New class of compact diode pumped sub 10 fs lasers for biomedical applications

Le, T.; Mueller, A.; Sumpf, B.; Jensen, Ole Bjarlin; Hansen, Anders Kragh; Andersen, Peter E.

Published in:
Frontiers in Ultrafast Optics: Biomedical, Scientific, and Industrial Applications XVI

Link to article, DOI:
10.1117/12.2208589

Publication date:
2016

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

Citation (APA):
Le, T., Mueller, A., Sumpf, B., Jensen, O. B., Hansen, A. K., & Andersen, P. E. (2016). New class of compact diode pumped sub 10 fs lasers for biomedical applications. In *Frontiers in Ultrafast Optics: Biomedical, Scientific, and Industrial Applications XVI* (Vol. 9740). Article 97400D SPIE - International Society for Optical Engineering. https://doi.org/10.1117/12.2208589

New class of compact diode pumped sub 10 fs lasers for biomedical applications

T. Le[1]*[a], A. Müller[b], B. Sumpf[b], O. B. Jensen[c], A. K. Hansen[c] P. E. Andersen[c],
[a]Femtolasers, Fernkorngasse 10, 1100 Vienna, Austria; [b]Ferdinand-Braun-Institut für Höchstfrequenztechnik, Gustav-Kirchoff-Strasse 4, 12489 Berlin, Germany; [c]DTU Fotonik, Department of Photonics Engineering, Technical University of Denmark, Frederiksborgvej 399, 4000 Roskilde, Denmark

ABSTRACT

Diode-pumping Ti:sapphire lasers promises a new approach to low-cost femtosecond light sources. Thus in recent years much effort has been taken just to overcome the quite low power and low beam qualities of available green diodes to obtain output powers of several hundred milliwatts from a fs-laser. In this work we present an alternative method by deploying frequency-doubled IR diodes with good beam qualities to pump fs-lasers. The revolutionary approach allows choosing any pump wavelengths in the green region and avoids complicated relay optics for the diodes. For the first time we show results of a diode-pumped 10 fs-laser and how a single diode setup can be integrated into a 30 x 30 cm² fs-laser system generating sub 20 fs laser pulses with output power towards half a Watt. This technology paves the way for a new class of very compact and cost-efficient fs-lasers for life science and industrial applications.

Keywords: Tapered diode lasers, Second harmonic generation, Ti:sapphire lasers, ultrafast lasers, femtosecond lasers

1. INTRODUCTION

The fs-laser has become an irreplaceable light source for a vast number of applications in research, medicine, and security. In particular mode-locked Ti:sapphire lasers have found widest penetration into the commercial fs-laser market. Due to better thermal and material properties of sapphire over many other host media, Ti:sapphire lasers are regarded as the ultimate light source in terms of power, pulse duration and stability. They even come as turn-key devices that can work in difficult environments. However, in the majority of cases they are still a big cost factor in their role as a light source. Since first ultrafast lasers commercially became available in the early 1990s the basic principle of how a mode-locked laser delivers femtosecond pulses has not undergone ground-breaking changes in the sense, that their size, performance and cost still depend on power, size and cost of the available pump lasers. Starting with large frame Ar-Ion lasers at the beginning pump lasers nowadays based on diode-pumped frequency doubled Nd:Vanadate or Nd:YAG laser systems that are entirely solid-state and much more compact. But in fact, multiple wavelength conversion units, moderate electro-optical efficiencies and some level of complexity result in demanding manufacturing efforts, heavy and large device dimensions and water cooling requirements. Thus size and cost of a femtosecond Ti:sapphire laser primarily depend on the availability and technology of the pump laser.

Since the challenge to generate powerful continuous wave green light with diffraction-limited beam quality at small cost and dimension has not been accepted for a long time alternative light sources to the Ti:sapphire laser came up to existence. For instance femtosecond fiber lasers pumped with laser diodes deliver several 100 mW using an amplifying stage. Although power and pulse duration are limited by fiber non-linearities they have started to replace Ti:sapphire lasers in many areas like THz generation or two-photon polymerization. However, Erbium doped fibers have to be frequency doubled thus limiting their usefulness in the 800 nm wavelength range where biological tissues have less absorption or common photo-conductive switches for THz generation are readily available. Also in optical coherence tomography the Ti:sapphire laser had been replaced by very cost-effective super-luminescence light emitting diodes which fortunately accelerated the market penetration of OCT devices rapidly[1]. Also wavelength swept sources based on semiconductor optical amplifiers at 1050 nm enabling better penetration and faster scanning are gaining more relevance[2].

