Optics Communications 392 (2017) 167–170

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Efficient generation of 3.5 W laser light at 515 nm by frequency doubling a single-frequency high power DBR tapered diode laser

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ARTICLE INFO

Keywords:
Diode lasers
Second harmonic generation
Tapered diode lasers
Visible lasers

ABSTRACT

More than 3.5 W of green light at 515 nm is generated by frequency doubling a single-frequency high power DBR tapered diode laser. The frequency doubling is performed in a cascade of PPMgLN and PPMgSLT crystals in order to reach high power and avoid thermal effects present in PPMgLN at high power. The green light is diffraction limited (M^2 < 1.1) and single-frequency operation is demonstrated with a linewidth less than 2 pm.

1. Introduction

Lasers in the green spectral range are required for a number of applications within biomedicine, holography, laser pumping and displays [1–3]. For many years the argon-ion laser was the workhorse in many of these applications with the possibility to generate multiple watts of light at several wavelengths in the blue-green spectral range, with the 515 nm line having the highest output power. Argon-ion lasers are heavily power consuming with efficiencies typically below 0.1%. Argon-ion lasers have to a large extent been replaced by frequency doubled diode-pumped solid state lasers (DPSSL) with significantly higher efficiency and long lifetime, although their wavelength at 532 nm does not match the absorption spectrum perfectly in all cases. Many important fluorophores used in fluorescence spectroscopy and other biomedical applications are specifically developed for the 515 nm wavelength and are not effectively excited by 532 nm. Also the 515 nm wavelength is extensively used in Raman scattering and for instrumentation in general like e.g. laser Doppler anemometry, 515 nm is an important wavelength. Another application is for pumping of Ti:sapphire lasers, where the absorption peak is located around 490 nm and lasers at shorter wavelengths than 532 nm will increase the efficiency.

DPSSLs at 532 nm are commercially available at power levels ranging from mW to tens of watts. They provide high power stability, narrow spectral linewidth and an excellent beam quality. However, they are also relatively complex with a free space cavity and expensive to manufacture due to the high precision demands on the alignment of components. Alternatives for DPSSLs are direct emitting diode lasers, frequency doubled fiber lasers or directly frequency doubled diode lasers.

Diode lasers emitting in the green spectral region have appeared recently and are attractive due to their high simplicity and efficiency. Lasing in GaN based diode lasers has been demonstrated at many wavelengths ranging from 500 to 532 nm [4]. In this spectral range, the lasers are limited to about 100 mW output power in a single spatial mode due to the narrow ridge waveguide. Higher power is possible by using a broad area diode laser where up to 1 W is commercially available but at the expense of a degraded beam quality [5].

Frequency doubled fiber lasers enable green light generation with high power in the fundamental spatial mode. High power frequency doubled fiber lasers have been demonstrated both in single pass configurations and in external cavity configurations [6–9]. Such lasers are attractive due to their good performance but their high cost limits widespread adoption.

Frequency doubling of diode lasers to watt-level of visible output has been enabled by development of high power near-infrared tapered diode lasers [10,11]. Frequency doubling of these lasers has generated watt-level output power in the blue-green spectral range with excellent spectral and spatial quality [12–14]. Cascaded frequency doubling, where two or more crystals are used to enhance the conversion efficiency in single-pass frequency doubling, has been investigated both for use with tapered diode lasers and fiber lasers resulting in a significant improvement of the conversion efficiency [6,15].

Some applications still rely on the 515 nm wavelength from the

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http://dx.doi.org/10.1016/j.optcom.2017.01.060
Received 7 July 2016; Received in revised form 8 December 2016; Accepted 30 January 2017

argon-ion laser which cannot easily be targeted by solid state lasers although good performance has been demonstrated with frequency doubled Yb:YAG lasers [16]. Frequency doubling of tapered diode lasers is ideally suited to target all wavelengths in the blue-green spectral range due to the wavelength flexibility of semiconductor lasers. A further advantage of diode lasers over solid state and fiber lasers is that the relaxation oscillation frequency is outside the detection bandwidth of most detection systems. Thus very low relative intensity noise can be achieved.

In this work, we demonstrate highly efficient generation of more than 3.5 W light at 515 nm by cascaded frequency doubling of a high power DBR tapered diode laser in periodically poled MgO-doped lithium niobate (PPMgLN) and MgO-doped stoichiometric lithium tantalate (PPMgSLT) crystals. The green light has an excellent beam quality with $M^2 < 1.1$ and the linewidth of the green light is measured to less than 2 pm. Such a laser source could be an ideal replacement for argon-ion lasers.

