DTU Library

Diffraction-limited 577 nm true-yellow laser by frequency doubling of a tapered diode laser

Christensen, Mathias; Vilera, Mariafernanda; Noordegraaf, Danny; Hansen, Anders Kragh; Buss, Thomas; Jensen, Ole Bjarlin; Skovgaard, Peter M. W.

Link back to DTU Orbit

Diffraction-limited 577 nm true-yellow laser by frequency doubling of a tapered diode laser

Mathias Christensen[*a,b], Mariafernanda Vilera[a,b], Danny Noordegraaf[a], Anders K. Hansen[b], Thomas Buß[a], Ole B. Jensen[b], Peter M. W. Skovgaard[a]

[a]Norlase ApS, Brydehusvej 30, 2750 Ballerup, Denmark; [b]Technical University of Denmark, Department of Photonics Engineering, Frederikssborgvej 399, 4000 Roskilde Denmark

ABSTRACT

A wide range of laser medical treatments are based on coagulation of blood by absorption of the laser radiation. It has, therefore, always been a goal of these treatments to maximize the ratio of absorption in the blood to that in the surrounding tissue. For this purpose lasers at 577 nm are ideal since this wavelength is at the peak of the absorption in oxygenated hemoglobin. Furthermore, 577 nm has a lower absorption in melanin when compared to green wavelengths (515 – 532 nm), giving it an advantage when treating at greater penetration depth. Here we present a laser system based on frequency doubling of an 1154 nm Distributed Bragg Reflector (DBR) tapered diode laser, emitting 1.1 W of single frequency and diffraction limited yellow light at 577 nm, corresponding to a conversion efficiency of 30.5%. The frequency doubling is performed in a single pass configuration using a cascade of two bulk non-linear crystals. The system is power stabilized over 10 hours with a standard deviation of 0.13% and the relative intensity noise is measured to be 0.064 % rms.

Keywords: Visible lasers, tapered diode laser, second harmonic generation, 577 nm

1. INTRODUCTION

The use of yellow lasers in the medical industry has received special attention due to its highly selective absorption in oxygenated hemoglobin. Today the dominant wavelength for a number pf treatments involving photocoagulation of blood is 532 nm. However, the higher selectivity of 577 nm light makes it possible to achieve the same therapeutic effect but at the same time decrease the damage to surrounding tissue. For this reason 577 nm has been investigated for, e.g., opthalmology[1,2]. Yellow lasers are also suitable for flow cytometry[3] because they can used to selectively excite certain fluorophores.

For most applications the ideal laser would be a laser diode emitting directly at the desired wavelength. While progress is being made with pushing laser diodes towards the yellow region they are, unfortunately, still far from emitting enough light for medical treatments. For this reason second harmonic generation (SHG) is the predominent way to reach the green and yellow spectral regimes. While green lasers at 532 nm lasers have become a commodity due to the diode pumped solid state (DPSS) technology, the yellow to orange spectral range has proved to be more difficult to reach. Using exotic lasing materials, lasers at 570 nm have shown 1 W of output power[4]. In optically pumped semiconductor lasers (OPSLs) the laser crystal has been exchanged with a disk of semiconductor material. This gives a higher degree of freedom with regards to available wavelengths and these lasers have shown output powers of 20 W at 588 nm[5]. However, these systems are based on free space cavities which make them highly susceptible to external perturbations and great care therefore has to be taken with regards to, e.g., temperature stabilization of the cavity. At the same time their electrical to optical conversion efficiency is low. Raman fiber lasers can also produce high output powers with excellent beam quality at wavelengths which are otherwise difficult to reach. Using two Raman fiber amplifiers with a common seed in combination with external frequency doubling, 25 W of 589 nm light has been demonstrated[6]. Unfortunately, these systems quickly become rather complex and as a result very expensive. This high price tag limits widespread use.

*mac@norlase.com; Phone +45 9397 7472; www.norlase.com

Another option to reach the yellow spectral region is direct frequency doubling of laser diodes. If this is done in a single pass configuration, then the only cavity in the system is the laser diode itself, making the whole system highly insensitive to external perturbations. However, efficient single pass frequency doubling requires a combination of high power, good beam quality and high spectral stability. Tapered laser diodes have now shown several watts of power around 1154 nm which have yielded 860 mW of yellow light by frequency doubling with a waveguide non-linear crystal[7]. Unfortunately, it is not possible to scale this system to several watts of output power due to thermal lensing in the waveguide crystal.