---

[1] tuan.le@femtolasers.com; phone: +431503700248; www.spectra-physics.com

Frontiers in Ultrafast Optics: Biomedical, Scientific, and Industrial Applications XVI, edited by
Alexander Heisterkamp, Peter R. Herman, Michel Meunier, Stefan Nolte, Proc. of SPIE Vol. 9740,
97400D · © 2016 SPIE · CCC code: 0277-786X/16/$18 · doi: 10.1117/12.2208589

But none of these light sources can fully replace the femtosecond Ti:sapphire laser providing the highest axial resolution in OCT or the broadest THz spectra[3,4].

In this work we present latest results of using frequency doubled tapered diode lasers to pump femtosecond Ti:sapphire lasers. The pump laser consists of a spectrally stabilized, high-efficient, high brightness tapered diode laser combined with a periodically poled nonlinear crystal. In contrast to alternative solid-state laser technologies no additional optical resonator is required to achieve SHG efficiencies up to 19 % with one non-linear crystal only in single-pass configuration[5]. As alignment tolerances are significantly relieved compared to a resonator concept, innovative mounting and packaging technologies can be applied, aiming at significantly reduced costs, improved compactness and improved performances with respect to low amplitude noise and long term power stability. Using this concept 82 mW from a mode-locked Ti:sapphire laser pumped by a single-pass frequency doubled DBR-tapered diode laser was already demonstrated[6]. However, very recently a new concept for power scaling the second harmonic generation by cascading conversion stages was introduced[7]. Using two nonlinear crystals 39 % optical efficiency was achieved from a 9.5 W DBR-tapered diode laser. In this work we report on the first results obtained using a two stage conversion scheme to pump an ultra-broadband Ti:sapphire laser.

2. EXPERIMENT

The pump laser consists of a 6 mm DBR-tapered diode laser generating 10.5 W of light at 1064 nm. Two separate electrical contacts control the currents through a 4 mm tapered diode section and half of a 2 mm ridge wave guide section. The DBR diode laser is mounted p-side up on a CuW heat spreader which is again mounted on a 25 x 25 mm conduction cooled package mount. The astigmatic emission from the diode is collimated by an aspheric lens in the fast axis and a cylindrical lens is used to correct the astigmatism and collimate the beam in the slow axis. The collimated beam is then sent through a half-wave plate and an optical isolator to prevent light reflected back to the DBR diode laser. A second half-wave plate is used after the isolator to adjust and optimize the second harmonic generation. For single-pass configuration a lens is used to focus the beam into a 30 mm PPMgLN crystal with a beam waist diameter of approximately 60 µm. The crystal is angled cut at 10°, antireflection coated at 1064 nm and 532 nm and temperature stabilized at 35 °C. The SHG output power reaches up to 1.7 W. The sealed housing of the DBR diode laser plus conversion stage (laser head) has a foot print of about 140 mm x 89 mm. Emission of this setup is used to pump a standard dispersive mirror based cavity that supports pulse durations down to 10 fs[8]. Our gain medium is a Ti:sapphire crystal with 4 mm optical path. The absorption is $\alpha = 4.25\ \mathrm{cm}^{-1}$ (±5 %) at 514 nm with a FOM of ~150. The pump beam having a collimated diameter of about 2.5 mm is focused into the crystal with an AR-coated $f = 35$ mm lens. Two dichroic curved mirrors are focusing and directing the beam to both arms of the x-folded cavity. The angles are optimized to compensate for astigmatism inside the crystal. All plane mirrors in the fs-laser are negative dispersive supporting reflectivities higher than 99.5 % with an average GVD of about $-40\ \mathrm{fs}^2$ between 700 nm to 900 nm. Soft aperture mode-locking is initiated by disturbing one end mirror. The pulse repetition rate that basically determines the pulse energy is set by the length of the cavity. In this work we report on results with a 300 MHz cavity (length ~0.5 m) pumped with single-pass SHG and a 125 MHz cavity (length ~1.2 m) pumped with double cascaded SHG configuration.