2. The experimental setup

The laser source consists of a 6 mm long distributed Bragg reflector (DBR) tapered diode laser with a third order surface grating. The ridge waveguide of the tapered laser is 2 mm long with a 1 mm long unpumped DBR section and a 1 mm long pumped ridge waveguide section. The tapered section is 4 mm long with a taper angle of 6°. A detailed description of the diode structure and layout can be found in [17]. The ridge and tapered sections are contacted separately to allow for independent current control of both sections. The tapered diode laser was mounted p-side up on a CuW heat spreader, which was mounted on a 25×25 mm^2 conduction cooled package mount allowing efficient cooling.

The DBR tapered diode laser is capable of emitting more than 12 W of light around 1030 nm as shown in [17]. In our case the ridge section is operated with 300 mA injection current and the heatsink temperature is kept at 20 °C. An output power of 9.7 W is reached at 14 A current to the tapered section as shown in Fig. 1(a). The spectrum of the laser at 9.7 W output power was measured with an optical spectrum analyzer (Advantest Q8347, 3 pm resolution, 35 dB dynamic range) and is shown in Fig. 1(b). The measured spectral width (FWHM) is limited by the resolution of the spectrum analyzer to 0.006 nm and the side mode suppression is larger than 17 dB, with the measurement being limited by the optical spectrum analyzer. The beam profile of the tapered laser in the focal region is shown in Fig. 2. This measurement is performed by focusing the collimated beam from the laser onto a CCD camera using a 300 mm focal length lens. Here it can be seen that the beam has a near-Gaussian beam profile in the fast axis (vertical), while in the slow axis, the beam profile shows a strong central lobe with some lower power side-lobes. The power content of the lateral central lobe was measured to 70% at 9.7 W output power after collimation.

The scheme of the experimental setup for frequency doubling of the DBR tapered laser is shown in Fig. 3. The output from the DBR tapered diode laser is collimated to an approximately circular beam with 1 mm diameter using an aspherical lens for collimating the fast axis and a cylindrical lens for collimating the slow axis and elimination of astigmatism. The beam is passed through an optical isolator with more than 30 dB isolation to prevent feedback to the diode laser and a half-wave plate is inserted after the optical isolator to rotate the polarization to vertical. Two plane folding mirrors are inserted to compact the setup and direct the light through the nonlinear crystals. A 45 mm focal length lens is used to focus the beam to approximately 40 µm radius inside the first nonlinear crystal (PPMgLN). Two curved mirrors with 100 mm radius of curvature and highly reflecting at both 1030 nm and 515 nm are used to collimate and refocus the fundamental and generated second harmonic light into the second nonlinear crystal (PPMgSLT). A plane-parallel 3 mm thick BK7 plate is inserted at Brewsters angle between the two curved mirrors to adjust the phase delay between the fundamental and second harmonic to allow for constructive interference between the incoming and generated frequency doubled light in the second crystal [15,18]. After the second crystal, a filter is used to separate the fundamental infrared light from the generated green light. The generated green light is collimated to a diameter of approximately 1.5 mm. A small fraction of the green light is sent to a photodiode in order to monitor the power level and through feedback to the injection current, the green laser power can be stabilized. All components are mounted on a compact baseplate and enclosed by a lid with total dimensions of 183×114×50 mm^3.

The first nonlinear crystal in the cascade is a 2×0.5×40 mm (width×height×length) PPMgLN crystal (HCPhotonics) poled with a period of 6.25 µm. The crystal is antireflection coated at 1030 nm and 515 nm and temperature stabilized using an oven to achieve phase