We present a laser system emitting 1.1 W of diffraction limited light at 577 nm. The system is based on cascaded frequency doubling of a tapered laser diode using two periodically poled lithium niobate (PPLN) crystals. A cascade of two crystals was chosen in order to significantly increase the efficiency compared to what can be achieved with a single crystal, increasing the output power potentially even beyond the sum of the powers achievable with each crystal individually[8]. The linewidth of the laser is measured to be below 4 pm and the beam quality (M^2) of the second harmonic is 1.04 and 1.03 in the horizontal and vertical axes respectively.

2. SETUP AND RESULTS

The system is based on a tapered laser diode similar to the ones described by R. Bege et al.[7]. The laser diode consists of three sections: The rear mirror of the cavity is defined by a Distributed Bragg Reflector which selects a single longitudinal mode. Next to this a ridge waveguide to defines the transverse mode of the laser after which a tapered section allows the fundamental mode to diverge and thereby be amplified to a level which cannot be reached in ridge waveguide laser. The laser diode has separate contacts for the ridge waveguide section and the tapered amplifier. The output power and the wavelength of the laser diode is shown as a function of the current to the tapered section in Figure 1. The wavelength shows sudden drops in the wavelength of 30-35 pm, which corresponds well to a longitudinal mode-hop of the laser diode. Figure 2 depicts the optical spectrum of the tapered diode laser at 6 A. The linewidth of the laser diode is <4 pm, limited by the resolution of the optical spectrum analyser (OSA). An Advantest Q8347 was used to record all spectra.
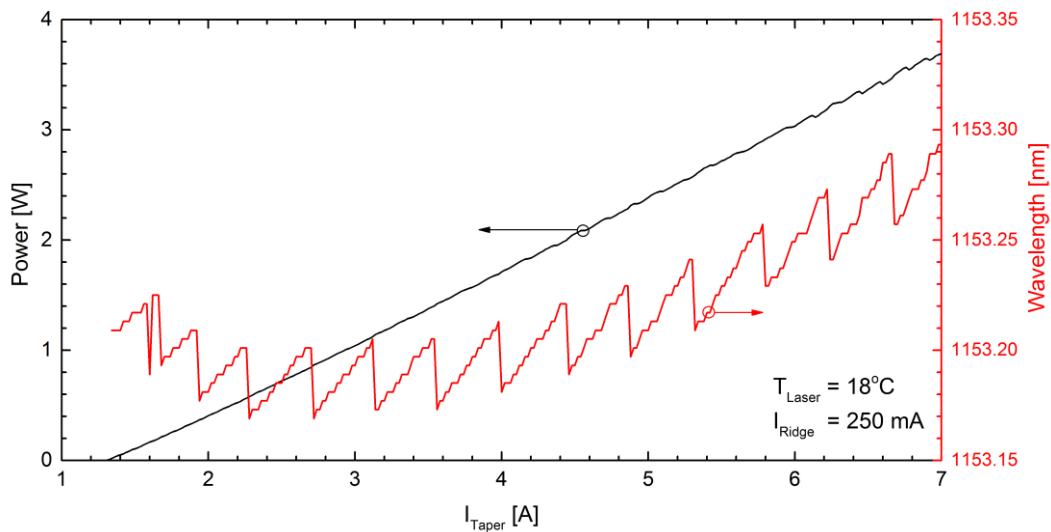

