Novel low-loss 3-element ring resonator for second-harmonic generation of 808nm into 404nm using periodically poled KTP

Holm, J.; Jensen, Ole Bjarlin; Sumpf, B.; Erbert, G.; Andersson-Engels, S.; Andersen, Peter E.; Petersen, Paul Michael

Published in:
Nonlinear Frequency Generation and Conversion: Materials, Devices, and Applications 6

Link to article, DOI:
10.1117/12.700544

Publication date:
2007

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Holm, J., Jensen, O. B., Sumpf, B., Erbert, G., Andersson-Engels, S., Andersen, P. E., & Petersen, P. M. (2007). Novel low-loss 3-element ring resonator for second-harmonic generation of 808nm into 404nm using periodically poled KTP. In P. E. Powers (Ed.), *Nonlinear Frequency Generation and Conversion: Materials, Devices, and Applications 6* Bellingham: International Society for Optical Engineering. SPIE Proceedings Series, 6455 https://doi.org/10.1117/12.700544

Novel low-loss 3-element ring resonator for second-harmonic generation of 808nm into 404nm using periodically poled KTP

Jesper Holm[a,b*], Ole Bjarlin Jensen[a], Bernd Sumpf[c], Götz Erbert[c], Stefan Andersson-Engels[b], Peter E. Andersen[a] and Paul Michael Petersen[a]

[a]Risø National Laboratory, Optics and Plasma Research Department, Frederiksborgvej 399, 4000 Roskilde, Denmark.
[b]Lund Institute of Technology, Department of Physics, Professorsgatan 1, 22100 Lund, Sweden.
[c]Ferdinand-Braun-Institut für Höchstfrequenztechnik, Optoelectronics Department, Gustav-Kirchhoff-Strasse 4, 12489 Berlin, Germany.

ABSTRACT

We present a novel ring resonator for second harmonic generation consisting of only two spherical mirrors and a refractive element. In our work we use periodically poled KTP as a nonlinear material for generating the second harmonic using an 808nm tapered grating stabilized external cavity laser as pump source. With 286mW of fundamental 808nm radiation coupled into the resonator, we generate 130mW blue light at 404 nm, resulting in a power conversion efficiency of 45%.

Keywords: Optical resonators, tapered lasers, second harmonic generation, KTP

1. INTRODUCTION

There is a growing need for blue laser sources within medical applications, spectroscopy and optical data storage. These sources must be operated in both continuous wave (cw) and pulsed modes, depending on their specific application. Many of these applications require the beam to be close to diffraction limited in order to achieve a small spotsize. The GaN-based direct semiconductors can be used up to power levels of 60mW[1], and still maintain their spectral and spatial properties. To increase the power output further the waveguide must be a broad area waveguide, in order to reduce the facet intensities, resulting in degrading the spatial and spectral qualities as several modes are allowed to oscillate simultaneously.

To achieve higher output powers it is therefore common to frequency double a pump laser in a nonlinear interaction process. In order to reach our target wavelength of 404nm, an 808nm source is required for the second harmonic generation (SHG) process. This wavelength is in the gain band of the Ti:Sapphire laser. However, this laser system itself is normally pumped by a frequency doubled Nd:YAG laser, requiring an additional conversion procecss that reduces the overall conversion efficiency and increase the overall size of the system[2]. Other systems like dye lasers, and alexandrite lasers can also reach 404nm, but they are expensive and inefficient.

Only recently the spectral properties of high power diode lasers at 808 nm were improved to such a point where direct doubling of the output has become feasible. Several Watts of output power can be generated from the tapered laser structure[3], while maintaining single longitudinal mode operation[4].

The nonlinear process can be done in different ways: single-pass (nonresonant), intracavity or extracavity, relative to the lasing cavity. The conversion is of second order and hence depends on the pump intensity squared. By using an external cavity that resonates the fundamental, the conversion efficiency can be greatly increased compared to nonresonant setups.

In this work we report on a new design of external resonator, consisting of only 2 mirrors and a nonlinear crystal. We have pumped it with an external cavity Littrow stabilized tapered laser diode of 1W. We obtained 130mW of 404nm blue light with a coupled fundamental power of 286mW, resulting in a power conversion of the resonator of 45%.

