Technical University of Denmark

3.5 W of diffraction-limited green light at 515 nm from SHG of a single-frequency tapered diode laser

Jensen, Ole Bjarlin; Hansen, Anders Kragh; Müller, André; Sumpf, Bernd; Petersen, Paul Michael; Andersen, Peter E.

Published in:
Proceedings of SPIE

Link to article, DOI:
10.1117/12.2249671

Publication date:
2017

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

3.5 W of diffraction-limited green light at 515 nm from SHG of a single-frequency tapered diode laser

Ole Bjarlin Jensen[*a], Anders Kragh Hansen[a], André Müller[b], Bernd Sumpf[b], Paul Michael Petersen[a], and Peter E. Andersen[a]

[a]DTU Fotonik, Department of Photonics Engineering, Technical University of Denmark, DK-4000 Roskilde, Denmark, [b]Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik, Gustav-Kirchhoff-Straße 4, 12489 Berlin, Germany

ABSTRACT

Multi-Watt efficient compact green laser sources are required for a number of applications e.g. within biophotonics, laser pumping and laser displays. We present generation of 3.5 W of diffraction-limited green light at 515 nm by second harmonic generation (SHG) of a tapered diode laser, itself yielding more than 9 W at 1030 nm. SHG is performed in single pass through a cascade of two nonlinear crystals with re-focusing and dispersion compensating optics between the two nonlinear crystals. The laser is single-frequency and the output power is stabilized to better than ±0.4%.

Keywords: tapered diode laser, second harmonic generation, visible lasers, 515 nm

1. INTRODUCTION

Lasers in the blue-green spectral range are used in many applications within biophotonics and as pump sources for Ti:sapphire lasers [1,2]. Traditionally this spectral range was covered by argon-ion lasers with direct emission at several lines in the blue and green spectral range including 488 nm and 515 nm. Argon lasers, however, are very power consuming with a very low overall efficiency. They have in many applications been replaced by frequency doubled diode pumped solid state lasers (DPSSL) with higher efficiency and good stability. Some applications still rely on the exact wavelengths of the argon-ion laser. For instance, have fluorophores used in fluorescence spectroscopy been developed specifically for excitation at 515 nm. Lasers at 515 nm are also widely used within Raman scattering and for instrumentation. Pumping of Ti:sapphire lasers are also performed with 515 nm lasers, which is beneficial over 532 nm pumping because of the higher absorption cross section at 515 nm.

Frequency doubled DPSSLs at 532 nm are available in many power levels with the possibility of having high output power, narrow spectral linewidth and excellent beam quality. DPSSLs rely on intracavity frequency doubling of the infrared light generated by the neodymium doped solid state laser crystals. The use of a cavity puts strict demands on the exact alignment and mechanical stability of the cavity components in order to ensure proper operation. This leads to high costs as they are expensive to manufacture. Alternatives to DPSSLs are frequency doubled fibre or diode lasers or diode lasers emitting directly in the visible spectral range.

Direct green light emitting diode lasers have emerged in the recent years and up to 1 W output power is available from a broad area diode laser[3]. The use of broad area structures increases the available output power but at significantly lower beam quality.

Near infrared fibre lasers are available with high output power and narrow spectral linewidth in a diffraction limited output beam. Efficient frequency doubling of fibre lasers have been demonstrated in a single pass through a nonlinear crystal or using external enhancement cavities[4–6]. The high cost of frequency doubled fibre lasers limit their adoption in cost sensitive applications.

Diode lasers are good candidates for frequency doubling but until recently the efficiency has been limited by the low power of single-mode lasers or the poor beam quality of broad area lasers. The introduction of tapered diode lasers has enabled generation of high output power in a near diffraction limited beam and the use of internal Bragg gratings ensures a narrow linewidth[7]. Such tapered lasers have been frequency doubled with visible output power levels in the watt range

[*]ojen@fotonik.dtu.dk; phone +45 46774553; fax +45 46774588; www.fotonik.dtu.dk

Nonlinear Frequency Generation and Conversion: Materials and Devices XVI, edited by Konstantin L. Vodopyanov, Kenneth L. Schepler, Proc. of SPIE Vol. 10088, 1008803
 · doi: 10.1117/12.2249671

with good spectral and spatial characteristics[8]. In order to further enhance the conversion efficiency cascaded frequency doubling has been introduced resulting in up to 39 % optical to optical conversion efficiency[9]. Frequency doubling of tapered lasers has until now concentrated on generation of light at 488 nm, 532 nm and 562 nm[10–12].