Figure 1. Power (black line) and wavelength (red line) of the laser diode as a function of the tapered amplifier current. The sudden drops in the wavelength of 30-35 pm corresponds to a hop between longitudinal modes of the laser diode.
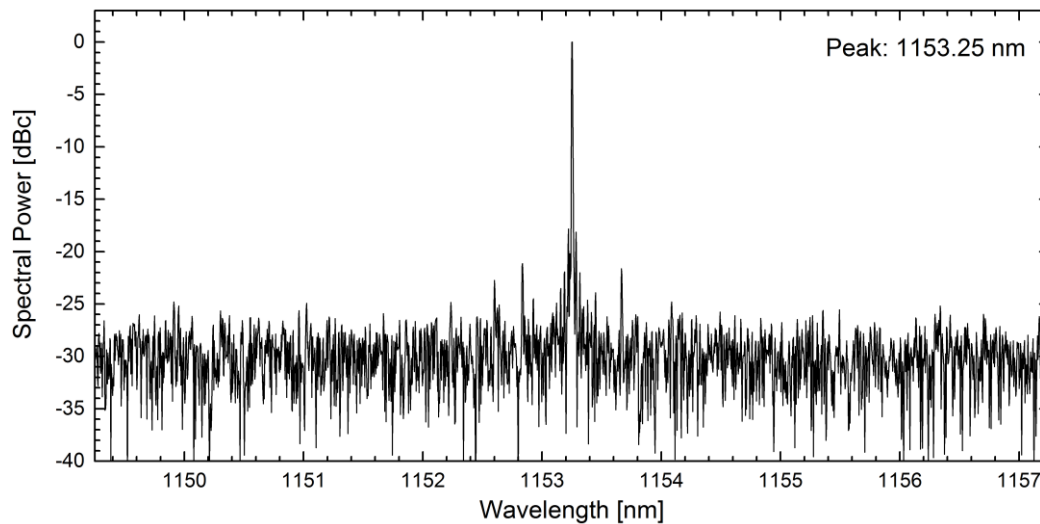
Figure 2. Spectrum of the laser diode. The laser was operated at 18°C, 250 mA through the ridge waveguide section and 6 A through the tapered amplifier section.

We measured the beam properties of both the collimated fundamental light and the second harmonic with an M2-200S system from Ophir Photonics. The system measures the M^2 using the second moment with a 300 mm lens. Figure 3 shows an image of the beam profile of the fundamental light in the focal plane of the lens, corresponding to an image of the virtual source point inside the laser diode. At the chosen current to the tapered section of 6 A, the M^2 was 2.35 in the horizontal axis and 2.04 in the vertical axis. The emitted beam from tapered laser diodes usually consists of a powerful Gaussian-like central lobe and a number of higher order side modes. For this particular laser diode 87% of the power is in this Gaussian-like central lobe at this current, so the side lobes are difficult to see from the figure.
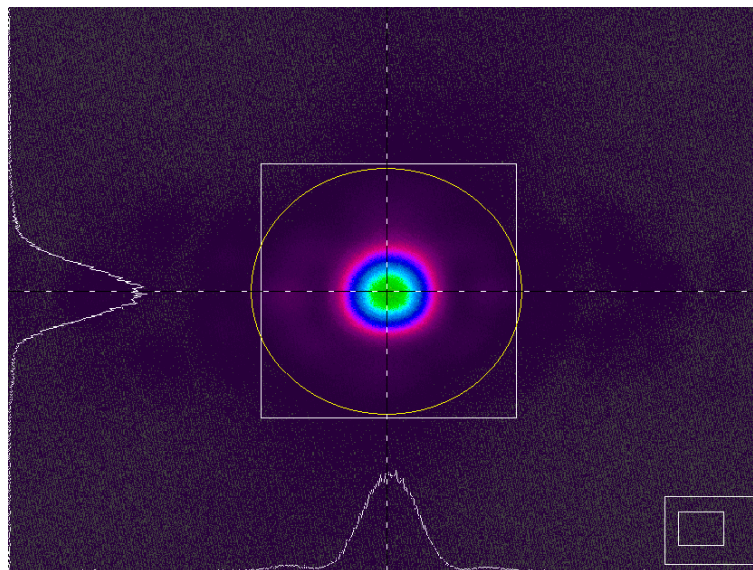

Figure 3. Image of the virtual source point of the laser diode. The measured M^2 values are 2.35 and 2.04 in the horizontal and vertical axis respectively. The laser was operated at 18°C, 250 mA through the ridge waveguide and 6 A through the tapered amplifier.

