [11]. The effective nonlinearity d_{eff} is calculated to 7.2 pm/V for low pump powers. However as the crystal

heats up, the effective interaction length in the crystal becomes shorter, resulting in d_{eff} being reduced to 5.5 pm/V, if L is held constant at 30 mm. At the same time the normalized efficiency drops to 0.82 %/W for the highest cw power level observed.

The conversion efficiency is plotted in Fig. 4 along with the predicted results, and shows similar leveling off due to thermal effects in the crystal with increased pump power.
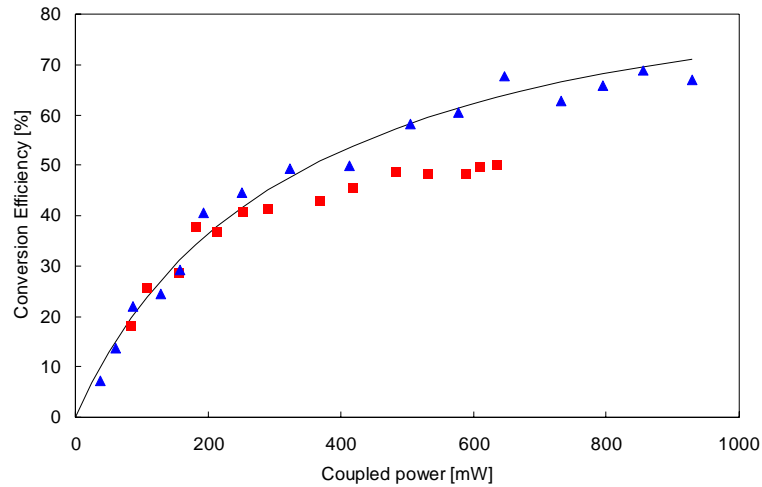

Fig. 4. The conversion efficiency as a function of coupled pump power. Same legend as Fig. 3.

To stabilize the setup for cw operation, a polarization-locking scheme [20] has been employed. The power fluctuations of the locked resonator are within 5% during 30 minutes of operation. The thermal effects actually self-stabilizes the resonator, due to a phenomenon called self-locking [21, 22], and the resonator is almost as stable running self-locked, as when electronically locked. Large external perturbations will actively be compensated for by the electronic locking circuitry, but not by the self-locking effect. The thermal self-locking can be obtained by adjusting the DC bias level to the piezo, thereby manually adjusting the mirror position. The power fluctuations are within 7 % when running in self-locked mode, where the system can remain stable for up to 30 minutes. It is possible to achieve higher cw powers for shorter periods of time in the self-locked mode, but these cannot be locked using the polarization lock.

4. Conclusion

In conclusion we have demonstrated a high power, compact 404 nm frequency doubled source, yielding 318 mW of cw power. The pump source was an external cavity tapered amplifier diode laser using grating feedback in the Littrow configuration to achieve single-mode operation. In scanning mode 930 mW could be mode matched to the doubling cavity resulting in peak powers of 620 mW of the SH beam, a conversion efficiency of 67%. In cw mode only 630 mW of the pump laser could be coupled into the cavity. This is believed to be due to thermal effects inside the crystal. The conversion efficiency in cw mode was 50%.

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