515 nm laser emission is still in use for certain applications and this wavelength is not easily reached by DPSSL laser although frequency doubling of Yb:YAG lasers has shown good results[13]. The extended wavelength selectivity of diode enables targeting any wavelength in the blue-green spectral range.

Here, we present efficient generation of 515 nm light by cascaded frequency doubling of a tapered diode laser. More than 3.5 W output power is generated by use of a cascade consisting of a periodically poled MgO-doped lithium niobate (PPMgLN) and a MgO-doped stoichiometric lithium tantalate (PPMgSLT) crystal. The linewidth of the 515 nm light is less than 2 pm and it has an excellent beam quality with $M^2 < 1.1$. This laser source could benefit applications still relying on argon-ion lasers as a possible substitution with significantly less power consumption and greatly reduced foot print.

2. EXPERIMENTAL SETUP

The diode laser is a 6 mm long distributed Bragg reflector (DBR) tapered diode laser. The ridge waveguide is 2 mm long split between a 1 mm long third order DBR grating and a 1 mm long ridge waveguide section. The tapered section is 4 mm long and has a taper angle of 6°. The ridge section and tapered sections have separate electrical contacts for individual control of the injection currents. The DBR tapered laser was mounted on a 25 x 25 mm^2 conduction cooled package for efficient cooling.

Such a diode laser has previously been shown capable of emitting more than 12 W output power around 1030 nm with narrow linewidth and good spatial properties[14]. Here, we operated the laser with 300 mA injection current to the ridge waveguide section and up to 14 A injection current to the tapered section and with a heatsink temperature of 20°C. At 14 A injection current to the tapered section an output power of 9.7 W was achieved as shown in Figure 1. The spectral width of the laser was investigated using an optical spectrum analyzer (OSA) (Advantest Q8347) and a spectral linewidth of 6 pm was measured limited by the OSA resolution. The measured spectrum is shown in Figure 2.

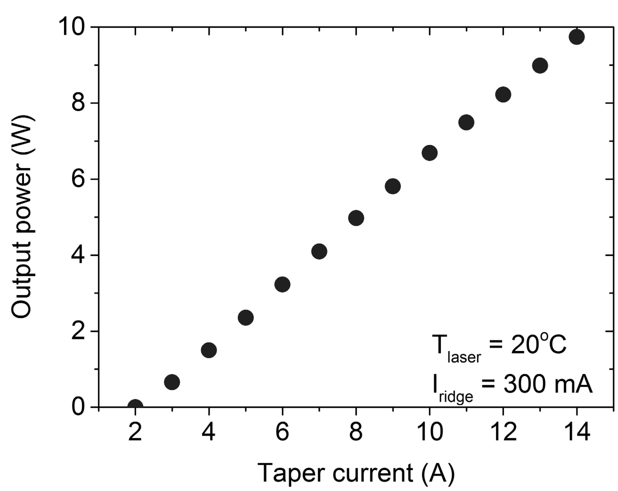

Figure 1. Output power vs injected current to the tapered section of the DBR tapered laser. The laser is operated at a temperature of 20°C and with 300 mA current to the ridge waveguide section.

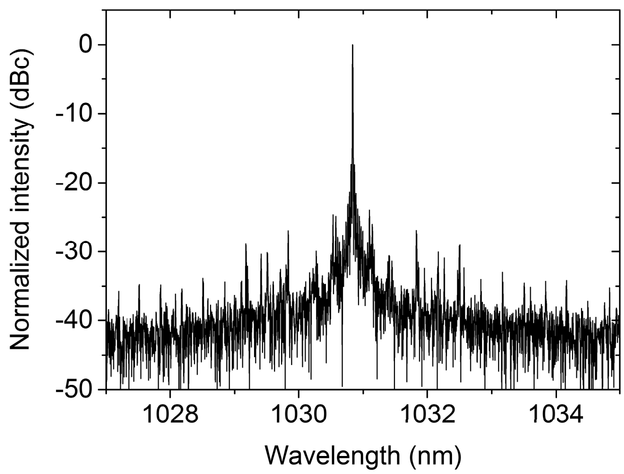

Figure 2. Spectrum of the DBR tapered laser operated at with 300 mA current to the ridge section, 14 A current to the tapered section and at a temperature of 20°C.