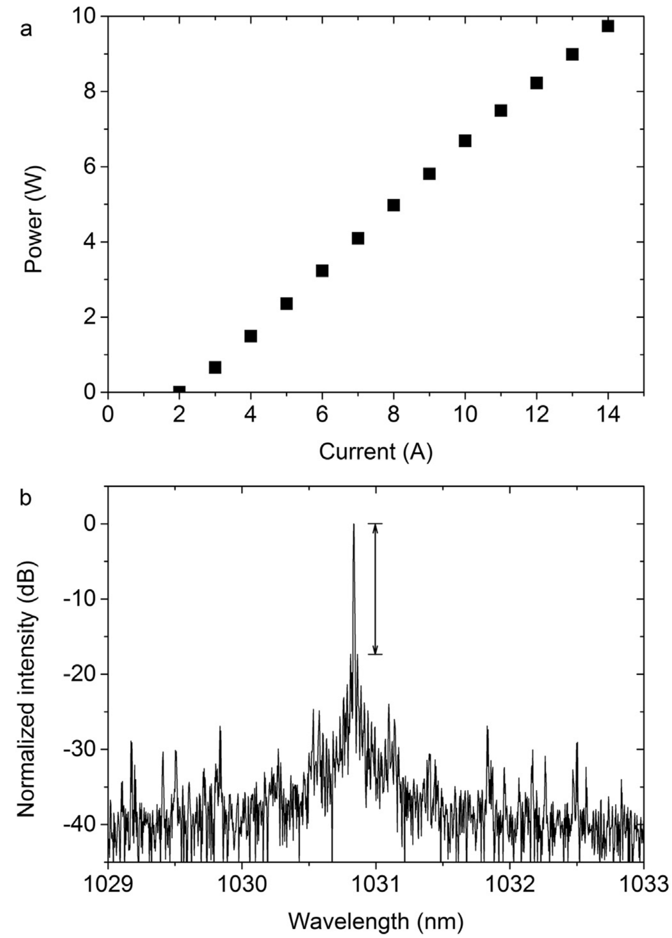

Fig. 1. Output power vs. taper section current for the DBR tapered diode laser at 20 °C temperature and 300 mA ridge section current (a). Spectrum of the DBR tapered diode laser at 9.7 W output power (b).

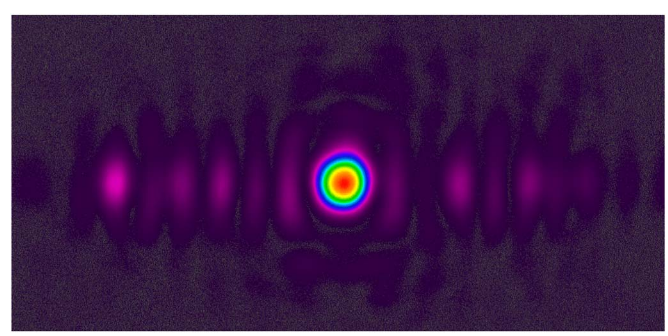

Fig. 2. Beam profile at the focus for the DBR tapered diode laser at 9.7 W output power.

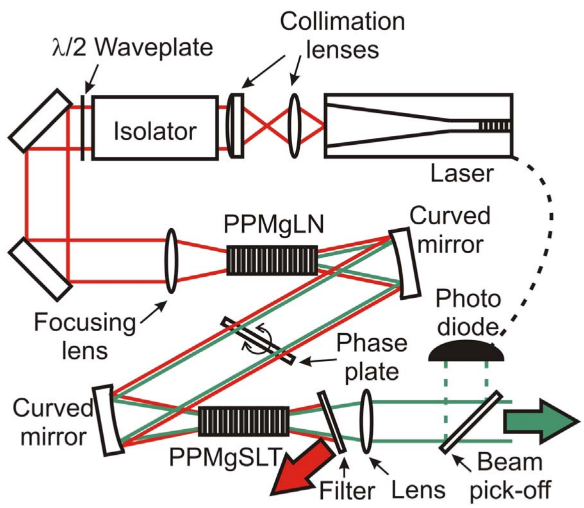

Fig. 3. Sketch of the experimental setup for cascaded second harmonic generation of a DBR tapered diode laser.

matching. In the experiments, the crystal temperature was approximately 62 °C depending on the operating conditions of the tapered diode laser. The second nonlinear crystal is a 2×0.5×30 mm PPMgSLT crystal (Oxide) poled with a period of 7.21 µm. This crystal is cut with 2° angled facets and antireflection coated at 1030 nm and 515 nm. In the experiments, the crystal temperature was kept at approximately 60 °C. The choice of crystal dimensions was limited by availability. The PPMgLN crystal was chosen for its high nonlinearity, while the PPMgSLT crystal was chosen for its ability to handle high visible power levels.

3. Experimental results

After having passed through the optics and the optical isolator, 9.3 W of 1030 nm light is available before the PPMgLN crystal. Out of this laser power, 70% is contained in the diffraction limited central lobe. The central lobe is responsible for the majority of the second harmonic generation as it has the highest intensity and is optimally phase matched, unlike the side-lobes. At optimal phase matching, up to 2.35 W of output power can be generated in the PPMgLN crystal at the second harmonic wavelength of 515 nm. This corresponds to a conversion efficiency of 25.3% and a nonlinear conversion efficiency of 3.3%/W or 36% and 7.4%/W respectively if only the central lobe power is considered. When the temperature of the PPMgLN crystal is far from phase matching, the infrared light passes this crystal and enters the PPMgSLT crystal. When the PPMgSLT crystal is optimally phase matched, 760 mW is generated at 515 nm. This corresponds to a conversion efficiency of 8.2% and a nonlinear conversion efficiency of 0.93%/W or 12% and 2.0%/W considering only the central lobe power. The dependency of the generated power at the second harmonic on the input fundamental power is shown in Fig. 4(a).