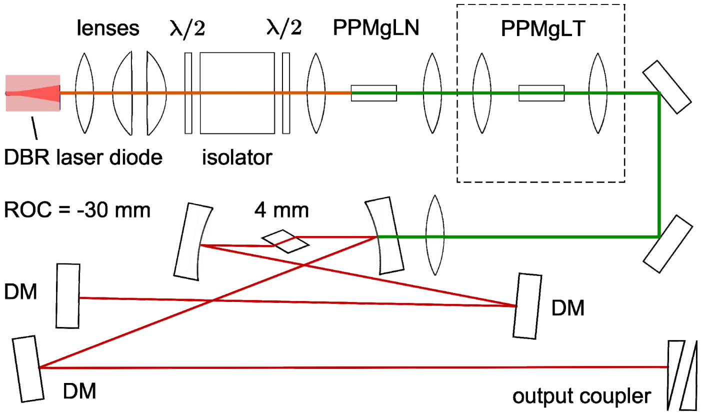
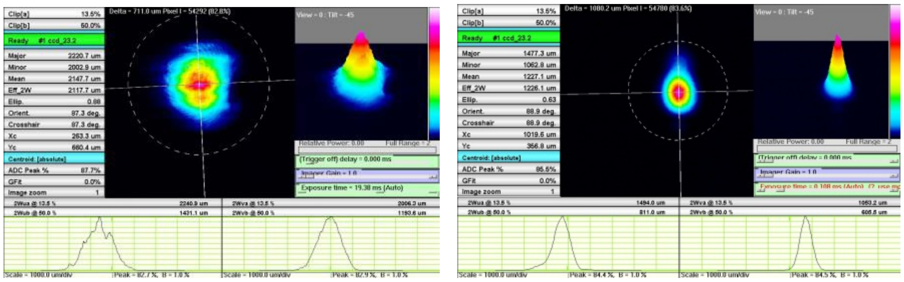


Figure 1: Optical scheme of how fs-laser light is generated starting from a DBR tapered diode laser. The dashed square denotes the additional conversion stage to enhance the second harmonic output. DMs are dispersive mirrors.

The beam profile of the single-pass configuration is measured using a WinCamD-UCD3 camera from DataRay Inc. Throughout 1 W to 1.6 W behind the first SHG stage the beam cross sections show ripples and distinct deviations from axial symmetry (see Figure 2). For comparison a conventional diode pumped solid-state (DPSS) laser (gem 532 from Laser Quantum) is used. Swapping between both pump light sources shows that the pump efficiency is 10 % to 15 % less for the frequency doubled DBR diode laser. However, the structured beam profile is not translated into the femtosecond laser which delivers a smooth intensity profile as normal (Figure 2: right). The beam is used to pump a 300 MHz femtosecond Ti:sapphire laser delivering sub 20 fs pulses. At 1.5 W more than 190 mW output power with pulse energies in the order of ~0.65 nJ is obtained. Figure 3 shows the spectral shape and mode-locked output power of the fs-laser recorded over 17 hours. The spectrum corresponds to a pulse duration of about 15 fs. Although the FWHM bandwidth is 67 nm it is perceivable that the spectrum extends from below 700 nm to more than 900 nm indicating that larger FWHM bandwidths can be accepted. Hence, more effort towards fine-tuning intra-cavity dispersion leads to the formation of a 125nm FWHM spectral bandwidth from the Ti:sapphire laser. Although the overall spectral coverage is not extended which is probably restricted by the used dispersive mirrors the shape of the spectrum supports pulse durations below 10 fs as is shown in Figure 4. The average output power of the sub 10 fs laser amounts to about 115 mW.