Tapered diode lasers typically emits a beam which in the focus consists of a powerful central lobe and some smaller side lobes. This was also the case for this particular laser with a focused beam profile as shown in Figure 3. Here a strong central lobe is seen with some low power side lobes. We measured the power content of the central lobe to approximately 70 % of the total output power after collimation of the laser.

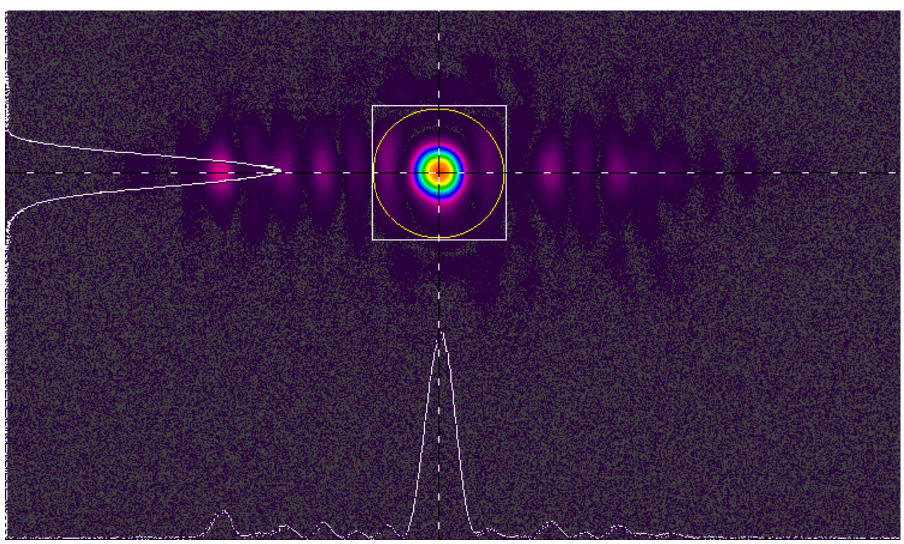

Figure 3. Measured beam profile of the DBR tapered laser at 9.7 W output power.

Frequency doubling of the DBR tapered laser in a cascade of two nonlinear crystals was performed in a setup as sketched in Figure 4. An aspherical lens was used to collimate the beam in the fast axis to a beam width of approximately 1 mm. Due to the astigmatism of the tapered diode laser, an additional cylindrical lens was inserted to collimate the beam in the slow axis and to compensate for the astigmatism. This resulted in an approximately circular collimated beam with 1 mm diameter. An optical isolator with more than 30 dB isolation was inserted to protect the laser against feedback from the following optical components. After the optical isolator a halfwave plate was inserted to ensure vertical polarization as needed by the frequency doubling. In order to compact the setup, we used two plane folding mirrors (not shown in Figure 4) to direct the beam through the first nonlinear crystal. A spherical lens with 45 mm focal length was inserted to focus the beam into the first nonlinear crystal with a beam waist radius of approximately 40 μm. The output beams at

1030 nm and 515 nm from the first crystal was collimated and refocused into the second nonlinear crystal using two curved mirrors with 100 mm radius of curvature. Both mirrors were highly reflecting at 515 nm and 1030 nm. The phase delay between fundamental and second harmonic beams was adjusted with a plane-parallel 3 mm thick BK7 plate inserted at Brewsters angle between the two curved folding mirrors. This allowed for constructive interference between the second harmonic light generated in the first nonlinear crystal and the second nonlinear crystal[15,16]. A dichroic filter was inserted to separate the light at 1030 nm from the light at 515 nm. A spherical lens was inserted to collimate the 515 nm beam to a diameter of approximately 1.5 mm. In order to enable active stabilization of the 515 nm output power, a small fraction of the green light was directed to a photodiode. The entire optical setup was mounted in a compact laser module with dimensions of 183 x 114 x 50 mm^3.