A sketch of the setup for frequency doubling is shown in Figure 4. The laser diode is collimated and an optical isolator is used to protect it from external feedback. The polarization is rotated to vertical using a half-wave plate to match with the crystallographic Z-axis of the PPLN crystal. The fundamental light is focused into the first crystal and both the

fundamental and second harmonic are collimated using a spherical mirror and sent through a glass phase plate to adjust for the phase mismatch between the two fields which accumulates during the propagation in air. Both beams are focused into the second crystal using an identical curved mirror after which the fundamental beam is dumped and the second harmonic is collimated. The whole system is enclosed in a case measuring 183 x 114 x 50 mm^3.
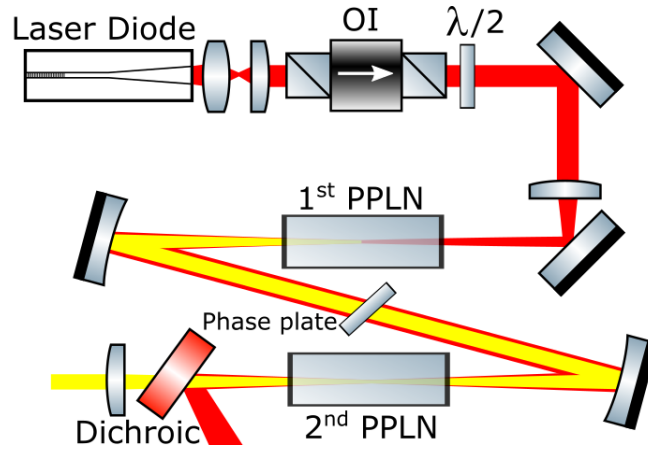

Figure 4. Sketch of the setup used for frequency doubling. OI: optical isolator, λ/2: half-wave plate, Dichroic: mirror with HR coating at 1154 nm and AR coating at 577 nm.

The second harmonic output power as a function of the fundamental power is shown in Figure 5. The power was varied by changing the current through the tapered amplifier and the measurements for individual crystals were performed by tuning the temperature of the crystals so that only one of them was phase matched at a time. The second harmonic power did not completely follow the quadratic fit (solid lines) as expected, this was because the laser diode was collimated at a fixed tapered current. Therefore, the slow axis was not exactly collimated at other currents. Additionally, the beam quality of the laser diode also decreases slightly at higher output powers. The maximum second harmonic power generated by crystal 2 was 434 mW, while the maximum for the cascade was 1125 mW yielding a cascade enhancement of 2.6 times. The maximum fundamental power was 3.69 W, yielding optical to optical conversion efficiencies of 11.8% and 30.5% for a single crystal and the cascade respectively. The spectrum of the second harmonic is shown in Figure 6. The linewidth of the second harmonic was <4 pm, limited by the OSA resolution.
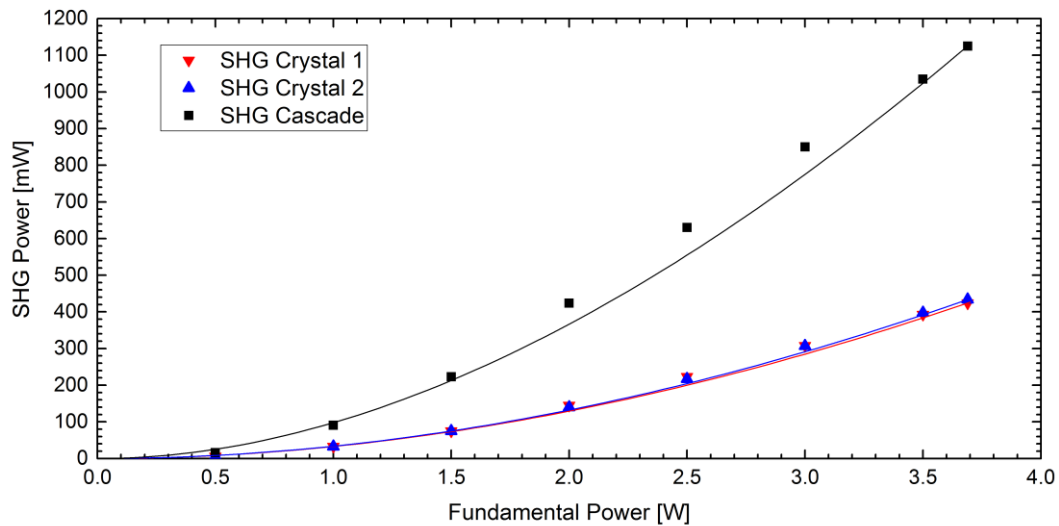