* jesper.holm@risoe.dk, phone: +45 46 77 45 72, fax: +45 46 77 45 88, www.risoe.dk

Nonlinear Frequency Generation and Conversion: Materials, Devices, and Applications VI, edited by Peter E. Powers,
Proc. of SPIE Vol. 6455, 645504, (2007) · 0277-786X/07/$15 · doi: 10.1117/12.700544

2. THE EXTERNAL RESONATOR

Due to the quadratic dependence on the pump intensity for the doubled beam, a circulating power as high as possible in the external resonator is needed. Contrary to intracavity setups we have no gain media to replenish the roundtrip losses, and therefore we must minimize the losses of the external resonator. The roundtrip losses originate mainly from non-perfect reflective coatings, scattering from surfaces and imperfections and absorption. A small amount is lost due to the diffraction of the beam out of the cavity, but this can be mitigated using larger sized optical elements. The absorption losses are mainly in the refractive elements e.g. the crystals used in frequency doubling cavities. These losses are material properties and hence cannot be controlled, except for choosing materials with suitable low absorption if possible.

Different external ring cavity configurations for SHG have been reported. The 4-mirror bowtie configuration[5] is used frequently due to its versatility and relative ease of implementation. Other resonator designs, like the three mirror coma and astigmatism compensated ring[6], have also provided good results. In order to reduce the mirror losses we have made a 2-mirror ring resonator, consisting of two spherical mirrors for focusing and one refractive element that doubles as a nonlinear optical element for the frequency conversion. In the work presented here we have used an 18 mm long periodically poled KTP crystal and mirrors with ROC of 51.8 mm, as a first implementation of the resonator.

A drawing of the resonator geometry is shown in figure 1. The angles of incidence (AOI) on the crystal are given by the Brewster condition, and thereby set the geometry of the entire resonator. The remaining three degrees of freedom are the crystal length L_c, the mirror separation L_m and the radius of curvature (ROC) of the mirrors. In this work we have chosen the mirrors to have identical ROC. Otherwise the crystal will not be placed symmetrically, and the AOI will no longer match the Brewster angle, which will lead to increased roundtrip losses of the resonator. As the ring is unidirectional, it is also possible to couple the beam into the resonator along parallel to the crystal. In that case the second harmonic beam will exit through the input coupler.

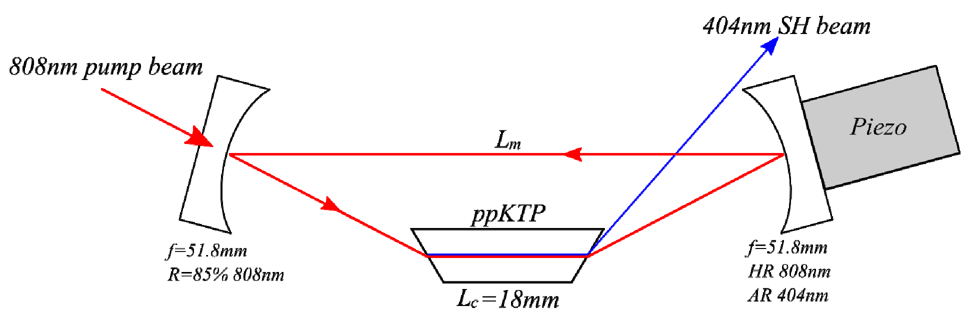

Figure 1: Sketch of the external 2-mirror cavity, seen from above. The drawing is not to scale. The blue beam can exit the cavity without being truncated by the half-inch mirror.

By using the ABCD matrix approach[7] the waist sizes of the eigenmode beam solution can be found for the resonator. Because of the thermal effects known to exist in KTP crystals[8], a large waist size in the center of the crystal is desired, in order to lower the intensity. The resonator has therefore been designed to have an 80 by 60 micron waist size in the crystal. This is quite large compared to the optimized Boyd-Kleinman[9] waist size of 21 microns, but this is needed to avoid the thermal problems and the gray tracking that is present in KTP crystals. The beam radius ($1/e^2$) as a function of the position in the resonator has been calculated and is shown in figure 2. The figure shows the beam as it evolves from the center of the crystal and through one roundtrip of the resonator. The part of the beam lying in the plane of the resonator (tangential) is in bold, and the out-of-plane part of the beam (sagittal) is the thin line. The polarization of the beam is at all points linear in-the plane of the resonator, in order to minimize the reflection on the Brewster interfaces. The two spherical mirrors are placed after 56 mm and 154 mm and an extra beam waist is formed between the mirrors. The discontinuity in the beam radius is due to the air/crystal interface, which introduces astigmatism due to the nonsymmetrical change in beam parameters for the two axes. The Gaussian stability (defined as half the trace of the resonators ABCD matrix) of the chosen experimental solution is 0.75 in the tangential plane and 0.41 in the sagittal plane.