Clip[a]	13.5%
Clip[b]	50.0%
Ready #1 ccd_23.2	
Major	2220.7 um
Minor	2002.9 um
Mean	2147.7 um
Eff_2W	2117.7 um
Ellip.	0.88
Orient.	87.3 deg.
Crosshair	87.3 deg.
Xc	263.3 um
Yc	680.4 um
Centroid: [absolute]	
ADC Peak %	87.7%
GFit	0.0%
Image zoom	1
2Wua @ 13.5 %	2240.9 um
2Wub @ 50.0 %	1431.1 um
2Wva @ 13.5 %	2006.3 um
2Wvb @ 50.0 %	1193.6 um

Delta = 711.0 um Pixel I = 54292 (82.8%)
View = 0 : Tilt = -45
Relative Power: 0.00 Full Range = 2
(Trigger off) delay = 0.000 ms
Imager Gain = 1.0
Exposure time = 19.38 ms (Auto)
Scale = 1000.0 um/div Peak = 82.7 %, B = 1.0 %
Scale = 1000.0 um/div Peak = 82.9 %, B = 1.0 %

Clip[a]	13.5%
Clip[b]	50.0%
Ready #1 ccd_23.2	
Major	1477.3 um
Minor	1062.8 um
Mean	1227.1 um
Eff_2W	1226.1 um
Ellip.	0.63
Orient.	88.9 deg.
Crosshair	88.9 deg.
Xc	1019.6 um
Yc	356.8 um
Centroid: [absolute]	
ADC Peak %	85.6%
GFit	0.0%
Image zoom	1
2Wua @ 13.5 %	1494.0 um
2Wub @ 50.0 %	811.0 um
2Wva @ 13.5 %	1063.2 um
2Wvb @ 50.0 %	605.5 um

Delta = 1000.2 um Pixel I = 54780 (83.6%)
View = 0 : Tilt = -45
Relative Power: 0.00 Full Range = 2
(Trigger off) delay = 0.000 ms
Imager Gain = 1.0
Exposure time = 0.108 ms (Auto) (? use m
Scale = 1000.0 um/div Peak = 84.4 %, B = 1.0 %
Scale = 1000.0 um/div Peak = 84.5 %, B = 1.0 %

Figure 2: left: Beam profile of the single-pass SHG output measured at different powers; right: beam profile of the mode-locked Ti:sapphire laser pumped by the DBR diode laser with a single-pass SHG stage.

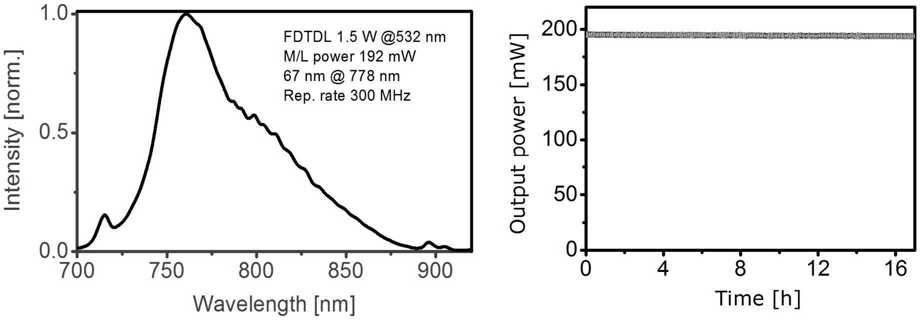


Figure 3: left: spectral intensity of the DBR diode pumped femtosecond laser; right: power monitoring over 17 hours