Figure 5. Second harmonic power as a function of the fundamental power. As expected the power of the cascade exceeds the sum of the powers from the crystals individually. The markers indicate experimental measurements and the lines are quadratic fits. The laser diode was operated at 18°C and 250 mA through the ridge waveguide.
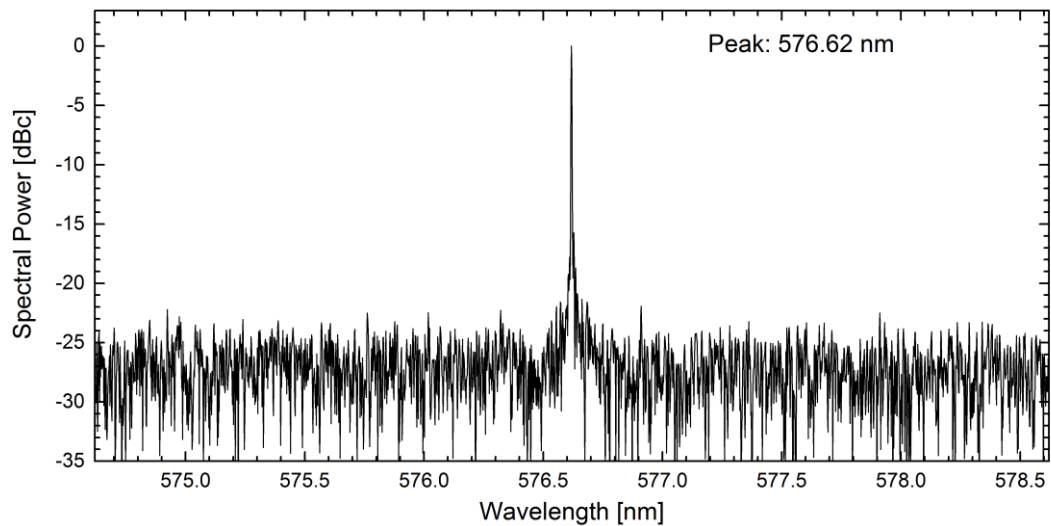
Figure 6. Spectrum of the second harmonic light. The laser was operated at 18ºC, 250 mA through the ridge waveguide section and 6 A through the tapered amplifier section.

The focus beam profile of the second harmonic is shown in Figure 7. Since the efficiency of the second harmonic process is intensity dependent it will be more efficient for the central lobe than for the higher order modes. The beam quality (M^2) of the second harmonic is, therefore, improved to 1.04 in the horizontal axis and 1.03 in the vertical axis.
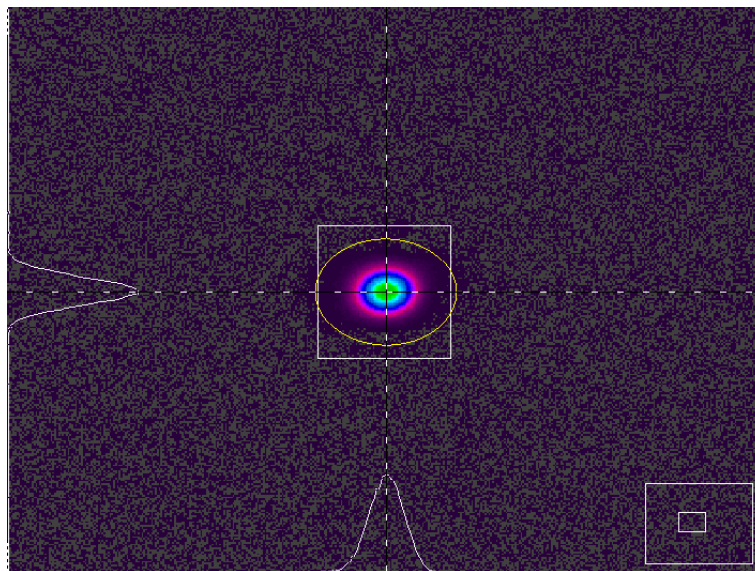

Figure 7. Focus beam profile of the second harmonic beam. M^2 values are measured to be 1.04 and 1.03 in the horizontal and vertical axis respectively. The laser was operated at 18°C, 250 mA ridge waveguide current and 6 A tapered amplifier current.