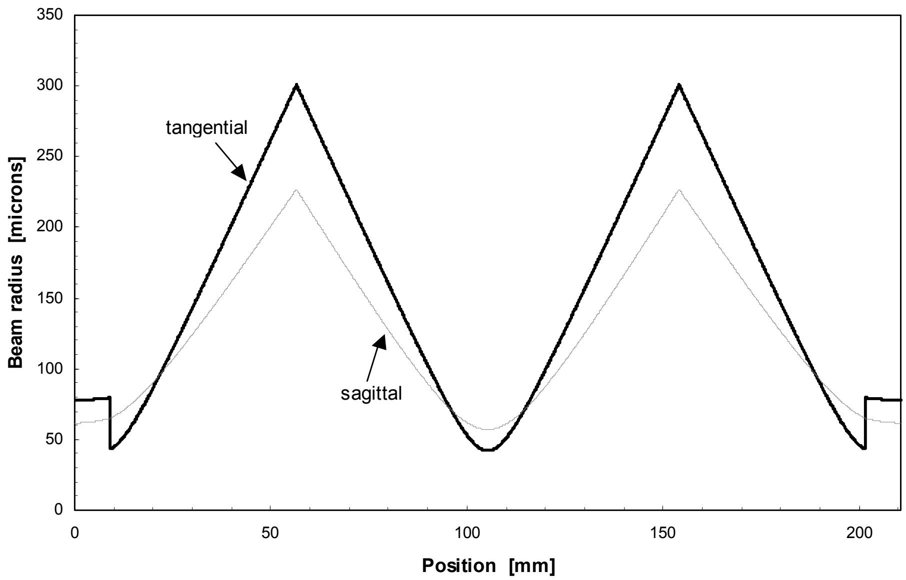

Figure 2: The beam size as a function of the position in the resonator. One roundtrip is shown for the case used in the experiment. Bold line is the tangential part of the beam, thin is the saittal part. The discontinuity is due to the astigmatism introduced by the Brewster interface.

The resonator is astigmatic and requires cylindrical focusing optics in order to achieve a good mode match. The external focus can be made circular on the expense of the crystal focal region (figure 3). This will considerably ease the mode matching as standard spherical optics can be used. The Gaussian stability[7] in this configuration is –0.39 and –0.52 for the two directions. This configuration will however maximize the ellipticity of the beam within the crystal. This can be an advantage if the nonlinear crystal is phase matched by angle tuning. Such tuning will lead to walk-off of the second harmonic beam and thereby limits the interaction region of the crystal. It has been shown[10] that elliptical focusing in this case can improve the conversion efficiency of the crystal compared to circular focusing.

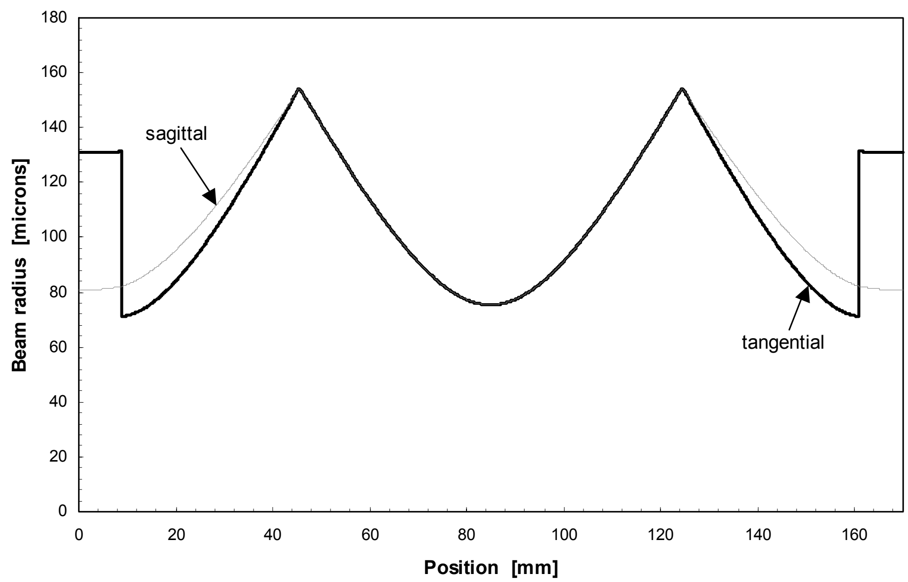

Figure 3: The beam radius plotted for a resonator with a circular inter-mirror focus. The astigmatism is maximized inside the crystal, degrading the focal region.