The nonlinear crystals used in the cascade was a 2 x 0.5 x 40 mm (width x height x length) PPMgLN crystal poled with a period of 6.25 µm and a 2 x 0.5 x 30 mm PPMgSLT crystal poled with a period of 7.21 µm. The crystals were antireflection coated at 1030 nm and 515 nm and temperature stabilized in ovens at approximately 60°C to ensure proper phase matching. The main reason for choosing two different crystals were the high nonlinearity of PPMgLN and the superior power handling capability of PPMgSLT.

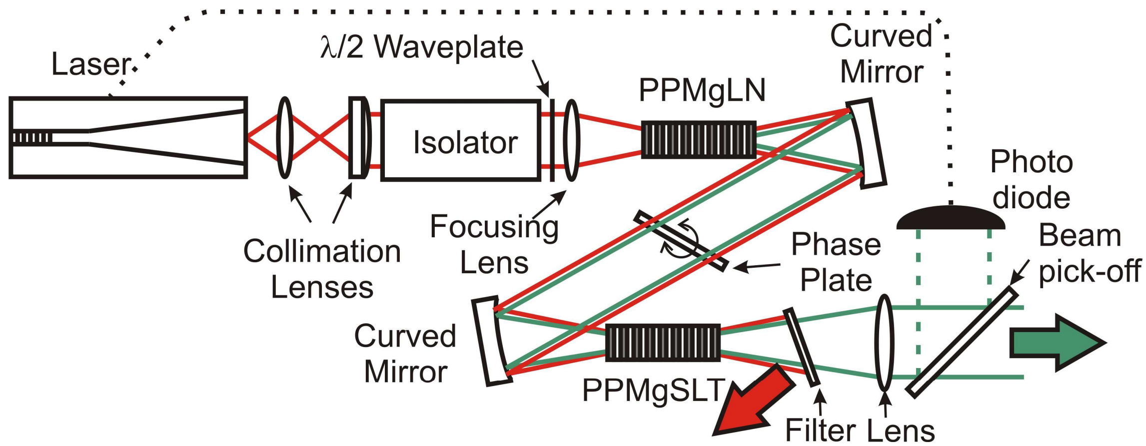

Figure 4. Principle sketch of the experimental setup used for cascaded frequency doubling of a DBR tapered diode laser.

3. EXPERIMENTAL RESULTS

9.3 W of 1030 nm laser light was available before the PPMgLN crystal. Approximately 70 % of this power was contained in the central lobe of the beam. The majority of the second harmonic light is generated by the power contained in the central lobe as the intensity in this part of the beam is highest and that it can be optimally phase matched in the nonlinear crystal. In the phase matched PPMgLN crystal, up to 2.35 W of output power was generated at 515 nm. A conversion efficiency of 25.3% and 3.3%/W nonlinear conversion efficiency was achieved. If only the power contained in the central lobe is considered, the conversion efficiency and nonlinear conversion efficiency were 36% and 7.4%, respectively. When the PPMgSLT crystal is phase matched and the PPMgLN crystal is not phase matched, it was possible to generate 760 mW at 515 nm in the PPMgSLT crystal alone at 8.2% conversion efficiency and 0.93%/W nonlinear conversion efficiency. When considering only the central lobe power an efficiency of 12% was achieved and the nonlinear conversion efficiency was 2.0%/W. With both nonlinear crystals optimally phase matched and the phase plate rotated for optimum constructive interference, up to 3.58 W was generated at 515 nm. A conversion efficiency of 38.5% and a nonlinear conversion efficiency of 5.7%/W was achieved in the cascade and when only considering the power contained in the central lobe, the conversion efficiency was 55% and the nonlinear conversion efficiency was 14%/W. The second harmonic output power vs the input power at 1030 nm is shown in Figure 5. The generated second harmonic power does not follow the expected development for depleted SHG (shown by the lines). This is because the laser power is changed by changing the current to the tapered section of the laser. This results in changed beam profile and astigmatism and thus less optimum focusing in the nonlinear crystals. The electrical to optical efficiency of the laser system including the power used for temperature control was 7%. This high efficiency makes such a laser system more efficient than most solid state lasers and far more efficient than argon ion lasers. The efficiency of the cascading concept is underlined by the fact that the cascaded second harmonic power is larger than the sum of the second harmonic powers generated in the individual crystals.