A small fraction of the beam was picked out after collimation of the second harmonic, monitored with a photodiode and used for power stabilization of the second harmonic. The resulting stabilized second harmonic power over a period of 10 hours is shown in Figure 8. The standard deviation of the power over the full period was 1.04 mW, corresponding to 0.13 % of the mean power.
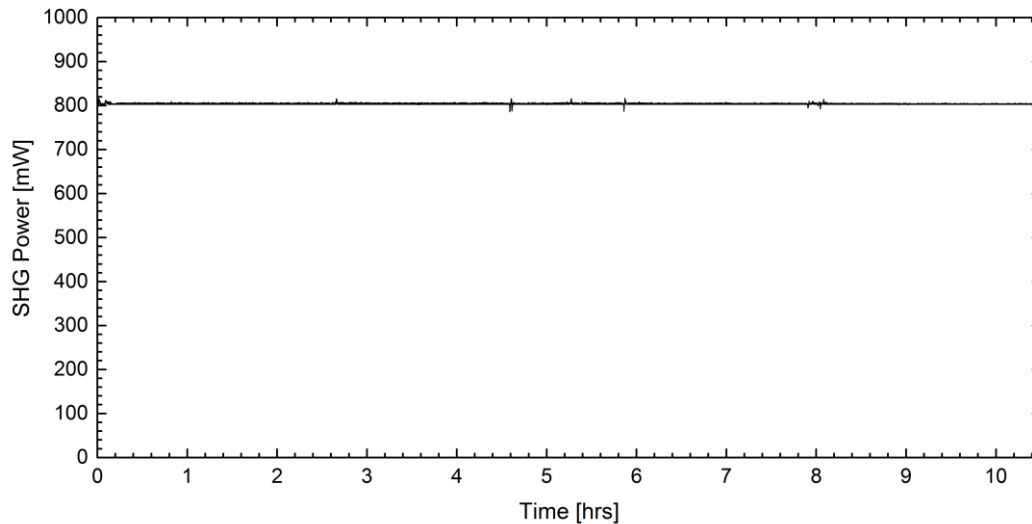
Figure 8. Power stability of the second harmonic light over 10 hours. The standard deviation over the full 10 hours is 1.04 mW, corresponding to 0.13%.

The cumulative relative intensity noise (RIN) of the second harmonic in the range from 100 Hz to 1 MHz is shown in Figure 9. The RIN of the tapered laser diode is dominated by the RIN of current through the tapered section since the relaxation oscillations of the laser diode is in the GHz range. This RIN of the laser diode will then be transferred through, and amplified by, the second harmonic process. This process and a description of how the RIN was measured has been published elsewhere[9]. Using a low noise power supply (Norlase Aurora One) for the laser system, the total RIN in the full measurement range was measured to be 0.064 % rms. The sudden increase in the integrated RIN at 300 kHz is due to a noise peak from the current supply which is transferred to the optical RIN.
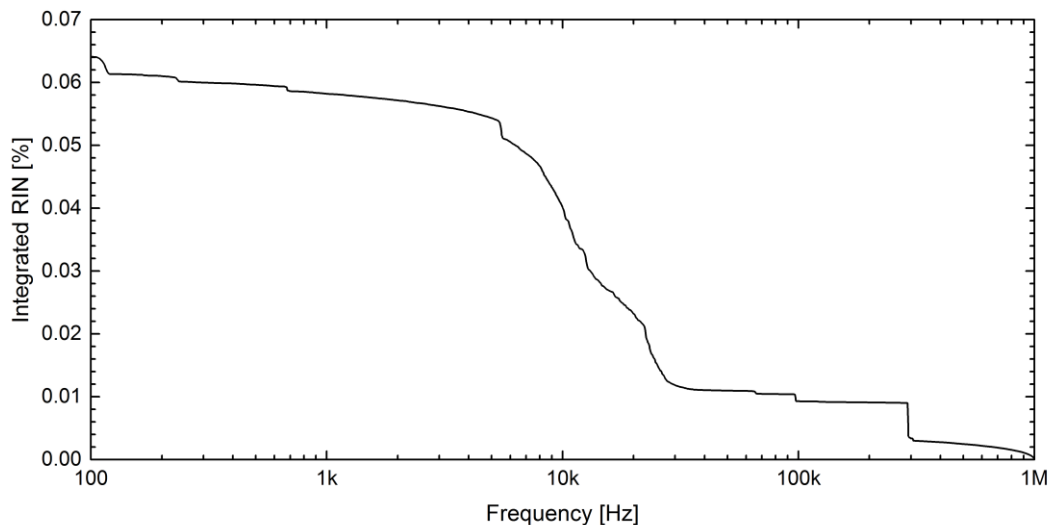