There are two points along the edges of the main stability interval, the focus is circular within the crystal (figure 4). Only very narrow regions around these points will have circular focusing. As our application can accept a small amount of ellipticity, we have chosen to increase the ellipticity in order to make the resonator optically more stable.

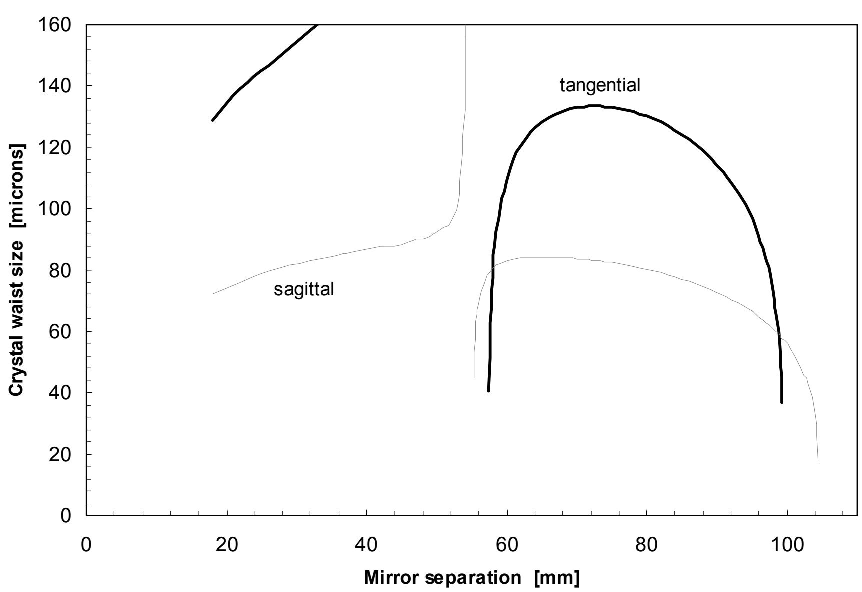

Figure 4: Calculated beam waist sizes in the crystal as a function of the mirror separation *L*.

The Gaussian stability of the resonator is shown in figure 5. It shows the main stability region of operation in the interval 55mm to 100 mm. For longer separations the resonator is unstable, as the mirrors focal lengths are too short. The region below 53mm is also stable, but practically unusable due to the very large crystal waist, and large ellipticity of the external focus, as shown in figure 4.

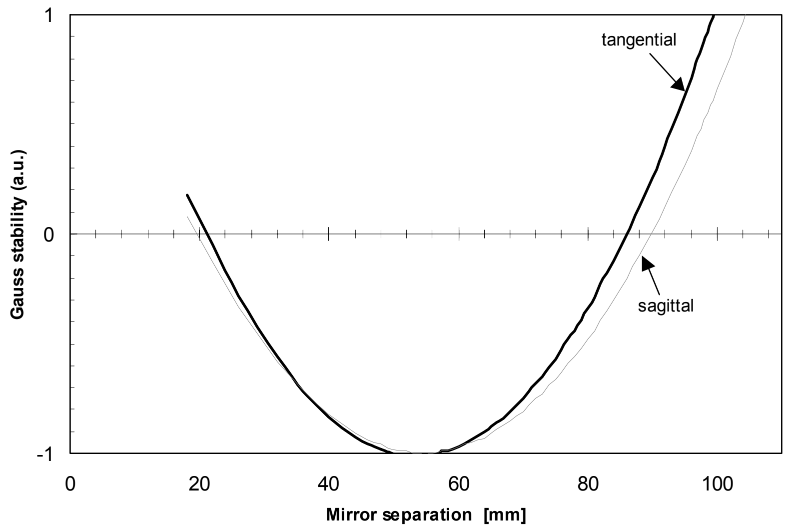

Figure 5: Gaussian stability of the resonator with a 18mm ppKTP crystal and two spherical 50mm mirrors. The region around 55mm is unstable. Bold black: tangential, thin gray: sagittal.