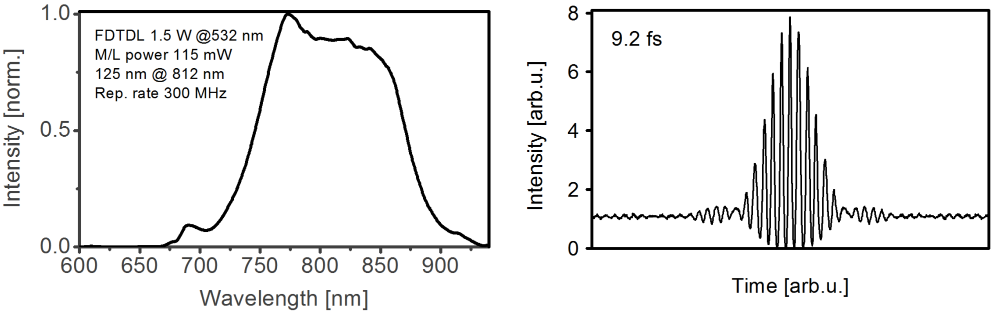


Figure 4: frequency-doubled tapered diode laser (FDTDL) pumps a sub-10 fs Ti:sapphire laser emitting spectral bandwidth of 125 nm; right: measured autocorrelation corresponds to 9.2 fs assuming a hyperbolic secant squared form of laser pulses

In order to scale up the output power of the fs- laser two SHG stages after the DBR tapered diode laser are applied. The optical setup is similar to what has been reported by Hansen et al[7]. Using two different crystals whereas the first one is chosen for most efficient second harmonic generation while the second crystal does better handle thermal effects, 2.4 W of light at 532 nm is obtained. In order to achieve even higher pulse energies and pulse peak intensities we change the repetition rate of the Ti:sapphire laser to 125 MHz by enlarging its cavity length 2.4 fold. When pumped with 2.4 W it delivers output powers of 400 mW in cw and 320 mW in mode-locked operation. This is a 1.7 times higher average power output over the single SHG stage case. However, with regard to pulse energy a four-fold improvement is obtained. Figure 5 shows the femtosecond laser and the pump laser on an optical breadboard. The size of the pump laser that includes both single-pass SHG stages is 183 x 114 x 50 mm³. Its sealed encasement sits on a water cooled base plate which is temperature stabilized at 20 °C. The same cooling is applied to the femtosecond laser. No additional beam shaping, e.g. with cylindrical lenses, is used. Light pulses from the Ti:sapphire laser have spectral FWHM bandwidth of 36 nm centered at 816 nm which corresponds to a pulse duration of about 25 fs.

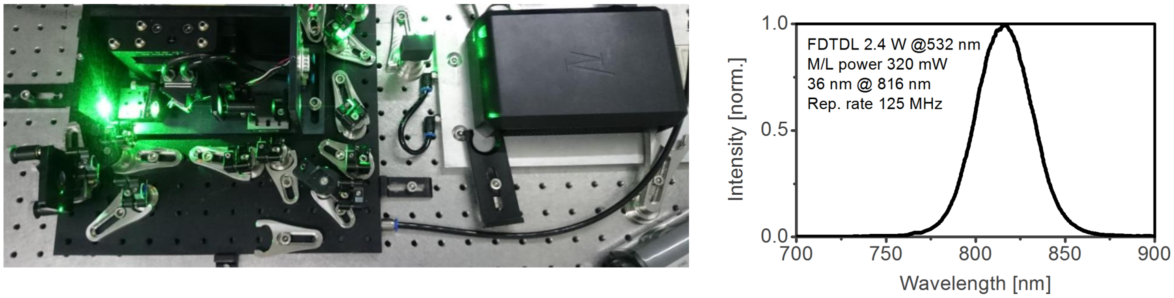


Figure 5: left: laboratory setup of a 125 MHz laser which is pumped by a frequency-doubled tapered diode laser (FDTDL); right: spectral intensity of pulses generated from the FDTDL at 2.4 W