Figure 9. Measurement of the cumulative integrated RIN of the second harmonic, starting at 1 MHz and ending at 100 Hz. The total RIN in the range 100 Hz to 1 MHz is 0.064 % rms. The laser was operated at 18°C, 250 mA ridge waveguide current and 6 A tapered amplifier current.

3. CONCLUSION

We have demonstrated a compact laser system with 1.1 W of true-yellow light at 577 nm using single pass cascade frequency doubling of a tapered laser diode. The combination of the high power diode laser and the cascade of non-linear crystals enable a conversion efficiency of 30.5%, eliminating the need for an external cavity for frequency doubling. Moreover, the beam quality of the second harmonic is close to being diffraction limited with an M^2 of just 1.04 and 1.03

in the horizontal and vertical axis respectively. We have shown that the laser can be power stabilized over 10 hours with a standard deviation of 0.13% and that the relative intensity noise in the range 100 Hz to 1 MHz is 0.064 % rms. The whole system is encased in a case measuring 183 x 114 x 50 mm^3. The combination of small footprint and absence of a free space cavity enables more widespread use of yellow lasers in the medical industry.

FUNDING

REFERENCES

[1]   Inagaki, K., Ohkoshi, K., Ohde, S., Deshpande, G. A., Ebihara, N.., Murakami, A., "Comparative efficacy of pure yellow (577-nm) and 810-nm subthreshold micropulse laser photocoagulation combined with yellow (561–577-nm) direct photocoagulation for diabetic macular edema," Jpn. J. Ophthalmol. **59**(1), 21–28 (2015).

[2]   Kwon, Y. H., Lee, D. K.., Kwon, O. W., "The Short-term Efficacy of Subthreshold Micropulse Yellow (577-nm) Laser Photocoagulation for Diabetic Macular Edema," Korean J. Ophthalmol. **28**(5), 379–385 (2014).

[3]   Kapoor, V., Karpov, V., Linton, C., Subach, F. V., Verkhusha, V. V.., Telford, W. G., "Solid state yellow and orange lasers for flow cytometry," Cytom. Part A **73A**, 570–577 (2008).

[4]   Fang, Q., Lu, D., Yu, H., Zhang, H.., Wang, J., "Self-frequency-doubled vibronic yellow Yb:YCOB laser at the wavelength of 570 nm," Opt. Lett. **41**(5), 1002 (2016).

[5]   Kantola, E., Leinonen, T., Ranta, S., Tavast, M.., Guina, M., "High-efficiency 20 W yellow VECSEL," Opt. Express **22**(6), 6372–6380 (2014).

[6]   Feng, Y., Taylor, L. R.., Calia, D. B., "25 W Raman-fiber-amplifier-based 589 nm laser for laser guide star," Opt. Express **17**(21), 19021–19026 (2009).

[7]   Bege, R., Blume, G., Jedrzejczyk, D., Paschke, K., Feise, D., Hofmann, J., Bugge, F.., Tränkle, G., "Yellow laser emission at 578 nm by frequency doubling with diode lasers of high radiance at 1156 nm," Appl. Phys. B **123**(109), 1–11, Springer Berlin Heidelberg (2017).

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

[9]   Tawfieq, M., Hansen, A. K., Jensen, O. B., Marti, D., Sumpf, B.., Andersen, P. E., "Intensity Noise Transfer Through a Diode-pumped Titanium Sapphire Laser System," IEEE J. Quantum Electron. **PP**(99), 1–1 (2017).