3. EXPERIMENTAL RESULTS

3.1 The tapered laser diode

The laser system consists of a tapered amplifier in an external cavity configuration. The laser diode is a 4 mm long AlGaAs waveguide with a single GaAsP quantum well structure. The ridge section is 1 mm long, followed by a tapered section of 3 mm with a taper angle of 4°. The ridge section is index guided whereas the tapered power amplifier section is gain guided.

The diode employs a super-large optical cavity design[3] that lowers the local intensity in the lasing region by increasing the width perpendicular to the gain region. This allows for a larger mode to propagate, but hence also results in lower overlap with the single quantum well structure used as the gain region, leading to lower amplification. Another benefit from this increased thickness design is the lower divergence angle associated with the fast axis, as low as 15° (FWHM) has been obtained, allowing for slower collimators to be used and easier coupling to the external cavity.

On the output facet a 0.5% reflecting coating has been applied for feedback, and for use in the external cavity a <0.1% AR coating has been applied to the back facet. The ridge section is approximately 3 microns wide, to improve the coupling efficiency, and decrease the intensity in the waveguide.

3.2 The laser system

The laser system is schematically shown in figure 6. The diode is used in a Littrow configuration[4]. A fast aspheric lens is used one focal length away from the back facet to collimate the beam. The lens has a focal length of 3.1 mm and a numerical aperture of 0.68 and is optimized for working in the 810 nm range. The collimated beam is incident on a gold coated blazed grating (1200 lines/mm, blazed for 750nm) mounted in the Littrow configuration, providing approximately 85% feedback to the diode. The polarization of the laser is linear along the fast axis and the grating is operated with the lines perpendicular to the polarization. Tuning of the lasing mode can be accomplished by tilting of the grating. The length from the collimating lens to the grating is 40mm, thus the FSR of the extended cavity is 3 GHz, while 11 GHz for the diode itself. The output collimator is identical to the external cavity collimator, positioned to collimate the fast axis.

Due to the gain guiding nature of the tapered region the output beam is astigmatic. This is compensated for by a series of cylindrical lenses, used to modematch the beam to the external doubling resonator, which need an elliptical pump beam.

The laser diode is mounted p-side down on a standard C-mount in order to provide the best possible thermal contact. The length of the diode (4mm) compared to the standard C-mount size of 4.2mm ensures that the beam will not be truncated by the hard edge aperture of the C-mount itself when mounted p-side down. The C-mount is mounted in a copper slab, with an embedded thermistor for thermal management of the diode. Both collimating lenses are also placed in copper slabs and all three slabs are placed on an aluminum heatsink that are actively cooled by a peltier element. The temperature is held constant at 25 °C, throughout all experiments.

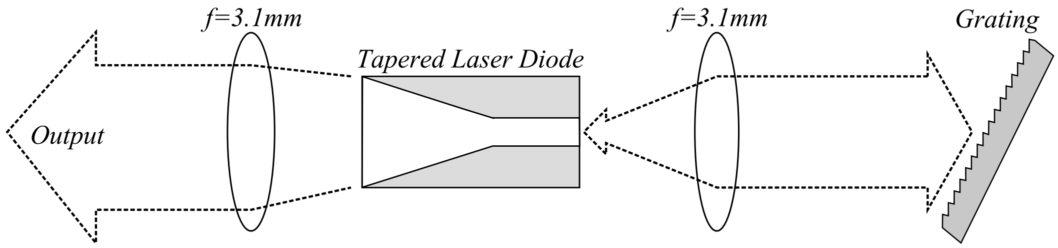

Figure 6: The grating stabilized laser source. The grating is used in the Littrow configuration where tuning of the wavelength is obtained by rotating the grating. (For illustration the laser diode is turned 90° around the optical axis in the drawing)

The current-power diagram for the laser diode (shown in figure 7) shows a threshold current of 1.8 A, and a slope of 1.03 W/A. When used as a cw pump, the laser is operated at 25 °C, and with 970mw of output power at 808nm. The power fluctuations of the laser are within 2% for several hours. The lasing wavelength is stable on the same longitudinal mode for several hours when thermal steady state has been reached for the entire laser system setup, which usually takes about 30-45 minutes. The side mode suppression is more than 20 dB, as can be seen from the OSA scan in figure 8.