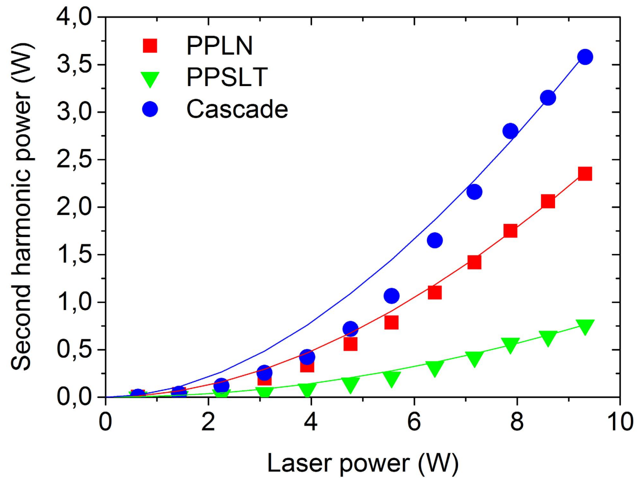

Figure 5. Second harmonic output power with only the first crystal (PPLN) phase matched, only the second crystal phase matched (PPSLT) and with both crystals in the cascade phase matched (Cascade). The crystal temperatures were optimized at every measurement point. Calculated second harmonic power based on the expression for depleted second harmonic generation and the nonlinear conversion efficiencies at maximum input power are included as lines.

A small fraction of the second harmonic power is send onto a photodiode. By providing feedback to the laser it was possible to stabilize the output power. A measurement of the second harmonic power over a duration of 2 hours was performed and the result is shown in Figure 6. The power was stabilized to approximately 3.2 W and the maximum power fluctuations are less than ±0.4% over the two-hour experiment.

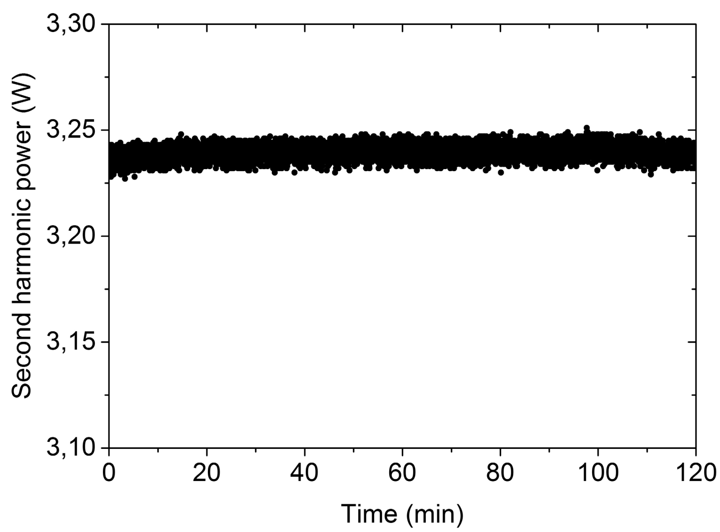

Figure 6. Second harmonic output power measured over a period of two hours using feedback to the laser.

The spectrum of the generated green light was centered at 515.4 nm as shown in Figure 7. The linewidth of the green light was measured to 0.002 nm limited by the resolution of the optical spectrum analyzer.

The generated second harmonic beam is improved in quality compared to the incoming infrared light by the nonlinear process[17]. A nearly Gaussian beam profile is generated and the beam propagation parameter was measured to $M^2_x = 1.08$ and $M^2_y = 1.07$ with a Spiricon M2-200s profiler following the ISO 11146 standard. The caustic curve is shown in Figure 8 and the beam profile in the focus is shown in Figure 9. A slight ellipticity is seen in the second harmonic beam.