3. DISCUSSION

Despite its non-smooth beam profile the frequency doubled diode laser is shown to fully replace solid-state lasers for high demanding applications like pumping femtosecond lasers in the sub 20 fs range. We achieve close to 200 mW output power with only 1.5 W from a one SHG stage single-pass configuration. The spectral bandwidth of the femtosecond laser easily supports sub 20 fs laser pulses while its base covers almost the full spectral bandwidth of the used dispersive mirrors. We also saw no significant deviation from a pump beam alignment optimized for a state-of-the-art solid-state pump laser, i.e. only very little re-adjustment of the pump lens was required to compensate for different beam divergences of both pump lasers. No compromise in spectral bandwidth and pulse duration is required since even 10 fs laser pulses can be realized. For the first time a sub 10 fs laser is shown to be pumped directly by a single tapered diode laser. This result paves the way for very cost effective high-end femtosecond lasers for being used in applications that basically need a few mW impinging on the region of interest like multi-photon microscopy, THz spectroscopy or optical coherence tomography. Such a fs-laser has already been employed by König et al.[9] inside a commercial multi-photon tomograph and successfully imaged autofluorescence signals from several unstained biological samples, i.e. human skin, adherent cells and epithelial layers as well as stroma of cornea samples. Hence, tapered diode lasers with simple external frequency conversion stages could simply replace bulky and expensive solid-state lasers to finally make affordable fs-lasers possible. Currently the size of this pump laser is mainly determined by the size of the optical isolator. Further development on better robustness of the diode laser to back reflection could avoid necessity of optical isolators and bring down the size of the laser head packaging considerably since the length of the DBR diode laser is only 6 mm. For the first time a cascaded frequency conversion scheme is used to pump a femtosecond Ti:sapphire laser. Although 320 mW marks the highest mode-locked output power ever recorded from a fs-laser pumped by a tapered diode laser we assume that the efficiency can be improved by further optimizing the beam quality emerging from the SHG stages. The moderate efficiency might be caused by thermal effects or formation of astigmatism which has to be reinvestigated. However, due to the larger output power and lower repetition rate the Ti:sapphire laser delivers pulses already reaching 100 kW peak intensities. The laser head can be designed to have a 285 x 285 mm² foot print which already includes the “high power” tapered diode laser. Figure 6 shows how the head size of the femtosecond laser changes over the standard version with a single SHG stage after the tapered diode laser.

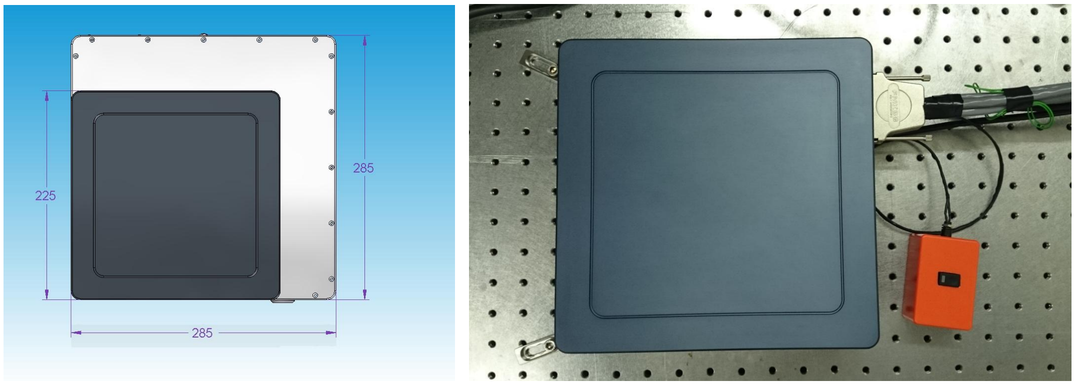


Figure 6: left: size of the laser head containing the 125 MHz Ti:sapphire laser and the “high-power” frequency doubled diode laser (white) compared to the very compact 300 MHz version with a standard 1.5 W version of the pump laser; right: a compact 300 MHz version on an optical breadboard. The orange box simply holds a button to initiate mode-locking of the femtosecond laser.

4. SUMMARY

Frequency doubled diode lasers are very promising candidates to replace existing bulky and expensive lasers used to pump femtosecond lasers. Particularly Ti:sapphire lasers provide very short light pulses and will immensely benefit from new pump light sources since they deliver high light peak intensities even at lowest average powers. This new class of pump laser even meets the criteria to produce fs-lasers providing sub 10 fs pulses. We have shown that a laser head of the size of a sheet of paper is able to generate >190 mW of optical pulses in the sub 20 fs range. By a small enlargement of the foot print, i.e. 25 % on both sides, the power is increased to 320 mW with even 4 times higher pulse energies. However, we guess that this is only the first stage of what can be expected from performances of sub-20 fs or sub-10 fs lasers pumped with this novel kind of lasers. Hansen et al.[7] already reported about 3.7 W diffraction limited green light ($M^2 = 1.25$) from a two stage cascading configuration while Müller et al.[10] could demonstrate up to 4 W green light by sum-frequency generation of spectrally combined tapered diode lasers. Combining both schemes Hansen et al.[11] recently showed that 5.5 W can be reached with conversion efficiencies up to 50 %. Hence, the technology to frequency convert high-end or so-called “high-brightness” laser diodes has opened up a new route to very compact and powerful pump lasers that facilitate very compact and cost-effective sub 20 fs lasers in the 0.5 W or even several Watts range.