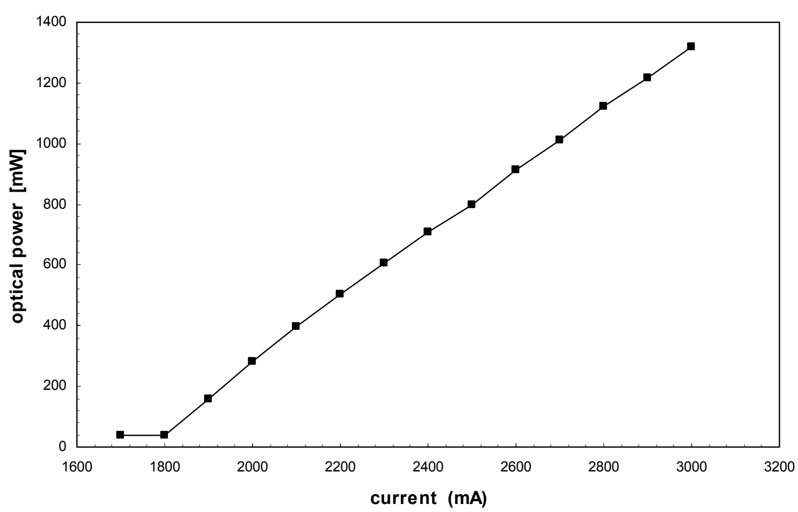

Figure 7: The optical output power as function of the current. Threshold current is 1.8A and the slope 1.03 W/A.

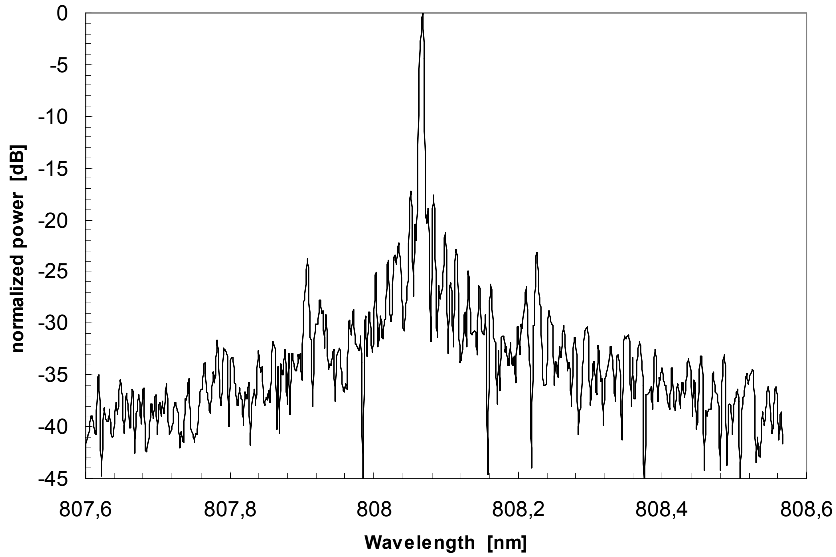

Figure 8: The recorded laser spectrum on an Advantest AQ8347 spectrum analyzer with 4 pm resolution. The mode spacing of the longitudinal modes is 20 pm.

The linewidth of the laser has been measured with a scanning Fabry-Perot interferometer (Burleigh), having a FSR of 15 GHz and a Finesse of 1200. The resolution of the interferometer was 12.5 MHz and too large to measure the intrinsic linewidth. However, the effective linewidth of the diode is around 100 MHz. The rather large bandwidth is a problem for high finesse resonators, and therefore requires a very compact cavity with a large FSR or a low Finesse cavity.

The laser is protected by an optical isolator providing 30dB of isolation in order to avoid optical feedback from the optics in the path. A double isolation stage has been tested but it did not decrease the measured bandwidth of the diode, and was subsequently omitted in order to reduce the losses of the system.