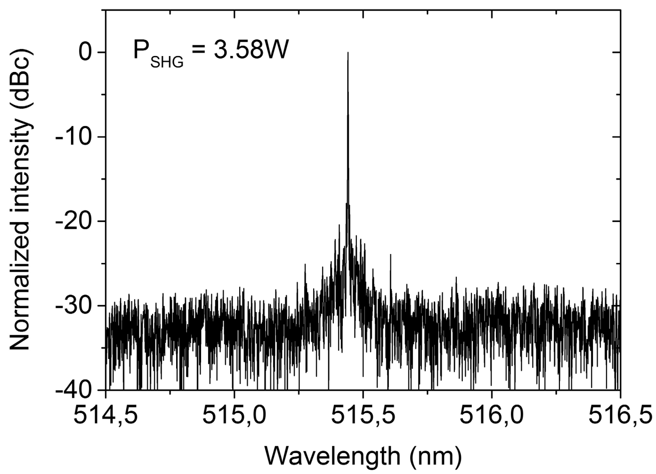

Figure 7. Measured spectrum of the second harmonic light measured at maximum output power.

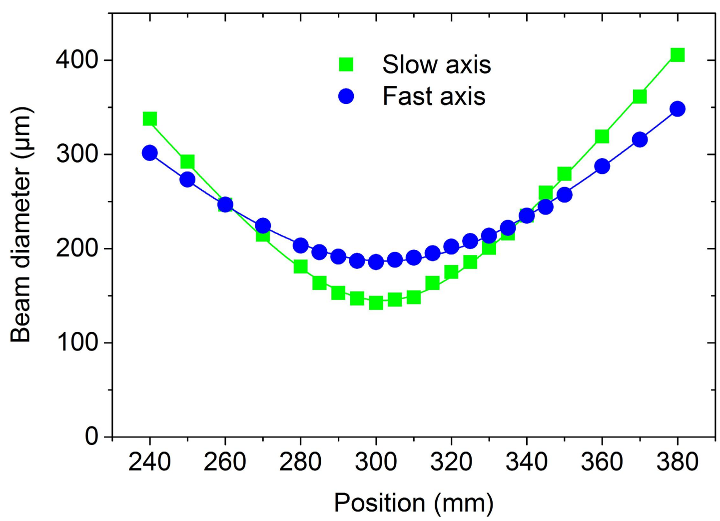

Figure 8. Measured beam diameter at different positions when focusing the second harmonic light with a 300 mm focal length lens.

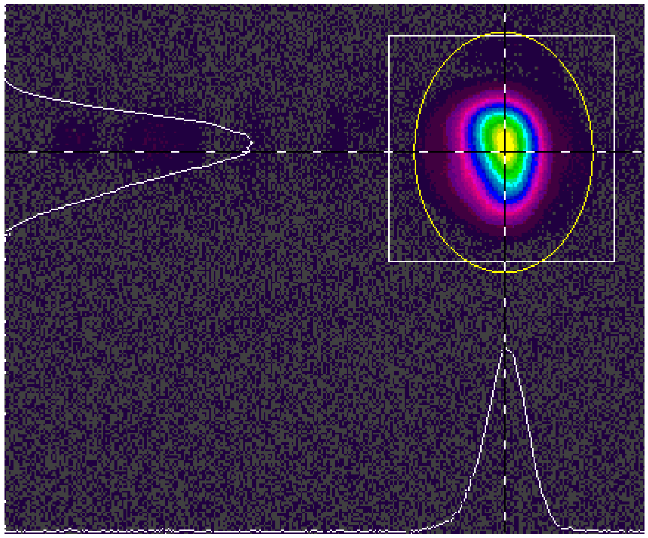

Figure 9. Beam profile in the focus for the second harmonic beam.

4. CONCLUSION

We have demonstrated a 3.5 W laser source at 515 nm with excellent beam properties with $M^2 < 1.1$ by cascaded second harmonic generation of a 1030 nm DBR tapered diode laser. A PPMgLN and a PPSLT crystal were used to optimize conversion efficiency and power handling simultaneously. The 515 nm light is single-frequency with a linewidth below 2 pm. Such a laser source could be a good alternative to argon ion lasers in many applications and is well suited for pumping of Ti:sapphire lasers.

REFERENCES

[1] Müller, A., Marschall, S., Jensen, O.B., Fricke, J., Wenzel, H., Sumpf, B., and Andersen, P.E., "Diode laser based light sources for biomedical applications," Laser & Photonics Reviews 7(5), 605–627 (2013).