Acknowledgement: This work has received funding from the European Union's Seventh Framework Programme (FAMOS, FP7-ICT-2011-3-5a) under grant agreement n° FP7-ICT-317744.

REFERENCES

[1] Stephen G. Anderson, "Optical Coherence Tomography,", SPIE professional, January 2014, <https://spie.org/membership/spie-professional-magazine/spie-professional-archives-and-special-content/spie-professional-archives/archived-issues/2014_jan_archive_spie_pro/2014-january/featured-articles/oct_anderson?ArticleID=x105085,”>

[2] Krstajić, N.; Childs, D.T.D.; Matcher, S.J.; Livshits, D.; Shkolnik, A.; Krestnikov, Igor; Hogg, R.A., "Swept-Source Laser Based on Quantum-Dot Semiconductor Optical Amplifier—Applications in Optical Coherence Tomography," in Photonics Technology Letters, IEEE , vol.23, no.11, pp.739-741 (2011)

[3] Kampfrath, Tobias and Nötzold, Jan and Wolf, Martin, “Sampling of broadband terahertz pulses with thick electro-optic crystals,” Applied Physics Letters, 90, 231113 (2007)

[4] Prashanth C. Upadhya, Wenhui Fan, Andrew Burnett, John Cunningham, A. Giles Davies, Edmund H. Linfield, James Lloyd-Hughes, Enrique Castro-Camus, Michael B. Johnston, and Harvey Beere, "Excitation-density-dependent generation of broadband terahertz radiation in an asymmetrically excited photoconductive antenna," Opt. Lett. 32, 2297-2299 (2007)

[5] Ole Bjarlin Jensen, Peter E. Andersen, Bernd Sumpf, Karl-Heinz Hasler, Götz Erbert, and Paul Michael Petersen, "1.5 W green light generation by single-pass second harmonic generation of a single-frequency tapered diode laser," Opt. Express 17, 6532-6539 (2009)

[6] André Müller, Ole Bjarlin Jensen, Angelika Unterhuber, Tuan Le, Andreas Stingl, Karl-Heinz Hasler, Bernd Sumpf, Götz Erbert, Peter E. Andersen, and Paul Michael Petersen, "Frequency-doubled DBR-tapered diode laser for direct pumping of Ti:sapphire lasers generating sub-20 fs pulses," Opt. Express 19, 12156-12163 (2011)

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

[8] A Xu, L., A Tempea, G., A Poppe, A., A Lenzner, M., A Spielmann, C., A Krausz, F., A Stingl, A., A Ferencz, K., “High-power sub-10-fs Ti:sapphire oscillators,” Applied Physics B Lasers and Optics 65, Number 2, Page 151 (1997)

[9] König, K., Andersen, P., Le, T. and Breunig, H. G., "Multiphoton imaging with a novel compact diode-pumped Ti:sapphire oscillator," Microsc. Res. Tech. 78, 1154–1158 (2015)

[10] André Müller, Ole Bjarlin Jensen, Karl-Heinz Hasler, Bernd Sumpf, Götz Erbert, Peter E. Andersen, and Paul Michael Petersen, "Efficient concept for generation of diffraction-limited green light by sum-frequency generation of spectrally combined tapered diode lasers," Opt. Lett. 37, 3753-3755 (2012)

[11] Anders K. Hansen, Peter E. Andersen, Ole B. Jensen, Bernd Sumpf, Götz Erbert, and Paul M. Petersen, "Highly efficient single-pass sum frequency generation by cascaded nonlinear crystals," Opt. Lett. 40, 5526-5529 (2015)