When operated in a cascade, with optimal phase matching for both the PPMgLN and the PPMgSLT crystals and the phase plate rotated for optimum constructive interference, up to 3.58 W can be generated at 515 nm. This corresponds to a conversion efficiency of 38.5% and a combined nonlinear conversion efficiency of 5.7%/W for the cascaded crystals. Assuming that primarily the central lobe of the fundamental beam contributes to the frequency conversion, a conversion efficiency of 55% of the central lobe power is achieved and a nonlinear conversion efficiency of 14%/W. This high efficiency shows that there is no penalty in generation of shorter wavelengths despite the shorter poling period and thereby following increase in poling errors and the higher absorption present in the nonlinear materials at shorter wavelengths. The electrical to optical efficiency of the laser is approximately 7%

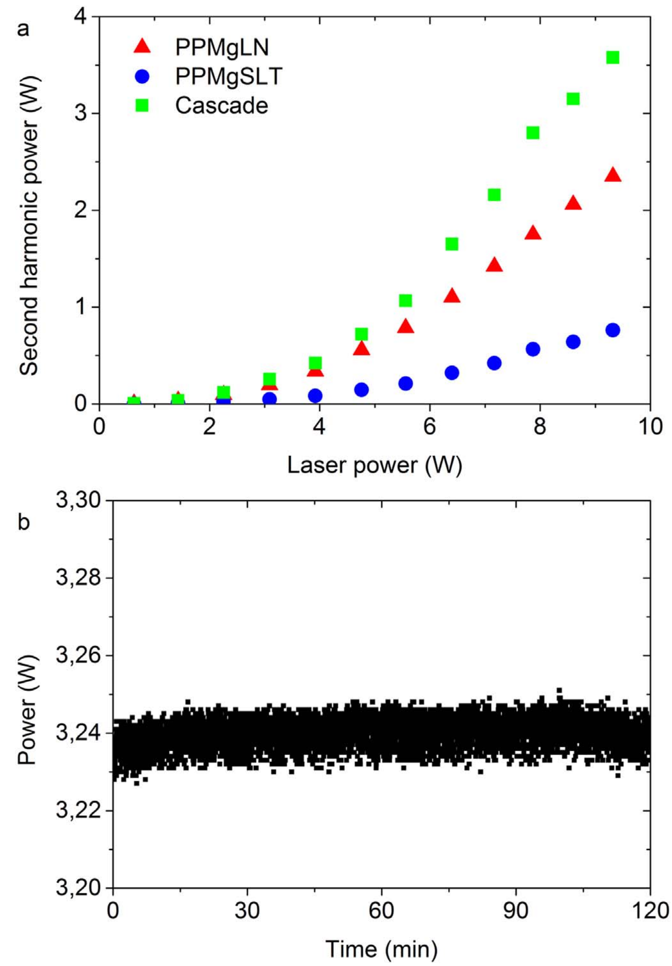

Fig. 4. Power of the second harmonic beam versus input fundamental power for the PPMgLN crystal, PPMgSLT crystal and the cascade (a). Power stability measured over 2 hours with active stabilization (b).

including the power used for temperature control of the laser and crystals. This compares favorably with the efficiency of solid state lasers typically below 5% and Argon ion lasers well below 1%. The dependency of the generated power at the second harmonic on the input fundamental power in cascaded operation is also shown in Fig. 4(a). The power in the cascaded configuration is larger than the sum of the generated power achievable in the individual crystals. This underlines the efficiency of the cascading concept. According to the theory described by Hansen et al.[15], the cascade enhancement is defined as the nonlinear conversion efficiency of the cascade divided by the nonlinear conversion efficiency of the first crystals. The theoretical cascade enhancement at perfect constructive interference and beam overlap is 2.3 using the measured crystal nonlinearities for the central lobe. The experimental cascade enhancement is 1.9, which is in good agreement with the theory, especially considering the non-optimal geometry of the second crystal where the angled input facet results in a slightly different internal propagation angle for the fundamental and second harmonic beam. Further power scaling is possible using cascaded sum frequency generation of beam combined lasers, where more than 5.5 W has been demonstrated at 532 nm [19]. In Fig. 4(a), the generated power does not follow the typical squared hyperbolic tangent expression for second harmonic generation including depletion because the fundamental power is changed by changing the current to the tapered section of the laser diode. This current change simultaneously changes the power, the beam profile and the astigmatism meaning that the focusing conditions inside the nonlinear crystals are not optimized at lower input power.