[2] Unterhuber, A., Považay, B., Müller, A., Jensen, O.B., Duelk, M., Le, T., Petersen, P.M., Velez, C., Esmaeelpour, M., et al., "Simultaneous dual wavelength eye-tracked ultrahigh resolution retinal and choroidal optical coherence tomography.," Optics Letters 38(21), 4312–4315 (2013).

[3] "Nichia Corporation," <http://www.nichia.co.jp/en/product/laser.html> (16 December 2016).

[4] Samanta, G.K., Kumar, S.C., Devi, K., and Ebrahim-Zadeh, M., "Multicrystal, continuous-wave, single-pass second-harmonic generation with 56% efficiency," Optics Letters 35(20), 3513–3515 (2010).

[5] Kontur, F.J., Dajani, I., Lu, Y., and Knize, R.J., "Frequency-doubling of a CW fiber laser using PPKTP, PPMgSLT, and PPMgLN," Optics Express 15(20), 12882–12889 (2007).

[6] Kim, J.W., Jeong, J., Lee, K., and Lee, S.B., "Efficient second-harmonic generation of continuous-wave Yb fiber lasers coupled with an external resonant cavity," Applied Physics B Laser and Optics 108(3), 539–543 (2012).

[7] Sumpf, B., Hasler, K.-H., Adamiec, P., Bugge, F., Dittmar, F., Fricke, J., Wenzel, H., Zorn, M., Erbert, G., et al., "High-Brightness Quantum Well Tapered Lasers," IEEE Journal of Selected Topics in Quantum Electronics 15(3), 1009–1020 (2009).

[8] Jensen, O.B., Andersen, P.E., Sumpf, B., Hasler, K.-H., Erbert, G., and Petersen, P.M., "1.5 W green light generation by single-pass second harmonic generation of a single-frequency tapered diode laser.," Optics Express 17(8), 6532–6539 (2009).

[9] Hansen, A.K., Tawfieq, M., Jensen, O.B., Andersen, P.E., Sumpf, B., Erbert, G., and Petersen, P.M., "Concept for power scaling second harmonic generation using a cascade of nonlinear crystals," Optics Express 23(12), 15921–15934 (2015).

[10] Maiwald, M., Schwertfeger, S., Güther, R., Sumpf, B., Paschke, K., Dzionk, C., Erbert, G., and Tränkle, G., "600 mW optical output power at 488 nm by use of a high-power hybrid laser diode system and a periodically poled MgO:LiNbO3 bulk crystal.," Optics Letters 31(6), 802–804 (2006).

[11] Jensen, O.B., and Petersen, P.M., "Generation of single-frequency tunable green light in a coupled ring tapered diode laser cavity," Optics Express 21(5), 6076–6081 (2013).

[12] Hansen, A.K., Christensen, M., Noordegraaf, D., Heist, P., Papastathopoulos, E., Jensen, O.B., and Skovgaard, P.M.W., "Efficient Generation of 1.9 W yellow light by Cascaded Frequency Doubling of a DBR Tapered Diode Laser," Applied Optics 55(32), 9270–9274 (2016).

[13] Guo, X., Hou, W., Peng, H., Zhang, H., Wang, G., Bi, Y., Geng, A., Chen, Y., Cui, D., et al., "4.44W of CW 515 nm green light generated by intracavity frequency doubling Yb:YAG thin disk laser with LBO," Optics Communications 267(2), 451–454 (2006).

[14] Müller, A., Fricke, J., Bugge, F., Brox, O., Erbert, G., and Sumpf, B., "DBR tapered diode laser with 12.7 W output power and nearly diffraction-limited, narrowband emission at 1030 nm," Applied Physics B 122(4), 87 (2016).

[15] Fluck, D., and Günter, P., "Efficient second-harmonic generation by lens wave-guiding in KNbO3 crystals," Optics Communications 147(4-6), 305–308 (1998).

[16] Hansen, A.K., Andersen, P.E., Jensen, O.B., Sumpf, B., Erbert, G., and Petersen, P.M., "Highly efficient single-pass sum frequency generation by cascaded nonlinear crystals," Optics Letters 40(23), 5526 (2015).

[17] Karamehmedović, E., Pedersen, C., Jensen, O.B., and Tidemand-Lichtenberg, P., "Nonlinear beam clean-up using resonantly enhanced sum-frequency mixing," Applied Physics B 96(2-3), 409–413 (2009).