3.3 Experimental implementation

The experimental configuration of the resonator is shown in figure 1. The input coupler is a spherical mirror with a ROC of 51.8 mm, having a reflectivity coating of 85% on the concave surface, while the flat surface is AR coated. The folding mirror is for symmetry reasons of identical ROC, but with a high reflectivity (HR) coating of 99.8%. The crystal is a periodically poled flux-grown KTP crystal with a length of 18 mm (average). It has been poled with a period of 3.4 µm for second harmonic generation of 808nm at 50°C. The phasematched wavelength can be tuned by changing the temperature of the crystal at a rate of 0.06 nm/°C. The only remaining free parameter, the mirror separation, was chosen to 97 mm in order to obtain a focus inside the crystal of 80 by 60 µm. The resonator length is 225 mm, resulting in a free spectral range (FSR) of 1.3 GHz.

In order to lock the resonator the HR mirror has been mounted on a piezo, to allow the path length of the resonator to be changed. By ramping the voltage to the piezo, the transmission peaks can be measured, and the finesse of the cavity was measured to 31 when the crystal was phasematched. The linewidth of the resonator is given as the ratio between the FSR and the finesse, and was found to be 43 MHz. This is smaller than the effective bandwidth of the diode, but the electronic lock was faster than the laser fluctuations, resulting in a stable beam.

Of the 970 mW output from the laser, 728 mW was incident on the resonator. The losses in the beam path were mainly due to the optical isolator. Of this incident power 286 mW were modematched and coupled into the cavity. Due to the low reflectivity of the input coupler, the resonator is not impedance matched, resulting in a large part of the incident beam to be reflected. The maximum obtained power was 130 mW of blue power in a slightly elliptic beam. This results in a power conversion efficiency of the resonator of 45%.

Because of the large material dispersion between the fundamental and the second harmonic, the exit angle from the crystal is not identical for the fundamental and the second harmonic beams. In this particular geometry the generated blue beam can escape the resonator without interference with the piezomounted mirror, thereby avoiding the mirror losses of ~5%.

4. CONCLUSION

We have demonstrated a new ring resonator design, consisting of only two spherical mirrors and a nonlinear crystal, cut at non-parallel Brewster angles. We have calculated the eigenmode of the resonator and the Gaussian stability parameters for an experimental implementation using the ABCD matrix approach. The experimental implementation consisted of two 50mm mirrors and an 18 mm long ppKTP crystal. With this setup we succeeded in generating 130mW of blue 404nm light with a coupled 286mW of fundamental light, from our grating stabilized external cavity tapered diode laser. The power conversion efficiency for the resonator was 45%.

The project is supported by the European union in the projects WWW.BRIGHT.EU (IP 511722) and WWW.BRIGHTER.EU (IP 035266). The authors acknowledge the technical support of B. Sass.

REFERENCES

1. Nichia Corporation, www.nichia.com, dec 2006.
2. W. R. Rapoport and P. Khattak, "Titanium sapphire laser characteristics", Appl. Opt. 27 (1988) 2677.
3. A. Knauer, G. Erbert, R. Staske, B. Sumpf, H. Wenzel and M. Weyers, "High-power 808 nm lasers with a super-large ptical cavity", Semicond. Sci. Technol. 20 (2005) 621.
4. M. Chi, O. B. Jensen, J. Holm, C. Pedersen, P. E. Andersen, G. Erbert, B. Sumpf and P. M. Petersen, "Tunable high-power narrow-linewidth semiconductor laser based on an external cavity tapered amplifier", Opt. Exp. 13, (2005) 10589.
5. M. Brieger, H. Büsener, A. Hese, F. v. Moers and A. Renn, "Enhancement of Single Frequency SGH in a Passive Ring resonator", Opt. Comm. 38 (1981) 423.
6. J. S. Nielsen, "Generation of 90-mW continuous-wave tunable laser light at 280 nm by frequency doubling in a KDP crystal", Opt. Lett. 20 (1995) 840.
7. A. E. Siegman, "Lasers", 1986, University Sciene Books, Sausalito, USA.
8. R. Le Targat, J. –J. Zondy and P. Lemonde, "75%-efficiency blue generation from an intracavity PPKTP frequency doubler", Opt. Comm. 247 (2005) 471-481.
9. G. D. Boyd and D. A. Kleinman, "Parametric interaction of focused Gaussian light beams" J. Appl. Phys. 39 (1968) 3597.
10. T. Freegarde, J. Coutts, J. Walz, D. Leibfried and T. W. Hänsch, "General analysis of type I second-harmonic generation with elliptical Gaussian beams", J. Opt. Soc. Am. B. 14 (1997) 2010.