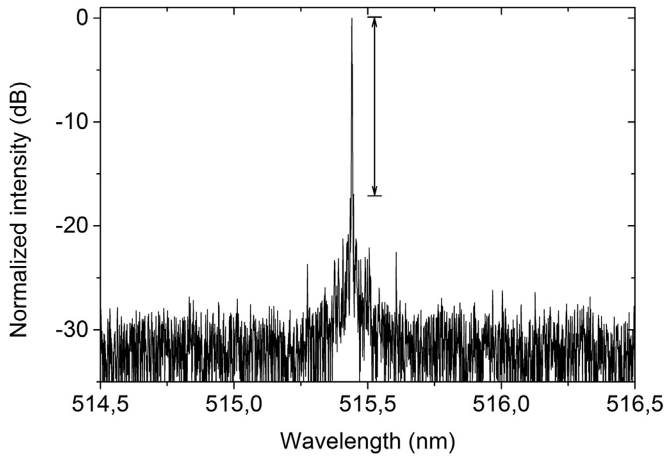

Fig. 5. Spectrum of the generated green light at 3.5 W output power.

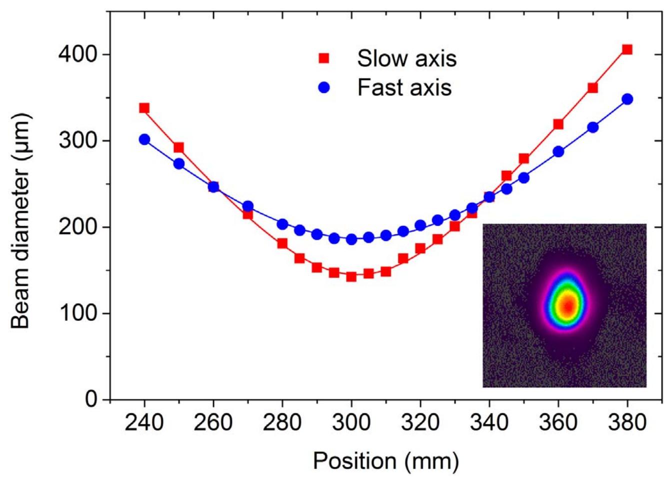

Fig. 6. Measured beam diameter vs. position for the 515 nm laser at 3.5 W output power. The inset shows the beam profile at focus. The beam profiler uses a 300 mm focal length lens to focus the beam on a CCD camera.

The second harmonic power was stabilized using photodiode feedback and the power stability was measured over two hours with power measured every second and the measurement result is shown in Fig. 4(b). The power is stabilized at approximately 3.2 W and over 2 hours the maximum power fluctuations are less than ±12 mW (±0.4%). The spectrum of the green light is centered at 515.4 nm with a spectral width of less than 0.002 nm limited by the optical spectrum analyzer and a side mode suppression of more than 17 dB with the measurement being limited by the optical spectrum analyzer. The spectrum is shown in Fig. 5.

The beam propagation ratio of the 515 nm light was measured to M_x^2 =1.08 and M^2_y =1.07 at maximum output power using a Spiricon M^2–200 s profiler applying the second order moments as specified in the ISO 11146 standard. The resulting caustic curve is shown in Fig. 6 where the beam profile at the focus is included. It can be seen that the beam is stigmatic but with a slight ellipticity. The excellent beam quality of the generated green light indicates that no thermal handling problems are present.

Measurements have been performed to compare the absorption in a 3 mm long Ti:sapphire crystal at 515 nm and 532 nm in order to estimate the increase in pumping efficiency using 515 nm. The measured absorption coefficient at 532 nm was 4.42 cm^{-1} while at 515 nm the absorption coefficient was measured to 4.99 cm^{-1} corresponding to a 13% increase. This indicates that 515 nm is more efficient than the conventional 532 nm for pumping of Ti:sapphire lasers.

4. Conclusion

In this study, we demonstrated a 3.5 W laser source at 515 nm by cascaded second harmonic generation of a 1030 nm DBR tapered diode laser in a PPMgLN and a PPMgSLT crystal. The generated light is diffraction limited with $M^2 < 1.1$ and a narrow linewidth below 2 pm. A power stability of better than ±0.4% was demonstrated. Such a light source could be an ideal replacement for Argon-ion lasers and would be well suited for pumping of Ti:sapphire lasers. Further power scaling is possible using cascaded sum frequency generation of beam combined lasers.

Acknowledgements

This research was supported by the European projects FAMOS (FP7 ICT 317744) and MIB (H2020 667933).

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